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DATA ACQUISITION AND PROCESSING TECHNIQUES FOR VOLTAGE CONTRAST MEASUREMENTS

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Abstract

The effects of several data acquisition techniques on the accuracy of voltage contrast measurements are studied. In particular, the effect of using a voltage reference region directly connected to an external voltage source in performing the image intensity-to-voltage mapping of a node whose voltage is to be determined is examined. This is found to allow improved voltage measurement. The actual reference curves were obtained by least squares fitting the measured intensity-voltage reference data alternately to a quadratic and a cubic function. In addition, various mapping algorithms are considered including ones based alternately on the use of unprocessed, subtracted and normalized data. Using these techniques, one should expect voltage errors with means of approximately 25 mV and standard deviations of approximately 160 mV even with an unmodified commercial SEM incorporating no additional hardware to increase precision.

KEY WORDS: voltage contrast measurement, voltage referencing, image intensity-to-voltage mapping, subtraction, normalization, scanning electron microscope, integrated circuits.

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Introduction

Although the first observation of voltage contrast on the scanning electron microscope (SEM) was reported almost thirty years ago[7], the routine use of this phenomenon to measure voltages on operating semiconductor integrated circuits (ICs) has awaited the marriage of the SEM with the modern digital computer. Only during the 1980's has real progress been made in understanding and quantifying the relation between secondary electron current (image pixel intensity) and local voltage[5]. Using various electronic means such as multigrid energy analyzers and stroboscopic techniques[1,2,5] as well as image processing techniques[4], typical voltage accuracies of approximately 100 mV[1,3,6] and in some cases even of 10 mV or less[4] are reported. Unfortunately, exactly how these accuracies are measured and even how they are defined is usually omitted in the published literature.

The basic idea of voltage contrast, i.e., of a variation in image intensity caused by a local variation in the electric field near the surface of an operating IC, is rather simple. This local field is superimposed onto the field of the secondary electron collector so as to decrease (when positive) or increase (when negative) the number of secondary electrons collected at any instant. However, the exact relationship between image intensity and locally applied voltage is affected by many variables, some of which are given in Table 1.

Although much effort has been expended in investigating these areas, it is unlikely that the effects of these and other parameters on voltage contrast accuracy will ever be completely predictable in practice. Therefore it will be difficult to achieve accuracies limited only by electronic noise (on the order of microvolts[5]).

We have investigated the degree of improvement which can be obtained by using a reference region in the vicinity of a node whose voltage is to be determined. The purpose of this study is to obtain absolute voltage from image intensity measurements using referencing as well as any other data processing technique available, in this case, subtraction and normalization. Much smaller errors will result if one measures relative voltage or voltage sensitivity (the smallest detectable voltage change) as is sometimes reported in the literature.

Table 1

Factors Affecting the Relationship Between Local Applied Voltage and Unprocessed Image Contrast

DEVICE PARAMETERS
- a. Device topography and underlying structure;
- b. Material composition;
- c. Device surface condition including cleanliness;
- d. Perturbations in local electric field caused by applied voltages on neighboring nodes;

SEM PARAMETERS
- a. Operating electronic parameters (accelerating voltage, beam current, etc.);
- b. Electronic noise and drift in above parameters;
- c. Other SEM parameters (vacuum, geometry, presence of additional grids or other electronic elements, etc.);
- d. Beam and secondary electron collector angles with respect to specimen surface;

SEM-DEVICE INTERACTIONS
- a. Charging effects;
- b. Secondary electron variations from contamination buildup;

EFFECTS OF DATA ACQUISITION TECHNIQUE AND PROCESSING
- a. Area and time of integration;
- b. Settling scans before data-taking;
- c. Characteristics of A/D converter.

Sometime before the unknown voltage is measured, the reference region is ramped through a complete series of voltages from zero to the maximum applied voltage and the corresponding image intensities are stored. The resulting data are least-squares fit alternately to a quadratic and a cubic polynomial curve and the unknown voltage is determined by referencing to these curves. The effects of performing other types of data processing along with referencing are studied including subtraction and normalization. Some workers have reported that normalization is superior to subtraction[8] while others believe the two methods are equivalent[2].

