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DESIGN AND APPLICATIONS OF IN-SITU DIFFERENTIAL SCANNING ELECTRON MICROSCOPY

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Abstract

Contrast enhancement in the scanning electron microscope (SEM) is usually achieved by either of the two techniques of black level suppression, and differential imaging. This paper is mainly concerned with the latter method. Differential imaging of SEM images is commonly accomplished by either using a selective electronic filtering circuit (time sensitive) on the video signals, or the post processing of a collected digitized image (application of special kernel operatives). A technique is described that is capable of generating true in-situ SEM differential video signals of local sample features. Characteristics of this method are enhanced sample feature-boundary sensitivity, suppression of large background signals, and the ability to perform critical pattern alignments prior to feature measurements. Results are presented on the application of the technique to the general field of electron microscopy, as well as to integrated circuit micro-metrology.

Key Words: Scanning Electron Microscope, differential imaging, in-situ, pattern alignment, feature-boundary, stereology, linewidth, deflection.

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Introduction

The video signals generated in the SEM are most commonly fed through a series of video amplifiers that apply linear gain and a DC offset {Wells 1974, Reimer 1985}. These contrast and brightness controls are often insufficient for imaging low contrast features, particularly if a large background is present in the video signal. In many materials studies we wish to concentrate on the characterization of feature boundaries. Examples of this application include, in particular, stereology and the measurement of integrated circuit critical dimensions (IC/CD) {Morton 1972, Weibel 1979, Bennett et al 1985}. For each of these applications improved feature detection is needed to unambiguously locate feature edges with high sensitivity, as well as to be able to suppress impeding background signals.

The enhancement of feature edges is often attempted in the following two ways: i) by using frequency selective electronic filtering (time differentiation), or ii) by post processing stored digitized images, through the application of various kernel constructs {Reimer 1985}. Electronic differentiation is a time derivative phenomenon. Accordingly, the relationship between an electronically differentiated signal and the spatial variations on the sample is directly dependent on the e-beam scan speed. Since there are many situations where the lack of sufficient S/N necessitates slow scanning speeds, electronic differentiation cannot be a universal solution to the problem of contrast, as this type of differentiation is unsuitable for slow speeds. Even in those cases where one can successfully perform electronic differentiation, the resulting signal is only a representation of the x-derivative of the sample. Yet, there are important cases in which this constraint poses a severe limitation. Computer aided post processing of the digitized images, on the other hand, obviously prolongs the process of obtaining the final image. Furthermore, it should be stressed that the outcome of such an exercise essentially suffers from the limitations of the originally acquired image, such as the increased sensitivity of the signal to features along the primary scan direction.

In this paper, we describe the design and application of an in-situ differential imaging technique to general microscopy as well as metrology. A fundamental characteristic of this method is that it directly effects an enhancement of feature boundaries, by providing a true differential video signal of local sample

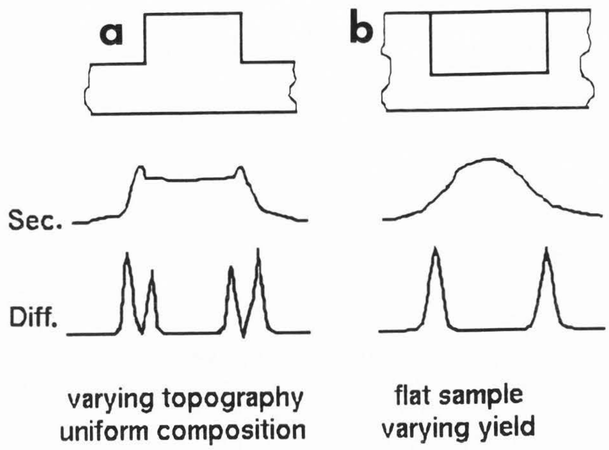

Fig. 1. Schematic overview comparing conventional secondary electron (SE) signal with rectified in-situ differential signal on two types of samples: (a) a sample with varying topography but uniform composition; (b) a flat sample of varying composition.

