APPLICATION NOTE

Scan-assisted lock-in RCI on low-resistance samples

In collaboration with

point electronic GmbH

www.pointelectronic.de

Lock-in amplification is used in Scanning Electron Microscopy (SEM) and Electrical Failure Analysis (EFA) to improve imaging quality and to access signals masked by noise or high offsets. To apply lock-in amplification in SEM the beam and thus the signal is modulated according to a reference frequency, which is usually achieved by an electrostatic beam blanker. Here, we introduce scan-assisted beam modulation, which is compatible with any SEM and is integrated in an EFA system with digital lock-in amplification. This approach boosts the RCI workflow by fully removing low-frequency noise, typical for two-probe measurements, and extending RCI capabilities to low-resistance samples without significant hardware investments.

INTRODUCTION

SEM-based EFA techniques, such as Electron Beam Induced Current (EBIC), Resistive Contrast Imaging (RCI) and Electron Beam Induced Resistive Change (EBIRCH) are used to characterize internal electrical fields, to image resistance distribution, as well as to localize defects in transistors, capacitive structures and metal lines of Integrated Circuits (ICs) [1-10]. Lock-in amplification can enhance these techniques by increasing Signal-to-Noise Ratio (SNR). It also helps to manage signals with high offsets, to extract lifetime and diffusion length of minority charge carriers, and to precisely localize defects in ICs [11-16].

In lock-in EFA, the electron beam is modulated according to a reference signal with a certain frequency. As a result, the desired signal oscillates with that frequency, while most of the noise remains random. The lock-in amplifier multiplies the measured signal by the reference waveform and integrates the product over a certain time namely the pixel dwell time. This filters the result, isolating only the component of the signal that matches the modulation frequency. This signal is averaged over several cycles to ensure effective noise filtering. This way, even small beam-induced changes can be detected against the noisy background.

Beam modulation in this context means turning the electron beam on and off, according to reference lock-in frequency. One way to achieve that is to use an electrostatic beam blanker. However, such setup is expensive, takes days of SEM down time for installation, and cannot be used in some SEMs all together.

Here, we present scan-assisted beam modulation - an alternative to electrostatic beam blanker which does not require any changes to the SEM column. In scan-assisted beam modulation, SEM scan coils toggle the beam between a reference point and the intended beam position on the sample. The deflection cycle is driven by the reference signal of an integrated digital lock-in amplifier, which is also used to demodulate the collected EFA signal. This approach requires no changes to the SEM column, only a suitable scan controller. Such beam modulation setup costs one order of magnitude less and does not introduce any tool down time.

To illustrate the technique, we show how scan-assisted lock-in EFA removes low-frequency noise typical in RCI measurements in low-resistance samples from 10kΩ to 100Ω and compare it with the in-situ preamplification approach [3], and show the technique applied to the metal line detection on an IC.

EXPERIMENTAL SETUP

- Integrated nanoprobing and EFA system with scan-assisted beam modulation and lock-in amplification from Imina Technologies and point electronic GmbH
- Zeiss Supra for lock-in RCI experiments
- Tescan Clara for the lock-in EBIRCH measurements

As shown in Figure 1, the EFA system has two components: a controller and an imaging unit. EFA controller manages signal routing, preamplification, current compensation, biasing, and a needle cleaning module. The imaging unit is a scan controller based on the advanced Digital Imaging Scanning System generation 6 (DISS6) scan engine. It controls the scan and digitizes the signal, connecting to the SEM via the standard external scan interface. EFA imaging unit simultaneously acquires up to 20 signals, including Secondary Electrons (SE) and EFA nanoprobing signals. Here, the firmware also includes a digital lock-in amplifier and the specialized scan mode that we present in this application note. Four NANO+ nanoprobers are used to electrically contact the samples and to collect the current during the measurements.

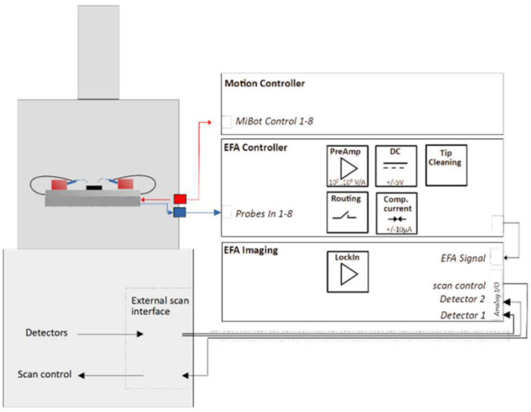

Figure 1. *EFA Nanoprobing system setup consisting of a nanoprober platform, nanoprobing motion controller, EFA controller for EBIC, EBAC, RCI and EBIRCH, and EFA imaging unit for image acquisition, scan mode setting and lock-in amplification.*

Regular SEM scanning deflects the electron beam over the field of view pixel-by-pixel and row-by-row, from top left to bottom right. As the electron beam briefly dwells at each pixel, the signal is digitized and averaged.

