Scanning Microscopy

Volume 1 | Number 1 Article 3

12-7-1986

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Scanning Microscopy, Vol. 1, No. 1, 1987 (Pages 23-30) 0891-7035/87$3.00+.00
Scanning Microscopy International, Chicago (AMF O'Hare), IL 60666 USA

ELECTRON BEAM INDUCED CURRENT ANALYSIS OF VOLTAGE BREAKDOWN SITES IN THIN MOS OXIDES

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(Received for publication May 07, 1986, and in revised form December 07, 1986)

Abstract

Voltage breakdown sites on thin (<100Å) MOS capacitors have been identified by the electron beam induced current (EBIC) technique, using a scanning electron microscope (SEM). EBIC spots coincide with voltage breakdown locations and their image intensity can be changed by varying the applied bias or the electron beam accelerating voltage. Total current and the number of EBIC spots were the same in both accumulation and depletion conditions for a fixed beam potential and bias voltage. This suggests that the observed EBIC spots were due to defects in the oxide only. This EBIC method for identifying defects has been found very useful in characterizing thin MOS oxides.

Key Words: Electron beam induced current (EBIC), scanning electron microscope (SEM), thin (<100Å) MOS oxide, oxide defects, voltage breakdown site identification, EBIC spots.

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Introduction

The electron beam induced current mode of scanning electron microscopy has found a wide range of applications in semiconductor device characterization for which extensive descriptions have been provided by Bresse (1977), Leamy et al. (1978), Holt and Lesniak (1985), and Schick (1985). The EBIC method makes use of the generation of mobile charge carriers in the area below the point of impingement of the electron beam. Under the influence of an internal field, electrons and holes are forced to move in opposite directions. The resulting induced current is collected by an external circuit and becomes the video signal displayed on the SEM's CRT.

The internal field required for the collection of mobile charge carriers may be created by p-n junctions (Gonzales, 1974; Schick, 1974; Beall and Hamiter, 1977; and Chi and Gatos, 1977) or Schottky barrier structures (Kawado, 1980). Specific EBIC techniques have allowed the observation of oxidation-induced stacking faults in silicon (Ravi et al., 1973 and Kawado, 1980) or the correlation of stacking faults near the $Si-SiO_2$ interface with voltage breakdown in thin (220 Å) MOS oxide capacitors (Lin et al., 1983).

The purpose of this work was to study the feasibility of imaging thin oxide defects on MOS capacitors by the EBIC technique (Green, 1966). These defects are associated with voltage breakdown (Bhattacharyya et al., 1986), without being related to stacking faults near the $Si-SiO_2$ interface. With the absence of a p-n junction or a Schottky barrier, the applied bias across the thin oxide capacitor provides the field necessary for charge collection. The ability to image defect sites on oxide capacitors that are restricted to the oxide only, makes this EBIC method unique and different from the above referenced techniques.

When an electron beam of sufficient energy impinges upon the capacitor surface, charge carriers (electrons and holes) are generated within a certain excitation volume of the Si substrate. These carriers diffuse randomly, become trapped and recombine, until all excess carriers are eliminated. This process continues, as long as the area is exposed to the electron beam. Under the influence of an electric field, however, the carriers are forced to move in opposite directions. This allows them to be detected in an external circuit. A capacitor biased in accumulation has the applied electric field across the oxide only, with no space charge region present in the semiconductor (Si). In order to observe an electron beam induced current, there has to be a conducting channel in the oxide itself. In depletion, even though the carriers might be separated by the electric field in the depletion region, a conducting path in the oxide is necessary, as well, to register a significant increase in current in the external circuit. A conducting channel, allowing the electron beam induced current to flow at the moment the electron beam scans across it, is coincidental with a defect through the oxide. Without a channel through the oxide and in the absence of a p-n junction or an Al Si Schottky barrier, no appreciable conduction current would flow but displacement current will flow.

