Overview of CD-SEM – and beyond

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Abstract. The CD-SEM, which has been the major tool for critical dimension metrology for the last twenty years, now faces severe challenges to its utility and predominance. The problems that must be solved are outlined, and the possible scenarios for progress are described.

INTRODUCTION

The dimensions of features, such as those of the transistor gate and interconnect structures, are so crucial to producing integrated circuits (IC) that the metrology of a linewidth, or a contact/via diameter, is routinely referred to as a critical dimension or CD measurement. The scanning electron microscope (SEM) has been the main method of CD measurement for many years because it offers acceptable throughput speed, site specific measurements, and widely accepted – if not well founded – procedures for interpreting the results obtained. Since its introduction as a specialized tool twenty five years ago, the CD-SEM has been continuously improved to keep up with the ever evolving demands of the devices that it has to measure. During that same period other, newer, approaches such as optical scatterometry and atomic force microscopy have been introduced and have also shown considerable promise for CD metrology. The purpose of this review, therefore, is to see whether the CD-SEM is now at the end of its era of dominance, or whether it can continue to offer sufficient performance and operation advantages to remain the tool of choice.

SPECIFYING THE CD-SEM

Stripped of its wafer cassette handler, the laser controlled stage, and its specialized data processing capabilities the CD-SEM is just another scanning microscope. It is therefore subject to all of the usual constraints and compromises that any electron optical device faces. Unfortunately, in the case of a CD-SEM, each of the operational choices that have to be made have implications that seriously impact other aspects of the instrument. Table 1 summarizes the key parameters that define SEM operation - the probe size, the beam current, the beam energy, and the scan speed – the current trend in the magnitude of that parameter, the perceived factors which are driving that trend, and the consequences that follow a decision to make a change in response to the trend. It is clear that two factors, charging and beam induced damage, stand out as being responsible for the choices in operating condition that are now common. Thus the downward trend towards in beam energies, and the search for ever faster scan speeds, mostly represent a response to the desire to eliminate charge induced artifacts in the image and to minimize the shrinkage (or, occasionally, the swelling) of resists. While the amount of current in the probe has remained essentially constant because of the necessity of maintaining a satisfactory signal to noise ratio, the requirement to measure ever smaller features with improved precision has led to the need for significantly smaller beam spot sizes. In a consumer SEM competing requirements of this kind can usually be resolved by relaxing one of the constraints on the system – typically the recording time for an image – so allowing the other parameters to be maintained at desirable values. In a CD-SEM, however, this artifice is not possible. For example, the need to manage charging, and if possible to minimize resist damage, by lowering the beam energy directly conflicts with the requirement for ever better imaging resolution, but neither resolution nor charge control can be ignored in metrology. Lower beam energies also result in a reduction in gun brightness and hence reduced beam currents, but 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 effects, but
### Table 1. CD-SEM parameters and the factors which drive their choice

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Trend</th>
<th>Drivers</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>Lower</td>
<td>Charging</td>
<td>Degraded electron-optical performance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Beam Damage</td>
<td>Diffraction limited</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poor source brightness</td>
</tr>
<tr>
<td>Beam Current</td>
<td>Constant</td>
<td>Trade-off between throughput rate, damage and charging</td>
<td>Marginal signal to noise</td>
</tr>
<tr>
<td>Spot Size</td>
<td>Smaller</td>
<td>Resolution “Precision”</td>
<td>Lower beam current</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Degraded Signal/Noise</td>
</tr>
<tr>
<td>Scan Speed</td>
<td>Higher</td>
<td>Throughput control</td>
<td>Stress on video components</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Charge control</td>
<td>Poor linearity</td>
</tr>
</tbody>
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only at the expense of factors, such as decreased image quality and degraded signal to noise ratio, which are again crucial to metrology.

This situation is occurring now because the CD-SEM, in its current form, is faced with fundamental limitations rather than with shortcomings in design or execution. If the CD-SEM is to have a useful future it will therefore be necessary to re-think the definition of what the tool does and how it does it, so that the conflicts discussed above can be avoided and the necessary improvements in performance can be obtained within the necessary time period.

