Progress towards critical dimension low vacuum scanning electron microscopy

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PROGRESS TOWARDS CRITICAL DIMENSION
LOW VACUUM SCANNING ELECTRON MICROSCOPY

by

Vasiliki Tileli

A Dissertation
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ABSTRACT

Low vacuum scanning electron microscopy (LVSEM) is proposed and evaluated for next generation Critical Dimension (CD) metrology. Its ability to control charging artifacts and hydrocarbon contamination in order to obtain high signal-to-noise ratio, high resolution image data from insulating materials make the technology an excellent match for the increased use of high-k dielectrics and shrinking feature size in the semiconductor industry. The presence of a gas in the LVSEM chamber means that the probe characteristics and secondary electron amplification, detection, and signal-to-noise ratio differ significantly from conventional high vacuum tools. In order for low vacuum CD approaches to be viable, all of the processes must be understood and described to the degree of accuracy currently available on high vacuum systems. Consequently, the focus of this thesis is to determine an analytic form of the signal-to-noise ratio for two detector configurations: the simplified steady-state cascade system operating in the well defined Townsend’s discharge region, and the high resolution, low vacuum immersion lens secondary electron detector, for which the physical amplification process has not been studied in the past. A physically realistic and ultimately predictive model, which could potentially be incorporated in CD simulation codes such as NIST’s MONSEL, is developed. Its effectiveness is verified with experimental data acquired as a function of gas pressure for all important operating parameters, such as electron beam energy and current, detector bias, cascade distance, and gas type, and its capability for optimization of the imaging conditions is discussed. Noise characteristics are also analyzed using Monte Carlo gain histograms and pure statistical methods.
Και πρώτα απ’όλα τι εννοούμε λέγοντας παιδεία;

Τη πληροφορία, την τεχνική, το δίπλωμα εξειδίκευσης
που εξασφαλίζει γάμο, αυτοκίνητο, κι ακίνητο,
με πληρωμή την πλήρη υποταγή του εξασφαλισθέντος,

ή

tην πνευματική και ψυχική διάπλαση ενός ελεύθερου ανθρώπου,
με τεχνική αναθεώρησης κι ονειρικής δομής,
με αγωνία απελευθέρωσης,
και με διαθέσεις μιας ιπτάμενης φυγής προς τ’άστρα;

Manos Hatzidakis “Τα σχόλια του Τρίτου”, 1980
To Ralph
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CHAPTER 1
INTRODUCTION

In the relentless effort of keeping up with Moore’s law [1] well into the 21st century, the semiconductor industry does not only require new nanolithography approaches and materials stacks, but innovative metrology techniques are also necessary. Today, some of metrology’s traditional forces are beginning to redline insofar as their inspection, measurement and test capabilities are concerned; limited by the continuous evolution towards smaller device structures and novel, high-k material approaches, new technologies applying more complex models for characterization are being sought.

In a nutshell, critical dimension (CD) metrology involves the accurate and reproducible measurements of line widths/pitches and contact holes/vias found in technologically important integrated circuits (ICs), such as transistor gates and interconnect structures [2]. These structures are made using a complex sequence of lithography and plasma etching steps. The actual dimensions of the features at each step are critical for the proper operation of the devices. For example, the gate width in any transistor influences the device’s speed. It has been shown that degradation of the line-width accuracy directly impacts the electrical performance of the transistor (off-state leakage and device drive currents) [3].

At this time, production in semiconductor technology is at 45nm but research for any given technology generation begins several years in advance [4]. Already the semiconductor industry is experimenting on the 16nm node, and the International
Technology Roadmap for Semiconductors (ITRS) projects that in 10 years the smallest feature size will be less than 10nm [5]. In the Metrology section of the 2008 update, it is stated that the most critical issue needed to be addressed, besides the obvious resolution challenges of inline metrology tools, involves the standardization of the CD measurement process. The conversion of massive quantities of raw data to information useful for enhancing the yield of a semiconductor manufacturing process is critical to the real-time integration of any CD metrology technique. Current leading in-line characterization techniques involve scanning electron microscopy (CD SEM), atomic force microscopy (CD AFM), optical scatterometry (OCD), and small angle x-ray scatterometry (CD SAXS). It is acknowledged that no current single CD measurement instrumentation or technology can provide process engineers with the tools required to facilitate lithographic and etch control for the sub-32nm manufacturing technology. Each one demonstrates advantages but also significant deficiencies.

CD AFM is mostly operated in “tapping” mode where the cantilever is maintained in constant-amplitude oscillation. This configuration has enabled the tip to be rapidly scanned across the test surface while reducing drag artifacts or damage to the tip or surface, arising from shear forces during contact scanning mode. While this technology is highly accurate and capable of providing true three-dimensional information of material structure [6, 7], it is limited by its applicability for space and hole measurements. Additionally, the throughput is low, lower than any other CD metrology technique, and inevitable tip wear/calibration remains a pressing issue. In addition, though promising tip size and shape advances has been made, such as “boot-shaped” tips [8] and single carbon nanotube probes [9], implementation challenges still
OCD is a mean-field metrology technique based on the analysis of scattered light from a periodic array of features (grating). It is a non-destructive, non diffraction-limited and fast optical tool [10]. It has excellent precision values, $3\sigma$ of 0.75 nm have been reported, and their results are in good agreement with other techniques such as top down, cross-sectional SEM and AFM. The main limitation of optical scatterometry is that it performs a “statistical” measurement, i.e. it provides an average value of the dimensions of the periodic structure without being able to provide information about isolated or individual features. In addition, optical constants (index of refraction -n- and absorption -k-) of each layer have to be known and can change during processing (e.g. after annealing).

CD-SAXS is a transmission scattering alternative that compliments the existing technologies. It can easily quantify the pattern shape in arrays of nanostructures with periodicities in the range of 10 to 500 nm with sub-nm precision, is non-destructive, is capable of quantifying buried or free-standing patterns, and is straight-forward to interpret via scattering theory [11]. CD SAXS requires high energy x-rays that can penetrate the supporting Si substrate. Such x-rays can be obtained at a synchrotron source where the x-ray energies are tunable. However, coupling CD-SAXS to a synchrotron facility limits its utility to industry. To address this problem, laboratory scale SAXS instruments for critical dimension measurements on periodic nanoscale patterns are currently being designed, installed, and tested [12, 13].
CD SEM is still acknowledged as being the fab’s workhorse, almost two decades after its introduction as an in-line instrument [14]. Overall, some of the advantages it offers are acceptable throughput and speed, site specific measurements and high resolution imaging, currently, the state-of-the-art CD SEM systems enable accurate profile analysis to assess the quality of line widths and contact holes with close to 1nm spatial resolution and an ability to differentiate structures separated by less than 1nm [15]. With its high resolution credibility established, the main issues inhibiting its life span beyond the 22nm node include surface charging and contamination\(^i\) [5]. Another issue involves the standardization of the CD measurement process for any instrumentation. The conversion of massive quantities of raw data to information useful for enhancing the yield of a semiconductor manufacturing process is critical to the real-time integration of any CD metrology technique. To this end, CD SEM offers widely accepted procedures for interpreting the results. Notably, the National Institute of Standards and Technology (NIST), has developed, and continues to advance, a model-based-library Monte Carlo simulator, called MONSEL, that enables the quantitative

\(^i\) Charging, while electron beam imaging, occurs on insulating samples or samples with poor contact to the specimen holder, which is usually grounded. The incoming beam electrons will interact with the specimen and produce various signals. If the electrons are not backscattered, they will be swept away from the sample through the ground contact. If this contact is poor or does not exist, then electrons will start accumulating in the sample. The specimen will acquire a surface potential known as “charging”. This surface potential will lower the energy of the incoming electrons, and in cases of strong charging the beam is deflected. Contamination usually arises from hydrocarbons adsorbed on the surface of the specimen. Upon interaction with the electron beam, layers of carbon gradually build up. Both charging and contamination add a dynamic component into the CD measurement error.
interpretation of SEM images, and thus, the accurate calculation of top and bottom line width values, sidewall angles, corner rounding, and heights of lines from top down SEM intensity profiles. In briefii, MONSEL takes into account all parameters that affect the line-width obtained from the SEM including the properties of the electron beam, specimen, and electron detectors. Hence, the simulation code encompasses a detailed analysis of the signal contributing to the image formation in high vacuum scanning electron instruments. One complication, for which this code or any other simulation software cannot account for, is potential charging of the specimen, which causes deflection of electron trajectoriesiii and ultimately erroneous CD measurements.

To this end, this research explores low vacuum SEM (LVSEM) as the solution to the above-mentioned limitations of CD SEMs, and a detailed systematic analysis of the implementation of this innovative approach for accurate and reproducible CD measurements is undertaken. LVSEM utilizes a gaseous specimen chamber environment to alleviate the effects of specimen charging while electron imaging. In addition, its proven capability of high resolution imaging [17] make it an attractive instrumentation for next generation CD metrology. Some representative micrographs of technologically important non-conductive structures are depicted in Figure 1.1.

ii A more detailed review follows at the next chapter.

iii Studies for the evaluation of e-beam charging on CD SEM measurements are continuously being driven by the industry’s need to fully account for its effect, though a complete physical picture of the effect is not available as yet. Recently, Abe et al., developed a charging simulator to predict the influence of charging and they report good agreement of simulated and measured data on their preliminary results [16].
Specifically for CD measurements, however, it is the ability to interpret correctly the imaging data that is essential. This involves understanding and accurately modeling of all processes taking place during image formation, including electron-specimen interactions, and signal generation, detection, amplification, and processing. These processes are sufficiently well understood in high vacuum systems for the current technology node. However, nearly all of these processes are fundamentally different in low vacuum instruments due to the gaseous specimen chamber environment. Therefore, a complete understanding of the low vacuum image formation process is needed to enable quantitative image analysis and optimal selection of the operating parameters. This is particularly pertinent to CD metrology where, in general, the electron fluence delivered to the sample must be minimized, and the characteristics of both the imaging signal and noise must be accounted for.

Image formation and signal-to-noise optimization are well understood in high vacuum SEM. Emitted secondary electrons (SEs) are typically collected by a biased
scintillator, amplified by a photomultiplier, and then processed electronically [18]. The typical gain of the photomultiplier is $10^5 - 10^6$. The noise characteristics of each stage of the signal chain are well understood and can be measured for a given system configuration [19]. In an optimized system, the noise is dominated by statistical fluctuations in the SE arrival rate at the collector, which is limited by shot noise in the incident electron beam.

In LVSEM, the image formation process is more complicated than in high vacuum instruments due to the gaseous environment of the specimen chamber. LVSEM has a much wider operating parameter space, adding gas composition and pressure, and compounding the roles of conventional SEM parameters in the image formation process [20, 21]. For example, changes in the electron beam energy or the working distance between the sample and the objective lens influence detector gain, the charge-compensation behavior of gaseous ions and the probability of primary electrons being scattered by gas molecules prior to reaching the specimen surface [20, 22]. In addition, the signal processing occurs in a different order: In most low vacuum instruments, emitted SEs are amplified by a gas ionization cascade before collection. The amplified signal is then detected either as a current induced in an electrode by the movement of charged particles in the gas, or by measuring the concomitant gas scintillation. Consequently, the gas cascade is the first amplification stage and therefore plays a significant role in LVSEM noise behavior (since noise introduced in the first amplification stage is amplified by subsequent gain stages [23]). Optimal imaging requires the selection of operating parameters that maximize image signal-to-noise ratio whilst satisfying application-specific requirements such as charging artifact...
minimization [17], charge-induced image contrast enhancement [24], and contamination reduction/violatilization control [25].

To recapitulate, this research’s objective entails the explicit modeling of the physical phenomena taking place in low vacuum instruments and couples them to existing physics for the electron-beam/specimen interactions. Hence, the modeling approach follows electrons starting from their emission point, as they enter the gas-filled specimen chamber, enter and exit the specimen, find their way to the detector, and are captured by it.

At the next chapter, chapter 2, after providing a detailed overview of the CD SEM measurement process and the low vacuum imaging characteristics, the fundamental challenges for the realization of low vacuum CD metrology are outlined. In chapter 3, the analysis of the signal and noise characteristics of the gas cascade amplification is dedicated to the environmental secondary electron detector (ESD). This detector configuration operates in the Townsend discharge region where a constant electric field across the cascade distance is assumed. The well-defined statistical properties of this structure are analytically described and verified with adequate experimental measurements. In chapter 4, the analysis continues with non-local electric field structures coupled with magnetic fields. In particular, the gain and noise characteristics of the low vacuum immersion lens amplifier are detailed and an analytical description for all physical processes taking place in the image formation is provided. Chapter 5 summarizes the advances produced in this thesis concerning the realization of a low vacuum CD metrology tool and provides an outlook on further considerations need to be elucidated in the future.
CHAPTER 2

BACKGROUND

2.0 Introduction

Dedicated critical dimension scanning electron microscopes (CD SEMs) remain the industry’s preferred instrumentation for in-line assessment of line pitches/widths and contacts/holes. In this chapter, CD SEM’s critical operation aspects are reviewed and its specifications and advances are discussed. In addition, the aspects of imaging in low vacuum scanning electron microscopes (LVSEM) differentiating it from its high vacuum counterparts are detailed. The innovative approach of CD LVSEM is discussed and the fundamental challenges for its implementation as an in-line CD measurement technology are described. Thus, the discussion here is restricted to the fundamental issues that have direct relevance to the development of a low vacuum critical dimension scanning electron microscope and is not intended to cover the wide spectrum of gaseous physics\textsuperscript{iv} as encountered in the instrument.

\textsuperscript{iv} The specific processes with which this thesis is concerned are treated separately and in detail at the following chapters.
2.1 CD SEM Basics

2.1.1 Design

A CD-SEM is a highly specialized version of a conventional laboratory scanning electron microscope designed for low voltage operation to prevent damage and charging to the IC chip. Concerning their design, the chief differences are due to the high performance, single-purpose nature of these tools, and can be divided into two categories: stage modifications to enable wafer handling and provide highly accurate and mechanically stable positioning, and modifications to the imaging capability such as electrostatic scan deflectors that ensure highly accurate and reproducible beam positioning [2, 26]. However, since image fidelity is limited by the usual electron optics constraints imposed in any electron column, the discussion focuses on the operating aspect of the instrument.

2.1.2 Operation

The need for charge control and electron beam induced damage minimization, has led to low voltage operation of CD SEMs (typically between 0.2-2.5 V). Even though this directly conflicts with the requirement for even better imaging resolution by means of increasing the lens aberrations\(^\text{\textdagger}\), this effect is compensated by incorporation of a series of electric and magnetic quadrupole lenses [28, 29]. The process of suppressing

\(^\text{\textdagger}\) Lens aberrations include spherical and chromatic aberration, coma, axial astigmatism, distortion, and non-axial errors. Most of them can be avoided by on-axis alignment of the electron beam and by the use of small apertures. Particularly for low voltage SEM, the resolution is mainly limited by the chromatic aberration due to its inverse dependency on the electron beam energy [27].
charging artifacts at low accelerating voltages is linked to the surface potential of the insulating sample that influences the trajectories of secondary, backscattered, and primary beam electrons. Whether the surface potential of a non-conductor is positive or negative, depends on the total electron emission yield, $\sigma = \eta + \delta$. $\eta$ and $\delta$ denote the BSE and SE yield respectively. The dependency of $\sigma$ on primary electron energy, Figure 2.1, shows two crossover points, $E_1$ and $E_2$, at which the total yield equals unity and no charging occurs [27]. Typically, CD SEMs operate between these two crossovers [30]. Thus, when the beam energy is set between these two points, the total yield is greater than unity, i.e. the number of electrons emitted as backscattered and secondaries is greater than the number of primary electrons hitting the sample. This excess emission results in a positive charging of the specimen surface. In this case, all SEs with exit energies smaller than the surface potential return to the specimen and equilibrium is reached when the effective SE coefficient is reduced to $\delta = 1 - \eta$. Thus, the image in low voltage operation forms effectively by backscattered electrons and not by secondaries. In contrast, fine-tuning the primary electron beam to the critical energy $E_2$, at which point the incident electrons on the specimen equal those emitted (SEs and BSEs) inhibits charge accumulation and balances the surface potential. However, this value is specimen dependent, it can vary within the imaged area, and it is a strong function of the electron fluence of the irradiated region. Thus, in CD SEM low voltage operation, the energy lays between the two crossovers points and, effectively, the signal is complimentary to backscattered electron detection.
Besides the influence on the surface potential, low beam energies result also in a reduction in gun brightness and hence reduced beam currents. However, smaller features and larger wafer sizes actually demand increased probe currents if throughput rates are to be held constant. Higher scan speeds improve throughput and alleviate many charging artifacts, but only at the expense of factors, such as image quality and signal-to-noise ratio degradation, which are crucial to CD metrology.