Feature size reduction in MOS VLSI integrated circuits has been paralleled by the reduction of oxide thickness. Thin oxides can now be manufactured (<100 Å), therefore the critical importance of high voltage breakdown strength and low defect density is emphasized. Oxide integrity can be tested by applying a ramped dc voltage across an oxide capacitor until irreversible breakdown occurs. While such a voltage stress provides voltage and current values at the breakdown level, it neither reveals information about the exact location of a breakdown site nor does it show whether the overall breakdown involves more than one defect site on a given capacitor.

Experimental Procedures

Polysilicon gate capacitors were used for electrical measurement of the thin oxide properties, as well as for EBIC imaging of voltage breakdown sites. Capacitors of 3.2 mm^2 area (Figure 1) were fabricated on p-type <100>, 5-7Ωcm, 100 mm Si wafers, using a test mask set. The thin oxide was grown in a local oxidation of silicon (LOCOS) structure at 950°C in dry O_2 with Ar dilution. The oxide thickness of 90 Å was measured by ellipsometry; the index of refraction, n, was 1.46. Polysilicon (2500 Å) was deposited immediately following thin oxide growth. In order to avoid any deterioration of the thin oxide, neither plasma etching of polysilicon nor plasma resist stripping was applied.

Breakdown measurements were performed on an automatic prober-stepper and a Keithley test system. The test program detected breakdown voltage by measuring the voltage at which a threshold current of 10 μA occurred. Contact for the breakdown voltage measurements was made on an aluminum pad over the thick field oxide.

Figure 2 shows a contour map of the spatial distribution of the oxide breakdown voltage. The solid line represents the contour of the mean breakdown voltage of 5.54V. The + and - symbols indicate sites on the wafer where the breakdown voltage values are lower or higher, respectively, than the mean value. In the regions where there are no actual data points, the lines are extrapolated on the basis of the measured data. Regions on the contour map with a + symbol represent capacitors with a breakdown voltage lower (less negative) than the mean value, since the breakdown voltage was measured in accumulation on p-type wafers. Such capacitors became candidates for EBIC evaluation because of their demonstrated low voltage breakdown strength. As a result they were separated from the wafer and coated with a thin layer of sputtered Au on the backside silicon prior to mounting on a SEM sample stub. This assures good ohmic contact.

The experimental arrangement for imaging capacitor breakdown sites in the EBIC mode is shown in Figure 3. A Philips 505 SEM provided the electron beam and video display. The current signal was amplified by a Keithley 427 current amplifier. Direct contact to the polysilicon electrode of the capacitor was made by a micromanipulator-controlled tungsten needle probe, through which a negative or positive bias (0-20V) was applied using a dc power supply. The spot size of the electron beam used was 1000 Å.

A typical defective or leaky capacitor would generate an electron beam induced current approximately two orders of magnitude greater than one with acceptable breakdown characteristics. Upon contact of the tungsten needle probe with the poly-silicon surface of the capacitor, one or several diffuse bright spots would appear on the SEM display screen in the secondary electron detection mode. The intensity of the spot would depend on the acceleration potential of the electron beam and the degree of damage in the oxide. Improved EBIC spot imaging was achieved by using the Y-modulation mode of the SEM, which enhanced the display of very marginal spots.

Results

The defective capacitors were biased both in accumulation and depletion. Under either test condition, the total current and the intensity of the EBIC spots increased when the beam acceleration voltage (14-30 keV) was increased, while the bias remained fixed. The same was observed when the beam acceleration voltage was fixed and the bias voltage was increased (Figure 4). The presence of a current when biased with the electron beam switched off (Figure 4) indicates inherent leakage in the oxide. This current was found to show a similar dependence on applied bias, as was observed when the electron beam was switched on. It was also observed that the total current and the number of EBIC spots at a fixed beam acceleration voltage and bias voltage were the same in both accumulation and depletion conditions. Table 1 shows examples of nearly identical current readings at negative versus positive bias settings of 0.25 V intervals and a fixed beam acceleration voltage (26 keV).

