APPLICATION NOTE

Strategies to identify physical origins of contrast in EBIRCH

INTRODUCTION

The Electron Beam Induced Resistance Change (EBIRCh) is an increasingly popular Electrical Failure Analysis (EFA) technique for defect localization in dielectrics. It highlights the precise location of leakage on defective gates. The spatial resolution of EBIRCh is sufficient for a TEM lamella to be prepared for further physical failure analysis. EBIRCh is very straightforward to implement, however, we do not completely understand the fundamental origin of its signal.

In this application note based on our recent paper [1], we discuss the contrast generated by EBIRCh and how to separate it from other phenomena, and gain a better understanding of this technique.

EBIRCH PROCEDURE

Preliminary steps to prepare for EBIRCh investigation include device delayering, device and nanoprobe cleaning, and device characterization.

• LAND PROBES: land the first nanoprobe to bulk, source or drain, and the second nanoprobe to the gate of the device-under-test, as shown in Figure 1.

• BIAS: apply a constant voltage to the device-under-test (further referred to as bias voltage) and measure the current, which we call dark current.

• IMAGE: scan the electron beam over the device, and measure the current passing between the probes. We refer to the resulting image acquired as the Electrical Analysis (EA) image.

• MIX: mix the corresponding SEM and EA images in order to see the precise location of a failure. This image is our “localization image”.

A device with a leaking gate will produce a colored EBIRCH spot in the localization image, as shown in Figure 1b. This spot corresponds to the change in the current measured between the probes when the electron beam hits the defect site. Since the voltage applied to the device is constant, the change in current is caused by a change in the defect resistance when the electron beam hits its location.

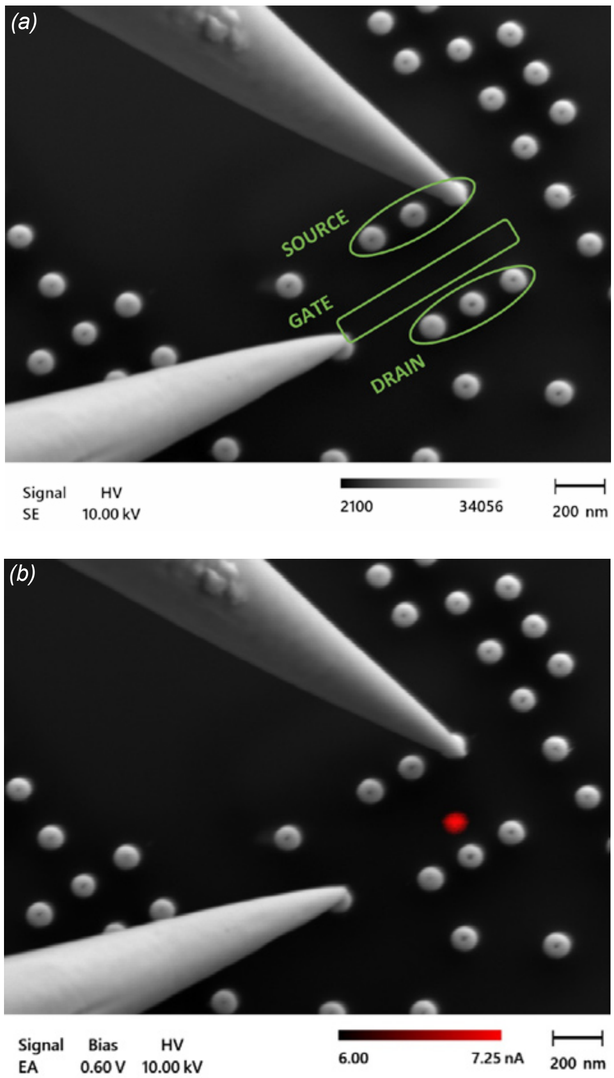

Figure 1. (a) SE image of PMOS showing device structure, and (b) corresponding EA image after a soft failure is induced, showing EBIRCH spot.

EQUIPMENT

The devices used for this experiment were PMOS transistors from a 180 nm technology die, delayered and cleaned using standard procedures.

