NONDESTRUCTIVE SUBMICRON DIMENSIONAL METROLOGY USING THE SCANNING ELECTRON MICROSCOPE

Michael T. Postek
National Bureau of Standards
Microelectronics Dimensional Metrology Group
Gaithersburg, MD 20899

INTRODUCTION

The evolution of integrated circuit dimensions into the submicron region for the Very Large Scale Integration (VLSI) and Very High Speed Integrated Circuits (VHSIC) programs necessitates inspection techniques with a resolution exceeding that of the optical microscope. Inspection using scanning electron microscopes (SEM), operated in the low accelerating voltage mode, is becoming common place in the on-line fabrication of these submicron devices due to the high spatial resolution and greater depth of field afforded by these instruments. Use of the SEM is necessitated by the desire of many processing facilities which presently work at a 10% process control level to implement process control of 5% or better. This means that the process precision goal is now (or soon will be) in the nanometer range. Even though optical microscopes can be useful for critical linewidth measurement and inspection to about 0.5\(\mu\text{m}\), many fabrication lines presently are integrating low-voltage scanning electron microscopes into the production sequence at chip levels of 1.25-\(\mu\text{m}\) geometry and below. This enables the training of operators and the acquisition and development of expertise and experience with control charts for this type of instrumentation. Advanced scanning e-beam instruments are presently being developed to facilitate this work and to do automated inspection.

THE SCANNING ELECTRON MICROSCOPE METROLOGY INSTRUMENT

The architecture of a typical scanning electron microscope wafer inspection instrument is similar to most modern SEMs designed for low accelerating voltage operation with the exception that it is modified to accept and view large wafers. The instrument may also have a cassette-to-cassette wafer-transfer system to facilitate sample loading and linewidth measurement capabilities. In this instrument, a finely focused beam of electrons is moved or scanned from point to point on the specimen's surface in a precise rectangular motion called a raster pattern. Depending upon the design, the electrons originate from a source that may either be heated to a high temperature (thermionic emission), extracted at room or near room temperature (cold field emission), or a combination of both (thermally assisted field emission). One measure of the performance characteristics of the electron source, regardless of the type, is brightness. Brightness is the current density of the electron beam per unit solid angle subtended at the specimen. Brightness is proportional to
the intrinsic emission current density of the source, and it increases linearly with accelerating voltage. The electron beam, once generated, travels down the column where it undergoes a multistep demagnification with magnetic lenses so that when it impinges on the sample, the beam is about 1 to 3 nm in diameter (for 30 keV operation). Depending upon the particular application and specimen composition, the operator optimizes the proper conditions for any given magnification by adjustment of accelerating voltage, beam current, and spot diameter.

The electron beam is precisely deflected on the sample in the raster pattern either in an analog or digital manner, depending upon the design of the particular instrument. Most newer instruments employ digital scanning in a real-time frame storage system and include auto-focus and auto-astigmatism correction. The beam deflection on the sample is synchronized with the deflection of the display cathode ray tube (CRT) so there is a point-by-point visual representation of the specimen on the CRT screen as the electron beam scans the specimen. The smaller the area scanned by the electron beam, in the raster pattern relative to the display CRT size, the higher the magnification.