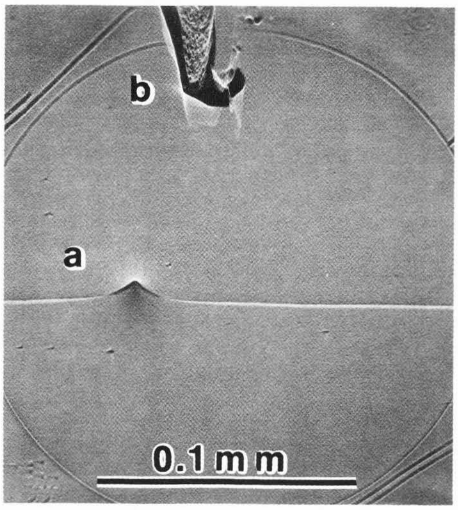

Figure 1: Circular capacitor of $3.2mm^2$ area with EBIC spot (a) and probe contact (b) in y-modulation mode.

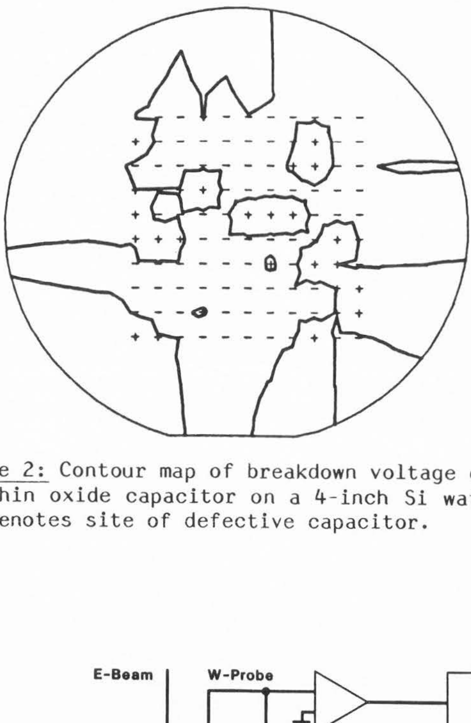

Figure 2: Contour map of breakdown voltage data for thin oxide capacitor on a 4-inch Si wafer. (+) denotes site of defective capacitor.

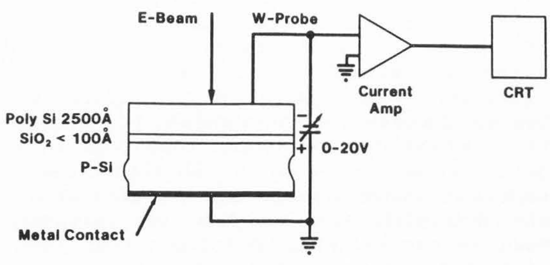

Figure 3: Experimental arrangement for EBIC imaging of thin MOS oxide defects.

Table 1. EBIC measurements of nearly identical readings at negative versus positive bias settings and 26keV beam voltage.

Bias(V)	Current(A)
-1.00	2.01×10^{-5}
-0.75	1.88
-0.50	1.65
-0.25	1.32
0	0.65
+0.25	1.33
+0.50	1.65
+0.75	1.82
+1.00	1.95

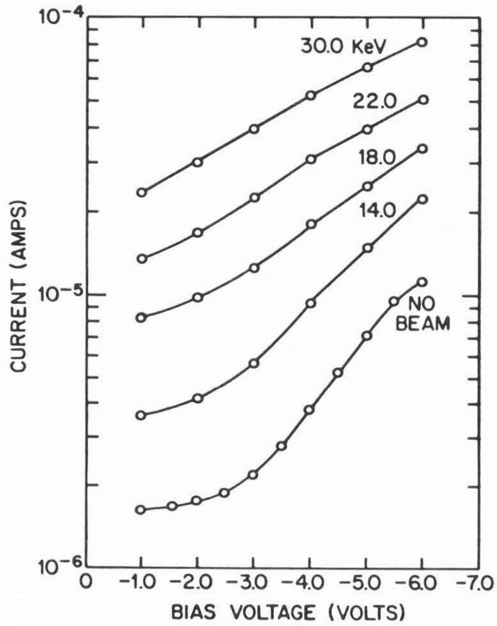

Figure 4: Electron beam induced current (EBIC) distributions as a function of negative bias at various electron beam energies.