### POSSIBLE SOLUTIONS

Table 2 displays a list of some of the problems that afflict the CD-SEM, together with one more possible solutions for each of these areas. In addition a third column indicates the ‘collateral damage’, or inescapable side effects, associated with that choice. It is evident that no solution is perfect, and that for each problem every solution has one or more undesirable consequences. It is not, therefore, possible to define an ideal solution but only to identify one or more options which might have the least side-effects. Some of these options can be grouped together to form possible scenarios for consideration:

(a) the mixture as before

The first option is to accept the status quo and to seek to optimize that situation as far as possible. Several routes the achieve of the necessary steps that must be taken are evident. First, since gun brightness $\beta$ (i.e. the current density per unit solid angle) falls linearly with beam energy it is necessary to find emitters of higher intrinsic brightness to overcome the losses associated with operating at such low accelerating voltages. A candidate solution in the Nanotip Field Emitter which offers a gain of up to 100x in brightness when compared to a conventional field emitter at the same energy. As shown by Vladar et al. at NIST [1] such nanotips can indeed demonstrate the benefits of higher beam currents and smaller probe sizes when employed in a (suitably modified) CD-SEM. While promising there are still practical problems to be solved. Nanotips are cold field emitters, and therefore they display more noise and drift that a Schottky emitter. This fact is made worse because, unlike conventional tungsten cold field emitters, the nanotip cannot safely be flashed to clean them prior to use. In addition some questions such as their useful lifetime, and exactly how nanotips can be commercially manufactured, installed and serviced, are still the subject of research.

Secondly, the wavelength $\lambda$ of low energy electrons is large (since $\lambda$ varies as $1/E^{1/2}$) and so, for a given beam convergence angle $\alpha$ the diffraction disc, equal in size to $\lambda/\alpha$ is large. The effect of diffraction must be balanced against the spherical, and chromatic aberrations also present in the probe forming lens (Figure 1) by choosing the optimum value of $\alpha$. As a result a CD-SEM is always operated at a condition close to diffraction limiting, and the size of the Airy disc represents a hard limit to the achievement of smaller probe diameters. If however the aberrations of a lens can be reduced in some manner then $\alpha$ can be made larger and the diffraction disc becomes smaller. Fortuitously one common approach to low voltage operation involves the use of retarding fields.
TABLE 2. Some key problems, some possible solutions, and their side effects

<table>
<thead>
<tr>
<th>Key Issue</th>
<th>Possible Solutions</th>
<th>Collateral Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>Aberration correction</td>
<td>Higher beam current into a smaller probe, but collapse of the Depth of Field</td>
</tr>
<tr>
<td></td>
<td>Higher beam energy</td>
<td>Higher beam current into a smaller probe.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Depth of Field about constant</td>
</tr>
<tr>
<td>Charge Control</td>
<td>Still lower beam energies</td>
<td>Problem in maintaining optical performance</td>
</tr>
<tr>
<td></td>
<td>Low vacuum operation</td>
<td>Possible loss in resolution and contrast.</td>
</tr>
<tr>
<td>Beam induced damage</td>
<td>Ultra-low energy</td>
<td>Reduction in usable scan speed</td>
</tr>
<tr>
<td>(carbon carry-over)</td>
<td>High beam energies</td>
<td>Electron-optical performance</td>
</tr>
<tr>
<td>3-D information</td>
<td>“Stereo imaging”</td>
<td>Unproven</td>
</tr>
<tr>
<td>Throughput</td>
<td>Modeling</td>
<td>Requires two exposures.</td>
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<tr>
<td></td>
<td></td>
<td>Limited geometries</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Needs extensive pre-computation. Accuracy may be limited by charging</td>
</tr>
<tr>
<td>Cost and delay in developing and</td>
<td>“Common Platform”</td>
<td>Complex technology and data handling.</td>
</tr>
<tr>
<td>delivering new tools</td>
<td></td>
<td>Statistical rather than site-specific data</td>
</tr>
</tbody>
</table>

in the region just above the sample to slow the electron from some high initial energy \(E_0\) to some lower landing energy \(E_L\). If this deceleration occurs over some sufficiently short distance \(S\) then to a good approximation \(C_s\) the spherical and \(C_c\) the chromatic aberration coefficients of the lens become \([2]\)

\[
C_s = - C_c = \left(\frac{E_L}{E_0}\right) S
\]

