9-18-1987


David C. Joy
University of Tennessee

Follow this and additional works at: https://digitalcommons.usu.edu/microscopy

Part of the Biology Commons

Recommended Citation
Available at: https://digitalcommons.usu.edu/microscopy/vol2/iss1/6

This Article is brought to you for free and open access by the Western Dairy Center at DigitalCommons@USU. It has been accepted for inclusion in Scanning Microscopy by an authorized administrator of DigitalCommons@USU. For more information, please contact digitalcommons@usu.edu.

David C Joy
EM Facility, University of Tennessee and Metals and Ceramics Division, Oak Ridge National Laboratory

(Received for publication May 01, 1987, and in revised form September 18, 1987)

Abstract
The interpretation of high resolution secondary electron images, and quantitative measurements of micrometer size features on integrated circuits, both require accurate modelling of the process of image formation in the scanning electron microscope. A Monte Carlo model, based on the semi-empirical theory of Salow, has been developed which permits the simultaneous computation of the secondary and backscattered yields. The physical constants necessary to apply this model can be derived from straightforward measurements of the total electron yield as a function of beam energy. On the basis of simplifying assumptions line profiles and images can then be simulated for specimens of a given geometry. The application of this technique to the problem of critical dimension metrology in the SEM is illustrated. A comparison of computed and experimental data shows that good qualitative and quantitative agreement is achieved, the quality of the comparison being limited mainly by the poor signal transfer characteristics of the video-chain of the microscope and effects such as sample charging which are not considered in the simulation.

Key Words Secondary electrons, Monte Carlo simulation, backscattered electrons, critical dimension metrology

Address for correspondence
David C Joy, EM Facility, Dept. of Zoology Walters Life Sciences Building, University of Tennessee, Knoxville, TN 37996 Phone No. (615)-974 3638

Introduction
Transmission electron microscopists have made extensive use of computer simulations as tools for image interpretation. Scanning electron microscopists, on the other hand, have almost always relied on analogies as a means of understanding the images produced by the scanning electron microscope (SEM). While this approach is successful enough when the microscope is restricted to qualitative tasks, and is operated at medium and low magnifications, it is not adequate when the instrument is performing at near atomic levels of resolution or when quantitative information, such as the width of a feature, must be extracted from the image. In such cases detailed modelling of the process of image formation is necessary if the micrograph is to be interpreted correctly. This paper describes one approach which allows secondary and backscattered signal intensities to be calculated for a specimen of arbitrary geometry and hence permits the computation of line profiles or two-dimensional images of features of interest.

The Secondary Electron Image
Secondary electrons are those with energies less than about 50eV produced from the specimen under the bombardment of the incident electron beam (Seiler 1983, Reimer 1983). Although secondary electrons are produced at all points along the trajectory travelled by the incident electron as it moves through the specimen, since the secondaries are low in energy and so have mean free paths (MFP) of just a few nanometers, only secondaries produced within a short distance of a surface will escape and form part of the detected signal. Following Drescher et al. (1970) it has been usual to refer to these various components as SE1, SE2, and SE3. However, as pointed out by Peters (1984), these components differ not only in their origin but also in their information content. Since they have very different spatial resolutions, this implies that the form of the image, and the nature of the contrast that it is displaying, will vary with the resolution and magnification of the microscope. Thus, for

57
independent of the beam position, and so constant. Thus the expected.

Based on this analysis, Peters (1984) has provided magnifications, where the pixel size is comparable with the order of the secondary electron escape depth or less will the example, only in those cases where the pixel size is of the necessary to be able to model both the generation function and the final image from SE3 electrons will vary with the instrument and may range from zero to as high as 50%.

In terms of what must be done to compute the form of an image, Peters' analysis can be re-stated in the following way. The secondary signal leaving the sample is the product of two terms:

\[ \text{SE signal} = \text{generation function} \times \text{escape probability} \] (1)

There are then three important cases corresponding to the secondary components discussed above.

