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EFFECTS OF LOCAL FIELDS ON ELECTRON BEAM VOLTAGE MEASUREMENT ACCURACY

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Abstract

Voltages at various levels have been measured on unpassivated aluminum lines in an integrated circuit (IC) test structure with widths and spacings ranging from 1.5 µm to 8 µm. For the measurements a pulsed electron beam (e-beam) system with 1 keV electrons was used in conjunction with a planar retarding field analyzer. Examination of the results shows that the voltage measurement accuracy is affected by local fields created by the potential differences between neighboring conductors on the IC. They also reveal how these fields and measurement errors are related to the conductor line width and spacing, the supply voltage level and the strength of the extraction field above the circuit.

Key Words: Electron beam probing, integrated circuit, planar retarding field analyzer, local field effects, e-beam voltage measurement accuracy.

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Introduction

As ICs are becoming faster and the minimum dimension for metal line width is approaching 1 µm, the necessity of using the e-beam probe for design verification and circuit characterization has increasingly gained acceptance. The requirements of non-destructive and nonloading probing of ICs can, under certain conditions, only be met by the e-beam probe. The voltage waveforms of a node in an IC can be measured, using the quantitative voltage measurement method. This requires the beam to be blanked in synchronization with the frequency at which the circuit under test operates, in order to sample the signal stroboscopically. Both the theoretical and experimental aspects of the e-beam voltage measurement technique have been described by many authors [1-18]. The focus of this work is on the accuracy of DC-voltage measurements on an IC test device with unpassivated aluminum lines of various widths and spacings down to 1.5 µm. Work on such fine geometries has not been reported previously.

The difference in potentials of neighboring lines creates a local field above the surface of the device. This field causes the emitted secondary electrons (SE) to be focused or defocused and can create potential barriers above the lines measured, which will contribute to the error in the voltage measurement. The effects of line width, spacing, applied specimen voltage (V_A) and extraction field (E_{ext}) on this error and their relations to the local field are shown in this work.

The Principle of E-beam Voltage Measurements

A planar retarding field analyzer and some SE trajectories are shown schematically in Figure 1. At the point of entry of the primary electron (PE) beam, secondary electrons are emitted from the conductor's surface. They are accelerated towards the extraction grid and subsequently slowed down by the retarding grid. Only SE with a sufficient energy component normal to the grid planes will pass this retarding grid. A weak deflection field

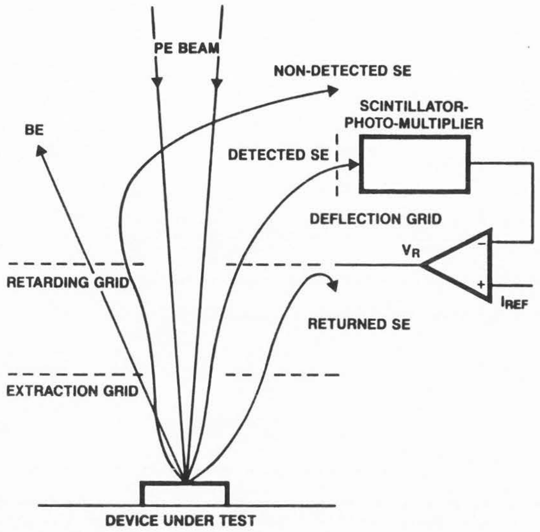

Figure 1. Schematic display of a planar retarding field analyzer, some SE trajectories and the feed back loop from detector to retarding grid to regulate the SE current.

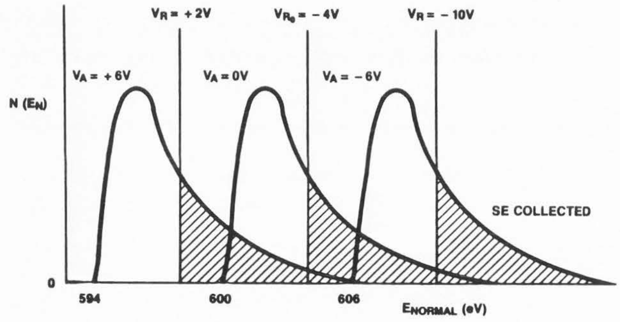

Figure 2. Distribution of the normal component of the SE energy at different specimen voltages upon passing the extraction grid at 600 V. The equal sized hatched areas represent the SE passing the retarding grid at given voltages.

bends the paths of the remaining SE towards the scintillator/photo-multiplier collector system, while the trajectories of the high energy primary and back-scattered electrons (BE) remain largely unaffected.

A positive applied voltage to the conductor causes a reduction, a negative voltage an increase in the kinetic energy of the SE upon passing the extraction grid and entering the retarding field. Therefore the entire SE spectrum is shifted with the applied voltage (V_A), as shown schematically in Figure 2.

During calibration of the system, the conductor measured needs to be at a known constant voltage. This is achieved by grounding all of the IC by turning it off. The retarding grid voltage (V_R) is now adjusted to V_{R_0}, so that the collected SE current reaches a predetermined value (I_{ref}), represented by the hatched area of the middle SE curve in Figure 2.

While taking measurements, the feedback loop from the SE collector to the retarding grid keeps the SE current constant by adjusting V_R, as is illustrated in Figures 1 and 2. The shift in V_R is a direct measure of the shift in applied specimen voltage, if the shape of the SE spectrum remains unchanged. This last condition is essential for accurate voltage measurements. In the spectrometer used a separate power supply changes the extraction grid voltage simultaneously with the retarding grid voltage to keep the potential between the two grids and their effect on the SE trajectories constant. Factors affecting the shape of the SE curve will be discussed later.