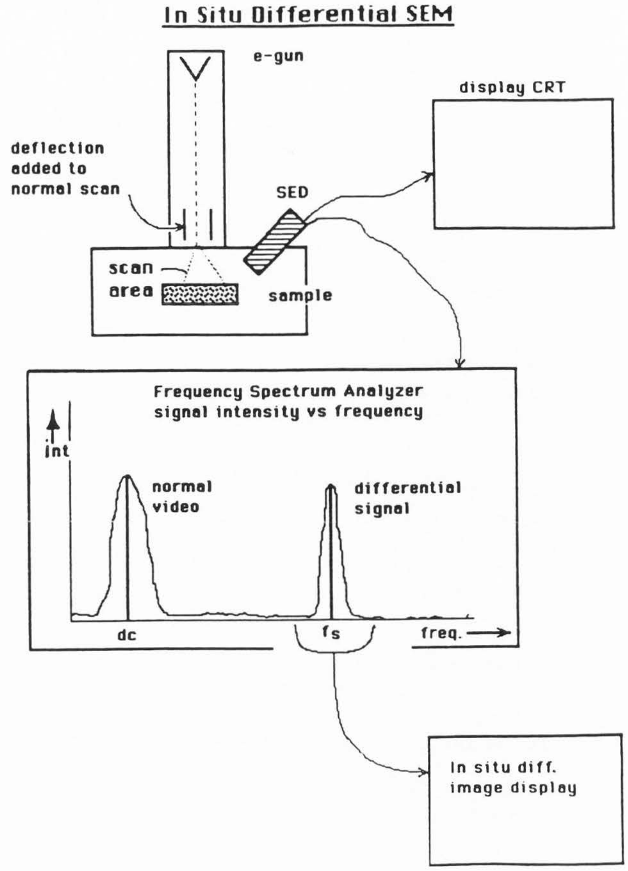

Fig. 2. Schematic of the system configuration showing how the extra deflection is added to conventional SEM, and how in- situ differential signal is extracted.

features. Since differentiation increases image clarity and sensitivity to subtle variations, for a given SEM resolution, the accuracy of feature measurement is expected to increase. These concepts are schematically depicted in Fig. 1, where a comparison is made between a conventional and a rectified-differential secondary electron (SE) video profiles of two types of samples: a sample of uniform composition but varying topography, and a sample with no topography but varying composition.

Principle

The basic aspects of the technique are best described with reference to Fig. 2. In its simplest embodiment, the method calls for a sinusoidal alteration of the relative position of the e-beam, to the sample, at a given point. This can be effected by superimposing a high frequency, low amplitude, signal on the SEM scan generation current. In the absence of a local variation on the sample, the resulting video signal consists only of a DC signal, which is representative of the general secondary electron yield (for the secondary electron mode). However, if a variation does exist on the sample, then the video signal will include a term, centered on the deflection frequency, which is a measure of the differential yield. If the deflection frequency is arranged so that the beam performs at least two deflection cycles during a given pixel acquisition time, the differential signal becomes independent of the scan speed. This enables the technique to be used with low scan speeds, to achieve sufficient S/N.

The theory of operation in the in-situ differential mode has been discussed elsewhere {Sicignano and Vaez Iravani 1988}. Briefly, for a flat sample consisting of two regions with varying yield, at the moment of the passage of the beam on the line of separation of the two regions, we can write for the output video signal:

$$I_{out}=(\delta_m+\Delta\delta\sin\omega_s t)(\cos\phi)^{-1}(1+\sin\phi) \tag{1}$$

where ϕ is the sample tilt angle, δ_m is the mean secondary electron yield of the two materials, $\Delta\delta$ is half the difference in the secondary electron yield, and ω_s is the added local deflection frequency. Here, we have assumed a zero azimuth angle between the sample and secondary electron detector (SED). In this expression, we have included only the terms in DC, and the fundamental frequency. We thus have:

$$I_{diff} \propto (\Delta\delta) \tag{2}$$

i.e. the signal obtained at f_s is proportional to the differential secondary electron yield. In a similar, though slightly more involved, way, it can be shown {Sicignano and Vaez Iravani 1988} that for the case of a sample with topography, but no material variations, the differential signal obtained at f_s is proportional to the slope of the structure under examination:

$$I_{diff} \propto (\Delta\phi) \tag{3}$$

where $\Delta\phi$ is the local variation in the sample tilt.