Experimental Method

System Description

The experiments were carried out on an ETEC Autoscan SEM interfaced to two PDP 11/23 computers as shown[9] in Figure 1. One computer was used for SEM control and data acquisition while the other served as the device controller. In addition to the video monitors associated with the SEM, the system was also interfaced to an AED 512 color graphics terminal. With this setup, we are able to digitize 512 x 512 pixel images to 12-bit accuracy and store an 8-bit deep image in the graphics terminal frame buffer.

In addition to the previously discussed computers, a PDP 11/73 computer interfaced to another AED 512 color graphics terminal was used for all data processing and plotting.

Because the SEM was shared with clinical users, we were unable to make major modifications for research purposes. Thus, features available to many other research scientists such as energy analyzers, stroboscopic (beam-blanking) capabilities and similar features were not present. However, having these capabilities was not crucial since we were mainly concerned with the relative improvements which could be obtained using the techniques discussed.

Two 12-bit digital-to-analog converters were driven by the device control computer and could be connected to any two inputs on the device under test. This allowed the inputs to be operated in 4096 different voltage levels between 0 and 10 volts.

To allow us to monitor the SEM during the course of these experiments, a monitoring protocol was developed and used regularly. Before each data-acquisition session, several SEM parameters were recorded and plotted versus time. This allowed us to see immediately if any parameter deviated from its nominal value and to take corrective action when required. The parameters monitored were filament voltage, accelerating voltage, emission current, vacuum pressure and leak rate, and the resulting beam current stability.

Device Preparation

The devices studied were the following Honeywell test chips: 2171, 3559, and a composite metal defect (CMD) test structure. These are DIP (dual in-line package) devices containing various test circuits. Each device was unencapsulated and depassivated. Before being scanned, each device was cleaned for two hours in an argon plasma produced in a vacuum evaporator. Considerable variation in the results and increased loss of contrast from contamination of the device surface during scanning were observed in preliminary runs when this precaution was not followed. All specimens were stored in desiccators under partial vacuum.

Experimental Protocol

The main operating parameters used during all data-taking sessions reported herein were:

1. Accelerating voltage: 2.5 or 5 kV
2. Beam current: 0.1 nA
3. Magnification: 100 - 900X
4. Secondary electron collector voltage: 285 V
5. Stage tilt: 45 degrees

We began by selecting one area on one of the test devices (Figure 2) as the reference region and one as the supposedly unknown or sample region. In actual practice, the reference region should be directly connected to an input pin whereas the sample region may be anywhere inside the device. Because we wanted a reliable measure of the true voltage at the sample region, we selected a region which was also directly connected to an input. Since the test regions on the device shown in Figure 2 (2171) are close to bonding wires, significant horizontal field components are introduced which would be expected to reduce the accuracy of the voltage measurement. Therefore other devices of a second geometry were also studied in which the test regions were not located near bonding wires (Figure 3).

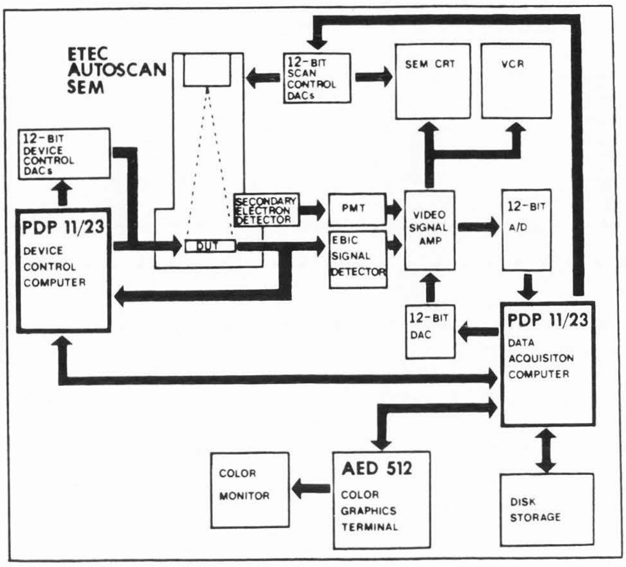

Figure 1: SEM/computer system.