Experimental

E-beam Probing System

The commercially available instrumentation used for the voltage measurements consists of an ICT 8410 e-beam probing system with a planar retarding field analyzer (spectrometer), combined with a scintillator/photomultiplier SE collection system; a pulse generator for beam blanking and a device under test (DUT) stage with electrical feed-throughs to allow external control of the DUT. Data acquisition and display are computer controlled. This e-beam system is fitted to an AMRAY 1610 scanning electron microscope (SEM) with a LaB_6 gun, a beam blanker and a turbo-pumped high vacuum system.

Test Device

To determine the effects of line width and spacing on the accuracy of the e-beam voltage measurements a test device was devised, which consists of unpassivated aluminum lines on silicon-dioxide. They are configured in a comb-like structure to make it possible to apply different voltages to neighboring lines, a feature most ICs lack. The 1 μm thick Al 1% Si metal layer was sputtered onto 0.6 μm thermally grown oxide on <100> silicon.

Conductor line widths used were 1.5, 2, 2.5, 3, and 8 μm. All lines were 1.5 mm long. An aluminum line with a width of 3 μm and a spacing to its neighbors of 2 μm will be referred to as a "3.0-2.0" line.

A SEM micrograph of the end of the 2.0-1.5 line is shown in Figure 3. Notice that each set of lines consist of one 8 μm conductor with two smaller lines at one side, separated by 8 μm from a set of two small conductors and another 8 μm separation, after which the sequence repeats.

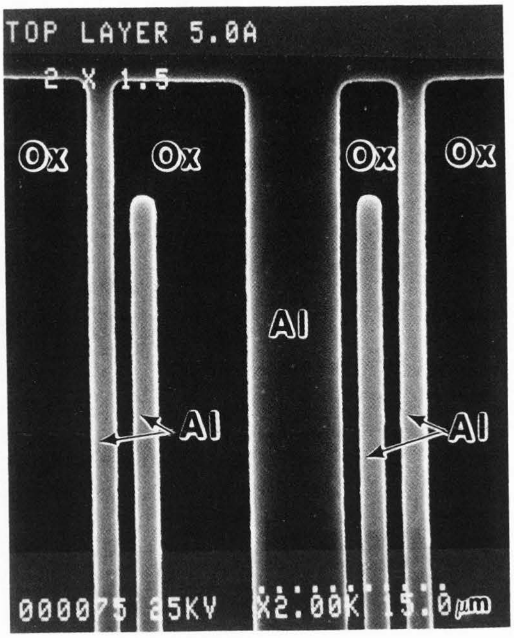

Figure 3. SEM micrograph of the end of a set of lines; on the left a pair of 2 µm wide aluminum conductors separated by 1.5 µm oxide and on the right a 2.0-1.5 line in the center with 8.0 and 2.0 µm wide adjacent conductors.

Positioning of the Beam

The static voltage contrast mode of the e-beam system was used to determine the location of the area of interest. The final positioning of the beam was done in the waveform measurement mode by centering a cross hair on the center of the stroboscopic image of the line, distinguishable at slow line scan operation of the SEM, before switching to the spot mode to take the measurements. After each measurement the beam was put on a new, carefully centered, spot.

Worth noting is, however, that it is possible for the beam to shift during the measurements, because of changing extraction and retarding grid voltages. When the grids and the primary beam are not perfectly perpendicular to each other, varying the grid voltage will cause the beam to move. We found that this could amount to as much as 0.1 µm/V. Since the beam was positioned at a retarding grid voltage of 3 to 4 Volt, the shift will especially have an effect on negative voltage measurements with consequently negative retarding grid voltage and a larger difference with the grid voltage during the positioning of the beam. At a grid voltage of -6 V the beam could have moved partially off the 2 µm line and irradiate the surrounding oxide. This contributes considerably to the voltage measurement error.

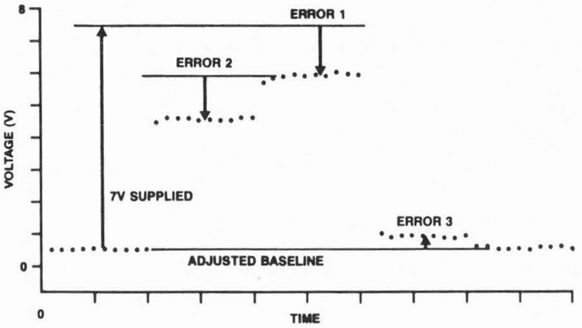

Figure 4. Demonstration of a measurement sequence and error definitions for a 3.0-3.0 line with switching voltage of 7 V and an extraction field of 900 V/mm.

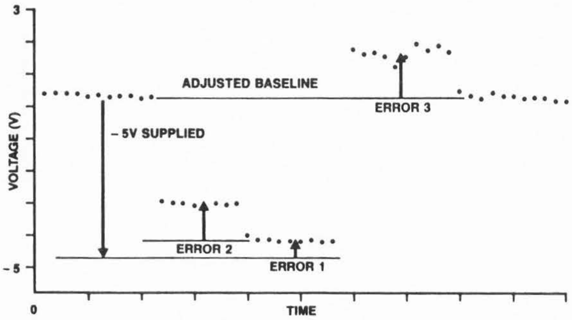

Figure 5. Demonstration of a measurement sequence and error definitions for a 3.0-3.0 line with switching voltage of -5 V and an extraction field of 300 V/mm.

