APPLICATION NOTE

Advances in EFA with color coded multi-channel nanoprobing

INTRODUCTION

Increasingly complex semiconductor device developments, such as three-dimensional device architecture, pose serious challenges in failure analysis. To ensure efficient and safe device operation, engineers need to localize and understand electrical failure in elements with complex shapes and overlapping structures and fields. It becomes increasingly hard to interpret images and to correctly distinguish between Electron Beam Induced Current (EBIC) and Electron Beam Absorbed Current (EBAC), or between Resistive Contrast Imaging (RCI) and Electron Beam Induced Resistance Change (EBIRCH). This trend poses two somewhat opposite requirements on the failure analysis workflow: on one hand, more complex data has to be collected, but at the same time, there is a need for more intuitive data visualization and interpretation.

In this application note, we show several examples that illustrate how to combine multi-channel imaging and color coding to bring this much-needed improvement.

METHODS

Multi-channel nanoprobing is based on 8x miBots™ nanoprobing system from Imina Technologies SA with an integrated EFA system from point electronic GmbH, a dedicated in-situ EFA board with 8x pre-amplifiers, and an 8x multi-channel signal (MICS) amplifier. Each of the nanoprobes has independent parallel routing and amplification, so 8x independent nanoprobe images can be recorded simultaneously. Such setup collects much more data as compared to established EFA techniques, where only one nanoprobe image can be recorded at a time.

Calibrated gains and offsets of the MICS amplifier and EFA imaging enable quantitative measurements on the images collected by each nanoprobes. This way, we can confirm our signal interpretation by comparing measured values in the scan with measured current of the primary beam.

Samples presented here were delayered using standard equipment and imaged at room temperature using a Clara SEM from Tescan. Acceleration voltage and working distance were optimized for each sample.

COLOR CODING

Localization image is usually composed of the reference signal (typically Secondary Electrons) in grayscale mixed with a single current collection image colored from black to red. The resulting red-on-grayscale images are excellent for displaying location and shape of EFA features, but they don't display any information about the direction or intensity of the current through the sample.

Color coding assigns color to each of the probers. It is more suitable for a complete visualization of complex systems.

EXAMPLES

Nanoprobe color coding

Sample: a double transistor with a common source.

Experiment: three nanoprobes are routed to three independent channels of the MICS amplifier and landed on the device: one on the common source and two on the drains. Individual red, green and yellow colors represent signals from each respective probe. Signals from all nanoprobes and SE are acquired simultaneously, and color mixed as shown in Figure 1.

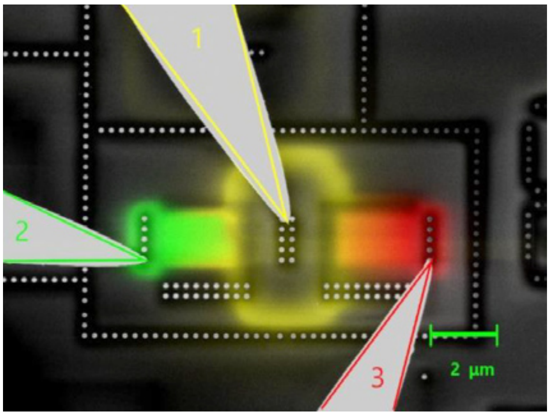

Figure 1. Example of nanoprobe color code (signal from each nanoprobe is assigned a different color) on a double transistor with a common source.

The resulting color-coded image is now straightforward to interpret, as signals in the image can be easily tracked to each nanoprobe. We can now focus on the position and shapes of EBIC signals.

Sample: a 7 nm CMOS device.

Experiment: the signal from probe 1 is blue, 2 is red, and 5 is green. Acceleration voltage is optimized to produce only EBAC and RCI signals.

Using this approach, we can map multiple nets at the same time, both in the proximity of the probes, and on a wider scale, away from the probes.

These examples feature only three probes each, but the approach can naturally extend to up to eight nanoprobes.

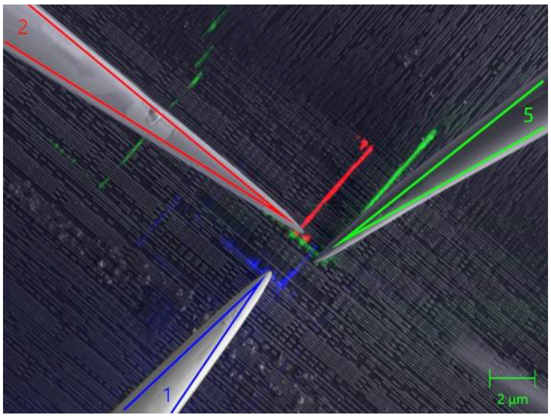

Figure 2. Example of nanoprobe color code (signal from each nanoprobe is assigned a different color) on a complex interconnect network.