**SE1** Since the mean free path of the incident electron is, except at low beam energies (i.e., less than 2keV), much greater than the MFP for escape of the secondaries then within the escape region the incident electron is effectively unscattered and the generation function is uniform. Consequently, the SE1 contrast is controlled by the escape probability. Note that this will be invariant with beam energy.

**SE2** The generation function is determined by the total backscatter signal passing through the escape region. The escape probability, however, will depend on individual escape paths available to the secondaries in this region and these may vary significantly from point to point without changing the backscatter yield. Thus, while the generation is controlled by the backscatter yield, the SE2 signal will not necessarily be identical in either information or resolution to the BSE signal.

**SE3** The generation function is proportional to the total backscatter yield from the sample. Since the secondaries are produced over the whole irradiated area of the polepiece and walls, the escape probability will be effectively independent of the beam position, and so constant. Thus the SE3 signal will carry the same information and resolution as the BSE signal. Since the presence of the SE3 signal is an artefact of the microscope, however, the contribution to the final image from SE3 electrons will vary with the instrument and may range from zero to as high as 50%.

When attempting to compute contrast it is clearly necessary to be able to model both the generation function and the escape probability for the specimen of interest. The resolution with which this can be done will determine the conditions under which the resulting calculation is valid. In order to compute SE1-type contrast, both functions must be known at a resolution better than the secondary electron mean free path, i.e., a few nanometers. If the data is only known at a resolution of tens of nanometers or worse, then the calculation can only produce results for the SE2 (and related SE3) contrast modes.

**Modelling SE Production**

As discussed above, the calculation of secondary electron production involves two steps, specifying a generation function, and then a secondary electron escape probability. In the procedure used here the starting point for the generation function is a Monte Carlo simulation of the incident electron trajectories. For computations of SE2 (and SE3) images, i.e., for simulations of images obtained at magnifications of 10,000x or less, a plural scattering model is used (Joy 1986, 1987; Love, et al. 1977; Bishop 1979; Myklebust, et al. 1979). This divides the electron range into typically 60 steps of approximately equal length, and models the trajectory with these segments. The "resolution" of the simulation is therefore of the order of 2% of the electron range. Thus, at 15keV in silicon the resolution would be 50 nanometers, while at 5keV it would be 10nm. These values are consistent with the expected pixel resolution, of a few tens of nanometers, in the images of interest.

Secondary electron generation is incorporated into the trajectory simulation using the semi-empirical approach described originally by Salow (1940), and developed later by others (e.g. Dekker 1958). Consider an incident electron of energy \( E \) at some depth \( Z \) beneath the surface. The number of secondary electrons, \( N \), produced is

\[ N = \frac{-1}{\varepsilon} \frac{dE}{dZ} \] (2)

where \( \varepsilon \) is the energy needed to produce one secondary electron. When moving from the continuous analytical model to the numerical Monte Carlo method the energy loss \(-dE/dZ\) is replaced by the energy deposition, determined from the Bethe law or some other expression, occurring along each segment of the calculated trajectory. Given a suitable value for \( \varepsilon \) the secondary generation function is thus fully determined.

For a flat surface normal to the incident beam the escape probability is also readily determined. The secondaries are assumed to diffuse away from their point of creation with a characteristic length \( \lambda \) (Dwyer and Matthew 1985, Powell 1984). The escape probability from an isotropic source of unit strength located at a depth \( Z \) beneath the surface is then

\[ I(\theta,Z) = \exp\left(\frac{-Z}{\lambda \cos(\theta)}\right) \] (3)

where \( \theta \) is the angle of emission relative to the surface normal. Ignoring the effects of refraction and reflection at the surface, the integrated escape probability \( p(Z) \) from depth \( Z \) is then (Wittry and Kyser 1965)

\[ p(Z) = 0.5 \exp\left(\frac{-Z}{\lambda}\right) \] (4)