Measurement Sequence and Error Definitions

In the waveform measurement mode the pulsewidth of the beam blanking system was set at 5 ns, the number of data points (dots forming a waveform) at 50, the noise attenuation at 30 mV and the beam blanking repetition time at 10 µsec (pulsed beam frequency at 100 kHz). After aligning and positioning the beam on a grounded aluminum line, the voltage analyzer would automatically calibrate before taking a measurement. Despite this calibration the measurements on the grounded line would unexpectedly be slightly above zero Volts. This voltage level will serve as our zero level adjusted base line instead of the calibrated zero level in the determination of the subsequent measurement errors. The zero level offset and its association with the calibration of the spectrometer requires further attention.

Since the measurements (dots) are taken subsequently at a rate of one every one or two seconds we could measure several DC voltages in one "waveform" measurement sequence. First the center line was switched on, second the adjacent lines, while keeping the center line on, third the center was turned off and last the adjacent lines were returned to the ground level by turning them off, as well. Examples of the measurement sequence for a 3.0-3.0 line with switching voltages of 7 and -5 Volts are given in Figures 4 and 5, respectively. In these figures the error definitions of the three different measurements are demonstrated, as well. Downward pointing arrows in those figures are represented by negative values for the corresponding error voltages.

Error 1 is defined as the difference between the actual voltage supplied (previously defined base line plus switched voltage) and the voltage measured for both center and adjacent lines turned on. This error gives a good indication of the geometry-independent effects on the voltage accuracy of the e-beam system.

Error 2 is defined as the difference between the voltage level with both lines switched on and the level for only the center line switched on. This error clearly gives a good indication of the geometry dependency of the voltage measurements. The total voltage measurement error under these conditions is the sum of errors 1 and 2, although in reality the ground level error should be taken into account, as well.

Error 3 is defined as the difference between the voltage measured on the center line with only the adjacent lines turned on and the voltage level of the adjusted base line.

Results and Discussion

Before discussing the individual measurement results in detail, they are presented graphically below. We studied the measurement error based on the effects of the metal pitch (Figure 6) and of the extraction field on 8.0-3.0 (Figure 7), 3.0-3.0 (Figure 8) and 2.0-2.0 lines (Figure 9). An overview of the data figures and their corresponding line geometries and extraction fields is shown in Table 1.

Table 1. Overview of the data figures with corresponding line geometries and extraction fields.

Figure	Line	E_{ext}[V/mm]
6	3.0-3.0,2.5-2.5, 2.0-2.0,1.5-1.5.	600
7	8.0-3.0	300,600,900
8	3.0-3.0	300,600,900
9	2.0-2.0	300,600,900

Errors 1, 2, and 3 are given in the Figures 6-9 a, b and c, respectively. These measurements were taken at a primary electron beam energy of 1 keV with beam current of 0.2 nA and a beam diameter of approximately 100 nm. Additional measurements at beam energies of 2 and 2.5 keV did not show any other behavior of the error. At higher beam energies the surrounding oxide would charge more, making it more difficult to position the beam. Measurements with larger spot size (and consequently higher beam current) did not affect the measurement error of the 8 μm conductor, but did increase all errors for the smaller lines up to 50% of the applied voltage for both error 2 and error 3. This would make it impossible to distinguish between signals coming from the line of interest and the adjacent conductor.

Factors Affecting the Voltage Measurement Accuracy

The performance of a SE analyzer is determined by the shape of the SE curve. Effects that change the curve equally for all specimen voltages, will only limit the voltage resolution. If, however, the shape of the SE curve depends on the specimen voltage, this will cause measurement errors. These two categories [Menzel and Brunner,1983[12]] can be subdivided into several separate effects:

1) Measurement errors caused by the specimen voltage dependency of the SE trajectories
   - in extraction field (global field effect).
   - within the analyzer (deflection field effect).
   - above the IC surface (local field effect).
2) Voltage resolution limitation caused by lower SE yield due to
   - the build up of a contamination layer.
   - small spot size and low beam current.
   - low transmission of SE by grids.
   - high background signal.

Since the measurement sequence was geared towards the determination of the voltage level error and not to determine the resolution of the system, we shall only discuss the effects of the first category.

Global and Deflection Field Effect

With both the center and the adjacent lines at the same voltage the measurement would still differ by 10 to 15% from the voltage applied to the device. This difference, defined as error 1, increases with smaller line widths, as shown in Figure 6,a. This could be caused by the primary beam irradiating the oxide and generating secondary electrons independent of the supplied voltage, which could explain all of the error above 10%. This does not explain, however, the remaining 10% error for 3 and 8 μm lines at an extraction field of 600 V/mm and the effect of this field, shown in Figures 7-9, a.