By choosing \(E_0\) to be a few keV, \(E_L\) to be a few hundred electron volts, and \(S\) to be a millimeter or less, effective aberration coefficients of the order of tens of micrometers can be achieved compared to the real values of several millimeters. This solution (figure 1) allows \(\alpha\) to be increased by a factor of 3 - 4x, leading to both a welcome drop in probe size and an increase in the probe current (since that varies as \(\alpha^2\)). Alternatively, lens aberrations can be compensated using one of the ‘aberration correctors’ now available from companies such as the unit from CEOS (in Germany) available on a prototype tool from JEOL, or the NION system (from the USA) which has been fitted to several scanning transmission microscopes. These devices allow \(C_s\) and sometimes \(C_c\) to be set to a chosen magnitude and provide the same benefits as the retarding field system but in a more flexible, if expensive, fashion.

The drawback of either approach is that the depth of field falls substantially and declines to values in the nanometer range \([5]\) which make the observation of any structure of normal aspect ratio very difficult (Figure 2) without recording a through-focal series. Although software to synthesize high depth of field images from a through focus series has been demonstrated by Hitachi High Technologies the time required for multiple exposures, and the increase in beam damage, may represent practical deterrents.

![FIGURE 1. The balance between the electron diffraction disc and the spherical and chromatic aberrations errors for an uncorrected lens (Cs = 5mm, Cc = 3.5mm) and a lens operated in retarding mode (Cs and Cc equal to 500 micrometers) at a beam landing energy of 800eV. It is assumed that the energy width of the electron source is 0.3eV](image-url)
FIGURE 2. The imaging depth of field for the uncorrected and corrected lens configurations of Figure 1. For comparison specified depth of field data from the ITRS Road Map is shown to the routine employment of such a technique.

In summary, choosing to do nothing other than to incrementally improve the current arrangement is a safe and commercially viable solution, but presents only limited opportunities for performance improvement and leaves several insuperable areas of difficulty unresolved.

(b) the high energy route

An alternative scenario is to abandon the search for even lower energies and to move, instead, in the opposite direction towards higher energies. Since such a move flies in the face of received wisdom overemphasizing the understandable skepticism will require significant experimental data and theoretical support even though the benefits of making such a change are clear. First, raising the beam energy provides much improved gun brightness without the need for any new technology or development. Thus a conventional Schottky source at 20keV has higher brightness than a nanotip at 200eV, and another order of magnitude more brightness at 200keV. Second, at higher beam energies chromatic aberration, resulting from the inherent energy spread of the source, rapidly ceases to be the dominant aberration. This not only allows a smaller probe size to be obtained but allows the use of the highly stable, although higher in energy spread, Schottky emitter in place of the less stable, but narrower in energy spread, cold field emitter without any performance penalty. Third, the minimum probe size that can be obtained falls rapidly at high energies where diffraction and spherical aberration are the dominant optical effects. The limiting probe diameter is $C_e^{1/4} \lambda^{3/4}$, so each factor of four increase in energy decreases the probe size by almost a factor of two times without the need for any lens improvement. Finally, the reduction in electron wavelength with higher energy eliminates diffraction as a problem and allows a useful (although still not ideal) depth of field to be attained without compromising the imaging resolution. From the instrumentation perspective therefore a move towards higher beam energies is highly beneficial and economically advantageous because all of the components required already exist.

The difficulties with higher energy operation relate to the problems of charging, and beam damage. The original impetus for low voltage operation was the desire to choose a beam energy equal to the “E2” cross-over [6] value so that dynamic charge balance was achieved. Irradiation of insulators at energies above their E2 energy (which is typically 1-2keV) results in the build up of large amounts of negative charge and high surface potentials because all of the beam energy is deposited within a thin polymer, or oxide, layer. Electrons with energies of 10keV or higher have a substantial range (a micrometer or more) in silicon and other device materials and so deposit their charge deep in the substrate leaving little or none in the surface resist layers. Under the condition where the incident beam penetrates insulating, or poorly conducting, layers the charging that does occur is positive in sign and self-limiting in magnitude. Because high energy incident beams are much stiffer than sub-keV beams this means that image artifacts and distortion due to charging are unlikely.