Tip: use primary colors so overlapping structures produce a color that has a direct relationship with mixed signals (like red+yellow = orange, or blue+yellow = green).

Current color coding

Sample: a large transistor structure

Experiment: here, color is coded by current direction and intensity. We used blue-black-red color scheme, where:

- Red shows negative current direction;
- Blue shows positive current direction;
- Black shows a signal with a value of zero;
- Pixels of equal current values have the same color intensity.

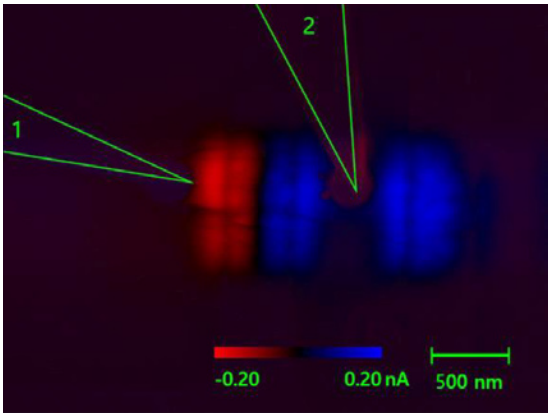

Figure 4. Color mix from nanoprobes 1 and 2 of Figure 3.

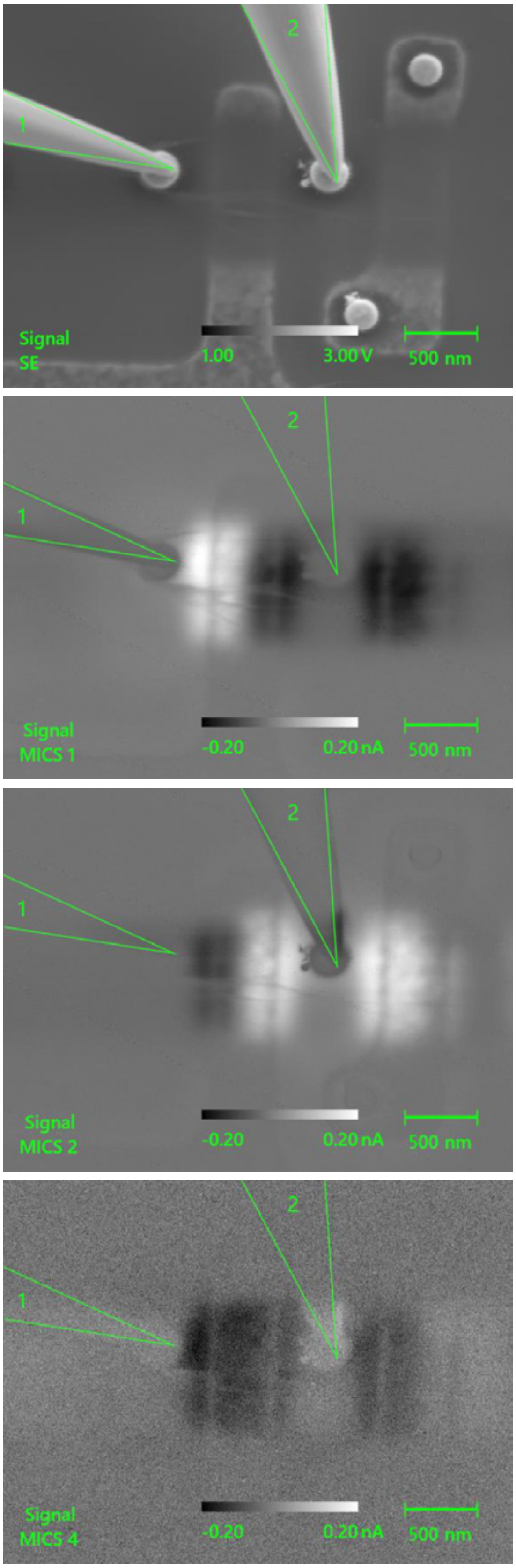

Figure 3. Example of raw images from multi-probe configuration with nanoprobe 1, 2 and 4 connected for imaging. Grayscale is already prepared for mixing, with images displayed with same range from -0.20 nA (black) to 0.20 nA (white).

Two nanoprobes are landed on source and drain; both nanoprobes and the bulk are routed to three distinct amplifier channels. Raw grayscale images are shown in Figure 3, and the color-mixed image is shown in Figure 4.