NONDESTRUCTIVE LOW ACCELERATING VOLTAGE SEM OPERATION

The techniques used in "nondestructive" operation of the SEM, as used in this context, have only been in practice for about the past 3 to 5 years. Historically, scanning electron microscopy was done at relatively high accelerating voltages (typically 20 to 30 keV) in order to obtain both the best signal-to-noise ratio and resolution. The higher the accelerating voltage, the shorter the wavelength of the electron, and thus the better the diffraction limited resolution. At high accelerating voltages, nonconductive or semiconducting samples require an overcoating of gold or a similar material to provide a current path to ground and to improve the signal generation from the sample. Further, early instruments were designed to accept only reasonably small samples so the large wafer samples, typical of the semiconductor industry, needed to be broken prior to inspection. In modern semiconductor device processing, this procedure is considered a destructive technique because a broken or coated wafer cannot be processed further. Modern on-line inspection during the production process of semiconductor devices is designed to be nondestructive which requires that the specimen be viewed in the scanning electron microscope uncoated and intact. High accelerating voltages interacting with the sample can also damage the devices [1], and low accelerating voltage inspection is thought to eliminate, or at least minimize, such damage. In order to accomplish this in the SEM, the sample is viewed at low accelerating voltages. Low accelerating voltage, in this case, is generally defined as below 2.5 keV. Further advantages derived by operating the SEM at low accelerating voltages are that the electrons impinging on the surface of the sample have less energy, penetrate into the sample a shorter distance, and have a higher cross-section for the production of secondary electrons near the surface where they can more readily escape and thus be collected. Thus, in this context, nondestructive evaluation requires that the sample not be broken and that it be viewed in an instrument at an accelerating voltage below the point where electron beam damage will become a problem. Hence, an understanding of the sample's electrical characteristics is useful prior to examination.

SPECIMEN-BEAM INTERACTIONS AND SIGNALS GENERATED

The incident electron beam enters into and interacts directly with the sample as it is scanned. This results in a variety of signals being generated that are useful for semiconductor inspection and analysis [2].
For historical reasons, the major signals of interest to microelectronics dimensional metrology and inspection are divided into two broad groups: backscattered and secondary electrons. However, it must be understood that this distinction is often arbitrary, especially at low beam energies.

Backscattered electrons (BSE) are those electrons that have undergone either elastic or inelastic collisions with the sample and are re-emitted with an energy that is a significant fraction (generally 50 to 80%) of the incident beam energy. The backscattered electron yield varies with the sample and detector geometry and atomic number of the specimen, but is relatively independent of the accelerating voltage. Backscattered electrons are re-emitted from the sample surface in approximately straight lines, and consequently, they must be detected by placing a detector in their path. The size and position of the detector affects the image, and thus any measurements made from it. Therefore, the particular characteristics of the detector must be taken into account when analyzing the observed backscattered electron signal for metrological purposes.

The secondary electrons (SEC) are arbitrarily defined as those electrons that have between 1 and 50 eV of energy. The secondary electrons are the most commonly detected for low accelerating voltage inspection since their signal is much stronger than any of the others. Due to the low energy of the secondary electron signal, the electron paths are easily influenced by any local electric or magnetic field. The collection efficiency of an SEC detector relates directly to its position and potential. Detectors that have a location at some off-axis angle, as in many instruments designed to accept detectors for x-ray microanalysis, show preferentiality of detection. In these cases, it is not possible to achieve the symmetrical video profiles necessary for precise linewidth metrology. To compensate for an off-axis position of the secondary electron detector, the sample can be physically rotated toward it until the video profile of the line becomes symmetrical; then the structure can be straightened on the display CRT by adjusting the raster pattern with digital raster rotation. Since an error can be introduced using this technique, it is much more desirable to have an on-axis detector [3] or two similar detectors on either side of the sample and the signals properly balanced and summed [4].

The primary electron beam can enter into the sample for some distance, even at low accelerating voltage; thus, it is important to define this interaction volume. The maximum range of electrons can be approximated using the expression derived by Kanaya and Okayama [5].

\[
\text{Range} = 0.0276AE^{1.67/0.899}_o/\rho \text{nm} \tag{1}
\]

where: \(E\) is the primary electron beam energy (keV), \(A\) is the atomic weight (g/mol), \(\rho\) is the density of the material (g/cm\(^3\)), and \(Z\) is the atomic number. Using this equation the calculated range of electrons in a carbon (graphite) specimen can be shown to vary from 0.003 nm at 1.0 keV to 0.45 nm at 20.0 keV. If it is considered that this calculated range approximates the boundaries of the electron trajectories as a region centered on the beam impact point (Fig. 1), then it can be seen that the backscattered electrons emerging from the surface area of this region do not, in general, carry much information about the high resolution details making up the surface topography of the specimen. The secondary electrons, due to their inherently low energy, cannot reach the surface from deep in the specimen, so typically they escape from a region only 5 to 10 nm beneath the surface. Therefore, they do carry surface specific information.
Fig. 1. Illustration of the region of interaction that results when an electron beam is incident on a sample and the types of secondary electrons that can originate from this interaction. The electron range in the specimen is shown as R.