In some very difficult cases, such as the metrology of binary Lithography masks, the charging potentials...
that are induced are so large at high beam energies that mechanical damage to the sample could result (from dielectric breakdown) unless some pro-active form of charge control was initiated. This can be done by changing from high vacuum operation, to a mode in which the sample is surrounded with an atmosphere of some gas as a pressure in the range 1-100Pa. As shown in figure (3) the effect of this is to rapidly reduce the surface potential and hence to reach a stable condition leaving the surface at, or very close to, ground potential. This mode of operation, made familiar by the Variable Pressure SEMs (VPSEMs) requires little user intervention and works transparently to the operator even on the most complex samples. There are, however, a couple of problems that must be solved before this mode is suited for routine CD metrology.

(a) The electron probe is scattered by its interaction with the gas. This does not severely degrade the probe size, but it does result in a significant loss of contrast and a fall in signal to noise ratio. Figure (4) shows a high resolution image of gold sputtered onto magnetic recording tape recorded in a field emission VPSEM operating at a pressure of 400Pa (three Torr) of air. The upper half of the micrograph shows the appearance of the image as recorded. Although high resolution detail is visible the contrast is very low because of the beam scatter, and the flood of ions which also reaches the detector. The lower portion of the micrograph shows the appearance after histogram expansion to remove the unwanted background. Careful image handling will therefore be required.

(b) Conventional secondary electron detectors cannot be employed in a gas environment because they induce flash-over in the gas. Although efficient Gaseous Secondary Electron Detectors [7,8] are available these rely on displacement currents generated by ion drift in the gas. As a result the transit time of the ions becomes a limiting factor and scan speeds must be significantly slower than the TV rates employed in high vacuum tools.

A reduction in beam damage has also often been associated with operation at low beam energies. In this case, however, that conclusion is misleading. The interaction of electrons with a solid becomes stronger as their energy is lowered (Figure 5), so the rate at which energy is deposited - and the hence the amount of damage that is produced continues to increase even for energies as low as 100eV. However, the volume of the sample affected by such damage, and consequently the apparent severity of the damage, scales with the electron range and this falls as about \( E^{3/2} \). When the beam energy is increased therefore the volume of material that is subject to damage rises rapidly. As is the case for imaging, the situation will be worst when the size of

![FIGURE 4. High resolution image of gold sputtered on to magnetic recording tape, recorded at 20keV and a pressure of 400Pa. The field of view of the image is 1 micrometer. The upper portion of the image is the 'raw' image, the lower half is after digital processing.]

![FIGURE 5. The variation of electron stopping power (in eV/angstrom) for silicon as a function of electron energy E. Above 10keV the stopping power continues to fall as about \( 1/E \)]
charge implanted in gate oxide layers show that threshold shifts at 200keV would be only be a few millivolts as compared with the 0.5 to 1 volt values experienced for equivalent exposure doses at 1keV beam energy. Mizuno and others are evaluating device damage [9] to verify these predictions. The upper useful limit of beam energy is reached when knock-on damage begins. This occurs at about 85keV for carbon and about 220keV for silicon, suggesting that the energy region between about 30 and 80keV is the ideal one for experimentation.

Assuming that these predictions about charging and damage are confirmed by detailed studies it is clear that operation at beam energies far above those now in use offers significant benefits. In particular all of the advantages discussed above can be achieved using only technology that is currently available and already in production. There is thus a considerable economic incentive to investigate this route, and the expectation is that performance sufficient to meet the ITRS specification for the 65nm and 45nm technology nodes is already available.

