The emergence of electrical analysis in electron microscopy

DR. GRIGORE MOLDOVAN

point electronic GmbH, Erich-Neuss-Weg 15, D-06120 Halle (Saale), Germany

BIOGRAPHY

Grigore (Greg) Moldovan is the Chief Technology Officer of point electronic GmbH – a supplier of electronics and software for electron microscopy. He manages technology, development and marketing. Greg holds a PhD from University of Nottingham, and has previously worked for Oxford Instruments, University of Oxford and University of Cambridge. He is a scientist and a microscopist.

ABSTRACT

A new kind of analysis is emerging in electron microscopy, breaking away from the traditional boundaries of structure and composition, and establishing itself firmly within the area of imaging electrical properties. As a field in its own right, it comes packed with a coherent collection of dedicated techniques, electronics and software; and it's applied across scales from bulk materials to nanodevices, from fundamental research to routine failure analysis. What is this field, where it comes from, and what is driving this development?

CORRESPONDING AUTHOR

point electronic GmbH
Erich-Neuss-Weg 15,
D-06120 Halle (Saale),
Germany.
email: grigore.moldovan@pointelectronic.de

INTRODUCTION

Electrical analysis in electron microscopy is a field emerging alongside the traditional structure and composition characterisation in SEM, FIB-SEM and STEM. There are several fundamental topics within electrical analysis, reflecting a large cross-section of applications that ranges from electrical failure analysis to fundamental device research.

Development of some electrical analysis techniques goes back in time to the origins of electron microscopy, but development has intensified in recent years due to transition from optical to electron microscopy techniques, driven in part by the Moore's Law.

Perhaps the most important topic in electrical analysis is electrical resistance or conductivity. The ability to map resistance in devices with high resolution was a major discovery in electron microscopy and failure analysis – a breakthrough that now enables a new generation of electrical failure analysis techniques for nanometre-sized device technology[1]. It provides means for identifying locations of defects in complex 3D interconnects, thus continuing the heritage of optical techniques to bridge between device characterisation and physical analysis.

A second topic for electrical analysis is direct imaging of internal fields in semiconductor devices, whether for technology development, failure analysis of reverse engineering [2]. This spans across from solar cells, optoelectronics to high-power HEMT and CMOS. Third, but not least, is research into electrical activity of defects, as part of material science and electronics engineering, in particular for high-volume low-cost devices such as photovoltaics [2].

KEY CONCEPTS

In order to bring into view the many original strands that make up today's electrical analysis, here is an overview of key concepts required to track its development and understand its breath of reach.

- Specimen Current: arguably the precursor of electrical analysis, it describes the current measured from the specimen. It may be used for very general imaging, similar to the conventional signals and detectors; so much so that not all specimen current signals are useful for electrical analysis, and therefore the term has been superseded.
- Charge Collection: was a term used to describe the condition where specimen current is charge absorbed, induced or otherwise originating from the application of the electron beam. It may be thought of as an operation mode of the microscope where the specimen itself acts as a detector for charge, i.e. the charge collector.
- Absorbed Current: somewhat a misnomer, originally intended to describe a specimen current produced by simple absorption of electron from the primary beam into the specimen. Perhaps less obvious at the time was that an electron beam can also remove electrons from the specimen, but the term has stuck and now describes all such basic charge exchange.
- Resistive Contrast: describes a condition where contrast in specimen current reveals resistance changes across the specimen. It's one of the founding concepts for electrical analysis in electron microscopy, first to reveal that resistance can be mapped with very high spatial resolution.
- Resistance Change: a term that has crossed over from optical probing techniques, which describes a condition where the total resistance measured across a sample is temporarily changed due to the action of the electron beam. The origin of this reversible change may be local heating, charging or others.
- Induced Current: describes a specimen current collected from the electron-hole pairs generated by energy loss of the primary electrons into the specimen. This only applies to materials with a band gap, and thus also able to support an internal electric field, and thus it's generally applied to semiconductor devices.
- Electron Hologram: describes a holographic image of the specimen that includes information on electric fields, as well as magnetic fields and thickness. Extraction of a thin lamella from the device is necessary, as this is a transmission technique.