Conventional CD-SEMs form their images using the low energy secondary electrons (SEs), produced as the electron beam scans across the sample. The useful component of these emissions (SE$_1$) are arbitrarily defined as the electrons generated by the primary electron beam and have between 1 and 50 eV of energy, the distribution of which peaks around 3 eV. Their collection mechanism is based on the detector design introduced by Everhart and Thornley [18] comprising of a scintillator/photomultiplier tube structure. The detector’s operating principle has as follows [27, 31]. Electrons from the specimen enter a cylindrical metal box through a window of metal gauze and SEs are attracted towards the window by a positively biased grid (100-200 V). The collected electrons are accelerated to the scintillator with a bias of 10 kV and are converted to

![Total yield curve (η=BSE yield and δ=SE yield) as a function of electron beam energy (E). Low voltage SEM operates close to the E₂ point where the emission yield is unity and no net charge accumulates in the electron beam irradiated region on the specimen.](image-url)
light quanta. Then, the light is conducted by total internal reflection in a light guide to a
photomultiplier. At the photocathode, the photons are converted back into electrons, and
the electrons are accelerated onto successive electrodes of the photomultiplier (a.k.a.
dynodes) producing an ever increasing cascade of electrons until the final collector is
reached. The typical gain is on the order of $10^5$-$10^6$, and is adjustable by selecting the
voltage on the dynodes [31].

The performance of the detector, known as the detective quantum efficiency
(DQE), is measured as the ratio of the output signal-to-noise (SNR) to the input SNR.
The statistics of the input electron current passing from the specimen to the Everhart-
Thornley detector/amplifier is similar to that flowing in a saturated diode. If $I$ is the
mean value of the current, and $\Delta I$ is the instantaneous departure from its mean, it
follows that

$$\overline{\Delta I^2} = 2eI\Delta f$$

(2.1)

where $\Delta f$ is the effective bandwidth at which amplification is to be provided and $e$ is the
electronic charge (for details on shot noise see Chapter 3). Thus, the input signal-to-
oise ratio, governed by the usual Poisson electron emission statistics, is given by

$$SNR_{input} = \frac{I_{in}}{\sqrt{\Delta I_{in}^2}} = \frac{I_{in}}{\sqrt{2eI\Delta f}}$$

(2.2)

Shockley and Pierce derived an expression to describe the signal-to-noise ratio in an
electron multiplier system [32], and it is their expression that has been used to describe
quantitatively the output statistics of the ET detector [19, 27, 33, 34]. Considering the
input SNR is given by shot noise statistics, the output SNR for the multi-stage multiplier with m independent stages is

\[
(SNR)_{\text{output}} = \sqrt{\frac{1}{2e\Delta f (1 + B)}}
\]  

(2.3)

where

\[
B = b_1 + \frac{b_2}{m_1} + \frac{b_3}{m_1m_2} + \ldots + \frac{b_n}{m_1\ldots m_{n-1}}
\]  

(2.4)

where \(m_i\) is the average number of electrons produced at stage \(i\) by one incident electron, and \(b_i\) is the relative mean-square deviation (variance) in the gain of the \(i\) stage. Considering Poisson statistics of the gain distributions for the different dynodes, it is concluded that if the amplification is sufficiently large, the multiplication process does not reduce the SNR appreciably. Moreover, the overall reduction of SNR is only slightly greater than if caused by the first stage acting alone, in other words, the first dynode of the photomultiplier is the dominant agent in producing changes in \(B\). From detailed experimental studies, it has been demonstrated that the factors affecting the noise amplitude are primarily the material of the scintillator and the voltage of the photomultiplier. In conclusion, it has been theoretically indicated and experimental proved that an optimized Everhart-Thornley detector optimally provides a value of \(B\) of ~0.8, making it a high signal-to-noise structure.
2.1.3 Measurement process

Typically, for CD measurements, SEM information is distilled in the form of a plot of secondary electron intensity as a function of position. The resulting line is called an intensity profile. Figure 2.2 shows a top-down SE image of two different chrome lines on a quartz substrate and the corresponding intensity profiles used to evaluate the CD. The peaks give an indication of the position of the edges and by knowing the position of both edges (left and right) one can determine the width of the feature. Close to the edge of the line, however, the diffusion length of the SE signal causes an increase in intensity, the co-called blooming effect. This is well demonstrated at Figure 2.3, a Monte Carlo simulation of electron trajectories near the edge of a line [35]. The dense vertical column above the top of the line is mainly composed of electrons in the primary beam. These electrons scatter within the sample forming an active volume inside the line. When the active volume makes contact with the sample surface, backscattered and secondary electrons emerge. These are visible as the long straight trajectories at varying angles in the vacuum region outside of the line. The characteristic bright line edges in a secondary electron signal are therefore due to the additional SEs that escape the sample when the sidewall is within the active volume. The bright image peaks produced by the line’s edges have a finite width. The width is large compared to the desired measurement resolution (0.18nm for 2009 according to the ITRS), so the measured value at the line width depends, in an important way, on how within this peak the edge is defined. Commercial CD SEMs may make this assignment in a number of ways.

CD SEMs generally offer the metrology engineer a choice of algorithm. The principles by which the methods operate are generally known, but the details are
proprietary. This makes the exact correlation between peak position in an intensity profile and actual edge position of the feature strongly correlated to the sophisticated simulation packages and their physical methods of treating the problem. Accordingly, we limit our discussion to the Monte Carlo electron transport modeling approach, based on first principle physics, which has been shown to produce good fits to the measured images.

MONSEL (MONte Carlo simulation for Secondary ELectrons) is a model-based library technique developed at the National Institute of Standards and Technology (NIST). It has three main components. The first is a Monte Carlo simulation code in which there are thoroughly implemented the physical processes governing the

![Figure 2.2](image1.png)  
**Figure 2.2:** Secondary electron top-town image of two different width Cr-on-quartz lines and the corresponding intensity profiles. (image taken in low vacuum SEM, P=0.3 Torr H₂O, E₀=10keV)

![Figure 2.3](image2.png)  
**Figure 2.3:** Monte Carlo simulation of electron trajectories (black lines in various angles) near the x-sectional edge of a line (shown in red) and the corresponding line profile (in blue).[35]
interaction of the electron beam, the sample and the instrument itself. The second component is software that can search, and if needed interpolate between, a library of precompiled line profiles for model geometries. As a final step, a non-linear least squares algorithm solves for the particular set of parameters that produce the best-fit between measured and calculated images [36].

The calculation of the expected secondary electron image, by means of Monte Carlo simulations of electron trajectories is based on parameters describing the sample (i.e. composition, edge positions, wall angles, etc.) and the instrument (electron source, beam energy, distribution of electron landing positions with respect to the beam impact point, position and field of the detector, detector amplification characteristics, etc.). MONSEL uses Mott elastic scattering, an explicit treatment of inelastic scattering events that generate secondary electrons, and continuous energy losses as specified by the modified Bethe formula. Individual incident electrons and all of their offspring (due to SE generation) are followed through elastic and inelastic scattering events until the escape the sample or their energies fall below the sample’s work function, making escape impossible. Simulating enough electrons for good statistics is time-consuming and depends on the number of incident electrons (beam current), their energy, and a number of landing positions, assuming the detector-sample correlation remains constant. Thus, a pre-computed model-based library of simulated results is employed.

In this way, the edge positions are determined and consequently, the feature sizes. In Figure 2.4, an accurate MONSEL reconstruction of the actual shape, both line width and sidewall angles, of a polycrystalline Si line from a top down image SE intensity profile is shown [15]. The component that is the factor limiting the accuracy of
this method involves the correct simulation of the impinging electron beam on the specimen, the secondary electron trajectories inside the specimen and their successive path to the detector. The computer program is going through continuous development for more accurate results. Recently, Villarrubia et al. [37] implemented the code in Java for modeling of 3-D specimen geometries to meet the semiconductor industry’s needs that evolve towards inherently 3-dimensional structures, and demonstrated successful modeling of a FinFET transistor. In addition, they continuously update the physical models of e-beam–specimen interactions to improve the accuracy of their simulations.

In a recent study, the sensitivity of SEM width measurements to different model assumptions was evaluated [38]. The edge assignment error, defined as the difference between the models outputs and the actual edge position, was calculated to be ±2-3nm on silicon. The continuous shrinkage of feature sizes could ultimately render such uncertainty significant, however, current specifications, discussed next, are met.

Figure 2.4: Example of MONSEL’s accuracy. (a) Line profile taken from a top down polycrystalline Si line (in black) and corresponding simulation fit (in red). (b) x-sectional modeled reconstruction of the actual shape (in red) and overlaid x-sectional image of the same line after it was cleaved. [15]

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2.1.4 Specifications

The Advanced Metrology Advisory Group (AMAG), comprised of representatives from the International SEMATECH Manufacturing Initiative (ISMI) consortium member companies, the National Institute of Standards and Technology (NIST), and SEMATECH personnel, has developed a unified specification for an advanced CD SEM [39]. This document addresses the critical areas of improvement of the instrument, with recommendations and a testing criterion for each. This specification is updated every year and the reader is referred to this document for insight on the technical aspects for testing the instrumentation. Here, the significant performance specifications needed to be evaluated for measurement error minimization are introduced. A summary of the current state-of-the art CD SEM specifications is included in Table 2.1.

A. Precision

Precision is defined as the total variation in multiple CD measurements needed for determining the value of the measured quantity. It includes reproducibility, i.e. the closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement, repeatability, i.e. the closeness of agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement, and matching between instruments of the same model.
B. Accuracy

Accuracy is defined as the closeness of the agreement between the result of a measurement and the true value of the measurand. The attributes of an accurate measurement system are identified to be beam steering accuracy, linearity and testing of algorithms, analysis of instrument sharpness, and the apparent beam width (ABW, a measure of the practical resolution using a step-walled non-shrinking photoresist and/or poly-Si samples). The specification is <8nm on a poly-Si sample at the 45nm node. It is proposed that a CD AFM is used as a reference system providing ~1nm traceability, i.e. the property of a result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards.

C. Interaction with sample

Charging, contamination, and photoresist shrinkage caused by e-beam irradiation are specified as major issues inhibiting accurate metrology. Charging of non-conductors appears as soon as the electron beam hits the specimen, but contamination tends to build up slower. Contamination usually arises from hydrocarbons adsorbed on the surface of the specimen. Upon interaction with the electron beam, layers of carbon gradually build up. In addition, particles that may land on the surface during handling contribute to contamination enhancement and lead to inaccurate and imprecise CD measurements. Currently there are no specifications targeted for the minimization of these effects, and thus, the discussion focuses on appropriate methodology for the characterization of contamination and charging as a function of dose.
Table 2.1: Current state-of-the-art CD SEM specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image resolution (@ 1kV)</td>
<td>~1.5 nm</td>
</tr>
<tr>
<td>Accelerating voltage range (in-line instruments)</td>
<td>0.5-2.5 kV</td>
</tr>
<tr>
<td>$3\sigma$ repeatability</td>
<td>&lt; 1 nm</td>
</tr>
<tr>
<td>Throughput</td>
<td>100 wafers/h</td>
</tr>
<tr>
<td>Pattern recognition probability of detection</td>
<td>&gt; 99%</td>
</tr>
</tbody>
</table>

D. Performance matching

Matching error is defined as the measurement uncertainty arising from changing measurement tools. In order to improve throughput, multiple CD-SEMs are used at the same time. Variation in measurement due to instrumentation is unacceptable. Therefore, all machines have to be properly calibrated and tested for agreement with each other. The matching specification is <0.36 nm difference in the mean values between two tools for the 90nm generation CD SEMs.

E. Throughput

Throughput of a CD SEM is the number of production wafers CD measurement per hour. By large, CD SEM maintains the best throughput qualifications among different CD instrumentation technologies but sacrifices to the systems throughput are allowed when the precision and accuracy values of the instrument are better than the specifications. Currently, state-of-art systems are capable of processing 100 wafers per hour.
F. Instrumentation outputs

CD control requires sophisticated engineering and SEM diagnostics. Apart from the CD measurement itself, it is required that an advanced tool outputs raw line scans, total electron dose, signal smoothing parameters, detector efficiency, and signal-to-noise ratio. The evaluation of these parameters is projected to provide optimization of the process.

G. Pattern recognition/stage navigation accuracy

The “capture rate” for pattern recognition is defined as the number of successful pattern recognitions divided by the total number of targeted sites. Successful recognition implies a measurement on the correct feature and not the satisfaction of the detection algorithm, which can sometimes occur when the examined feature is not the targeted one but a similar one. This may happen when many similar features exist in the field of view. Therefore, a warning should be available for pattern recognition failures. An unsuccessful recognition can also occur due to stage navigation inaccuracy, which depends on the stage movement mechanism, the accuracy of the predetermined feature coordinates and the use of beam shift. The 90 nm CD SEMs must be able to measure features 100 μm from the nearest pattern recognition target.

2.1.5 Advances

The CD SEM instrument has gone through continuous improvements and advances since its introduction for evaluation of the semiconductor industry’s multistep lithography process. In brief, the factors currently imposing the greatest limitations are resolution, charge control, e-beam induced damage and contamination [40, 41].
Consequently, continued improvements and innovations are needed to meet the industry demands. New SEM technology, which could potentially increase the instrument’s resolution, includes brighter and more monochromatic electron guns, nano-tips as emitters, electron energy filters, more sophisticated electron-optical columns, automatic landing position control, and compensation for sample stage vibration and drift [41]. Next, several specific variations of the technique are reviewed.

**H. High Voltage CD SEM**

It was proposed that abandoning the CD SEM’s low voltage operation by replacing it with significant higher voltage electron beams could prove to be a viable solution to current resolution limitations [40]. The advantages it offers are gun brightness enhancement, chromatic aberration minimization, and depth of field improvement, all possible with existing technology. In addition, the increased intensity at the edges of the CD features due to diffusion of the SE signal can be averted in high voltage mode by detecting instead of the low energy SEs (0-50eV), the low-loss electrons, which are electrons backscattered from the specimen with energy very close (~3%) to that of the primary beam. These electrons can be guaranteed to have only traveled a small distance in the sample before being ejected as a result of a single, high angle, scattering event. In this case, the spatial resolution is only limited by the probe size of the incident beam since there is no diffusion problem to consider. However, the major concern of implementation of this technology for CD evaluation is the possibility of damage due to the high-energy incident beam electrons to transistors when inevitable it will be employed to their active regions. To this end, Rice et al. [42] performed an evaluation study on fully functional devices using a 200 keV high voltage (HV) SEM.
Their results showed that transistors subjected to HV radiation were being altered. Even though the devices remained fully functional, the noticeable change in performance indicated that the devices were no longer working properly leading to the conclusion that the devices are at risk of a catastrophic failure some time in the future. The general conclusion drawn by this study was that the HV SEM, in its present form, is not an attractive CD metrology technology.

I. Helium Ion Microscopy

Recently, a novel ion source technology has emerged. The helium ion microscope (referred to as SIM, scanning ion microscope) is based on a cold finger noble gas field ion source (GFIS) with a single atom emitter. The advantageous specifications include a smaller virtual source size (~0.1nm), higher brightness (3×10^{10} A/m^2SrV), and smaller intrinsic energy spread (<8 eV) [43]. It was predicted to produce SE images with 0.25nm resolution [44]. Apart from the physics of the He ion beam and the ion column’s innovative technology, this ~3x greater spatial resolution than a conventional SEM is also attributable to the higher generation efficiency of the site-specific SE_{1s} and the suppression of SE_{n1s} due to the deeper penetration range of the He ions. These remarkable characteristics of the He ion microscope make it a promising technology for different applications, including CD metrology [45]. The semiconductor industry is investigating it as a promising technique to replace the low voltage SEM based on the high spatial resolution and better charging capabilities (possible by implementation of an in situ flooding electron gun). Numerous studies have surfaced the past few years on critical issues/problems specific to CD metrology applications, such as pervasive positive charging and ion implantation. Livengood et al. [46] focused
their study on the potential evasiveness of He ions on various substrates under different imaging conditions to insure compatibility of this technology with the current employed CD SEM. According to their work, preliminary damage study data for intermediate dose (i.e. intermediate scan rate) indicated that the He ions causes little to no damage to Si substrates. However, it was noted that more work needs to be done to determine the extent and control of the damage. Another significant inhibiting issue for CD applications of this novel technology lies to the little knowledge of the fundamental physics of low energy ion-solid interactions, signal generation, and detection mechanisms, all critical aspects for accurate and reproducible measurements of CD features. Joy et al. [47] began the investigation on image formation in the Helium ion microscope by comparing line profiles from electron and He ion beams for metrology purposes. It was demonstrated that ion induced SE edge profiles are narrower and better defined that the electron induced edge profiles. The true edge positions though cannot be determined by observation but they must be estimated based on appropriate modeling. In an effort to create a foundation for the application and interpretation of ion induced images for metrology, Ramachandra et al. [48, 49] introduced IONiSE, a Monte Carlo simulation program describing the interactions of 5-50 keV energy He ions with solids and predicting the production of ion induced SE emission. In addition, Ohya et al. [50], discussed the SE emission from He ion microscope and compared it with low voltage SEM. They demonstrated that the He ion microscope shows enhanced performance for voltage contrast imaging of nanometer structures, and its topographic sensitivity is higher that on the SEM due to the strong dependency of the SE yield versus incident angle for He ions. However, considering the early phase in development
of the Helium ion technology, much work needs to be completed before any resolute evaluation for implementation in CD metrology is undertaken.