In the comb-like structure of the test device, not only the measured and its neighboring conductors are switched on in the determination of error 1, but most of the device is at the same voltage. Focusing of SE by local fields created by other lines than the two adjacent ones, can therefore be ruled out as a cause of this measurement error, although field lines generated by the surrounding charged oxide could still affect the SE trajectories. The substrate and die attach pad of the package, however, were still grounded. We noticed that applying the specimen voltage to them as well would decrease error 1 to approximately 7% of the specimen voltage. This indicates that the bending of the extraction field by conductors far away from the point of entry of the primary

Figure 6a

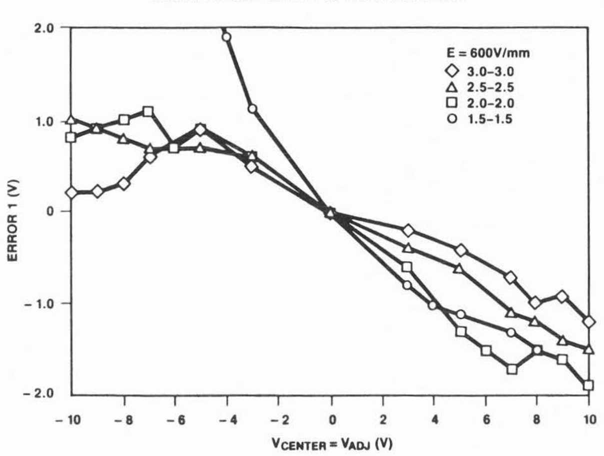

Figure 6b

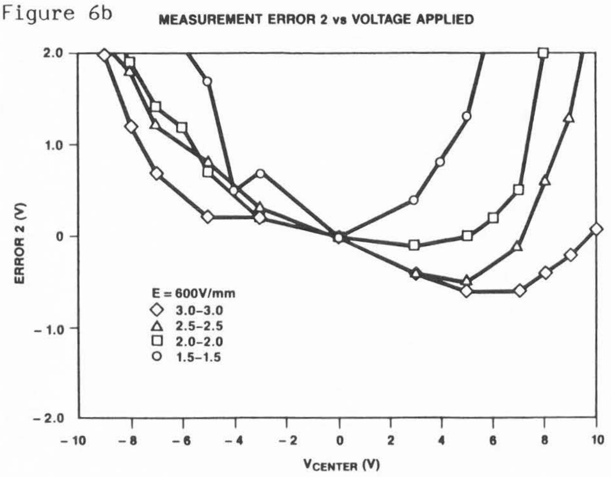

Figure 6c

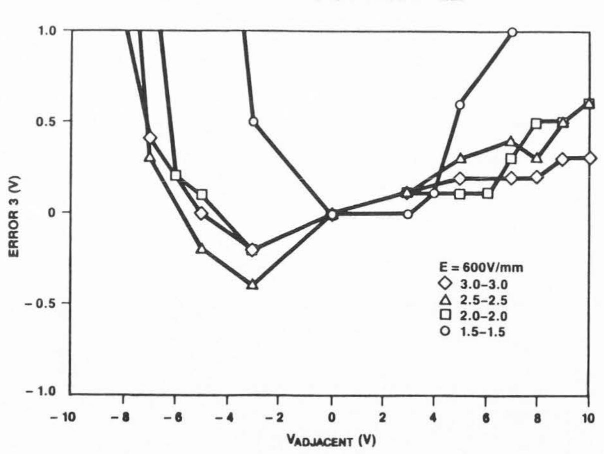

Figure 6,a b c. Errors 1, 2 and 3 respectively versus the applied voltage for 3.0-3.0, 2.5-2.5, 2.0-2.0 and 1.5-1.5 lines at an extraction field of 600 V/mm.