Experiments were carried out in a ZEISS Sigma SEM and a Tescan CLARA SEM. To match the experimental conditions in both microscopes, the electron beam current was measured using a Faraday cup inserted at the sample position. Both microscopes could therefore be set up under similar conditions with a beam current in the range of 3 nA. A range of acceleration voltages has been explored on both SEMs to provide insights into the origin of contrast in EA images.

An Imina Technologies' nanoprobing system equipped with four miBots™ and a Thermal stage with a temperature range of -30˚ to 150˚C was used to electrically contact the transistors and to change the device temperature from room temperature to 150˚C.

An EFA system from point electronic GmbH was used to apply the voltage bias, to amplify currents and to record calibrated EBIRCH, EBAC/RCI and EBIC images, as well as to clean the nanoprobes. Bias voltage has been applied to Low, and device current has been measured on High. Amplification of current has been carefully set for each image to prevent saturation to black or white values, and therefore to preserve all raw shapes and intensities.

A semiconductor parameter analyzer Keithley 4200ASCS was used to characterize devices and to induce soft failures.

Simultaneous Secondary Electron (SE) and EA images were saved into uncompressed 16-bit TIF files, including complete hardware calibration as XMP metadata. This way, pixel values can be displayed in measured currents, for a direct image-to-image comparison and quantified image interpretation. All the images presented here were prepared and exported using the DIPS6 app from point electronic GmbH.

To understand the EBIRCh signal, we induced defects in the gate dielectrics by applying voltage stress. Figure 1a shows probes in contact with the gate and source of a transistor. The device was stressed with increasing voltages on its gate until 1 μA was reached. Such stresses usually result in a short to the channel and therefore provide a path to the source or the drain. For localization, a bias was applied on the probed device, and the resulting localization image is presented in Figure 1b, illustrating a typical defect spot.

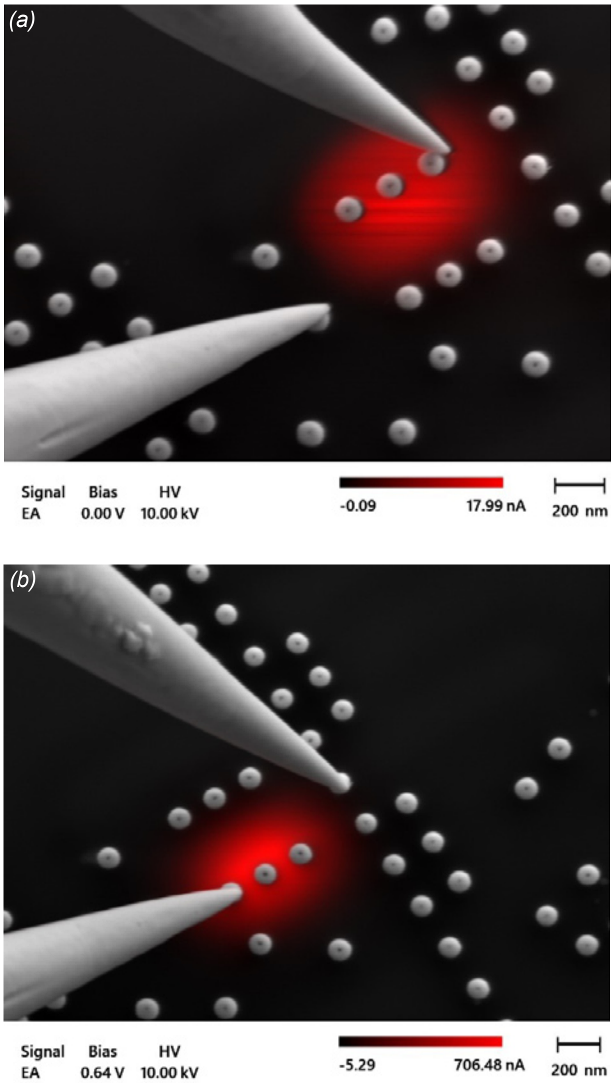

Figure 2. (a) unbiased localization image of defect from Figure 1 at 10 kV, and (b) localization image of a reference device recorded in similar conditions.

RESULTS & DISCUSSION

In the series of experiments presented here, we have investigated the effects of different factors such as acceleration voltage, bias voltage, beam current, temperature and device stability. Each of these factors sheds some light on the physical phenomena underlying EBIRCh signal.