J. Low Vacuum CD SEM: The Proposed Approach

The central trade-off in low voltage CD-SEM metrology of dielectric specimens is as follows: high beam current is not desirable since it inevitably results in charging artifacts; however, low current operation is also not acceptable since it affects image quality by deteriorating the signal-to-noise ratio. Currently, the trend is to use low dose imaging to address charging issues, including lowering the beam energy while increasing the scan speed. Such approach can no longer be valid since the signal-to-noise ratio is compromised, which directly conflicts with the requirement for even better imaging resolution. To address these inhibiting issues, low vacuum SEM has emerged the past years as an attractive solution for next generation CD metrology. Its operation removes restrictions on beam energy, and therefore corresponding restrictions on resolution. Several articles [17, 42, 51-53] have cited the instrument’s capability for photolithographic mask inspection based on the high resolution, artifact-free imaging of chrome on quartz masks. Additional advantages include contamination elimination [54], and possibility for in situ mask editing and repair, by injecting appropriate precursor gases. Indeed, the 2007 ITRS Roadmap has identified LVSEM as the leading candidate technology for next-generation critical dimension metrology of photolithographic masks for the semiconductor industry. All publications thus far evaluate only qualitatively the instrument’s capability for CD metrology. However, for CD measurements, the ability to interpret correctly the imaging data is essential. This involves the understanding and accurately modeling of all processes taking place during image formation, including
electron-specimen interactions, and signal generation, amplification, and detection. These processes are sufficiently well understood in high vacuum systems for the current technology node. All instrumentation interactions are accounted for in the modeling algorithms used to calculate the physical CD of the features but MONSEL or any other theoretical model is not capable of accurately simulating the interaction between the electron beam and an insulating specimen. This thesis, thus, is concerned on the quantitative aspects of its in-line implementation. Such effort constitutes initially in identifying all aspects different from conventional high vacuum instruments and determining their relative importance, before the quantitative resolution of most critical ones is attempted. First, the implications of a gaseous specimen chamber environment are considered.

2.2 Low Vacuum SEM Basics

The discussion focuses on the operating characteristics of electron beam imaging in a gaseous specimen chamber environment. We limit the discussion to the primary principles discriminating it from high vacuum operation, while a more detailed review of its fundamental aspects and applications can be sought in Refs. [20, 21, 55] and references therein.

2.2.1 Design

The typical chamber pressure for operation of a SEM under low vacuum conditions is between 10-1300 Pa while the electron optical column is maintained in ultra high vacuum to ensure that the electron beam will travel to the chamber without
excessive scattering by residual gas atoms. Thus, to accomplish a significant pressure gradient between the specimen chamber and the electron gun, a more sophisticated vacuum system is employed with intermediate pumps and pressure limiting apertures. The latter poses a restriction on the field of view but it also allows for implementation of advanced electron columns for high-resolution low vacuum imaging.

Another major consideration of having a gas-filled specimen chamber subsides to signal detection. Everhart-Thornley (ET) amplifiers, utilized in conventional SEM instruments, use an intense electric field that causes the gas to break down at the high pressures employed in ESEM. To overcome this issue, signal detection in ESEM exploits the presence of the gas as the amplification medium. The principle of gaseous detector devices is based on the collection of charged particles or photons produced as a result of the ionizing action of various signals. Scintillation-type detectors collect photons produced by emitted electron-gas molecule interactions. Counting third order emission particles, with respect to the ones escaping the specimen, can produce additional noise in the system since the correlation with the specimen-related information weakens. Therefore, in this work, scintillation amplifiers are ignored, and the discussion focuses on electron amplification and detection mechanisms.

2.2.2 Operation

Contrary to low voltage SEM, where the electron beam is fine-tuned to a critical value $E_2$ so as to prevent insulating specimen from charging, low vacuum SEM operates above that critical point and utilizes the negative charge accumulation that inevitably occurs on the surface of non-conductors. The mechanisms and consequences of charging in electron-irradiated dielectrics can be found on the elaborate work of
Cazaux. The gaseous ions created by the ionizing avalanche neutralize the specimen’s surface making insulating imaging possible without any image artifacts.

The operating parameter space is significantly enlarged in low vacuum environment where, apart from variables in conventional SEM imaging, such as electron beam voltage and current, working distance, and dwell time, gas pressure and type, cascade distance, gas path length, and anode bias need to be considered. The choice of appropriate conditions is a formidable task that ensues the consideration of all electron-gas interactions.

2.2.3 Electron – gas interactions

A. E-beam scattering

When the primary electron beam enters a gas filled specimen chamber, the first interaction taking place is the scattering of electrons by gas molecules out of the focused probe. Collisions of electrons with gas molecules result in a low current density “skirt” of scattered electrons surrounding the central beam [22]. Typically, the scattered fraction of the beam is quite large compared to the imaging area and it can extend over several hundred micrometers. Physically, a collision occurs when the electron passes within a characteristic area around the gas molecule, known as the total cross-section $Q$. With each collision, the electron may lose some energy and inevitably, get scattered through some angle away from the initial direction. Skirt electrons are defined as the scattered events over a high enough angle that would land them away from focused probe on the specimen. Generally, this includes elastic and ionizing collisions, as most electronic excitation processes result in no appreciable momentum
transfer to the molecule. Within the single scattering approximation, the fraction \( f \) of primary electrons that do not scatter into the skirt can be described by \[56\]

\[
f = \exp\left(-\frac{Q_{\text{tot}}(E)P_\text{i}}{RT}\right)
\]

(2.5)

where \( P \) is the gas pressure, \( d \) is the gas path length, \( R \) is the gas constant and \( T \) is the temperature. \( Q_{\text{tot}}(E) \) is the total scattering cross section which is a function of primary beam energy.

According to Eq. (2.5), the broadening of the beam is primary a function of gas pressure, gas type, gas path length and beam energy. Under the pressure and beam energy regime encountered in low vacuum SEM operation, the oligo-scattering taking place, as described by Danilatos [20], only causes a minor deterioration in resolution. Most importantly, it reduces the SE signal creating a constant background, under the same operating conditions. In practice, for increasing skirt flux, the contrast deteriorates and consequently the signal-to-noise ratio.

**B. Gas cascade amplification**

In the gas cascade, ionization events occur when an electron and a gas molecule collide resulting in the generation of a gaseous ion and an additional free electron. The process repeats, driven by an electric field applied between the specimen and an anode, giving rise to a gas cascade that amplifies the secondary electron current by up to three orders of magnitude. The objective of a successful cascade process is one: to enhance the SE production while inhibiting these electrons from triggering a breakdown. Breakdown occurs when secondary ionization processes appear, which, with further increase of bias, become so pronounced that they control the discharge. They are
referred to as $\gamma$ processes and they result in the release of additional electrons from the cathode. A number of mechanisms can participate in the breakdown of a gas such as positive ions striking the cathode, photons emitted by excited gas, and metastables arriving at the cathode. They can trigger a self-sustained discharge leading to arcing, \textit{i.e.} high discharge current flooding the anode. The geometry of the cascade region inside the chamber and the field strength define the prevailing characteristics of the gas amplification. The experimental work of this thesis is focused on the on-axis, parallel plate, Townsend discharge system and the on-axis, high resolution, immersion lens detector. Thus, the gas cascade characteristics of each structure will be detailed at the corresponding chapters.

C. Breakdown processes

For a certain critical combination of field strength and pressure, a dielectric breakdown of the gas can occur in an ESEM chamber. In practice, when a potential difference is established between two electrodes in a gas, the gas behaves as an insulator unless the potential exceeds a certain value, known as the breakdown potential. This value is sharply defined, meaning that the gas insulates well for a bias that is a few Volts less than that required to initial a discharge, but once it exceeds that critical value current passes through the gas and the insulation breaks down. The breakdown processes affect in a complicated way the limits of low vacuum imaging both in very low pressures as well as in high ones. Paschen’s law determines the breakdown potential for a given set of conditions and dictates the maximum possible amplification, Figure 2.5. Paschen, in 1889 [57], predicted that the breakdown potential between two parallel electrodes depends only on the quantity of the gas, which is
measured by the product of the pressure $P$ and gap distance $d$. Thus, for a fixed distance, it depends only on the pressure. At high pressures, the potential is large; it diminishes with the pressure and reaches a minimum for a certain critical value of the pressure. When further reductions are made, the breakdown potential rises rapidly, and attains very high values for the low pressures.

![Paschen curves for different gases](image)

Figure 2.5: Paschen curves for different gases, graph adapted from A. von Engel [58].

The mechanisms behind the production of additional electrons that inevitably lead to breakdown are referred to as secondary processes and they involve secondary electron emission from surfaces. An electron can be released if the energy of an incident photon on the specimen is higher than the sample’s work function. In general, for incident, energetic particles or photons there are three distinct cases; secondary photoelectron emission from surfaces, secondary electron emission by positive ion impact from surfaces or by metastables from surfaces. The most accepted physical picture of this effect at low pressures describes this phenomenon in terms of the second Townsend coefficient, $\gamma$ [58].
\[ \gamma (\exp(\alpha d) - 1) = 1 \]  

(2.6)

which is valid for uniform fields and constant \( \gamma \), and is likely to hold at medium and low pressure. The pressure must be high enough to warrant the use of \( \alpha \), that is the number of collisions along the specimen-anode separation, \( d \), ought to be \( \gg 1 \) and the mean free path \( \lambda \ll d \). On the other hand, \( P \) must not be too large because the stopping power of the gas takes effect in that case, the field seems to have no effect, and collisions are inhibited. When the effect of the field diminishes, due to high gas pressures, excitation processes in the gas prevail and secondary emission processes by ions and metastables at the electrodes become insignificant. Typically, though, operation in ESEM is set below the breakdown potential where such effects diminish.

**D. Ion effects**

Physically, ions behave much different from electrons with regard to their diffusion and drift in their parent gases. As expected, electrons have much higher drift velocities and diffusion coefficients (by orders of magnitude) than ions under given conditions [59]. Due to their small mass electrons are accelerated rapidly by the applied electric field, and they lose little energy in elastic collisions with molecules (a fraction of the order of \( m_e/M \), where \( m_e \) and \( M \) are the electronic and molecular masses, respectively). Therefore, electrons can acquire kinetic energies at which inelastic collisions become important, unlike the heavier ions. Particularly for water vapor, it is approximated that the ionization cross-section for its positive ion (leading to a doubly ionized positive ion) is less than \( 10^{-20} \) cm at 200 eV [60]. Also, a difference between electrons and ions develops in connection with their collision cross-sections [61].
Electronic excitation of atoms and molecules is an important factor in electron collisions even for impact energies of less than 10 eV, and in molecular gases the onset of vibrational and rotational excitation occurs at energies below 1 eV [62]. These energies are often attained by electrons whereas the corresponding modes of excitation by ions are higher, and the excitation cross-section curves peak at energies considerably above the thresholds imposed in low vacuum operation mode [63]. Therefore, ions have insufficient energy to produce much excitation as well.

In general, secondary electron (SE) imaging in low vacuum is dominated by the behavior of gaseous ions. Positive ions drifting towards the specimen’s surface are responsible for the suppression of charging artifacts by capturing negative charges accumulating close to the specimen’s surface. The effects of ions, however, are multiple and deleterious in some cases: they can perturb the cascade amplification field and the landing energy of the primary beam by the accumulation of space charge at and above the sample surface; they can damp the SE signal by recombining with emitted electrons, they can influence the charge balance of the specimen and they can result in smearing of the image due to their long ion drift times.

For the purposes of this thesis, the contribution of ion-related phenomena is excluded from the analytical modeling.
2.3 Fundamental Implementation Challenges of LVSEM to CD Metrology

2.3.1 Resolution

Resolution, in a SEM, refers to the size of the finest details that can be observed under electron irradiation. Typically, probe size and resolution are interrelated. The resolution can be worse but not better than the probe size and it is linked to the detection mode. As far as the SE mode is considered, the high-resolution information is the result of the excitation of SEs by the incident electron probe within an exit depth, usually of the order of a few nanometers. In addition, when determining resolution, the delocalization of SE generation needs to be considered. Both the decay of plasmons and the inelastic scattering processes result in a delocalized excitation of SEs. Hence, the resolution of SE emission is limited to a value close to 1-2 nm [27].

Nowadays, the electron probe size is made smaller than that exit depth by means of field-emission electron guns. Thus, the highest resolution achievable is limited to a volume of the size of the exit depth. Furthermore, the probe diameter must be comparable with or smaller than the feature itself, this is referred to as measurement resolution. Apart from the probe diameter, the limiting sharpness of SEM micrographs is dependent upon the electron beam current, convergence angle, and accelerating voltage. In a high vacuum microscope, the probe diameter is defined by the emitter and the electron optics/lenses throughout the column. Typically, the highest resolution image is achieved through small beam diameters containing sufficient beam current to exceed the visibility threshold for the contrast produced by the features of interest while maintaining a high enough beam energy to minimize the chromatic aberrations.
Currently, CD SEM manufacturers report resolution specifications of ~1.5nm at 1keV for state-of-the-art instruments. Operation though, as mentioned above, is restricted to beam energies between 0.4-2 keV to accommodate charging and damage free imaging and hence the beam current is kept at high values to counteract the inevitable loss in signal-to-noise ratio. This constraint restricts the probe size by affecting the performance of the electron optics, which at low accelerating voltages is significantly worse than at higher energies. The alternative of keeping relatively high the beam energy coming down the column and decelerating it only when it reaches the specimen by biasing appropriately the stage, is not preferred in CD metrology since such biasing could be detrimental for the device itself.

![Figure 2.6: High-resolution images of (a), (b) gold on carbon, (c) Pt-decorated gold on carbon, and (d) Au-decorated tin balls, taken using the low vacuum immersion lens detector. [Images (a), (c) and (d) are courtesy of NIST](image1.png)](image2.png)

Figure 2.6: High-resolution images of (a), (b) gold on carbon, (c) Pt-decorated gold on carbon, and (d) Au-decorated tin balls, taken using the low vacuum immersion lens detector. [Images (a), (c) and (d) are courtesy of NIST]
In low vacuum instruments however, such restrictions on beam energy are removed and this allows the effective beam energy to be chosen on different criteria, such as contrast enhancement and charge control. Imaging in a gaseous specimen chamber environment has been criticized in the past of ultimately resulting in lower resolution imaging than its high vacuum counterpart due to the presence of the gas. It has been argued and proven though that the main effect of the interaction of the primary beam with the gas molecules consists of creating a diffused constant background while maintaining the focused probe as defined by the electron optics. Figure 2.6 depicts the instrument’s capability for high-resolution imaging on both standard specimens and CD specific line widths of photolithographic masks, taken on a FEI Nova NanoSEM 600. Such resolution is achieved with current electron optics. Any further improvement in the electron optics, like the aberration corrected SEM approach, can be implemented also in low vacuum instruments. This way, further advances in spatial resolution are probable.

2.3.2 Signal-to-noise ratio

The signal-to-noise characteristics are well understood in high vacuum SEM. Emitted secondary electrons (SEs) are typically collected by a biased scintillator, amplified by a photomultiplier, and then processed electronically [18]. The typical gain of the photomultiplier is $10^5 - 10^6$. The noise characteristics of each stage of the signal chain are well understood and can be measured for a given system configuration [19]. In an optimized system, the noise is dominated by statistical fluctuations in the SE arrival rate at the collector, which is limited by shot noise in the incident electron beam.
In LVSEM, the signal processing occurs in a different order: In most low vacuum instruments, emitted SEs are amplified by a gas ionization cascade before collection. The amplified signal is then detected either as a current induced in an electrode by the movement of charged particles in the gas, or by measuring the concomitant gas scintillation. Consequently, the gas cascade is the first amplification stage and therefore plays a significant role in LVSEM noise behavior (since noise introduced in the first amplification stage is amplified by subsequent gain stages [23]).

During the gas cascade process, the contribution of the normally amplified SEs reaching the detector provides the desired specimen information. However, the stochastic nature of the process results in some emitted SEs contributing to the cascade less efficiently than others do. This distribution of amplified SEs is a function of the wide parameter space employed in LVSEMs, such as gas pressure and anode bias, and inhibits the useful information by associating certain noise statistics with the SE amplification process. In addition, in the presence of the gas, all other emissions and the primary beam electrons themselves inevitably are amplified. The most significant emission contributing to the gas cascade amplification, after the secondary electrons, is the backscattered ones; the probability of amplification of other emissions (i.e. x-rays) is very small. Their contribution is also a noise consideration. Their information content is not useful and it actually deteriorates the image quality by introducing excess noise.

Both signal and noise statistical processes are formulated according to the operation principle of the detection system. Each detector configuration employed for imaging is expected to demonstrate different behavior due to the unrelated physical
processes for the cascade amplification. In particular, in this thesis, the two important cases, that of the on-axis constant field detection and the one that employs magnetic fields for cascade enhancement, are detailed. Their image formation process, including the signal and noise contributions, will be defined quantitatively at the next chapters, and appropriate, analytical models describing the cascade amplification are derived and accessed as to their useful implementation in CD simulation codes like MONSEL.

2.3.3 Charge control

The excellent charge control of non-conductive materials has been established previously and was already visually demonstrated in the introductory chapter. Due to the minimization of charging artifacts, low vacuum SEM is expected to show significant improvement on pattern recognition and, consequently, stage navigation (already technical advances such as laser interferometer for stage navigation have been implemented in low vacuum instruments). Thus, an automated version of the instrument designed for CD metrology could offer better accuracy and higher throughput, while minimizing the operator’s intervention. However, due to the vast operating parameter space (almost double than in high vacuum microscopes) acquiring an artifact-free image can be challenging and, consequently, time-consuming.