In the Monte Carlo generation model the production of secondaries is assumed to occur uniformly along each step of the trajectory. If the \( Z \) coordinates of the start and finish of

![Diagram](image-url)
the k-th trajectory step are Z_k and Z_{k+1} respectively, then the corresponding escape probability to the surface \( p(Z_k, Z_{k+1}) \) becomes

\[
p(Z_k, Z_{k+1}) = \frac{0.5 \lambda}{(Z_k - Z_{k+1})} \left\{ \exp\left(\frac{-Z_k}{\lambda}\right) - \exp\left(\frac{-Z_{k+1}}{\lambda}\right) \right\}
\]  

Equations (2) and (5) together with the Monte Carlo simulation provide the complete generation and escape probability function for the incident electron along its path. By simulating a suitably large (5000-10000) number of trajectories the secondary, and simultaneously the backscattered, yield from the material can thus be calculated provided that the relevant material characteristics and the parameters \( \varepsilon \) and \( \lambda \) are known.

A computer program embodying all of these steps has been written in "Turbo Pascal" (Borland International, Scotts Valley, CA 95066) to run on IBM compatible personal computers equipped with an 8087 floating-point processor. The code is relatively short (about 300 lines) and, depending on the hardware in use, computes two to three trajectories per second. Statistically, meaningful results are therefore produced in a reasonable time. Source code listings of the program are available on request from the author.

**Experimental Tests of the Model**

In order to be able to apply this model, values of the parameters \( \varepsilon \) and \( \lambda \) must be supplied. The procedure used here has been to measure the sum of the secondary yield \( \delta \), and the backscattered yield, \( \eta \), as a function of incident beam energy for samples of interest and then iteratively determine the values of \( \varepsilon \) and \( \lambda \) which match this experimental data over the energy range. \( \delta + \eta \) is readily measured in the SEM using a calibrated specimen current amplifier and a Faraday cup. If the incident beam current measured in the Faraday cup is \( I_b \) and if the measured specimen current on a horizontal and featureless region of the sample is \( I_s \), then by current balance

\[
-I_b + (\delta + \eta) = I_s = 0
\]

from which \( \delta + \eta \) is given directly. If the obvious precautions are taken then values reproducible to about 5% are obtained (Joy 1987). Data of this type is also available in the literature for a few materials (e.g. Seiler 1983, Moncrieff and Barker 1978) and has also been used.

Figure 2 plots the experimental yield \( \delta + \eta \) for copper over the energy range 1 to 30keV, and the corresponding predicted yield curve derived from the computer model discussed above and with the parameter \( \varepsilon \) equal to 125eV, and \( \lambda \) equal to 2.5 nm. The agreement between the experimental and predicted data is seen to be good over the whole energy range. Equivalently, encouraging results have also been obtained for a wide range of other elements and compound materials since in each case it has been possible to find values of \( \varepsilon \) and \( \lambda \) which reproduce the experimental data over the desired range with good accuracy. Thus, the validity of the type of approach is established, and the same principles can now be extended to more complex but useful geometries.

**Computation of Signal Profiles**

The practical application of the principles discussed above will be illustrated in the context of "critical dimension metrology". As the size of semiconductor circuitry has decreased, the problem of measuring and verifying the width and spacing of individual structures in the integrated circuit has increased. Since many such features are now submicrometer in size, optical methods are of limited value and so the scanning electron microscope is increasingly used as a tool with which to attempt to make such measurements (Postek and Joy 1987). The assumption of the metrologist is that the secondary electron line trace across the feature of interest is interpretable in terms of the geometry of the feature, given a knowledge of the electron-optical and other relevant parameters. Leaving aside the substantial experimental difficulties involved in designing, setting-up, and calibrating a microscope for this type of operation (Postek and Joy 1987), a key problem is then predicting what form the signal profile would have from features of given geometry under variable experimental conditions, so that general algorithms capable of extracting the relevant data can be devised and tested. A comparison of predicted and experimental profiles also helps to identify the problems and limitations in the microscope optics and electronics that might otherwise be unnoticed. However, to be useful the simulations performed must be fully quantitative, rather than simply illustrative.