Typically the additional sinusoidal deflection signal (f_s) is in the 50 kHz to 500 kHz range, and its amplitude is adjusted to result in a local e-beam deflection such that the displayed resolution is not degraded. The amplitude is also adjusted for the magnification being used and the probability of encountering sample variations between pixels.

Fig. 3 shows the x (horizontal) mode of differentiation. In this mode we are sensitive to

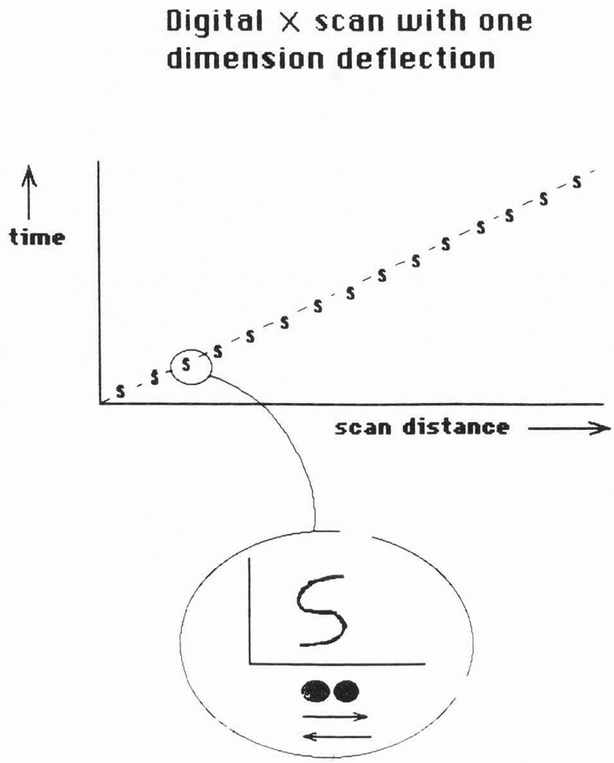

Fig. 3. x-scan mode of operation in the in-situ differential SEM, using added deflection along the x-direction.

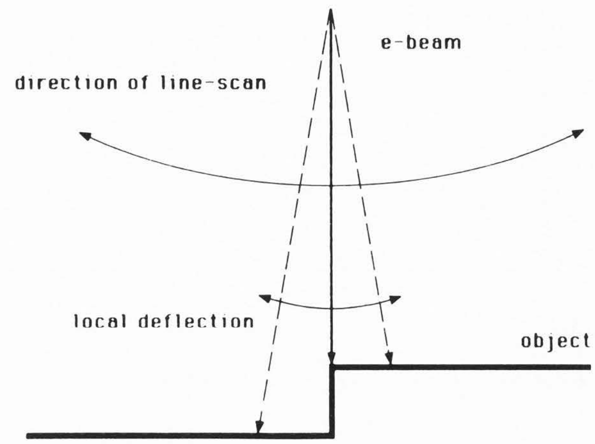

Fig. 4. Effect of added deflection on the position of beam (highly exaggerated)

Table 1. Various methods of embodiment for the in-situ differential SEM, and their effect on the signal.

Deflection Mode	Effect on Signal
X	Sensitive to vert. feature edges.
Y	Sensitive to horiz. feature edges.
X+Y in phase ≠ amplitude	Define axis of differentiation.
X+Y in quadrature = amplitude -Circular-	Equal sensitivity all directions.
Mechanical deflection	Same as electron beam deflection.
Z Thru-focus	Similar to Circular deflection.

feature boundaries along the y (vertical) direction. Fig. 4 shows the effect of the imposition of an additional periodic signal on the beam position. The various methods of embodiment for the in-situ differential SEM are listed in table 1. Feature edge detection direction can be selected by superimposing the additional deflection signal in a variety of modes. In particular, when equal amplitude quadrature signals are added to the x and y scan signals, the result is an in-situ differential video signal equally sensitive to feature boundaries in all directions of the x-y plane.

It should be noted that Balk and co-workers {Balk and Kubalek 1973, Balk et al 1975 } have previously used a similar technique, in one dimension, and have presented a number of linescans. However, the basic driving force behind their work appears to have been to generate an AC signal (which could then be detected by a lock-in amplifier) in general, and to suppress the DC bias current in obtaining EBIC/EBIV images, in particular. Such goals can, as the authors note, alternatively be achieved by intensity modulating the electron beam. Yet, the in-situ differential technique offers some unique features both in imaging as well as in metrology, and as such should be recognized as a powerful and independent imaging modality. Of particular significance is the ability of the technique to define the axis of differentiation, as we introduced above. This provides us with a reliable way to achieve feature alignment, as is discussed in the following section.