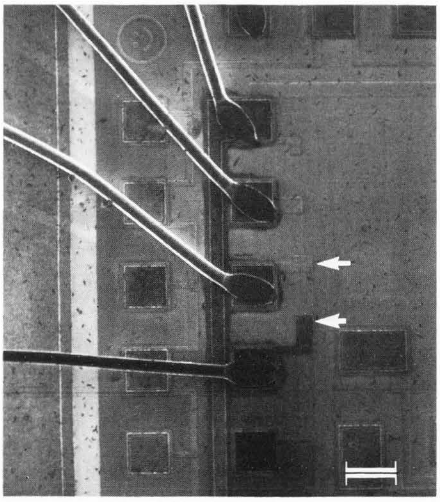

Figure 2: Honeywell 2171 test device: Three serial polysilicon resistors. Reference and sample sites on aluminum runs adjacent to bonding pads (arrows). Bar = 100 µm.

Before actually recording the data from the device, we performed six "warm-up" scans at the same place. Previous experiments had indicated that an improved stability in the results occurs when this is done. A 15 x 15 pixel area of the reference region was then scanned four times at 0 volts and the results were recorded and averaged. The voltage was increased in 0.2 volt steps up to 5.0 volts and at each voltage another four scans were made. This same procedure was then repeated for the sample region.

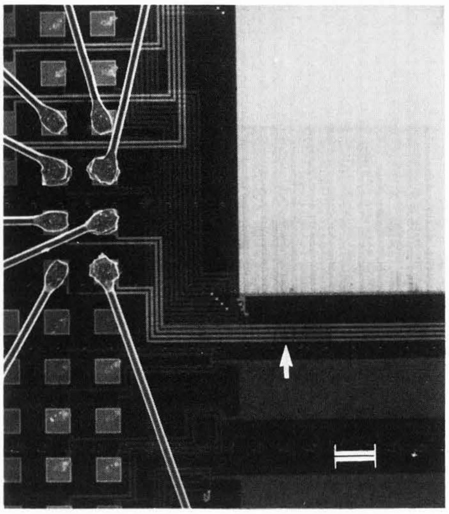

Figure 3: Honeywell Composite Metal Defect Test Structure. Reference and sample sites on aluminum runs away from bonding pads (arrow). Bar = 100 µm.

A reference curve for determining the image intensity-to-voltage mapping was produced by fitting the reference voltage V and the reference intensity I to polynomials of the form:

$$V(I) = \sum_{n=0}^{N} c_n I^n \qquad (1)$$

where c_n is the nth coefficient and N = 2(3) for a quadratic (cubic) polynomial. Then the subtracted form of the sample intensity I_s^{sub} is defined as:

$$I_s^{sub}(V) = I_s(V) + I_r^{fit}(0) - I_s(0) \qquad (2)$$

and the normalized form I_s^{nor} by:

$$I_s^{nor}(V) = I_s(V) \times I_r^{fit}(0)/I_s(0) \qquad (3)$$

where I_s is the sample intensity and I_r^{fit}, the fitted value of I_r at 0 volts, was determined by solving equation (1) for the case where V = 0. The results of quadratic and cubic fits to a typical reference data set are shown in Figure 4 and clearly show the improved accuracy obtained from the cubic fit. Now the final value for the measured voltage V_{sm} is estimated three ways for each of three different time delays between referencing and sampling as explained below. The three types of estimation come from substituting into equation (1) each of the 26 independent sample intensities (measured at 0.0, 0.2, 0.4, ... 5.0 volts) in unprocessed, subtracted or normalized form. Since the actual applied voltage for each sample value V_{sa} was known, we can define a voltage error E as:

$$E = V_{sm} - V_{sa}. \qquad (4)$$

The above procedure for determining sample voltages and errors was repeated on 25 complete data sets.

Analysis and Results

An example of the results obtained (with a cubic fit to the reference data) for image intensity versus applied voltage is shown in Figure 5 for unprocessed, subtracted and normalized sampled data. The improvement obtained from normalizing the data is apparent in this example. The accuracy obtained is shown more directly in Figure 6 which plots voltage error versus applied voltage.