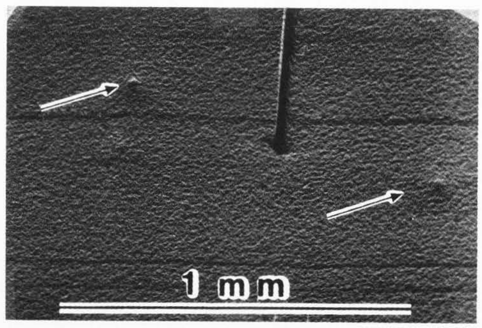

Figure 5: EBIC spots in Y-modulation in capacitors (90Å oxide) as observed in accumulation or depletion.

In Figure 5 typical EBIC spots can be seen in the Y-modulation mode of the SEM. These

EBIC spots were observed in accumulation (-0.75 V bias) and depletion (+0.75 V bias) conditions, as shown in Table 1, with no appreciable change noticeable with respect to bias polarity. The defect site of these EBIC spots is typical for a capacitor location denoted by (+) in Figure 2. The dark line in the center of the SEM micrographs in Figure 5 is due to an inadvertent tungsten probe scratch mark.

A direct correlation was found between defective capacitor sites, as indicated by (+) in the breakdown voltage contour map, and the observation of EBIC spots. Capacitors whose breakdown voltage was less than 3.51 V showed EBIC spots. Capacitor sites in Figure 2, denoted by (-), where the breakdown voltage was greater than 7.57 V, did not produce EBIC spots under the same experimental conditions.

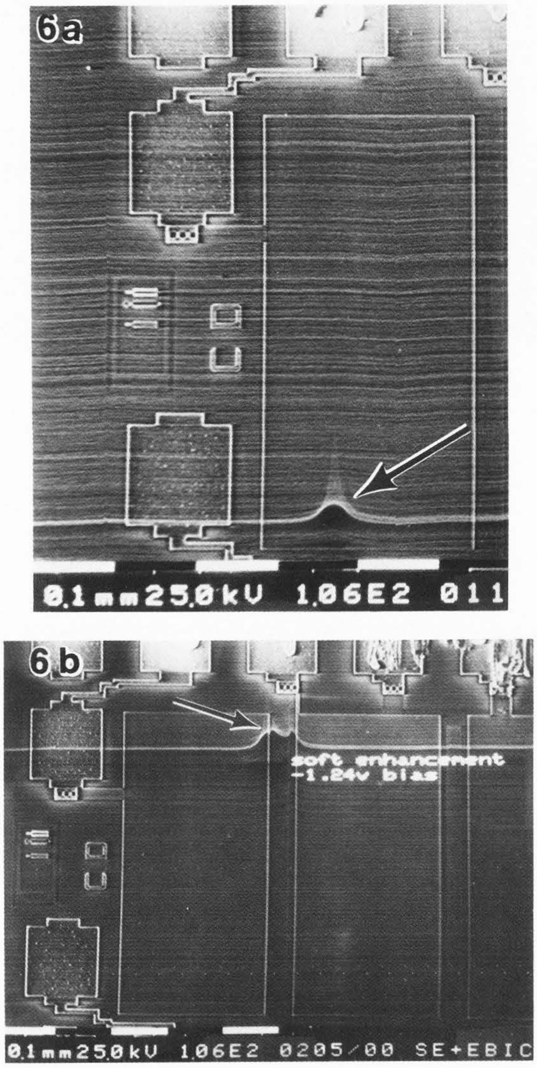

Figure 6: Y-modulated EBIC signals, indicated by arrows, on capacitors (450Å), showing different locations of the defects in the oxide: (a) within the field of the capacitor, (b) at the LOCOS edge of the capacitor.

Thin oxide capacitor structures of 450Å thickness, similar to the one shown in Figure 3, have been examined, as well, using the EBIC technique, to locate voltage breakdown sites. Figure 6 displays Y-modulated EBIC signals superimposed on secondary electron images of two capacitors of the same area at different sites on the same wafer. In both cases the capacitors were biased in accumulation. It can be seen from Figure 6 that a defect associated with the EBIC signal can be located within the capacitor's area(a) or at the LOCOS edge(b).