Role of the beam acceleration voltage

We start with the localization image at 0 V bias voltage, shown in Figure 2. When we compare it to the Figure 1b, the observed spot changed its location, shape, and the current range. Resistance change of the defect would only cause a change in the current range. The change of the spot location and shape [Figure 2a], suggest additional electrical activity of the source. Increased EA current at 0 V voltage suggests that the current might be induced.

To verify if induced current contributed to the signal, we measure the Electron-beam Induced Current (EBIC) on a reference transistor, as shown in Figure 2b. EBIC reveals a similar spot location and shape. Even though the observed features do not fully coincide, we conclude that EBIC current contributed to the unbiased localization image.

The EBIC signal can be suppressed at a positive bias voltage. To fully exclude the EBIC contribution, we drop the acceleration voltage of the electron beam so it cannot reach silicon. Figure 3a shows an unbiased localization image recorded at 6 kV, where the EBIC signal does not occur.

Role of the sample bias voltage

Figure 3a presents the unbiased sample corrected for the EBIC contribution. Comparing it to the biased sample from Figure 1b, we still see changes in the spot shape and location. To test if the electron-beam-absorbed current (EBAC) accounts for these changes, we perform Resistive Contrast Imaging (EBAC/RCI) on a reference device, as presented in Figure 3b. The image shows a uniform EBAC/RCI current along the gate. The drop in EBAC/RCI current in Figure 3b coincides with the defect location in Figure 1b. The absorbed current in the unbiased device should be leaking through the defect into the grounded parts of the sample.

Under bias, the device exhibits a more complex behavior, as shown in Figure 4 (mixed color image) and 5 (EA images). As we sweep the voltage bias from -1.5 V to 0 and then to 1.5 V, the current at the defect site changes its sign/contrast from white to black corresponding to the bias polarity. The current values change from 6 nA to 0.5 nA and then to -5 nA, respectively. Such behavior indicates a direct relationship between the sourced voltage and the direction of the current measured at defect site. EBAC/RCI image would not change upon changing the bias polarity, so other mechanism is also responsible for the observed behavior.

The change of contrast could be caused by Electron-beam-induced resistance change (EBIRCh). Local heating or temperature gradients could lead to the resistance change giving rise to the Seebeck effect.

Role of the beam current and the beam scanning speed

Before we investigate the resistance change, we look at the effects of the electron beam current and the beam scanning speed to exclude them as a source of contrast change. Varying pixel dwell time from 1 μs to 20 μs has no effect on the defect contrast and shape. Rotating the scan on the same defect did not reveal any relationship to the defect shape or measured currents either. Varying the beam current from 0.4 nA to 2.5 nA gave a linear increase in defect contrast without any change in spot shape.

Role of temperature

To investigate the thermal behavior of the signal, we imaged each defect at room temperature, then at 150°C, and then again at room temperature. The probes in this experiment were landed on the gate and bulk of the device.

Figure 6 presents a defect that showed two distinct changes at 150°C and returned to its initial behavior after cooling. At 150°C, the EA current has increased, and the defect active area has significantly increased, extending much further into

