Cost-effective imprint template fabrication for step and flash imprint lithography

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Cost-Effective Imprint Template Fabrication for Step and Flash Imprint Lithography

Abstract of
A thesis presented to the Faculty
of the University at Albany, State University of New York
in partial fulfillment of the requirements
for the degree of
Masters of Science
College of Nanoscale Science and Engineering
Department of Nanoengineering

Adam Munder
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Abstract

The College of Nanoscale Science and Engineering (CNSE) is studying imprint template fabrication with the 100kV Vistec VB300 Gaussian E-Beam writer. The major goal is to develop and advance imprint template fabrication technology using low cost quartz wafers for proof-of-concept demonstrations.

The Molecular Imprints NanoImprint Lithography (NIL), Imprio® 300 system, uses templates to imprint in a low-viscosity UV cured material at a low pressure and room temperature. This minimizes magnification and distortion errors, and enables precise pattern placement compared to the other imprinting methods such as Soft Lithography and Hot Embossing. However, the cost of writing time on the imprint templates using 100kV Gaussian writer can become expensive. More industry and academic university collaboration is needed. With regard to ITRS requirements in the near future, NIL is a potential candidate for 22nm and beyond.

To advance imprint template fabrication, a low cost quartz wafer development process was demonstrated at CNSE that planned to transfer a specific pattern onto the Molecular Imprints 65mm template format. A number of tools including e-beam, coat/develop and etch were modified to accommodate both the 65mm imprint template and the 3-inch wafer format. Over 100 cycles of learning were completed on 3” quartz wafers and infrastructure strengths and weaknesses in support of imprint template fabrication were identified.
Cost-Effective Imprint Template Fabrication for Step and Flash Imprint Lithography

A thesis presented to the Faculty of the University at Albany, State University of New York in partial fulfillment of the requirements for the degree of Masters of Science College of Nanoscale Science and Engineering Department of Nanoengineering

Adam Munder
2011
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I want to greatly express my gratitude to Professor John G. Hartley for giving me a unique, exciting and challenging project for my thesis work. Through my MS program, I have been transitioned to different mask technology projects such as EUV Mask Flatness and Mask Holder Design Optimizations for VB300 Electron Beam Lithography. In addition, I was able to do some E-Beam patterning applications for the other research groups. This increased my experience and I was faced with the limitation of using E-Beam lithography for fabricating post-CMOS physics devices and a biological application. I also want to thank both Dr. Michael Yakimov and Dr. Serge Oktyabrysky for letting me use their etcher system. Therefore, I did not need to drive to Cornell University to use their etcher at the beginning of my research activity and doing etch by myself at CNSE benefited my work by helping me understand the different variable parameters when etching chromium and quartz. In addition, Dr. Yakimov helped maintain the etcher tool. I want to give a lot of respect to Ravi Bonam for starting up basic VB300 standard processes for Advanced Lithography Group and he was the first person guiding me to use VB300. Not only Ravi Bonam, I want to thank Ananthan Raghunathan and Adam Lyons for attempting to mature proximity effect correction mechanism at a critical point in the middle of my project. Close to the end of my work, Adam Lyons helped me a lot with handling infrastructure for mask manufacturing at CNSE. Matt Malloy also led me to use a Hitachi CDSEM and attempted to set up
automated measurements for quartz wafers.
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Acronyms

Buildings
CNSE = College of Nanoscale Science and Engineering
CNF = Cornell Nanoscale Center of Science and Technology
NFS = NanoFab South Building of CNSE
CESTM = Center Environmental Science and Technology Management Building of CNSE

Companies & Conferences
TSMC = Taiwan Semiconductor Manufacturing Company
GF = Globalfoundries
MII = Molecular Imprints
EIPBN = Electron, Ion, Photon Beam Technology and Nanofabrication

Tools & Technologies
S-FIL™ = Step and Flash Imprint Lithography
E-Beam Lithography = Electron Beam Lithography
Litho = Lithography
NIL = Nanoimprint Lithography
UV = Ultraviolet
DUV = Deep Ultraviolet
EUV = Extreme Ultraviolet
PVD = Physical Vapor Deposition
E-Beam Evaporator = Electron Beam Evaporator
ECD = Electrochemical Deposition
CMP = Chemical Mechanical Polishing
E-Beam = Electron Beam
AFM = Atomic Force Microscopy
SEM = Scanning Electron Microscopy
eSEM = Environmental Scanning Electron Microscopy
XPS = X-Ray Photoelectric Spectrometer
EDX = Energy Dispersive X-Ray
HVM = High Volume Manufacturing
CPU = Central Process Unit
DMM = Digital Multimeters

E-Beam Parameters
GB = Gaussian Beam
TFE = Thermal Field Emission
GDS = Graphical Data System File Format
GDSII = Graphical Data System II File Format
XRZ = Coordination Data File Format
PSF = Point Spread Function
CATS = Fracturing Operation Software
PEC = Proximity Effect Correction
VEP = Readable Machine Format File for VB300
BSS = Beam Step Size
FWHM = Full Width at Half Maximum

Etcher Technology
E-Chuck = Electrostatic Chuck
RIE = Reactive Ionization Etching
ICP = Inductively Coupled Plasma
DC = Direct Current
RF = Resonance Frequency

Materials & Chemicals
Cr = Chromium
Qz = Quartz
SiO₂ = Silicon Oxide
Si = Silicon
E-Beam resist = Electron beam resist
MoSi=Molybdenum disulfide
ULTE = Ultra Low Thermal Expansion
TMAH = Tetraethyl ammonium hydroxide
Warm Hydrogen Fluoric = Warm HF
DI Water = Ionized Water
MIBK = Methyl isobutyl ketone
NaOH = Sodium Hydroxide
KOH = Potassium hydroxide
IPA = Isopropanol
NaCl = Sodium Chloride
Fn = Fibronectin
Cl₂ = Chlorine
O₂ = Oxygen
HCl = Hydrochloride
CCl₄ = Carbon tetrachloride
CHF₃ = Trifluoromethane
CF₄ = Fluorocarbon
AlF₃ = aluminum fluoride
Measurements

\( \text{nm} = \text{Nanometer} \)
\( \mu \text{m} = \text{Micrometer} \)
\( \mu \text{C/cm}^2 = \text{Micro-Coulomb per squared centimeter} \)
\( m\text{C/cm}^2 = \text{Milli-Coulomb per Squared centimeter} \)
\( \text{mg} = \text{Milligram} \)
\( C = \text{Celsius} \)

Resists

\( \text{ZEP} = \text{Positive tone electron beam resist from Nippon Zeon} \)
\( \text{SAMs} = \text{Self-assembled monolayers} \)
\( \text{PMMA} = \text{Polymethylmethacrylate} \)
\( \text{HSQ} = \text{Hydrogen Silsesquioxane} \)
\( \text{CAR} = \text{Chemically Amplified Resist} \)
\( \text{NEB} = \text{Poly vinyl phenol based, chemically amplified, negative tone e-beam resist} \)
\( \text{SU-8} = \text{Negative-tone, chemically amplified, epoxy based photoresist originally developed by IBM} \)

Lithography Process

\( \text{CD} = \text{Critical Dimension} \)
\( \text{LWR} = \text{Line Width Roughness} \)
\( \text{LER} = \text{Line Edge Roughness} \)
\( \text{RLS} = \text{Resolution, Line Edge Roughness and Sensitivity} \)
\( \text{CDU} = \text{Critical Dimension Uniformity} \)
\( \text{BSS} = \text{Beam step size} \)
\( \text{Exel} = \text{field size divided by bit system for pattern generator} \)
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1 Introduction

This thesis focuses on a complete understanding of the quartz wafer development process, which is similar to S-FIL™ template fabrication processes. The College of Nanoscale Science and Engineering (CNSE) studied imprint template fabrication technology with the Vistec VB300 100kV E-Beam Gaussian Writer. CNSE used low cost quartz wafers and the major goal was to demonstrate a quartz wafer development process transferable onto individual imprint templates.

1.1 Motivation

The thesis proposed here was trying to find an alternative cost-effective imprint template fabrication for Step and Flash Imprint Lithography (S-FIL™) after developing the quartz wafer development process at CNSE. S-FIL™ may be a candidate for manufacturing 22nm node transistor and beyond [1] and non-IC applications [2], which require high resolution. As an application of a low cost template development process non-IC applications will be examined as a potential fabrication for S-FIL™. However, S-FIL™ for IC applications needs to meet defect control level, yields, ‘Resolution Line Edge Roughness and Sensitivity’ (RLS) and throughput [5] before Semiconductor Industry can use it. Molecular Imprints introduced S-FIL™ to the Semiconductor Industry during the last decade because of its ability to meet and exceed device resolution
and feature density requirements. Its price tag is still attractive to the Semiconductor Industry because it offers the lowest Cost of Ownership (CoO) among the competing 22nm node lithography solutions [3]. International SEMATECH addressed some critical issues on process and template [6] and called for industry involvement. This is essential to improve the imprint template manufacturing for the S-FIL™. International SEMATECH had another concern with a high cost for fabricating imprint templates [6]. Gaussian E-Beam writer technology has been demonstrated for high-resolution feature patterning. International SEMATECH and the Semiconductor Industry [7] need to better understand how to fabricate the high-resolution imprint template. A number of articles indicated that resolution of the fabricated templates had been limited by E-Beam lithography [9][10][11][12].

1.2 Literature

This Thesis references a large body of literature on history, competitive lithography solutions and S-FIL™ technology including template fabrication processes. Current imprint template fabrication technology has made progress but still needs to find a cheap way to fabricate the imprint template.

1.2.1 History

Gordon Moore made his famous statement based on his observation about doubling the density of the IC in 1965 [13]. He was the co-founder of Intel and the first person
recognizing that the number of transistors per unit area on ICs had approximately doubled every 18 months. Later, this was formally recognized as Moore’s Law. Moore predicted that this trend would continue for the foreseeable future. However, the pace has been slowed down a bit recently due to limited resolution of pattern [15][8]. Nevertheless, data density has still doubled approximately every 18 months. Moore’s Law becomes less accurate with the struggle to shrink pattern sizes. Fortunately, the Semiconductor Industry has introduced a number of chip architectures such as 3D interconnection, intelligent circuit designs and multi-processors to allow more data per IC. The Semiconductor Industry was able to use lithography to increase the amount of data per IC. Scientists and engineers introduced amazingly competitive lithography solutions in order to meet Moore’s Law. Some believe that popular optical lithography will be the bottleneck of shrinking the pattern to 20nm features and beyond soon due to complicated engineering systems and skyrocketing costs.

1.2.2 Competitive Lithography Solutions

Lithography is the engine that has driven the world’s high technology economy today [14] since the breakthrough with fabricating integrated circuit in 1959 [15]. Photon-based lithography has dominated the technology in the industry to date. Scientists and engineers all over the world have expanded to several photolithography architecture systems including Deep UV (DUV) and Immersion (193i). They are the most heavily used because of their excellent high throughput and because they use light to simply
make patterns selectively using masks. They can yield many wafers every hour. Various lithographic tools have evolved to sustain the Semiconductor Industry today as well as in the future. The industry contributions are continuously focusing on improved resolution, new materials and processes.

A complex engineering system with optics, double patterning technologies, immersion and shortened wavelength to 13.5nm are steering to the needs for Next Generation Lithography (NGL). Extreme Ultraviolet (EUV) is not ready for HVM as of mid-2011 due to limitations of the power source, resist performance and masks defect levels [16]. In the meantime, the costs have skyrocketed [16]. E-Beam Direct Write Technology (EBDW) is projected to cost less than EUV and Immersion Lithography and therefore is of interest to a number of IC companies. Single Gaussian E-Beam Writers such as the
Vistec VB300 are capable of patterning high-resolution structures in material resists but with serious throughput limitations. S-FIL™ has the same resolution capability as the Gaussian writer technology [18][19][20]. The current technology for 4X masks manufacturing uses a variable shaped beam and character projection, which make the writing times faster. A long writing time is not acceptable for manufacturing direct-write wafers. Gaussian writer technology is suitable for high-resolution, low-volume chips and prototype devices, but it is not appropriate for HVM.

1.2.2.1 Alternative E-Beam Technology

Scientists and engineers introduced some new E-Beam system architectures at a number of conferences and publications. They can be found in ebeam.org website. MAPPER, KLA-TENCOR, MultiBeam Corp and other companies have developed different innovative electron beam configurations. There are a few types of potential beam technologies: Single source/Single column, Multi source/single column, Multi-source/Multi-column, Multi-Shaped (MSB) and reflective optics. Mapper Lithography and KLA-Tencor take serious action focusing on a single source with a single column. Advantest and Multibeam Corp focus on multi sources with a single column and multi sources with multi columns, respectively. Figure 2 a shows the different Multi-Beam system architectures.
KLA-TENCOR with sponsorship from DARPA has put significant effort in developing reflective optics using a MEMS device to control a mirror array to reflect electrons from the digital pattern generator, as shown in Figure 2 b. Consequently, E-Beam teams keep introducing innovations in stage, data pipeline, columns in a system and others.
1.2.2.2 Photolithography

The Semiconductor Industry uses photolithography with reasonable cost to make computer chips for HVM. Photolithography uses 193nm wavelength of light to transfer a geometric pattern from the 4X mask to a light-sensitive chemical resist on the wafer substrate. The multiplication of light wavelength and coefficient factor divided by numerical aperture gives minimum feature size.

\[ CD = k_1 \frac{\lambda}{NA} \]

Equation 1

Where
- \( CD \) = Critical Dimension
- \( \lambda \) = Wavelength of light
- \( k_1 \) = Coefficient Factor
- \( NA \) = Numerical Aperture

Numerical Aperture is a measure that gathers light rays and resolves a sufficient good image at a distance between objective lens and image plane [21]. It is not always possible to achieve 100 percent when shrinking CD. The numerical aperture of an optical system, as shown in Figure 3, is defined by,

\[ NA = n \sin \theta \]

Equation 2

The index of refraction \( n \) depends on the material of lens and theta, \( \theta \), is the half-angle of the maximum cone of light that enters or exits the lens. As for CD, decreasing wavelength and increasing the numerical aperture give the most minimum feature size as
possible. CD can be imaged as proportional to the wavelength and inversely proportional to NA [132].

![Figure 3 Numerical Aperture of an optical system](image)

Source: [132]

To continuously increase the NA, the air gap between the final objective lenses and substrate is immersed in water to increase the index of refraction. The index of refractive of water is ~1.4 compared to ~1.0 for Air. This method is applied to immersion lithography that can shrink the CD by 30 to 40 percent. The value of NA for immersion lithography is larger than dry lithography’s.

### 1.2.3 Nanoimprint Fabrication Methods

Professor Stephen Y. Chou from Princeton University initially proposed NanoImprint Lithography in the mid-1990s and named it NIL [2]. It is one of the most promising
technologies for high throughput nanoscale patterning. A number of groups developed additional imprinting technology concepts, which have some benefits and limitations. An extensive body of literature [2][10] explains three different imprint lithography technologies: Hot Embossing Nano-Imprint Lithography, Soft Imprint Lithography and UV Nanoimprint Lithography.

1.2.3.1 Hot Embossing Nanoimprint Lithography

This technology uses a heated solid template to imprint in resist to form a pattern (HE-NIL) [31]. This process is similar to S-FIL™, but it does not use UV light lamp to cure the resist. HE-NIL presses the solid stamp into a thermoplastic material to form a pattern. During this process stage, heat and pressure is well controlled and applied in the area under the stamp. After cooling the pattern, the stamp is lifted up when the pattern material is below the glass transition temperature.

1.2.3.2 Soft Imprint Lithography

Professor George M. Whitesides from Harvard University proved the concept of soft imprint lithography (SIL) [31]. It is a low cost, non-photolithographic strategy for carrying out nanofabrication. Its elastomeric template is made of Polydimethylsiloxane (PDMS) and this is good to have alkanethiol molecules (ink) on it to transfer easily onto the surface of gold by contact. When the PDMS template with a relief structure comes in contact with the gold surface, the chemical reaction forms self-assembled monolayers.
(SAMs) around 100nm. SAMs are hydrophobic and act as the etching stop layer for either a dry or a wet etching process. All these techniques for SIL are still in their early stages of development.

1.2.3.3 Laser Assisted Direct Imprint

A research group at Princeton University believed that Laser Assisted Direct Imprint (LADI) is the potential of direct patterning on substrate without complicated chemical etching. Professor Stephen Y. Chou in 2002 [29] demonstrated a rapid technique for directly patterning nanostructure. Without imprinting a thin resist film, LADI can pattern straightforward on substrate, i.e. Silicon, Ge, III-V compounds, but requiring quartz template. LADI uses a single excimer laser pulse to melt a thin surface layer of silicon; a mold is fast embossed into the liquid layer. Chou demonstrated Sub-10nm features and beyond on the silicon substrate. Cooling and curing the molten layer, the features on the mold were transformed to the silicon substrate. Both S-FIL and LADI use the same approach to get their molds fabricated out of the quartz material.

1.2.3.4 UV Nanoimprint Lithography

Step and Flash Imprint Lithography (S-FIL™) [4] is an alternative to photolithography and is a form of ultraviolet nanoimprint lithography (UV-NIL). S-FIL™ is a trademark for Molecular Imprints (MII). It has demonstrated for sub-100nm geometric pattern in a number of publications [6][9][10][11][12] and was widely used in fabricating memory
devices for the Semiconductor Industry in last 10 years. It uses an imprint template as a mold that smoothly stamps on an array of pico-liter sized drops of a low viscosity monomer on predefined subfields on a wafer. This imprints high-resolution features in different locations on a large substrate under low pressure and at room temperature, which effectively minimize magnification and distortion errors. The S-FIL™ creates precise pattern placements compared to the other imprinting methods like Soft Lithography with a PDMS template and Hot Embossing Lithography with a heated solid mold [10][11][12]. Molecular Imprints introduced this unique S-FIL™ technology using the step and flash approach for fairly good throughput with four 300mm wafers each hour. Immersion lithography, by comparison, can carry more than 100 wafers per hour and becomes significantly expensive when using a double patterning technology [3].

Figure 4 shows all three different fabrication sequences for Soft Lithography, HE-NIL and S-FIL
S-FIL™ does not use any projected photons or electrons to form a pattern. It is a molding process rather than imaging process. The inkjet technology deposits an array of pico-liter UV curable resist spreading on predefined subfields on the 300mm wafer, as shown in Figure 6 a. This works by displacing a very thin fluid layer on the wafer with a contact mold. After the mold displaces the fluid, a mercury arc lamp serving as a source of broadband actinic radiation cures the fluid, as shown in Figure 6 c. Then, the mold pulls away from the substrate leaving the pattern behind, as shown in Figure 6 d. Then, the process moves on to the next copy.

### 1.3 S-FIL™ Technology

Molecular Imprints supplies this technology with the Imprio 300, as shown in Figure 6. In the sophisticated, market today, as for throughput, four 300mm wafers per hour have
successfully passed through Imprio 300 with 32nm half pitch with less than 10nm 3σ alignment [26]. This system performs at a room temperature and uses a low-pressure level to press the template on the 300mm wafer. This minimizes magnification and distortion errors, and creates precise pattern placements compared to the other imprinting methods like soft lithography with a soft template and HE-NIL with a heated solid mold.

![Figure 6 Molecular Imprints Imprio 300](image)

International SEMATECH operates the nanoimprint system installed at CNSE’s Nanofab facility for testing the standard IC process. International SEMATECH also purchased imprint templates including 22nm half-pitch lines from Dai Nippon Printing (DPI) a supplier, who has a strong relationship with Molecular Imprints. The Imprio 300 currently demonstrates 22nm half-pitch lines printing on 300mm wafer substrate.
1.4 Advantages and Challenges of Step and Flash Imprint Lithography

Intel fellow Sam Sivakumar said, “EUV is too late for Intel’s 14nm node, and may be too late for the development of 10nm generation design-rules.” Intel is known for leading the world in the race to printing the smallest features, and Intel plans to proceed with manufacturing 10nm node in HWM in 2015. S-FIL™ may be considerably a candidate for sub-10nm resolution, but the NGL cannot achieve this within a reasonable budget for most manufacturers.

EUV can potentially achieve sub-10nm resolution, but it is very expensive and may be too late for the development of sub-10nm. DUV lithography cannot get there because it has the limitation with shrinking light wavelengths to make structures smaller on the wafers. Immersion lithography can shrink down to 22nm resolution, but it is still expensive.

Intel continues to use immersion double-patterning (193i-DP), which is expected to
extend to the 11-nm resolution announced last February 2011. Intel is different from
taiwan semiconductor manufacturing company (TSMC) and Globalfoundries (GF)
because TSMC and GF work with customers to manufacture chips. EUV is forced to put
in TSMC and GF’s picture to manufacture the chips for small to medium size volume
chips.

The S-FIL™ can shrink below 10nm resolution structures printed on the wafers,
but the E-Beam lithography and directed self-assembly must be feasible to get sub-10nm.
That is the major challenge for making sub-10nm imprint templates. Without the
challenges of fabricating imprint templates, S-FIL has many advantages over NGL.

S-FIL™ offers a good throughput, low cost, high reproducibility and the capability
of creating patterns with features as small as 10nm over large areas. The Semiconductor
industry recognizes that S-FIL™ has the ability to pattern high-resolution features
compared to the other next generation lithography (NGL) like EUV, double patterning
and immersion lithographies, which have difficulty meeting the HVM requirements.

First, EUV lithography requires a complex engineering system with optics and
shortened wavelength to 13.5nm. The complex engineering system needs to a number of
reflective optics and performs at an ultrahigh vacuum level and use expensive fabricated
precision reflective masks. To limit losses and limit contamination on the optical
surfaces ultrahigh vacuum is required. Reflectivity losses are due to large numbers of
reflective optics with typical individual reflectivities of 66%. In addition, oxidation built
up on the mask and airborne contaminates can further contribute to reflectivity
degradation.

Second, immersion 193nm lithography uses the same technology as conventional 193nm lithography, but it replaces the usual air gap between final lens and the wafer surface with a liquid medium that has a refractive index greater than one. The resolution is increased by a factor to equal to the refractive index of the liquid. Third, there is another way to shrink denser pattern using immersion lithography, which uses double patterning technology. This requires best alignment automations to pattern twice in two different overlay layers using two different masks, respectively, at different times. It becomes even more complicated and expensive than EUV technology [3]. Fourth, the 100kV Gaussian E-Beam writer is widely capable of patterning high-resolution features, but it is excessively slow to pattern in an electron sensitive resist coated substrate.

However, S-FIL™ does not have a limitation with optical proximity effects and light wavelength to achieve high-resolution patterns. It also has a better throughput than the 100kV Gaussian E-Beam writer. However, the challenges remain, especially with the template and process for sub-20nm resolution. S-FIL™ is also eventually a potential candidate for sub-10nm applications [34]. S-FIL™ was widely capable for fabricating memory devices such as hard drive and bit patterned media. The Hard Drive Industry decided to stop using imprint lithography for bit patterned media in early 2011 [27] and changed its focus to heat assisted magnetic recording (HAMR), which is much cheaper than the imprint lithography.
1.4.1.1 Flexible Rules

The template realistically replicates the imprint resist on the substrate. Optical Proximity Correction (OPC) and Mask Error Enchantment (MEEF) have no contributing factors in imprint lithography. 1X template manufacturing does not present more challenges. It provides the designers with complete freedom to design structures without any lithography based design rules. What you see is what you get.

1.4.1.2 Lower Capital Cost

![Figure 8 Cost of Ownerships of Different Lithography Solutions](source: [3])
MII provided the chart showing that S-FIL™ has both a lower fixed and a lower mask cost than other 22nm lithography solutions. However, 1X template manufacturing is a major concern due to the expense of writing time. A longer writing time means a higher cost. A capital expense usually dominates the lithography fixed costs. However, imprint lithography has a relatively lower cost, except for manufacturing imprint templates. Imprint lithography does not require expensive precision lenses, mirrors and advanced source required by 193nm and EUV.

1.4.1.3 Three Dimensional Printing

E-Beam lithography can fabricate multi-level or curved features etched into the quartz templates. Then, S-FIL™ has the capability of three-dimensional printing and is a potential candidate for single step imprinting of dual damascene structures (multilevel features) [28], shown in Figure 9, or direct imprinting of micro-lenses for CMOS imaging devices (curved features) discussed in the referenced paper [17].

Figure 9 Imprinted dual damascene with barrier metal and copper fill
1.5 IC and Non-IC Applications

1.5.1.1 Rising Nanotechnologies

Nanotechnology is a broad term and its definition from the Merriam Webster online dictionary (http://www.merriam-webster.com/) is, “the science of manipulating materials on an atomic or molecular scale especially to build microscopic devices….”

Now nanotechnology is a part of modern civilization and it is continuously changing aspects of the way we live. The nanotechnology revolution in manufacturing is changing both society and the way we make things, not limited only to the Semiconductor Industry. It is the next phase of Moore’s Law [25].

1.5.1.2 Semiconductor Industry

The Semiconductor Industry pushes to a 22nm node transistor and beyond on Si substrate for making computer chips. The crucial driver for reliable and high-throughput lithography machine is the ability to shrink transistors on an IC chip. With its continuous effort to make faster and more powerful chips, the Semiconductor Industry is still pushing to decrease the length of the transistor gate to 22nm by today.

1.5.1.3 Non-IC Applications

Not only for electronics, S-FIL™ stamps the imprint template to define patterns in imprint resist on substrates to form structures through etching or lift-off process for
optics, optical devices, biology, materials, and Micro-electro-mechanical systems (MEMS) [34].

One such non-IC application was selected as a demonstration target for the template manufacturing process. The biological application selected is a screening tool for analyzing Fibronectin (Fn), which is a large flexible protein stabilized by intermolecular ionic interactions. Fn can be either a compact or an elongated structure when it is in contact with mica, silica and ethylated silica surfaces, depending on intermolecular ionic interactions [35], as shown in Figure 10 below.

This study case was suggested by Professor Magnus Bergkvist [36] who designed the screening tool for Fn. His design pattern includes two different features: isolated 10nm
dot array for holding Fn and large alignment markers, as shown in Figure 11 b and c, revealing on a Si substrate, as shown in Figure 11 a, or a SiO\textsubscript{2} film on top of Si substrate through the etching process. This was for proof-of-concept demonstration using Vistec VB300. Atomic Force Microscopy (AFM) will be able to see the alignment marker with its optical microscope and investigate the structure of Fn held by 10nm bump array near alignment marker.

NIL is reasonable with its price to fabricate biological applications [34]. Instead of using Vistec VB300 to write on resist coated Si substrate, the S-FIL\textsuperscript{TM} process imprints the negative-tone image of the resist structures on the Si substrate. In order to have the
recessed contacts on the template, the reversal image is required on the template to imprint 10nm spot array in negative-tone image on Si substrate. The reversal image will be explained in the section 1.7.