Experimental Results

We have applied the in-situ differential technique to the imaging of a number of different samples. The experimental results were obtained using a Philips 535M SEM. In all the results presented here, the differential signal was rectified. The flexibility of the technique in providing us with a variety of direction sensitive differentiation modes is illustrated in Fig. 5. Here, the conventional SE image of a pattern etched in polysilicon is shown (5 (a)), along with the x (5 (b)), y (5 (c)), and two-dimensional (5 (d)) in-situ differential images of the same sample. This series of micrographs clearly demonstrates the power of this technique in providing information about the sample

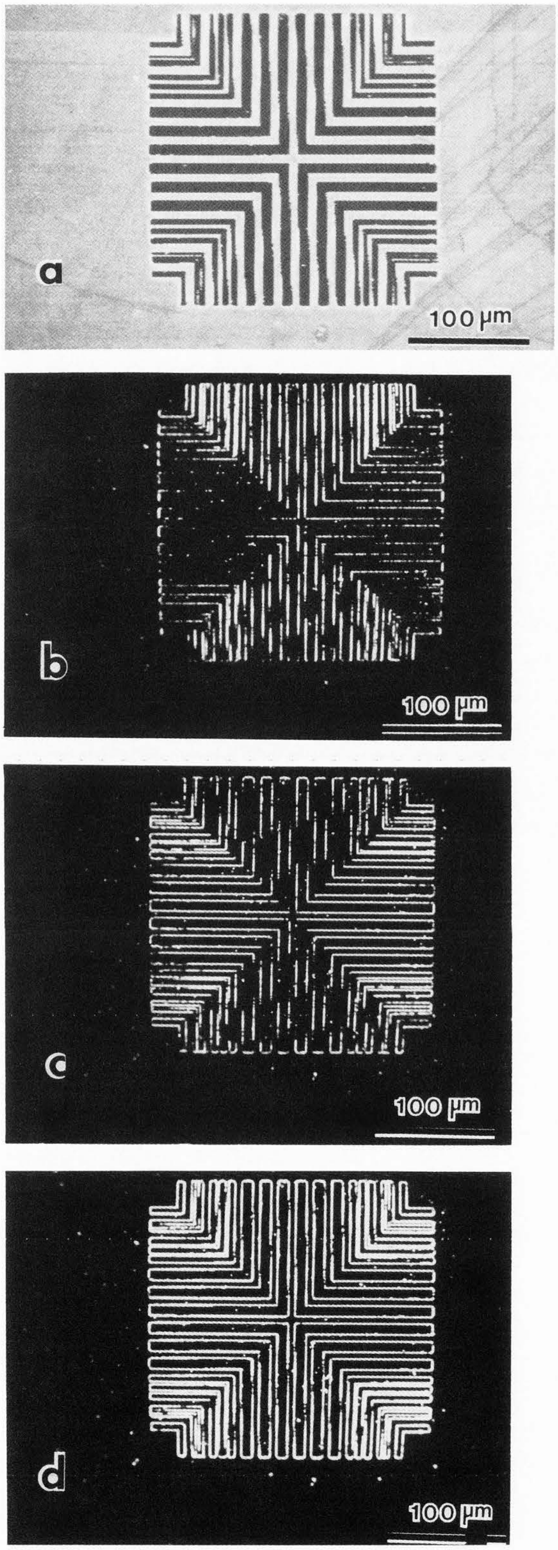

Fig. 5. Image of pattern etched in polysilicon illustrating flexibility of the technique: (a) conventional SE image; (b) is x-differential, (c) y-differential, and (d) is two- dimensional differential image.