To verify that the defects were indeed in the oxide itself and not in the underlying silicon substrate, the plasma nitride, the phosphosilicate glass, the poly-silicon gate and the gate oxide layers were selectively removed. This was followed by deposition of 3-400Å aluminum to create a Schottky contact. EBIC measurements were repeated on the same capacitors and no EBIC spots were observed. This is a clear indication that the EBIC spots seen previously were due to defects in the oxide itself and not in the silicon substrate.

Discussion

Two types of oxide defects were observed with the EBIC technique. While both types were showing EBIC spots associated with voltage breakdown sites, they differed in their location on a defective capacitor and also in their origin.

The cause for a defect at the capacitor edge (Figure 6a) can be attributed to the oxide isolation process (Kooi et al., 1976). During preparation of the LOCOS structure, an inadvertent chemical reaction may form silicon nitride (10-20Å) at the Si-SiO_2 interface near the edge of the nitride oxidation mask. Consequently, this anomalous silicon nitride formation hinders the subsequent gate oxide (<100Å) growth. The result is reduced oxide thickness in the area where the silicon nitride was formed. Such a weakened location in the oxide is a very likely site for voltage breakdown.

This problem can be controlled by introducing a sacrificial oxidation step prior to the gate oxide growth which consumes enough silicon to eliminate the small silicon nitride growth. The oxide then is stripped to provide a clean surface for the gate oxidation step.

Defects associated with EBIC spots in the field of a capacitor (Figure 6b) are thought to have their origin in particles. Such particles can be present on the substrate surface or be carried there with the process gases from either the gas sources, the furnace wall or wafer carrier. Proper material and equipment handling can usually prevent particle problems.

It is reasonable to assume that both the size of a nitride growth at the Si-SiO_2 interface near the capacitor edge and the size of a particle determine the severity of voltage breakdown in the oxide. It follows that the dimension of the associated leakage channel is proportional to the amount of EBIC measured.

Also proportional is the intensity of the EBIC signal displayed. The size of a Y-modulated EBIC spot, such as shown in Figure 6b, does not reflect the actual size of its corresponding defect. In reality these leakage channels can be expected to be micron or sub-micron features. The amplitude of the EBIC signal does, however, provide a relative measure of defect size, of which the induced current is a direct function. Multiple defects in a capacitor are displayed individually while their current is measured cumulatively.

The importance of this EBIC technique lies in its ability to locate oxide defects solely restricted to within the boundaries of thin MOS capacitors. While the voltage breakdown method can determine whether or not an oxide is leaky, it provides no clue about the number of defects or their locations. The EBIC technique, in comparison, can pinpoint an individual defect site in a capacitor. This can lead to a clue about the origin of such a defect as well as its prevention.

Conclusion

The application of this EBIC technique has demonstrated that the positions of electrically determined sites of voltage breakdown in MOS capacitors can be located. Such defects have been located within the limits of the oxide layer only, which allows for a direct approach to their solution.

Acknowledgement

The authors wish to thank C. Vorst for technical assistance and W. Stacy for valuable discussions and general support of this project.

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Discussion with Reviewers

J.D. Schick: If a conducting channel is present through the oxide, why is electron beam excitation necessary to cause current to flow through the channel when the capacitor is biased?

Authors: Electron beam excitation is not necessary to cause current to flow when the capacitor is biased. Figure 4 shows the distribution of leakage current of a capacitor at different bias settings under "no beam" condition. The increased current under electron beam exposure is due to the EBIC contribution in addition to the leakage current. With bias alone, no signal could be imaged on the SEM's TV screen. Also, the threshold for EBIC spot detection was 14 keV beam energy at negative or positive 4V bias, below those settings the instrumentation used was not sensitive enough to image an EBIC spot based on the current measured.

J.R. Beall: Do the oxide defects completely or partially bridge across the oxide layer? If partial bridges are detected what percentage of the oxide thickness is detectable?

Authors: Oxide breakdown sites are thought to be related to defects bridging completely across the oxide. Some of the defects may have involved partial bridging (thin areas, internal voids, etc.) prior to breakdown. No investigation of partial bridging was conducted. Our interest was focussed on sites of complete breakdown and on how to image them.