Imprint lithography is the key to the biology community for fabricating a number of biological research applications, including microfluidics, scaffolds for cell growth, analysis and drug delivery [34]. However, there were some challenges with biological applications because of the length of time to get revenue [37].

1.6 Imprint Template Fabrication

Some researchers from University of Texas at Austin [38] have tried to push E-Beam lithography to pattern high-resolution 20nm features and beyond on imprint templates. Industrialized mask shops are heavily involved in making 4X photomasks, not always focusing on the 1X pattern required for the newer imprint templates. Many mask shops are really ready to make 1X templates, except DPI because DPI and Molecular Imprints have a strong relationship for imprint template fabrications using the standard 6” mask. Imprint template are similar to masks used for photon-based lithography in a number of ways. Figure 12 shows the Imprint Mask design.
The imprint template fabrication is following a process similar to a conventional 6” x 6” x ¼” phase-shift reticle processing for the photon-based lithography. In the standard chromium (Cr) process, a fused silica reticle coated with a thin <15nm Cr film is spin coated with an E-Beam resist. Then, a hot plate bakes it to cast the solvent. An E-Beam writer exposes the electron-sensitive material followed by a developing process yielding either positive or negative tone images. The patterned resist forms the etch mask to pattern the Cr using dry chlorine-based etching. After stripping the E-Beam resist off, a fluorine-based etching transfers the images into the reticle to a depth of 2:1 ratio with the lines. A final design decision must be made in order to achieve the desired pattern sizes. For example, 22nm lines should have a 44nm trench depth. Last, a laser or other cutting method sections the fabricated reticle into four pieces with 65mm factor dimension each, as shown in Figure 13.

Before dicing into the four pieces from the protective overcoating 6” mask, individual pieces have the 15µm mesa structures, which are kept when etching the
outside of them.

![Figure 13 Four templates on a standard 6025 photomask substrate in top view](image)

The core out of the imprint template has less quartz and makes the backside-thinning plate more flexible. It is designed for high throughput. Imprint template backside thinning specifications, as shown in Figure 14, increase throughput by enabling better fluid flow control during imprinting.

![Figure 14 65mm Factor Imprint Template with Core Out](image)
1.6.1 Challenges

A major challenge is how we can build the templates for a nanoimprint system in real production.

First, writing time could become a roadblock for imprint template fabrication. Writing time for E-Beam lithography can become expensive.

Second, 1X pattern is the challenge for industrialized mask shops. The industry has not pushed to print smaller patterns on 4X mask until they have to fabricate 1X imprint template for S-FIL™. They are required to etch smaller structures on quartz templates as part of the template fabrication process.

Third, industrialized mask shops tend not to have a good writing strategy for 20nm features and beyond. It is not easy to write smaller structures in material resists and many universities have demonstrated this with some best efforts from their research laboratory. E-Beam lithography has unavoidably beam scattering event while writing on the mold [48][49]. Some of them have demonstrated less than 20nm features [47] by tweaking development process, thinner e-beam resist, manual dose assignment, improving write strategy. Industries generally find something that is good enough and then move onto other things. This is truly the norm in an industry environment [111]. Consequently, the E-Beam lithography frequently limits the quality of the mold fabrication process due to poor fundamentals for correcting the proximity effect.
1.6.2 Flow Processes for Imprint Template

S-FIL™ has two different flow processes: Feature Proud and Field Proud, as shown in Figure 15. They are similar to bright field and dark field in optical Lithography. A “Field Proud” contains cavities in the fused silica reticle that imprints a resist in negative-tone image on wafer substrates. On the other hand, a “Feature Proud” refers to imprint templates with feature rising from the fused silica reticle for positive-tone imprinting process. Having two different flow processes can have important implications for process robustness and throughput for advanced imprinting applications.

![Figure 15 Field Proud and Feature Proud](image)

1.6.3 1X Imprint Template Manufacturing

Figure 16 shows the conventional imprint template fabrication. A sputtering tool such as an E-Beam Evaporator deposits ≤15nm chromium (Cr) film onto the bulk quartz substrate. After resist apply, E-Beam lithography operating at 100kV accelerating voltage, electron beam scans across the electron-sensitive resist coated on the Cr-based quartz substrate. The thinner Cr pattern functions as a hard etch mask for the pattern
transfer onto quartz substrate through dry etch process. It also has a benefit of eliminating charging problems during E-Beam writing. After the exposure, the developing process removing exposed or unexposed resist dependent on positive or negative-tone resist, respectively. A descumming process removes the resist scum on the templates. A dry etch system first etches the Cr film with the patterned resist mask on it and second etch step removes the resist. A wet chemical also can remove the resist on top of the patterned Cr mask instead of using the dry etcher system. Then, the Cr mask protects the underlying quartz during the quartz etch process and turns into a relief structure followed by removal of the Cr. The relief structure on the imprint template is for proximity contact in the imprinting process. In order to avoid trapping resist in the relief structure, sufficiently deep trenches should be about 2:1 ratio for the imprinting process.

Figure 16 Fabricating Imprint Templates
1.6.4 E-Beam resists

Not many commercial resist systems are available for high resolution today. Different electron-sensitive resist materials are compatible to serve as a mold for S-FIL™. The properties of the resist including contrast, sensitivity and etch resistance have a big impact from a number of factors ranging from the manner of storage to the detailed development process. E-Beam resists compared in a number of articles in E-Beam lithography technology are shown in Table 1,

<table>
<thead>
<tr>
<th>Resist Type</th>
<th>Smallest printed features</th>
<th>Exposure Dose</th>
<th>Beam Voltage</th>
<th>Limiting Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSQ [95]</td>
<td>6nm isolated line 8nm half pitch lines</td>
<td>2000 – 4000 μC/cm²</td>
<td>100keV</td>
<td>High Dose required; expensive writing time</td>
</tr>
<tr>
<td>SU-8 [95]</td>
<td>22nm isolated lines 34nm lines and spaces</td>
<td>30 - 50 μC/cm²</td>
<td>100 keV</td>
<td>Higher sensitivity; high LER</td>
</tr>
<tr>
<td>SAMs [96]</td>
<td>25nm lines and spaces</td>
<td>150μC/cm²</td>
<td>50 keV</td>
<td>Complex etching process</td>
</tr>
<tr>
<td>NEB [95]</td>
<td>16nm lines and spaces</td>
<td>40 μC/cm²</td>
<td>100 keV</td>
<td>Fairly High LER</td>
</tr>
<tr>
<td>Fullerene [112]</td>
<td>14nm lines on a 200nm pitch</td>
<td>200 pC/cm²</td>
<td>30 keV</td>
<td>Difficultly fabricating thin, defect-free film resist layers and low sensitivity</td>
</tr>
<tr>
<td>Metal Oxide [98]</td>
<td>Sub-10nm lines with 30nm pitch</td>
<td>292.5 μC/cm²</td>
<td>20 keV</td>
<td>Instability of the pattern; low sensitivity</td>
</tr>
<tr>
<td>Nanocomposite [99]</td>
<td>100nm lines and spaces</td>
<td>26 μC/cm²</td>
<td>30 keV</td>
<td>Insufficient knowledge of the process of incorporating nanoparticles into the resist layer</td>
</tr>
</tbody>
</table>
A negative-tone Hydrogen Silsesquioxane (HSQ) resist and a positive-tone ZEP520A resist are the first choices to serve as the mold for S-FIL™. As of today, PMMA is well understood for having excellent resolution, but its etch resistance is significantly poor [54]. Chemically amplified resist (CAR) [12] is very difficult to handle when compared to HSQ due to acid diffusion length contribution with post apply bake. However, HSQ offers better Line Width Roughness (LWR) [43], very good latitude and linearity, but it has moderate contrast with high doses used in Gaussian E-Beam writer [42][43]. HSQ and ZEP520A [45] also have exhibited high plasma resistance. ZEP520A has a resolution limitation compared to HSQ, but ZEP520A has a reasonable cost for fast writing time for positive-tone image. NEB may be better than HSQ since it is about 7 times faster than HSQ, but its LER is significantly higher. The Gaussian E-Beam writer equipped with 50 MHz electronic rack must be improved with its speed writing for high-sensitivity resists [95]. Dr. Douglas Resnick explained [39] that it is not easy to bake NEB coating on an imprint template due to its thick glass plate.
1.6.4.1 ZEP520A

ZEP520A is a well-understood positive-tone resist available today according to a number of publications [46][47]. CNSE also had demonstrated 20nm half pitch lines in ZEP520A on Si wafer. It is chosen for the work at CNSE to directly fabricate positive-tone imprint template. Generally, positive-tone resists are likely to have more challenges than negative-tone resists because especially with etching the hard mask [45][73]. It is not easy to remove the material from the open areas through the plasma etch process. Microloading during etch is also a problem and is discussed in the referenced paper [73].

1.6.4.2 HSQ

HSQ resist is well understood for its high-resolution properties [51]. It is excellent for testing the E-Beam lithography machine for applying proximity effect corrections and testing for high-resolution patterns before considering the other resists.

1.6.4.2.1 Chemical Response to Electron Beam

At low exposure doses, the dangling Si bonds are not stable. A weak developer easily dissolves the unexposed and slightly exposed area close to the defined pattern. However, at a high exposure dose, the Si bonds become more stable due to network formation and the dissolution rate of HSQ decreases remarkably. In this case, a strong developer improves the dissolution rate with its effectiveness in bond scission. That means that the optimum dose shifts to higher doses, improving the contrast but
decreasing the sensitivity. Frye and Collins [51] studied HSQ and found that its properties of the simplest member of the family are silsesquioxane oligomers. They explained the chemical change during E-Beam irradiation. E-Beam lithography changes the silicon hydrogen bonds of cagelike HSQ oligomers into silanol groups. During E-Beam irradiation, the reaction with hydrogen and oxygen cut Si-H bonds. These Silanol groups are unstable and condense to break the caged molecule. The developer solution cross-links Silanol groups into a polymer network. The developers are usually tetraethyl ammonium hydroxide (TMAH), NaOH, KOH, and NaOH/NaCl (salty developer). They dissolve cage oligomers to form network polymers. The equation is below [52],

\[
\equiv Si\cdot H + OH \rightarrow \equiv Si\cdot O^{-} + H_{2}↑
\]  

Equation 3

HSQ acts as a negative-tone resist after the development by dissolving the final products with SiOH⁻. When E-Beam irradiates with the high-energy deposition into HSQ, the transition to the network structure leads to a lower value of the cage-network ratio and more Si dangling bonds. The higher the dose is, the more the network structure develops. Then, the Si bonds become more stable because of cross-linking.
As for salty developer, adding salt in alkali developer offers outstanding results with high resolution and high density patterning of HSQ [134].

HSQ has an amorphous structure after E-Beam exposure. Its structure is much same as SiO₂. Van Delft [53] studied aging and stored HSQ and shows that HSQ is not good after approximate 6 months for high-resolution patterning. When HSQ ages over time, sensitivity is continuously lost. The contrast and resolution will not be good. Van Delft observed and discovered that contrast and the dose does decrease with 0.1 y⁻¹ and 7 μC/cm², respectively, when HSQ is stored at 5° Celsius (C). Its molecular size distribution broadens gradually over time. In addition, HSQ is very sensitive to contamination. Nitrogen gas added inside the polyethylene or fluorocarbon bottles preserves HSQ on the limited shelf life. In addition, HSQ has to be stored at a low temperature. Van Delft also studied the effect of post-exposure delay time on contrast and inception dose when the samples are stored in either air or vacuum after the E-Beam exposure. The decrease in contrast and sensitivity after a delay time in air is due to
oxidation. This is a slow natural growth of the network formation.

### 1.6.4.3 E-Beam Resist Outlook

The high-resolution nanostructures in HSQ push the performance of both the lithographic tool and the resist material to the maximum value. There are many contributors that potentially limit the ability to achieve high-resolution: beam size, resist material, baking temperature, post exposure bake delay between baking and exposure, writing strategy, exposure dose and development process. Today many resist materials do not have high resolution; reasonable sensitivity; low line edge roughness (LER); high etch resistance; good contrast and low molecular size. E-Beam resist layers should be thin enough to minimize the effect of electron scattering while still being thick enough to serve as a mask for any down stream processing such as etching.

### 1.7 Alternative Imprint Template Fabrication

In the last decade, the body of literature on different fabrication approaches is growing. Positive-tone E-Beam resists have been limited with their resolutions. Today, researchers have not discovered a new kind of positive-tone resist. Therefore, HSQ is favorable because HSQ may result in a positive-tone high-resolution process by doing reversal image techniques: an electrochemical deposition (ECD) [55], a chemical mechanical polishing (CMP) [56], multilayer resists [57] and a lift-off process [55]. Figure 18 shows the clear relation between various image reversal techniques [55]. General flow chart is
for structuring a layer of material A (or D) on a substrate, using a resist C and secondary layers B and D (or A). The combination C on B typically acts a bi-layer resist.
Figure 18 Image reversal techniques
MIT demonstrated 15nm half pitch lift-off process on Si substrate [59] and it is possible to do this with the quartz substrate. The lift-off process is much cheaper than the other complicated reversal image techniques. After verifying the quartz wafer development process, the lift-off approach was ideally planned, as shown in Figure 19. A conductive polymer film applied on the negative-tone resist has a benefit of eliminating charging problems during E-Beam writing because the quartz substrate is an insulator. The conductive polymer consists of polyaniline [61]. IBM invented this and Showa Denko developed one called Z300 E-spacer [62], which is compatible with HSQ. After the exposure, DI water easily removes it. The HSQ should have enough sharp edges after developing it with TMAH.
Then, the E-Beam evaporator deposits a Cr film over the patterned HSQ structures and leaves open areas on the sidewalls. Warm buffer hydrofluoric acid (Buffered HF) and ultrasonic agitation can dissolve the patterned E-Beam resist and lift the Cr off. It leaves behind new open regions of the Cr layer to etch quartz. After stripping the Cr off, this produces surface recessed structures for positive-tone images.
2 Quartz Wafer Development Processes

The goal is to keep costs low, better understand template fabrication using proof-of-concept demonstration with the quartz wafer development process and introduce alternative fabrication methods later.

3” quartz (Qz) wafers, as shown in Figure 20 a, provides low cost substrates to develop full development process that can transfer on imprint templates, as shown in Figure 20 b. It is much cheaper ($35 ea.) than using the expensive and full specification substrates, which cost several thousands of dollars each.
To study the imprint template fabrication, a low cost quartz wafer development process had been planned that transferred onto the Molecular Imprints 65mm template format. The CNSE infrastructure had not been fully resolved especially Trion Minilock III Etcher. A number of tools including E-Beam, coat/develop and etch were modified to accommodate both the 65mm imprint template and the 3 inch wafer format. The quartz wafer development process used the similar fabrication process at industrialized mask shops. The major goal was to keep to the dominant industry standard as much as possible. The low cost quartz wafer development processes must be well understood before studying new alternative fabrications. It is favorable rather than spending hundreds of thousands of dollars on individual 65mm factor imprint templates especially...
expensive quality 6” masks. Before International SEMATECH funded this imprint template fabrication project, another CNSE graduate student, Ananthan Raghunathan, in the Advanced Lithography Group designed an adapter and Vistec built it, as shown in Figure 22. This adapter fits in a standard mask holder to accommodate 65mm imprint template format and Vistec built it.

Figure 22 The 65mm Template Holder

2.1 Quartz Substrate

Three-inch quartz (Qz) wafers purchased from www.universitywafers.com were used for the development process at CNSE. 65mm factor imprint templates are usually made of ultra low thermal expansion (ULTE) UV-fused silica photomask blanks certificated by Molecular Imprints. The template has to be rigid but transparent enough to let UV light to expose the cured imprint resist when it is stamped. The coefficient of expansion is specified between 0° and 300° Celsius and should be less than $7.5 \times 10^{-7}$. Table 2 shows the properties of quartz material and it is importance for substrate heating effect
consideration.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2.201</td>
<td>g/cm³</td>
</tr>
<tr>
<td>Conductivity</td>
<td>0.0138</td>
<td>W/cm -° C</td>
</tr>
<tr>
<td>Specific heat</td>
<td>0.703</td>
<td>J/g -° C</td>
</tr>
</tbody>
</table>

Source: [88]

Table 2 Properties of quartz substrate

### 2.1.1.1 Quality Quartz Surface

Three inch quartz wafers’ properties are similar to the imprint template supplied by Shin-Eshiu MicroSi, Inc [88]. A fabricated blank 65mm factor template with 15µm-raised mesa has approximately less than 3 Angstrom roughness compared to 3” Qz wafer’s roughness at less than 6 Angstrom. Through experimental quartz wafer development process, the surface quartz substrates do not have the expected quality to meet the surface roughness specification according to [www.universitywafers.com](http://www.universitywafers.com). The picture is shown with rough surface taken by FEI eSEM in the section 7.5. An etch based polishing process was developed to improve the surface roughness of the 3” wafers to an acceptable level.
3 Metal Deposition Film Process for Hard Mask

A hard mask on the quartz substrate requires an applicable metal for a pattern transfer process onto the quartz substrate through a dry etch process. The chromium pattern is first chosen. A glass plate is coated with Cr, which is conductive, and has a benefit to E-Beam lithography for eliminating the charging problems. The glass plate is an insulator and deflects the electrons away from the beam in collimation discussed in section 4.9. Historically, Cr was selected for this specific application because it is easy to deposit and etch, and is completely opaque. Many industrialized mask shops have many techniques today that are available to repair any defects in the Cr layer that were developed in early 90s and 2000s [87]. With a strategy to fabricate the high-resolution relief structure on quartz substrate, decreasing the thickness of the chromium layer on the quartz substrate has two significant benefits [45]: (1) minimizing the critical dimension loss during pattern transfer processes and (2) a thinner layer of electron beam resist improves high resolution.
3.1 Plasma Vapor Deposition

Electron beam evaporation (E-Beam evaporation) and sputtering both can be classified as Physical Vapor Deposition (PVD). PVD covers a number of different deposition technologies for depositing Cr or other the applicable metal. The two most important technologies for depositing the applicable metals are evaporation and sputtering.

E-Beam Evaporation Process is used at CNSE to deposit Cr film or other applicable metal films. Chromium is first chosen because it is inexpensive compared to the other applicable metal films. Historically, Cr is used in standard industry for mask etching on quartz with some advantages here. It suppresses the charging problem in E-Beam writing, functions as an absorber and the chromium oxide as antireflective (AR) film. While Cr has a long history as an absorber in the mask industry, recently Molybdenum disulfide (MoSi) has come to replace Cr for a variety of reasons. MoSi material is better for attenuating phase-shift masks and depositing multilayer for reflective mirror on EUV masks.

The choice of the deposition methods (i.e. evaporation or sputtering) depends on what technology is available for the specific material. The sputtering technology is the most widely used for accomplishing thin films for VLSI fabrication [105]. A sputtering of Cr has the advantage of high throughput, good adhesion and excellent thickness uniformity using high vacuum chamber [87].

In evaporation, the substrate is placed inside a vacuum chamber with a target Cr
material to be deposited. The source material is then heated to the point where it starts to boil and evaporate. This process requires a high vacuum (10^{-6} to 10^{-7} Torr range) to allow the molecules to evaporate freely in the chamber, and they subsequently condense on all surfaces. A high kinetic energy beam of electrons is directed at the material for evaporation. After the beam impact on the source, the high kinetic energy is converted into thermal energy, heating up and evaporating the target Cr material.

Sputtering is a deposition technology fundamentally different from evaporation. In a sputtering tool, the material is released from the material source at much lower temperature than evaporation. The substrate is placed in a vacuum chamber with the target material, and an inert gas such as argon. The inert gas is introduced at low pressure. A gas plasma is struck using an RF power source and the gas becomes ionized. The ions are accelerated towards the surface substrate, causing atoms of the source material to break off from the target in vapor form and condense on all surfaces including the substrate. There are many different ways how to manage the ion bombardment.

Advantages offered by evaporation for PVD [105]

- High film deposition rates
- Less substrate surface damage from impinging atoms as the film is being formed, unlike sputtering that induces more damage because it involves high-energy particles
- Excellent purity of the film because of the high vacuum condition used by evaporation
- Fewer tendencies for unintentional substrate heating.
Disadvantages of using evaporation for PVD [105]

- More difficult control of film composition than sputtering;
- Absence of capability to do in situ cleaning of substrate surfaces, which is possible in sputter deposition systems;
- Step coverage is more difficult to improve by evaporation than by sputtering;
- X-ray damage caused by electron beam evaporation can occur.

There are two PVD options at CNSE. One sputtering tool, managed by Professor Gregory Denbeaux, was not suitable for the quartz wafer development process because it was not in the cleanroom. The experimental development process used the Varian 780 E-Beam evaporation to deposit Cr film on the quartz wafers in the CESTM cleanroom at CNSE.

After Cr etch, the edges of the Cr pattern are a little rough, as shown in Figure 23, using positive-tone ZEP process. The sputtering tool should be better and should decrease the edge roughness as much as possible. A better layer with smaller grain size will result in smoother edges. Evaporation creates larger Cr grains than the sputtering because sputtering bombard individual atoms onto the quartz substrate. Then, the pattern transfer process on the quartz substrates should be much improved.
3.1.1 E-Beam Evaporation Process

The 3” Qz wafer is coated with Cr film using E-Beam evaporator at low rate deposition to achieve thickness uniformity. Ellipsometer measured the thickness with one point on the center of the 3” Qz wafer. The three different thicknesses that were evaluated are 15nm, 10nm and 6nm. 10nm Cr film deposition film had been empirically used on the on quartz wafer for suitably readable for VB300 machine’s height sensor discussed in section 4.8. Doing lift-off process of nanometer patterns become important for reversing the image on the quartz substrates [66]. Deposition rate depends on the location and orientation for the wafer in the chamber and the quartz substrate has to be orientated properly to get all Cr film deposition uniformity on the substrate, as shown in Figure 24 and 26.
Figure 24: Avoid unaligned sample in the E-Beam Evaporator

Equation 4 [106] is the rate for evaporating Cr material.

\[
 r_{\text{evap}} = \sqrt[2]{\frac{M}{2\pi k T}} P_e
\]

Equation 4

Where \( r_{\text{evap}} \) = evaporation rate
\( M \) = atomic mass
\( K \) = Boltzmann’s constant
\( T \) = temperature
\( P_e \) = vapor pressure
Figure 25 Cr Deposition process

Figure 25 shows the importance of the deposition process according to the equation below [106],

\[ r_{dep} = \frac{r_{evap} \cos \theta}{\Omega d^2 \rho} \]

Equation 5

Where

- \( r_{dep} \) = deposition rate (thickness/sec)
- \( r_{evap} \) = evaporation rate (mass/sec)
- \( \Omega \) = solid angle over which source emits (unit less steradians)
- \( d \) = source to substrate distance
- \( \rho \) = material density
- \( \theta \) = inclination of substrate away from direction to source
4 Gaussian E-Beam Writer Technology

To write high-resolution images on the imprint template GB E-Beam writer technology is typically used. The E-beam writer consists of an electron optic column that shapes complex electron interactions into a single Gaussian beam to expose a polymer film coated substrate. Vistec Semiconductor, Inc fabricated the advanced GB tool at CNSE, model VB300, which is installed in the class 1 mini-environment at CNSE’s Nanofab Facility as shown in Figure 26. It has a theoretical minimum spot size down to ~2nm and is equipped with an electronics rack up to 50 MHz.

Figure 26 Vistec Electron Beam Lithography System

Figure 27 is a schematic of the E-Beam column. In the schematic, the gun is equipped with a Thermal Field Emission (TFE) source, which accelerates a voltage beam at 100kV through three successive lenses. Two of lenses are magnetic and the other is electrostatic to demagnify the image emitted from the TFE source.
There are some major advantages and disadvantages with this Gaussian Writer Technology. See bullets below.
Advantages

- Better resolution
- Reduced space charge effects
- Increased noise immunity

Disadvantages

- Reduced resist sensitivity
- Increased resist heating
- Increased substrate heating
- Increased currents and voltages required for optics and deflectors
- Backscatter range increases requiring more complex proximity correction algorithms
- Reliability more challenging

4.1 The E-Beam Lithographic process

The lithographic process includes coating and development of the wafer as well as how to properly scan the electron beam across the resist-coated substrate in a raster fashion.

4.1.1 Coat and Develop

The quartz wafers were coated first with ZEP520A resist for creating positive-tone image to create the relief structures. Its thickness is 40nm. The condition for making 40nm layer of ZEP520A is to dilute it at a 1:3 ratio with Anisole and spin coat at a ramping speed of 1,000 RPM/S, a spinning speed of 4,500 RPM for 60 seconds and baked it at
180° C for 2 minutes to evaporate solvent.

As for negative tone HSQ, a standard TMAH developer solution is preferred over the salty developer. The HSQ process with salty developer from MIT was considered but not needed for the minimum target resolution being considered in the proposed project. The salty developer process was not feasible for my research work because my work is not focusing sub-10nm features [134]. The project proposed targeted for 16nm half pitch lines. The process requires only 1 minute for developing the resist in TMAH followed by a rinse with distilled water for 1 minute. The TMAH developer seemed reasonable for 16nm half pitch lines.

![HSQ Spin Speed Curve](image)

Figure 28 HSQ Spin Speed Curves
6% HSQ was diluted with two parts of MIBK to achieve at 2% HSQ. d/do is the nominal thickness. The contrast of resist determines how small of an image modulation can be converted into image in resist. Dose is the number of electrons per unit area required to achieve the desired chemical response in the E-Beam resist. Its unit is micro-Coulombs per squared centimeter (µC/cm²). The contrast curve shows that the HSQ molecules crosslink at ~600 µC/cm² for half-millimeter square pattern.

As for positive-tone ZEP520A resist, different thicknesses of ZEP520A resists were evaluated with diluted thinner solution supplied by MicroChem and Ellipsometer RC2 measured them. In order to clear the resist, a dose of 160 µC/cm² is needed for half-millimeter square with the same spot size and beam size step.
Figure 30 ZEP520A Spin Speed Curves

Figure 31 ZEP520 A10 Contrast Curves
Table 3 shows the different dilutions of ZEP520A with Anisole. The contrast curve shows that the ZEP520A molecules are chain scission at \( \sim 160 \mu \text{C/cm}^2 \), as shown in Figure 31.