Higher energy operation can also facilitate the task of providing a solution to one other fundamental, long term, problem in metrology. Conventional CD-SEM form their images using the low energy secondary electrons (SE) that are produced as the electron beam scans across the sample. At the edge of a line, the diffusion range of the SE signal causes an increase in intensity in the vicinity of every edge, as shown in Figure (7). This "edge bright line" in typical resists is a few nanometers in width and so degrades the accuracy with which edge positions can be determined. Further when the width of a line become comparable with the SE diffusion range then the blooms from the two edges overlap and determination of the line width is no longer possible at all, is shown in Figure (8). As a result the ultimate limit of the CD-SEM seems to be ~5nm for silicon lines, and the consequences of this bloom effect already make precision linewidth determination difficult. With a high energy incident beam an alternative, and preferable, signal collection scheme is available. This employs the low-loss electrons,
which are electrons backscattered from the specimen with energy very close (~3%) to that of the incident beam [10,11]. These electrons can be guaranteed to have only traveled a small distance in the sample before having been ejected as the result of a single, high angle, scattering event. The predicted spatial resolution is limited only by the probe size of the beam, since there is no diffusion problem to consider. The signal is closely related to the geometry of the feature, simplifying the analysis of profiles, and charging is of negligible consequence. The problems with the Low Loss Method are the low signal level available because of the small fractional contribution of quasi-elastically scattered electrons, the need to energy-filter the signal to exclude electrons other than the low loss component, and optimizing the geometry to permit full-wafer coverage at normal incidence. These difficulties are not fundamental in nature and work is presently in progress to provide solutions.

(c) a step beyond - novel technologies

A third scenario is to abandon any attachment to the concept of metrology based on the SEM and to look for some solution that wins by avoiding all of the pitfalls to which conventional microscopies are prone. Excluding optical approaches and electrical methods the technique which best matches such a profile is electron holography. In the words of Diebold [12] “the beauty of electron holography is that it accomplishes the goal of ‘Process control through amplification and averaging microscopic changes’ ”. Holography simply implies the use of coherent electron illumination to generate interpretable interference patterns (or holograms). One proposal for doing this [13] is to use the Point Projection Microscope (PPM) topology. In this arrangement (Figure 9) a coherent electron beam from an atomic-sized nano-tip field emission source is reflected at roughly normal incidence from the sample and the hologram is formed above the specimen onto a CCD camera. The PPM illuminates a ‘footprint’ which is ten to twenty micrometers in diameter, and a hologram can be recorded in very rapidly so the possible throughput is high. Figure (10) shows an example of a reflection hologram recorded in a PPM from a sample irradiated at about 300eV energy. Multiple fringes can be seen decorating all the features of the object. For performing metrology the holograms can be treated in two distinct ways. In one approach the hologram is transformed into Fourier space. A spatial frequency analysis of the transformed holograms then provides a readout of all the line edge pair spacings in the footprint area. Since the hologram can be recorded in just tens of millisecond, and the frequency analysis can be performed in real time, this approach offers high speed statistical metrology. Alternatively the holograms can be reconstructed to yield a real-space image, allowing the linewidths of individual features to be measured as required. This route also permits the three dimensional form of a line to be...
reconstructed from the hologram allowing one to obtain information about the sidewall. Thus the PPM both amplifies microscopic changes, and provides statistical information over the analyzed area. Although the principle of the PPM is straightforward the development of a practical realization of the tool has been slowed by practical issues such as charging, the problem of achieving adequate mechanical stability for the nanotip, and the need to develop electron-optics which can make the PPM simple to use while maintaining it essential nature. As a result it is likely that one of the alternative routes discussed above will be a more likely candidate for 45nm node measurements [14].

Conclusions
The CD-SEM has become a vital tool in the production of high performance devices. Over a period of two decades it has been possible to continuously improve it so that it has kept pace with decreasing feature sizes while offering improved precision and faster throughput. However, as a result of the choices that have had to be made in order to deal with the effects of charging and beam damage the prospects for continued improvements in the CD-SEM as it now exists are doubtful. The alternatives that exist both abandon the familiar concept and take new directions. In one case the change would be to high energy operation, possibly accompanied by the use of a ‘low vacuum’ environment to eliminate charging and the use of low loss electrons to enhance resolution. In the other case the idea of imaging and site specific measurement would be replaced by the use of holography and statistical analysis. Both approaches would, in principle, be capable of providing metrology at a level capable of reaching the 45nm node or beyond. However the effects of economics, and the constraints of time, cannot be ignored and it may be that the high voltage mode is the best approach because it can be accomplished most cheaply and rapidly since it relies only on existing, and commercially available, technologies.

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References