As is always the case, more advanced concepts follow, such as biased analysis with lock-in amplification, or transient currents with beam blanking, but these are beyond the purpose of this introduction.

TECHNIQUES

Various approaches and workflows have developed over the years, sometimes to fit the needs of a particular device or fundamental research, but a new microscopist or analysis approaching this field today must manage a collection of complementary techniques. Only the basic techniques are presented here.

RESISTIVE CONTRAST IMAGING

With regards to electrical resistance, the most important technique is Resistive Contrast Imaging (RCI), see Figure 1. It makes use of the absorbed current and two electrical connections to the specimen to set up a current divider circuit, where the fraction of charge collected at each terminal is proportional its resistance to the position of the electron beam [1].

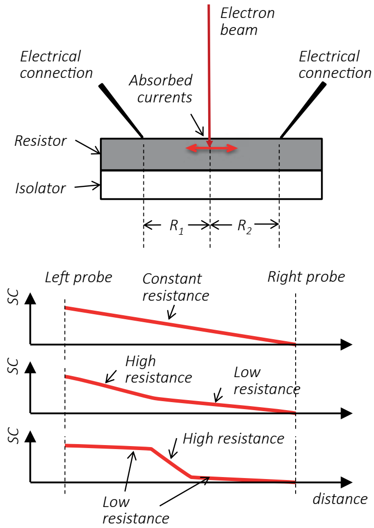
Resistance between the beam position and the electrical connection is thus revealed, at the same spatial resolution as the resolution of the microscope. For CMOS and MEMS devices, RCI is used in a lateral configuration (Figure 1) to image opens and shorts in tracks and vias across the device; and it's used in a

Microscopy and Analysis 34(3): S3-S5 (EU), June 2020

The RCI technique uses two electrical connections and the electron beam to set up a current divider circuit, where absorbed current reveals relative resistance to beam position.

In lateral current divider configuration, it's used to map connected networks in CMOS and MEMS devices.

Colour mix of black-white SE and black-red RCI signals showing a CMOS network ending in an open failure point (plan view, 282.1 µm image width)



Schematic of RCI setup, showing device with two electrical connections in a lateral current divider configuration

Current measured depends on the resistance between electrical connection and electron beam position

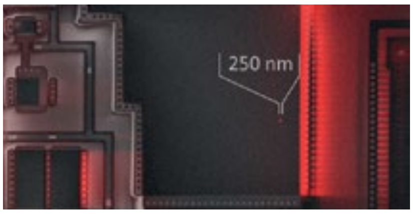
Typical line scans across resistors, showing that areas of constant sheet resistance give constant gradients in this lateral configuration

An open (high resistance area) is identified as a sudden drop in intensity

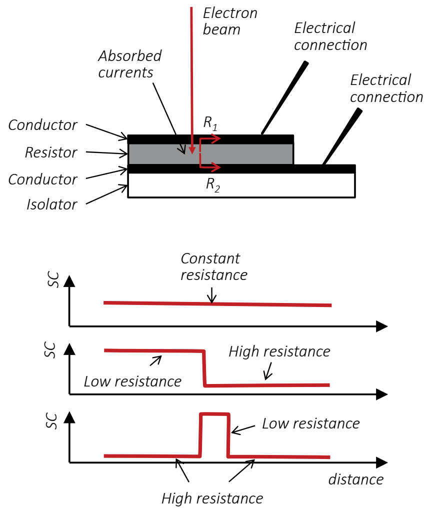
FIGURE 1 ***The Resistance Contrast Imaging (RCI) technique – lateral geometry***

RCI in normal geometry is an advanced case of RCI used when the resistance mapped is constructed between overlapping layers in the device, such as capacitors defined between metal layers or poly.

It requires careful use of acceleration voltage, such that charge from the electron beam is deposited into the lower layer.