The discussion in this work is restricted to steady-state charging behavior of the irradiated specimen. We confine the signal-to-noise analysis in effectively no-charging conditions in order to accommodate a complete and accurate physical description of the gas cascade ionization, independent of other process. For a thorough description of the charging behavior of insulators, the reader is referred to the work of Cazaux [64-70] and Fitting[71-74].
2.3.4 Contamination control

In electron microscopy, the growth of carbonaceous films, caused by cross-linking of hydrocarbon contaminant absorbates, is a major shortcoming since such films obscure the actual surface features and reduce resolution. Particularly for in-line device inspection, such film growth can inhibit the device’s performance. High vacuum (conventional) CD SEMs operate at a chamber pressure of \(\sim 10^{-5}\) Torr. Even at these low pressures the carbonaceous film growth persists, manifested as a black box over the irradiated area. As a step towards reduction of this film, while CD measurement acquisition, continuous plasma cleaning of the chamber is performed. This though, needs monitoring to prevent any possible chemical reaction with the different materials in the stack. On the contrary, imaging on low vacuum conditions has been reported to result in reduction of the hydrocarbon contamination. The set of images shown in Figure 2.7 were acquired specifically as an assessment of e-beam induced contamination [52]. The sample is a chrome-on-quartz optical mask with some residues and a pit defect. The image on the left was taken first at 50kX magnification and then at 100kX where the e-beam was left for 3min to irradiate the specific area. After this, a

![Figure 2.7: Set of images of an optical mask taken as an assessment of the e-beam induced absence of contamination under low vacuum conditions.[53]](image-url)
low magnification image was taken where there is no visible contamination due to the irradiation. In addition, it appears that the residue has changed shape; it is smaller and drier due to electron exposure. Moreover, it has been well demonstrated that under low vacuum conditions etching of the specimen surface is also possible. This kind of surface modification is unacceptable for CD metrology because it could affect the SE yield of the specimen and accordingly the accuracy of the CD measurements.

Figure 2.8: Secondary electron images of a Cr-on-quartz photolithographic mask acquired as a function of decreasing magnification: (a) high magnification image of a Cr absorber line; (b) and (c) the same region imaged at progressively reduced magnification. The insets (d) and (e) are digitally enlarged regions of image (b). Region (d) corresponds to the area imaged in (a). In (c), a dark rectangle (indicated by a dotted frame) corresponds to the area of image (b). Spatial resolution within the Cr grain structure seen in (a, d, e) is shown on the images. \[P = 107 \text{ Pa}, V_0 = 14 \text{ kV}, I_0 = 76 \text{ pA}, t_D = 12 \mu \text{s}\] [54]

The issue of contamination-free imaging by electron induced carbon volatilization, a process that competes with film growth in low vacuum SEM, has been recently addressed. Toth et al. [54] showed that contamination buildup and surface cleaning occur under conditions of low and high electron flux respectively. This effect is well demonstrated in Figure 2.8a-c where SE images of a fixed region of a Cr-on-
quartz mask were acquired at successively reduced magnification. Figure 2.8c contains a dark rectangle corresponding to the area in (b) suggesting a carbonaceous film growth caused by electron irradiation. On the contrary, acquisition of image (a) did not produce an analogous rectangle suggesting a reduced film growth at elevated magnifications. For this work, a previous model was implemented and it predicted that contamination built up is eliminated at a sufficiently high electron flux.

It is noted that even though the hydrocarbon concentration is not well controlled it is accepted that imaging under the beam currents, dwell times, and magnifications typically used for high-resolution ESEM imaging yields no net significant contamination effects in low vacuum electron images. In cases where contamination is observed, the carbon volatilization rate can be increased by increasing the electron flux.

2.3.5 Bandwidth limitation

In a low vacuum SEM chamber, most ions are generated near the anode and travel to surrounding surfaces prior to recombination. Relative to the electrons, the ions drift ~3 times slower [75], and since, in principle, the detection mechanism is based on total charge induction, their corresponding transit time confines the effective bandwidth of gas cascade induced signal detectors, and limits the minimum pixel dwell time needed to suppress image smearing artifacts. Dependencies of ion lifetime on detector and image acquisition parameters and sample charging have not been characterized in the past. An understanding of ion kinetics is needed to elucidate the fundamental limits and improve the performance of current low vacuum detectors. Bandwidth issues are not explicitly dealt with at this thesis, and the detector structure discussion is confined to a region where the pixel dwell time rises above the ion transit limit.
2.3.6 Gas considerations

It this study, the primary amplification medium used, both for the theoretical work and experimental measurements, is water vapor. Water exhibits one of the highest amplification efficiencies of any pure gas [76], while due to the complexity of its molecule, it provides self-regulating mechanisms for absorption of secondary electron emission processes, such as Auger electron emission, which leads to stable imaging and limits the pre-breakdown phenomena. Another advantage it offers is its compatibility for many in situ experiments involving hydration, dehydration, and wet-sample imaging. For the purposes of this thesis though, water vapor is solely used as a stabilizer of the surface charge accumulation of non-conductive specimens as well as an efficient amplification medium. For semiconductor industry applications, the specimen chamber environment is kept in the pressure range of 0.1-1.5 Torr of water vapor.

Recently, a study has surfaced by Bruley et al. involving Cr migration of 193nm binary photolithographic masks (the sample under study)[77]. This has appeared as a new type of degradation of chrome-on-glass (COG) masks for in-line wafer processing. Four elements were identified as possible candidates for this failure; the presence of Cr, 193nm light exposure, charge, and water vapor. It has concluded that since the first three are unavoidable, controlling Cr migration lies in controlling the ambient humidity. In addition, their results showed that the presence of water facilitates the migration of the highest Cr oxidation state (CrVI), the mechanism proposed for the oxide formation.

Thus far, there has been no report of such a failure taking place in while mask inspection in a low vacuum instrument. Nevertheless, the behavior of alternative gases is also included in this research, insofar as the gain and noise characteristics for the
high-resolution low vacuum detector are concerned, and their effect is studied quantitatively at chapter 5.

2.4 Summary

This chapter has presented background information on the fundamental aspects of critical dimension scanning electron microscopy. Low vacuum SEM (LVSEM) has been presented as an alternative high-resolution, artifact-free, next generation approach for CD metrology. The basics of the technique have been reviewed and the fundamental implementation challenges have been outlined. The discussion continues with a complete analytical description of the signal and noise characteristics as encountered in different secondary electron detector configuration in LVSEM.
CHAPTER 3

ENVIRONMENTAL SECONDARY ELECTRON DETECTOR (ESD)

3.0 Introduction

This chapter focuses on the stochastic nature of the gas cascade multiplication in the Townsend’s discharge region, which introduces noise as a result of randomness in the positions at which free electrons are generated. This noise is in addition to the usual shot noise stemming from the Poisson nature of the emission of electrons, and the electronic noise of the circuitry used to post-amplify the detected signal (as in a conventional SEM). Thus, in the following, analytical expressions for the total noise are developed and their dependencies on instrument operating parameters, including gas pressure, beam energy and sample-detector separation are discussed. The analysis yields a predictive model of the signal-to-noise ratio (SNR) for a gas cascade generated by a constant electric field (i.e., a steady-state gas cascade) [82]. Furthermore, a method for measuring noise directly at the output of the pre-amplifier is established. Finally, the modeling results are compared to experimental measurements of signal and noise dependencies on LVSEM operating parameters. The model predicts well the trends in the experimental data, and hence, enables optimization of the LVSEM imaging process and analysis of its stochastic nature.

vi Analytical and Monte Carlo models of the LVSEM imaging signal for the detector geometry discussed in this chapter are described in the literature [55, 56, 78-81].
3.1 Detector Specifics

3.1.1 Overall gas cascade ionization process

The most common detector configuration in ESEM consists of a positively biased electrode positioned directly above the specimen, to create an approximately constant electric field between the point of secondary electron (SE) emission on the specimen and the anode, schematically illustrated in Figure 3.1. This parallel plate scheme is widely known as the Townsend gas capacitor structure, named after John S. Townsend who first studied the ionization of gases in this parallel plate configuration [83]. When an electron moves between these two plates, in the presence of gas, it is likely to excite or ionize the gas molecules by collisions providing its energy exceeds the ionization threshold of the gas. The presence of the electric field, directed towards the specimen, leads to a unilateral gain by impact ionization between electrons and molecules whereas the excited atoms travel the gap distance unaffected by the field.

Figure 3.1: Schematic diagram of the anode-specimen configuration under study. Also shown are the ionizing collisions inside the gas-filled specimen chamber. A: ionizing events caused by secondary electrons emitted from the specimen; B: gas cascade multiplication; C: ionization caused by backscattered electrons; D: ionization caused by primary electrons.
Cascade multiplication takes place in regions where free charge carriers (electrons) have sufficient kinetic energy to ionize gas molecules. Any initial electron (considered as the ancestor) moving along the gap distance $d$, produces $\alpha$ daughter electrons and $\alpha$ positive ions per unit length via impact ionization events. The offspring, electrons and ions, are subsequently separated by the field and move in opposite directions. The electrons can, by a sequence of collisions, be multiplied a number of times, whereas the slow moving, heavy ions never reach the ionization energy needed to ionize the gas, and therefore do not contribute to impact ionization. If the distance between the electrodes is equal to a few electronic mean free paths, an electron produces $\alpha d$ ionizing collisions and since one electron produces one new electron per impact, the total number of electrons at the collector electrode is $2^\alpha d$. However, in the real case, the number of mean free paths is sufficiently large and distributed, thus ionization is treated as a continuous phenomenon. Then, under steady-state conditions, the increase in the number of ion pairs along an element of length $dx$ is $\alpha dx$ per electron, and for $N_x$ electrons at $x$ we have [58]

$$dN = N_x \alpha dx$$

(3.1)

By integrating through the gap distance, an expression for the total number of electrons $N$, which directly corresponds to the total amplified current $I$ [55, 58] gives:

$$\frac{N}{N_c} = \frac{I}{I_c} = \exp(\alpha d)$$

(3.2)

where $I_c$ is the initial current entering the cascade region.
Correspondingly, the multiplication factor $M_{SE}$ (i.e., gain) for secondary electrons (SEs) escaping the specimen’s surface upon e-beam irradiation and traversing a gap distance $d$, takes the form [20, 55, 56, 58]

$$M_{SE} = \exp(\alpha d)$$

and the total SE amplified current is

$$I_{SE} = \delta I_0 \exp(\alpha d)$$

where $\delta$ is the SE emission coefficient and $I_0$ is the primary beam current.

The ionization process for PEs and BSEs is somewhat different. If each primary electron generates $S_{PE}$ ion pairs per unit path length and pressure, the ionizing action of $I_0$ will produce an increment of electron current $dI_{PE}(x')$ at each point $x'$, at the opposite direction from $x$, along the gas-path-length $l$, where

$$dI_{PE}(x') = -I_0 S_{PE} P d x'$$

The electrons in this increment will then be subject to the multiplication process represented by Equation (3.3), so that, if they are considered to get accelerated by the field from $x'$ to $x$, the increment at $x$ takes the form

$$dI_{PE}(x) = -I_0 S_{PE} P d x' \exp[\alpha(x-x')]$$

The multiplication process extends to $x=d$, while the ionization path of the primary beam extends from $x'=l$ to $x'=0$. Thus, under saturation conditions, the total PE amplified current reaching the anode is

$$I_{PE} = [I_0 S_{PE} P l] \frac{\exp(\alpha d - 1)}{\alpha d}$$
The first term represents the PE-initiated current and the second term represents the PE multiplication gain\textsuperscript{vii}.

Assuming the back-scattered electrons traverse the same path length $l$ as the one covered by the PEs in the opposite direction\textsuperscript{viii}, with an entirely similar ionizing effect along the cascade distance $d$. Hence, Equation (3.7) is used to obtain the corresponding current by replacing the ionization efficiency to $S_{BSE}$, appropriate for the lower energy BSEs\textsuperscript{ix}, and initiated BSE current with $\eta I_0$, where $\eta$ is the BSE emission coefficient. Therefore

$$I_{PE} = [\eta I_0 S_{BSE} P I \left[ \frac{\exp(\alpha d - 1)}{\alpha d} \right] $$

\textbf{3.1.2 Ionization efficiency characteristics}

Townsend’s first ionization coefficient $\alpha$ is defined as the mean number of ionizing collisions per unit distance traversed by a carrier drifting under the influence of a constant electric field. Typically, the ionization efficiency in the gap is perceived in three discrete stages [79], as demonstrated by the qualitative ionization curve of Figure 3.2. At the first stage, no ionization events are likely to occur; this is usually referred to as dead space. This distance corresponds to the path the average electron has to travel under the influence of the electric field in order to surpass the ionization threshold of

\textsuperscript{vii} The PE (and BSE) gain is one electron less than the SE cascade since no ancestor electron is needed to trigger the process.

\textsuperscript{viii} In practice, $l$, the PE path length equals the minimum BSE ionizing distance, since the BSE’s high scattering angle elongates its ionizing path.

\textsuperscript{ix} A good approximation yields the average BSE energy to be close to 2/3 of that of the PEs.
the gas. The second stage, the sick space, is characterized by an increasing number of electrons exceeding the ionization threshold and a corresponding rise in the ionization efficiency. At this stage, the kinetic energy of the electrons, acquired by the electric field, prevails over the stopping power of the gas and the ionization probability continually increases. The extent of the sick space can vary from a few percent of the gap distance to the entire cascade region. Under specific operating parameters, the last stage, region III, is realized. At this point, the increasing kinetic energy of the electrons, as imparted by the potential difference between the electrodes, is equilibrated by the opposing force exerted on them by the stopping power of the gas leading to a steady-state distribution of kinetic energies, i.e. swarm conditions, and the ionization efficiency saturates accordingly. An analytical expression for the complete energy range is not available, however, in the case of constant electric field, i.e. position-independent ionization efficiency, von Engel has analytically approximated its value [58]. Thus, for a given field strength, $E$, $\alpha$ is determined by the gas pressure, $P$, and gas type according to:

![Figure 3.2: Qualitative ionization efficiency curve as a function of position in the gap for intermediate gas pressure showing the different ionizing regimes. Region I: no ionizations; Region II: increasing ionization efficiency; Region III: constant ionization, i.e. swarm conditions.](image-url)
\[
\frac{\alpha}{P} = A \exp \left( -\frac{B}{E/P} \right)
\]  

(3.9)

where \( A \) and \( B \) are gas-specific constants defined as:

\[
A = \frac{1}{\lambda_i} \quad \& \quad B = \frac{V_i}{\lambda_i}
\]  

(3.10a&b)

where \( \lambda_i \) is the mean free path of inelastic scattering of an electron in the gas at 1 Torr, and \( V_i \) is the ionization energy of the gas in eV. Thus, the average amplification can be predicted by combining Eqs. (3.3) and (3.4), for a given set of parameters, in the range of validity of \( A \) and \( B \), before breakdown occurs.

3.2 Analytical Model of Noise

A model of noise in LVSEM must incorporate contributions from shot noise in the incident beam, electron emission processes, the gas cascade amplification process, and detector electronics. In the following, each contributing process is analytically described. At the end of this section, a comparison in terms of the excess noise factor

\[ x \]

Von Engel [58] states the range of pressure-field combinations for which Eq. (3.9) is valid, and the measured \( A \) and \( B \) values for this range. Although LVSEM is not restricted in this range, corrections to the values of the gas-specific constants for the conditions encountered in low vacuum SEM are reported in the literature by Thiel et al. [79] and Thiel [56].

\[ xi \]

Typically, low vacuum operation is restricted to a region where the effects of secondary processes required to produce breakdown is not pronounced, therefore these effects are not included in the present analysis.
figure of merit of the analytical model, which assumes steady-state conditions, with its value as, derived from first principles physics and branching process statistics is given.

### 3.2.1 Beam shot noise

Walter Schottky in 1918 predicted that a vacuum tube would exhibit time-dependent current fluctuations due to the discreteness of the electrical charge [84]. He drew the analogy between electrons and the small pellets of lead that the hunters use for a single charge of a gun, hence the term shot noise. In any electron microscope, electrons are emitted by the cathode randomly and independently, and arrive at the sample surface with the same statistics. Assuming that the electron arrival events are uncorrelated, the current is described by a Poisson process with the property that the mean squared fluctuation of the number of emission events is equal to the average count. Thus, classical shot noise in the primary beam is given by [32, 85]

\[
N_B = (2eI_o b)^{0.5}
\]

(3.11)

where \( e \) is the electron charge, \( I_o \) is the primary beam current and \( b \) is the signal bandwidth. The factor of 2 appears because positive and negative frequencies contribute identically.

Current stability considerations are ignored in the present analysis. Generally, excess noise can come about via work function fluctuations of the Schottky emitter caused by absorption/desorption of gas molecules [86]. However, the cathode in the system under study is well isolated from the high-pressure specimen chamber, and is kept at ultra high vacuum on the order of \( 5 \times 10^{-10} \) Torr (at pressures >10^{-8} Torr residual gas absorption is negligible).
3.2.2 BSE and SE emission statistics

The first step of the electron cascade is the electron-specimen interaction [27]. The emission probability of backscattered electrons is described by a binomial distribution, *i.e.* each primary electron is either absorbed or backscattered. The cascade of the Poisson distribution of the PE and the binomial distribution of the BSE becomes Poisson leading to a noise amplitude of the form:

\[ n_{\text{BSE}} = (2e \eta \sigma_b)^{0.5} \]  

(3.12)

where \( \eta \) is the backscattered electron yield.