Raw images from probe 1 and probe 2 produce a strong contrast. The black in the first image becomes white in the second one, and vice versa. The contrast reversal suggests EBIC as a contrast source. The left-most feature appears brighter and larger in the raw image from the probe 1 as compared with the raw image from the probe 2. This apparent difference in intensity and size is associated with RCI contrast overlapping with EBIC signal. It removes contrast from the features further away from the probe. This RCI artefact disappears when the multi-probe signals are mixed in color, as shown in Figure 3a, because the overlapping RCI contrast is the same in each raw image. Figure 5 shows EBIC signal obtained at the contact level of a 7 nm technology die. This image confirms that the current color coding approach is independent of spatial resolution of the device technology.

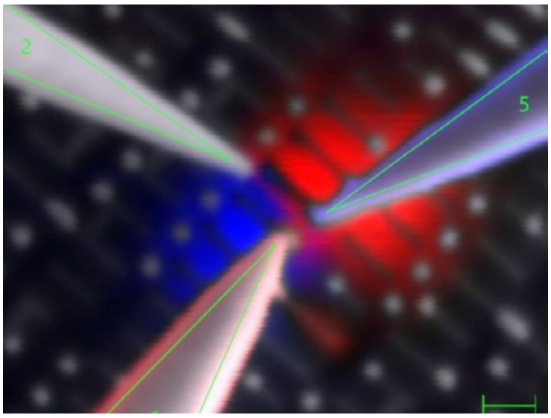

Figure 5. Current-coded color mix on a 7 nm technology node die.

Tip: when a non-zero value is chosen as black level, it should be clearly marked in the image or the image caption, otherwise it can lead to misinterpretation. Also note that for two terminal devices where EFA images have only one signal and only one sign, the multichannel color-coding reproduces the conventional black-red color localization images.

IMAGE MATH

Localization image is usually obtained with multiple nanoprobes in contact with the device, with only one of them used for EFA imaging and the rest for grounding or biasing. As a result, several signals of different physical origin are mixed into the signal from the EFA imaging nanoprobe, which then requires complex image interpretation.

EBIC and EBAC signals are usually admixed. RCI image also gets unwanted EBAC contribution, depending on the probing configuration used. With multi-channel nanoprobing, we can realize any image math, not only addition of the signals from every nanoprobe connected to the sample, and only keep the signal that we are interested in. This capability is of great value for many-terminal devices and has capacity to process novel technologies with additional complexity.

Example

Sample: a large conventional structure, where a line was cut open with a Focus Ion Beam (FIB) to produce a basic defect that shows an RCI contrast.

- Sum of EFA signals reveals underlying EBAC contrast, as opposing RCI contrasts and EBIC fields cancel each other.
- Difference of images reveals a presence of an RCI contrast

Adding image math to signal mixing brings new opportunities for failure analysis. For example, simply collecting all signals and adding them together is of immediate interest, because EBIC and RCI signals from different probes cancel each other as they have opposite signs, and the resulting sum image only shows EBAC contrast.

A simple EBAC/RCI example is given here in Figures 6-7 to illustrate this outcome. We used a Focused Ion Beam (FIB) to cut an open line, producing a reference RCI structure. One nanoprobe was connected to the line and routed to channel MICS2, and another one, was in contact with the device ground and routed to channel MICS3, as shown in Figure 4 (probes outside of field of view).

We observed a difference between the darker and the brighter line (RCI), as the nanoprobe connected to the line collects the absorbs current in it, whereas the nanoprobe connected to the bulk collects the current absorbed in the entire sample, minus the current going to the other nanoprobe. The general structure and topography of the device are also visible in these images because the amount of the absorbed current (EBAC) depends on local surface topography and composition, similarly to the SE contrast. This example illustrates how EBAC and RCI contrasts always overlap in the same raw image, and how EBAC is closely related to SE.

Image match was used to sum up signals from the two nanoprobes, as shown in Figure 7. The resulting EBAC image has only composition and topography contrast, similar to the SE image, except that the SE image has additional edge contrast due to collection efficiency of secondary electrons (SE detector collects more signal from the closest edge).

We use signal difference in Figure 5, as the EBIC currents are of opposite signs in the two probes. Different signal math can be used to highlight other internal fields in the device, for example adding signals from probe 1 and 3 provides an image of the internal field underneath the source drain, i.e. the underlying isolation field, as shown in Figure 8.

Tip: image math has the advantage of full dynamic range/ digitization, whereas color mix is limited to the 8-bits of RGB image format.

Tip: it is important that pixel values used for image math are measurements/quantitative values, for example currents in nA, so that output pixel values can have a direct interpretation.