K. Köhler: Quite often self-healing breakdown can occur in MOS structures. Could your technique be used to analyse or at least detect these sites?
Authors: We have not investigated this effect.

P. Lin: Please explain how the amplitude of the EBIC signal provides a relative measure of defect size.
Authors: In our experimental setup, the oxide defect primarily provided the path for EBIC. The intensity of EBIC spots correlated with the amount of current measured, indicating large defects at sites of strong EBIC spots and small defects at sites of weak EBIC spots. The relative difference in EBIC spot intensity can be displayed more visibly in Y- modulation (Fig. 1), where the height of the amplitude of the EBIC signal (a) correlates directly with the EBIC spot intensity, the current measured and therefore also with the defect size.

J.R. Beall: How does the detection of oxide defects relate to the oxide and oxide defect electron-hole generation energy?
P. Lin: Does carrier - recombination at the defects also affect the EBIC signal amplitude?
Authors: Carrier - recombination takes place in the silicon area only and not in the oxide. As the carriers (electrons or holes) reach the conducting path at the defect site, they can no longer recombine.

J.D. Schick: With a 100 nm spot size, why does the EBIC spot not reflect the actual size of the defect?
Authors: The EBIC spot size is determined by the diameter of the excitation volume in relationship to the diffusion length of the charge carriers. Therefore it is possible for an EBIC current to flow through a given conductive path in the oxide before and after the beam crosses the oxide defect. That explains why the EBIC spot size can be changed by changing the beam potential (excitation volume) without changing the beam spot size.

J.D. Schick: If a probe scratch, which is probably a depression in the surface, causes a dark line, is this a reduced or increased EBIC signal?
Authors: A scratch, being a depression in the surface, causes an increased EBIC signal and appears brighter than the background under negative bias condition in the secondary electron detection mode.

J.D. Schick: You state a leaky capacitor would "generate" an EBIC current 2 orders of magnitude greater than a good capacitor. Does this include the "dark" current, also, since the device is leaking to begin with?
Authors: Yes.

J.D. Schick: Since the majority of the excitation volume in the range of beam voltages you used was well below the oxide of interest, did you do any measurements in the 3-5 keV range when the oxide would be included in the larger portion of the excitation volume?
Authors: In the 3-5 keV range no appreciable EBIC signal could be displayed. The minimum beam potential at which EBIC spots could be imaged was 14 keV.

J.R. Beall: Is the increase in capacitor current due to increased acceleration voltage produced by the increased primary electron energy? Is the increased current due to increased bias voltage produced by increased defect leakage current?
Authors: As can be seen from Fig. 4, EBIC could be increased by increasing the beam potential and/or the bias voltage. Negative or positive bias produced very similar results (Table 1).

J.D. Schick: How do you explain an increase in EBIC current with an increase in electron beam energy? Did the increase in beam voltage cause an increase in bias voltage?
Authors: Increasing the electron beam energy also increases the excitation volume in silicon and proportionally the production of electron-hole pairs. This also allows the current flow through the conductive path in the oxide to increase. The bias voltage is not affected by this process.

J.D. Schick: Could you please clarify the polarity of your EBIC measurement. A defect in a capacitor which may be the site of the leakage and/or premature breakdown might produce decreased EBIC signal or increased EBIC signal depending on the precise nature of the defect.
Authors: A defect always produced an increased signal depending on the severity of the defect and independent of the polarity of the bias applied. The simplicity of this method lies in the consideration that only a defect in the oxide would permit an EBIC signal to be imaged.

J.R. Beall: What is the significance in obtaining the same defect current levels in the accumulation and depletion conditions?
Authors: At the absence of silicon defects, a p-n junction or a Schottky barrier, the only path provided for EBIC to conduct is the defect (breakdown site) in the oxide. Therefore accumulation and depletion conditions produced essentially the same results, which is evidence for the defects imaged by EBIC being limited to the area within the oxide only.

J.D. Schick: Did you measure the bias on the capacitor or the outpout setting of the D.C. power supply to determine the bias?
Authors: To measure the bias, a D.C. voltmeter was connected to the contact where the lead to the tungsten needle probe was jointed with the bias line.