To demonstrate the general principles involved, let us take the simple case of a silicide conductor strip, one micrometer wide and 0.7 micrometers high, laid down on a substrate of oxide (i.e. SiO). The geometry is shown in cross-section in figure (3). To predict the signal profile it is necessary to be able to compute the secondary yield for an 0.7 microns Oxide

![Cross-section of silicide line structure on an oxide substrate typical of the features of interest in line width measurement.](image)

\[\text{Si licon substrate}\]

\[\text{0.7 microns Oxide}\]

\[\text{1.4 microns}\]

\[\text{0.7 microns}\]

\[\text{0.7 microns Oxide}\]

\[\text{1.0 microns}\]

\[\text{Si licon substrate}\]

Fig. 3. Cross-section of silicide line structure on an oxide substrate typical of the features of interest in line width measurement.
computations are required to produce the entire profile. Typically, calculations are made at points spaced by 10nm or so, and thus many computations are required to produce the entire profile.

The generation function is obtained using the Monte Carlo model in the way discussed above, although the simulation itself has to be generalized to account for the fact that the beam will pass through more than one material. More account must also be taken of defining what constitutes a backscattered electron. Electrons leaving the strip with a component of velocity towards the substrate will not form part of the BSE signal but will re-enter the specimen where they efficiently produce secondary electrons because of their energy and angle of entry. Each electron leaving the specimen is therefore tested to see if it will be recollected and, if this occurs, the trajectory simulation is continued from the new impact point until the electron finally comes to rest or permanently leaves the specimen.

The secondary electron escape probability function also requires generalization since the expression of equation (5) applies only to a single, infinite, surface. When, for example, a secondary is produced within the silicide strip there are three possible surfaces, and consequently the escape probability is higher. The procedure used here is to calculate the perpendicular distances between the start and finish of each trajectory step and each of the surfaces defining the volume containing that step. If these distances are \( A \) and \( A_1, B \) and \( B_1, C \) and \( C_1 \) etc., then the escape probability is:

\[
p = p(A, A') + p(B, B') + p(C, C') + \ldots
\]  

(7)

where

\[
p(A, A') = \frac{0.5 \lambda}{(A - A')} \left\{ \exp\left(\frac{-A}{\lambda}\right) - \exp\left(\frac{-A'}{\lambda}\right) \right\}
\]  

(8)

It is clear that this approximation is an over-simplification since it does not take account of the relative solid angles subtended at the generation point by each of the exit surfaces. As a result, the escape function tends to be overestimated in regions close to edges and corners. However, because the exponential terms decay in a distance of order \( \lambda \) the error is confined to a region which is narrow in comparison with the resolution of the simulation and so does not form a major limitation to the utility approach. This simplification is not valid for higher resolution simulations however, and in such cases an exact tabulation of the escape probability must be calculated and used (Joy 1987, to be published).

**Results**

Figures (4) and (5) show computed secondary electron profiles across the feature of figure (3) at beam energies of 10 and 5keV respectively. The profiles displayed are for the computed emitted secondary signal, which for this level of resolution is essentially SE2 type. If the effects of an SE3 component were of interest then the corresponding backscatter profiles would be added, at some appropriate level, to the secondary profiles to account for the SE3 contribution. Each line profile comprises 512 data points, at a uniform spacing of 10nm, of which number approximately 50 pixels were directly calculated, while the rest were obtained by interpolation and reflection about the center of the feature. The data for each beam position represents the integrated result of 5000 trajectories and the statistical scatter in the data results from the limited number of trajectories simulated at each pixel. The original computation assumes a point electron probe for generality, but the profiles as shown here have been convoluted with a Gaussian 25nm FWHM for the effect of finite probe diameter.