Conversely, the emission probability of secondary electrons is not binomial since a single PE can excite zero, one or more SEs with decreasing probability\(^{xii}\). Even though the distribution of the SEs is not entirely random, a good approximation yields a Poisson distribution, and the noise amplitude takes the form:

\[ n_{\text{SE}} = [2e(\delta(\delta + 1)I_o b)^{0.5} \]  

(3.13)

where \( \delta \) is the secondary electron yield.

3.2.3 Gas cascade statistics

The secondary electron emission current from the primary beam impact point is amplified according to Eq. (3.3). However, there are several other contributions to the total cascade current, including those initiated by ionization events in the gas by primary and backscattered electrons. Finally, there is a background contribution generated by the so-called electron skirt that surrounds the primary beam (introduced at \( \sigma_b \)).

\(^{xii}\) For example, two SEs can be created by the PE and its BSE trajectory through the surface exit depth.
When determining the signal-to-noise ratio of the contrast-carrying component of secondary or backscattered electron images, the background and all the remaining signal contributions must be subtracted from the total cascade current. However, all of these processes contribute to noise in the imaging signal. The noise characteristics of gas cascade amplification will be statistically similar for all contributions (PEs, BSEs, and SEs).

A. Cascade noise approach

The only previous work involving LVSEM noise characteristics was done by Durkin and Shah in the early days of the technique [87]. Their hypothesis was that the cascade statistics could be modeled with equations similar to those used in avalanche photodiodes (APDs)\textsuperscript{xiii}. Although their approach provided some useful insights, the experimental proof had complications due to the use of nitrogen gas. Nitrogen gas gives rise to significant secondary ionization effects in discharge processes. That is, photoelectrons and Auger electrons can be generated when the N$_2^+$ ions neutralize at chamber surfaces [58]. These electrons can also participate in the cascade process, adding to the ionization current and producing additional ions. If this feedback process is sufficiently efficient, the nonlinear effects can dominate both the amplification and noise behavior of the gas cascade. In this work, the amplifying gas is water vapor, which, due to its molecular complexity, has additional mechanisms for internally absorbing the excitation energy resulting in a negligible secondary ionization coefficient [58]. In addition, Durkin and Shah incorrectly used the noise statistics of the

\textsuperscript{xiii} A review on the theory of APDs can be sought at Refs. [88, 89]
conventional avalanche photodiode (CAPD) to model those of the LVSEM chamber. In such a diode, both holes and electrons have the capability of impact ionization, with equal ionization efficiencies. However, in a low vacuum SEM only electrons contribute to the cascade process; positive ions do not gain enough energy to cause further ionization effects [58]. Hence, in our approach, the noise statistics of the single carrier initiated/single carrier multiplied APD are employed.

Following the approach of Durkin and Shah [87], we employ McIntyre’s equations for calculating noise in avalanche photodiodes [90, 91]. This is expected to be a good estimate since the physical process of gas ionization in the presence of an electric field is similar to that of electron-hole pair production in an avalanche photodiode. Accordingly, the multiplication noise $N$ is given by:

$$N = \left(M^2 F\right)^{0.5}$$

(3.14)

where $M$ is the multiplication factor (nominal gain), and $F$ is the excess noise factor (gain uncertainty).

**B. Excess noise factor statistic**

The excess noise factor represents the statistical fluctuations in the gain that introduce multiplicative noise [92]. In cascade amplification of SE signals, this phenomenon is easily understood by considering the gain histogram generated by a Monte Carlo simulation of the amplification process [79]. Figure 3.3 depicts the histograms for three different nominal gains achieved by simulating three different pressures with identical electric field strengths. The histograms show the distribution of actual gains realized by 10,000 individual secondary electrons emitted from a specimen surface. Because the ionization collisions are stochastic in nature, not all electrons
produce an identical number of daughters. While the ensemble average gain is well defined, some electrons produce several times more daughters than the average, while others only produce a small fraction. This translates into spurious variation in the signal current equating to noise. Thus, a broader distribution equates to increased noise. As the average gain increases, so does the breadth of the distribution, consistent with Eq. (3.14). (Note that this analysis does not take recombination of daughter electrons and ions into account [21, 58, 93, 94].)

McIntyre’s theory was developed for avalanching in a uniformly multiplying p-n junction where only one type of carrier (electron or hole) is injected into the depletion layer, but both carriers are capable of impact ionization. In LVSEM, electrons are the only type of carrier that has the capacity for impact ionization. Ionized gas molecules do
not obtain enough kinetic energy to ionize the gas [58]. For this reason, McIntyre’s theory will be reduced to the case of single carrier initiated/single carrier multiplied (SCISCM) avalanche photodiode. This provides the lowest possible noise for the diodes [95].

Under SCISCM conditions at high average gain, the gain distribution is well described by a Gaussian, as can be seen in the histograms presented in Figure 3.3. By definition, the width of the distribution at $e^{-1}$ is $2\sigma$, where $\sigma$ is its standard deviation. This is mathematically equivalent to the conventional root-mean-square measure of noise riding on a modulating signal. As amplification approaches unity, however, the distribution necessarily becomes asymmetric, and in the limiting case, the width approaches unity. Thus, the excess noise factor in Eq. (3.14) is a measure of the extent to which the gain distribution is described by a Gaussian. Under SCISCM conditions, $F_e$ takes the form:

$$F_e = 2 - \frac{1}{M} \quad (3.15)$$

C. Individual cascade noise components

Excess noise in the gas amplification process is generated by all amplified signal components, involving SEs, backscattered electrons (BSEs) and primary electrons (PEs). As described earlier, Moncrieff et al. have derived expressions for the amplified current of each component [55]. Thus, combining Equations (3.14) and (3.15), using each cascaded current [Eqs. (3.4), (3.7) and (3.8)], and correcting for the noise statistics of each emission process [Eqs. (3.11)-(3.13)], gives three equations for the secondary, backscattered and primary electron contributions to noise:
\[
N_{SE} = \left[ 2eI_0 b (\delta (\delta + 1)) \exp(\alpha d) (2 \exp(\alpha d) - 1) \right]^{0.5}
\]  
(3.16)

\[
N_{BSE} = \left[ 2eI_0 b \eta S_{BSE} P_l \left( \frac{\exp(\alpha d) - 1}{\alpha d} \right) \left( \frac{2}{\exp(\alpha d) - 1} - 1 \right) \right]^{0.5}
\]  
(3.17)

\[
N_{PE} = \left[ 2eI_0 b S_{PE} P_l \left( \frac{\exp(\alpha d) - 1}{\alpha d} \right) \left( \frac{2}{\exp(\alpha d) - 1} - 1 \right) \right]^{0.5}
\]  
(3.18)

$l$ and $d$, the actual electron path length in the gas and the cascade distance (approximated by the sample-anode gap) are assumed identical for the particular detector configuration under study (illustrated schematically in Figure 3.1). For simplicity, both values will be referred to as anode-specimen separation, $d$, in the following discussions.

### 3.2.4 Thermal noise of the detection system

Thermal noise, also known as Johnson-Nyquist noise after the two physicists who first studied it in a quantitative way, involves the fluctuating voltage over a conductor [96, 97]. In the electronic circuitry connected at the output of the cascade generated current, the resistors in the pre-amplifier define the lower limit of the signal that can be resolved. The spectral density of the thermal noise is the mean-squared current fluctuation per unit bandwidth $b$, and is described by

\[
N_{DE} = \left( 4kTb/R \right)^{0.5}
\]  
(3.19)
where \( k \) is Boltzmann’s constant, \( T \) is the temperature, and \( R \) is the effective resistance in the electronic circuit.

### 3.2.5 Total signal and noise formulas

The total noise involves the statistical summation of all contributions [85]. The cascade noise components add linearly since they are independent of each other, while the beam and detector noise add in quadrature, since the pre-amplifier is connected to the gas cascade amplifier in series:

\[
N = \left[ N_B^2 + (N_{SE} + N_{BSE} + N_{PE})^2 + N_{DE}^2 \right]^{0.5}
\]  

(3.20)

The above equation collates the modeled noise processes in the linear cascade in a LVSEM. Conversely, the signal expected to reach the anode includes all SEs (including those generated by the skirt since the scattered primary beam electrons will also create SEs when striking the specimen, which will inevitably enter the cascade and contribute to the background signal), BSEs and PEs. The equation describing the total signal is:

\[
I = \left( \delta \exp(\alpha d) + \frac{\eta S_{BSE} P}{\alpha} \exp(\alpha d - 1) + \frac{S_{PE} P}{\alpha} \exp(\alpha d - 1) \right) I_o
\]  

(3.21)

For the model calculations both SE and BSE yield coefficients were taken from a web-based database [98], described in Ref. [99]. In some cases, it was necessary to extrapolate the values to higher energies. The relevant electron-scattering cross sections were taken from a review paper [60]. All model input data are shown in Table 3.1.
Table 3.1: Input data for ESD™ model calculations of the Cu target. The gas fitting parameters and the cross-sections correspond to water vapor.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE yield[98]</td>
<td>δ</td>
<td>0.3 for 15keV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2 for 30keV</td>
<td></td>
</tr>
<tr>
<td>BSE yield[98]</td>
<td>η</td>
<td>0.32 for all energies</td>
<td></td>
</tr>
<tr>
<td>gas fitting parameters</td>
<td>A</td>
<td>1.0</td>
<td>events Torr⁻¹ mm⁻¹</td>
</tr>
<tr>
<td>[56]</td>
<td>B</td>
<td>21.6</td>
<td>Volts Torr⁻¹ mm⁻¹</td>
</tr>
<tr>
<td>total scattering x-section [60]</td>
<td>Q(E₀)</td>
<td>0.12 for 15keV</td>
<td>mm⁻¹ Torr⁻¹</td>
</tr>
<tr>
<td>PE ionization efficiency</td>
<td>Sₚₑ</td>
<td>Q(E₀)</td>
<td>mm⁻¹ Torr⁻¹</td>
</tr>
<tr>
<td>BSE ionization efficiency</td>
<td>Sₑₑₑ</td>
<td>Q(²/₃E₀)</td>
<td>mm⁻¹ Torr⁻¹</td>
</tr>
<tr>
<td>bandwidth</td>
<td>b</td>
<td>1 for all noise data</td>
<td>Hz</td>
</tr>
</tbody>
</table>

Eqs. (3.20) and (3.21) were used to construct the examples of predicted signal current and noise contributions shown in Figure 3.4. For this typical range of imaging conditions, gain increases as a function of pressure for fixed anode bias and working distance, and the amplified secondary electron current comprises the most significant contribution to the total signal. At very low gains (pressure), the noise is dominated by the detector electronics. As gain increases, though, the excess noise from the gas cascade (dominated by the secondary electron amplification) swamps the detector contribution. The background contributions from backscattered and primary electron ionizations are about an order of magnitude lower in both the signal and noise plots. Under these conditions, the shot noise of the beam makes an insignificant contribution.
The model allows the interpretation of experimental data and can isolate the individual contributing factors to both the signal and noise.

3.2.6 Evaluation of steady-state cascade assumption

In an attempt to evaluate the \textit{a priori} assumption of steady-state conditions and position-independent ionization efficiency for the particular detector geometry, we turn to statistical theory and specifically the branching process methodology \cite{100}. The scheme of the cascade process is depicted in Figure 3.5 where \( n \) total ionizations are possible to occur in a gap distance \( d \). Prior to the statistical analysis of the stochastic ionization process, it is noted that the profile of the excess noise factor, \( F \), as predicted by the analytical model, is depicted in Figure 3.6. For deterministic amplification, as expected in the high vacuum case where gain is unity, \textit{i.e.} zero ionization events, its value is equal to one. After that, it exhibits a rapid increase for gain values up to two orders of magnitude, and for even higher nominal gain values, it saturates at 2, achieving the maximum noise case for the system.

![Figure 3.4: Modeled Signal and Noise contributions of the individual components. \([E_0=15\text{keV}, I_0=300\text{pA}, V_a=400\text{V}, \ d=5\text{mm}, \ and \ the \ noise \ is \ referenced \ to \ 1Hz \ bandwidth]\)](image-url)
The statistical discussion is based on the theory of single carrier multiplication in avalanche devices as developed by van Vliet and Rucker [101]. Their work considers the discrete statistical process that a finite number of ionizations $N$ can occur per carrier transit through an avalanche region of finite length $w$. Thus, unlike previous studies [102-104] which explicitly or tacitly assumed that the ionization efficiency is kept constant through a large avalanche region, they approached the problem from the onset of the cascade, monitoring at most one carrier ionization per primary carrier, to the drain electrode, where $N$ total daughters are carried off. Their theory relating to the one–carrier process approximates well the case of gas cascade amplification where swarm conditions are attained only for a fraction of the cascade distance. Considering the multiplication process as depicted in Figure 3.5, let $m_n$ represent the size of the $n$th generation (i.e. total number of offspring of the $(n-1)$th generation). If $y_i$ represents the number of offspring of the $i$th number of the $n$th generation, then
\[ m_{n+1} = \sum_{i=1}^{\infty} y_i = M. \]  

(3.22)

The distribution is given by:

\[ p_n = P\{\text{an individual } n \text{ daughters}\} \geq 0, \]

and the generating function

\[ P(z) = \Phi_n(z) = \sum_{n}^{\infty} p_n z^n. \]  

(3.23)

We denote \( X \) the tree of the total branching process and by considering all subtrees arising from the first, second, \( \ldots, n \)th ionization event of the incoming carrier as \( y_n, y_{n-1}, \ldots, y_1 \) we have:

\[ X_n = 1 + p_1 + p_2 + \ldots + p_n \quad \text{and} \]

\[ X_n = 1 + y_n + y_{n-1} + \ldots + y_1. \]  

(3.24)

(3.25)

We note that there is no correlation between the position of each subtree or their ionization efficiency. Therefore, we assume that each branch, fed by a Bernoulli trial [105], has an ionization probability \( \gamma_i \) where \( i = 1, 2, \ldots, n \). Following van Vliet’s analysis, we conclude on the recurrent relationship of the form:

\[ \phi_{n-i+1}(z) = \phi_{n-i}(z)[\gamma_i \phi_{n-i+1}(z) - \gamma_i + 1]. \]  

(3.26)

By differentiating and applying the appropriate boundary conditions, the analysis for multiplication for position dependent ionization probability yields:

\[ M = \prod_{i=1}^{n}(1 + \gamma_i). \]  

(3.27)
where $\gamma_i = \alpha_i \lambda_i$, the product of the ionization probability per unit length, a.k.a. $\alpha(x_i)$, times the mean-free-path required for the ionization to occur. Also, it follows that

$$\sum_{i=1}^{n} \lambda_i = d$$

where $d$ is the cascade distance. For $n=1$, we have:

$$M = (1 + \gamma_1)^n = (1 + \alpha_i d)$$ \hspace{1cm} (3.28)

For swarm conditions we get:

$$M = \lim_{n \to \infty} \left(1 + \frac{\alpha_i d}{n}\right)^n = \exp(\alpha d),$$ \hspace{1cm} (3.29)

as predicted by Eq.(3.2). 

In the literature, an analytical description for the position dependent mean-free-path is non-existent. Thus, we base the discussion on the ionization cross-sections for water vapor. A collision between a SE and a gas molecule leads to an ionizing event if the energy of the electron exceeds the ionization threshold of the gas. For water vapor, the ionization potential ($V_i$) is 12.6 V[60]. For a single ionization event ($n=1$), we approximate the collision energy of the electron to ~200 eV, considering 400 Volts potential across the parallel electrodes. According to ionization cross-section data,[60] graphically represented in the inset of Figure 3.6, the electron’s mean-free-path upon the onset of the cascade is determined to be ~$(1.54 \text{ Å})^{-1}$, whereas for swarm conditions we assume a mean electron energy of ~20 eV, leading to $\lambda = (0.5 \text{ Å})^{-1}$. Correspondingly, two points are included Figure 3.6 to represent the mfp position dependent calculation of the excess noise factor as a function of the average gain. The result indicates that the analytical approach, although it does not include the effects of dead and sick space, approximates well the position dependent ionization probability [106]. Hence, the
statistical weight of the electrons that do not possess enough energy to impact ionize is not significant for the case of a uniform electric field across the cascade region (for the conditions encountered in low vacuum imaging). In other words, the assumption of swarm conditions for the gas cascade amplification in constant electric field is an excellent approximation.

Figure 3.6: Excess noise factor ($F$) as a function of the average gain analytically modeled from the Monte Carlo distributions (line) and calculated through the mean-free-path position dependent theory (solid circles). Also shown the high vacuum case where deterministic amplification occurs. Inset: Ionization cross-section curve for water vapor [60] used for the mean-free-path calculation.