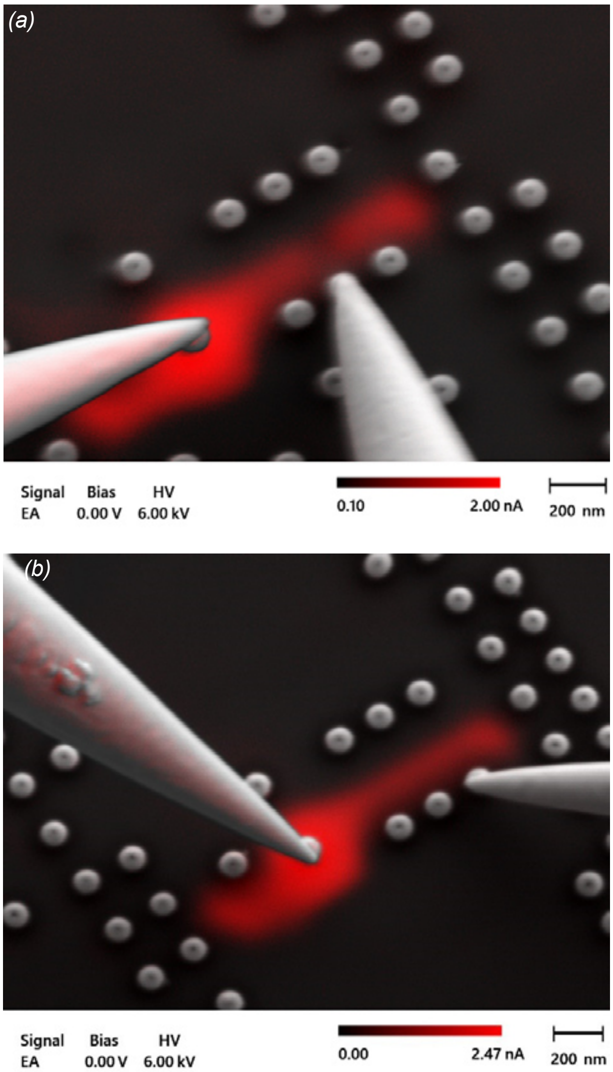

Figure 3. (a) Unbiased localization image of the defect from Figures 1-2 at 6 kV, and (b) localization image of reference devices recorded at a similar voltage 6 kV.

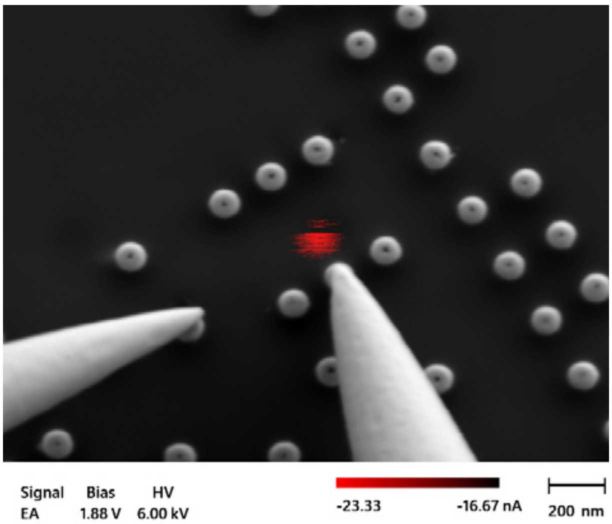

Figure 4. Biased localization image of the same defect from Figures 1-3, with an acceleration voltage of 6 kV.

the area of the gate. The reversibility of this behavior upon cooling implies that the observed effects are temperature-driven, and do not originate from changes in structure or composition.

The increase of the defect active area at a higher temperature cannot be explained by the resistance change or the Seebeck effect. It could be related to temperature-driven changes in voltage contrast and the work function. EBAC and SE signal are closely related, as they describe yields of electrons remaining and leaving the device, respectively, and therefore both depend on bias and work function. Work function does depend on temperature, and can account for the additional contrast recorded at 150°C.

Role of device stability

To assess stability of devices during the experiment, we acquired time series under constant experimental conditions and looked for changes in currents or active areas. We also examined each defect by returning to the initial conditions at the end of each measurement. As presented in Figure 7, the defects were stable over the observed period. This result was expected, as the bias used to induce the defects was much higher than the bias for EBIRCh.

We evaluated potential radiation damage by curing the device at high temperature in-situ using the heating stage. The curing did not change the defects. It is still possible that radiation damage occurred during the experiment, but it was too small to produce a significant effect.

CONCLUSIONS

We found multiple factors that affect the contrast in the EBIRCh localization images.

• If the acceleration voltage is high enough for the electron beam to reach the device junctions, induced currents can contribute to the signal. For example, if a short is a leakage from source to gate, it can become visible when unbiased or reverse-biased.

• Absorbed currents contribute to the recorded images through resistive contrast, so EBAC/RCI usually displays a weak signal from the gate within the raw EA image. Defect sites are also visible at zero bias, which is equivalent to the EBAC/RCI technique, although with a weaker contrast than the EBIRCh.

• An additional contrast change appears when a bias is applied across the defect, and it depends on the sign and value of the bias voltage. It is reversible over the voltage range applied here, and it is not associated with the scan direction or scan speed.

• A significant reversible increase in the active area of a defect and a small increase in the defect contrast are observed at high temperature.