As a check on the amount of error contributed by statistical fluctuations alone (i.e., excluding systematic errors), we examined the result of mapping the individual reference data against their own cubic-fitted reference curves

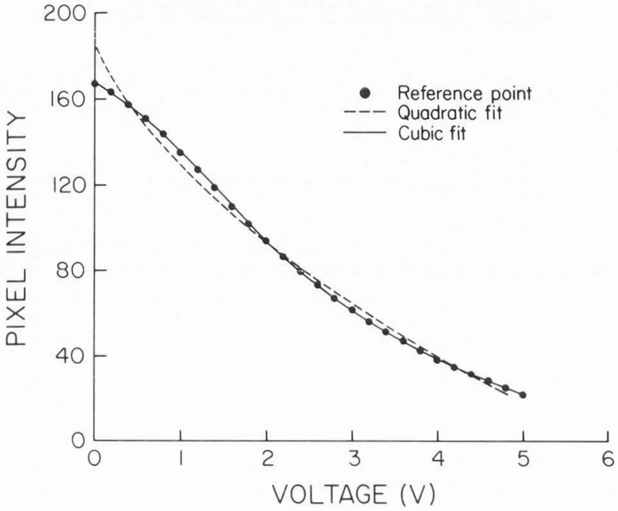

Figure 4: Quadratic and cubic fits to reference data.

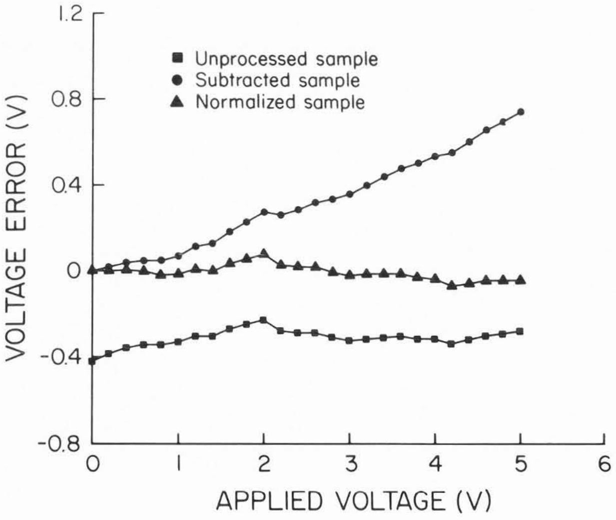

Figure 6: Voltage error versus applied voltage for unprocessed, subtracted, and normalized sample data using cubic fit.