It should be understood that secondary electrons can originate from points other than the point of impact of the primary electron beam [6]. Those that do originate from the point of impact are referred to as SE Type I electrons. The SE Type I electrons are the most desirable for metrology. Secondary electrons are also created by re-emergent backscattered electrons at the sample surface (SE Type II) and at the pole piece of the instrument (SE Type III). Other contributions to the collected secondary electron signal include line-of-sight backscattered electrons and other sources particular to each instrument (SE Type IV). The effects of these four types of contributions to the actual image or metrology have not been fully evaluated.

The behavior of the total electrons emitted from a sample per unit beam electron (Fig. 2) is extremely significant to nondestructive low accelerating voltage operation. The points where the curve crosses unity (i.e., E-1 and E-2) are the points where no net electrical charging of the sample will occur. During irradiation with the electron beam, an insulating sample such as photoresist or silicon dioxide can collect beam electrons and develop a negative charge causing a reduction in the primary electron beam energy incident on the sample. If the primary electron beam energy is 2.5 keV and the particular sample has an E-2 of 2.0 keV, then the sample will develop a charge to about -0.5 keV so as to reduce the effective incident energy to 2.0 keV and bring the yield to unity. This charging can have detrimental effects on the electron beam and degrade the observed image. If the primary electron beam energy is chosen between E-1 and E-2, there will be more electrons emitted than are incident in the incident beam, and the sample will charge positively. Positive charging is not detrimental as it is only limited to a few electron volts because of the resulting barrier to the continued emission of the low energy secondary electrons. This reduction in the escape of the secondaries limits the surface potential, but reduces signal
as these electrons are now lost to the detector. The closer the operating point is to the unity yield points E-1 and E-2 (Fig. 2), the less the charging effects. Each material component of specimen being observed has its own total emitted electron/keV curve, and so it is possible that, in order to completely eliminate sample charging, a compromise must be made to adjust the voltage for both materials. For most materials used in the present semiconductor processing, an accelerating voltage in the range of about 1.0 keV is sufficient to reduce charging and minimize device damage (Fig. 3).

Although operation at low beam energies is useful for the inspection of semiconductor samples with a minimum of sample damage and charging, a detrimental result is a reduction in the beam current available from the electron source (as compared with high voltage operation); thus, the signal-to-noise ratio is poorer. This results in a loss in apparent sample detail. High brightness filaments and digital frame storage techniques for multi-scan signal integration, or slow scan rates coupled with photographic or electronic integration, help to overcome this problem. The more abiding problem with low accelerating voltage operation is the lower resolution (as compared to the higher beam energy operation) characteristic of this mode of operation. If an instrument equipped with a high brightness lanthanum hexaboride filament is capable of 4 nm resolution at 30 keV accelerating voltage, it may be only able to resolve about 10 to 12.5 nm of resolution (under similar conditions) at 1 keV. This limitation must be understood and factored into the precision requirements for submicron metrological applications.

**SCANNING ELECTRON MICROSCOPE-BASED METROLOGY**

The basic premise underlying the use of the scanning electron microscope for critical dimension measurement for semiconductor research and production applications is that the video image acquired, displayed, and ultimately measured reflects accurately the structure of interest. However, the electrons detected do not necessarily originate at the point of impact of the primary electron beam, and the effects of the four types of electron contributions to the actual image or linewidth measurement (Fig. 1) have not been fully evaluated. Errors in measurement can also be introduced by sample charging and environmental influences (e.g., stray magnetic fields and vibration). In measurement applications, error due to the actual location of signal origination or other sources usually will not affect pitch measurements as the errors cancel [7,8]. However, in linewidth measurement, many potential errors are additive and thus will give twice the edge detection error to the measured width. The

![Fig. 2. Schematic drawing of the total yield of electrons for a specimen plotted as a function of incident beam energy.](image-url)
Fig. 3. Scanning electron micrograph of uncoated photoresist taken at 1.0 keV accelerating voltage.