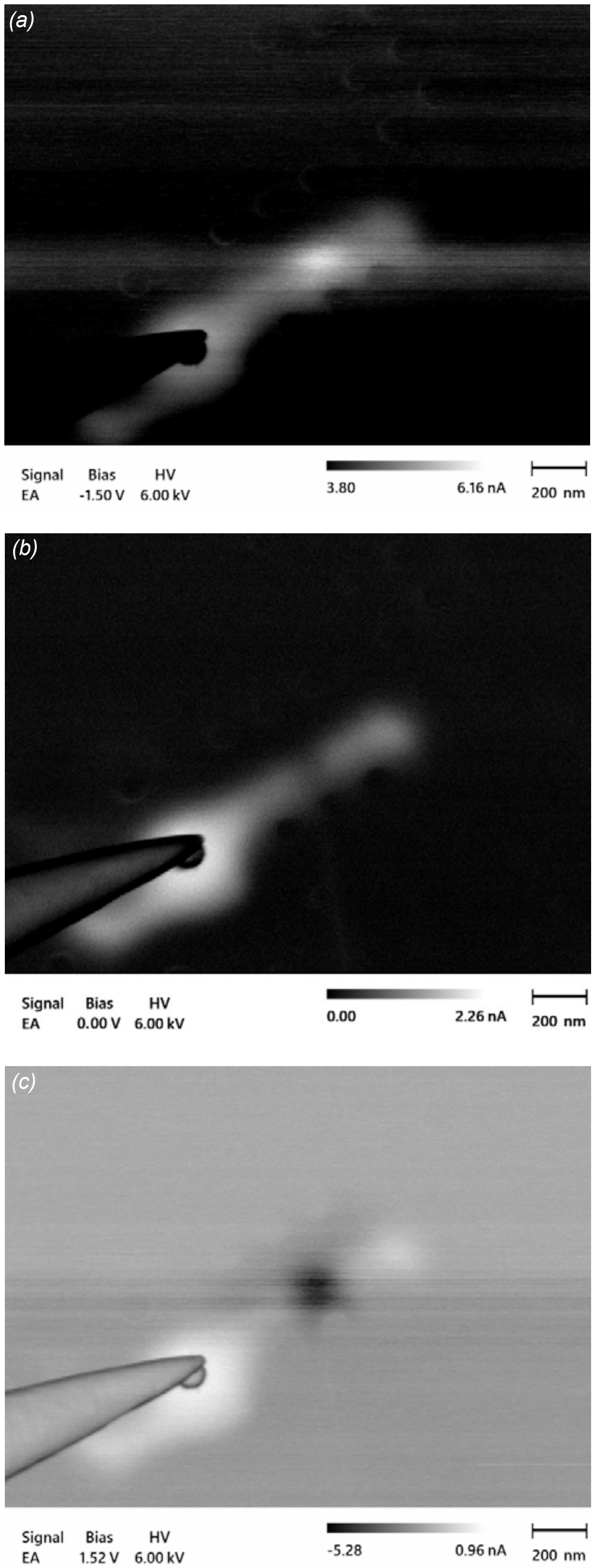

Figure 5. EA images of the same defect under a range of bias voltages: -1.5V (top), 0V (middle) and 1.52V (bottom), and at an acceleration voltage of 6 kV

Contrast of the defects strongly depends on bias voltage, beam current and device temperature:

• Relationship to bias voltage is not linear, including a contrast reversal.

• Dependence on beam current is remarkably linear, with the normalized defect contrast remaining constant over the entire experimental range used here.

• Heating to 150 °C produces a significant increase in the defect active area, probably due to the changes in the work-function of the dielectric.

• Defects induced in this study were stable for the period of typical EBIRCh experiment.

Based on how EBIRCh signal is influenced by different experimental conditions, EBIRCh data interpretation must be based on a range of bias voltages to avoid the risk of analyzing the features that originate from other sources, such as induced currents at junction sites. Localization images acquired at zero bias help to distinguish resistance-related currents from induced and absorbed currents. Heating provides additional insights into the physical origin of contrast.