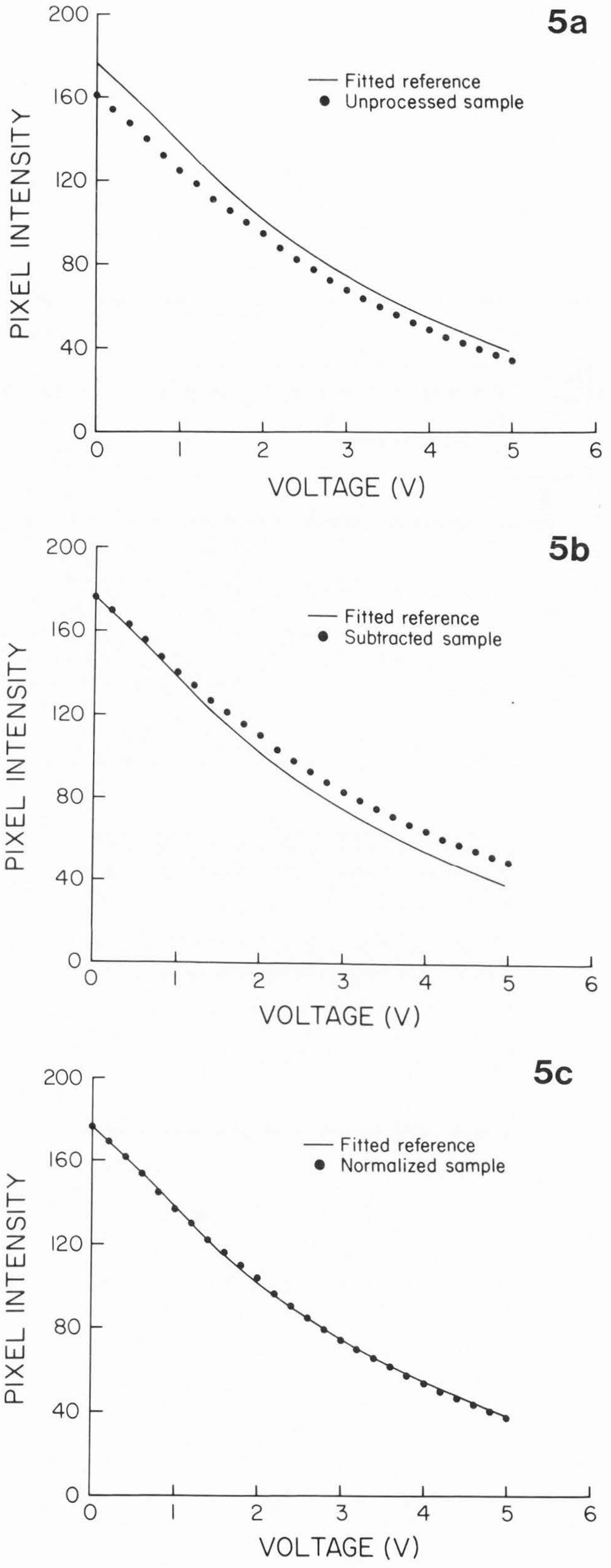

Figure 5: Pixel intensity versus voltage for cubic fitted reference data and (a) unprocessed sample data; (b) subtracted sample data; (c) normalized sample data.