For scan-assisted beam modulation, the scan controller moves the electron beam back-and-forth between a fixed reference point and the intended position on the sample, according to the reference clock of a lock-in amplifier, as shown in Figure 2. Reference position can be any point from the available field of view (the top left pixel in our example).

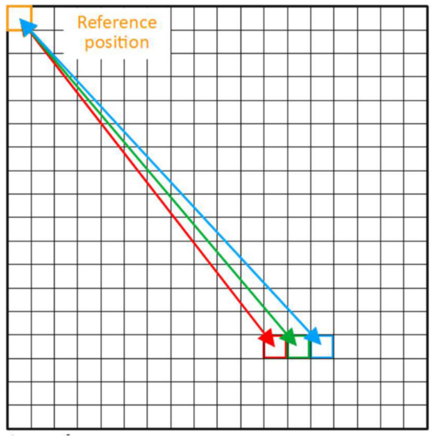

Figure 2. *Scan-assisted beam modulation for three successive pixels. Triggered by a reference clock, for each pixel position and during each pixel acquisition time, beam position is deflected 10 times between the actual scanning position and a fixed reference position.*

Figure 3 shows the periodic deflection of the beam position driven by the reference frequency of the lock-in amplifier which results in a signal modulation with same frequency as intended for lock-in amplification. Note that the signal at the reference position is not necessarily zero, as it would be the case for beam blanking, but is constant. The reference frequency can be set in the range 100Hz to 100MHz, and needs to match the maximum distortion-free scanning speed of the SEM. This limitation is the biggest operational difference between scan-assisted beam modulation and the electrostatic beam blanker, which can operate at much higher frequencies. Pixel acquisition time is configurable with 10ns steps, and in this experiment, we set it to 5-10 times the period of the reference clock, or lock-in modulation, to allow for sufficient signal averaging by the lock-in amplifier.

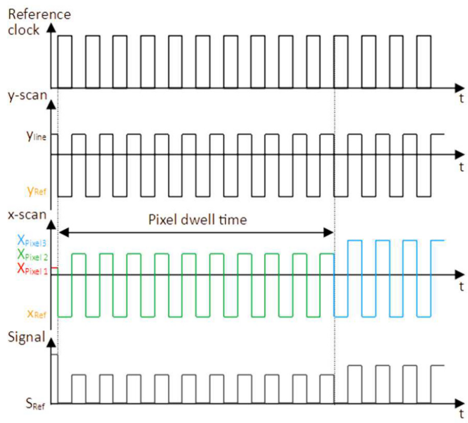

Figure 3. *Principle of scan-assisted beam modulation, for the same three pixels in Figure 2. Triggered by the reference clock, the X and Y scanning signals are defined such that the beam is deflected 10 times, within the pixel acquisition time, between a reference position and the actual position.*

We used a maximum reference frequency of 10kHz for the Zeiss Supra and 30kHz for the Tescan Clara. Note that the maximum frequency might be higher, if the reference point is closer to the point of interest, for example the center of the scanning field rather than top left. With pixel dwell time 5x the modulation period, we get a good SNR in lock-in amplification, resulting in a minimum dwell time of 500μs for the Zeiss Supra and 167μs for the Tescan Clara.

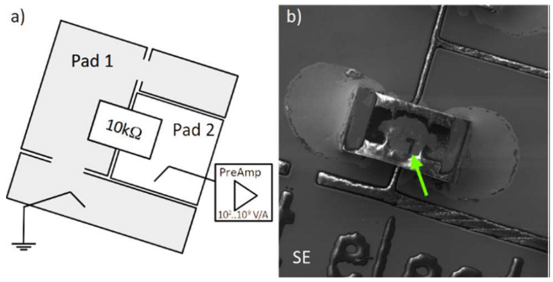

Figure 4. *a) Schematic and b) SE image of setup used to study the general issue of increasing low frequency noise with decreasing resistance in a twoprobe measurement. Resistor is placed over two contact pads, pad 1 is grounded and pad 2 is connected to the pre-amplifier.*

RESULTS AND DISCUSSION

A. Scan-assisted lock-in RCI: 10kΩ, 1kΩ and 100Ω resistors

Two-probe EFA measurements of low-resistance devices suffer from stronger low-frequency noise than higher-resistance ones. To illustrate this trend, we compare RCI measurements of 10 kΩ, 1 kΩ and 100Ω resistors, each of them soldered to two contact pads. Pad 1 is connected to the ground, and we measure current in the pad 2, as shown in Figure 4a for the 10kΩ resistor. Each resistor is polished to remove the passivation layer and to access a metal spot in the center, as shown in the SE image for the 10kΩ resistor (Figure 4b). The green arrow indicates an L-shaped cut in the metal spot, which is used for resistance tuning during resistor production.