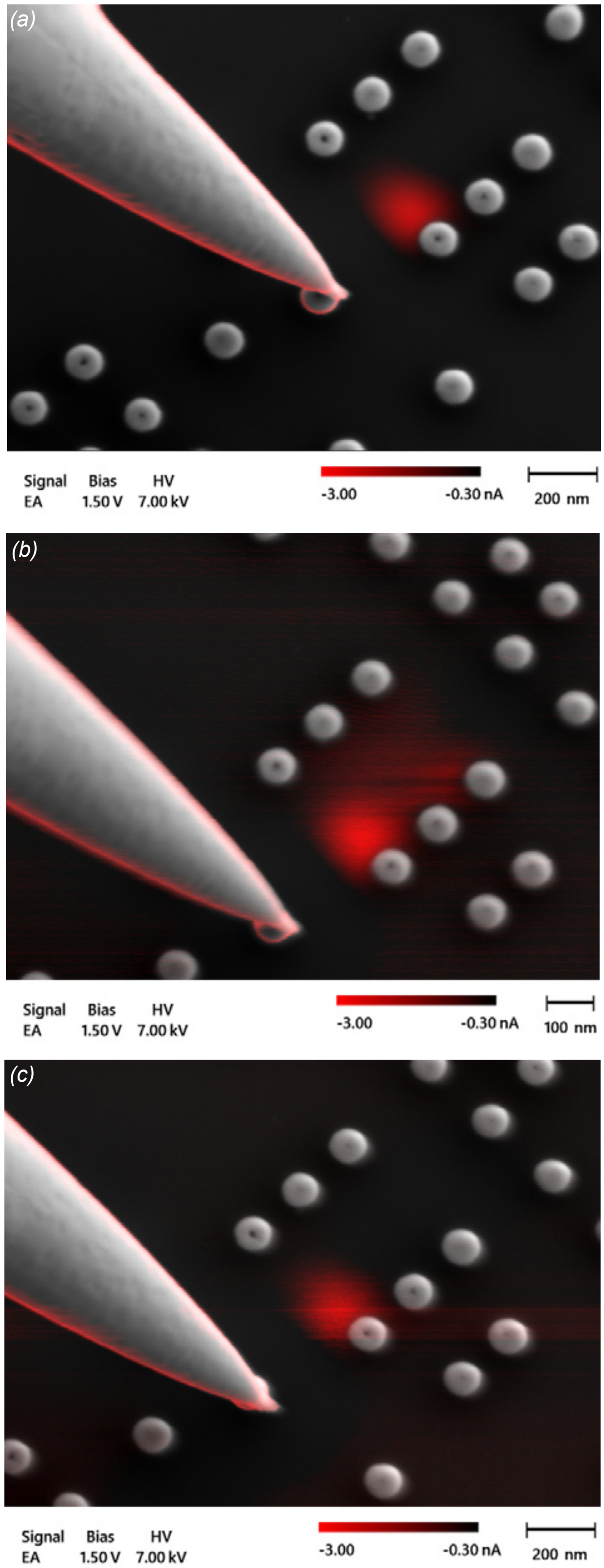

Figure 6. EBIRCH localization of a defect at (a) 25˚C (b) 150˚C and (c) back to 25˚C.

REFERENCES

[1] Grigore Moldovan, William Courbat, Strategies to Identify Physical Origin of Contrast in EBIRCH, Conference Proceedings from the 48th International Symposium for Testing and Failure Analysis, 2022, pp. 277-283

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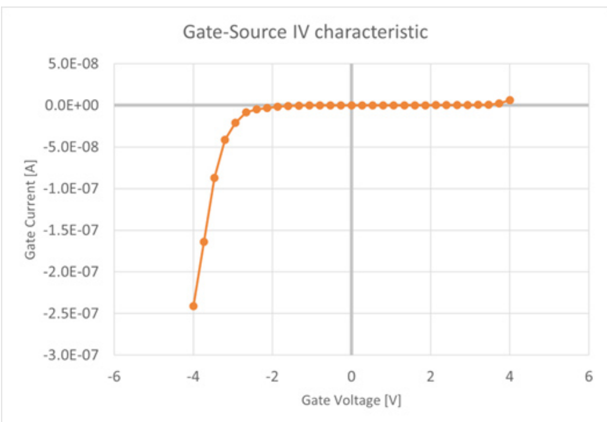

Figure 7. Typical current-voltage sweep over an induced defect.

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