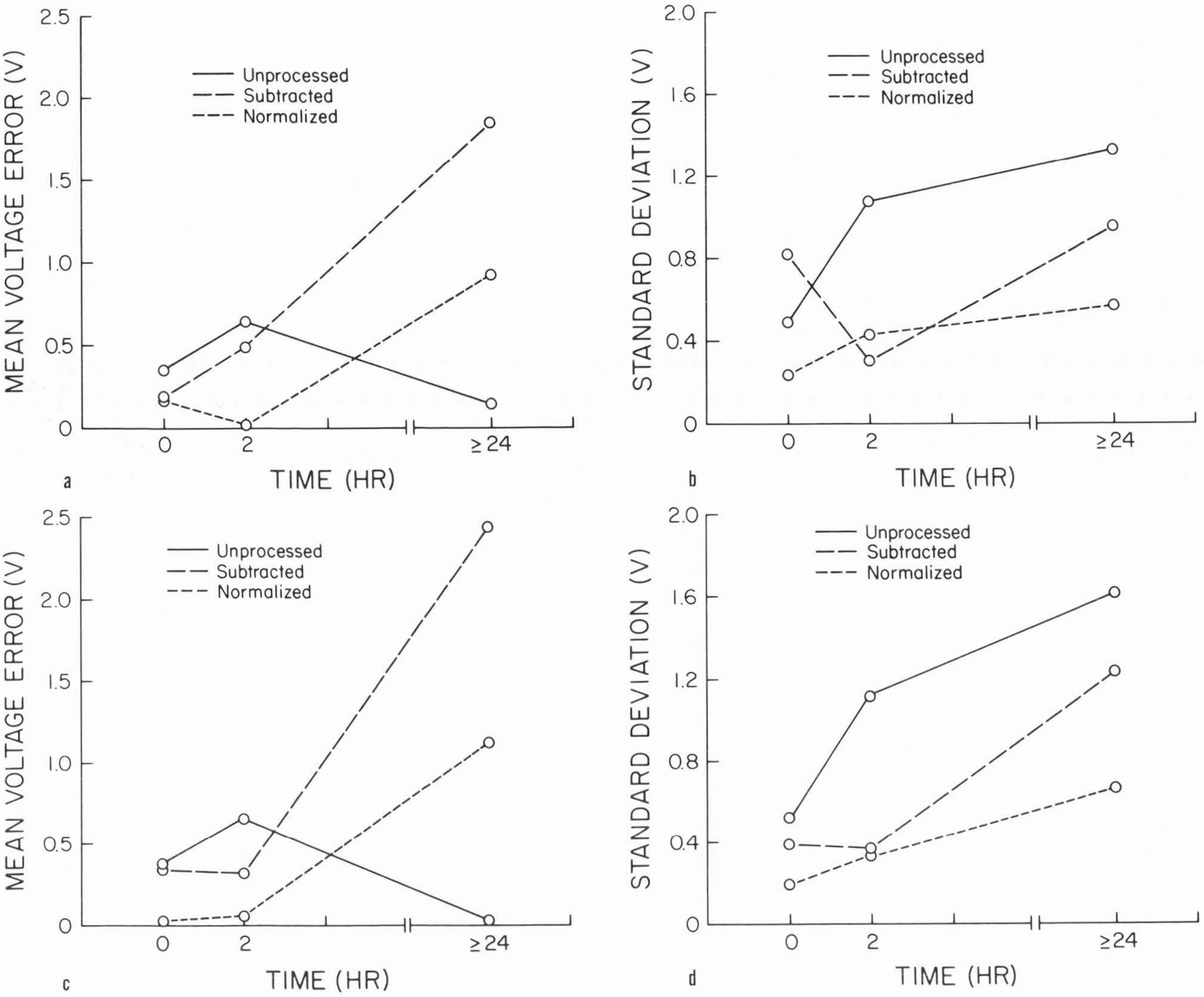

Figure 7: Voltage error parameters versus referencing delay time for unprocessed, subtracted, and normalized data: (a) mean voltage error for quadratic reference fits; (b) standard deviation of the error for quadratic reference fits; (c) mean voltage error for cubic reference fits; (d) standard deviation of the error for cubic reference fits.

(self-referencing). The overall voltage error for self-referencing was 1 mV with a standard deviation of 29 mV. This then gives a measure of the statistical error on our SEM. Presumably, the statistical error would be even smaller with a microscope specially modified for voltage contrast measurements.

The grand means and standard deviations for all the data with three time delays from referencing to sampling are shown in Figure 7 and Table 2. A total of 25 runs were made in each of the two geometries with 26 voltages per run. The various time delays (no delay, 2-hour delay and over 24-hour delay) were studied to understand how frequently referencing is required when it is used. The longest time delays are equivalent to having no referencing as such since system drifts dominate other effects. Minimum error is produced when the reference curves are updated frequently.

Table 2

Results of Statistical Analysis of Voltage Errors For 3559 and CMD Test Chips

FIT	PROCESS	MEAN (mV)	STD DEV (mV)
quad	unproc	- 81	207
	subtr	655	269
	norm	207	207
cubic	unproc	- 86	224
	subtr	69	138
	norm	- 24	130

In interpreting these results, it is probably correct to put more emphasis on the standard deviations than on the means because the latter may be correctable with further study, whereas the former arises more from drifts and random variations in the data.

Conclusions

In summary, we have studied four major factors which affect voltage measurement accuracy: device geometry, use of reference region including degree of polynomial fitted, type of processing used, and time delay between referencing and sampling. The results support the following conclusions.

1. Referencing and sampling should be performed as far from bonding wires as practicable.
2. Cubic polynomial fitting is superior to quadratic fitting (Figures 4 and 7, Table 2).
3. Normalization is preferable to using subtracted or unprocessed data (Figures 5 and 7, Table 2).
4. Minimal (i.e., less than about five minutes) time delay between referencing and sampling is desirable (Figure 7).

Finally, we believe that the results clearly indicate the desirability of jointly performing all four of the techniques given above, from which one can obtain voltage errors with means of approximately 25 mV and standard deviations of approximately 160 mV even with an unmodified commercial SEM incorporating no additional hardware to increase precision.

Our findings provide encouragement for further studies of quantitative voltage contrast methods. Particular areas for future research include studies of the extent to which the techniques reported herein can overcome local field effects as well as more detailed studies of the contributions of individual parameters to the overall systematic error.

Acknowledgements

The authors would like to thank Mr. Ron Kalin (Honeywell Solid State Electronics Div., Plymouth, MN) for supplying us the test devices used in this research and for helpful comments on our program. We are also grateful to Ms. Ossie Crabtree for her dedicated secretarial assistance. This research was supported by contract #83-01-025 from the Semiconductor Research Corporation.

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Discussion With Reviewers

S. Gorlich: The microfields near bond wires are known to cause significant errors, and this effect is intensively studied (e.g., Ura et al., 1984); but no measurements are shown to this point.

H. Fujioka: You do not mention the local field effect which affects the voltage measurement accuracy in the SEM. How can you calibrate the potential, where the reference and measurement points differ in the potentials and geometry of the surrounding regions?

Authors: Our objective in this paper is to present several data processing methods which can be used for data from any hardware arrangement for measuring voltage by voltage contrast. Although we have not studied the effects of potential variations in neighboring regions, useful voltage measurements can be made even with such local fields, depending on the proximity and magnitude of the source of the field perturbation. We are aware of work by other investigators to reduce these effects. Any improvements made in reducing local field effects and other sources of variation could be expected to result in further reduction of voltage measurement error. We would be very interested to see our algorithms used in combination with other techniques on a dedicated SEM system.