Figure 7a

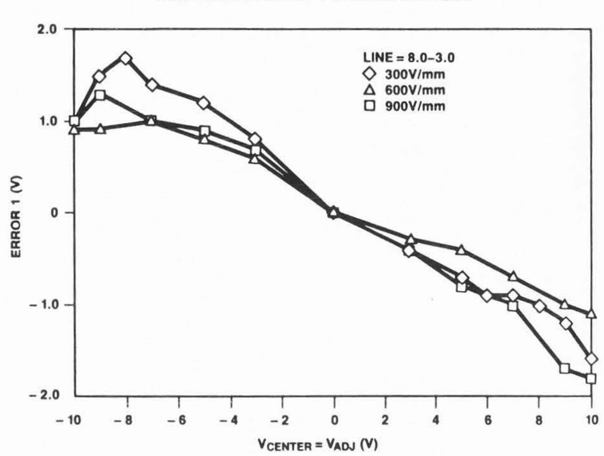

Figure 7b

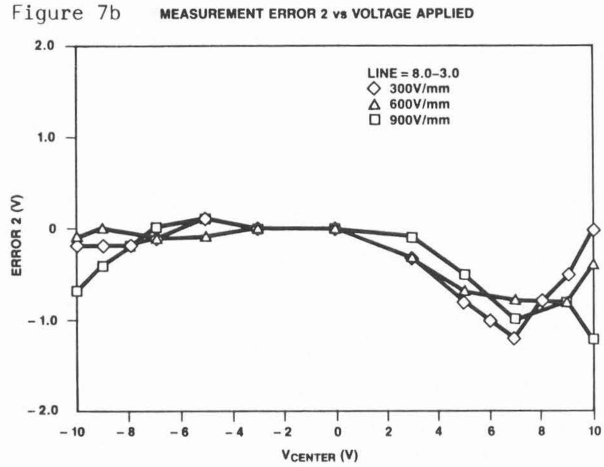

Figure 7c

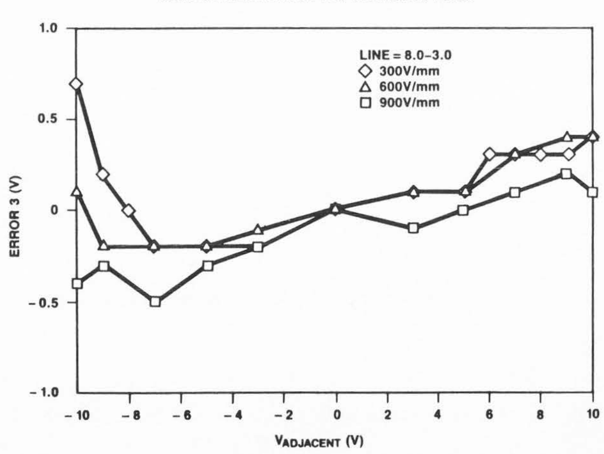

Figure 7,a b c. Errors 1, 2 and 3 respectively versus the applied voltage for 8.0-3.0, lines at an extraction field of 300, 600 and 900 V/mm.

Figure 8a

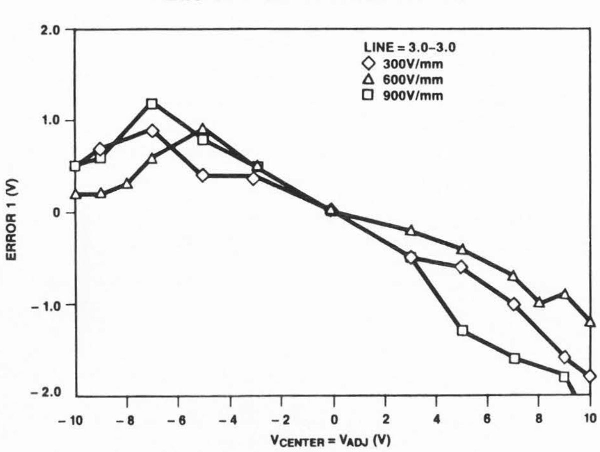

Figure 8b

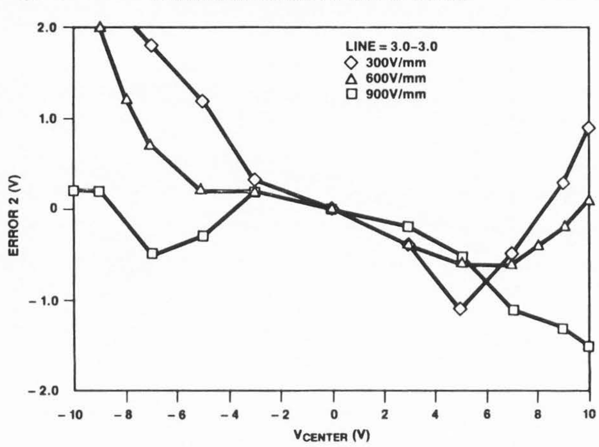

Figure 8c

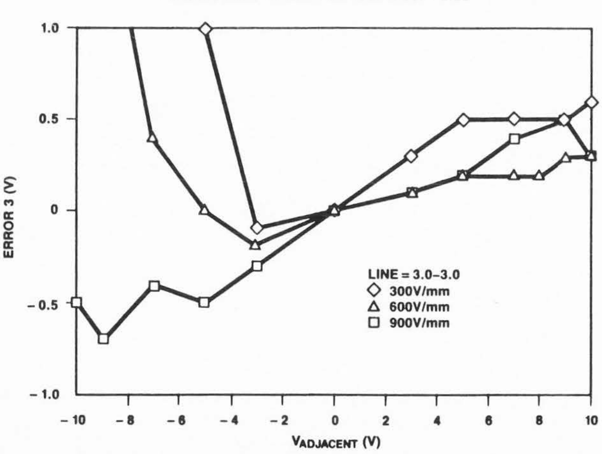

Figure 8,a b c. Errors 1, 2 and 3 respectively versus the applied voltage for 3.0-3.0, lines at an extraction field of 300, 600 and 900 V/mm.