The dotted lines on figures (4) and (5) are the result of experimental measurements from features identical to that shown in figure (3). This experimental data was recorded on a Cambridge 250 SEM using a microcomputer-based system to scan the beam at 10nm steps and digitize and record the signal. The pixel step and probe size were chosen to correspond to those used in the simulation. The computed and experimental data have been scaled so as to match signal intensities from the substrate at a point far from the feature. This was achieved by blanking the beam at the end of each experimental line profile to allow the true zero-level of the data to be established. The profiles therefore compare both the relative form and the true absolute magnitudes of the experimental and simulated data.

The level of agreement, both relative and absolute, is seen to be excellent especially in the critical edge regions at both beam energies. The shape of the edge profile, on which all the measurement algorithms depend, is very well simulated and the ratio of the peak edge signal to the substrate level is also accurately predicted showing that the absolute secondary yields computed from the model at both energies are correct. The greatest discrepancy between the measured and computed data occurs in the center of the feature in each case. While this certainly results from some of the limitations of the simulation, it is also equally certain that the experimental data is deficient. This is because, even on research quality SEMs, the bandwidth, slew-rate, and DC restoration characteristics of the video chain are only marginal at best. Consequently, the profile as recorded is corrupted by the recording system and especially at any point where signal levels are changing rapidly. Substrate charging also affects the measured form of the profile. While no problem was encountered at 10keV, because the beam range in the oxide was sufficient to deposit the majority of the energy into the underlying silicon, charging was visually evident in the image at 5keV unless care was taken to minimize the beam current and recording time.

**Summary**

The procedure described here for the simultaneous computation of secondary and backscattered electron yields is capable of predicting both the form and the absolute magnitude of contrast effects at the submicrometer level with good accuracy. Realistic simulations of contrast effects in secondary electron imaging are now, therefore, possible. An application of this technique to linewidth measurement shows that, while refinements are undoubtedly necessary, the quality of the simulation is high enough for it to be a suitable tool for basic studies of the theory and practice of metrology in the SEM.

**Acknowledgments**

The author is grateful to Drs. D. K. Atwood, D. E. Newbury, M. Postek and K-R Peters for valuable discussions on various aspects of this work.

**References**

Bishop H E, (1979), "The history and development of Monte Carlo Methods", in Use of Monte Carlo Calculations in EPMA and SEM, ed K F J Heinrich, NBS Special Publication #460, p5-15


Z. Radzimski: The component SE3 of the total detected SE signal depends on the geometry of the SEM chamber and then the efficiency of SE collection. Are these factors somehow included in the present calculation?

Author: The SE3 signal carries the same information as the backscattered (BSE) signal. The effect of an arbitrary SE3 component being added to the SE1 and SE2 signals can therefore be simulated by adding some fraction of the BSE profile to the corresponding SE profile. The magnitude of the BSE contribution is found by achieving the best match to experimental data.

Z. Radzimski: How universal are the values $\epsilon$ and $\lambda$ for certain material and for a wide energy range of primary electrons. How is $\epsilon$ related to surface state (what do you mean by "if obvious precautions are taken" in sample preparation)? Do you expect that $\epsilon$ and $\lambda$ can be decomposed to more fundamental physical parameters?

M. T. Postek: What effect does sample contamination play in the acquisition of the experimental data for the modelling factors $\epsilon$ and $\lambda$, and what measures have been taken to reduce this as a potential problem?

Author: The values of $\epsilon$ and $\lambda$ for a given material certainly depend on the state of cleanliness of the sample surface. In the experiments cited here the "obvious precautions" that were taken consisted of chemically cleaning the surface of oxide or hydrocarbon residues before insertion in the SEM, and operating the instrument in such a way that no visible contamination was built up. Samples prepared to this level of cleanliness give reproducible results in a particular SEM. Insufficient cross-checking has so far been done to make a definite judgement, but preliminary results show that for materials such as C, Si, Cu, Ag, Au, different workers in...
other laboratories using different microscopes, get electron yield data which is close enough to that originally reported to return values of ε and λ that are close to those given here. Experiments on materials that easily oxidise or contaminate, or that are performed in instruments which are of poor vacuum quality, will certainly give more variable data, reflecting the fact that the total electron yield is no longer a uniquely defined property of the specimen.