S. Gorlich: Referencing is known to be the only way for absolute voltage measurements.

Authors: While some of the general techniques presented here may have been published previously, the specific techniques, individually and in combination, which we have used have not been published to our knowledge.

L. Kotorman: The accelerating voltages used for this work are 2.5 keV to 5 keV. With these energies non-equilibrium charging conditions exist especially on insulators. What changes or damage (if any) may occur on the IC sample? The literature and the recent trend of SEM manufacturers strongly suggest the need of much lower energies than these. What are your comments on this?

Authors: We are aware of the recent successes of other investigators using low accelerating voltages, and we are not proponents of using higher voltages. The high voltage power supply of our ETEC Autoscan, however, is not stable at accelerating voltages less than 2.5 keV. Secondly, our investigation of non-passivated devices required a chemical depassivation process which was performed at Honeywell. The process was not completely effective for some devices, leaving a thin layer of the passivation material on the surface. In such cases, it was necessary to use 5 keV to penetrate the passivation residues. Steps were taken to minimize the effects of device charging in our results (such as cleaning the device in an argon plasma, avoiding scanning between measurements, lowering the number of scans per measurement, etc.). We did not experience device damage at the accelerating voltages used.

The purpose of our paper was to discuss quantitative techniques used that can be applied with any set of operating conditions.

L. Kotorman: Why was a single quadratic or cubic fitting used to generate the voltage-intensity curve? Is it possible that using more than one equation would give an even more accurate relation? I am especially referring to Figure 6, where it is apparent that at 2V applied voltage a sudden change occurs in the error values on all three curves.
S. Gorlich: Of course, fitting with four parameters is superior to fitting with three parameters. Fitting with five, six, etc. would be even better, but that is not a new result.
Authors: We found that a cubic fit was quite adequate. There would be no significant gain to using a higher order fit, and in fact higher order fits may introduce error by causing oscillations or excessive deviations between data points. The sudden change in Figure 6 does not occur in repeated experiments. Figure 6 represents only one experiment as an example. All three curves in this figure are error plots for the three techniques applied to the same data set and would therefore be expected to reflect any spurious local anomalies.

L. Kotorman: How do you monitor the beam current stability?
H. Fujioka: What is the measure of the stability in beam current during the experiments?
Authors: Beam current was measured with an ammeter using a Faraday cup. Once adjusted to the desired level, the current was measured every 15 seconds for 5 minutes. In this manner, beam current was found to be stable to within 0.6% during the time required for one measurement (3-5 minutes).

J.R. Beall: Is argon plasma used to remove contamination from the device surface? How was exposure period determined?
Authors: An argon plasma was used to remove contamination from the devices. A two hour exposure to the plasma was found to provide sufficient cleaning to conduct the experiments.

D. Koellen: What were the widths of the traces in Figure 3 where potentials were measured? Have there been measurements made on narrow lines (i.e., approximately 1-3 microns) or on complex geometries?
Authors: Line widths for the metal runs in Figure 3 are approximately 7 microns. Since our study indicated that statistical effects were significantly smaller than systematic effects, it should be possible to examine smaller areas (1-3 microns) without a significant loss of accuracy. Devices with more complex geometries were not used, but our results indicate that similar voltage accuracy could be obtained.

L. Kotorman: What do you think is the physical reason behind the need of warm up scans? What would happen if you used many more warm up scans? Would the results be different if you started the measurements at the most positive value and decreased this value gradually to zero instead of the other way around?
J.R. Beall: What is occurring during "warm-up" scans that improves stability? Is this beam/image or voltage contrast stability?
Authors: Warm-up scans are used to establish equilibrium conditions on the device surface. We believe an initial charging effect occurs when the secondary electrons first begin to escape the scanned area. When the primary electron beam begins to scan a particular area, the resulting cascading scatter/release of secondaries from the local surface exceeds the incident beam current, leaving a positive charge in that region. Soon, however, the positively charged area begins to reduce the number of electrons reaching the detector. Eventually, an equilibrium is reached between the kinetic scattering and the charge attraction processes. The warm-up scans insure that this equilibrium has been attained prior to actual data collection. Six warm-up scans were found to be the minimum number required to alleviate non-monotonic behavior of the voltage/intensity relationship occurring early in sampling. No more than six were used in an effort to reduce charging.