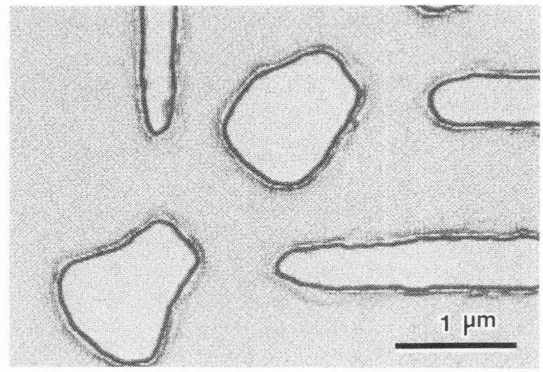

Fig. 6. Part of the pattern of Fig. 5 shown at much higher magnification, using a laser printer at negative contrast, indicating detail of boundaries.

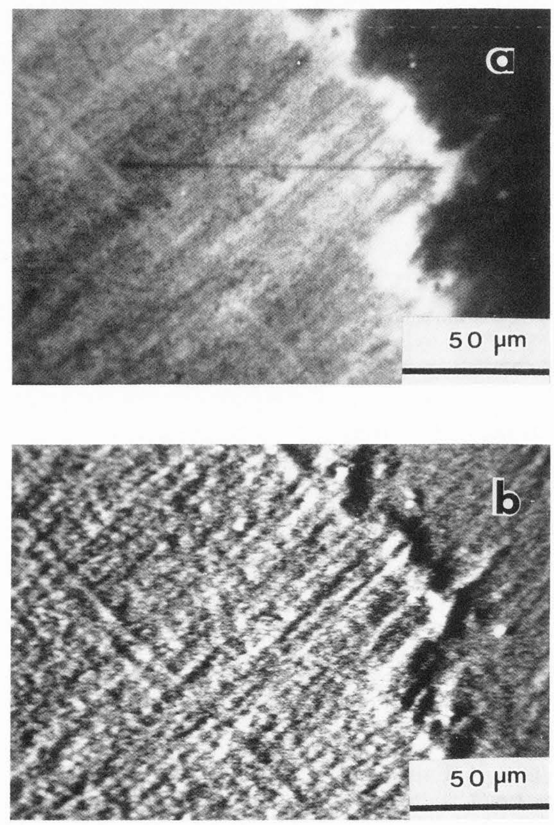

Fig. 7. Image of recrystallized polysilicon: (a) is conventional SE image; (b) in-situ x-differential image.

edges in any desired directions. The top right hand corner of the sample was imaged at a much greater magnification, and the resulting micrograph is shown in Fig. 6. This image, which was recorded with a laser printer (using negative contrast), demonstrates the ability of the method to detect the precise location of the maximum slope of the secondary emission down to a single pixel.

The application of the technique to the general field of SEM imaging is depicted in Fig. 7, where the

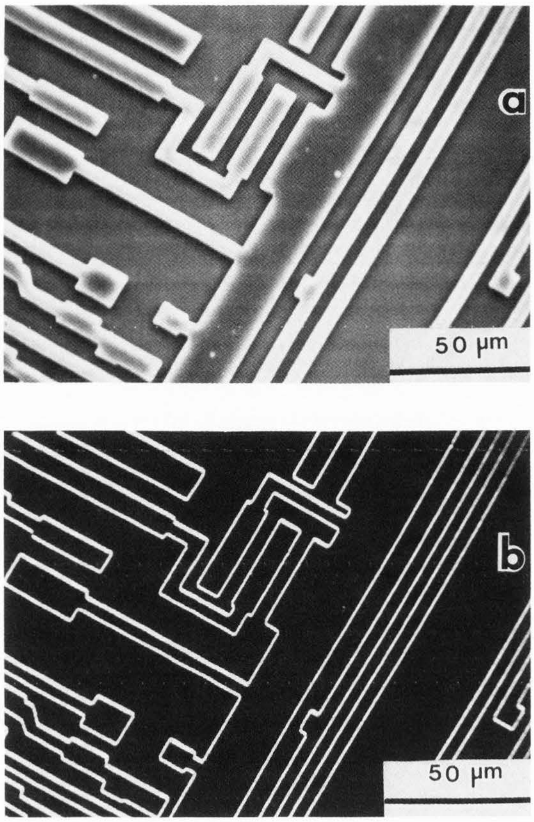

Fig. 8. A low magnification, 30 kV, image of a reactive ion etched aluminum pattern: (a) conventional SE image; (b) in-situ two dimensional differential SE signal. All Al edges appear as bright pixels.