### 3.3 Experimental Procedure

#### 3.3.1 Modified detector structure and sample

Experimental data were acquired using an FEI Nova NanoSEM 600. In such an instrument, in normal operation mode, the highest pressure that can be achieved is 1.5 Torr (water vapor was the amplification medium). This upper limit is set by the
dimensions of the final pressure-limiting aperture (attached to the detector) \textsuperscript{xiv}. Typically, the Townsend gas capacitor detector, the one under examination here, is operated at higher pressures. Hence, a modified detector was used to perform the measurements. A 200 $\mu$m aperture was attached to the bottom of a regular, radially symmetric low vacuum detector. This allowed specimen chamber pressures of up to 4 Torr whilst maintaining high and ultra-high vacuum in the mid column and the field emission electron source region, respectively.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.7.pdf}
\caption{(a) Schematic illustration of the sample-detector geometry inside the chamber and (b) the target structure adapted from Ref. \cite{56}.}
\end{figure}

The sample-detector geometry is shown in Figure 3.7(a). The target was a screened Faraday cage with a 75 $\mu$m mesh Cu TEM grid placed 200 $\mu$m above the top of a Cu rod, Figure 3.7(b). This structure was designed for characterizing LVSEM amplification profiles \cite{56} as it prevents distortion of the electric field at the beam

\textsuperscript{xiv} The diameter of the pressure limiting aperture is directly related to the field of view of the instrument. Thus, the dimensions of the PLA of commercially available detectors are optimized to provide the highest possible field of view while maintaining the necessary pressure gradient needed for stable operation of the electron emitter.
impact point. The Cu rod-grid assembly was electrically grounded and the electron beam’s focal point was set at the grid’s plane, while the beam was irradiating the surface of the Cu rod.

3.3.2 Data acquisition and conversion

The standard configuration for the FEI Nova NanoSEM involves the connection of the low vacuum detector to an electrically floating pre-amplifier for signal enhancement. The pre-amplifier output was connected in parallel to the microscope image acquisition system, a digital volt meter (RadioShack DVM, signal data acquisition), and a spectrum analyzer (Agilent E4401B, noise data acquisition). Impedance issues due to the connections were taken into account when determining the measured values.

Signal and noise were measured as a function of water vapor pressure using different operating conditions such as beam energy ($E_o$), anode-specimen separation ($d$), anode voltage ($V_a$) and beam current ($I_o$). All measurements are expressed in terms of electron current measured at the input of the pre-amplifier. The response of the pre-amplifier was calibrated prior to the measurements. This way, the output voltage values were converted to the corresponding input current rates.

3.3.3 Spectrum analysis

A spectrum analyzer was utilized for the noise measurements due to the simplicity of acquiring the data in a useful manner requiring minimum mathematical manipulation. The analyzer measures the sinusoidal signal in the frequency domain, rather than in the time domain. It splits the signal into its frequency components, by
means of Fourier transforms, permitting the recording of its spectral content, thus the
term spectrum analyzer. Noise in the spectrum appears between the signal harmonics. If
the signal-to-noise is not high enough, the noise level can be distorted. Thus, a
featureless area of the sample along with controlled beam defocusing facilitated in
elimination of any possible interference of the tails of the signal harmonics with the
overall noise level.

The spectrum analyzer implements a resolution bandwidth filter, and thus, the
magnitude (or envelope) of the signal is specified by its magnitude and phase, its real
and imaginary components\(^{\text{XV}}\). The probability density function (PDF) of each
component is Gaussian distributed, thus the histogram of the distribution of the
envelope is expected to be described by Rayleigh statistics.

The measurement of the power noise was performed in linear scale, \(i.e.\) it was a
voltage-envelope measurement. Power averaging was implemented which introduced a
consistent under-measurement of noise from squaring the average instead of averaging

\(^{\text{XV}}\) In contrast, an oscilloscope outputs a baseband signal, \(i.e.\) only its real component. This variation in the
rate of current flow is described by a Gaussian distribution.

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the square. For correction of the measured level at the output of the analyzer, the built-in noise marker function was utilized [107]. This function manipulates the measured level of the output to represent the input spectral noise density. In detail, it corrects for the under-response due to voltage-envelope detection, and it measures the average noise level referenced to an ideal 1 Hz noise power bandwidth, thus avoiding miscalculation of the system’s bandwidth xvi. Finally, it outputs a noise value in $\mu V/\sqrt{\text{Hz}}$, and provides a value proportional to the entire noise power spectrum, assuming white noise is governing our system. This assumption is confirmed by the display spectrum in a wide frequency domain, Figure 3.8.

It is noted that the specific analyzer operates in the range between 9 kHz to 1.5 GHz. This range exceeds the operating instrument’s range. For the measurements here, the scan speed of the instrument was set to 0.2 μsec per frame, both to avoid internal filtering and facilitate proper pre-amplifier response, and the resolution was 512×442 pixels per frame. These settings provide a line frequency response at ~ 10 kHz, thus operation was limited to the lower end of the analyzer.

---

xvi The bandwidth of the system, while operating in low vacuum, is limited by the ion drift to the specimen, as mentioned in chapter 2. The only reported work on this area, at least to the author’s knowledge, is by Morgan and Phillips [108]. They reported bandwidth enhancement by placing a grounded Frisch grid with 1mm wire spacing between the anode and the specimen. They evaluated this enhancement qualitatively by the lack of image smearing under high screening conditions. However, in a quantitative manner, ion drift behavior in low vacuum SEM has not been characterized as yet for any detection configuration.
3.4 Results

Experimental measurements of the total signal and noise for a range of different operating conditions were performed. The effects of beam energy ($E_o$), anode-specimen separation ($d$), anode bias ($V_a$), and beam current ($I_o$) were investigated. Figs. 6–9 compare the experimentally obtained values with the model results for the corresponding set of conditions. Signal is expressed as the cascade current (nA) in all cases, whereas the noise is in units of pA/$\sqrt{\text{Hz}}$. In the case of white noise, this value is proportional to the total power in the noise spectrum, integrated across all frequencies. Because the scaling factor is not available for these measurements (since the bandwidth of the measured data is unknown), an absolute signal-to-noise ratio cannot be determined. Consequently, this discussion will focus on the dependency of noise and relative signal-to-noise ratio on operating conditions. In addition, it is noted that concerning the amplification medium, the approach is generic. Although the signal and noise curves are calculated and measured for water vapor, a simple substitution of the gas specific constants for any other gas in the equations is sufficient for predicting its behavior.

Overall, both the signal and noise model predictions are in good agreement with the measured values. The gain profile of the linear cascade follows directly from its dependence on ionization efficiency, Eq. (3.9). The shape of the gain profile and the underlying physical phenomena have been discussed extensively elsewhere [56, 79]. To briefly summarize, total signal increases as the primary beam energy is lowered, Figure 3.9, due to an increase in the SE yield and an increase in the gas ionization efficiency of
backscattered and primary electrons, as indicated by Eqs. (3.7) and (3.8), and Table 3.1. The pressure at which maximum gain occurs is given by

$$P_{\text{max}} = \frac{V_a}{d} \frac{1}{B}$$  \hspace{1cm} (3.30)

That is, for a given gas, $P_{\text{max}}$ is linearly proportional to the electric field strength and inversely proportional to the gap distance, as can be observed in Figure 3.10. Substituting Eq. (3.30) into Eqs. (3.3) and (3.9), shows that the maximum gain is an exponential function of the anode bias only;

$$M_{\text{SE, max}} = \exp \left( 0.368 \frac{A}{B} V_a \right)$$  \hspace{1cm} (3.31)

consistent with the data shown in Figure 3.11. Finally, the total signal is proportional to the incident current (Eq. (3.21) as seen in Figure 3.12 (again, noting that sub-linear electron-ion recombination effects are negligible [21, 58]). The noise only increases as the square-root of the current, thus the SNR also increases as the square root of the beam current, as is typical.
Figure 3.10: Signal and Noise as a function of pressure for different anode-specimen separations. \([E_0=15\text{keV}, I_0=100\text{pA}, V_a=400\text{V}]\)

Figure 3.11: Signal and Noise as a function of pressure for different anode biases. \([E_0=15\text{keV}, I_0=100\text{pA}, d=5\text{mm}]\)
The measured noise behavior follows the model predictions very closely for all conditions, validating the approach. Furthermore, both modeled and experimental noise curves track very closely with the gain behavior, suggesting that they are intimately linked. This is consistent with the contention that under most conditions, the excess noise factor dominates total noise, as predicted by Eqs. (3.14) and (3.15). From the preceding observations, we conclude that the model, presented here, for predicting noise and gain accurately represents the processes taking place in the signal chain, and therefore is a valid tool for understanding and optimizing imaging conditions.

3.5 Discussion

The signal-to-noise ratio (SNR) provides a useful figure of merit for describing the performance of any imaging system, and allows assessment of the role of different operating conditions on image quality. Having proven the validity of the models for signal and noise in the previous section, the model is now used to predict trends in the SNR in an effort to optimize imaging for the vast operating parameter space of LVSEM.

The total cascade current reaching the detector, as described by Eq. (3.21), contains a significant background component in addition to the amplified secondary electron signal that is desired for imaging. Both background and SE amplification processes contribute to total noise, but it is only the SE signal riding above the background relative to the total noise that gives rise to the desired image contrast. Furthermore, secondary electrons generated by primary electrons in the skirt (defined in chapter 2, Eq. (2.4)) contribute to the background and not the desired SE signal. For
most operating conditions, increasing the pressure causes an increase in the cascade current through increased gain, but the SE to background ratio decreases as more and more primary electrons are scattered into the skirt. Figure 3.13 illustrates this situation, comparing the predicted signal-to-noise ratio (SNR) of the total signal with the SNR of the desired SE component, that is, just the amplified signal derived from secondary electrons emitted from the nominal beam impact point at the sample surface and not the skirt. The inset shows the individual signal and noise components making up the

Figure 3.13: Signal-to-noise ratio (SNR) as a function of pressure ($E_0=15\text{keV}$, $I_0=200\text{pA}$, $V_a=400\text{V}$, $d=5\text{mm}$), calculated for the total signal reaching the anode (black solid line) and for the SE contrast-carrying imaging signal component (red dashed line). The inset shows the calculated signal and noise distributions used to generate the SNR curves.

SNR curves. Both SNR curves show a rapid increase with pressure up to approximately 1 Torr. At higher pressures, the SNR of the total signal continues to increase, while the SNR for the SE signal begins to diminish as the skirt starts to dominate the pressure dependence of the SE signal. At very low pressures ($<< 1\text{ Torr}$) the gain is poor due to a
reduced ionization frequency (i.e., the cascading electrons do not reach a steady-state swarm condition [58, 79]), and electronic pre-amplifier noise is the dominant noise component. The curves also predict the maximum to be located at lower pressure for the desired SE amplified SNR, finding that agrees with the established operating procedure of working just below the apparent amplification maximum [78].

The signal-to-noise ratio is a function of nearly all of the instrument parameters available to the user. However, optimizing the operating conditions in practice can be greatly simplified through the use of a master curve and applying a few simple scaling rules. A master curve is facilitated by noting that pressure and anode-specimen separation are nearly always present as a product. This reciprocity has been discussed and demonstrated elsewhere [56]. For example, both the fraction of electrons scattered into the skirt, and the gain realized by the cascade can be kept constant over a range of pressures so long as the anode-specimen distance is adjusted appropriately. Figure 3.14 shows the predicted SNR as a function of the pressure – anode-specimen separation product for several anode biases. With this graph, the SNR can be found for any combination of pressure and distance. As anode bias is increased, the SNR also increases, but rapidly saturates as the value approaches 500V. Scaling with beam

![Figure 3.14: Modeled SE amplified SNR plotted as a function of the pressure – anode-specimen distance product for a number of anode biases. \(E_0=15\text{keV}, I_0=100\text{pA}\) ](image)

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current is accomplished by noting that these SNR values have been determined for 100 pA and recalling that SNR increases as the square root of the current. Changes in beam energy have a minimal impact, as the chief effects are changes in the secondary emission coefficient and both the elastic and inelastic scattering coefficients of the high-energy electrons contributing to the background. The values associated with these processes change slowly with beam energy and tend to offset each other’s effects on the SNR.

3.6 Summary

In this chapter, the noise statistics of gas cascade amplified signals in low vacuum SEM have been linked with gas gain behavior, which is influenced by LVSEM operating parameters. The model of noise presented here for the Townsend’s discharge region has been experimentally verified and can be used as an effective tool for optimizing imaging conditions and analyzing signal data. Of particular note are two findings. First, for moderate to high gas gain conditions, the signal-to-noise ratio of the cascade process is a constant, dominated by the excess noise associated with this stochastic phenomenon. Second, the signal-to-noise ratio and overall image quality decrease as the pressure – anode-specimen separation product is increased, due in part to scattering of primary electrons into the skirt, and in part to an increase in the noise component from background processes such as primary electron ionization of the gas. The discussion continues on the signal and noise characteristics of non-uniform electromagnetic field-assisted gas cascade amplification.
CHAPTER 4
LOW VACUUM IMMERSION LENS DETECTOR (HELIX™)

4.0 Introduction

An optimized detection system for high resolution, low vacuum, charging and distortion-free imaging has been described by Thiel et al. [109]. Its capability for high gas cascade amplification current and self-regulating positive ion flux reaching the specimen surface while operating at low working distances and low accelerating voltage, has enabled critical dimension low vacuum SEM applications. In the following, the commercial implemented configuration is analyzed from a physical, quantitative point of view insofar as the cascade statistics as a function of operation conditions are concerned. The objective is to develop a predictive model for the performance of the structure to enable optimization of operating conditions and quantitative interpretation of image data as required for critical dimension metrology applications.
4.1 Detector Specifics

A schematic of the detector configuration is shown in Figure 4.1(a). It is attached at the bottom of the pole piece, which is considered zero working distance ($z=0$). The sample is placed at $z=WD$, which is regarded as the positive $z$ direction. The detector structure consists of a stack of three electrodes concentric about the optic axis ($r=0$): a grounded pressure limiting aperture (PLA) positioned inside the pole piece separates the high vacuum electron column from the low vacuum specimen chamber, a positively biased anode connected to a floating pre-amplifier is the detection electrode, and a typically grounded ion trap helps in the self-regulation of the ion current reaching the grounded specimen. These three electrodes along with the specimen’s surface create and define the electrostatic field. The numerical\textsuperscript{xvii} evaluation of the equipotential contour plot is illustrated in Figure 4.1(a) as well. The direction of the electric field alters above and below the anode plane whereas its magnitude weakly penetrates down to the specimen’s surface to attract the emitted SEs\textsuperscript{xviii}. Thus, unlike previous studied detector structures, such as the Townsend’s gas capacitor (TGC) where the electric field created is constant within the cascade region, this detection mechanism creates a more complex field structure, the properties of which define the cascade characteristics and the overall gain attributes of the system. An inspection of the potential and field for two cases, one produced along the optic axis, and one confined radially at the anode plane yields the plots of Figure 4.1 (b) & (c) respectively. At the optic axis, the potential has a

\textsuperscript{xvii} An analytical solution of Laplace equation is not possible for the system.

\textsuperscript{xviii} Due to the short working distance and low operation pressure of the structure, the effect of the background contributions (BSEs, skirt PEs, and their ionization processes) is minimized \cite{109}. 
characteristic maximum value located approximately at the anode plane. This value is referred to as the saddle potential, $V_s$, the significance of which is demonstrated later. For the radial dimension confined at the anode plane, the potential applied at the electrode creates an electric field gradient pointing towards the optic axis. The minimum value of the potential is located at the saddle point, $V_s$. Assuming the

Figure 4.1: (a) Cross-sectional detector geometry and equipotential contour plot as created by the positively biased anode (green electrode). The top grounded blue electrode represents the PLA, and the bottom blue one is the ion trap. The specimen, also grounded, sits at the bottom edge, at $z=$WD. Numerical simulation using Quickfield of (b) on-axis $V_z$ & $E_z$ and (c) anode plane $V_r$ & $E_r$. [sample at 4.5 mm working distance]
electrodes dimensions remain constant\textsuperscript{xix}, the saddle potential is strongly dependent on the anode bias $V_a$ and weakly dependent on the working distance. Finally, the detector structure and the specimen are immersed in a magnetic field parallel to the optic axis. Its magnitude is approximately constant, at least in the anode plane\textsuperscript{xx}. Hence, along the optic axis, the electric and magnetic fields are parallel below the anode plane, and antiparallel above. Conversely, within the anode plane and away from the optic axis the fields are crossed.

The electromagnetic field structure created by the immersion lens and the biased anode governs the classical motion of the emitted secondary electrons (SEs). To study the trajectory of the electrons, an in-house Monte Carlo simulation software was used. The trajectory of a single SE from its emission point to its detection is depicted in Figure 4.2. The motion of the electron is a superposition of two harmonic oscillating modes: an axial path along the beam axis and a cycloid path following the inner curvature of the anode. In detail, when a SE is first emitted from the specimen at the beam impact point, it will accelerate in the negative $z$-direction as attracted by the saddle potential while following a helical path as imposed by the magnetic field. When it reaches the $z$ coordinate of the saddle point, it will begin decelerating until it reverses direction back towards the specimen. The electron will continue its oscillating motion

\textsuperscript{xix} All forthcoming Monte Carlo and analytical modeling related to the Helix\textsuperscript{TM} detector is performed for the dimensions of the commercially available electrode configuration. The working distance (WD) is fixed at 4.5 mm, unless otherwise specified.

\textsuperscript{xx} The immersion lens used to produce the magnetic field was designed such that its off-axis components are negligible.
until it dissipates its kinetic energy (equal to $eV_s$). At that point, the electron is redirected and confined approximately to the anode plane, as attracted by the lateral component of the electric field. The perpendicular component of the magnetic field forces the electron to a cycloidal path following the inner curvature of the anode. Accordingly, kinetic energy equal to $e(V_a-V_s)$ needs to be dissipated before the electron can be collected at the anode. At each stage, the dissipation of the energy of the particle is assumed to occur primarily through inelastic collisions with gas molecules leading to distinctive ionizing cascades. Thus, the device acts as a two-stage amplifier and as such its gas ionization behavior is comprehensively described and analytically modeled at the next section.