We have not studied the effects of reversing the order of voltage stepping.

L. Kotorman: Are you continuing to scan the sample after a measurement or are you turning the beam off? In other words, what experimental conditions should be observed if one would like to reproduce this data?
Authors: Scanning of the sample is not continued between measurements. Continued scanning of the area increases charging effects on the measurement sites. The beam is instead removed to a remote location on the test device. We did not have beam blanking hardware to remove the beam from the column and beam switching was not under computer control. Other experimental conditions are outlined in the paper.

J.R. Beall: What is the relationship between the number of reference voltage increments measured to normalized data accuracy?
Authors: In theory, increasing the number of steps decreases the overall error. In practice, however, the increased scanning time increases the effects of contamination charging and system

drift, thereby affecting the intensity values from the later measurement steps and increasing voltage measurement error. The number of steps used here could probably be reduced by a factor of two without significant reduction in measurement accuracy. The sampling frequency is clearly greater than the most significant frequency component of the data.

D. Koellen: How much time does a typical measurement require (including the measurement of a reference voltage)?
Authors: A measurement from a sample site at one voltage requires only a second or two, but our procedure was to measure the reference site over the given voltage range followed immediately by a series of sample measurements over the same range (in the case of minimal time delay between referencing and sampling). The total time required to complete a reference series and a single sample measurement, including warm-up scans is less than one minute. However, the speed could be increased by at least a factor of ten with improved hardware and software and using less statistical averaging with little loss in voltage accuracy.

D. Koellen: Can you comment on the non-linear relationship between the pixel intensity and conductor potential (e.g., Figure 4, 5)? Is this due to detector response, topology effects or directly the dependence of intensity on conductor potential?
Authors: This nonlinearity is primarily due to the shape of the secondary electron energy distribution. (Wells OC. (1974). Scanning Electron Microscopy, McGraw-Hill, NY, 63.)

H. Fujioka: Would you please explain why there is a significant difference in standard deviation between subtraction and normalization methods?
Authors: The reason that normalization is preferable to subtraction is presumably related to the occurrence of a greater drift in system gain than in system baseline. However we have not identified the cause(s) of this drift.

L. Kotorman: What are the variables chiefly responsible for the drift in the error curves so pronounced on Figure 7a to 7d?
Authors: We believe the variables principally responsible for time drift are: (1) contamination of test device; (2) variation in cleaning efficiency and (3) changes in SEM operating parameters (a) electronic drifts, especially in beam current (over long time periods); (b) vacuum changes from leaks and outgassing.

J.R. Beall: With the major part of conductors inaccessible from external terminals, what magnitude of error is realized as the distance from reference to sample voltage increases?
Authors: For the sites chosen, the sample-to-reference distances varied from 10 to 200 microns. Thus our results reflect the accuracy which can be obtained over this range; however, we have not specifically studied accuracy versus sample-to-reference distance.

D. Koellen: Have you observed any effects due to hillocks, glass residue, steps, or other anomalies?
Authors: We concentrated our study on the abilities of our data processing techniques to improve voltage measurement accuracy. Any effects from variations of the device surface smaller than the sampling area were not only reduced by averaging over that area, but the nature of the subtraction and normalization processes substantially diminishes the effects of device topography from the intensity values.

Passivation residue has been a problem. Due to residues left over in the depassivation process, it was necessary to increase accelerating voltage to 5 keV on some devices, which succeeded in generating secondaries from below the remaining passivation, but at the same time increased charging effects so as to increase measurement error.

J.R. Beall: Was a loss in voltage sensitivity (resolution) experienced due to the nonlinear voltage contrast response of the Everhart-Thornley detector?
Authors: The Everhart-Thornley detector has a linear response in the energy range of the secondary electrons (< 50 eV).

L. Kotorman: How does the A/D converter affect the measurements? Are you suggesting that the speed and accuracy needed with recent A/D's are difficult to obtain?
Authors: An analog to digital converter is an integral device with (a) inherent quantization error and (b) linearization error so that the converter is one of the factors in causing voltage measurement error. The contribution to overall error, however, is small relative to other sources.

D. Koellen: Have you used this method to measure negative potentials or potentials greater than 5 volts?
Authors: No.

J.R. Beall: Is the measured/calculated error attributed to factors of Table 1?
Authors: Yes.

Additional Reference

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