<table>
<thead>
<tr>
<th>ZEP520A</th>
<th>Diluted with Thinner Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEP520 A10</td>
<td>1:0</td>
</tr>
<tr>
<td>ZEP520 A8</td>
<td>1:1</td>
</tr>
<tr>
<td>ZEP520 A6</td>
<td>1:2</td>
</tr>
<tr>
<td>ZEP520 A4</td>
<td>1:3</td>
</tr>
<tr>
<td>ZEP520 A2</td>
<td>1:4</td>
</tr>
</tbody>
</table>

Table 3 Diluted ZEP520A with Thinner Solution

4.1.2 Electron Dose and Contrast

The dose depends on the feature size ranges.

<table>
<thead>
<tr>
<th>Depending Parameters</th>
<th>Scaling</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern Size</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td>Pattern Density</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td>Isolated Features</td>
<td>Decrease</td>
<td>Extremely Increase</td>
</tr>
<tr>
<td>Resist Thickness</td>
<td>Decrease</td>
<td>Decrease</td>
</tr>
<tr>
<td>Acceleration Voltage</td>
<td>Increase</td>
<td>Increase</td>
</tr>
</tbody>
</table>

Table 4 Dose Dependencies

Figure 32 shows the clear relationship between a decreasing pitch and a tight dose control for achieving at 22nm lines on 44nm pitches. The experiment included a matrix of dose range from 120 to 300 \( \mu \text{C/cm}^2 \) and pitch variation with a constant parameter - 22nm width line with +/- 2nm variation. A shaded triangle below indicates ideally acceptable dose ranges, which were determined by LEO 1550 SEM and verified by SUMMIT Software.
The contrast curve [63] shows the behavior of the resist.

In the particular place with dose to clear, the equation shows the curve contrast,

\[ T_E(E) = T_0 \gamma \ln \left( \frac{E_0}{E} \right) \]  

Equation 6

Where \( T_0 \) = thickness
\( \gamma \) = the slope of thickness
\( E_0 \) = the particular place that is dose-to-clear
\( E \) = energy deposition
With the 100kV Gaussian E-Beam Writer, a thinner resist layer is favorable to improve the high-resolution images on the resist coated quartz substrate. The thinner resist layer has more advantages over the thicker resist, as shown in Table 5.

<table>
<thead>
<tr>
<th>PRO</th>
<th>Thicker Resist layer</th>
<th>Thinner Resist Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• High etch resistance* for pattern transfer process</td>
<td>• Decreased dose&lt;br&gt;• Decreased resist heating&lt;br&gt;• Reduced currents and voltages required for optics and deflectors&lt;br&gt;• Forward scattering range decreases simplifying proximity correction algorithms&lt;br&gt;• Less broadening effects on sidewalls</td>
</tr>
<tr>
<td>CON</td>
<td>• Increase dose&lt;br&gt;• More broadening effects on sidewalls affected by proximity effect&lt;br&gt;• Forward scattering range increases requiring more complex alpha proximity correction algorithms</td>
<td>• Low etch resistance* for pattern transfer process</td>
</tr>
</tbody>
</table>

*Ratio of etch resistance depending on individual commercial resists

Table 5 Thicker and thinner resist layer using 100kV electron beam

4.1.3 Pattern Resolution

Line edge roughness (LER) becomes critical when the pattern size shrinks. To avoid poor resolution, adjusting spot spacing and dose can minimize the LER. The developer effectively cross-links or scissions resists for negative and positive tone images, respectively. The PEC mechanism needs to be improved to give better Critical Dimension Uniformity (CDU) over a large pattern area. The PEC algorithm becomes too complicated for the specific resist material, HSQ, and will need extensive study to resolve this PEC mechanism. It may be more that process contributes significantly to resolution limitations in HSQ.
Adam Lyons and Ananthan Raghunathan used an empirical experiment with variation matrix to find optimal PEC parameters for Si substrate. CNSE will need to do some empirical experiments on the quartz substrates to find optimal PEC parameters. The empirical experiments were done on 300mm wafers and made use of an automated CDSEM to gather the large amounts of data needed for the analysis in a reasonable time.

### 4.2 Parameters

The Vistec VB300 has four different lithographic parameters: Spot size, Beam Step Size (BSS), Dose and Frequency. Spot size depends upon beam current given by the electron column. The Vistec VB300’s pattern generator uses a 20-bit system. As for address grid resolution, there are $2^{20}$ possible exposure positions of the beam in each axis. Exels are fundamental units where the field size is divided by 1048576 for specific 20-bit system. BSS is flash-to-flash spacing by an integral multiple of exels. Frequency is the speed at which the tool is capable of stepping from spot to spot and has an upper limit of 50MHz.

The relationship is between current, frequency and grid. It affects the quality of lithography.

\[
\text{AreaDose} = \frac{\text{Current}}{\text{Frequency} \times \text{grid}^2}
\]

Equation 7

Current is beam current. Spot size is determined by beam current. Spot size is best estimated by root sum of squares of contributions from aberrations, diffraction, demagnified source size and intrabeam scattering (Boresch effect). The grid is the beam...
step size. The VB300 is equipped with the electronic racks that support up to 50 MHz frequency to deflect beam and write the pattern. In Figure 34 [95], the shaded areas with two different resists indicate the nominal dose ranges for ZEP520A and HSQ. The three curves represent different beam currents and the maximum dose deliverable at those currents for different step sizes. The frequency of the tool is 50 MHz and the minimum dwell time of the beam at any spot is two nanoseconds. This sets a lower limit to the deliverable dose at any given step size.
4.3 Fine Tuning of an E-Beam Lithography Machine

A fine-tuned E-Beam lithography strongly depends on optimum beam quality. Focus and astigmatism has to be well tuned. The electron column in the Vistec VB300 consists of lenses containing unavoidable aberrations in its performance. Clearly, electron optics is in contrast to the situation in light optics and using combinations of lenses cannot cancel the effects of aberrations. Controlling a complex interaction of electron beam physics in the electron column can minimize these effects. Fundamental physics of controlling the electron are explained in the appendix 13.2.1.

![Diagram showing FWHM, Demagnified Source, Spherical aberration, Chromatic aberration, Diffraction, and Boersch Effect]

Figure 35 Fine-tuning of an electron beam

All effects from demagnified source, spherical aberration, chromatic aberration, diffraction and Boersch effect must be reduced as much as possible to achieve fine spot size of the electron beam. The Boersch Effect is Coulomb repulsion between electrons. The Gaussian E-Beam Writer needs to have a good control to narrow axis spot size before focusing on a Full-Width-Half-Maximum (FWHM) of a Gaussian distribution and a printability of E-Beam resist with threshold. Figure 35 shows fine-tuning of electron beam.
4.4 E-Beam Scanning

4.4.1 Gaussian distribution

The 100kV E-Beam Gaussian writer exposes each spot at a specific location with a Gaussian dose distribution. This is the probability starting from the true point and a number of electrons distributed across the certain distance on the grid. This becomes complicated for the large pattern area due to probability of the number of electrons distributed in each shot spot including proximity effect. The proximity effect correction will be explained in detail in section 4.5.2.4. The half-maximum points are the full width at half maximum (FWHM) for a Gaussian from the true point.

\[ e^{-\frac{(x_0 - \mu)^2}{2\sigma^2}} = \frac{1}{2} f(x) = \frac{1}{2} \]

The function of maximum x is same as mean, \( \mu \). Therefore, the function of x is cancelled out. Solving for the FWHM with the given equations below:

\[ e^{-\frac{(x_0 - \mu)^2}{2\sigma^2}} = \frac{1}{2} \]

\[ -\frac{(x_0 - \mu)^2}{2\sigma^2} = -\ln 2 \]

\[ -(x_0 - \mu)^2 = -2\sigma^2 \ln 2 \]

\[ x_0 = \pm \sigma \sqrt{2\ln 2} + \mu \]

The given equation for FWHM is

\[ FWHM = 2\sigma \sqrt{2\ln 2} \]

Equation 8
In 2D view, the Gaussian function is the distribution function in radial for uncorrelated variates X and Y. The standard deviations for X and Y variations are ideally equal for continuously moving spot: $\sigma = \sigma_x = \sigma_y$.

$$f(x, y) = P(x, y) = \frac{1}{2\pi \sigma_x \sigma_y} \exp \left[ \frac{(x - \mu_x)^2 + (x - \mu_y)^2}{2\sigma^2} \right]$$

Equation 9

The FWHM must be higher than the threshold line where the resist will be printed properly with reasonable dose rather than giving too much dose. An overdose will raise the bottom of the Gaussian closer to the resist threshold. See Figure 37 below. FWHM is equal to the spot size.

$$FWHM = 2\sigma \sqrt{2\ln 2} = \sigma \sqrt{8\ln 2}$$

Equation 10
4.4.2 Spacing Spots of Gaussian

In order to make lines with few electron beam passes, adjusting relative dose depends on the dwell time and the spot-to-spot spacing. Spacing spots of Gaussian profile is shown in Figure 38. It is better to get uniform width spots across an area in the predefined shapes. If the spacing is too large, then line edge roughness increases. The 100kV Gaussian writer adjusts the spot spacing by beam size step with selective doses to create uniform lines because the proximity effect broadens the effective spot and the optimum step size is proportional to the spot size. Dose depends upon spot spacing, thus spot distance is very important.
Electron beam contributes dose by passing 6 times in 22nm line in cross section, as shown in Figure 39.
4.4.3 Continuously Moving Spot

Generating a continuously moving spot is given here in which the distribution function depends on time with respect to X and Y is shown below.

\[
P(x, y, t) = \frac{1}{2\pi \sigma_x^2} e^{-\left(\frac{(x-\mu_x(t))^2}{2\sigma_x^2} + \frac{(y-\mu_y(t))^2}{2\sigma_y^2}\right)}
\]

Equation 11
4.5 Proximity Effect Correction Algorithms

In nanolithography, the printed patterns are generally getting smaller and denser. A number of proximity effect correction algorithms used in 4X mask manufacturing do not work well [76] for the smaller pattern 1X imprint template. In most cases, sub-20nm imprint template requires a manual manipulation of the design data [104].

4.5.1 Influence of Proximity Effect

Proximity effects are due to the interaction of the electrons between the beam and the properties of the resist and substrate. Those interactions with Coulomb forces and collisions cause electrons to scatter throughout a resist and a bulk substrate. The
scattering range strongly depends upon the initial energy due to the accelerating voltage beam and the atomic number of the scattering target. The forward scattering is a function of the accelerating voltage and does not have much effect on a thinner electron-sensitive resist. With high accelerating beam voltage, i.e., 100kV, electron beam picks up the pace and thrusts through the thinner resist layer with less forward scattering, the beam blur becomes less. As the electron beam enters the thinner resist, forward scattering broadens the distribution of the electrons passing through the resist material. Most of the electrons pass through the resist, the backscattering process contributes to long range scattering as the electrons scatter off from atoms in the bulk substrate and travel amok through the resist out of the bulk substrate. This is the proximity effect, as shown in E-Beam scanning.

![Figure 41 Proximity Effect](image)

The three different events can be seen in Figure 42 before they contribute the total deposited beam energy. The first peak is coming from the incident beam. The backward
scattering is a greatly stretched distribution across from the electron beam because the backscattered electrons travel through the bulk far away from the incident beam. This is an inelastic collision with a great angle of emitting electrons near the core of atoms. Electron beam gives electrons scattered with small angle collision in the resist layer. This is recognized as forward scattering.

VB300 direct-write vector beam lithography operates at 100 keV with a 500um field size and half nanometer grid. With 100 keV accelerating voltage beam, the forward scattering in thinner resist, i.e. sub-50nm resist layer, becomes unimportant. Many essential factors contribute to the optimized process: E-Beam source energy, thickness of resists, and exposure dose. Consequently, operating at high voltage at 100 keV reduces forward scattered electrons and backscattered electrons are the major concern.

4.5.2 Correction

The influence of the proximity effect needs to be corrected to effectively control the size of patterns in resist. Figure 43 illustrates proximity effect, where A is the primary exel
(incident point of the beam). B is the proximity exel and receives part of the dose delivered at exel “A”.

The PEC software looks to correct the dose distribution across the pattern design and to ascribe different dose modulations into addressable shape levels for controlling pattern sizes in an E-Beam resist.

### 4.5.2.1 Beam Energy Effect

The resist layer experiences unavoidably undesired energy deposition by backscattering events induced by electron beam. A simulation with Point Spread Function (PSF) can predict where the E-Beam resist and the substrate will retain energy. The PSF shows the distribution of the accumulated energy from the electron beam in the E-Beam resist.

100kV accelerating beam voltage increases the size of interaction volume in the bulk substrate. The width and depth of secondary electron distribution increases with beam energy and the volume interaction becomes narrow at the point where the beam enters the resist layer, creating a bottleneck. The penetration depth increases
proportionally to the accelerating voltage \(V\) as \(V^{3/2}\) [76]. The high-precision simulation software for a 10nm-Cr-based quartz wafer showed that the thinner E-Beam resists on the bulk quartz substrate for both ZEP520A and HSQ have about the same forward scatter events. Both of them have the same results with trajectories of backscattered electrons exiting from the bulk substrate. A lower energy beam, i.e. <50 keV, is easily deflected compared to the higher energy beam. As electron beam slow down, the energy can deflect easily. Operating at 100 keV accelerating voltage, not many electrons will elastically collapse with the resist atoms and gives the lower lateral spread in the resist layer.

### 4.5.2.2 Essential Forward Scattering Situation

Printing 20nm lines and beyond should include both forward and backward scattering controls. Many E-Beam writers operating at 100kV voltage do not include the forward scattering parameter in data treatment through PEC algorithms [76]. There is still a small influence of forward scattering events when operating at 100kV accelerating voltage beam. With 20nm and 16nm lines with 2:1 ratio, not many problems arise. They have been demonstrated in patterned E-Beam resists, etched Cr patterns, and 20-16nm raised relief structure. The forward scattering range might be considered in this study case for imprint template manufacturing [79]. As industrialized mask shops approach the critical dimensions of target patterns for 20nm half pitch structures and beyond, they cannot ignore influences of the forward scattering event [76]. A phenomenon of the experiments
conducted for this thesis showed that 20nm and 16nm lines with 1:1 pitch can be printed in the small area, but their structures are not sharp. The alpha correction must be modified or pattern area must be extremely small, i.e. <5 micron, for being isolated from rising PEC be sufficiently isolated for rising PEC. 40nm and 32nm spaces between 20nm and 16nm lines, respectively, give space to print solid structures compared to 1:1 pitch patterning, as shown in Figure 147 a and 149 a. Pattern fracturing software was not able to fracture down to 2-5nm minimal physical shapes that would be required for forward scattering correction. A long computing time and large data volume are prohibitive due to the limited memory size [76]. Complex hierarchical levels with proximity correction can be improved in many different ways. A cluster of many computers can share the responsibility to run the complex PEC process. Speed and computation chips are also improving about every two years.

4.5.2.3 Electron-solid interactions

Electron-solid interactions become more complex when the electrons hit the resist-coated substrate. When an electron beam exposes a resist, some molecular chains in the resist molecules will break or crosslink depending on a positive or negative tone resist followed by the developer process. As for positive-tone, breaking molecules are accompanied by an increase in solubility. For negative-tone resist, the molecules are not crosslinked and wiped out by the developer process where the electron beam is not fully in contact with resist [117][118][119][120].
For electron beam lithography, it is very important to know the three dimensional distribution of energy deposition in the resist after exposure [114]. Most electron beam lithography machines currently use electron beams with 15-100 keV energy per electron. The free path of an electron is 10µm or more, which is at least an order of magnitude more than the resist thickness [114]. The electrons can travel through the resist layer and enter the substrate. As the electrons penetrate the resist and the substrate, they experience many scattering events depending on the spot size and the accelerating beam voltage.

In forward scattering, an electron can collide with another electron from one of the atoms from the substrate and/or resist. The incident electron will change its direction and transfer part of its energy to the atom. This happens with the Gaussian distribution because the probability of electrons that are given in the E-Beam resist layer. Due to the extra energy level, the atom will become excited because one of its electrons in the atom goes to an excited level. Ionization occurs when one electron leaves the atom, creating a secondary electron in the resist material. When the target atom is a resist molecule chain, the molecular chain may break or crosslink due to this excitation or ionization. The scattering angle due to inelastic scattering is small. Forward scattering happens [115],

\[
p_f(r) = \frac{1 - \eta}{\pi \alpha^2} \exp\left(-\frac{r^2}{\alpha^2}\right)
\]

Equation 12

Where \( \alpha = \) forward scattering range
\( \eta = \) the backscatter coefficient
The forward scattering induced by the incident beam and creates the Gaussian
distribution of electrons in the E-Beam resist layer. Its range is between the half
maximum points of the shaped spot.

In backscattering, an electron collides with the much heavier nucleus, which
results in a great elastic scattering event. The electron continues to have most of its
energy and definitely changes its direction. After backscatter events in the substrate,
electrons return through the resist at a significant distance from the incident beam. The
backscatter flux can be predicted where the resist will be additionally exposed. The
backscatter comes from a distribution of electrons per unit area [115]:

\[
\rho_s(r) = \frac{\eta}{\pi \beta^2} \exp\left(-\frac{r^2}{\beta^2}\right)
\]

Equation 13

Where \( \eta \) = the backscatter coefficient
\( \beta \) = the backscatter range

The backscatter range, \( \beta \), is from the Gruen range [115], which you can find in the
original referenced paper [116]:

\[
\beta(\mu m) = 0.04 (kV)^{1.75} / \rho (g/cm^3)
\]

Equation 14

With a thinner e-beam resist, the substrate is expected to dominate the backscatter. For
composite materials, \( Z \) is a mass weighted combination of each element. \( Z \) gives a great
influence on the backscattering event and is only weakly dependent on the accelerating
beam voltage [115]. For quartz material composition, SiO\(_2\) has one silicon element and
two oxygen elements. Si and O have 14 and 8 atomic numbers, respectively. The total atomic number of 10 gives a great backscattering event. This is the effective atomic mass that means $\frac{1(14) + 2(8)}{3} = 10$.

As the primary electrons slow down, energy is slowly dispersed and forms many secondary electrons with energies in the range $< 50$ keV. They have low energies and their range is only a few nanometers. Therefore, they contribute little to the proximity effect compared to high accelerating beam voltage, i.e. 100 keV. The primary beam with the forward scattering effectively causes a widening of the exposure region. This is one of the main limiting factors in high-resolution images. The distance a typical electron travels before losing all its energy depends on both the energy of the beam voltage and the type of material it is traveling in. The fraction of electrons, $\eta$, that are backscattered is roughly independent of beam energy. It does have a strong relation to the substrate material. The quartz (SiO$_2$) gives significantly less backscatter than Si. In general, substrates with a low atomic number give less backscattering than substrate with high atomic number.

Forward scattering can be divided into different characteristic distribution and unique behaviors. It does increase the effective beam diameter. One of the proposed equations is below [114],
\[ d_f = 0.9 \left( \frac{R_t}{V_b} \right)^{1.5} \]  

Equation 15

Where \( R_t \) = the resist thickness in nm  
\( V_b \) = the beam voltage in kV  
\( d_f \) = is the effective beam diameter

A slightly different relation for the resist thickness dependence is given [80],

\[ d_f \propto R_t^{1.75} \]  

Equation 16

During the scattering events, the Rutherford formula [121][122] below describes when the electrons are elastically scattered before the electrons stop traveling. This equation is for alpha particle. The scattering of alpha particles from nuclei can be modeled from the Coulomb force and treated as an orbit. The electron energy should be large enough for the orbital electrons. This formula is proved for scattering off a point target, but no structure is evident. This is the first evaluation for the nuclear radius.

\[ N(\theta) = \frac{N_i nLZ^2k^2e^4}{4r^2KE^2\sin^4(\theta/2)} \]  

Equation 17

Where \( N_i \) = number of incident alpha particles  
\( n \) = atoms per unit volume in target  
\( L \) = thickness of target  
\( Z \) = atomic number of target  
\( e \) = electron charge  
\( k \) = Coulomb’s constant  
\( r \) = target-to-detector distance  
\( KE \) = kinetic energy of alpha  
\( \theta \) = scattering angle

The Bethe equation [122] can ideally describe the electrons being slowed down and stopping scattering. The given stopping distance for Bethe equation is below [115],
\[ r(\mu m) = \frac{2.76 \times 10^{-2} A \cdot V^{1.67}}{\rho Z^{0.89}} \]  

Where \( \rho \) = Density, (g/cm\(^3\))

\( Z \) = Atomic Number,
\( A \) = Atomic Mass
\( V \) = Accelerating Voltage

It is not easy to determine the right fundamental physics to seek different components and correct the proximity effect. It is not yet clear what is the best method for understanding the electron-solid interactions. The equations above must be investigated more and there is a need to discover new underlying physics somehow related to the proximity function discussed in the next section.

### 4.5.2.4 Fundamental Correction

A simple PEC mechanism will be explained here rather than trying to understand the complicated mathematical descriptions for advanced PEC mechanism used in commercial software. Commercial software uses a Fourier Transform to reduce the computation time. Exposure can certainly test the effectiveness of PEC by doing numerous iterations until the pattern size is satisfied. Correcting the proximity effect originally comes from the historically phenomenal experiments. It seems not accurate for all detailed stacks especially the HSQ resist. After the PEC algorithm is set up, then the simulation can predict an energy profile assigned to the addressable shapes, but not always work well. The energy deposition profile gives the response of a single point.
exposure and a convolution is used to describe the exposure of a pattern design,

\[ E(x,y) = f(r) \cdot d(x,y) \]  

Equation 19

Where \( r = \sqrt{x^2 + y^2} \) in coordination of the pattern design, \( E(x,y) \) is the energy deposited in the E-Beam resist, \( f(r) \) the point exposure profile and \( d(x,y) \) the input dose as a function of position. The image \( E'(x,y) \) can be obtained from \( E(x,y) \) by

\[ E'(x,y) = \begin{cases} 0 & \text{for } E(x,y) < \tau \\ 1 & \text{for } E(x,y) \geq \tau \end{cases} \]

\( \tau \) is an experimentally determined development threshold. The above equations indicate undeveloped and developed resist, respectively. An overview of this concept [74] based on ideal mathematical descriptions above is shown in Figure 44.

Small pixel sizes are necessary to obtain an accurate image, but it is unacceptably long computation time. An efficient method [82] is developed with addressable shapes. Separating the total exposure in two different components reduces the memory
requirements: the forward scattering and backscattering situations. The forward scattering situation can be evaluated around the critical point and the backscattering situation can be evaluated in a coarser grid without degradation.

There are essentially three methods of proximity effect correction. These are background correction exposure, shape modification and dose modification. Those will be a tradeoff for high writing time for the E-Beam lithography technology instead of exposing with specific dose in each pixel.

As for dose modification, there are many different proximity correction schemes have been proposed in the literature [82][92][93]. The major problem is to determine the required dose for each addressable shape with a reasonable computation. The dose modulation, as shown in Figure 45, is set up to the specific dose level to meet the threshold in the edge of the shape.

Before figuring out the dose modulation, the proximity function is developed here. The backscatter from the substrate results in extra dose at points on the resist where the dose was not intended. This results in effective degradation in resolution. The
proximity effect correction schemes commonly make use of a double Gaussian approximation given below,

\[
f(r) = \frac{1}{1 + \eta} \left( \frac{1}{\pi \alpha} e^{-\frac{r^2}{\alpha^2}} + \eta \frac{1}{\pi \beta^2} e^{-\frac{r^2}{\beta^2}} \right)
\]

Equation 20

Where \( \eta \) = the ratio of the backscattered energy to the forward-scattered energy
\( \alpha \) = the forward scattering range parameter
\( \beta \) = the backscattering range parameter

The referenced paper [131] proposed that the proximity function is often approximated by a sum of three Gaussian terms:

\[
f(r) = \frac{1}{(1 + \eta + \nu)} \left( \frac{1}{\pi \alpha} e^{-\frac{r^2}{\alpha^2}} + \eta \frac{1}{\pi \beta^2} e^{-\frac{r^2}{\beta^2}} + \nu \frac{1}{\pi \gamma^2} e^{-\frac{r^2}{\gamma^2}} \right)
\]

Equation 21

Where \( \eta \) = the ratio of the backscattered energy to the forward-scattered energy
\( \alpha \) = the forward scattering range parameter
\( \beta \) = the backscattering range parameter
\( \gamma \) = the corresponding long-range backscattering parameters

The problem can be simplified, thereby reducing the calculation time, by splitting the dose modification into a problem of forward scattering and back scattering correction [92][93]. With dose modification, it is possible to achieve a good proximity effect correction.
In this shape modification method, a single specific dose is used for each shape level. The shapes found in the pattern image are modified. A good example of a shape modification method is the correction scheme discussed in [81][82]. The shape modification takes a pattern with rectangular elements. The first correction step is to replace each rectangle with its inner maximum rectangle size, as shown in Figure 46. The second correction step is to find and fix the effect of proximity effect interaction in the different elements. Each edge in shapes is adjusted so that the midpoint of the edge will be equal to the experimental threshold.

![Figure 46 Reducing Rectangle Size](image)

The final correction step is to modify the shapes at critical points connected to the
neighboring shapes, as shown in Figure 47.

![Figure 47 Shape modification of critical points.](image)

### 4.5.3 VB300 Data Preparation

The GDSII layout is the raw layout you would like to see at the end of lithography process. GDSII is the hierarchical library data type that can save all complex patterns instead of loading all data once in the layout on a PC machine (www.layouteditor.net). This is the default standard layout library file format. It lists sub-cells referenced by the selected structure. Each cell is indented to indicate its level in the hierarchy. To convert GDSII to something the VB300 system can write, SYNOPSIS CATS software is used. CATS is the fracturing operation software with the proximity corrector module software, PROXECCOTM. CATS is a graphical interface software that writes CAD design data into machine readable file format for the VB300 system. It supports ½ nm grid size VEP format and interprets for VB300 how much dosage it will assign to fractured shapes. During the data treatment in CATS, PDF Solution PROXECCOTM software implements
proximity effects corrections automatically.

4.5.3.1 CATS fracturing

Data preparation includes fracturing, sizing, Boolean operations and definitive data processing. Fracturing operations involve breaking design polygons into fractured rectangles. CATS fracturing can improve the efficiency and volume of data. This merges neighboring figures and eliminates multiple exposures and reduces the total number of figures and the time required for VB300 exposure. CATS software generates compact data that contains as few exposures as possible. Efficiency is attributed to these essential factors: smaller data files, fewer exposures and shorter exposure time. This makes the data generated in CATS more efficient for VB300. With Alpha correction factor, small figures should receive a special treatment due to the alpha proximity effect. This depends on the pattern size. The elbow structure pattern should not have a data volume issue with alpha corrections. It was not be able to fracture less than 1-micron minimal fractured shape. CATS has a precise mode that is computationally intensive. Alpha correction accuracy is mainly limited by the figure size, i.e. sub-20nm features, because the pattern areas range from 20nm to 10-micron, as shown in Figure 190. Alpha Correction cannot be well optimized in these pattern areas for sub-10-micron field size. A trade-off between fine fracturing accuracy, reasonable data volume and correction time must be made.
Minimum distance value is set up for defining the smallest size of a figure that can be produced in either dimension when fine fracturing the data. The number of doses is established to 256 for distinguishable doses. It specifies the number of dose levels and influences the required resolution of the transformation grid of the correction. The fractured pattern typically did not use all of them, depending on the size of pattern area. The more complex pattern is and the bigger pattern, the more doses are assigned. As for the dose evaluation setting, the average is the more accurate setting and analyzes the entire area of the figure. The density mode in CATS is set up to full field that calculates the dose distribution by convolution.