Figure 4.2: Monte Carlo simulation of a single SE trajectory inside the detector structure, plotted in (a) x-z plane (parallel to the beam axis) and (b) x-y plane (normal to the beam axis). (i) depicts the secondary electron emission point (specimen plane) and (ii) depicts the transition from the vertical oscillation of the axial stage to the radial oscillation of the magnetron stage (anode plane). Fig. reproduced from Ref. [109].
4.2 Analytical Model of Gain and Noise

The axial motion, confined in the optic axis, is described as a bound, harmonic oscillation with a damping factor arising from the stopping power of the gas. To describe this first stage, the term “penning” is used as the particle motion is analogous the axial motion of a particle in a Penning trap [110]. The cycloidal and magnetron motion, confined in the anode plane, arises from the influence of only the magnetic field, and the transverse magnetic and electrostatic fields. To describe this second stage, the term “magnetron” is employed in reference to the motion of a particle in a Magnetron device [111]. The frequencies of the two distinct motions are considered decoupled and therefore each stage, insofar as the gain and noise characteristics are concerned, is dealt with discretely and in order of occurrence.

![Diagram](image)

Figure 4.3: Monte Carlo simulated gain as a function of pressure for different anode biases for each stage. The values indicate the maximum magnetron ($V_m = V_a - V_s$) and penning stage ($V_p = V_s$) potential. [Simulation conditions: $V_a = 400$ V, WD = 4.5 mm, B = 0.22 T for 10,000 initial electrons]
Prior to the description of each stage, the assumption of decoupled motions is assessed by Monte Carlo (MC) simulations\textsuperscript{xxi}. The MC predictions of the average gain as a function of gas pressure for different anode biases are shown in Figure 4.3. The two behaviors exhibit different and complex dependencies on pressure, thus, gain and noise characteristics are expected to be functions of the energy partitioning between the two modes. For example, for low pressures, below 0.5 Torr, the penning amplification seems to be more efficient than the magnetron even though more energy (greater potential drop) goes into the magnetron motion. However, the ability to model adequately each motion by the Monte Carlo method, verifies the assumption of the forthcoming analysis for the device as a decoupled two-stage amplifier.

The statistics of each motion are extracted and are depicted in Figure 4.4. Considering the well-behaved gain distributions for the pressures simulated, it is evident that the behavior follows the ESD statistical characteristics, \textit{i.e.} a Poisson-like behavior for low pressures eventually evolves into a Gaussian distributed gain function. Thus, it is evaluated that the gain and noise distributions for each mode follow the avalanche statistics already employed for the case of the Townsend’s gas capacitor detector. Specifically, the average gain of the magnetron is located at lower values than the penning one, thus making the variance of the latter greater. As the pressure increases, the two modes become comparable at which point their distinctive character is lost and the two-stage amplifier is expected to reduce to a regular ESD type detector. It is noted that the peak for gain values approximately equal to 1 in the case of the penning gain statistics is an artifact of the separation of the two modes, and it arises from electrons

\textsuperscript{xxi} The MC program is capable of isolating the two modes, allowing the individual behavior to be studied.
re-directed into the magnetron stage quickly after their emission. Thus, the effect is more pronounced at higher pressures for which the electron’s axial harmonic motion is predicted to damp quickly.

Figure 4.4: Monte Carlo gain statistics for each stage for increasing gas pressure. [Simulation conditions: \( V_a=400 \text{ V}, \text{WD}=4.5 \text{ mm}, \text{Bf}=0.22 \text{ T} \) for 10,000 initial electrons]

### 4.2.1 Penning stage

**A. Motion description**

An adequate description of the penning motion as a damped harmonic oscillator is now given. The electron travels along the z-axis influenced by the parallel magnetic field and parallel and anti-parallel electrostatic field. Typically, a charged particle in a magnetic field is bound radially to a field line forcing it in a circular cyclotron orbit, but it is not bound axially, so that the slightly disturbance moves it along the field line. On the axial dimension, it is bound by the electrostatic field created by the saddle potential. Ideally, at \( r=0 \), the axial motion is considered decoupled from the magnetic field, thus the basic assumption yields that the electron travels along the optic axis parallel to the
magnetic field, and therefore it is unaffected by it. The only force exerted on the electron is due to the electric field created by the saddle potential. This acts as the restoring force in the classical harmonic oscillator expression. In addition, a frictional force exerts on the electron arising from the stopping power of the gas molecules. For the pressures encountered in Helix imaging, the motion is described as an under-damped harmonic oscillator; that is the amplitude of the oscillator gradually decreases to zero, though the electron never stops oscillating. The retardation of the electron due to inelastic encounters that produce excitation and ionization occurs in finite steps as inflicted by energy thresholds of each process. When the energy of the electron falls below the threshold energy for these processes, its distribution reaches a steady-state. The electron then suffers only elastic collisions drawing energy from the field without exchanging it with other electrons [112, 113]. At the limit of an ideal penning motion, the electron would be trapped at the equilibrium position describing an oscillating motion due to its thermal energy, unaffected by the gaseous medium.

The equation of motion of the particle in the z-direction is:

\[
F_z = -e\vec{E}(0,z) + \left( -\frac{dE}{dz} \right) \Rightarrow m \frac{d^2z}{dt^2} = -e\vec{E}(0,z) + \left( -\frac{dE}{dz} \right)
\]  

(4.1)

We consider the frequency of the oscillating motion to be symmetric about the z-axis, thus:

\[
\omega_z = \sqrt{\frac{eV_s}{mz_0^2}}
\]

(4.2)

\[\text{xxii The gas molecules are considered to be at rest.}\]
where $z_0$ denotes the maximum $z$-range of the oscillation from the equilibrium position. This is considered approximately equal to the distance between the anode plane and the specimen.

To describe the magnitude of the stopping power of the gas, $S$, we consider its dependencies on the inelastic scattering cross-section as a function of energy, $\sigma_i(E)$, corrected for their energy thresholds, $eV_i$. The expression is normalized to the density of the gas molecules, $n$, at 1 Torr. It yields:

$$S = n \sum_i eV_i \sigma_i(E) = \frac{N_A}{RT} \sum_i eV_i \sigma_i(E)$$

where $N_A$ is Avogadro’s number, $R$ is the gas constant, and $T$ is the temperature. This approach is valid by considering the electrons, and thus their retardation, as an ensemble average quantity.

At a first approximation, a linear energy term for the stopping power expression in Eq. (4.1) can be extracted from the Eq. (4.3) for the energy range 0-100 eV. However, the numerical solution of the electron’s motion for the low pressure operation mode of this detector requires consideration of the mean free path dependency of the

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xxiii An analytical description of the total cross-section of water vapor as a function of energy is not available.

xxiv It is noted that momentum transfer during ionization or the effective path length shortening due to elastic scattering is not accounted for.

xxv Assuming that the “penning” electron has at least one ionizing collision in its first swing, the probability of its energy exceeding 100 eV diminishes as the saddle potential remains below 200 V. This is true since the anode bias does not exceed 400 V in normal operation mode.
ionization probability, an attribute that is not analytically defined. Thus, the stopping power term with respect to its dependency on velocity becomes complex. Therefore, instead of explicitly solving the equation of motion, Eq. (4.1), we take a different, empirical approach by implementing the gas fitting parameters for the prediction of the overall gain of the penning stage, described below.

B. Gain characteristics

The collision process for the penning stage is considered randomly distributed and it is described by Poisson statistics. The probability of a collision \( p(i) \) leading to an ionization event depends only on the mean number of those events, \( M_p \), according to:

\[
p_n(i) = \frac{M_p^i}{i!} e^{-M_p} \quad \text{for } i = 1,2,\ldots,n
\]

The amplification of such a randomly distributed process can be considered equal to the total number of ionization events, \( n_{tot} \), times the total path length, \( L \), each electron travels until it dissipates the energy provided to the particle by the saddle potential \( V_s \).

\[
M_p = n_{tot}L
\]

In effect, the total path length, \( L \), is given by:

\[
L = \frac{eV_s}{S}
\]
where $\bar{S}$ denotes the average stopping power of the gas\textsuperscript{xxvi}.

Empirically, Eq. (4.6) can be described as a function of the gas fitting parameters $A$ and $B$, already described in chapter 3\textsuperscript{xxvii}. Accordingly, the total number of ionization events equals $A$ times the pressure, $P$, whereas the stopping power of the gas is described as the product of $B$ times the gas pressure, $P$. Implementing these two equalities and Eq. (4.6) into Eq. (4.5), the average gain for the penning stage takes the form:

$$M_p = V_s \frac{A}{B}. \quad (4.7)$$

It is independent of the gas pressure and is determined only by the saddle potential and the gas fitting parameters.

Unlike previous studies for constant electric field structures where the nominal gain has been demonstrated to have an exponential dependency on the potential driving the cascade [56], for the penning amplification this effect reduces to a linear dependency. To elucidate this difference we consider the collision probability and the kinetic energy loss of the electron. The penning process is less energetic, since it is not driven by the anode potential but by the saddle potential. This latter value is always smaller than the value of the former; thus, the average number of collisions for the penning process decreases compared to that in the conventional Townsend’s gas

\textsuperscript{xxvi} Again, a mean energy for the ionization scattering cross-section is considered for collisional events between electrons and gas molecules.

\textsuperscript{xxvii} The reader is reminded that $A$ and $B$ are related to the inelastic scattering cross-section as given by Eqs. (3.10 a&b).
capacitor model. Moreover, in the case of the penning effect, the collision probability is statistically randomized and significantly reduced due to the low gas density. Therefore, the potential driving the penning process tends to have a less dramatic effect on the dissipation of the kinetic energy of the particle when compared to the case of a uniform, steady-state cascade, as predicted by Eq. (4.7).

Already in Figure 4.3, Monte Carlo simulations for the penning gain were presented. The results predicted a diminishing dependency on pressure as the saddle potential ($V_p$ on the graph) increases. To investigate further the validity of Eq. (4.7), Monte Carlo simulations of the penning gain as a function of saddle potential for different pressures were generated, Figure 4.5. The plot indicates that the average gain of the penning stage increases linearly with saddle potential, as Eq. (4.7) predicts, and, for the pressures pertinent to an under damped harmonic oscillator, it remains constant. Thus, the empirical approach for evaluation of the penning amplification is valid.

![Figure 4.5: Monte Carlo simulated penning gain as a function of saddle potential for different gas pressures. The result confirms the empirical derived formula for the penning gain.](image)
C. Noise characteristics

Following the Poisson distributed penning amplification, the noise is expected to exhibit shot-like behavior. According to the already derived noise formula for unilateral avalanche amplification (chapter 3), the amplitude of the penning noise, $N_p$, equals

$$N_p = \left(M_p F_p\right)^{0.5}$$

(4.8)

$F_p$ denotes the excess noise factor for the penning process.

4.2.2 Magnetron stage

A. Motion description

In the $xy$ – anode plane, the plane perpendicular to the static and spatially uniform magnetic field, the electron executes a fast circular orbit with an angular, cyclotron frequency

$$\omega_c = \frac{qB}{m}$$

(4.9)

and Larmor radius

$$r_L = \frac{m v_{xy}}{eB}$$

(4.10)

The additional, transverse component of the electrostatic field created by the potential drop between the anode electrode and saddle point, forces the electron to a slow magnetron rotation along the anode periphery. The resulting compound motion has the epicycle form shown in Figure 4.6(b). The magnetron motion arises from the velocity filter that the perpendicular E and B fields impose on the particle. The expression of the drift velocity of the particle in the anode plane yields
\[ v_D = \frac{\vec{E} \times \vec{B}}{|B|^2} \]  

(4.11)

Thus, the particle moves through these fields unimpeded. Although this is strictly only true for constant fields, we can approximate it to be the case for the Helix™ since the potential close to the anode, where the magnetron motion is confined, is much higher than the average energy required for impact ionization and, at first approximation, is considered constant. Therefore, a constant drift velocity in the anode plane is considered.

Figure 4.6: Projection of the motion of an electron in the Helix™ upon the \( xy \) – anode plane. The motion is the superposition of (a) circular cyclotron and magnetron motions producing (b) epicycles. The magnetic field is directed out of the plane of the paper and the electrostatic field points towards the center of the magnetron circle. Fig. adapted from Ref. [110]

In this stage, an ionization collision between an electron (light particle) and a gas molecule (heavy particle), displaces the electron cyclotron orbit center radially outward (\( i.e. \) the magnetron radius increases) and the collision also changes the ion
cyclotron radius. The process continues until the electron strikes the detection electrode. However, the electron is not captured by the anode unless it has dissipated all its kinetic energy. Two factors need to be considered at this point. First, the electron can only further increase its magnetron orbit radius a finite number of times before it reaches the anode, and second, Monte Carlo data, Figure 4.3, revealed that even though the magnetron stage is more energetic than the penning one, its average gain is relatively low. Thus, it is predicted that in the magnetron stage non-ionizing electron energy loses are favorable. They can include elastic and inelastic collisions with other particles, such as ions and electrons, and can be justified due to the density of ions and electron cloud close to the anode.

B. Gain characteristics

The analytical description for the amplification of the magnetron stage is based on the pressure equivalent concept, as previously described by Blevin and Haydon [114] for the case of transverse magnetic and electric fields. They determined that the effect of the transverse magnetic field on the properties of the electron avalanche is primarily dependent on the variation of the mean free path with respect to the electron’s velocity. Their analysis assumed that the magnetic field does not affect the form of the velocity distribution function, but only has the effect of reducing the mean energy. This way they concluded that in crossed electric and magnetic fields the electrons behave energetically as they would if only the electric field was present and the pressure was increased from $P$ to:
\[ P_e = P \left( 1 + \frac{\omega_c^2}{\nu^2} \right)^{1/2} \]  \hspace{1cm} (4.12)

where \( \omega_c \) is the electron cyclotron frequency, given by Eq. (4.9), and \( \nu \) is the effective electron-molecule collision frequency described by the equation [115]:

\[ \nu = \frac{\nu}{\lambda_1} \]  \hspace{1cm} (4.13)

where \( \lambda_1 \) denotes the mean free path per Torr of the electron in the gas, and \( \nu \) is the electron’s velocity. The interpretation of this quantity is straightforward only for the case of a constant value. In the general case, however, it is a function of electron energy and it can only be regarded as an empiric quantity. Blevin and Haydon used the drift velocity analysis for the determination of the effective cross-section of a collision [114]. We take a different approach. We consider the electron motion to be driven by the velocity component introduced by the potential drop between the anode and the saddle point. Hence, Townsend’s first ionization coefficient takes the form:

\[ \alpha_m = A P_e \exp \left( -B \frac{P_e}{E_r} \right) \]  \hspace{1cm} (4.14)

The main effect of the pressure-equivalent concept on Townsend’s first ionization coefficient is shown in Figure 4.7. A significant enhancement is evident at low pressure, the regime of interest for the operation of the detector, whereas the effect is mitigated at elevated pressures.
Finally, integration for the total number of ionizing events in the magnetron times the distance in the anode plane the motion is confined to, $r$, yields the magnetron amplification equation:

$$M_m = \exp(\alpha_m r)$$

(4.15)

This distance is determined through Monte Carlo ionization probability plots as a function of the radial distance, Figure 4.8. The first peak close to the optic axis ($r=0$) is attributed to penning ionization whereas the magnetron ionization effectively takes place 0.5 mm away from the optic axis and it peaks very close to the anode (located at $r=1.25$ mm). The position of separation of the two motions is independent of pressure, as shown, and it is expected to be dependent primarily on the anode radius. It is reminded that the dimensions of the electrodes in the detector structure are considered constant, and thus, the radial dimension of the magnetron ionization for Eq. (4.16) is estimated to be 0.75 mm.
C. Noise characteristics

The behavior of the magnetron noise, $M_m$, renders the same statistical rules as the penning one. Therefore, it follows

$$N_m = \left( M_m F_m \right)^{0.5}$$

(4.16)

where $F_m$ denotes the excess noise factor for the magnetron process.

4.2.3 Total gain formula

The total gain of the system is simply the product of the amplification of each stage. The equation has as follows

$$M_T = M_p M_m = \left( V_s A B \right) \exp \left( AP_c \exp \left( \frac{-BP_c r}{V_s - V_s} \right) \right)$$

(4.17)

The amplification of each stage is strongly dependent on the potential feeding each motion. A graphic representation of the total modeled gain from the two distinct components as a function of anode bias is depicted in Figure 4.9. All input parameters used for model calculations are included in Table 4.1. The penning gain increases
linearly with anode bias that directly corresponds to the linear dependency on the saddle potential as predicted by Eq. (4.7). The increase of the magnetron gain shows a weaker dependence on anode bias. This is ascribed to the high potential drop between the saddle point and anode plane\textsuperscript{xxviii}. This way, the electron quickly gets attracted to the steady magnetron orbit and its collision probability will primarily depend on the gas pressure.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>magnetic field strength</td>
<td>$B$</td>
<td>0.22</td>
<td>Tesla</td>
</tr>
<tr>
<td>total mean-free-path [60]</td>
<td>$L_{\text{tot}}$</td>
<td>0.216</td>
<td>mm (at 1.0 Torr)</td>
</tr>
<tr>
<td>mean ionization energy</td>
<td>$\bar{E}$</td>
<td>25</td>
<td>eV</td>
</tr>
<tr>
<td>penning maximum z-range</td>
<td>$z_0$</td>
<td>4.5</td>
<td>mm</td>
</tr>
<tr>
<td>magnetron cascade distance</td>
<td>$r$</td>
<td>0.75</td>
<td>mm</td>
</tr>
<tr>
<td>gas fitting parameters [56]</td>
<td>$A$</td>
<td>1.0</td>
<td>events Torr\textsuperscript{-1} mm\textsuperscript{-1}</td>
</tr>
<tr>
<td>(same as for ESD\textsuperscript{TM} model)</td>
<td>$B$</td>
<td>21.6</td>
<td>Volts Torr\textsuperscript{-1} mm\textsuperscript{-1}</td>
</tr>
</tbody>
</table>

Table 4.1: Input data for Helix\textsuperscript{TM} model calculations. The gas specific parameters correspond to water vapor.