The precision of any SEM-based metrology system is composed of two basic components: the precision of the actual instrument itself assuming an ideal sample, and the precision of the actual sample [9]. The instrumentation design and limitations must also be considered as a factor adding uncertainty to the measurement. For example, scan linearity, pixel point resolution, magnification compensation, and lens hysteresis can be significant influences that must be considered, understood and compensated for, if possible. Jensen [7], Jensen and Swyt [8], Seiler and Sulway [9], and Nyyssonen and Postek [3] discuss these and other instrumental limitations in the scanning electron microscope, and the reader is directed to these references for further information. All of the instrumental limitations must be properly assessed and understood in order to properly interpret the measurement results. Some of the factors that today can limit the precision of submicron SEM metrology are now discussed.

The Definition of Linewidth

Scanning electron microscope metrology and optical metrology have one thing in common at the present time; there is no well-defined definition of the meaning of the linewidth of most specimens. The first consideration that must be developed and defined when describing the term linewidth is what is actually being physically measured. Depending upon the lithographic process level, the term linewidth measurement may vary relative to the structures importance to subsequent processing steps. Many of these structures have a trapezoidal cross-section. Whether the critical dimension is defined as the width of the top surface edge or the base width of a line is a significant question that must be understood and designed into the measurement process. Due to the large depth of field of the SEM inspection instrument, this distinction becomes important since, if the conditions are properly chosen, both regions could be simultaneously in acceptable focus. Another situation for linewidth definition error develops when an undercut sample is being observed. This situation may not be readily detected unless the sample is highly tilted. In all cases, unless the measurement procedures are properly established, confused data reporting and errors in measurement will result. A further confusion to any of the above instances would be introduced if the line were asymmetrical in cross-section. This would yield an asymmetrical waveform and complicate the interpretation of just where the edges were located. This discussion of the definition of a linewidth has been limited to the description of the position on a particular structure identified.
as the edge and not how to make the measurement. Further work modeling the scanning electron microscope signals and to relate them to the physical edge is necessary before the actual linewidth can be accurately defined. This is similar to what was done in the optical microscope for photomasks [10].

Environmental Factors

The scanning electron microscope metrology system used for nondestructive on-line inspection is usually located in a clean room. However, little attention has been paid to the consequences imposed by the clean-room air scrubbing vibration and stray magnetic fields on the metrology instrumentation. The SEM metrology instrument is an imaging system and, as such, the problems posed by the clean room environment are readily observable in the images. It should be noted that these problems can also detrimentally affect other clean room instrumentation, but their effects may not be directly observable in real time and so the significance may be lost. In most cases surveyed, the SEM metrology instruments presently operating in the typical clean room are not performing optimally. This is usually due to two main reasons: excessive vibration and stray electromagnetic fields. Both of these environmental problems can be eliminated given proper clean room engineering.

Sample Charging Effects

Sample charging and its effect on measurements made in the SEM have been studied [11-13]. Negative charging results when the electron beam voltage exceeds E-2 (Fig. 2). This charging can detrimentally affect the measurement in several ways. The foremost effect is the possible deflection of the electron beam as the sample builds up an appreciable charge approaching that of the initial accelerating voltage. This may either manifest itself as an obvious beam deflection where the image is lost or a more subtle and less obvious effect on the beam. The small effects are the most damaging to metrology as they may manifest themselves either as a beam deceleration or a beam deflection. A subtle beam deflection around a line structure can move the beam a pixel point or two, thus invalidating the critical dimension measurement. One pixel point deflection of a 1-μm line measured at 10,000x magnification with a 512 pixel point digital scan corresponds to about 38 nm linewidth error. Positive charging may also have detrimental effects on the measurements as a positively charging structure can attract information carrying secondary electrons from adjacent pixel points, thus distorting the measurement profiles.