Figures 5a-c show typical RCI images acquired with ex-situ preamplification in normal scan mode (no lock-in) for each resistor. The clearly visible horizontal stripes result from the low-frequency noise picked up along the cables and connectors before the external preamplification. As expected, SNR gets worse in devices with lower resistance.

RCI maps the resistance as a function of distance to the ground probe, with maximum at pad 2, zero at pad 1, and gradual change between them when scanning over the resistor. When the e-beam hits the pad 1, the absorbed current goes to the ground, and we observe no signal. With the beam on the pad 2, we collect all absorbed current. As the beam scans the resistor, the absorbed current is divided between both pads, and the signal collected in the

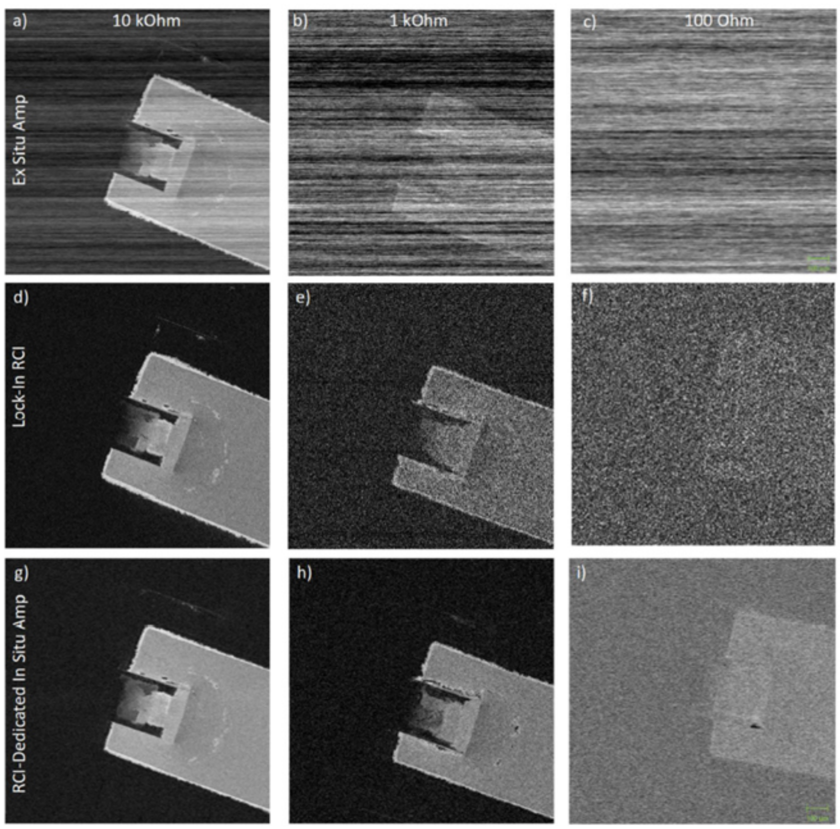

Figure 5. *a-c) RCI measurement on 10kΩ, 1kΩ and 100Ω resistor with ex-situ-amplifier connected to pad 2. d-f) Lock-in RCI on 10kΩ, 1kΩ and 100Ω resistor with scan-assisted beam modulation at 10kHz, 5kHz and 500Hz respectively. g-i) RCI measurement on 10kΩ, 1kΩ and 100Ω resistor with RCI-dedicated in-situ-amplifier.*

pad 2 is defined by the relative resistances from the beam position to each pad. The relative resistance and therefore the RCI signal are changing continuously within the resistor, except for the L-cut (not shown here) where it is changing instantly.

Figures 5d-f show scan-assisted lock-in RCI on 10 kΩ, 1 kΩ and 100 Ω resistors. The low-frequency noise is completely removed. The reference point is in the upper left corner, and the modulation frequency set to 10kHz.