Figure 9a

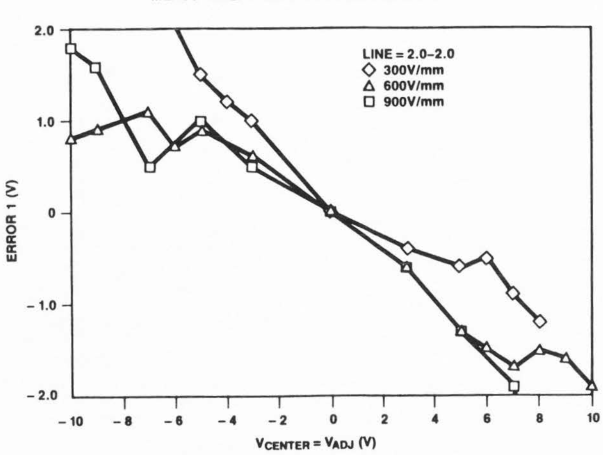

Figure 9b

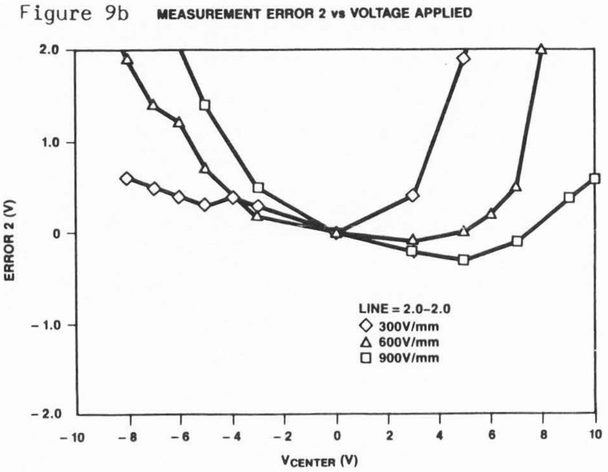

Figure 9c

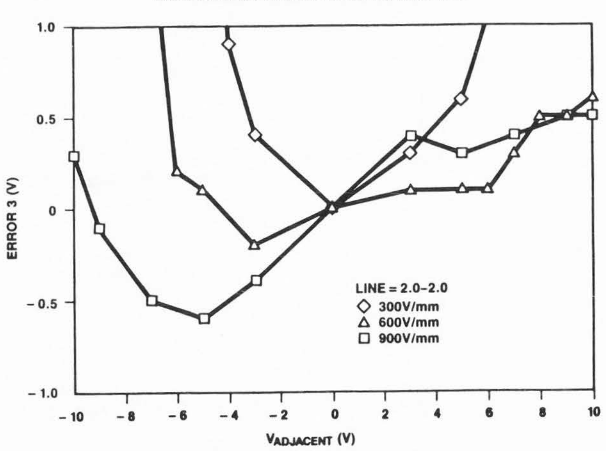

Figure 9,a b c. Errors 1, 2 and 3 respectively versus the applied voltage for 2.0-2.0, lines at an extraction field of 300, 600 and 900 V/mm.

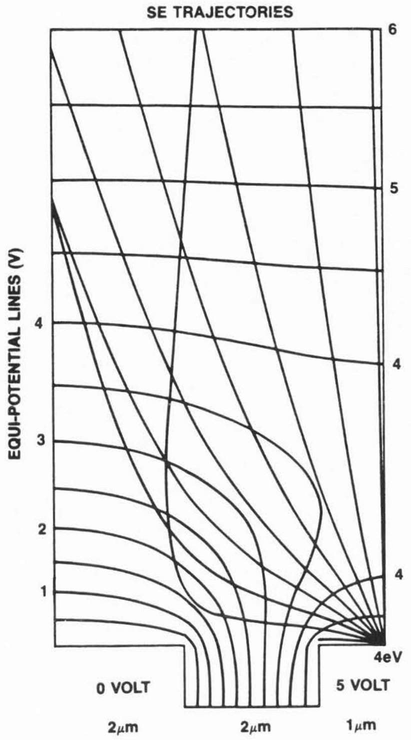

Figure 10. Demonstration of the focusing effects of the grounded adjacent conductors on SE emitted with an energy of 4 eV from a 2.0-2.0 line at 5 Volt with an extraction field of 600 V/mm.

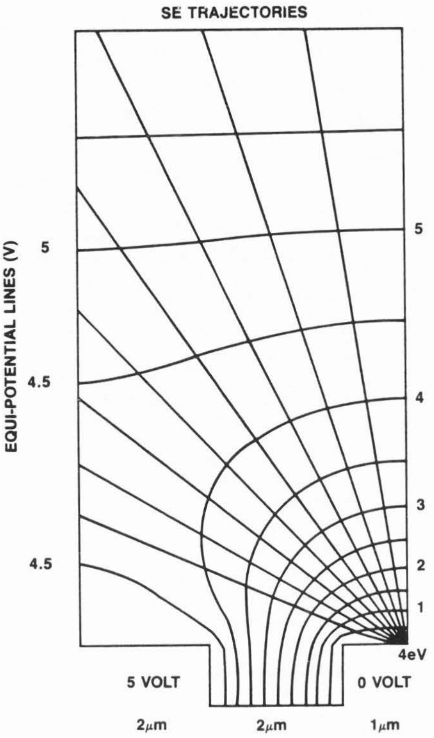

Figure 11. Demonstration of the defocusing effects of the adjacent conductors at 5 Volt on SE emitted with an energy of 4 eV from a grounded 2.0-2.0 line with an extraction field of 600 V/mm.

electron beam still affects the secondary electron yield. We call this the global field effect.

Measuring the voltages on a large aluminum stub yielded an error of 5% of the voltage applied. This reflects the influence of the shift in voltage difference between deflection and retarding grid due to different specimen voltages, which we call the deflection field effect. The 2% of applied voltage difference between the voltage measured on the test device with all lines and substrate at the same voltage and the result of the measurements on the large stub could be contributed to the effects of the charged oxide on the test device.

According to the data in Figures 7-9,a the extraction field influences the size of error 1. It seems that at a field of 600 V/mm its contribution to the error is minimized. The "global" geometries of die size, grid wires and distance between grid and IC surface could play a role here.