ε and λ cannot be decomposed to fundamental physical parameters because in both cases they represent averaged properties of the sample. ε effectively represents the initiation of energy of the cascade process which generates the secondaries, and λ represents the energy-weighted mean free path of the secondaries in the cascade from the initiation energy to their escape energy.

L. Reimer: I doubt that it is possible to accurately measure (ζ+π) in an SEM unless special precautions are used (e.g. Reimer and Tolkamp, Scanning 3, p 35 (1980)).

Author: The problems associated with measuring anything in the SEM are considerable. The measurement performed here is probably the simplest since no separation of BSE from SE is required. The major sources of error are recollection of signal by the sample background irradiation by scattered electrons, charging of the sample or its surroundings, leakage currents, and the precision of measuring device used. The precautions mentioned in the text attempted to eliminate or reduce each of these problems. Thus, problems due to recollection were minimized by using a long working distance (and tested by irradiating an adjacent but electrically isolated gold foil), measurement and leakage errors were reduced by using relatively high beam currents, and charging was eliminated by thick carbon coating of all exposed surfaces.

Z. Radzimski: Backscattered electrons are widely accepted for surface reconstruction in the SEM as well as in electron beam lithography (registration mark detection). What advantages are involved in using SE for the kind of quantitative measurements discussed in this paper?

Author: As shown by Reimer, Riepenhausen and Schierjott ("Signal of backscattered electrons at Edges and Surface Steps", Scanning 8, p 164-177, (1986)) BSE signals are indeed of value for metrology. The reason for the concentration on SE signals is that the design of a backscatter detector suitable for low voltage, high bandwidth, operation is a difficult problem, especially when a large solid angle of collection is required and little chamber space is available. As a consequence most current commercial instruments use secondary electrons because the detector system can be placed out of the way (e.g. through the lens) while still remaining efficient. This situation may well change as better BSE detectors become available.

L. Reimer: I do not agree with the sentence "at lower magnifications SE2 and SE3 contrast will dominate". Just at these magnifications we have the most important contrast information of δ(ϕ) by surface tilt. I propose to distinguish between contrast present at any magnification (surface tilt contrast, for example) and contrast caused by the diffusion or MFP of secondaries. I assume you mean the latter?

Author: Both SE1 and SE2 (with SE3) electrons have a "tilt" contrast component. Since the SE1 signal is defined as coming from the unscattered incident electron (K-R Peters, "Generation, collection and properties of an SE1 enriched signal", in Electron Beam Interactions, D F Kyser et al., Eds., SEM Inc.:Chicago, p 363-372, 1984) however, its "tilt" contrast component is a function of the surface environment within a few λ of the beam point. At low magnifications point-to-point variations in the SE signal arise from topography on the scale of the interaction volume, and so are a function of the SE2 and SE3 signals. It is true that the SE1 signal is contributing but its contribution is constant, since the probe diameter is much greater than λ. At high magnifications the situation is reversed since the field of view is now smaller than the interaction volume. Thus, the SE2 and SE3 components are constant and only changes in SE1 yield can generate contrast.

L. Reimer: Please make a critical appraisal of the approximations used in your paper. For example, is equation (3) in accordance with modern theories of SE emission from such workers as Schou, Bindi and co-workers, Rosler and Braver?

Author: This paper makes two fundamental assumptions. First, that the yield of secondary electrons is proportional to the stopping power of the target (equation 2). This assumption is central to all models and theories of SE production. Second, that the escape of secondaries is determined by the dynamics of the cascade model. Equation (3) then represents a particularly simple statement, "the straight line approximation", which can be derived from this model. The cited paper by Dwyer and Matthew (1985) examines this straight-line approximation and concludes that it gives an adequately accurate representation of the physical situation when compared with other more complex theories. Under the experimental conditions assumed here, where the pixel resolution is several hundred angstroms, this model is certainly accurate enough because all dimensions are large with respect to λ. At higher magnifications where this is not true more thought is required in order to correctly compute the true escape probability. None of the predictions made on the basis of these assumptions are in contradiction with any experimental data of which I am aware.