The resistor-pre-amplifier circuit acts thereby as a low-pass filter. Figure 6 shows how its bandwidth changes with the resistance of the resistor (solid black line). The horizonal black line shows the scan coils limit. We found the maximum lock-in RCI modulation frequencies to be 500Hz for 100Ω and 5kHz for the 1kΩ resistors. The values ca. 7x lower than the resistor-pre-amplifier circuit bandwidth are optimal for scan-assisted lock-in RCI at 100Ω and 1kΩ, as shown with the diagonal red line in Figure 6. So the speed of scan-assisted beam modulation is limited by the resistance-pre-amplifier circuit bandwidth rather than the scan coils operation range, which means that an electrostatic beam blanker does not offer any advantage for this range of resistors.

Finally, Figures 5g-i show RCI maps of the 10kΩ, 1kΩ and 100Ω resistors recorded with RCI-dedicated in-situ pre-amplifier. Efficiency of both approaches for 10kΩ is similar. For the 1kΩ resistor, the in-situ pre-amplifier gives a better SNR than the scan-assisted lock-in RCI. In case of the 100Ω resistor, the RCI-dedicated in-situ pre-amplifier shows a clear advantage. Still, scan-assisted lock-in RCI is useful as it extends the range of failures observable with an external pre-amplifier, especially where in-situ electronics are not available.

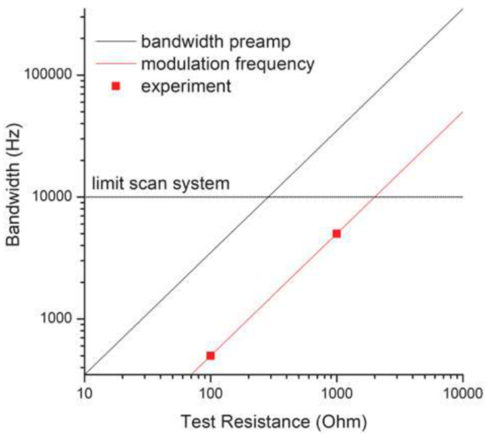

Figure 6. Bandwidth of test-resistor preamp system and maximum modulation frequency as a function of resistance.

B. Scan-assisted lock-in RCI at IC

Figure 7a shows a low-magnification SE image of an IC, with probe 1 landed on the power supply bonding pad and probe 2 on the substrate grounding pad. The corresponding RCI image in Figure 7b is dominated by the low-frequency noise, and the Figure 7c shows the same image collected using scan-assisted lock-in RCI. Here, the beam is modulated at 10kHz, and the reference point is set in the lower left quarter. The power supply network becomes clearly visible when we use scan-assisted lock-in RCI.

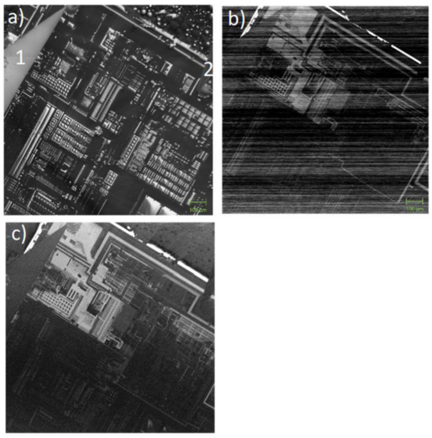

Figure 7. a) Image of IC with low-resistance failure, with probe1 landed on drain and probe 2 landed on ground b) RCI image with current collected from probe 1, showing low-frequency noise. c) Lock-in RCI with 10 kHz modulation frequency and current collected from probe 1, showing removal of low-frequency noise.

SUMMARY

We present the scan-assisted lock-in EFA and show how it removes the low-frequency noise from RCI on resistors down to 100Ω. This approach significantly extends the range of established localization techniques to failure cases of lower resistance, without compromising the speed, ease-of-use or spatial resolution. Scan-assisted beam-modulation is a simple, effective, and affordable alternative to electrostatic beam blanking. It circumvents complex and expensive hardware changes to the SEM column and associated downtime.

We also find that for resistances below 10kΩ, limitations in modulation frequency are determined by the bandwidth of the resistor-pre-amplifier circuit. Therefore, electrostatic beam blankers, while capable of operating at higher frequency, offer no practical advantage for this low-resistance range.

We also compared the capacity to remove noise between scan-assisted lock-in EFA and RCI-specific in-situ pre-amplifier. Both approaches are comparably effective in removing low-frequency

noise in samples down to 10kΩ, but for 1kΩ and 100Ω devices, in-situ pre-amplifier shows a better SNR. This observation highlights the importance of avoiding noise sources where possible.