Local Field Effects

The difference in potentials of neighboring lines creates local field above the surface of the IC. This field affects the trajectories of the SE in two ways. First, it causes the SE to be focused or defocused and thus to gain or lose energy in the direction normal to the surface of the IC. Figure 10 shows the focusing of SE emitted with energies of 4 eV from a 2.0 μm line surrounded symmetrically by two conductors with 2.0 μm separation and an extraction field of 600 V/mm. The SE emitted by a line with a higher potential than its adjacent lines are focused and more SE will reach the collector. To keep the current constant, though, V_R will be decreased automatically. If the adjacent lines are at a higher potential than the center, the SE will defocus, as shown in Figure 11. The SE gain less vertical energy than they would have gained with a homogeneous extraction field and V_R has to increase to keep the collected SE current constant. The focusing and defocusing effects on the ideal SE distribution, as given in Figure 2, are shown in Figure 12. The shift in retarding grid voltage (V_R) is under both conditions less then the shift in the applied voltage (V_A), as was expected from the error 2 behavior in Figures 4 and 5.

The focusing of SE results in negative values for errors 2 and 3, while defocusing causes small positive values for these errors. The measurements in Figures 6 - 9, b and c indicate that these errors are approximately 10% of the applied voltage. The strength of

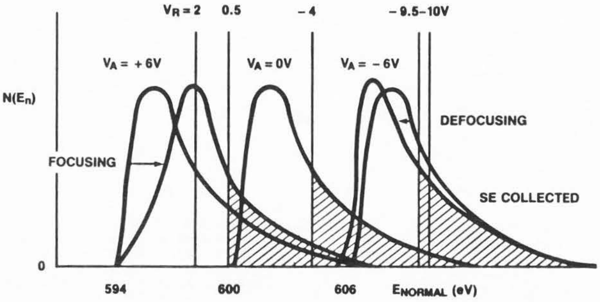

Figure 12. Demonstration of the focusing and defocusing effects on the distribution of the normal component of the SE energy at different specimen voltages upon passing the extraction grid at 600 V. The equal sized hatched areas represent the SE passing the retarding grid at given voltages.

the extraction field or the distance to the adjacent conductor does not seem to affect these errors and therefore the focusing of the SE very much. The apparent defocusing effects and related positive error values on the left side of Figures 6-9,b are larger than those on the right side of Figures 6-9,c, especially for the smaller lines and weaker extraction field. This could be caused by the forementioned effect of PE-beam shift on the SE energy spectrum.

Second, the local field creates a potential barrier above conductors which are at a higher voltage level than their neighbors. The low energy SE return to the conductor because of this field, as shown in Figure 13 or the SE emitted with energies of 2 eV. Since these SE would not have reached the detector anyway, because of the retarding field in the analyzer, this barrier does not affect the measurement until it is large enough to return SE to the conductor, which would have passed the retarding grid otherwise. Fewer electrons will reach the detector. To keep the number of SE detected constant, V_R will be enlarged. The same happens when the negative potentials of the surrounding lines are increased. Under both conditions the negative value of errors 2 and 3, due to the focusing effect, will change sign and rise steeply because of the barrier.

Indeed, on the right side of Figures 6-9,b (error 2) and the left side of Figures 6-9,c (error 3) we observe the focusing effect turning into a barrier effect at higher voltages. Very noticeable is the increase of the potential barrier effect with declining extraction field and with decreasing distance to the adjacent conductor. This relationship is demonstrated in Table 2, which gives the voltages at which error 2 equals zero, indicating that the barrier effect annuls the focusing effect on SE.

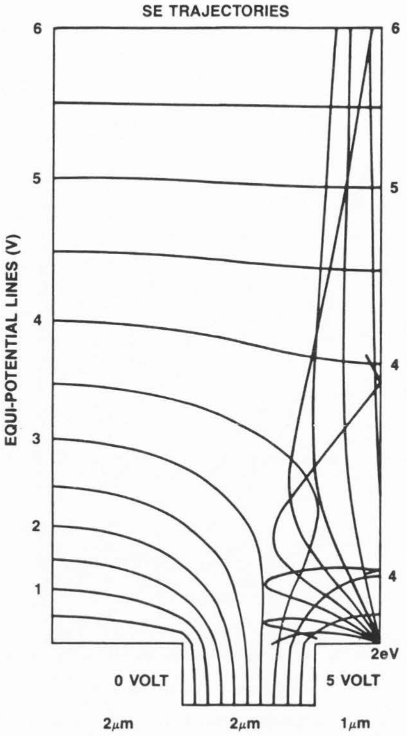

Figure 13. Demonstration of the combined focusing and barrier effects of the grounded adjacent conductors on SE emitted with an energy of 2 eV from a 2.0-2.0 line at 5 Volt with an extraction field of 600 V/mm.

Table 2. Voltages at which error 2 equal 0 V and the barrier effect therefore annuls the focusing effect on SE, for different extraction fields and line geometries.

	E_{ext} [V/mm]		
line	300	600	900
1.5-1.5	n.a.	<3	n.a.
3.0-1.5	n.a.	3.5	n.a.
2.0-2.0	<3	5	7.5
2.5-2.5	n.a.	7.5	n.a.
2.0-3.0	n.a.	9.0	n.a.
3.0-3.0	9	9.5	>10
8.0-3.0	10	>10	>10

Conclusions

We conclude that the voltage measurement error with both the adjacent and the center conductor switched on (error 1) is dependent on the following effects with approximate contributions of the error percentage:

>10%	SE emitted from oxide.
10 to 5%	Global field effects. Focusing of SE by: Substrate, surrounding metal and oxide.
5 to 0%	Deflection grid effects.

Furthermore, there is some influence of the extraction field on this error, which seemed to be minimized at a field of 600 V/mm for the test device used.