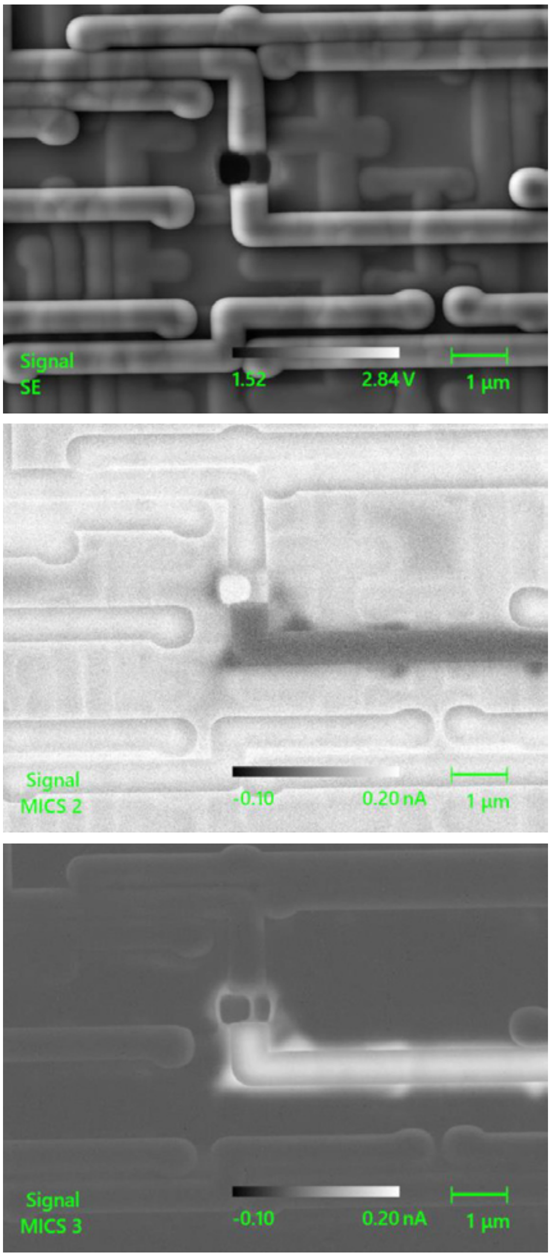

Figure 6. Raw grayscale images from multi-probe configuration on an opened line, with two nanoprobes routed to imaging channels MICS 2 and MICS2. Grayscale is already prepared for mixing, with images displayed with same range from -0.10 nA (black) to 0.20 nA (white).

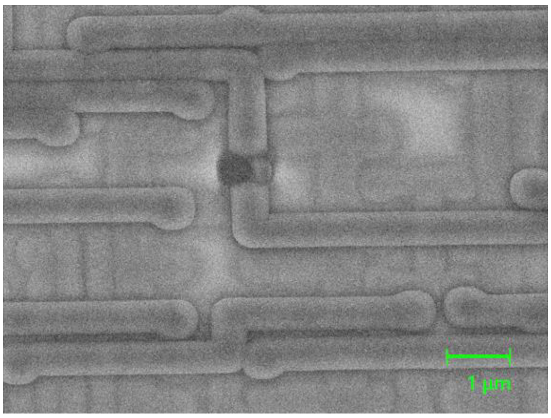

Figure 7. Sum of signals from nanoprobes 1 and 2 from Figure 6, showing EBAC contrast only.

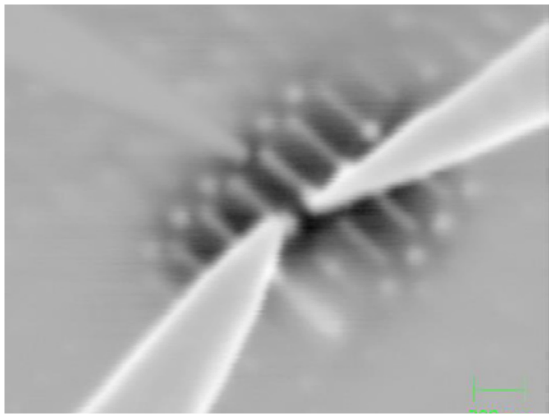

Figure 8. Sum of signals from nanoprobes 1 and 3 from Figure 5, showing EBIC from the isolation field.

CONCLUSION

Simultaneous acquisition of EFA signals for each nanoprobe and color coding of signals offers a significant improvement in EFA data acquisition, visualization, and analysis. We show how Imina Technologies' nanoprobing setup can be used in combination with point electronic's advanced EFA module to achieve color coding by nanoprobe, color coding by current, and image math.

The examples we show illustrate not only advantages in data analysis, but also the ability to distinguish between overlapping internal fields and varying resistance. New dedicated electronics and software added to our integrated EFA solution, include multiple independent channels and advanced software for color coding. These improvements are essential as devices become increasingly complex in structure and fields, with many overlapping features and multiple origins of contrast.

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