AUTHORS

Rene Hammer, Wolfgang Joachimi, and Grigore Moldovan, point electronic GmbH, Halle, Germany

Willy Lim and Anya Grushina, Imina Technologies SA, Cugy, Switzerland

REFERENCES

Scan-assisted Lock-in RCI and EBIRCH for localization of low resistive defects, R. Hammer, W. Joachimi, W. Lim and G. Moldovan, 2025

[1] H. J. Leamy, “Charge collection scanning electron microscopy”, Journal of Appl. Physics, Vol. 53(6), R51-R80, 1982

[2] C. A. Smith, C.R. Bagnell, E.I. Cole, F.A. DiBianca, D.G. Johnson, W.V. Oxford, and R.H. Probst, “Resistive contrast imaging: A new SEM mode for failure analysis”, Transaction on electron devices, Vol. 33, Issue 2, pp. 282-285, 1986

[3] G. Moldovan, W. Joachimi, G. Boetsch, J. Jatzkowski, and F. Altmann, “High-Resolution Resistance Mapping in SEM”, ISTFA Conference proceedings 2018, pp. 353-357, 2018

[4] H. Tomokage, Y. Ishiwata, H. Souno, M. Kawakami, and N. Sonoda, “Defect Characterization in Metal-Oxide-Semiconductor Field-Effect-Transistors with Trench Gates by Electron Beam-Induced Current Technique”, Solid State Phenomena, Vol. 63-64, pp. 407-412, 1998

[5] G. Moldovan and W. Courbat, “Strategies to Identify Physical Origin of Contrast in EBIRCH”, ISTFA proceedings 2022, Vol. 48, pp. 277-283, 2022

[6] P. Roltman,and W.R. Bottoms, “Scanning electron microscopy”, book Vol. 1, pp. 731-738, 1977

[7] M. Simon-Najasek, J. Jatzkowski, C. Grose and F. Altmann, “A New Technique for Non-Invasive Short-Localisation in Thin Dielectric Layers by Electron Beam Absorbed Current (EBAC) Imaging”, ISTFA proceedings, Vol. 38, pp. 61-66, 2012

[8] J. Jatzkowski, M. Simon-Najasek, and F. Altmann, “Localization of Weak Points in Thin Dielectric Layers by Electron Beam Absorbed Current (EBAC) Imaging”, ISTFA proceedings, Vol. 40, pp. 491 – 495, 2014

[9] K. Dickson, G. Lange, K. Erington, and J. Ybarra, “Electron Beam Absorbed Current as a Means of Locating Metal Defectivity on 45nm SOI Technology”, ISTFA proceedings, Vol. 36, pp. 413-422, 2010

[10] B. A. Buchea, C.S. Butler, H.J. Ryu, W.Chuang, M. von Haartman, and Tom Tong, “High Resolution Electron Beam Induced Resistance Change for Fault Isolation with 100 nm2 Localization”, ISTFA proceedings, Vol. 41, 387 - 392, 2015

[11] T. Fuyuki and H. Matsunamis, “Measurement of lifetime and diffusion constant of minority carriers by phase shift technique in EBIC”, Electronics and Communications in Japan (Part I: Communications), Vol. 63, Issue 12, pp. 81-86, 1980

[12] S. B. Vasco, N. Baier, C. Lobre, C. Cervera, N. Pere-Laperne, A. Evirgen, and O. Gravrand, “Use of Electron Beam-Induced Current Technique to Characterize Transport Properties of Narrow-Gap-Energy Materials for IR Detection”, Journal of Electronic materials, Vol. 53, pp. 5850-5857, 2024

[13] P.R. Parsons, J.C. Dyment, and G. Smith, “Differentiated electronbeam- induced current (DEBIC): Quantitative characterization of semiconductor heterostructure lasers”, Journal of Applied Physics, Vol. 50; pp. 538-540, 1979

[14] F. Rolf, C. Hollerith, and C. Feuerbaum, “High Resolution Localization Using Lock-in Based Electron Beam Methods”, ISTFA Conference proceedings 2017, pp. 446-450, 2017

[15] W.C. Michels and N.L. Curtis, “A Pentode Lock-in Amplifier of High Frequency Selectivity”, Rev. Sci. Instrum., Vol. 12, pp. 444 – 447, 1941

[16] L.J. Balk, E. Kubalek, and E. Menzel, “Microcharacterization of electroluminescent diodes with the scanning electron microscope (SEM)”, IEEE Transactions on Electron Devices, Vol. 22 Issue 9, pp. 707-712, 1975