Proper adjustment of the accelerating voltage to the appropriate points on the total electron emission curve can minimize, if not completely eliminate, sample charging. Rapid TV-rate or near TV-rate scanning is also being employed by several manufacturers to reduce charging. Under these conditions, the electron beam dwells on the sample for less time per point than in slow scan; thus, the charge has less time to develop (but signal-to-noise may be poorer). Another possible charge reducing technique is to tilt the sample toward the detector. Tilting the sample permits sample inspection at higher accelerating voltages without charging effects; however, care must be taken during the critical dimension measurements to minimize possible error that tilt may introduce [11].

Accelerating Voltage and Signal Detection Effects

The magnitude of the errors introduced to the linewidth measurement relative to the mode of signal detection and of beam acceleration voltages has been studied [14]. A silicon wafer sample with a silicide layer
patterned with micrometer and sub-micrometer lines is shown in Fig. 4.
This sample was observed and measured under controlled conditions at
several accelerating voltages and electron detection conditions. A micro-
graph showing the effect of the choice of signal detection (secondary
or backscattered electron imaging) is demonstrated in Fig. 5. In that
micrograph, the actual physical width of the line and the characteristics
of the beam electrons were not changing as the micrograph was being taken.
The only difference was the manner of signal detection in the instrument.
The results of additional measurements of the secondary and backscattered
signals demonstrate that, depending upon the electron detection mode
used to image and measure the structure of interest, a variety of measure-
ment results can be obtained (Table I). In all instances, measurements
of the secondary electron signal yield a larger result than an identical
measurement of the backscattered electron signal (see Fig. 5). Further,
measurement-broadening effects of the beam penetrating relative to the
accelerating voltage are apparent. The reasons for this variability
becomes obvious if the video waveforms are displayed (Fig. 6). As can
be seen, the waveforms obtained at the two different accelerating voltages
are significantly different, due in part to the range of the primary
beam into the sample. This clearly demonstrates that measurement criteria
for each accelerating voltage must be established so that electron beam
effects can be properly accounted for and that knowledge of the electron
beam/sample interaction effects must be understood. Changes in apparent
dimension can be attributed to the uncertainties contributed by; electron
beam interaction effects, solid angle of electron detection, detector
sensitivity, and the criterion used to determine the edge location in
the computation of linewidth. These data further suggest that if several
instruments are operating on a production line, care must be exercised
that all are working with the identical accelerating voltage, other instru-
ment parameters, and measurement conditions.

MONTE CARLO MODELING AND LINEWIDTH METROLOGY

The above discussion demonstrated that many factors contribute posi-
tively or negatively to scanning electron microscope metrology. Many
of the previously identified influences can be modeled using the Monte
Carlo technique in an effort to develop increased measurement accuracy
and precision. The Monte Carlo simulation is a computer modeling method
by which trajectories of individual electrons are tracked through a solid.
The Monte Carlo technique has many benefits. Because each electron is

Fig. 4. Scanning electron micrograph of a 0.75-μm silicide on silicon
line.
Table 1. Nominal 0.75 micrometer linewidth (average of 40 scans)

<table>
<thead>
<tr>
<th>keV</th>
<th>SEC</th>
<th>SD</th>
<th>BSE</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.916</td>
<td>+0.0140</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>3.0</td>
<td>0.891</td>
<td>+0.0092</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>5.0</td>
<td>0.856</td>
<td>+0.0098</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>10.0</td>
<td>0.774</td>
<td>+0.0224</td>
<td>0.564</td>
<td>+0.0054</td>
</tr>
<tr>
<td>20.0</td>
<td>0.703</td>
<td>+0.0125</td>
<td>0.556</td>
<td>+0.0073</td>
</tr>
<tr>
<td>30.0</td>
<td>0.0669</td>
<td>+0.0178</td>
<td>0.563</td>
<td>+0.0052</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.802</td>
<td>0.561</td>
<td>+0.004</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>+0.102</td>
<td>+0.004</td>
<td></td>
</tr>
</tbody>
</table>

NA = Not applicable
SD = Standard deviation of the indicated average and is a measure of the variability.

Fig. 5. Multiple detector micrograph showing the effect of the choice of detector (backscattered and secondary electron) on the image and thus the measurement.