L. Reimer: It is not clear what differences in the calculated linescans are, when considering the generation depth and exponential path effect of SE and using SE emission at the point where the BSE leave the surface. In the linescan there are 100 channels per micrometer or 1 channel per 10nm, so what sense is it to calculate with a MFP of 2-5nm?

Author: The SE emission is not calculated at the point where the BSE leave, but at all points along the electron trajectory. It is the proximity of each step of the trajectory to the adjacent surfaces and edges that determines the SE yield.
Modelling a profile at 10nm steps implies that structure on a finer scan can be neglected, thus the surfaces can be treated as flat and smooth. Variations on the scale of 10nm or larger have plenty of effect on secondaries with an MFP of 2.5nm, e.g. 10% of the emitted electrons emerge from depths greater than 3λ.

**L. Reimer:** This paper is not a real theory or calculation scheme of SE emission, but a modification of the older Monte Carlo method for BSE, where one only assumes a proportionality of SE generation considering the direction of PE and BSE through the surface and their energy.

**Author:** As indicated above the fundamental assumption of this paper are common to all recent models of SE emission. By coupling these assumptions to a Monte Carlo model the essential information on stopping power and depth distribution is found in a physically realistic way. This approach has been successfully applied before (e.g. R. Shimizu, "Secondary electron yield with primary electron beam of kilo-electron-volts", J. Appl. Phys., 45, p 2107-2111, (1974), and K. Murata, "Monte Carlo calculations on electron scattering and secondary electron production in the SEM", Scanning Electron Microscopy 1973; II:267-275) and this paper simply extends and generalizes that earlier work. The ultimate test of any method is whether or not good data can be computed using it. As demonstrated here the model predicts both absolute yields and line profile shapes with a high degree of accuracy. It is therefore a useful and valid way to tackle the problem of image interpretation.

**M. T. Postek:** Would the author expand further on his comment regarding the effect of amplifier bandwidth and slew-rate on the video profile? How can these factors alter the profile?

**Author:** Because the SEM image is processed and displayed in real-time, the only record we have of the signal is what emerges from the end of the video chain. The form of this signal depends on the transfer characteristic of the amplifiers, and the desirable assumption is that this should be linear and aperiodic (i.e. not bandwidth limited). Since many SEMs have the capability of operation at TV scan rates it is often taken for granted that this implies a high bandwidth. This is not necessarily true under the more demanding set of conditions used for metrology. Normal signals represent relatively small contrast changes, 5-10% or so, on a fixed DC background, so the relevant parameter of an amplifier is its "small signal bandwidth", and this may readily be extended to 10 or 20MhZ. In metrology, however, the region of interest is the edge of the sample where the signal is not only changing rapidly but swinging from its lowest to its highest value. In such a case it is the full-signal bandwidth that is relevant, and this can be two to four orders of magnitude lower than the corresponding small signal value (i.e. 100khZ instead of 20MhZ). In addition the inability of the amplifier feedback loop to cope with the large, rapidly varying, signal (the "slew-rate" limitation) produces non-linearity and a long transitory period over which the signal base line is changing. Finally, operation under these conditions leads to strong frequency dependent phase shifts in the amplifier response. The net effect of these phenomena is to produce a profile which bears little resemblance to the variation of yield from the specimen. The contrast levels are different, the edges are shifted and distorted, and the profile is assymmetric. It is easy to demonstrate these effects on any current SEM, but less easy to suggest a way to avoid them. Certainly, the popular technique of using a TV-rate scan to fill a framestore which is then read-out by a computer represents the worst possible case, but even slow-scan methods are deficient unless great care is taken.