The focusing of SE is largely independent of the extraction field (300 <E_{ext}<900 V/mm) and metal pitch (3.0-11.0 μm) and causes the voltage level measured to be an additional 10% smaller than the level with the adjacent lines at the same voltage. The potential barrier above the conductor returns the low energy SE, which affects the measurements only at higher voltages. Extraction field and metal pitch determine the depth of this barrier and its effect on the voltage measurements. For metal pitch below 4 μm it is recommended to increase the extraction field above 600 V/mm to reduce the effect of the barrier on the measurement error. At voltages below 6 Volt, metal pitch between 4 and 6 μm and extraction fields above 600 V/mm the total measurement error (error 1 + error 2) is approximately 20% of the voltage applied.

Acknowledgments

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Discussion with Reviewers

K.D. Herrmann: What is the reason for the zero level offset at calibration?

Authors: It seemed to be caused by a hardware problem on the calibration computation board.

H. Fujioka: What is the difference in definiton between our Type I and II errors (text ref. 8) and your errors 1, 2, and 3?

Authors: Type I local field effect error is split into errors 1 and 2 to distinguish between real local field effects (error 2) and the error caused by other (global) effects (error 1). The definitions for Type II local field effect and our error 3 are the same. The data were not compared with ours, because both the beam energy (25 keV) and the IC geometries (8.0-12.0 lines) differ considerably from ours.

L. Kotorman: How are the blanking system and the applied beam enable pulse conditions related to the measurements?

What is the DC equivalent beam current used? If one would use continuous beam instead of pulsed beam, should not he expect greater signal to noise ratios and, overall, more accurate measurements?

Authors: The beam was enabled 5 ns each 10 μsec and the continuous beam current was 0.2 nA. The equivalent DC beam current was therefore 0.1 pA. Decreasing the beam enable pulse to 1 ns would severely increase the measurement errors, possibly due to the scattering of the beam during opening and closing of the blanking system and the low number of electrons passing through. Increasing this pulse to 20 ns didn't affect the measurements; the signal to noise ratio might be greater, the global and local field effects and therefore the measurement errors remain the same.

K.D. Herrmann: How can the fluctuations of approximately 750mV of error 3 in Fig. 5 be explained, although the noise reduction was set to 30 mV? How is the noise reduction controlled?

Authors: Each voltage measurement point in Figures 4 and 5 is the result of multiple measurements. The averaging time depends on the noise attenuation level. Differences between individual points are caused by macro-effects, such as contamination build-up or charging of the oxide.

L. Kotorman: What would the authors estimation be concerning the 'statistical' fluctuation of the data presented in Figures 6 to 9?

Authors: The fluctuations between repeated voltage measurements at different locations, although dependent on the centering of the beam, were below 5% of the applied voltage until the barrier effect started, which could cause the voltages to differ considerably.

H. Fujioka: Figures 7 to 9 seem to conclude that an increase in the extraction field in the spectrometer used does not necessarily provide a better voltage measurement accuracy. In your opinion, what is the reason for these results?

Authors: The strength of the lateral local field (5 V/2 μm = 2500 V/mm in Figures 10, 11 and 13) is so much stronger than the extraction field that the focusing and defocusing, (but not the barrier) effects of this local field on the voltage measurement accuracy remain largely unaffected by the extraction field.

L. Kotorman: Is it not surprising that no change occurred in the error behavior when the primary beam energy was changed from 1 keV to 2.5 keV? Is the error dependent on the value of the accelerating voltage? If so, then what accelerating voltages would you recommend to use? The secondary yield for most (if not all) materials changes from positive to negative value in the range of 800 eV to about 2 keV primary beam energy. Please comment on this.

Authors: Since the voltage measurement depends only on the shift of the SE energy distribution curve and not on the shape of this curve, the SE yield does not affect the voltage measurement directly. Only the negative charging of the surrounding oxide, creating potential barriers above the conductors, starts obscuring the image of the smaller lines with wider spacings at higher beam energy.

L. Kotorman: The beam indicated potential shift on a small isolated capacitive mode may be significant, and it is not mentioned in the text. Do the authors have any suggestions on how to minimize this possible measurement error?

Authors: Since all metal lines are connected to a voltage supply, the net electron injection or ejection does not cause their potential to change.

H. Todokoro: You conclude that the error above 10% is caused by the primary beam shift and that the remaining 10% is caused by other effects. Please explain in more detail how your conclusion was obtained.

Authors: The value of error 1 was the same for all lines 3 μm and wider. For smaller lines error 1 increased with decreasing line width, leading to the conclusion that beam shift and oxide irradiation started having effect.

L. Kotorman: If the primary beam partially irradiates the surrounding oxide (unavoidable at times as you mentioned it), at what voltage levels do you think the most measurement error would occur due to this?

H. Todokoro: You estimate the beam shift due to the retarding grid potential change is 2 μm. It means that the lines having less than 2 μm cannot be measured by your e-beam system. Do you have any idea how to decrease the beam shift?

Authors: The estimated shift was approximately 0.1 μm/V, resulting in 0.5 μm shift for 5 V applied voltage. Low voltages can therefore still be measured on sub-micron lines. Making the grids perfectly perpendicular to the beam would reduce this problem.

K.D. Herrmann: Did you perform similar investigations on passivated test structures?

Authors: No.