\textsuperscript{xxviii} The absolute value of the magnetron-driven potential is higher than 100 eV for all modeled curves.
4.2.4 Total noise formula

In the case of the Helix™, the statistical addition of each contribution includes both individual penning and magnetron terms but it requires an additional term arising from the multiplication of the first stage by the second one. In effect, the total noise of the two-stage amplification process yields

\[ N^2_T = (N^2_p + N^2_p M_m)^2 + N^2_m \]  \hspace{1cm} (4.18)

By substituting the penning and magnetron noise expressions, as presented in Eqs. (4.8) and (4.17), the total noise formula takes the form

\[ N^2_T = \left( M_p (2M_p - 1)^{0.5} + M_p \left( 2M_p - 1 \right)^{0.5} M_m \right)^2 + M_m (2M_m - 1) \]  \hspace{1cm} (4.19)

Clearly, the first term, which includes contributions from the penning noise and its multiplication by the magnetron stage, increases much faster than the second term. Thus, the dedicated magnetron noise is expected to have minimum effect in the noise statistics and therefore, its contribution can be eliminated. This conclusion is confirmed by the theory for electron multi-stage amplification as detailed by Shockley and Pierce.
in 1938 [32]. Their work showed that the first amplification stage carries the dominant noise contribution of the entire multi-stage structure. To conclude, after elimination of the magnetron stage due to its insignificant contribution, the total noise formula is reduced to

\[ N_T = \left( M_p \left(2M_p - 1\right)\right)^{0.5} \left(1 + M_m\right) \]  

(4.20)

### 4.3 Experimental Details

Experimental data were acquired using a FEI Nova NanoSEM 600. This is the dedicated instrument for operation of the detector structure under examination. Hence, it comprises a field emission gun with a high-resolution electron column and the capability of an immersion lens for operation of the Helix™. The magnitude of the magnetic field applied is directly linked to the working distance and cannot be uniquely altered.

For the collection of the signal and noise data, xxix a platinum target was used as the specimen. Even though it is located at a short working distance (i.e. very close to the device), it is not expected to alter in any way the electric field structure since the equipotential lines generated by the anode potential barely penetrate to its surface, as illustrated in Figure 4.1.

Data were collected for different gases including water, carbon dioxide, nitrogen, and argon. Their purity is ~99.9%. In the following signal and noise plots as a function of pressure, the pressure range of each gas differs. This is due to the difficulty

xxix The signal and noise were measured with the same method as described previously in Chapter 3.
of the pumping systems employed in handling mainly light vapors. In this case, the molecules can diffuse in the upper column and the pressure keeps increasing with time until the high vacuum necessary for operation breaks down. For the specific pressure limiting aperture dimensions, the maximum pressure range for stable operation of the instrument defined the experimental measurement regime.

4.4 Results and Discussion

4.4.1 Signal and noise characteristics

Experimental measurements of the total signal and noise were acquired as a function of water vapor pressure for a wide range of anode bias. The results for low anode biases are shown in Figure 4.10, and the effect for high anode bias values is illustrated in Figure 4.11. Overall, both signal and noise curves exhibit similar characteristics. The effect at low anode biases agrees with the model predictions. For the operating conditions used, the signal shows a rapid increase for very low pressures, indicative of the low probability of ionization events, but quickly the signal curve saturates due to the controllable energy loss by ionization, excitation and elastic events at the two-stage amplification process. In addition, the overall intensity of the curves increases with increasing anode bias since more energy is provided and thus more energy needs to be dissipated before the electron is captured at the anode. Already, in Figure 4.10 however, a peak located at approximately 0.3 Torr water vapor appears for both signal and noise curves. The effect is more pronounced for very high biases xxx, xxx Data were collected for anode biases close to the breakdown potential. The maximum anode bias shown corresponds to the highest potential for stable measurements over the operating pressure range.

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Figure 4.11. This low-pressure peak is not predicted by the model that considers all “conventional” gain characteristics for primary ionization processes. Thus, it probably reflects a secondary ionization process, or many processes acting simultaneously, that result in excessive gain but equally, if not more, noise augmentation. The position of the peak is consistent with pressure and independent for anode biases \(^{xxx}\). For reproducible measurements, required for critical dimension related applications, operation where this peak is located should be avoided due to the instability of the gas discharge \(^{xxxii}\).

\(^{xxx}\) It is reminded that this research does not include secondary ionization effects for the development of the amplification theory and model.

\(^{xxxii}\) Typically, during collection of data in the vicinity of the low pressure peak and close to the breakdown potential, the signal took a long time to reach a steady state condition.
4.4.2 Signal-to-noise ratio for low anode bias

Next, the model predictions are compared to the experimental measurements for low anode bias where only primary ionization processes persist. The results are depicted in Figure 4.12. The trend of the overall increase of the SNR as a function of bias is well predicted, however, there are discrepancies between the modeled and measured curves. Particularly for very low pressures (0.2 Torr and below), the model overestimates the nominal signal-to-noise ratio value. At such low gas densities, a significant component of emitted secondary electrons escape the detector volume at the negative z-direction to the upper column and/or are captured at the pressure limiting aperture (PLA) at their first swing of the penning stage. The collisional probability decreases with decreasing pressure, and if an ionizing event does not occur on that first swing, then the probability of electron loss above the PLA increases. This effect poses the low-pressure limit for useful Helix™ imaging.

It is noted that the analytical model, treated as a two-stage amplification process, excludes the transient regime between the penning and magnetron cascade. To this region, we ascribe the term sick space since it cannot be explicitly treated.
Approximately, this region radially extends from the optic axis to the cut-off limit of onset of the magnetron motion. Considering the good overall agreement between the analytical modeled and experimentally measured SNR, Figure 4.12, sick space, as encountered in the Helix™, is not a prevailing contributor for impact ionization phenomena and the overall gain mainly encompasses dependencies of the penning and magnetron amplification stages, as modeled.

Figure 4.12: Measured (symbols) and modeled (lines) signal-to-noise ratio as a function of anode bias. [experimental conditions are the same as in Figure 4.10, P=1Torr water vapor]

4.4.3 Effect of gaseous species

The amplification and noise characteristics of CO₂, Figure 4.13, N₂, Figure 4.14, and Ar, Figure 4.15, is investigated and compared to H₂O. Carbon dioxide vapor shows similar characteristics with water vapor. It exhibits conventional, well-predicted gain intensity at low anode biases, and irregular enhancement for higher bias attributed to secondary ionization processes. It is noted that CO₂ discharges at higher anode biases but the water’s ionization efficiency is significantly superior. Conversely, the gain and noise characteristics of nitrogen and argon are considerably different and primary ionizations processes seem to prevail. However, their overall ionization efficiency is low making them non-attractive for enhancement of the signal-to-noise ratio.
Figure 4.13: Signal and Noise as a function of CO₂ pressure for different anode biases. \( [E_0=5\text{keV}, \quad I_0=95\text{pA}, \quad V_t=0\text{V}, \quad WD=3.5\text{mm}, \quad B=0.22\text{T}] \)

Figure 4.14: Signal and Noise as a function of N₂ pressure for different anode biases. \( [E_0=5\text{keV}, \quad I_0=95\text{pA}, \quad V_t=0\text{V}, \quad WD=3.5\text{mm}, \quad B=0.22\text{T}] \)

Figure 4.15: Signal and Noise as a function of Ar pressure for different anode biases. \( [E_0=5\text{keV}, \quad I_0=95\text{pA}, \quad V_t=0\text{V}, \quad WD=3.5\text{mm}, \quad B=0.22\text{T}] \)
4.4.4 Effect of anode bias

Signal and noise data were collected as a function of anode bias for different gas vapors confined to the conventional amplification regime. The results for the pressures used for each vapor are illustrated in Figure 4.16.

![Graph showing signal and noise as a function of anode bias for different gas vapors](image)

Figure 4.16: Signal and Noise as a function of anode bias for different gas vapors. \([E_0=5\text{keV}, I_0=92\text{pA}, V_i=0\text{V}, WD=3.5\text{mm}, B=0.22\text{T}]\)

Plotted in a log scale, the signal curves show a linear increase until secondary ionizations processes take effect and the curve diverges from linearity. Overall, water vapor exhibits superior signal values. Evidently, the gain for polyatomic gases pertains linearity for a wide range of anode biases. Nitrogen’s gain behavior converges quickly to non-linearity for low anode bias\(^{xxxiii}\). Noise, however, remains at a low limit at very low anode biases, and subsequently, it exponentially increases.

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\(^{xxxiii}\) As noted previously, nitrogen vapor exhibits significant secondary ionization effects in discharge processes, such as photoelectron and Auger electron emission by its impact with chamber surfaces. Polyatomic gases can dissipate these effects due to their molecular complexity.
4.4.5 Relevance of the results to mask inspection

The most significant parameters influencing the operation of the Helix™, namely the gas pressure and the anode bias, are investigated for heavily charging and technologically important specimens, insofar as their imaging behavior is concerned. A series of images acquired as a function of water pressure for 28 nm imprinted lines on a quartz template is depicted in Figure 4.17, and another set of images acquired as a function of anode bias for 195 nm chrome lines on a quartz substrate is depicted in Figure 4.18.

It is evident by Figure 4.17 (a) that there is a minimum useful operating pressure below which two factors inhibit low vacuum operation. First, the gas cascade amplification driving the imaging signal is significantly reduced. Again, this damping is ascribed to the increase to those secondary electrons escaping from the detector volume to the upper column and/or are captured at the pressure-limiting aperture (PLA) at their first swing of the penning stage. Second, image smearing occurs at very low pressures (below 0.2 Torr). Due to the damping of gas gain, the positive ion flux reaching the specimen does not suffice to suppress specimen charging and imaging artifacts arise. Over a wide range of higher pressures (Figure 4.17 (b), (c), and (d)), however, the image artifacts are sufficiently suppressed and the specimen preserves its integrity.

The effect of anode bias on the imaging behavior of a photolithographic mask is illustrated in Figure 4.18 (a-e). All images exhibit artifact-free behavior for the high magnifications used to inspect in detail the delineation of the line-widths. Note that the beam energy is 15 keV facilitating high-resolution imaging.
Figure 4.17: Micrographs of 28nm line-widths imprinted on a quartz template acquired as a function of water pressure. \([E_0=10 \text{ keV}, I_0=0.14 \text{ nA}, V_a=350 \text{ V}, V_{it}=0 \text{ V}, \text{WD}=4.5 \text{ mm}]\) [Specimen courtesy of SEMATECH]

Figure 4.18: Micrographs of ~195nm Cr lines on a quartz substrate acquired as a function of anode bias. \([E_0=15 \text{ keV}, I_0=0.3 \text{ nA}, P_{\text{water}}=0.5 \text{ Torr}, V_{it}=0 \text{ V}, \text{WD}=5 \text{ mm}]\) [Specimen courtesy of NIST]

The rationale behind the development of a low vacuum critical dimension scanning electron microscope has as follows: capability of high resolution imaging while (i) preserving the integrity of the specimen, (ii) minimizing the imaging artifacts,
and (iii) maximizing the signal-to-noise ratio. At first look, both image sets\textsuperscript{xxxiv} indicate that this is true for a wide range of imaging conditions. Indeed, high resolution imaging has been established with the introduction of the particular detector structure [109], contamination reduction/volatilization effects are being modeled for a thorough understanding of the processes involved [54], while imaging artifacts are sufficiently being suppressed. Last, optimization of the signal-to-noise ratio is also tackled by means of the model presented here [116]. It is reminded that CD metrology requirements include fast and reproducible results in conjunction with minimum operator intervention. Thus, the need for this physical SNR model over either fast Fourier transform analysis or operator judgment is pertinent to high-quality low vacuum operation.

4.5 Summary

In this chapter, the gain and noise statistics for the low vacuum, high-resolution, magnetic-field assisted detector device have been theoretically described, analytically modeled, and experimentally evaluated. The description was based on a two-stage amplification process: a penning process that corresponds to the motion of a particle in a Penning trap, and a magnetron process that corresponds to the motion of a particle in a Magnetron device. It has been analytically predicted that the nominal gain of each stage is mainly affected by the anode bias. This attribute defines the potential energy supplied

\textsuperscript{xxxiv} These two image sets are utilized in the discussion as an example of low vacuum behavior in high magnifications of non-conductive specimens. By no means is this behavior expected to extent over the vast operating regime of low vacuum scanning electron microscopy.
to the electron and it is unequally partitioned between the two motions (for the specific detector dimensions examined, more energy is going into the magnetron motion). The noise statistics have been treated by the theory of electron amplification in multi-stage amplifiers, and it was predicted that the penning noise component dominates, in contrast to the magnetron one, which contributes a statistical insignificant amount.
CHAPTER 5

CONCLUSIONS

This research produced a practical analytical model for signal and noise in low vacuum scanning electron microscopy (LVSEM). The strength of the model consists of its development from first principle physics describing the motion of an electron in a gas medium driven by the influence of static electric and magnetic fields.

The results indicate that excess noise from the gas cascade amplification is the dominant contributor to the total noise and its statistical properties, linked to the variance of the gain distributions, provide useful insight on the gain fluctuations, which compromise the signal-to-noise ratio in LVSEM. It was evaluated that gains approaching unity are well described with Poisson statistics, for which the variance equals the mean, while large gains assume a Gaussian distribution, for which the variance is independent of the mean. Particularly for the Townsend’s discharge region, the introduction of the statistical method of recurrent generating functions of mean-free-path dependent ionization probability revealed that the statistical weight of the electrons which do not possess enough energy to impact ionize is not significant. Thus, the swarm conditions theory used to describe the amplification in this region throughout the literature was proven a good approximation.

With respect to the high resolution, magnetic field assisted, low vacuum detector, the decomposition of the motion and amplification of the electron into two components allowed for implementation of Penning trap and Magnetron device physics.
for the analytical description of the nominal gain. This way, the noise statistics were treated by the theory of electron amplification in multi-stage amplifiers, and it was predicted that the penning noise component dominates, in contrast to the magnetron one that contributes a statistical insignificant amount. As far as the effect of the instrument’s operating conditions on the overall gain is concerned, it was predicted that the two-stage amplification process is mainly dependent on the anode bias that defines the electron’s kinetic energy partitioned between the two modes.

Finally, the analytical modeled curves were verified experimentally. A measurement set-up for acquiring noise data directly linked to the cascade current induced at the detection electrode was established. This way, a correct assessment of the physical principles defining the cascade process is facilitated.

To conclude, all preceding results presented in this thesis have demonstrated the ability to quantitatively interpret, and therefore predict, image data in a gas-filled specimen chamber of a scanning electron microscope, as required for implementation of the technique for in-line semiconductor applications. It was analytically and experimentally demonstrated that signal and noise characteristics of low vacuum SEM can be modeled with sufficient accuracy to enable critical dimension metrology measurements.

5.0 Future Directions

The newly developed signal-to-noise ratio model for quantitative analysis of the primary ionization effects involved in the gas cascade amplification can form the platform on which more complicated features of the image formation process in low
vacuum scanning electron microscopy can be integrated. For example, it is critical to incorporate in the model the secondary ionization effects (i.e. pre-breakdown processes) leading to excessive noise. In the case of the magnetic field assisted detector, this was demonstrated to be primarily function of gas molecules used as the amplification medium and anode bias. The requirement for higher operating anode bias, on particular material inspection, is radically necessitated by the unique, in cases, contrast mechanisms of LVSEM. To this end, studies can be undertaken to link these contrast mechanisms to the signal-to-noise ratio enhancement as predicted by the model. In addition, further studies based on the enhancement of the SNR can include the effect of the dimensions of the detector structure on the nominal gain. By altering the dimensions of the electrodes, the electron’s penning and magnetron efficiencies can be tuned accordingly towards optimization of the overall amplification process.

Ultimately, the first step in the overall objective of the foundation of a fully functional (semiconductor-ready) critical dimension low vacuum scanning electron microscope has been accomplished in this work. The predictive signal-to-noise ratio model developed here can well be incorporated into CD simulations codes like MONSEL serving as a correction for the instrumental effects including the physical aspects of the gas cascade amplification. The next steps can include establishment of the limits of charge control and contamination reduction, and identification of the optimal gas composition for CD measurements. Water vapor is not necessarily desirable (for example chemistry effects on resist imaging occur), and the interesting amplification characteristics of gas mixtures should be explored.
BIBLIOGRAPHY


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