Individually followed, everything about it (its position, energy, direction of travel, etc.) is modeled. Therefore, it becomes straightforward to take into account the sample geometry, the position, and size of detectors and other relevant experimental parameters.

A new approach to the Monte Carlo technique has been reported [15,16] in which a simple diffusion transport model for the secondary electrons is combined with a Monte Carlo simulation for the incident electrons. This procedure allows both the secondary (SE Type I + SE Type II) and the backscattered signal profiles to be computed simultaneously with very little increase in computing time. Once those data are available, the effect of other signal components, such as the SE Type III component, can also be estimated.

The ability to model signal profiles for some given sample geometry and composition is an important tool for linewidth metrology. Modeling provides a quantitative way of examining the effect of various experimental variables (such as beam energy, probe diameter, choice of signal used, etc.) on the profile produced and gives a way of assessing how various
Fig. 6. Overlay of two digitally acquired video signal profiles of the 0.75-μm silicide on silicon line; one profile was taken at 1.5 keV and the other done at 30 keV. Note the variation in shape between the two profiles.

algorithms deal with these profiles to determine a criterion of edge detection and, thus, a linewidth.

STANDARDS FOR SCANNING ELECTRON MICROSCOPE METROLOGY

A project being undertaken at the National Bureau of Standards at the present time is the development of national standards for SEM linewidth metrology. The only magnification standard reference material (SRM) presently available for calibrating scanning electron microscopes is SRM 484. SRM 484 is a pitch sample and has served well for several years and is still useful for many SEM applications. But, SRM 484 was developed prior to the recent interest in low accelerating voltage operation and wafer inspection. SRM 484 in its present form is unsuitable for use in new nondestructive inspection instruments for two main reasons: a lack of suitable contrast in the 1.0 keV accelerating voltage range and the overall size which is not compatible with newly introduced wafer inspection instrumentation. A project has been initiated at NBS to physically modify SRM 484 without altering its calibration or certification procedures to make it suitable for low accelerating voltage operation (Fig. 7a,b). The linewidth measurement standard developed for the optical microscope, SRM 474, is not designed or recommended for use in the SEM and it should not be used for this purpose. The optical theory and modeling for the SRM 474 is not directly adaptable to the SEM and, therefore, the criteria developed to determine the edge location are not applicable for anything but an optical measurement. From the above discussions of the electron beam effects and the requirements for modeling, this should be apparent as the two types of instruments are totally independent of each other in both the underlying physics and operation. SRM 474 could, however, be used to measure pitch at low accelerating voltage under conditions where the sample is not charging. In this mode, the magnification of the instrument could be calibrated. However, again the reader is warned that continuing this adjustment process to include linewidth measurements is not recommended because such calibration results would be only valid for chrome-on-glass photomasks. For the present time, product precision is a prime concern to the semiconductor industry; until such national standards for SEM linewidth measurement are available, the best that can be done is the establishment of a series of internal
"golden" samples within a particular organization for each level of processing [17], and that the established pitch standards be used to properly adjust the magnification of an instrument. This series of well-characterized internal standards is used to develop offsets to the instrument for each level and also to periodically check the instrument's measurement drift.

CONCLUSIONS

Proper metrology with any type of instrument is not a trivial matter and the SEM is no different! Precise metrology is required for nondestructive inspection and measurement during the manufacture of integrated circuits with submicron features. An understanding of the areas that can be problems associated with the scanning electron microscope is even more important here than in any other commercial application of the SEM. The uncertainties associated with each instrument in each environment must be assessed and understood for metrology to be done properly. It has been the goal of this paper to put its limitations and capabilities into perspective and to indicate what can actually be expected from this type of instrumentation at this time. As this instrument matures in the field of nondestructive analysis and research is done to improve the theoretical understanding of the physical processes going on in this instrument, the entire field of scanning electron microscopy in all its diverse applications will be furthered.

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Fig. 7. a) Scanning electron micrograph of SRM 484 viewed at 20.0 keV after treatment of the SRM to enhance the contrast of this sample for low accelerating voltage. b) The same treated SRM 484 viewed at low accelerating voltage (1.0 keV).
REFERENCES