4.5.3.1.1 Using PROXECCO™ in CATS

CATS coordinates with the 3rd Party software, PROXECCO™, for correcting proximity effects on pattern generation. Input to the Paraproxx module in PROXECCO™ software that collects requested parameters such as fracturing parameter and optimization.
Paraproxx is the function that generates a PEC file at the end for CATS. It first uses the proximity function, which is from either Gaussian parameters such as alpha, beta and eta or Sceleton derived PSF. Optimization, transformation and fracturing parameters can be controlled in Paraproxx, but have some limitations incorporating with CATS such as shifting the relative dose range in the dose map assigned to the fractured pattern design, limiting fracturing down the minimal fractured pattern size to 1-micron instead of 100nm. As for the experimental quartz wafer, the proximity function is convoluted with a PSF model generated by the Sceleton Simulation. There is another way to input values for forward and backward scatterings and ratio of incident beam to backscattering. This is the other way to find those input values using the empirical PEC experiment with matrix of input values variations. Different options with fracturing parameters can command Paraproxx to generate specific PEC files. PEC files provide all the information needed during the single correction steps like convolution, fracturing and other options.

4.5.3.2 Proximity Correction Implementation

The proximity correction implemented in the CATS reads the proximity correction module to control the dose distribution.
The pattern design is setup here through the software. Naturally, the forward scattered dose deposits across the pattern design. Background dose deposits more energy in middle than the neighboring structures far away from the middle. This is the influence of the proximity effect on pattern generation. Then the dose modulation is required to add in each shape levels that are fractured by CATS. Each shape level is assigned with specific dose. It is prohibited for fracturing software to fracture the pattern to the pixel level due to computing resource limits.
Control of exposure time controls how many electrons are injected into bulk quartz substrate (ignore thinner resist) for getting approximately right Gaussian distribution fitting. The dose modulation is required to give a right dose in each shape level. Fractured shapes near the corner and edge receive more dose than the fractured shapes in the middle of the pattern design.

4.5.3.2.1 Dose Modulation Implementation

Proximity effect corrections with dose modulation are implemented in the fractured pattern design. The pattern design is fractured into different regions with specific dose assignment. In the middle of the pattern design, the relative dose is low compared to the high relative dose in the corner. A sample dose map is shown in Figure 51. There are no dose assignments in the spaces between the 22nm lines. Naturally, they will get some dose but that should be sufficient that will not print the resists there. They have to be less
than threshold line that is set up in the HSQ layer resist.

Figure 51 Proximity Effect Corrections Implemented in Fractured Pattern Design

### 4.6 Energy Profile Simulation

Coarse scattering events were studied with Casino Monte Carlo [113] before actually performing the high-precision Monte Carlo Simulation using Sceleton software.

There are two different case studies:

1. 30nm HSQ on 10nm Cr based quartz substrate
2. 30nm HSQ on Si substrate

<table>
<thead>
<tr>
<th>Set up Simulations for Casino Monte Carlo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerating Voltage Beam</td>
</tr>
<tr>
<td>Radius of beam</td>
</tr>
<tr>
<td>Traced electrons</td>
</tr>
<tr>
<td>Number of Displayed Trajectories</td>
</tr>
</tbody>
</table>

Table 6 Set up Simulations for Monte Carlo
The 100kV electron beam enters the Si substrate and creates a smaller interaction volume in Si substrate (55µm radial distance), as shown in Figure 52, compared to the quartz substrate (75µm radial distance). The Si has a backscattering coefficient ~0.11 where the ratio of backscattered electrons exit and enter. The Qz substrate has a backscattering coefficient at ~0.072.

Figure 52 Casino Monte Carlo Simulations for 30nm HSQ on Si

Figure 53 Casino Monte Carlo Simulations for 30nm HSQ on 10nm-Cr-based quartz substrate
The Casino simulation shown in Figure 54 illustrates the difference of 1,000 and 10,000 electrons for the quartz substrates and both of them have similar backscatter coefficient at ~0.072.

Monte Carlo shows almost no forward scattering event in the 30nm HSQ resist layer, which is considered thin. Backscattering is critical because if electrons exit amok from the quartz substrate, they naturally expose neighboring structures to the pattern design.
4.6.1 High Precision Sceleton Simulation

The Sceleton Simulation generates the point-spread function, which is the output and adapted to the needs of PEC mechanism. Sceleton is used to obtain the proximity function implemented in the PEC mechanism files. The PSF is a three-dimensional density probability function. Sceleton extracted the point spread distribution for the given vertical stack position $z$ from the simulation output obtained in simulation. The file was already created to describe the different materials. It is in the material database in sceleton.mda, as shown in Table 7.

<table>
<thead>
<tr>
<th>Description</th>
<th>HSQ</th>
<th>ZEP520</th>
<th>Cr</th>
<th>Quartz glass</th>
<th>Si</th>
</tr>
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<tbody>
<tr>
<td>nComp</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
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<td>1.22</td>
<td>7.2</td>
<td>2.20</td>
<td>2.33</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>c[2]</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7 Material Databases for Sceleton Simulation

Sceleton simulation traces where the electron trajectory is inside the detailed stack including the bulk substrate. It is embedded in CATS software.

The poor PSF file stored in the library folder at the CATS computer for fracturing the pattern designs was not simulated very well. HSQ dummy fills were exposed properly because PEC mechanism embedded with poor PSF file did not have a backscattering correction in large radial distance. Its parameters were poor and the simulation software missed the important statistics where the backscattering events were.
A new PSF file was quick test with extending the mesh numbers and steps to 200 and 50nm, respectively. The comparative results with poor and good PSF files are shown in Figure 56. The motivation was to improve the PSF parameters for the rest of this section.

Paraproxx generates the actual PROXECCO™ setup file for use in CATS. It takes the output of Sceleton as input and also takes quite a few options as input. Stepwise Function must be switched on for Sceleton output is used as input to Paraproxx. Then the output is the .pec format file. This is included in parameters adjusting the PEC mechanism for CATS.
The data management is refined to increase mesh numbers and increase steps. It improves the statistics of tracing the entire simulated forward and backward scattering events in the 10nm Cr based bulk Qz substrate. The different mesh numbers and steps are shown in Figure 58. It requires about 30 hours simulating the full energy density using the parameters given in Table 8.

<table>
<thead>
<tr>
<th>Data Management for Skeleton Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traced electrons</td>
</tr>
<tr>
<td>Lateral step</td>
</tr>
<tr>
<td>Vertical step</td>
</tr>
<tr>
<td>Lateral mesh number</td>
</tr>
<tr>
<td>Vertical mesh number</td>
</tr>
</tbody>
</table>

Table 8 Data Management for Skeleton Simulation

The output file of the xrz format file is established by extracting PSF values at specified height above the substrate. Typically, the extracting the height is half of the E-Beam resist thickness. Skeleton assumes an ideal Gaussian function and the CATS software asks for spot size of the electron beam. The Gaussian profile is convoluted with CATS to approximately give the energy level across the same addressable shape level.
The PSF files were created for optimized proximity correction for 30nm HSQ and ZEP520A layers on 10nm Cr based 350-micron thick quartz substrate with 20 million traced electrons. It improves the statistics of electron distribution for the quartz substrate because the #1 PSF has more statistics of electron distribution up to ~75µm radial distance. It is much better than the #2 old PSF with the combination of 100nm PMMA and 100nm Cr on the SiO₂.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Extra Coarse</th>
<th>Coarse</th>
<th>Standard</th>
<th>Finer</th>
<th>Extra Finer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injected Electrons</td>
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<td>1.E+05</td>
<td>1.E+05</td>
<td>1.E+05</td>
<td>1.E+05</td>
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<tr>
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<td>1500</td>
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<td>15000</td>
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<tr>
<td>Vertical Mesh #</td>
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<td>1500</td>
<td>7500</td>
<td>15000</td>
<td>37500</td>
</tr>
<tr>
<td>Lateral Step</td>
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<td>20nm</td>
<td>5nm</td>
<td>2nm</td>
</tr>
<tr>
<td>Vertical Step</td>
<td>100nm</td>
<td>50nm</td>
<td>10nm</td>
<td>5nm</td>
<td>2nm</td>
</tr>
</tbody>
</table>

Figure 58 Simulated different PSF with varying mesh values

The Skeleton Simulation was evaluated with different parameters for higher statistics for
30nm HSQ resist on 10nm Cr based Qz substrate. Figure 58 shows the difference of vertical and lateral mesh numbers starting from extra coarse to finer. The mesh numbers are extremely fine to 2nm for both lateral and vertical steps reducing from 100nm each step. The forward scattering situation becomes important with finer mesh to 2nm for both lateral and vertical steps, but backscattering events are all the same.

After improving parameters for PSF for 30nm HSQ on 10nm-Cr-Based Qz substrate to achieve higher statistics of tracing the electrons, PSF files were investigated with the number of electrons: 1 million electrons, 4 million electrons and 20 million electrons.

Figure 59 VEP format File implemented with calculated PSF based PEC File

The PSF was simulated with 4 million electrons. The HSQ 100nm half-pitch grating in 150x150um field was exposed with 10nm BSS and 10nA beam current. After analyzing the dose array under LEO SEM, 525 $\mu$C/cm$^2$ dose level was sufficient for the middle of the pattern design, as shown in Figure 59. The plot with one of PSF with 4 million electrons is shown in Figure 61 for HSQ CDU 100nm half-pitch grating. eSEM collected
the different micrograph located in sites, as shown in Figure 60 and SUMMIT Software measured the CD.

![Diagram of 100nm Lines and Spaces](image)

**Figure 60** Manual measurements for 100nm half-pitch grating over 150x150µm field

![Graph of Width Line vs Radius Distance over HSQ CDU on 150x150µm field](image)

**Figure 61** HSQ CDU on 150x150µm field using PSF with 4 million electrons

The exterior boundary of the pattern design did not have sufficient dose and the sizes of
the printed lines were exponentially dropping when approaching to the corner of the design pattern. The process was to optimize newer PSF files with better statistics of electrons injected in the quartz substrate.

![Image](image.png)

Figure 62 LWR and LER increase at the corner of the 150x150µm field due to not enough dose

The plot, as shown in Figure 62, is same as the exposed sample evaluated with 4 million electrons PSF for HSQ half-pitch grating pattern from the Figure 61, with 525 µC/cm² base dose. SUMMIT software obtains LER and LWR. The plot indicates higher LWR and LER values in the exterior boundary of the 150x150um field. PEC with 4 million electrons PSF was getting better, but not satisfying at that time due to underdose exposure near end of the 150x150µm pattern field. The newer PEC mechanism embedded with 20 millions electrons was then studied.
The newer PSF with 20 million electrons was simulated with a long run time of about ~30 hours. Note the significant change in the dynamic range assigned to the dose corrections with the increased number of electrons in the simulation. The simulation was operated on the Linux Operating System with four Central Process Unit (CPU) cores.
The PSF simulated with 20 million electrons is much better for CDU measurements than the other PSF files with lower traced number of electrons as shown in Figure 65. The different PSF files were studied while the parameters are the same in PEC module embedded with CATS: average dose, full density mode, alpha correction and 10nm spot size. The tail of Gaussian was extended to get the dose contribution more accurate with the higher number of electrons to be traced.
After exposure using 100kV Vistec Gaussian Writer, LEO 1550 SEM inspected raw HSQ resist without etching to avoid any biases except for proximity effect. Clearly, PEC needs to be improved over CD uniformity on a large pattern field for HSQ resist. The Gaussian tail had been extended with more statistics, but not full satisfaction. We still have open questions here. The PEC mechanism may need to include additional physics beyond electron scattering such as substrate heating and process effects associated with HSQ resist. HSQ must be investigated more to understand the behavior related to process, PEC and substrate heating effect. However, printed ZEP520A resist has excellent results with CDU on the large pattern area. The different CDU for negative-tone HSQ resist and positive-tone ZEP520A are shown in Figure 66.
eSEM collected the micrograph and measured the line width for Figure 66. The two different measured 100nm half-pitch grating for ZEP520A resist were collected from the dose array.
The .xrz format files generated by the Sceleton simulation for both the HSQ and ZEP520A stacks show that both stacks have the same backscattering events as expected since the substrate dominates the backscatter.

Consequently, the PEC has much improved through my experimental Qz wafers, but does not satisfy CDU uniformity targets over 150x150µm field for HSQ 100nm half-pitch grating pattern. The PSF was generated precisely to improve the accuracy of PEC, but more work is still needed to improve PEC by tweaking the other processes: coat, develop, e-beam scanning performance and substrate heating effect. Proximity function with third Gaussian terms or more can potentially make the PEC mechanism better. The proximity function for the quartz substrate does not give good CDU uniformity targets for only specific HSQ process. It is interesting to note that the same proximity function used for HSQ process satisfies ZEP520A process. For example, using 16 terms of Gaussian distribution as PSF becomes more accurate attempted by Dr. Tsunoda [76] for HSQ process. PSF file should have many Gaussian terms to approximate the corresponding long-range backscattering parameters and other additional factors, which contribute significant energy errors in large area. It needs to have a better linear combination of more Gaussian terms. HSQ seem to be very sensitive to PEC and its process somehow. The case study on HSQ has to be investigated more.
4.7 Writing Strategy

4.7.1 Electron Beam Exposure

As for dose to clear in resist material, the number of electrons delivered to in each area unit depends upon grid size, current and frequency. The double deflection blanker in the VB300 system can support data rates up to 50 MHz. It is important to have sufficient beam current to increase the speed writing time. This will help reduce costs as much as possible. The resolution of structures encountered in 20nm features and beyond is ultimately due to various factors such as BSS, electron sensitive material and exposure dose. BBS is the distance between two adjacent pixel exposures. The dwell time is calculated from a given beam current, required dose and BSS,

\[ T(\mu s) = \frac{10D \cdot BBS^2}{I} \]

Where BSS = beam size step (µm)
D = Dose (µC/cm²)
I = Current (nA)

![Figure 68 Writing time for each pixel exposure with fixed 2nm Beam Size Step](image)

Figure 68 Writing time for each pixel exposure with fixed 2nm Beam Size Step

The few beam size steps were evaluated to increase the distance between two
adjacent pixels. Increased distance between adjacent pixels will increase the speed of writing time, however the HSQ resist requires many overlay beam spots to form nice pattern with minimum LER and LWR. That is more important. As for beam size step, the beam size step needs to have an extremely short distance between two adjacent pixels.

Figure 69 Writing time depends on Beam Currents and dummy fill sizes

Figure 69 shows the difference between 1.2µm squares on a 1.7µm pitch (1.2/1.7µm) and 200nm squares on a 500nm pitch (0.2/0.5µm) with their speed writing times, respectively. Decreasing the size of dummy fills will reduce the writing time. 1.2/1.7µm dummy fills require more exposure pixels compared to 0.2/0.5µm dummy fills. Those data was collected from the preview simulation on the VB300 control computer.
4.7.1.1 PEC Mechanism Related to Writing time

PEC Mechanisms implemented in fractured pattern design affect how much the writing time will be. It is possible to optimize reasonable PEC mechanisms in each fractured pattern. Set up the effectiveness of PEC with reasonable resolution images. Larger the resolutions are, coarser the fractured sizes are. A thirty percent increase of the relative dose is assigned to the fractured pattern design will increase the writing time by 30 percent. Dummy Fills are much coarser features that can effectively minimize writing time because they are not critical compared to the other design patterns with 50nm features and beyond.

4.7.1.2 Writing Strategy for 20nm and 16nm half pitch lines

Tradeoffs to effectively minimize writing time are considered here for 20nm lines and beyond. Writing on a single E-Beam pass is not preferred, since the Gaussian distribution is pushed down near to the bottom, as shown in Figure 70.

![Gaussian Profile](image)

The resists were all exposed with a fixed beam step size, BSS, which is the distance between two adjacent exposures. Depending on the designed linewidth, the exposure of a
line is performed by scanning the beam once (single pass) over adjacent lines (n-exel line). The number of exels is defined as the number of times the BSS fits into the designed linewidth. An exel diagram is shown in Figure 71.

![Spot Size Diagram](image)

**Figure 71 Possible Writing Strategies**

The smaller the beam diameter that is used, the thinner the resulting line can become. Generally, the smaller beam diameter is better for writing thinner lines.

![Feature Bias Diagram](image)

**Figure 72 Feature Bias for 16nm Half Pitch Lines**

There is tradeoff between BSS and number of E-Beam passes in Figure 72. 16nm half-pitch grating in the small pattern area was exposed with 2nm BSS and 2nm spot size, as shown in Figure 148 a.
20nm half-pitch grating in the small pattern areas, as shown in Figure 74 b and c, were successful with correct BSS and spot size, except lower beam current, as shown in Figure 74 a. The spot size might not be corrected well or noise level rose during E-Beam writing due to excessively slow exposure. Noise frequency is not possible to be avoid during E-Beam writing. The disturbance leads to unwanted noise in an undesired position. Scanning the electron beam across the surface resist with 500pA and 1nA is much better than operating at 200pA beam current due to sensitively noisy level. Excessively slow electron beam scanning in raster affects noisy lines and lines could be shifted in a few nanometers and widened the designed width line.
Figure 74 printed 20nm half pitch lines in HSQ with (a) 280pA, (b) 500pA and (c) 1nA beam currents with 2nm, 3nm and 4nm spot sizes, respectively.

The spot size must be equal beam step size as shown in Table 9 to achieve the quality of high-resolution images. The VB300 control computer measured the writing time that the VB300 exposed varying sub-20nm features, as shown in Figure 190 in the appendix 13.8, in the 5-micron pattern area measured the writing time.

<table>
<thead>
<tr>
<th>Beam Current</th>
<th>Spot Size</th>
<th>BSS</th>
<th>Aperture Size</th>
<th>Base Dose</th>
<th>Relative Dose</th>
<th>CD</th>
<th>LER</th>
<th>LWR</th>
<th>Writing Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>nA</td>
<td>nm</td>
<td>nm</td>
<td>µm</td>
<td>µC/cm²</td>
<td>%</td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
<td>sec</td>
</tr>
<tr>
<td>1</td>
<td>~4nm</td>
<td>4nm</td>
<td>70µm</td>
<td>2100</td>
<td>&lt;1%</td>
<td>21.7</td>
<td>1.9</td>
<td>3.1</td>
<td>48.6</td>
</tr>
<tr>
<td>0.500</td>
<td>~3nm</td>
<td>3nm</td>
<td>70µm</td>
<td>2000</td>
<td>&lt;1%</td>
<td>20.9</td>
<td>1.5</td>
<td>2.7</td>
<td>95.6</td>
</tr>
<tr>
<td>0.280</td>
<td>~2nm</td>
<td>2nm</td>
<td>40µm</td>
<td>2100</td>
<td>&lt;1%</td>
<td>21.1</td>
<td>N/A</td>
<td>N/A</td>
<td>168</td>
</tr>
</tbody>
</table>

Table 9 Tradeoff with different parameters for 20nm half-pitch grating in small pattern area

0.28nA beam current is not designed for exposing the full chip to avoid changing the aperture size. 70µm aperture size was kept through the full exposure rather than
changing to 40µm. 70µm aperture size is required to achieve 500pA and 1nA beam current given by the electron column whereas the 40µm aperture size is used for achieving 280pA beam current. 20nm half pitch lines in the small pattern area are printed with 1nA beam current in lieu of 500pA. 1nA beam current gives 4nm spot size, whereas 500pA beam current gives 3nm spot size.

Designed linewidth was evaluated by widening the spot size or sufficiently high dose to get single E-Beam pass. The example for 16nm half pitch is shown in Figure 75.

A high dose moves the threshold into the tail of Gaussian and increases the size of the line. One of examples is shown in Figure 76 with higher dose at 2500µC/cm² achieved single E-Beam pass on 2nm pixel line on a 20nm pitch. The 10nm spot size was
broadened by higher dose to print accurately 10nm lines with 2nm BSS. The other meaningful is that overdose raised the bottom of the Gaussian closer to the resist threshold, as shown in Figure 70. The single E-Beam pass is not suitable on a shrinking pitch less than 20nm, as shown in Figure 77, with 2500µC/cm² and 2nm BSS.

Figure 76 2nm pixel single lines on a 100nm pitch with printed 10nm lines on 10nm-Cr-based Qz substrate
4.7.1.3 Tradeoff between Writing Speed and Resolution

Tradeoff between writing speed and resolution is essential for reasonable throughput.

Table 10 shows the speed writing time for 0.2/0.5μm dummy fills. Data is collected from the VB300 control computer to predict the writing time.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Slowest Speed</th>
<th>Highest Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Current</td>
<td>5nA</td>
<td>25nA</td>
</tr>
<tr>
<td>Beam Size Step</td>
<td>12nm</td>
<td>25nm</td>
</tr>
<tr>
<td>Resist Sensitivity</td>
<td>100 μC/cm²</td>
<td>100 μC/cm²</td>
</tr>
<tr>
<td>Dose Time</td>
<td>28.8 nS</td>
<td>25 nS</td>
</tr>
<tr>
<td>Dose Frequency</td>
<td>34.72 MHz</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Exposure Time*</td>
<td>4 hr</td>
<td>1.25 hr</td>
</tr>
</tbody>
</table>

*For 13x13mm field

Table 10 Speed Writing time for 0.2/0.5μm Dummy Fills in ZEP520A
The writing speed time for 20nm half-pitch lines is essential because 500pA and 1nA beam current have similar results, except higher beam current. The spot size is optimized with sufficiently high-speed writing time at 500pA beam current for 16nm and 20nm. As for 22nm lines, 1nA beam current is chosen here to drastically decrease with the writing time for a large pattern area.

![Figure 78 20nm half pitch lines with (a) 200pA (b) 500pA and (c) 1nA beam currents.](image)

<table>
<thead>
<tr>
<th>Dose</th>
<th>Beam Current</th>
<th>BSS</th>
<th>Spot Size</th>
<th>Writing Time*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2100 μC/cm²</td>
<td>1nA</td>
<td>2nm</td>
<td>4nm</td>
<td>48.6 seconds</td>
</tr>
<tr>
<td>2100 μC/cm²</td>
<td>0.5nA</td>
<td>2nm</td>
<td>3nm</td>
<td>95.6 seconds</td>
</tr>
<tr>
<td>2100 μC/cm²</td>
<td>0.28nA</td>
<td>2nm</td>
<td>2nm</td>
<td>2.8 minutes</td>
</tr>
</tbody>
</table>

*5-micron pattern area with <1% relative dose

Table 11 Writing Time for 20nm half-pitch lines

### 4.7.2 Writing Strategy for Protein Cells

It was attempted to pattern eight of 12.75μm square arrays of 10nm dots on a 260nm pitch near the alignment marker in minimum writing time by flashing on each designed spot with a higher dose as much as possible in less dwell time for high throughput. The layout in GDSII is shown in Figure 11 a. It was insufficient because it requires filling a
shape with many spots (or smaller BSS than spot size) as much as possible to deposit more energy into the HSQ resist to create a 10nm spot, as shown in Figure 79 b. This method is better than flashing on each 10nm spot or the 10nm spot would be blurry. The HSQ was exposed at a very high dose and it was swept overlap in 2nm beam size step to produce a nice image of 10nm spot size. The smallest feature is a 10nm spot with 260nm pitch in HSQ resist on 10nm-Cr-based Qz substrate, as shown in Figure 79 c.

A variety of spot sizes were evaluated instead of focusing on 10nm spots. The electron beam is shot with spacing between certain points to overlap enough to form 10nm spots. This is the same as 15nm spots and it was difficult to tell if 10nm spots were patterned well with the high beam current. Higher beam current, i.e. 10nA, made a blurry image of 10nm in HSQ resist compared to the smaller beam currents. The parameter with 1nA beam current and 2nm BSS was optimized to form 10nm spots, as shown in Figure 80.
The initial experiment attempted to incorporate both alignment marker and the array of isolated dots into a single exposure, as shown in Figure 81 d. However, in this case the dots were not printed due to uncorrected scattered dose from the alignment targets. At that time, the PEC mechanisms implemented in the fractured pattern design was not clear. Once the PEC is well understood, then it should be able to print both the
alignment marker and the isolated dots. The PEC mechanism was supposed to incorporate the exposure on both alignment marker and 10nm spot array with the same beam current and the same BSS. The PEC mechanism will have to be investigated again with the newer PSF file and better parameters.

After failing to mature PEC mechanism, the strategy was to divide two different features for PEC mechanisms, respectively: 10nm spot array and marker alignment. The alignment marker was fractured and adjusted with PEC, as shown in Figure 82 a. The isolated dots do not have a PEC mechanics implemented in VEP format file, as shown in Figure 82 b. It has one dose assignment for all isolated dots across 12.75x12.75µm field. The two separated VEP files have different PEC mechanisms for 12.75um square of 10nm spot array and alignment markers, respectively, in the jobfile for VB300. !Cview software opens the two different VEP format files what they are supposed to look like for the exposure layout, as shown in Figure 82 c. 10nm spot array and alignment markers were printed successfully by integrating two pattern exposures in the jobfile.

Figure 82 (a) Corrected PEC implemented for optical marker, (b) no PEC implemented for 10nm spot array and (c) Integrated in the jobfile
4.8 Height Sensor for a thinner Cr film

Three different thick Cr layers were evaluated: 15nm, 10nm and 6nm. The initial experiment used a 15nm Cr film. A thinner Cr layer is better because it will minimize CD uniformity error for pattern transfer process. The 6nm Cr layer was the first designed in the experiment to minimize CD loss as much as possible during pattern transfer process on the quartz substrate. However, 6nm Cr was not feasible for this experiment because the VB300 system’s laser height sensor was not be able to detect the surface Cr layer. Laser photons easily transit the 6nm Cr film, which is too thin for the laser sensor to detect a reflected laser beam from the top. The experimental plan was changed to a more suitable 10nm Cr film for good laser height measurement and it was emphasized to keep it throughout the experiment. Software on a processor in the sensor unit for laser height then finds the “peak” on the CCD array, as shown in Figure 83. The software acquires all the elements in the array with a signal above threshold and calculates the center of gravity of the peak. It has to be debugged to find what the CCD array is seeing by attaching a scope to the sensor unit. Three different peaks should be visible for the top surface, backside surface and the chuck on the stage. For a substrate with an opaque top layer only a single peak should be seen. In principle, a laser height sensor should be able to select a single peak from multiple surfaces and use that as the basis for any height correction.
4.9 Charging Problems during E-Beam writing

The charging problems were noted in initial experiments when the grounding clips were not in contact with the underlying Cr film with the HSQ resist coated on the quartz substrates. The clips failed to puncture the resist layer to make a contact with 10nm Cr based on quartz substrate. The difference between the two cases is shown Figure 84.
The charging problem has been resolved in two different ways.