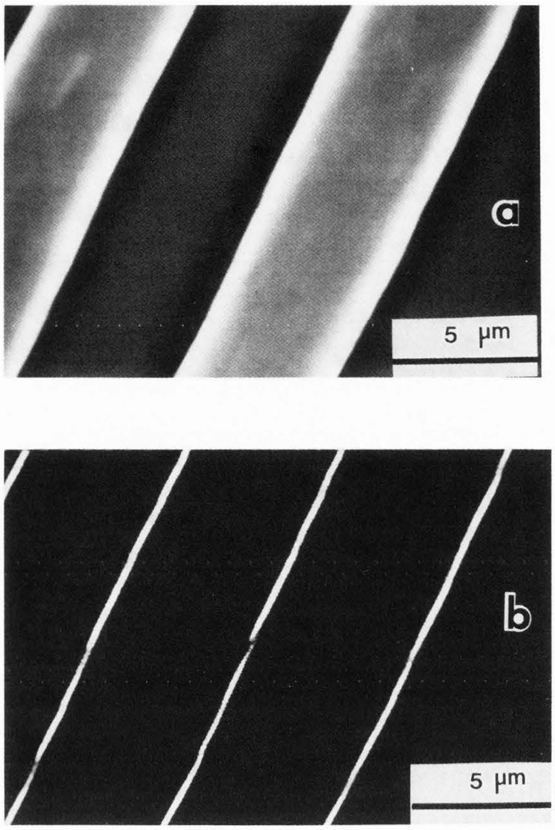

Fig. 9. A higher magnification view of the same sample as in Fig. 7, using 15 kV: (a) conventional SE image; (b) in-situ differential.

conventional, 7 (a), and in-situ x-differential, 7(b), (SE) images of a laser recrystallized polysilicon surface are shown. The deflection frequency in this case was 50 kHz. A great deal of subtle variations, mainly in the form of parallel lines running across the sample, are obvious in 7(b). These are due to small scale topography which resulted during the recrystallization process. It is particularly interesting to note that the details on the right hand side of the micrograph, where the secondary emission was poor (see Fig. 7(a)), are also equally visible in 7(b). The slight loss of lateral resolution in this figure is due to the saturation of the micrograph, as well as the fact that the deflection amplitude was somewhat greater than a pixel.

The ability of the technique to provide a feature boundary enhancement has direct applications in pattern recognition, as well as precision metrology. Here we illustrate this important point by presenting a number of different images. Figures 8 (a) and 8 (b) show the conventional and two dimensional in-situ differential SE images of a reactive ion etched (RIE) Al pattern, obtained at 30 kV. The corresponding higher magnification images of the same sample, obtained at 15 kV, are shown in Fig. 9 (a and b). The beam current in these experiments was 0.2 nA. These micrographs clearly demonstrate the power of the method in micro-pattern recognition.

An important attribute of this technique is its ability to perform differentiation in any desired direction. This aspect can be used in metrological applications, to align the features in a very precise manner. Briefly, the SEM is operated in the y-differential mode (or x-differential), and the sample, e.g. track, is positioned such that the differential signal is minimized (maximized). This ensures that the track is exactly aligned in the vertical (y) direction.

An example of the application of this method to precision metrology is shown in Fig. 10, where the 4 kV conventional SE (10 (a)), as well as the conventional (10 (b)) and the in-situ x-differential (10 (c)) inverted backscattered electron (BSE) linescans are shown. The sample in this case was photoresist on Si. Charging effects caused the SE image to constantly change. The BSE image was found to be much more stable. A Robinson type BSE detector was used for this purpose. The BSE mode provides us with a more quantitative method of performing topographic metrology {Haina and Reimer 1987}. Another example of this application is shown in Fig. 11, which depicts the conventional (11 (a)) and in-situ x-differential (11 (b)) linescans across the silicate gap of a ferrite magnetic recording head. This sample was flat, and the observed contrast was due to variations in the secondary yield. In such linescan mode applications, the differential signal provides us with precisely