J.R. Beall: Is there an explanation why capacitors with lower breakdown voltage can be detected by EBIC and capacitors with higher breakdown cannot?
Authors: Capacitors with lower breakdown voltage are the ones we have examined. Capacitors with higher breakdown probably can be forced to conduct a current by increasing the bias appropriately.

J.D. Schick: I assume the devices you are measuring were not irreversibly broken down.
Authors: Breakdown occurred at a current flow of 10 μA. Once broken down, oxide defects remained that way, as evidenced by repeated EBIC measurements. EBIC spots would reappear at the same locations with the same intensity.

G. Koschek: If the defects are due to particles wouldn't it be worthwhile to analyze their nature, for instance, by means of an electron microprobe?
Authors: The use of an electron microprobe would not apply in this work. The defects, such as voids, holes, thin areas, etc. may have been caused by particles, such as dust. The defects themselves are therefore a secondary effect. Since a particle is no longer present at a defect site, it cannot be analysed for its composition. The intent of this work was not to study the nature of particles with scientific interest but rather to use EBIC results to verify the presence of oxide defects. EBIC data could then be used to minimize or eliminate defect-causing particles by taking appropriate action (proper filtering of air supply and process chemicals).

J.D. Schick: Did you do any physical analysis on the located defects such as sectioning through a single defect and studying it under high resolution microscopy?
Authors: Physical analysis of oxide defects was not pursued. The purpose of this work was to develop a technique by which unspecific sites of electrical breakdown in thin oxides could be located through EBIC imaging.

G. Koschek: Which method was used to calibrate the e-beam spot size?
Authors: We had to rely on a fixed spotsize, which was approximately 1000Å, based on given equipment settings.

J.R. Beall: What was the incident beam current used for these measurements? Was it held constant for all beam voltages?
Authors: The incident beam current for the measurements was approximately 0.8 nA for all beam voltages. Since the beam spot size was fixed, the beam current could be considered constant.

J.R. Beall: Would time dependent dielectric breakdown (TDDB) stress tests be helpful in destructively verifying oxide defect locations identified by EBIC?
Authors: It probably would be difficult to correlate EBIC results with TDDB measurements.

D. Köhler: Can you exclude that the EBIC spots were due to interface states at the silicon/oxide interface?
Authors: It may be possible that interface states contribute to EBIC. We did not specifically address this issue.

G. Koschek: To what extent are the results influenced by the contact resistance between the tungsten needle probe and the poly-silicon electrode?
Authors: Contact resistance between the tungsten needle and the polysilicon electrode can be considered negligible. A bad contact simply would not provide a result. On occasion, attempts to make contact had to be repeated.

D. Köhler: Was any radiation damage observed such as described by P. Roitman and W.R. Bottoms, Scanning Electron Microscopy/1977, Vol I, p. 731-738?
Authors: Radiation damage was not observed.

J.R. Beall: What effect does the polysilicon film have on the detection resolution of capacitor defects? Can this method be used for capacitors having an aluminum film electrode?
Authors: Polysilicon in itself probably has no effect on the detection resolution of capacitor defects. Thickness can be adjusted for by changing beam potential. Aluminum probably could be used as well. We did not try aluminum because the technology employed requires polysilicon.

J.D. Schick: What was the doping of the polysilicon?
Authors: Polysilicon was doped with $POCl_3$ to a V/I = 5.0.

J.D. Schick: Since your DC bias was in some cases greater than break-down, did you AC couple your current amplifier for EBIC measurements?
Authors: No.

J.R. Beall: What proportion of the beam induced current flows in the current amplifier?
Authors: This current was not determined.

J.D. Schick: Where was the electron beam located on the capacitor when this measurement (and Fig. 4) was made?

Authors: The electron beam was scanned across the capacitor, being in view on the TV screen in the secondary electron detection mode.

D. Köhler: You proposed to introduce an oxidation step to avoid the silicon nitride growth. Did you perform this in practice and if so, what results did you obtain?
Authors: The sacrificial oxidation step referred to is part of standard processing during wafer fabrication and prevents the detrimental silicon nitride growth. For the sample shown in Fig. 6b, however, this procedure was not used and the defect, as shown by EBIC, has resulted.