1) For HSQ resist, TMAH solvent removes some HSQ resist coating on Cr/Qz wafer. As for ZEP520A resist, Acetone alcohol is used to remove the ZEP520A coating.

![Clip diagram](image1)

Figure 85 Clip punctured the underlying Cr layer through E-Beam resist

2) Make a puncture with the clip into the underlying Cr film with HSQ. This is not recommended because the Qz wafer will be stressed due to pressures from three punctures. The best way is to get the three metal pins in contact with the Cr film.

![3 Pins diagram](image2)

Figure 86 using solvent to remove the resist coating on Cr based Qz wafer

Screwing the clips to puncture the Cr film can stress on the quartz wafer that can be sag
or bow easily and offset the height uniformity beyond the standard +/- 10-micron range.

Too much puncturing the Cr/Qz wafer with two clips, a fringe pattern on the Cr/Qz wafers was seen by naked eyes and the height uniformity was not in +/- 10-micron range.

The fringe pattern has bright and dark lines viewed on the Cr/Qz wafers. The dark fringes are caused by destructive interference with light waves when the light reflecting off the top surface of the quartz wafers. The clips must be screwed gently to avoid the fringe pattern on the Cr/Qz wafers, the Cr layer must be grounded and can be checked with Digital Multimeters (DMM) each time and the alignment station can check the height uniformity before loading the stage into the E-Beam Lithography.

Without grounding the Cr layer, the E-Beam lithography carried many negative charges accumulated on the substrate surface due to 100 keV accelerating beam voltage. Then, negative charges caused beam deflection within E-Beam writing, as shown in Figure 87.

![Diagram](image)

Figure 87 Grounding the underlying Cr (a) and Ungrounding the Cr (b) during E-Beam writing

When the Cr layer is not grounded, it accumulates a charge on the Cr. Cr is a conductor, which forms an equipotential surface. The electron beam is reacting to it without forming
5 Pushing the Boundary and Beyond of High-Resolution Patterns

An exposure evaluation on a Si Substrate was first studied to better understand the high-resolution structures of HSQ before transferring onto a quartz substrate. The PEC was not optimized for a large pattern field. The small pattern area is sufficiently isolated that PEC issues do not arise. Figure 88 shows two elbow structures of 16nm half-pitch scatter test structure in 30nm HSQ layer. LEO 1550 SEM inspected the raw HSQ materials printed on the Si substrate and its measure instrument was not accurate to collect CD, LER and LWR results for dose range.
Figure 89 a and b show an isolated 6nm line and 8nm half pitch lines in HSQ. These are the best CD values achieved using the Vistec VB300. A cross section image of 10nm lines and 20nm spaces in HSQ are shown in Figure 89 c. 8nm half pitch lines were observed, but there was difficulty looking and taking pictures under SEM due to low resolution limiting to about ~5nm and not perfect 90° angle sidewalls were seen from top view micrograph, as shown in Figure 94. A 0.5nA beam current was operated with 4nm spot together with a 2nm beam step size. LER and LWR of patterns in HSQ have a very low variation compared to other resists like SU-8 and NEB [95]. The plots in Figure 90 below show the CD, LER and LWR variations in isolated HSQ lines with dose respectively. NEB resist was considered for use, but it has higher LER and LWR values due to the performance limitation of the Vistec VB300 Lithography. VB300 with the electronic rack, which supports the upper limitation of 50MHz, is insufficient for high sensitive NEB resist, which requires about 2nm BSS [95]. Therefore, The new E-Beam lithography needs to deliver low doses at smaller step size. A former PhD student, namely Junru Ruan, studied and designed the innovative high-speed blanker [125] that
can support up to 1 GHz. The blanker is responsible for deflecting the beam to make patterns. Vistec built it in 2010 and Professor John Hartley is in process of testing the new blanker sometime next few years. The next generation E-Beam lithography should be newly designed to deliver a dose in a short amount of time for achieving 10nm images and beyond with low LER and LWR.

![Figure 90](image)

Figure 90 (a) CD depends on Dose (b) LWR/LER depends on Dose for isolated lines

As for large pattern area, PSF models were not good due to low-resolution mesh number and simulation with only one thousand of electrons at that time for studying Si substrate before transferring onto Cr-based Qz substrate. The proximity effect correction was poor at that time for the large pattern areas. HSQ issue observations are shown in Figure 137.
6 Challenges of Printing High-Resolution Structures in HSQ

The Gaussian E-Beam Writer Technology needs to have good controllability to get high-resolution resists printed every time. Many researchers and workers in a number of publications suggested that thinner resist layers should improve the resolution [45]. The thinner ZEP520A down to 40-45nm is sufficient to act as Cr etch barrier. The resist layer could lose its selectivity when there is too much oxygen fed into ICP/RIE plasma process. Generally, ZEP520A is very sensitive to oxygen plasma [45] compared to HSQ. An amount of oxygen mixing can be reduced or timing can be reduced for the descum process. HSQ and ZEP520A were chosen with 30nm and 40nm thick layers, respectively, for effectively minimizing forward scattering events. ZEP520A resist requires thicker layer than HSQ since it is not easy to etch the Cr film into positive-tone pattern. The ZEP520A resist has to be thick enough for resisting against plasma process to protect the underlying Cr. The thickness of ZEP520A layer was verified by ellipsometry.

Printed features have their broadening effect on their sidewall in small pattern area, as shown in Figures 148a and 149a. It was not possible to have good pattern transfer processes for both Cr and Qz, as shown in Figures 150 and 151a. The ideally perfect E-Beam Resist pattern is shown in Figure 91. It was not possible to have an almost perfect 90-degree angle between lateral and sidewall.
The correct dose, as well as the development time, is related to the different resists and developers used. To get the correct dose, the exposure time must be set up right depending on how many electrons are injected into E-Beam resist layer correlating with electron sensitive material and development time. Negative tone HSQ resist will remain at the exposed area, while the unexposed parts of the HSQ will be etched away by the TMAH developer. In positive tone ZEP520A resist, the exposed part will be etched away, as shown in Figure 92.
In HSQ, the edge profile of a line exposed is bell-shaped, which is caused by the electron scattering. However, ZEP520A has more control over the profile. It is possible to get perfect vertical edge profiles. By using a higher dose and/or a short development time, the edge profile will be controlled by the energy deposition profile, and will have a poor shape. A low dose and long development time will yield a poor shape. With correct dose and develop, steep vertical edges can be obtained. Different situations are shown in Figure 93 [107][108][109].

The pattern design must have good proximity correct by focusing how many electrons can inject into resist during E-Beam writing. This is related to space and time to get a desirably approximate Gaussian distribution.
LEO 1550 SEM cannot read the clear image from top view very well. Figure 94 is one of the examples showing it is not possible to read the image well by looking at the top view with 30nm lines on a 100nm pitch.

The cross sections of 10nm lines with varying pitches were evaluated for understanding the HSQ profile. Figure 95 shows the broadening effects on the sidewalls, the scale broadening to 30nm pitch in lieu of 20nm pitch. The resist profile in HSQ was not satisfactory because the PSF was not always perfect in the center of the pattern area. The
micrographs, as shown in Figure 96, have poor edge contrasts coming from tightly regulated dose correction. The dose correction in the center of a large homogeneous array is a constant offset to the dose and an ideal PSF can be found at the center of the pattern area by doing a dose array.

Cloudy edges are shown in Figure 96 with printed 20nm and 16nm half pitch lines where the broadening effects are visible on their inclined sidewalls from top view. It is not from the limitation of operating SEM while shooting micrographs. 16nm and 20nm half-pitch lines, as shown in Figure 96, were not printed successfully due to poor PSF file and uncorrected forward scattering and backscattering.
There was not enough time with this experiment to feasibly study the correlation between the correct dose and development time. The data had not been collected well without good PEC.
7 Plasma Etching for 1X Imprint Template

After the introduction of the semiconductor device in the 1940s, the concepts of mask and etch were the potential industrial fabrications for manufacturing semiconductor devices [73]. Year after year, the etch process with the mask protecting part of the area become a widespread industrial practice for IC. The first method used was a wet chemical etch solvent to dissolve the material with the resist protecting part of the underlying area. The Semiconductor Industry started using the plasma etch process during the 1970s. Its technology continued to improve until the mid-1980. By that time, the Semiconductor Industry changed the strategy on how to use lithography in high volume manufacturing with 4X or 5X reduction [73]. Consequently, it made mask fabrication very easy and resulted in an industrialized mask shop’s vacation for decade. Until the mid-1990s, a traditional wet etch technology became very difficult for 4X mask fabrication when feature dimensions shrunk down to about half micron size.

7.1 Plasma Etch Process

Plasma processes are not in equilibrium. Plasma provides energy to break chemical bonds without the need for thermal energy and allows processes with strong temperature dependencies. This process is flexible for removing desired material. Characteristic features of a plasmas process include:

- Electrical Activity
- Collision of charged particles with neutrals
• Ionization of neutrals sustains the steady-state plasma
• Electrons are not in thermal equilibrium with the ions

Discharge is initiated when stray electron accelerates towards cathode and collides with neutral atom (A), forming an ion and two electrons:

$$e^- + A \rightarrow 2e^- + A^+$$  \hspace{1cm} \text{Equation 23}

Ions accelerate in opposite direction, collide with cathode and eject secondary electrons. Then the gas breaks down and a discharge is formed in the chamber. The electrode spacing is sufficient to allow electrons to gain energy in field for ionization.

### 7.2 Plasma Etching Technology

The Minilock Phantom III system, as shown in Figure 98, manufactured by Trion Technology, is a plasma etcher designed for research and failure analysis laboratories with state-of-the-art plasma etch capability using single wafers, dies or parts. This system etches both Cr and Qz using chlorine-based and fluorine-based gas mixtures, respectively. Not limited only to Cr and Qz etch process, this system can also descum, clean with oxygen plasma and strip E-Beam resist off, but the etch problems arise due to several reasons discussed later in the section 7.6.
In the Trion etcher tool, an electrostatic chuck (E-chuck) keeps the wafer cool during the plasma etch process. It has a helium pressure controller to build up a cooling layer of helium on the backside of the wafer. The Trion etcher tool supports both reactive ionization etching (RIE) and Inductively Coupled Plasma (ICP). The ICP is given the option here to create higher density plasma. It will increase etch rates and anisotropy. The chuck receives a negative DC bias, which increases ion bombardment and anisotropy while etching. The ICP is the primary plasma source that creates this plasma by inductively coupling the RF power in the vacuum via a copper coil connected outside of the ceramic tube above the chuck inside the chamber. The RF power supplies to the chuck with a potential DC bias. This accelerates the ions to the sample.
ICP power has a big influence with plasma etch performance compared to the RIE power, gas flow and pressure. Anisotropy rate can be important for getting a good profile. The following Table 12 explains the basic trends involved with basic plasma process according to a manual from Trion.

<table>
<thead>
<tr>
<th>Increase in Process Variable Condition</th>
<th>Etch Rate</th>
<th>Anisotropy</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>Increase</td>
<td>Decrease</td>
<td>--------</td>
</tr>
<tr>
<td>ICP Power</td>
<td>Increase</td>
<td>Decrease</td>
<td>No effect</td>
</tr>
<tr>
<td>RIE Power</td>
<td>Increase</td>
<td>Increase</td>
<td>No effect</td>
</tr>
<tr>
<td>Gas Flow</td>
<td>Increase (slightly)</td>
<td>No direct effect</td>
<td>Increase</td>
</tr>
</tbody>
</table>

Table 12 Increase in Process Variable Condition

### 7.3 Chromium Plasma Etching

The etchant of the Cr layer is chlorine-based chemistry to form volatile products of chromium. The chromium etch process requires high ICP to get the plasma distribution more uniform [73]. HCl and CCl₄ can be used as well, but Cl₂ was chosen for this experiment since most mask shops use this direct-compounded gas chemistry. It is not common to find HCl and CCl₄ used in any etchers [73].
Cl\textsubscript{2} and O\textsubscript{2} are the gas mixtures for Cr etch. Breaking down the chemical bonds of Cl\textsubscript{2} and O\textsubscript{2} in the chamber, the plasma etch reaction of chromium and the reaction of chromium oxide were assumed here,

\[
\text{Cr} + \text{CO}^* + 2\text{Cl}^* \rightarrow \text{CrO}_2\text{Cl}_2
\]

\[
\text{CrO}_x + (2-x)\text{O}^* + 2\text{Cl}^* \rightarrow \text{CrO}_2\text{Cl}_2
\]

Cl\textsubscript{2} and O\textsubscript{2} gas necessary to build the volatile Cr etch product CrO\textsubscript{2}Cl\textsubscript{2} increases the resist consumption especially in combination with high plasma power. In order to reduce the resist consumption, either the Cr-to-resist selectivity has to be raised significantly [126] or the Cr layer thickness has to be reduced. HSQ and ZEP520A resists were already chosen as discussed in section 1.6.4 that have the requisite properties to serve as the mold for SFIL\textsuperscript{TM}.

The Cr etch rate was proposed [77],

\[
\frac{W}{a + bW} = \frac{\text{O}_2}{\text{ICP}}
\]

Where \(a\) and \(b\) are constants; \(Q_{\text{O}_2}\) is oxygen flow rate [standard cubic centimeter per minute (SCCM)]; \(P_{\text{O}_2}\) is oxygen partial pressure (mTorr) and \(W_{\text{ICP}}\) is ICP power (watt).

The etch rate is a function of ICP power, pressure, gas compositions and flow rates. Experimental results show that the etch rate is determined by the oxygen flow, not the molar ratio (concentration).

The Cr layer consists of chromium and chromium oxide sublayers. X-ray
Photoelectron Spectroscopy (XPS) collected the results indicating there was native oxide layer on the Cr layer. The XPS showed a thin ~20–30 Angstroms CrO film on the surface with Cr underneath. A post doc student, Dr. Eric Eersch, reported this XPS analysis.

Figure 100 XPS result on native oxide layer on 10nm-Cr-based Qz substrate

Binding energy in parenthesis is from a reference data set for XPS machine.
The peak is shown in Figure 101 that intensity all the way up to the oxide is only ~20-30Å. The thickness is significantly close to accurate. The survey scan shows only Cr peaks, along with one O peak and one C peak. When chlorine and oxygen are used for plasma etching of the Cr layer, there is no significant difference in etch performance between these two sublayers [73].

After few initial etch works with the Trion etcher, a dark field microscopy is used to verify Cr etching with ZEP520A resist mask. The light traveled through the patterned Cr regions, as shown in Figure 102. Profilometer measured the depth of the combination of Cr and Qz etching. The Cr layer was very difficult to measure due to low-resolution measuring capability, but RC2 ellipsometer can. RC2 ellipsometer is high-resolution measuring capability and measured 14.5nm Cr thickness, as shown in Figure 185 in the appendix 13.3.5.
Figure 102 Microscopically Dark-field picture of (a) before etched and (b) etched Cr 500um Square and (c) Profilometer Data for 14.5nm Cr Etching

The profilometer scanned the etched 14.5nm Cr half-millimeter square in one pass and the trench plot shows in Figure 102 without etching Qz to make some best estimates on the combination of Cr and Qz etching. The profilometer has a limit of 5-Angstroms resolution. In order to verify the accurate Cr etching depth, the AFM scanned the depth of etched Cr pattern and the measurement shows it at about 13.5nm depth on Figure 103.
Figure 103 The plot of depth measured by AFM’s tip

Figure 104 AFM topography surface
After developing the excellent PEC mechanism for ZEP520A resist, Figure 105 shows opening regions of the Cr hard mask for the 13x13mm full chip after stripping ZEP520A off with oxygen plasma.

HSQ resist was demonstrated for excellent etch bias, as shown in Figures 106, 150 and 151. The Cr thick layer can be completely etched between the printed HSQ structures. Throughout the experiment, the 30nm HSQ was emphasized. The etch performance with HSQ selectivity against Cr has been excellent.
Unfortunately, the PEC had not been matured well for HSQ resist and ZEP520A resist was moved on to 22nm SRAM gate and positive-tone images required on imprint templates. ZEP520A resist is really much easier to stay with HSQ resist rather than ZEP520A, which will show later in Figure 130.

In order to get thick enough ZEP520A layer before it is whipped out by the etch plasma process, the 30nm, 40nm and 50nm layer thickness were evaluated. 40 - 45nm ZEP520A was found to be sufficient for designed 22nm features. If the resist thickness was more than 40nm, the resists would be collapsed easily, as shown in Figure 107, with thick 50nm ZEP520A layer. Unfortunately, the resist thickness cannot be easily reduced.
After descumming a printed ZEP520A resist with oxygen plasma when the Trion etcher was in good condition, the RC2 ellipsometer verified the thicknesses varied from 35-40nm. It was noted that the ZEP520A resist has a sensitivity to oxygen plasma throughout the etch plasma. Therefore, oxygen gas flow has to be reduced as much as possible [45]. Note that the ZEP520A layer can be run out if it is left in the oxygen plasma process more than 1 minute with low RF power with the recipe, as shown in appendix 13.4.5. The descum process is required to remove scum and resist residues Not using the descum process produces a poor result with Cr etching, as shown in Figure 108. This was the beginning of the test bench.
For low etch selectivity, the ZEP520A resist can erode changing the dimensions of the transferred images onto the Cr layer, as shown in Figure 109. CD losses during the etching of the thick Cr layer made the fabrication are impractical for 1X templates.

**Cl₂ / O₂ gas mixture**

In the design of all the experiments, ICP power had a significant effect on etch rate, uniformity, CD movement and microloading etch problems. The etch rate was noted in Table 14. Figures 130 and 141 show that the etch uniformity can be changed. The
referenced papers [45][73][87] discussed about the CD movement and microloading etch problems affected by ICP power level and microloading etch problems. When ICP power increased, etch rate and CD movement increased with it.

A thin Cr film is desired for better pattern transfer onto the quartz substrate. The Cr layer is excellent for Qz etch barrier, shown in Figures 125 and 126 with aggressively etch and remove quartz. The Cr layer is 20:1 etch selectivity. Both etch uniformity and CD movements are affected by Cr and ZEP520A selectivity.

The Cr had to be carefully plasma etched with timing rather than losing the ZEP520A layer. ZEP520A gets thinner before the pattern image transfer is recessed into the Cr layer and. A polymer formation is suspected to fill the etched Cr features across the full chip, as shown in Figure 110, and block the quartz etch process. Some recessed structures were not there in Figure 110 c.
Most of time, scum and Cl\(_x\) residues were stuck in the opening regions of the Cr layer, as shown in Figures 111 and 121. These blocks the next quartz etch process discussed in section 7.5.
22nm SRAM structure was attempted to get etched. After the etched Qz 22nm SRAM gate was inspected with eSEM and were measured using the SUMMIT Software. After stripping the Cr, the relief structure was not there.
The observations are shown in Figures 112 and 113. Both of them used the ZEP flow process. The samples were etched using the same Cr recipe, which can be found in the appendix 13.4.6. The Trion etcher tool eroded over time and the defects on the etched Cr sidewalls are shown in Figure 113. But, the Trion etcher was in a good condition that was able to etch the Cr layer in the early stage, as shown in Figure 112.

7.4 E-Beam Resist Stripping

The oxygen plasma stripped the E-Beam resist as much as possible with low RF power. This process is very important and requires a complete removal of ZEP520A resist for the next step of quartz etching. Prior to etching the quartz, it is very important to identify the commercial resist systems used in quartz wafer development process whether the resist needs to be stripped from the Cr or not. ZEP520A layer and residues cannot be laid on both the quartz and the Cr pattern where ZEP520A was exposed, developed, descummed
and used as resist mask to pattern Cr images using chlorine-based chemistry etch. They block the Qz etch process and no pattern transfers are recessed on the quartz substrate. However, HSQ is not necessary to be removed prior to etching the quartz. HSQ is very hard to remove because its structure is like amorphous SiO₂.

### 7.5 Quartz Plasma Etching

The etchant of the quartz substrate is a fluorine-based chemistry that forms volatile products of quartz in the opening regions of the Cr hard mask. Thermodynamic calculations for quartz plasma etching using a gas mixture of O₂ and CHF₃ and O₂ and CF₄, respectively:

\[
\begin{align*}
\text{CHF}_3 + 3\text{SiO}_2 & \rightarrow \text{SiF}_4(g) + \text{CO}_2(g) + \text{H} \\
\text{SiO}_2 + \text{CF}_4 & \rightarrow \text{SiF}_4(g) + \text{CO}_2(g)
\end{align*}
\]

There are different gas systems used for the quartz plasma etch including CF₄, C₂F₆, CHF₃, SF₆ with varying carrier gases such as Helium. So far it is not clear which is best for the top etch performance. Some resist residues like ZEP520A used for this study can interfere with the quality of the etch while some others are not. CHF₃ was emphasized in the experiment because it is reported to have better control over CF₄ for not producing polymers that much. CF₄ is also more likely to cause polymer formation discussed in referenced paper [90] [73]. Polymer can be used to control the profile and CD etch bias. Banqiu Wu [73] stated, "Polymer can used for profile and CD etch bias control by passivation mechanism…" But, it is not suitable for polymer cleaning process because
after Qz etch may leave defects on the quartz substrates.

Si$^{4+}$ is located in tetrahedral sites created by close packing of O$^{2-}$. Crystalline SiO2 (quartz) is formed by SiO$^4$. All Si$^{4+}$ are shielded from their nearest Si$^{4+}$ neighbors by an O$^{2-}$ along the “line of sight”. This principle follows Pauling’s Rule because Polyhedron tends to share corners only. Pauling explained, “The sharing edges and particularly of faces by two anion polyhedron decreases the stability of an ionic crystal structure.” It is really difficult to remove Si atoms from the tetrahedral sites. The ionic crystal structure of quartz material will be broken off in the plasma etching process.

The Trion machine etched the quartz substrate with CHF$_3$ mixed with an amount of O$_2$ to purge and sputter defects and polymers off. The ICP process was optimized for performing the quartz etch on quartz wafers as shown in Table 13Table 14. The Trion Machine etched the Qz in the opening regions of the Cr hard mask. Specifically, etching speed and deep trenches are not of interest for in this study case.

Controlling the quartz sidewall seems very good with the HSQ process according to the AFM measurements, as shown in Figure 117, but it was hard to know the exact angle profile due to low-resolution AFM tip. It seems very close to 90° angle profile. A number of cross sectional Qz wafers with relief structures, as shown in Figure 114, were attempted to take look under eSEM. The Qz wafers are amorphous and fragile that damaged the cross sections, not like a perfect crystallized Si wafer.
Figure 114 Cross Section of 3” Qz wafers with relief structures after stripping Cr

Depth of relief structures defined in the template has to be 1:2 ratio for the dense lines. The 20nm and 22nm lines design were the major goal in the experiment using HSQ and ZEP flow processes, respectively. Raised 1.7µm/1.2µm dummy fills or recessed large alignment markers were measured by the profilometer to know accurate depth of relief structures.

There are many arguments that many different experimental results have a great number of parameters: gas pressure, power, gas composition, etc depending on each etcher tool. A high etching speed is not the concern here because of shallow trenches required for high-resolution relief structures. It is significantly difficult to cope with a perfect anisotropy and a high selectivity to the patterned Cr film as a function like mask. The bottom of etched regions is not that important for imprinting process. The sidewalls of relief structures must be sufficiently smooth enough to imprint resists on a final substrate through S-FIL™.
Three different parameters are controlled to optimize the etching performance on quartz: RIE power, process pressure, process time, and concentration of gas mixture between CHF$_3$ and O$_2$. Etch depth increases monotonically with time for fixed etch parameters. The parameters are 10mTorr Pressure, 320 ICP Watt Power, 100 RIE Watt Power, 47 SCCM CHF$_3$ and 3 SCCM O$_2$. The etch rate plot, as shown in Figure 115, is monotonic with a linear regression coefficient close to 1 value. The data collection was not same as expected results in the later experiment because the no relief structures were demonstrated on a number of Qz wafers. The problems will be explained in section 7.6.

![Figure 115 Qz Depth Etch](image-url)
Figure 116 Micrographs of (a) poor Etched Qz and (b) good etched Qz surface after Cr is stripped off.