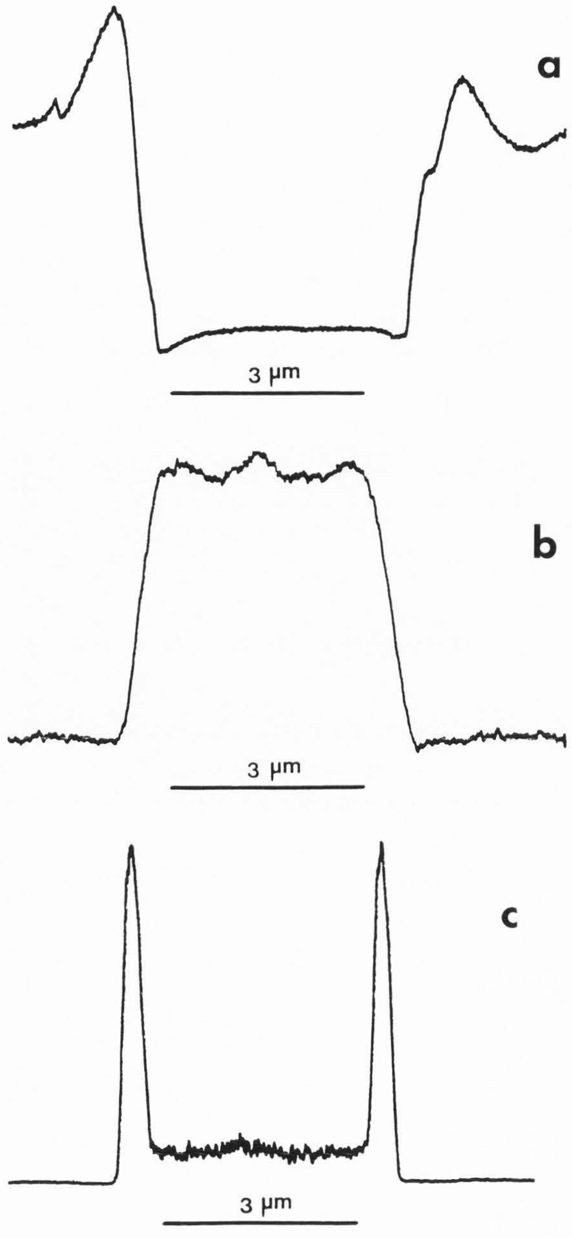

Fig. 10. Image of a photoresist line on Si at 4 kV: (a) conventional SE, showing effects of sample charging; (b) conventional BSE; (c) in-situ x-differential BSE scan.

defined peaks, corresponding to the greatest slope of the conventional signal, and well-defined zeros, corresponding to the exact positions of the maximum conventional signal. Precise metrology of such features is thus greatly facilitated.

Conclusions

The design and principles of operation of an in-situ differential scanning electron microscope have been described. The technique, which can easily be implemented in an existing SEM or STEM machine, affords selectivity in the axis of differentiation. Two

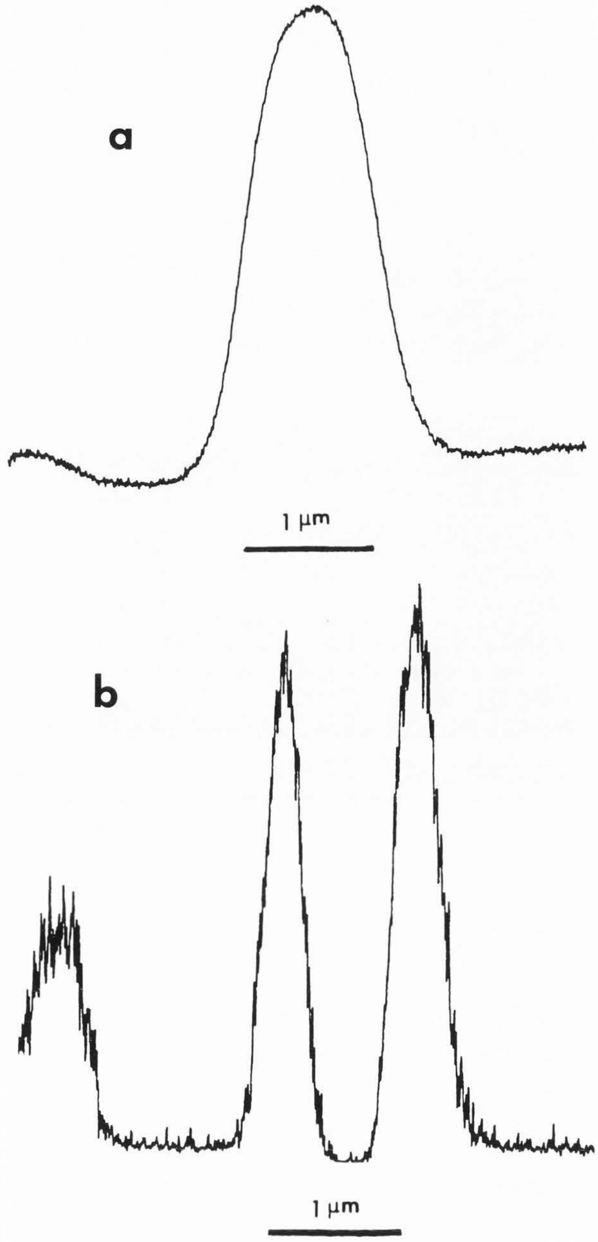

Fig. 11. Linescans across the silicate gap region of a ferrite magnetic recording head (no topography): (a) is conventional SE linescan; (b) is in-situ differential SE image, clearly delineating the ferrite-gap boundary.

dimensional spatial differentiation of samples can also be performed. In addition, the method provides us with a direct and accurate way of feature alignment. The applications of the technique in general imaging as well as micrometrology have been illustrated. We believe that the basic characteristics of the in-situ differential SEM should render the technique very useful in imaging low contrast objects, and, in particular, in precision metrology of integrated circuit critical dimensions.

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Discussion with Reviewers

P.W. Hawkes: What signal is obtained from a blunt or fuzzy feature boundary?
Authors: The simple theory of operation predicts that the AC signal obtained is proportional to the local difference in the secondary yield, or the local slope of the sample. Accordingly, the signal expected from a blunt edge would have a relatively "blunt" characteristic, i.e. a slowly varying appearance. The peak of this response, however, would still correspond to the point of maximum slope of the yield.

D.C. Joy: In a fully digitized system would you envisage applying this technique by a digital method, i.e. stepping the least significant bit of the scan signal? Would there be any merit in using the computer to scan a 3 X 3 rectangle about the nominal scan pixel so as to produce 2 dimensional edge detection?
Authors: Stepping the least significant bit of the scan signal, in a digitized system, would indeed produce a differential signal. In addition, scanning a small 3 X 3 rectangle around the nominal pixel would be the digital equivalent of the circular local deflection, as mentioned in the text. In applying such techniques, however, care has to be taken to ensure that the lateral resolution is not affected. One is assured of full resolution when the total local excursion of the beam is within a displayed resolution spot on the screen, for a given magnification.

Z. Radzimski: What is the amplitude of the high frequency signal for Fig. 8 and 9? Were the amplitudes in the x and y directions the same? Would you indicate some of the ranges on the scales in Fig. 3.
Authors: The added signal amplitude for Fig. 8 and 9 was slightly higher than would be required for a single pixel excursion of the beam. In addition, the amplitude of the signal added to the y scan was slightly higher than that applied to x. This resulted in somewhat asymmetric signal levels in the x-y directions. Figure 3 shows schematically the basic procedure for producing the in-situ differential signal in the x-direction. The positions of the e-beam spot have been shown in a rather exaggerated way for clarity. The figure does indicate that the generation of the true differential signal requires that at least two cycles are executed at each given pixel. The scan distance and the time scales are basically dependent on the individual case.

Z. Radzimski: Please clarify the sentence " In all the results the differential signal was rectified".
Authors: The differential signal due to a sample consisting of a narrow track of a material embedded in a different host material (with no topography), for example, would essentially consist of a positive peak for one edge, and a negative peak for the other edge. The detection scheme which we used, however, resulted in a unidirectional signal, which was then fed back to the display electronics of the SEM. Thus, a track would be characterized in the final image as two bright lines corresponding to the two edges.

Z. Radzimski: The accuracy of SEM metrology is mainly determined by the collection characteristics of the detection system, and the electron/material interaction. It is especially important when BSE are detected. What kind of BSE detector did you use in your experiment?
Authors: The BSE detector used was a Robinson type detector, which had a horse-shoe shaped collection cross-section, such that the detection was essentially independent of the scan/sample direction. The performance of this detector was found to be particularly satisfactory in a number of different applications.