Figure 116 a does not use oxygen gas flow to mix with CHF$_3$ for Trial #1 in Table 13. Figure 116 b shows that the addition of a small amount of O$_2$ and increasing ICP improve both the etch surface and sputtering the polymer formation off. The different parameters for etch trials are shown in Table 13. The addition of 5-10 percent O$_2$ helps remove this polymer and clear the sample surface for further etching with a bit higher ICP power level at 300 Watt. Six percent is used to supply oxygen gas flow into the chamber for etching for #2 Trial.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>#1 Trial</th>
<th>#2 Trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>O$_2$ gas flow</td>
<td>0 sccm</td>
<td>3 sccm</td>
</tr>
<tr>
<td>CHF$_3$ gas flow</td>
<td>47 sccm</td>
<td>47 sccm</td>
</tr>
<tr>
<td>ICP</td>
<td>200 watt</td>
<td>300 watt</td>
</tr>
<tr>
<td>RIE</td>
<td>50 watt</td>
<td>50 watt</td>
</tr>
<tr>
<td>Pressure</td>
<td>50 mTorr</td>
<td>50 mTorr</td>
</tr>
<tr>
<td>Etching Time</td>
<td>25 sec</td>
<td>25 sec</td>
</tr>
</tbody>
</table>

Table 13 Initial experiments with parameters

First, some estimates were made using different ICP power ranges with the fixed
constant parameter for RIE power level. Table 14 shows varying parameters. ICP power has to be about six times more than RIE power to generate enough dense plasma to open the regions of 1.2/1.7µm dummy fills in ZEP520A resist. ICP power has a significant influence on etch speed and removing both the polymer formation and defects.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>#1 Trial</th>
<th>#2 Trial</th>
<th>#3 Trial</th>
<th>#4 Trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICP</td>
<td>100 watt</td>
<td>150 watt</td>
<td>300 watt</td>
<td>320 watt</td>
</tr>
<tr>
<td>RIE</td>
<td>50 watt</td>
<td>50 watt</td>
<td>50 watt</td>
<td>50 watt</td>
</tr>
<tr>
<td>Pressure</td>
<td>10 mTorr</td>
<td>10 mTorr</td>
<td>50 mTorr</td>
<td>50 mTorr</td>
</tr>
<tr>
<td>Etching Time</td>
<td>120 sec</td>
<td>100 sec</td>
<td>26 sec</td>
<td>22 sec</td>
</tr>
<tr>
<td>Etch Rate</td>
<td></td>
<td></td>
<td>~ 4 Å/sec</td>
<td></td>
</tr>
</tbody>
</table>

Table 14 Design of Experiment on ICP & RIE power ranges

Figure 117 Etched Qz surface roughness
After the plasma etching parameters are satisfied, the etched surface between the dummy fills was scanned in a raster fashion with the AFM tip for surface roughness, as shown in Figure 117. Figure 120 shows less than half nanometer height variations and the highlighted red circles are shown in Figure 119 b.
In the end of the experiments, the Qz etch results were not the same as previous results because the Trion etcher was changed over time due to its poor condition discussed in Section 7.6. The Trion etcher tool was investigated fully. The same etch parameters were used to etch Cr, as shown in Figure 113. In order to remove the Cr pattern on the Qz wafers post Qz etch, chlorine-based chemistry plasma and ceric ammonium nitrate solution can remove the Cr layer. The Transene, INC supplied Chromium Etchants Type 1020. The HSQ flow process is different from the ZEP flow process. After developing in TMAH, HSQ is left with a porous silicon dioxide [127]. After exposure to oxygen plasma, HSQ becomes fully oxidized [128]. It requires use of wet etch solutions such as buffered oxide etch and warm buffer HF for HSQ removal. The etch characteristics are similar to SiO₂ and HSQ has higher etch rates [129]. Chromium Etchants Type 1020 is high purity ceric ammonium nitrate that etches the Cr layer with HSQ on it. It is interesting to note that HSQ can be easily lifted off. HSQ protects the underlying Cr film very well and it can be left on the top of the Cr pattern for the Qz etch.
Three different situations that disrupted the plasma etch process throughout the quartz wafer experiments: Cl\textsubscript{x} residues, polymer formation and plasma process mixing an undesired gas mixture. Not only those problems, the etch capability at CNSE using the Trion Etcher raised issues over time:

1. Shared etcher tool
2. Conditioned etcher tool
3. Most defects block the quartz etch step
4. Polymer formation
5. Worn-out anodized aluminum parts inside the etcher tool
6. Air leakage into chamber

Cl\textsubscript{x} residues, as shown in Figure 121, remained on the substrates after the Cr etch and collected the polymer formation and different gas mixtures during the plasma process. The bright areas of the alignment markers with Cr layer were etched with the ZEP520A resist mask. They should have the perfect squares, but some defects were stuck on sidewalls and cloudy defects were shown in the interior boundaries of the alignment markers. These blocks the next step with quartz etch. This must be avoided.
A number of students used the Trion etcher at CNSE to etch their samples with different gas mixtures. They etched over 1-micron thick resist that produced polymer byproducts in the etcher chamber. Most of polymer byproducts came from methane hydrogen based etching. The etcher was not always cleaned with the oxygen plasma after any etch works. After 6 hours of cleaning the chamber with oxygen plasma, the polymer coatings on the chamber walls inside the etcher tool were peeled off, as shown in Figure 122. Dr. Vincent Genova [123], who is the etch expert at Cornell University, saw some micrographs like Figure 121, shared the same problem experiences discussed in section 7.6 and showed the results with EDX results related to his etch work in the past.
The creation of grass and other plasma effects are significantly dependent on the Trion etcher used. After 6 months of using the etcher tool, it was difficult to get a good etched surface. The suggestion is to clean the chamber with oxygen plasma as much as possible. It is depending on the etcher history before starting the plasma etching process. If the etcher tool is heavily used to etch substrates with resist mask, then the oxygen plasma should be used as much as possible to reduce the possibility of having the polymer formation in the chamber. The chamber must be limited to only Cr etch work and will help avoid polymer formation.

An even worse situation is the polymer formation; carbon-fluorine polymers can form on etched Qz surface under certain plasma conditions. Polymer grass commonly has the appearance of a fat cylinder with the axis-oriented normal to the sample surface. The top end of the cylinder is often slightly concave. This type of grass is sometimes referred to as "tube worms", as shown in Figure 123.
Trion reported that Scanning Auger microscopy of the polymer grass shows a high concentration of carbon and fluorine on the grass [86]. XPS analysis of this layer shows the evidence of chemical bonding between the carbon and fluorine [90]. The tendency for polymer grass to form is sensitive to both the chemistry of the plasma and materials on the sample surface. The tendency of plasma to produce a polymer is usually described in terms of the fluorine-to-carbon ratio model [89] where a low ratio of fluorine to carbon is more likely to result in polymer formation. The addition of O₂ to the etch plasma tends to reduce polymer formation because oxygen plasma eliminates the polymer. RIE grass is due to a plasma etch chemistry, which results in polymer formation on the sample surface. Fluorine containing polymer residues from Qz etch will react with Al to form AlF₃ on the Cr surface, which is inert to chlorine etch [90]. Reducing the gas pressure, which increases plasma potential and therefore increases sputtering, can eliminate this. To maximize cycles of learning and to minimize experimental samples, the Cr hard mask on pieces of Qz substrates were employed with the etch variations.
The experiment showed the worst results:

1. The air leakage into the chamber at that time and the defects are shown in Figure 124. High chamber pressure formed polymer grass worse. A faulty gate valve was replaced but by then the etch effort was transferred to CNF.

2. Polymer formations were seen in Figure 123. This can be address by increasing the oxygen content of the plasma.

3. Weekly cleaning of the chamber was attempted, but it comes at the expense of a corrosive acid chemistry. HCl erodes the quality chamber walls that affected the plasma process reported by Trion engineers and Dr. Vincent Genova [123].

4. The presence of carbon and fluorine containing dielectric layers and aluminum are shown from XPS result, as shown in Figure 128. The anodized Al parts in the Trion etcher tool were worn out over time and Al interfered the etch plasma process.

![Patterned 22nm SRAM Resist and Etched Cr 22nm](image)

Figure 124 (a) Patterned 22nm SRAM ZEP520A Resist and (b) Etched Cr 22nm
After opening the chamber, air moisture forms hydrochloride (HCl), as shown chemical equilibrium below, and erodes metal parts, pumps, chamber walls, etc. It is not such a good idea to open the chamber frequently. The suspect was that the chamber wall had been eroded over time.

\[
\text{Cl}_2 + \text{H}_2\text{O} \rightarrow \text{HCl} + \text{HClO}
\]

\[
\text{HClO} \rightarrow \text{HCl} + \frac{1}{2}\text{O}_2
\]

The following factors could eliminate or reduce polymer grass: reducing the chamber pressure, decreasing the gas flow, adding O\textsubscript{2} to fluorine-based etch plasma and increasing the amount of fluorine in the chamber. Unfortunately, the etcher tool was not limited to only Cr etch, poor anodized Al parts, suffered with air leakage. First, lowering chamber pressure increases the plasma potential, increase sputtering of the surface and remove the polymer formation. Second, decreasing the gas flow rate to reduce the chamber pressure as much as possible and bombard atoms easily with increasing mean free path. Third, addition of O\textsubscript{2} to fluorine-based chemistry helps reduce the polymer formation. Fourth, increasing the amount of fluorine-based chemistry to get a higher ratio of fluorine to carbon to avoid making polymers during the etch plasma process. All of the processes were attempted to etch quartz, but there were no good results. Different parameters showed different results, as shown in Figure 125:
Figure 125 Attempting to improve Qz etch recipe

- Lower SCCM
- Increase O$_2$ level
- Lower Pressure Level

- Lower SCCM
- Increase O$_2$ level
- Lower Pressure Level
- Increase ICP & RIE powers

- Lower SCCM
- Increase O$_2$ level
- Lower Pressure
The design of experiment was attempted to remove the Al grass and polymer formation, but none of good recipes achieved.

The anodized Al parts in the Trion etcher tool wore out over time. CNF had the same
problem with anodization on the original O-shaped clamp and ordered a new O-shaped clamp from the Trion manufacturer in the past. The EDX result was collected at CNSE. After investigating the conditioned Trion etcher tool, the EDX result was collected to show the amount of Al grass laying on the sapphire wafer carrier.

![EDX Result](image)

**Figure 128 EDX Result**

Before using the Trion etcher tool, the chamber was cleaned as much as possible with CF$_4$ and oxygen plasma. Then, the Trion etcher tool was tried to keep the plasma process more stable through the Qz wafer development process. Table 15 shows the detail of many steps for cleaning the chamber and etching samples every time.
<table>
<thead>
<tr>
<th>Process</th>
<th>Recipes from Appendix</th>
<th>Process Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean the chamber with CF&lt;sub&gt;4&lt;/sub&gt;/O&lt;sub&gt;2&lt;/sub&gt; Plasma</td>
<td>21600 (6 Hr)</td>
<td></td>
</tr>
<tr>
<td>Stabilize Descum Process</td>
<td>13.4.5</td>
<td>600 (10 min)</td>
</tr>
<tr>
<td>Descum</td>
<td>13.4.5</td>
<td>5</td>
</tr>
<tr>
<td>Clean Chamber with Dense O&lt;sub&gt;2&lt;/sub&gt; Plasma</td>
<td>600 (10 min)</td>
<td></td>
</tr>
<tr>
<td>Stabilize Cr etch plasma process</td>
<td>13.4.6</td>
<td>600 (10 min)</td>
</tr>
<tr>
<td>Cr Etch</td>
<td>13.4.6</td>
<td>45</td>
</tr>
<tr>
<td>Strip E-Beam Resist with Light O&lt;sub&gt;2&lt;/sub&gt; Plasma</td>
<td>13.4.7</td>
<td>300</td>
</tr>
<tr>
<td>Unload the 3” Cr/Qz wafer (or Template)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean Chamber with CF&lt;sub&gt;4&lt;/sub&gt;/O&lt;sub&gt;2&lt;/sub&gt; Plasma</td>
<td>600 (10 min)</td>
<td></td>
</tr>
<tr>
<td>Stabilize Qz etch plasma process</td>
<td>13.4.8</td>
<td>600 (10 min)</td>
</tr>
<tr>
<td>Load the sample (or Template)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qz Etch</td>
<td>13.4.8</td>
<td>60</td>
</tr>
<tr>
<td>Clean with light O&lt;sub&gt;2&lt;/sub&gt; Plasma</td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>Strip Cr with light Cr etch</td>
<td>13.4.9</td>
<td>45</td>
</tr>
<tr>
<td>Clean the 3” Qz wafer (or Template) with light O&lt;sub&gt;2&lt;/sub&gt; Plasma</td>
<td>13.4.10</td>
<td>300 (5 min)</td>
</tr>
</tbody>
</table>

Table 15 sample etch processes

**7.7 Template Etching at CNF**

Cornell University’s Cornell Nanoscale Center of Science and Technology (CNF) was the last option to etch both Cr and Qz close to the end of the imprint template project at CNSE. The Cornell Trion etcher is shown in Figure 129.
Un fortunately, there was not enough time to continue the experiments before the project concluded. CNF had some similar problems with Trion etcher tools, which cannot be mixed with the different chemistries. It finally limited the etcher use to Cr etch only. Dr. Vincent Genova shared some problems he experienced before the etcher was limited only to Cr etch. He saw anodized Al parts being worn out and this was the same situation with the CNSE experienced with Trion etchers. He shared the following information on how to manipulate the Trion etcher:

- Worn-out Anodized Al Parts same as CNSE Trion Etcher
- Polymer Formation is seen after Cr and Qz etch
- Conditioned chamber walls degraded after opening chambers
- Keep the chamber walls at a higher temperature to stop forming polymer and stick it onto the substrate
• Deep etched trenches compared to my shallow etched trenches
• Seasoning the Cr etch process improves it drastically

CNF has a good preparation before doing Cr etch show the below bullets.

**Comparative Preparations for Cr Etch Process**

**CNSE Etcher**
- Clean the chamber for 6 hours
- After descumming, clean the chamber with O₂ plasma for 10 minutes
- Stabilize Cr etch process for 10 minutes without Cr target on the substrate
- Cr Etch with 4 Å/sec
- Remove e-beam resist with oxygen plasma

**CNF Etcher**
- O₂ plasma for 10 minutes
- 50% of N₂ & 50% of Cl₂ for 10 minutes
- Seasoning process with Cr target on the substrate for 10 minutes
- Cr Etch with 2 Å/sec
- Rinse with DI water before removing e-beam resist

The Cr recipe at CNSE had been developed similar to CNF’s Cr etch recipe. However, CNF advised to use the different RIE etcher to remove resist with oxygen plasma and etch quartz substrate with a Cr hard mask. It is better not to use the same chamber to etch both Cr and Qz because both of them require the different gas mixtures for etching.

**7.8 Etch Challenge**

CNSE faces some challenges with etch work especially the infrastructure with etch capability. In the beginning of the experimental quartz wafer process, the negative-tone E-Beam resist is suitable for solving etch loading problems, before moving onto ZEP520A flow process. This is shown in sections 10.6 and 10.7. While studying the ZEP520A flow process, the etcher tool was a challenge to manage with many issues
appearing after a half-year of experimentation. The condition of the etcher tool changed over time. The etch capability get worse near the end of the work at CNSE. This is shown in Figure 113. Before facing the problems with the etch capability, HSQ was found that it was much easier to handle than ZEP520A for the etch work at CNSE. Most areas outside of the HSQ pattern regions were easily etched out are shown in Figures 151 and 152. The referenced paper [73] reported that today the etcher can make negative uniformity much better than positive tone for masks with a high load in the pattern area, but not many masks accept the negative-tone images. Micro-loading effect etch was still not determined for measuring CDU across the full chip by hand. Cr etching can be done on 3” Qz wafers sitting on the custom adapter, as shown in Figure 181 b. An automated CDSEM can be used to gather the large amounts of data needed for the analysis. Etch bias changes for ZEP flow process were noted in Figure 130. The Cr layer with printed ZEP520A 25nm lines on a 100nm pitch was etched down to 15nm while etching the Cr layer down to 100nm in the different region. The correlation for printed ZEP520A and etched Cr was good, except for smaller features such as 25nm lines on the 100nm pitch. Therefore, the size designs need to be set up for achieving the right etched feature sizes.
Figure 130 Etch Bias for ZEP process, except Qz etch
8 Cleaning Template and Defect Control Levels

The ideal process to clean the final template is a megasonic cleaning. It is a gentler cleaning mechanism and less likely to cause damage. It creates megasonic energy at a higher frequency between 800 – 2000 kHz compared to typical ultrasonic cleaners at less than 100 kHz. The ultrasonic cleaning process damaged the relief structure of isolated 10nm dots array. The pillar of 10nm dots fell or bent as seen in Figure 131.

![Figure 131 Damaged rising isolated 10nm dots due to ultrasonic vibration bath](image)

Throughout the quartz wafer development process, the issues around cleaning and defect control have yet to be addressed. The tools are in three different cleanrooms at CNSE: NFE cleanroom, CESTM L136 Cleanroom and CESTM L244 Cleanroom. NFN
cleanroom with class 10 level has the Vistec VB300 and the S-Cubed PhotoFab located in a class one mini-environment chamber. Solvent and acid benches, the Varian 800 E-Beam Evaporator and the Trion Minilock III etcher are in the cleanrooms at CESTM building with approximately class 1000 levels. All tools must be in the same cleanroom to effectively minimize defect levels as much as possible. It was not easy to carry the samples to many different cleanrooms and many metrology tools are outside of the cleanrooms.

**NFN Cleanroom**
- Vistec VB300 E-Beam Lithography
- S-Cubed PhotoFab

**CESTM L136 Cleanroom**
- Solvent Bench
- Acid Bench

**CESTM L244 Cleanroom**
- Varian 800 E-Beam Evaporator
- Trion Minilock III Etcher

After counting particles on a cleaned 6” mask borrowed from International SEMATECH, the data showed that there are many defects laying on clean 6” mask that was went through processes as shown in Table 16.
<table>
<thead>
<tr>
<th>Development Processes</th>
<th>Cleanroom</th>
<th>Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polish Qz wafer surface</td>
<td>L244 Cleanroom</td>
<td>Trion Etcher Minilock III</td>
</tr>
<tr>
<td>Cr Film Deposition</td>
<td>L244 Cleanroom</td>
<td>Varian 980 E-Beam evaporator</td>
</tr>
<tr>
<td>Coat</td>
<td>NFN Cleanroom</td>
<td>*S Cubed PhotoFab</td>
</tr>
<tr>
<td>Bake</td>
<td>NFN Cleanroom</td>
<td>*S Cubed PhotoFab</td>
</tr>
<tr>
<td>Exposure</td>
<td>NFN Cleanroom</td>
<td>VB300</td>
</tr>
<tr>
<td>Develop</td>
<td>NFN Cleanroom</td>
<td>Cubed S Minitracker</td>
</tr>
<tr>
<td>Clean with Di water &amp; IPA</td>
<td>NFN Cleanroom</td>
<td>Cubed S Minitracker</td>
</tr>
<tr>
<td>Descum Process</td>
<td>L244 CESTM Cleanroom</td>
<td>Trion Etcher Minilock III</td>
</tr>
<tr>
<td>Cr Etch</td>
<td>L244 CESTM Cleanroom</td>
<td>Trion Etcher Minilock III</td>
</tr>
<tr>
<td>Oxygen Plasma</td>
<td>L244 Cleanroom</td>
<td>Trion Etcher Minilock III</td>
</tr>
<tr>
<td>Qz Etch</td>
<td>L244 Cleanroom</td>
<td>Trion Etcher Minilock III</td>
</tr>
<tr>
<td>Clean with Piranha Solution</td>
<td>L136 CESTM Cleanroom</td>
<td>Chemical Processing Bench</td>
</tr>
<tr>
<td>Clean with IPA/Acetone and</td>
<td>L136 CESTM Cleanroom</td>
<td>Chemical Processing Bench</td>
</tr>
<tr>
<td>Nitrogen purge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr Strip</td>
<td>L136 CESTM Cleanroom</td>
<td>Chemical Processing Bench</td>
</tr>
<tr>
<td>Clean with IPA/Acetone and</td>
<td>L136 CESTM Cleanroom</td>
<td>Chemical Processing Bench</td>
</tr>
<tr>
<td>Nitrogen purge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Megasonic Vibration Bath</td>
<td>L136 CESTM Cleanroom</td>
<td>Chemical Processing Bench</td>
</tr>
</tbody>
</table>

Table 16 Flow Process for Post-Inspection for Particle Counts
The 10 and 20 pixel sizes are about 88nm and 300nm particles, respectively. After investigating the flow process, the IPA alcohol bottle was found that its grade was not for semiconductor applications. It was obtained with the semiconductor grade one. The cleaned 6” mask was left in different cleanrooms for long time. The new cleaned mask needs to be inspected again few times to trace where the original defects come from.
9 Integration

Optimization of throughput for the 13x13mm full chip exposures was pushed with high effort. The full chip included many different features and dummy fills. Many features range from 22nm to 25nm lines and some are large features such as 100nm and 50nm lines. The dummy fill pattern contained the largest features with 200nm blocks on a 500nm pitch. The features of interest for high-resolution features and Professor Dr. Magnus Berkvigist’s biological screening tool for Fn.

Figures 134 and 135 show #1 and #2 pattern fields, respectively. Different GDS patterns are integrated into the 13x13mm full chip. The detail of identifying GDS pattern is shown in section 13.8.
The jobfile consists of different beam currents with respect to beam step sizes, as shown in Table 17, for high throughput. The VB300 control computer predicted about 30 hours of writing.
As for high throughput, the aperture size has to be set up right to reduce the aberration effects discussed in section 4.3. During the beam current change, different aperture sizes follow the relationship between spot sizes and beam currents according to the below plot.

![Spot Size vs. Beam Current](image)

**Table 17 Integration for High Speed Writing for the full 13x13mm chip**

<table>
<thead>
<tr>
<th>Negative Tone HSQ Resist</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spot Size</td>
<td>Features</td>
</tr>
<tr>
<td>22nm (25nA)</td>
<td>Dummy Fills</td>
</tr>
<tr>
<td></td>
<td>200nm square on 500nm pitch</td>
</tr>
<tr>
<td>10nm (10nA)</td>
<td>Alignment Markers &amp; 50nm – 200nm Features</td>
</tr>
<tr>
<td>4nm (1nA)</td>
<td>22-25nm Lines</td>
</tr>
<tr>
<td>2nm (500pA)</td>
<td>16 &amp; 20nm Lines</td>
</tr>
<tr>
<td>*30 Hours Writing Time</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Positive Tone ZEP520A Resist</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spot Size</td>
<td>Features</td>
</tr>
<tr>
<td>22nm (25nA)</td>
<td>Dummy Fills</td>
</tr>
<tr>
<td></td>
<td>200nm square on 500nm pitch</td>
</tr>
<tr>
<td>10nm (10nA)</td>
<td>Alignment Markers &amp; 50nm – 200nm Features</td>
</tr>
<tr>
<td>4nm (1nA)</td>
<td>22-25nm Grating</td>
</tr>
<tr>
<td>2nm (500pA)</td>
<td>16 &amp; 20nm Lines</td>
</tr>
<tr>
<td>5 Hours Writing Time</td>
<td></td>
</tr>
</tbody>
</table>

*Assume based on preview simulation on VB300 Machine

Figure 136 Spot Size depends on Beam Current
10 Results

10.1 Observation of CDU Issue

HSQ resist was just started studying for high-resolution images. An odd PEC behavior was recognized on 3” Si substrate in the initial experiments done in spring 2010. It was not like other commercial resist systems such as NEB, SU-8, ZEP520A and PMMA. The results of high-resolution HSQ images were collected for The 54th International Conference on Electron, Ion, Photon Beam Technology and Nanofabrication (EIPBN) in
spring 2010. Various isolated and dense features were feasible for CD, LER and LWR in small pattern area (<10x10µm field). The images and data measurements for CD, LER and LWR are shown in Figures 89 and 90 for studying the quality of Guassian E-Beam writer. The imprint template fabrication project at CNSE started in winter 2010 and requires high quality PEC to achieve good CDU across the full chip on the imprint template. CDU was not good for dense patterns printed in HSQ as shown in Figure 137. In the center of the array, the lines look good but in the corner of the array the lines are poor. It seemed that there are more factors beyond basic backscattering are contributing significant dose errors to the large pattern areas. The CNSE Advanced Lithography group showed a number of issues with HSQ PEC in a variety of projects between 2010-2011. PROXECCO™, the PEC module software in CATS [124] and Layout Beamer, does not assign doses correctly for large area patterns composed of sub-50nm shapes for HSQ. SYNOPSYS™ markets and maintains the CATS software and acknowledged the problem and had provided a work-around with the manual dose assignment. This is burdensome and becomes not clear to use for anyone. But, the PEC was improved later using a better PSF that obtained the excellent CDU for ZEP520A resist.
10.2 PEC Critical Dimension Uniformity

After improving the PSF file simulated by Sceleton with a better statistic for the thinner HSQ on 10nm-Cr-based quartz substrate, the curve drops in the interior boundary of the 500x500µm field, as shown in Figure 138. The workaround suggested by Synopsys™ is to modify the corrections by using manual dose assignment. It was difficult to manipulate with PROXECCO™ PEC module incorporating with CATS fracturing software. It was time consuming and was not easy to implement in practice. In the end, the results were successful with good CDU for ZEP520A resist, as shown in Figure 139.
The CDU over the large field with printed ZEP520A, as shown in the above plot, indicate an odd behavior that is different from HSQ. Two different data measurements were collected from the dose array. Consequently, the PEC mechanism for ZEP520A is excellent.
10.3 Ultimate Resolution ZEP CDU

Figure 140 Patterned ZEP520A 1:3 25 lines

Figure 141 Ultimate Resolution Images of (a) 22nm lines, (b) 25nm lines, (c) 25nm lines with 100nm pitch, (d) 25nm lines with 70nm pitch.
Figure 142 shows all different grating patterns on the same exposed 10nm-Cr-based Qz substrate.

10.4 High Resolution Printed ZEP520A Resist

Many high-resolution images in 40nm ZEP520A structures, as shown in Figures 143 to 145 below, were demonstrated in various areas. Not all high-resolution images are repeatedly printable across the full chip. The electron beam seems not to be effectively corrected across the array and large pattern fields with good astigmatism and good focus.
Figure 143 (a) 16nm and (b) 20nm Half Pitch Lines

Figure 144 (a) vertical and (b) horizontal 22nm Half-Pitch Lines

Figure 145 Elbow Structure of 22nm Half Pitch
10.5 Printed HSQ resist

Beam current was reasonably set up to 1nA with 2nm beam size step. The design process was focusing on the small pattern area (10x10µm²). The backscattering electrons do not appreciably affect the process during the E-Beam scanning on the small pattern area. LER and LWR are according to the chart indicating that lower LER/LWR is better with sufficiently higher dose, which is ~2100µC/cm². However, the 20nm and 16nm half-pitch lines are very difficult to measure for LER and LWR due to poor edge contrast.
They have broadening effects on the sidewalls of HSQ structures like the HSQ on Si substrate, as shown in Figure 95. In addition, it is difficult to make a better image transferred onto the Qz wafer, shown in Figures 155a and 156a.

16nm lines with varying pitches use the same dose as the 20nm lines. It was shown that it is possible to combine both 16nm and 20nm lines, but the pattern area is still small. However, the 1:1 lines might not printed well when the height measurement was set off with more than 10 micron between the final lens and the Cr/Qz substrate discussed in section 4.9. Dose, LER and LWR were optimized at 2100µC/cm² for 2:1 16nm lines grating and the relative dose is only less than 1 percent.
10.6 Etched Cr film with HSQ mask

Figure 150 and Figure 151 show good results with etched Cr film. Etched Cr features get edge roughness gradually on 1:1 pitch for the original raw resist structure. The recipe used to etch the Cr layer can be found in appendix 13.4.6. SUMMIT software was not able to obtain CD, LER and LWR values from the images taken by FEI NOVA 600 e-SEM. Shadowy contrasts near etched sidewalls, as shown in the micrographs below, interfered with the SUMMIT software’s ability to measure CD, LER and LWR. The shadowy contrasts are susceptible to Qz charging. The operating parameters for FEI NOVA 600 e-SEM needs to be changed to get better contrast images.
The smallest etched Cr was demonstrated in Figure 152 without giving any efforts in doing Cr etch over. The 6nm HSQ was printed first before doing Cr etch. SUMMIT Software measured the micrograph with 6nm.
10.7 Relief Structures

A variety of relief structures, as shown in Figures 153 - 155, were etched successfully in
only small pattern areas because they used HSQ flow process. The HSQ flow process was limited to only small pattern areas due to undeveloped PEC mechanism. The original recipe was developed can be found in appendix 13.4.8.

![Figure 154 20nm Lines with (a) 1:1 and (b) 1:2 (c) 1:3 (d) 1:4 pitch](image1)

![Figure 155 16nm lines with (a) 1:1 (b) 1:2 pitch](image2)
Figure 156 Relief structure of 16nm Half Pitch Scatter Test without optimized etched surface

Figure 157 (a) Alignment Markers for Optical (b) 10nm dots array
Figures 157 and 158 are designed for a screening test for protein cells as discussed in section 1.5.1.3. The alignment marker was exposed with 10nA beam current with 10nm BSS.

Some attempts to create nice 16nm half-pitching are shown in Figure 159 and some spaces between the relief structures were not cleared.
10.8 Best Results to Date at CNSE

As for the feasibility of high-resolution patterning structure, 16nm lines and spaces were demonstrated on patterned HSQ structures, etched Cr structures and relief Qz structure. Those are shown in Figure 160. The HSQ 16nm lines were exposed in the small pattern areas. This structure was sufficiently isolated that PEC issues do not arise. Etched Quartz structures are good. 16nm lines and with 32nm spaces are reasonable structure with good etched surface, as shown in Figure 118.

Expose/Develop Resist, Descum

Etch Chrome

Etch Quartz, Strip Chrome

Figure 160 Best Results for negative-tone process
10.9 Dummy fills

Writing time for Comparative Dummy Fill Patterns

![Write Time depending on Beam Currents](image)

Figure 161 Writing Time for Comparative Dummy Fill Patterns

1.2µm/1.7µm dummy fills, as shown in Figure 162, are used in the beginning of the experimental quartz wafer development process. The dummy fills in the 13x13mm full chip are shown in Figure 133. SEMATECH requested a change to 200nm square on a 500nm pitch and moved on to positive-tone ZEP resist, as shown in Figure 163.

![Figure 162 (a) HSQ Pattern on Cr/Qz wafer (b) Etched Cr Pattern (c) Raised 16nm Relief Structure](image)
Backward scattering events being exposed from two VEP files separated by more than the backscattering range, do not damage neighboring structures, as shown in Figure 164.

### 10.10 22nm SRAM gate

The printed 22nm SRAM gate array was exposed at 210 μC/cm² with 8nm Step beam size.
Designed 13nm SRAM Gate is exposed in 40nm ZEP520A with 5nA beam current, 260μC/cm² and 10nm BSS. SUMMIT™ software measured the 13-16nm opening gate structures in the 40nm ZEP520A.
Polymer formation seemed to be stuck in the opening region of etched Cr 22nm SRAM gate. None of 22nm SRAM gates were recessed on the quartz substrate. The dark shades are shown in Figure 167.

The printed 22nm SRAM gate array was exposed at 2100 $\mu$C/cm$^2$ with 2nm Step beam size.
11 Conclusion and Future Perspective

The College of Nanoscale Science and Engineering has been studying the quartz wafer development process as a low cost learning vehicle for imprint template fabrication. The areas of concentration have been: E-Beam resist process, PEC and etch work. The remainders, which must be completed for successful process, are PEC for HSQ and etch capability. The goal has been to find a cost–effective way to fabricate imprint templates for International SEMATECH.

Throughout the difficult experimental quartz wafer development process, limitations and obstacles on commercial resist systems were shown. High-resolution images in HSQ and ZEP520A were successfully demonstrated at CNSE with only best efforts. A major challenge related to CDU was that PROXECCOTM failed to accurately correct the smallest and densest structures encountered in sub-20nm HSQ over large pattern areas. However, ZEP520A CDU was excellent for the large pattern area that can print down to 22nm half pitch.

The focus of electron beam also was not corrected across the large pattern area, especially with the ZEP520A resist. It is very hard to tell if the quality of the electron beam affected the printability of the high-resolution images in sub-20nm HSQ structures, which require high dose. HSQ resist seems to safely ignore many electrons that are injected during the E-Beam writing and the contrast curve is shown in Figure 29. This is different from highly sensitive ZEP520A resist, which do not require that many electrons.
Consequently, there is still an open question about the commercial resist systems if PEC and the quality of E-Beam lithography are well understood.

As for infrastructure at CNSE, two major improvements are needed for the imprint template fabrication processes at CNSE: PEC for HSQ and etch capability at CNSE.

Controlling the proximity effect in the 100 keV E-Beam Gaussian Writer technology is the most challenging problem for producing high-resolution images on the quartz substrate. Algorithms could correct the proximity effect, but they are very complicated. There needs to be more studies with HSQ since it is significantly different from ZEP520A. There are many parameters involved with PEC to achieve high-resolution HSQ images.

CNSE faced some challenges in fabricating imprint templates due to poor etch capability and inexperience in the area of 4X mask manufacturing. The Trion etcher tool cannot remove polymer formation and needs to limit to only Cr etch work, not sharing with mixed chemistries. CNSE has to improve its infrastructure tools to better handle the complex quartz wafer development process.

As for an alternative fabrication process, we were behind schedule, running out of time and were not getting a good PEC mechanism for HSQ on the quartz substrate. Thus, this part of the project was never completed. It did not meet milestones for International Sematech and it was an unexpected challenge. CNSE needs to resolve the infrastructure of tools before it can investigate alternative fabrication processes.

Fabricating imprint templates could become a roadblock for the Semiconductor
industry due to expensive writing time required for 1X pattern on imprint template. But, there are many ways in which people are trying to improve the E-Beam tool, source, column, blanker, deflector, resist, etc., to increase its speed without sacrificing resolution.

The quartz wafer development process was a successful proof-of-concept demonstration at CNSE. The $35 quartz wafer is much cheaper than the full specification 65mm factor imprint template, which cost $5,000. Fabricating about 75 quartz wafers at CNSE costs only $2,625 raw materials. This is clearly better than spending $375,000 to do process development on individual 65mm factor templates.

New E-Beam resist systems must be innovated for high-resolution patterns for 20nm and beyond, especially positive-tone resist. No high resolution (sub 20nm), positive tone resist is found to date.

Multi-electron-beam lithography must be brought to the market to decrease the cost of writing time on both direct write applications and masks. Historically, E-Beam lithography is excessively slow with its throughput and not many scientists and engineers involved in the E-Beam field in the past 20 years. Nanoimprint Lithography was very new and it was quickly brought to the market in early 2000. During that period, the E-Beam Lithography must be pushed for high-resolution images required on imprint templates.
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13 Appendix

13.1 Fabrication Tools

13.1.1 Varian 980 E-Beam Evaporator

Figure 169 Varian 980 E-Beam Evaporator

Varian 980 E-Beam Evaporator deposits Cr film or other applicable metals onto the quartz substrate.
A mask patterns a Cr slot on the imprint template for grounding the isolated Cr mesa field.

13.1.2 S Cubed Photofab

S Cubed Photofab first provides for the spin and thermal processing of semiconductor wafers and it is later accommodated to accept the 65mm imprint template format with a
new spin chuck and a new bake adapter. The system combines independent process modules to perform the operation required by users. The substrate handling and process are fully automated under computer control. Process control instruction and parameters are programmed using a hierarchy of program levels: steps, recipes, and process.

Figure 172 Designed and Fabricated Holder accommodating the 65mm Imprint Template format

Figure 173 Designed and Fabricated Bake Adapter
13.1.3 Imprint Template Adapter for the Vistec VB300

![Imprint Template Adapter](image)

Tested the imprint placed in the adapter and measured the map of height of the isolated Cr mesa field using the VB300’s height sensor.

Figure 174 Imprint Template Adapter

13.1.4 Trion Phantom Minilock III system etcher

The Trion Minilock III etcher was designed for etching pieces held by 4” – 8” wafer carrier. It is customized to accept the 65mm imprint template dimensions. The automated handler transfers the carrier through the opening slot of the solid clamp. The solid clamp lifts the carrier with three hangers and an actuator brings the clamp onto the chuck for plasma etch process.

<table>
<thead>
<tr>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>18 in (.5 m) Wide</td>
</tr>
<tr>
<td></td>
<td>51 in (1.3 m) Deep</td>
</tr>
<tr>
<td></td>
<td>53 in (1.4 m) Tall – with ICP</td>
</tr>
<tr>
<td>Max RF Power</td>
<td>1000 Watts – ICP</td>
</tr>
<tr>
<td></td>
<td>600 Watts - RIE</td>
</tr>
<tr>
<td>System Power Requirement</td>
<td>15A, 208Vac (phase-to-phase) 3-phase for the system</td>
</tr>
<tr>
<td></td>
<td>20A, 208Vac (phase-to-phase) 3-phase for the remote pump box</td>
</tr>
<tr>
<td>Gas Channels</td>
<td>7 Maximum</td>
</tr>
<tr>
<td>Max Wafer Size</td>
<td>12 in (300mm)</td>
</tr>
</tbody>
</table>
Lift the carrier with three hangers

Clamp the carrier

The automated handler transfers the carrier through the opening slot of the solid clamp

Figure 175 Fabricated Solid Clamp Accommodating for Imprint Template Carrier
13.2 Detailed 100kV Gaussian E-Beam Writer

13.2.1 Fine Tuned E-Beam Lithography Machine

A fine-tuned E-Beam lithography strongly depends on optimum beam quality. Focus and astigmatism has to be tuned well. The electron column in the Vistec VB300 consists of lenses receiving unavoidable aberrations in its performance. Clearly, electron optics is in contrast to the situation in light optics and using combinations of lenses cannot cancel the effects of aberrations. Controlling a complex interaction of electron beam physics in the electron column can minimize these effects.

13.2.1.1 Spherical Aberrations and Diffraction Limitations

The VB300 is run at a 100kV to maintain resolution of the beam by bringing down spherical aberration. If the electron beam is not operated at higher voltage, then the spherical aberration becomes apparent in which lens magnetic field bend the electrons in trajectories away from the optic axis and broaden those rays near the axis. Most electrons arrive at the Gaussian image plane where the image appears when there is no aberration. The aperture of the lens diverge electrons to maximum and cross the optic axis at a point closer to the lens. This results in a disk, not at a point where all rays converge. The spherical aberration arises when the smallest disk occurs in front of the Gaussian plane. Schematic diagrams, as shown in Figure 176, show how (a) spherical aberration and (b) aperture diffraction, which blur into an enlarged spot at the Gaussian image plane.
The diameter disk is given by,

\[ D_s = \frac{1}{2} C_s \alpha^3 \]  \hspace{1cm} \text{Equation 25}

The wave of electrons naturally creates a circular diffraction pattern instead of a point at the Gaussian image plane. Electrons hit slightly at the edge of the small aperture, bounce off from the edge and thus create the diffractions in the image plane as a broad “Airy disk” intensity distribution. The spot size, \( D_d \), is defined with the half the diameter of the Airy disk as the diffraction contribution [69]:

\[ D_d = 0.61 \frac{\lambda}{\alpha} \]  \hspace{1cm} \text{Equation 26}

The wavelength, \( \lambda \), is calculated only with only a small error as
\[ \lambda = \frac{1.24}{\sqrt{E_0}} \]

Equation 27

Where \( \lambda \) = Wavelength of the Electrons (in nanometer)
\( \alpha \) = Beam Convergence
\( E_0 \) = Electrons of Energy (in electron volts)

### 13.2.1.2 Chromatic Aberrations

Chromatic Aberrations become not important for high accelerating voltage beam at 100kV. It can be neglected in this case only. With use of slowly accelerating voltage beam, electrons distribute into slightly different energies, \( E_0 \) and \( E_0 - \Delta E \), pointing at different locations in the image plane, as shown in Figure 177 [70],

![Figure 177 Chromatic Aberration](image)
The chromatic aberration results in a disk, $D_C$, in diameter,

$$D_C = C_C \left( D \frac{E}{E_0} \right)$$

Where $C_C =$ Chromatic Aberration Coefficient 
$\alpha =$ Convergence Angle 
$\Delta E/E =$ Fractional Variation in the Electron Beam Energy

### 13.2.1.3 Astigmatism

VB300 has a stigmator that can correct astigmatism effects. The stigmator consists of coils placed inside the final lens with magnetic fields to make the lens appear symmetric to the electron beam, as shown in Figure 178. The quality of 100kV Gaussian writer technology depends on spot profile at the image plane.

![Figure 178 Correcting Astigmatism Using Stigmator](image.png)
Axial and diagonal corrections are two different ways to minimize the effects of astigmatism. A PhD student candidate, Ananthan Raghunathan, at CNSE reported in his Master report that he had clearly saw some asymmetry between the right/left and top/bottom in 5x5 array of 10nm lines structures.

### 13.2.1.4 Lens Aberrations Enlarge Gaussian Probe

Aberrations force a larger spot, $d_p$, for a given current. Contributions to larger spot include blurring from:

<table>
<thead>
<tr>
<th>Contributions</th>
<th>Mathematical description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical aberration</td>
<td>Increases as cubic $\alpha^3$</td>
</tr>
<tr>
<td>Aperture diffraction</td>
<td>Decreases as $\alpha$</td>
</tr>
<tr>
<td>Chromatic aberration</td>
<td>Dominates at low kV</td>
</tr>
<tr>
<td>Astigmatism</td>
<td>Enlarges spot because lens not &quot;round&quot; to beam (fully correctable with stigmator)</td>
</tr>
</tbody>
</table>

Table 18 Aberration and Astigmatism Contributions

The Gaussian probe size, $d_g$, is contributed with the following factors from brightness, optimal alpha and maximum current, $i_p$.

$$d_g = \sqrt{\frac{4i_p}{\beta \pi^2 \alpha_2^2}}$$

Equation 29

With some assumptions, VB300’s electron column operates perfectly during exposure. As for optimized aperture diffraction, Vistec designed VB300 to trade off between spherical aberration and aperture size. Vistec Lithography Group involved this intelligent design system. Chromatic aberration is neglected because VB300 operates at high
accelerating voltage. The electron beam is trade off between probe and probe current to
form a sharp image of focus marker for giving nice probe current in electron sensitive
resist. Sum in quadrate the contributions to the final probe size, $d_p$:

$$d_p = \sqrt{d_g^2 + d_s^2 + d_d^2 + d_c^2}$$  \hspace{1cm} \text{Equation 30}

Substituting:

$$d_p = \left[ \frac{4ip}{\beta \pi^2 \alpha^2} + \left( \frac{1}{2} C_s \right)^2 \alpha^6 + \left( \frac{0.61 \lambda}{\alpha^2} \right)^2 + \left( \frac{\Delta E}{E_0 C_s} \right)^2 \alpha^2 \right]^{1/2}$$

Determine the optimum angle alpha

$$\alpha_{opt} = \left( \frac{d_p}{C_s} \right)^{1/3}$$  \hspace{1cm} \text{Equation 31}

Substituting alpha angle yields expression for minimum spot size:

$$d_{\text{min}} = K C_s^{1/4} \lambda^{3/4} \left( \frac{i_p}{\lambda^2} + 1 \right)^{3/8}$$  \hspace{1cm} \text{Equation 32}

At the limit of zero current, $d_{\text{min}}$ technically reaches theoretical resolution. Substituting

$d_{\text{min}}$ into the brightness equation:

$$i_{\text{max}} = \frac{3 \pi^2 \beta d_p^{8/3}}{16 C_s^{2/3}}$$  \hspace{1cm} \text{Equation 33}

The equations show us that $d_{\text{min}}$ decreases as beta increases, $\lambda$ decreases and $C_s$ decreases.

In addition, $i_{\text{max}}$ varies the 8.3 power of probe diameter is approximately equal to $d^3$.

Figure 179 shows the electron probe with different variables defined in the equations
mentioned above.

\[ V_o = \text{the electron beam accelerating voltage (kV)} \]
\[ \alpha_p = \text{the electron probe convergence angle} \]
\[ d_p = \text{the electron probe size} \]
\[ i_p = \text{the electron probe current} \]

Figure 179 Electron Probe

13.2.2 E-Beam Induced Substrate Heating

Resist and substrate heating comes from the incident electron beam and it could become critical for extremely small structures when image placement specifications get tighter. This is a concern in E-Beam lithography. It is not possible to avoid heat being deposited in the target of the substrate from the electron beam. Resist sensitivity varies with temperature causing unwanted line width variation. It is essential to consider the various compensation techniques available to improve throughput and proximity effect correction for the 1X pattern required for imprint templates and strategically writing for high
throughput for 4X mask manufacturing. With a complicated proximity effect correction (PEC) algorithm, the need for pixel based on dose modulation is to reduce the possibility of having resist heating effects depending on how electron beam scanned on the substrate in a raster fashion. It is not possible to eliminate natural beam heating. High voltage exposure is better for eliminating most of the proximity effect influence in the resist layer, but in nanometers. There are still some concerns with the substrate heating effect. The resist can be very sensitive to heating because most energy is dissipated in the quartz substrate not the Silicon substrate. The sensitivity of the resist can be shifted easily when the quartz substrate is heated to an appropriate temperature. Some studies show that the CD uniformity and image placement were degraded on optical masks. In modern EBL systems, resist heating is one of the major contributing factors to the CD error budget [94]. Every resist has its sensitivity responding to temperature.

We know that temperature affects the physical and chemical properties of resists. The E-Beam resist responses to heating are shown below [96],

\[
D_o = D_T (1 + \alpha \Delta T) \tag{Equation 34}
\]

Where \(D_o\) = dose to clear at room temperature
\(D_T\) = is the exposure dose to get dose to clear at temperature \(T\)
\(\alpha\) = a coefficient of thermal expansion

The equation above gives the increase in relative dose with temperature. Exposure dose \(D\) is the total energy deposited by electron beam and the resist heating component. Change of dose to clear due to heating is \(\Delta D = D_o - D_T\). The coefficient can be found
from the given equation below [96],

\[ \alpha = \frac{\Delta D}{\Delta T} \]

Equation 35

Through my exposure experiments on the quartz substrate, I thought I had seen some heating effect problems on the quartz substrate using HSQ resist required with extremely high dose. However, the PEC was actually the problem.

Conduction of heat in solids is introduced here. The heat equation follows:

\[ \frac{\partial T}{\partial t} = k \nabla^2 T + \frac{h}{\rho c^2} \]

Equation 36

Where \( T \) = temperature

\( k \) = thermal diffusivity

\( \rho \) = density of the solid

\( c \) = thermal heat capacity

\( h \) = heat source

This above heat equation is a general equation. It will not give a straightforward solution with the substrate heating effect with a space-time function. Dr. Groves [84] proposed a general solution of the heat equation using the Green’s Function. It involves a quite complex approach and it is difficult to solve and require a number of organizing values and calculations on Excel spreadsheet. Green’s Function, \( G \), is given,
It is the response of a system to a source point of heat. It describes the amount of energy deposited by the electron beam with the beam voltage, current density and material properties. The equation below describes the source term of the heat equation.

\[ h(x, y, z, t) = \frac{V_o Q \lambda(z/R_e)}{R_e t_e} \]

Equation 38

Where
- \( V_o \) = Acceleration Voltage
- \( Q/t_e \) = Current Density
- \( \lambda(z/R_e) \) = Everhart-Hoff factor

Then, heat capacity and the Green’s function are put in the general solution form to the heat equation is given by,

\[ T(x, y, z, t) = \int_{-d/2}^{d/2} \int_{-d/2}^{d/2} \int_{-h/2}^{h/2} \int_{-a/2}^{a/2} G(x, y, z, t, x', y', z', t') h(x', y', z', t') dx' \]

Equation 39

The first term represents boundary contributions, the 2\(^{nd}\) term represents a source contribution and the 3\(^{rd}\) term represents contributions from an initial distribution. This is complicated and Professor John G. Hartley at CNSE can explain the mathematics in detail on his teaching course [85].
With high exposure doses, heating from electron beam add more sensitivity to resist. This caused unwanted line width variation. All above equations related to heat equation solution is given in Professor Groves’ publication. The equations should be able to describe temperature rise due to beam-induced substrate heating. Dr. Groves’ data is shown in Figure 180 for the quartz substrate and Silicon substrates using VSB tool with 50kV and GB tool with 100kV accelerating voltage beams, respectively. He tries to show the different temperature rises in both of them.
Figure 180 (a) bulk quartz substrate with 50kV beam voltage and 30A/cm$^2$ (b) bulk silicon 100kV beam voltage and 50/cm$^2$ current density.

13.3 Metrology Tools

13.3.1 CDSEM

Hitachi SEM is used to measure CD, LER and LWR. It can have an automated process to measure different printed resist, etched Cr and etched quartz features. The 200mm wafer carrier is adapted to accept 3” quartz wafers.
13.3.2 Scanning Electron Microscopy

Figure 182 LEO 1550 SEM

The operating setting for LEO 1550 SEM is set up to 0.3 – 1 keV with 3mm distance work between a study substrate and a polepiece in the vacuum chamber. A user can view the substrate using a camera on the control computer. The stigmation and wobbled aperture were optimized using the finer joystick rather than using a scroll bar because of a great discrete shifting movement.
13.3.3 Environmental Scanning Electron Microscopy

Environmental SEM (eSEM) is same as the SEM, but uses a low water vapor in its chamber. eSEM reduces the charging problem on any material insulators. It is good for insulating quartz substrate. This metrology machine is suitable for measuring CD of etched Cr and etched Quartz features. Printed resists can be viewed as well especially ZEP520A, which is very sensitive to the electron beam. eSEM is better than using a regular SEM with high vacuum level.

13.3.4 Atomic Force Microscopy

Atomic Force Microscopy (AFM) is a very high-resolution scanning probe microscopy. This process uses a mechanical probe that feels the surface of the interest of region. Its
technology uses piezoelectric element that can control precise movements of scanning. It is used to measure the etched Cr and Qz features especially for 30nm features and beyond.

13.3.5 Ellipsometer

Figure 184 RC2 Woolman Ellipsometer owned by Dr. Alain Diebold under his research group

Ellipsometer is an optical technique for the investigation of thin films. It measures the accurate thicknesses of resist, thin Cr and bulk quartz substrate. It was used to verify the thickness of thin Cr film on the quartz substrate.
Figure 185 40nm ZEP520A Resist and 10nm Cr films on Quartz wafer measured by RC2 Ellipsometer
13.3.6 Profilometer

The profilometer is a measuring instrument that is used to measure a surface profile for a quick measurement rather than using AFM. Its resolution is not as good as AFM.

13.4 Flow Process

13.4.1 Polish Quartz Wafer

<table>
<thead>
<tr>
<th>Trion Minilock III Etcher System Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ICP power</td>
<td>300 Watt with +/-20 setoff reference</td>
</tr>
<tr>
<td>RIE Power</td>
<td>50 Watt with +/-10 setoff reference</td>
</tr>
<tr>
<td>Pressure</td>
<td>50 mTorr</td>
</tr>
<tr>
<td>Gas Mixture #1</td>
<td>3 sccm Oxygen</td>
</tr>
<tr>
<td>Gas Mixture #2</td>
<td>47 sccm CHF₃</td>
</tr>
<tr>
<td>Process Time</td>
<td>2 seconds</td>
</tr>
</tbody>
</table>
13.4.2 Cr Etch

<table>
<thead>
<tr>
<th>Varian E-Beam Evaporator Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerating Voltage beam</td>
</tr>
<tr>
<td>Thickness</td>
</tr>
<tr>
<td>Power in Percentage</td>
</tr>
<tr>
<td>Vacuum Pressure</td>
</tr>
<tr>
<td>Deposit Rate</td>
</tr>
</tbody>
</table>

13.4.3 Apply E-Beam Resist

<table>
<thead>
<tr>
<th>CEE 200CB Spin and Bake System and *Cubed S Photofab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spinning Coat Recipe</td>
</tr>
<tr>
<td>Achieved ZEP Thickness</td>
</tr>
<tr>
<td>Acceleration</td>
</tr>
<tr>
<td>Spinning Speed</td>
</tr>
<tr>
<td>Process Time</td>
</tr>
<tr>
<td><strong>Baking Recipe</strong></td>
</tr>
<tr>
<td>Bake Temperature</td>
</tr>
<tr>
<td>Process Time</td>
</tr>
</tbody>
</table>

*not tested yet with solvents

13.4.4 Develop

<table>
<thead>
<tr>
<th>Developing Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEP520A</td>
</tr>
<tr>
<td>Mixture</td>
</tr>
<tr>
<td>Develop</td>
</tr>
<tr>
<td>Rinse in Di water</td>
</tr>
<tr>
<td>Clean</td>
</tr>
</tbody>
</table>
13.4.5 Descum

<table>
<thead>
<tr>
<th>Trion Minilock III Etcher System Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICP power</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>RIE Power</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Gas Mixture #1</td>
</tr>
<tr>
<td>Process Time</td>
</tr>
<tr>
<td>Descum rate</td>
</tr>
</tbody>
</table>

13.4.6 Cr Etch

<table>
<thead>
<tr>
<th>Trion Minilock III Etcher System Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICP power</td>
</tr>
<tr>
<td>RIE Power</td>
</tr>
<tr>
<td>Pressure ICP/RIE Chamber</td>
</tr>
<tr>
<td>Gas Mixture #1</td>
</tr>
<tr>
<td>Gas Mixture #2</td>
</tr>
<tr>
<td>Processing Time with visibly Clearing 10nm Cr with +/-1nm</td>
</tr>
<tr>
<td>Processing Time for High Dense Pattern</td>
</tr>
<tr>
<td>Cr Etch Rate</td>
</tr>
<tr>
<td>Cr Etch Rate</td>
</tr>
</tbody>
</table>

13.4.7 Strip E-Beam Resist

There are two different ways to strip ZEP520A E-Beam resist: oxygen plasma and piranha solution. However, HSQ can be left on top of Cr film. The best process is with Piranha solution, which is a mixture of four parts of Sulfuric Acid with one part of Hydrogen Peroxide operating at 105° C to make sure that ZEP520A resist is completely removed. Nonetheless, use oxygen plasma to remove the residues such as Cl_x and foreign material on the Cr pattern based Qz wafers.
### E-Beam Resist

<table>
<thead>
<tr>
<th>E-Beam Resist</th>
<th>Piranha Solution</th>
<th>Oxygen Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEP520A</td>
<td>2/3 Sulfuric Acid</td>
<td>75 Watt ICP</td>
</tr>
<tr>
<td></td>
<td>1/3 Hydrogen Peroxide</td>
<td>35 Watt RIE</td>
</tr>
<tr>
<td></td>
<td>105° C Heat</td>
<td>50 mTorr</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 sccm Oxygen</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 seconds</td>
</tr>
</tbody>
</table>

#### 13.4.8 Quartz Etch

The recommended deep trenches are 40nm for achieving 22nm, 20nm and 16nm features. The height of the relief structure is about 20nm throughout the varying dense patterns. The major goal is to focus on 16nm half-pitch dense lines and the aspect ratio should be about two times of that. The 20nm deep trench is recommended because there are varying pattern with sizes ranging from 16nm to 1µm feature size.

#### Trion Minilock III Etcher System Parameters

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ICP power</td>
<td>300 Watt with +/-20 setoff reference</td>
</tr>
<tr>
<td>RIE Power</td>
<td>50 Watt with +/-10 setoff reference</td>
</tr>
<tr>
<td>Pressure RIE/ICP Chamber</td>
<td>50 mTorr</td>
</tr>
<tr>
<td>Gas Mixture #1</td>
<td>47 sccm O₂</td>
</tr>
<tr>
<td>Gas Mixture #2</td>
<td>3 sccm CHF₃</td>
</tr>
<tr>
<td>Process Time</td>
<td>20 sec</td>
</tr>
<tr>
<td>Quartz Etch Rate</td>
<td>4 Å/sec</td>
</tr>
</tbody>
</table>

#### 13.4.9 Cr Strip

Use Cr Etch 1020 Type chemical solution to strip the Cr layer off from the quartz substrate. This is a corrosive chemistry. 10nm Cr layer is stripped with 40 angstrom per second accurately. Rinse with distilled water for 60 seconds to make sure that the corrosive chemistry is removed completely. You should be able to see the relief structures with your naked eyes on varying features on the quartz substrate.
13.4.10 Clean

Clean the etched Qz wafers with Acetone and IPA alcohols and put them into the Megasonic Vibration bath to completely remove scum resist for 5 minutes.

13.5 SUMMIT Software

![Image of SUMMIT Software GUI and measured patterned resists]

Figure 187 (a) GUI of SUMMIT Software (b) measured patterned resists

After taking micrographs with scale bars, SUMMIT software measured the CD by following the exact bar scale given by SEM (or eSEM).
## 13.6 Skeleton PSF Files

### 13.6.1 Optimized PSF File for HSQ

**HSQ with 20 million electrons PSF**

<table>
<thead>
<tr>
<th>Scattering of electrons in matter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Copyright</strong></td>
</tr>
<tr>
<td>(C) Dr. B. E. Maile</td>
</tr>
<tr>
<td>Vorderer Berg</td>
</tr>
<tr>
<td>1986-2000</td>
</tr>
<tr>
<td>9</td>
</tr>
<tr>
<td>D-89186 Illerrieden</td>
</tr>
<tr>
<td>Germany</td>
</tr>
</tbody>
</table>

**Data Management**

<table>
<thead>
<tr>
<th>MeshRZNumberR: 16001</th>
</tr>
</thead>
<tbody>
<tr>
<td>MeshRZNumberZ: 16000</td>
</tr>
<tr>
<td>AllocSizeRZ: 256016000</td>
</tr>
<tr>
<td>MeshRZSizeR/nm: 5</td>
</tr>
<tr>
<td>MeshRZSizeZ/nm: 5</td>
</tr>
</tbody>
</table>

**Material Stack**

| StackDescriptor: HSQ_30 nm/Cr_10nm/Quartz_glass |
| NumberOfLayers: 3 |

| MaterialDescriptor: HSQ  |
| Thickness/nm: 30 |
| LayFlag: 1 |

| MaterialDescriptor: Cr  |
| Thickness/nm: 10 |
| LayFlag: 0 |

| MaterialDescriptor: Quartz_glass  |
| Thickness/nm: 350000 |
| LayFlag: 0 |

**Simulation Parameters**

| Injection Energy/eV: 100000 |
| Simulation Mode: P+ |
| skeleton Version: 2.19 |

**Simulation Status & Statistics**
Traced Electrons: 20000000
<Elastic Events>: 968
Escaped Electrons/%: 13.51
Escape EnergyLoss/%: 8.05
TimeStamp: 10/15/10 11:44

Simulation Performance
---------------------
Machine: ALPHASation / 500 MHz / OpenVMS_7.1
Processor Time/h: 23.61
Simulation Time/h: 23.67
CPU Allocation/%: 99.73
e-Frequency/(1/s): 234.68

Extraction Parameters
---------------------
Data Count: 16001
Delta_R/nm: 5
Delta_Z/nm: 5
Z-Range/nm: 15.000 .. 20.000
sceleton Version: 2.19

Data -------
---------------------
Radius Ri/um  Energy_Density/ Injected_Electron  E*(eV/um^3)
---------------------
0 2.17E+06
0.005 4.44E+02
0.01 7.99E+01
0.015 3.42E+01

13.6.2 Optimized PSF for ZEP520A

ZEP520A with 20 million electrons PSF

scattering of electrons in matter

Copyright (C) Dr. B. E.
1986-2000 Maile
Vorderer Berg 9
D-89186
Illerrieden
Germany

Data Management -------
---------------------
MeshRZNumberR: 20001
MeshRZNumberZ: 20000
AllocSizeRZ: 400020000
MeshRZSizeR/nm: 5
MeshRZSizeZ/nm: 5

Material Stack

StackDescriptor: ZEP520_ 40nm/Cr_10/Quartz_glass
NumberOfLayers: 3

MaterialDescriptor: ZEP520
Thickness/nm: 30
LayFlag: 1

MaterialDescriptor: Cr
Thickness/nm: 10
LayFlag: 0

MaterialDescriptor: Quartz_glass
Thickness/nm: 350000
LayFlag: 0

Simulation Parameters

Injection Energy/eV: 100000
Simulation Mode: P+
skeleton Version: 2.19

Simulation Status & Statistics

Traced Electrons: 20000000
<Elastic Events>: 968
Escaped Electrons/%: 13.51
Escape Energy Loss/%: 8.04
TimeStamp: 19:18

Simulation Performance

Machine: ALPHASTation / 500 MHz / OpenVMS_7.1
Processor Time/h: 26.56
Simulation Time/h: 26.67
CPU Allocation/%: 99.61
e-Frequency/(1/s): 208.34

Extraction Parameters

Data Count: 20001
Delta_R/nm: 5
Delta_Z/nm: 5
Z-Range/nm: 15.000 .. 20.000
skeleton Version: 2.19

Data

<table>
<thead>
<tr>
<th>Radius Ri/um</th>
<th>Energy_Density/Injected_Electron E*/(eV/um^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.22E+06</td>
</tr>
<tr>
<td>0.005</td>
<td>2.72E+02</td>
</tr>
</tbody>
</table>

13.7 PROXECCO™ PEC Files

```plaintext
# PEC file generated Thu Feb 3 15:46:18 2011
# PROXECCO Version 7.0 090210 - compiled Feb 26 2009
# -----------------------------------------------------------------------
# Proximity Function (Gaussian Approximation)
   MULTIGAUSS 3, 0.0039, 2.0099, 1.4750, 0.0058, 36.7144, 0.5819
   BEAM_WIDTH 0.0030
# -----------------------------------------------------------------------
# Dose Table: 1.0033 - 5.4150
   NUMBER_DOSES 256
   DOSE_SCALING 1.0000
   DOSE_RATIO 2.0000
# -----------------------------------------------------------------------
# Correction Mode
   ALPHA_CORRECTION 2
   QUALITY 0
   EDGE_BIAS 0.0000
   DENSITYMODE 1
# -----------------------------------------------------------------------
# Fracturing
   OUTPUT 3
   MIN_DISTANCE 1.0000
   GRID 0.0000
```
13.8 Identify GDS Pattern

Figure 188 A Hierarchical Level of GDS Structures

Top CDSAX - 150x150um grating fields

<table>
<thead>
<tr>
<th>V L22 P44</th>
<th>H L22 P44</th>
<th>V L22 P70</th>
<th>H L22 P70</th>
</tr>
</thead>
<tbody>
<tr>
<td>V L22 P55</td>
<td>H L22 P50</td>
<td>V L22 P50</td>
<td>H L25 P50</td>
</tr>
<tr>
<td>V L22 P55</td>
<td>H L22 P55</td>
<td>V L25 P60</td>
<td>H L25 P60</td>
</tr>
<tr>
<td>L22 P60</td>
<td>H L22 P60</td>
<td>V L25 P70</td>
<td>H L25 P70</td>
</tr>
</tbody>
</table>

L: Lines
P: Pitch
H: Horizontal
V: Vertical
Below CDSAX - 150x150um grating fields

<table>
<thead>
<tr>
<th>H L22 P44 V1</th>
<th>H L23 P50 V1</th>
<th>V L23 P50 V1</th>
<th>H L25 P70 V1</th>
</tr>
</thead>
<tbody>
<tr>
<td>H L22 P44 V2</td>
<td>H L23 P50 V2</td>
<td>h L23 P50 V2</td>
<td>H L25 P50 V2</td>
</tr>
<tr>
<td>H L22 P44 V3</td>
<td>H L23 P50 V3</td>
<td>H L23 P50 V3</td>
<td>H L25 P60 V3</td>
</tr>
<tr>
<td>H22 P65</td>
<td>H L23 P70</td>
<td>H L24 P70</td>
<td>H L25 P55</td>
</tr>
<tr>
<td>H L22 P75</td>
<td>H L22 P100</td>
<td>H L26 P60</td>
<td>H L25 P100</td>
</tr>
</tbody>
</table>

L: Lines V1 : +1nm space
P: Pitch V2 : +2nm space
H: Horizontal V3 : +3nm space
V: Vertical

22nm SRAM gate

Figure 189 22nm SRAM Gate
Isolated Lines in Figure 190 have 2nm - 20nm isolated lines with 1nm.
Backscatter Test

Figure 192 Backscatter Test

Bias 20nm & 16nm

20 – 2nm lines with 2nm step

1:1 Elbow Structures on the 32nm pitch

1:1 Dense Lines on the 32nm pitch

1:1 Elbow Structures on the 32nm pitch

1:1 Dense Lines on the 32nm pitch

Figure 193 Bias 20nm & 16nm Lines and Elbow Structure
Protein Chips

- 3x7 matrix
- Isolated dots array
  - 20nm, 15nm, 10nm
- 8 sets of 12.75um x 12.75um Array of spots with 260nm pitch
- Alignment Markers with 1 micron bar & 10um square for Optical Microscopy
- 100 micron Pitch between cells

Figure 194 Protein Cells
Figure 195 Uniformity Pattern

Figure 195 is for testing imprinting process uniformity in each corner in 13x13mm mesa field.
### 13.9 Python Jobfile Files

```python
Description
------------

Usage
-----

```ex ZEP_Cr_Qz_xxxxxx.py
```
dummy_fills.pg_strategy_erode = Erode.nodiscard # As erode.erode, but shapes that are eroded to zero width or height are exposed as single pass lines
dummy_fills.vru = 44 #beam size step should be 44VRU for 20nA
dummy_fills.dose_start = 160
dummy_fills.cells = (1,1)
dummy_fills.update_actions[CellRowCol.cell] = measure_current

SRAM_gate = Layout("SRAM gate across full chip at 5nA current with mea_c_update")
    SRAM_gate.centre = (0.00,-1.525)
    SRAM_gate.beam = '/home/vb/db/100kv_0mm524_5na_aper3_3Feb2011.test'
    SRAM_gate.align_after_beam_load = True
    SRAM_gate.calibrate = True
    SRAM_gate.actions[default_cells] = expose("/home/vb/users/munder/projects/Imprint/ZEP_VEP/bias_13nm_sram_042111.vep")
    SRAM_gate.pg_strategy_erode = Erode.nodiscard # As erode.erode, but shapes that are eroded to zero width or height are exposed as single pass lines
    SRAM_gate.vru = 20 #beam size step
    SRAM_gate.dose_start = 210
    SRAM_gate.cells = (1,1)

SRAM_22nm = Layout("SRAM gate across full chip at 5nA current with mea_c_update")
    SRAM_22nm.centre = (0.00,0.475)
    SRAM_22nm.beam = '/home/vb/db/100kv_0mm524_5na_aper3_3Feb2011.test'
    SRAM_22nm.align_after_beam_load = True
    SRAM_22nm.calibrate = True
    SRAM_22nm.actions[default_cells] = expose("/home/vb/users/munder/projects/Imprint/ZEP_VEP/22nm_sram_042111.vep")
    SRAM_22nm.pg_strategy_erode = Erode.nodiscard # As erode.erode, but shapes that are eroded to zero width or height are exposed as single pass lines
    SRAM_22nm.vru = 20 #beam size step
    SRAM_22nm.dose_start = 200
    SRAM_22nm.cells = (1,1)
CDSAX = Layout("dummy fills across full chip at 1nA current with mea_c_update")
CDSAX.centre = (0.00,0.375)
CDSAX.beam = '/home/vb/db/100kv_0mm524_1na_aper3_28Jun11.test'
CDSAX.align_after_beam_load = True
CDSAX.calibrate = True
CDSAX.actions[default_cells] = expose_by_zone("/home/vb/users/munder/projects/Imprint/ZEP_VEP/cdsax_042111.vep")
CDSAX.pg_strategy_erode = Erode.nodiscard # As erode.erode, but shapes that are eroded to zero width or height are exposed as single pass lines
CDSAX.vru = 8 #beam size step
CDSAX.dose_start = 210
CDSAX.cells = (1,1)
CDSAX.update_actions[CellRowCol.row] = measure_current

lines = Layout("dummy fills across full chip at 1nA current with mea_c_update")
lines.centre = (-0.90,0.9)
lines.beam = '/home/vb/db/100kv_0mm524_1na_aper3_3Feb2011.test'
lines.align_after_beam_load = True
lines.calibrate = True
lines.actions[default_cells] = expose("/home/vb/users/munder/projects/Imprint/ZEP_VEP/long_lines.vep")
lines.pg_strategy_erode = Erode.nodiscard # As erode.erode, but shapes that are eroded to zero width or height are exposed as single pass lines
lines.cells = (1,1)
#lines.cells = (1,6)
lines.pitch = (.13,.11)
lines.vru = 8 #beam size step
#lines.dose_operator = DoseOperator.add
#lines.dose_increment = 10
#lines.dose_update_on = CellRowCol.cell
lines.dose_start = 210

sub20_cdsax = Layout("sub20_cdsax at 500pA current")
sub20_cdsax.centre = (1.28,0.70)
sub20_cdsax.beam = '/home/vb/db/100kv_0mm524_500pa_aper3_6Feb2011.test'
sub20_cdsax.align_after_beam_load = True
sub20_cdsax.calibrate = True
sub20_cdsax.actions[default_cells] =
expose("/home/vb/users/munder/projects/Imprint/ZEP_VEP/sub20_cdsax_500pa.vep")

sub20_cdsax.pg_strategy_erode = Erode.nodiscard  # As erode.erode, but shapes that are eroded to zero width or height are exposed as single pass lines
sub20_cdsax.cells = (2,3)
sub20_cdsax.pitch = (.73,.78)
sub20_cdsax.vru = 6  #beam size step
sub20_cdsax.dose_operator = DoseOperator.add
sub20_cdsax.dose_increment = 10
sub20_cdsax.dose_update_on = CellRowCol.cell
sub20_cdsax.dose_start = 180

small_features = Layout("various small features at 500pA current with 3nm BSS")
small_features.centre = (-1.1,0)
small_features.beam =
'/home/vb/db/100kv_0mm524_500pa_aper3_6Feb2011.test'
small_features.align_after_beam_load = True
small_features.calibrate = True
small_features.actions[default_cells] =
expose("/home/vb/users/munder/projects/Imprint/ZEP_VEP/sub20_500pa_pce.vep")
small_features.pg_strategy_erode = Erode.nodiscard  # As erode.erode, but shapes that are eroded to zero width or height are exposed as single pass lines
small_features.cells = (1,13)
small_features.pitch = (.30,.30)
small_features.vru = 8  #beam size step
small_features.dose_operator = DoseOperator.add
small_features.dose_increment = 5
small_features.dose_update_on = CellRowCol.cell
small_features.dose_start = 180

small_features_28pa = Layout("various small features at 500pA current with 4nm BSS")
small_features_28pa.centre = (-1.4,0)
small_features_28pa.beam =
'/home/vb/db/100kv_0mm524_500pa_aper3_6Feb2011.test'
small_features_28pa.align_after_beam_load = True
small_features_28pa.calibrate = True
small_features_28pa.actions[default_cells] =
expose("/home/vb/users/munder/projects/Imprint/ZEP_VEP/sub20_500pa_pec.v ep")
small_features_28pa.pg_strategy_erode = Erode.nodiscard # As erode.erode, but shapes that are eroded to zero width or height are exposed as single pass lines
small_features_28pa.cells = (1,13)
small_features_28pa.pitch = (.30,.30)
small_features_28pa.vru = 7 #beam size step
small_features_28pa.dose_operator = DoseOperator.add
small_features_28pa.dose_increment = 5
small_features_28pa.dose_update_on = CellRowCol.cell
small_features_28pa.dose_start = 180

small_features3 = Layout("various small features at 500pA current with 3nm BSS")
small_features3.centre = (-1.7,0)
small_features3.beam =
'/home/vb/db/100kv_0mm524_500pa_aper3_6Feb2011.test'
small_features3.align_after_beam_load = True
small_features3.calibrate = True
small_features3.actions[default_cells] =
expose("/home/vb/users/munder/projects/Imprint/ZEP_VEP/sub20_500pa_pec.v ep")
small_features3.pg_strategy_erode = Erode.nodiscard # As erode.erode, but shapes that are eroded to zero width or height are exposed as single pass lines
small_features3.cells = (1,13)
small_features3.pitch = (.30,.30)
small_features3.vru = 6 #beam size step
small_features3.dose_operator = DoseOperator.add
small_features3.dose_increment = 5
small_features3.dose_update_on = CellRowCol.cell
small_features3.dose_start = 180

variation_lines = Layout("various small features at 500pA current with 4nm BSS")
variation_lines.centre = (-0.75,-0.52)
variation_lines.beam = 
'/home/vb/db/100kv_0mm524_500pa_aper3_6Feb2011.test'
variation_lines.align_after_beam_load = True
variation_lines.calibrate = True
variation_lines.actions[default_cells] = 
expose("/home/vb/users/munder/projects/Imprint/ZEP_VEP/lines_00.vep")
variation_lines.pg_strategy_erode = Erode.nodiscard # As
erode.erode, but shapes that are eroded to zero width or height are
exposed as single pass lines
variation_lines.cells = (3,9)
variation_lines.pitch = (.15,.090)
variation_lines.vru = 7 #beam size step
variation_lines.dose_operator = DoseOperator.add
variation_lines.dose_increment = 5
variation_lines.dose_update_on = CellRowCol.cell
variation_lines.dose_start = 160

CDSAX_full1 = Layout("dummy fills across full chip at 1nA current
with mea_c_update")
CDSAX_full1.centre = (8,0.00)
CDSAX_full1.beam = 
'/home/vb/db/100kv_0mm524_1na_aper3_3Feb2011.test'
CDSAX_full1.align_after_beam_load = True
CDSAX_full1.calibrate = True
CDSAX_full1.actions[default_cells] = 
expose_by_zone("/home/vb/users/munder/projects/Imprint/ZEP_VEP/cdsax_042
111.vep")
CDSAX_full1.pg_strategy_erode = Erode.nodiscard # As erode.erode,
but shapes that are eroded to zero width or height are exposed as single
pass lines
CDSAX_full1.vru = 7 #beam size step
CDSAX_full1.dose_start = 200
CDSAX_full1.cells = (1,1)
CDSAX_full1.update_actions[CellRowCol.row] = measure_current

CDSAX_full2 = Layout("dummy fills across full chip at 1nA current
with mea_c_update")
CDSAX_full2.centre = (-8,0.00)
CDSAX_full2.beam = 
'/home/vb/db/100kv_0mm524_1na_aper3_3Feb2011.test'
CDSAX_full2.align_after_beam_load = True
CDSAX_full2.calibrate = True
CDSAX_full2.actions[default_cells] = expose_by_zone("/home/vb/users/munder/projects/Imprint/ZEP_VEP/cdsax_042111.vep")
CDSAX_full2.pg_strategy_erode = Erode.nodiscard # As erode.erode, but shapes that are eroded to zero width or height are exposed as single pass lines
CDSAX_full2.vru = 7 #beam size step
CDSAX_full2.dose_start = 220
CDSAX_full2.cells = (1,1)
CDSAX_full2.update_actions[CellRowCol.row] = measure_current

P200L100 = Layout("P200L100 at 10nA current")
P200L100.centre = (-0.85,-1.45)
P200L100.beam = '/home/vb/db/100kv_0mm524_10na_aper3_27Jun11.test'
#P200L100.align_after_beam_load = True
P200L100.actions[default_cells] = expose("/home/vb/users/munder/projects/Imprint/ZEP_VEP/cell_P200L100_00.vep")
P200L100.pg_strategy_erode = Erode.nodiscard # As erode.erode, but shapes that are eroded to zero width or height are exposed as single pass lines
P200L100.cells = (1,4)
P200L100.pitch = (.25,.25)
P200L100.vru = 32 #beam size step
P200L100.dose_operator = DoseOperator.add
P200L100.dose_increment = 10
P200L100.dose_update_on = CellRowCol.cell
P200L100.dose_start = 160

P100L50 = Layout("P100L50 at 10nA current")
P100L50.centre = (-0.6,-1.45)
P100L50.beam = '/home/vb/db/100kv_0mm524_10na_aper3_27Jun11.test'
#P100L50.align_after_beam_load = True
P100L50.actions[default_cells] = expose("/home/vb/users/munder/projects/Imprint/ZEP_VEP/p100l50_cdsax_041911.vep")
P100L50.pg_strategy_erode = Erode.nodiscard # As erode.erode, but shapes that are eroded to zero width or height are exposed as single pass lines
P100L50.cells = (1,4)
P100L50.pitch = (.20,.25)
P100L50.vru = 32  # beam size step
P100L50.dose_operator = DoseOperator.add
P100L50.dose_increment = 10
P100L50.dose_update_on = CellRowCol.cell
P100L50.dose_start = 160

CDU_PEC = Layout("P100L50 at 10nA current")
CDU_PEC.centre = (1.3,-1.25)
CDU_PEC.beam = '/home/vb/db/100kv_0mm524_1na_aper3_3Feb2011.test'
CDU_PEC.align_after_beam_load = True
CDU_PEC.calibrate = True
CDU_PEC.actions[default_cells] =
expose("/home/vb/users/munder/projects/Imprint/HSQ_VEP/Manually_Dose_Levels_011811/Grating_CDU_011810.vep")
CDU_PEC.pg_strategy_erode = Erode.nodiscard  # As erode.erode, but
shapes that are eroded to zero width or height are exposed as single
pass lines
CDU_PEC.cells = (6,1)
CDU_PEC.pitch = (.25,.25)
CDU_PEC.vru = 8  # beam size step
CDU_PEC.dose_operator = DoseOperator.add
CDU_PEC.dose_increment = 10
CDU_PEC.dose_update_on = CellRowCol.cell
CDU_PEC.dose_start = 180

uniformity = Layout("various small features at 500pA current")
uniformity.centre = (0.05,0.05)
uniformity.beam = '/home/vb/db/100kv_0mm524_1na_aper3_28Jun11.test'
uniformity.align_after_beam_load = True
uniformity.calibrate = True
uniformity.actions[default_cells] =
expose("/home/vb/users/munder/projects/Imprint/ZEP_VEP/uniformity_101210.vep")
uniformity.pg_strategy_erode = Erode.nodiscard  # As erode.erode, but
shapes that are eroded to zero width or height are exposed as single
pass lines
uniformity.cells = (2,2)
uniformity.pitch = (9,9)
uniformity.vru = 8  # beam size step
uniformity.dose_operator = DoseOperator.add
uniformity.dose_increment = 10
uniformity.dose_update_on = CellRowCol.cell
uniformity.dose_start = 200

final = Layout("Combining all the Layouts")
final.vru = 20 # job doesn't run w/o this!
final.centre = (0,0)
final.cells = (17,1)
#final.actions[(0,0)] = do_sub_layout(small_features_28pa)
#final.actions[(1,0)] = do_sub_layout(small_features)
#final.actions[(2,0)] = do_sub_layout(small_features3)
#final.actions[(3,0)] = do_sub_layout(lines)
#final.actions[(4,0)] = do_sub_layout(variation_lines)
#final.actions[(5,0)] = do_sub_layout(SRAM_gate)
#final.actions[(6,0)] = do_sub_layout(sub20_cdsax)
final.actions[(8,0)] = do_sub_layout(uniformity)
final.actions[(9,0)] = do_sub_layout(P200L100)
final.actions[(10,0)] = do_sub_layout(P100L50)
#final.actions[(11,0)] = do_sub_layout(CDU_PEC)
final.actions[(12,0)] = do_sub_layout(dummy_fills)
#final.actions[(13,0)] = do_sub_layout(CDSAX)
#final.actions[(14,0)] = do_sub_layout(SRAM_22nm)
#final.actions[(15,0)] = do_sub_layout(CDSAX_full1)
#final.actions[(16,0)] = do_sub_layout(CDSAX_full2)


#final.actions[(11,0)] = do_sub_layout(CDU_PEC)
final.actions[(12,0)] = do_sub_layout(dummy_fills)
#final.actions[(13,0)] = do_sub_layout(CDSAX)
#final.actions[(14,0)] = do_sub_layout(SRAM_22nm)
#final.actions[(15,0)] = do_sub_layout(CDSAX_full1)
#final.actions[(16,0)] = do_sub_layout(CDSAX_full2)

top = Layout("Imprint Template")
#top.calibrate = True
top.vru = 20 #job doesn't run w/o this!
top.centre = (132.00, 195.00) #490 -top and left near the datum plane on 490 holder
    #top.centre = (93.464, 234.072) #475 holder for imprint template
    93.464 234.072
    #top.centre = (62.811, 271.219) #490 -lower and bottom near the datum plane on 490 holder
    #top.centre = (7.555640+76.868, 239.646784-10.825) #422 Holder
top.height_measure_point = (132.00, 195.00) #490 -top and left near the datum plane on 490 holder
    #top.height_measure_point = (62.811, 271.219) #490 -lower and bottom near the datum plane on 490 holder
#top.height_measure_point = (93.464, 234.072)  #475 holder for imprint template 93.464 234.072
#top.height_measure_point = (7.55640+76.868, 239.646784-10.825)  #422 Holder
   top.substrate_type = 1
   top.actions[default_cells] = do_sub_layout(final)

return top