Colour mix of black-white SE and black-red RCI signals showing a CMOS capacitor with a leakage failure point (plan view, 38.5 µm image width)



Schematic of RCI setup, showing device with two electrical connections in a normal current divider configuration

Current is now divided in a direction normal to the beam, i.e. depth of the device

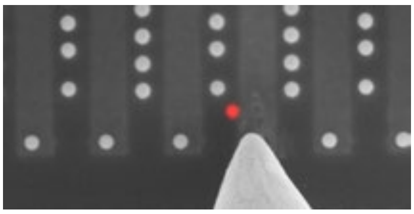
Typical line scans across resistors, showing that areas of constant sheet resistance give constant signals in this normal configuration

A leakage (low resistance area) is identified as a sudden peak in intensity

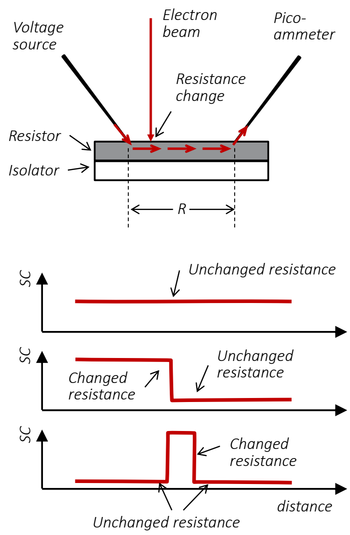
FIGURE 2 ***The Resistance Contrast Imaging (RCI) technique – normal geometry***

EBIRCh reveals device locations that are sensitive to the electron beam. Such locations present variations in the current forced through the specimen by an external voltage.

Physical origin of change may be varied, including local heating and charging. High beam currents tend to be used, but are not always necessary.



Colour mix of black-white SE and black-red EBIRCh signals showing a leakage point in a high power transistor (plan view, 5.1 µm image width)



Schematic of EBIRCh setup, showing device with two electrical connections, one used for a voltage source and the other for current measurement

Current measured is given by total resistance, and thus sensitive to resistance change due to the beam

Typical line scan profile, where constant current indicates no change, and current variations indicate beam sensitive material

For failure analysis, such local changes produce bright sports and thus localise failure sites

FIGURE 3 ***The Electron Beam Induced Resistance Change (EBIRCh) technique***

normal configuration (see Figure 2) to reveal leakages in capacitive structures and transistors.

ELECTRON BEAM INDUCED RESISTANCE CHANGE

Second with regards to electrical resistance, is the technique of Electron Beam Induced Resistance Change (EBIRCh), see Figure 3. Similar to Optical Beam Induced Resistance Change (OBIRCh), it forces a current through the device using a voltage source (i.e. bias) and detects locations where the electron beam is able to change the resulting current [4].

This is not a charge collection technique, as the absorbed current plays no role in the resulting contrast, but it may still be considered a specimen current technique as it measures the current from the specimen.

In contrast with RCI, the physical origin of EBIRCh is open to interpretation, local heating, fields or charge density, but the technique does provide easy localization of defective material in CMOS transistors, and it's therefore important.

VOLTAGE CONTRAST

For completeness, Voltage Contrast (VC) is an older technique also able to provide information on local resistance or conductivity, see Figure 4. VC works by manipulating the yield of secondary electrons, backscatter electrons, or indeed absorbed current, due to local surface fields at the specimen, which originate either from an external bias or due to self-charging under the beam.

However, VC is difficult to obtain, especially for smaller technology, and lacks spatial resolution, therefore has been largely superseded by RCI and EBIRCh.

ELECTRON BEAM INDUCED CURRENT

A further key technique for electrical analysis is Electron Beam Induced Current (EBIC), see Figure 5. This is somewhat more complex, as a sum of currents is present in the resulting images, including absorbed current from the electron beam, induced current from electron energy loss into the semiconductor, a biasing current from an applied voltage source, and also potentially a light induced current from *in-situ* illumination.

Briefly, the induced current is only collected at, and in the vicinity of, the probed junctions, and therefore EBIC maps the presence and shape of internal fields due to implantation or contacts [2]. Further, collection efficiency is reduced in the presence of electrically active defects, thus revealing location and strengths of grain boundaries, staking faults, dislocations and other crystalline defects [3].

SCANNING TRANSMISSION ELECTRON BEAM INDUCED CURRENT

Following the ever-shrinking technology nodes into the nanometre range, there is a renewed interest in TEM-based techniques. The new generation of biasing holders, in combination with FIB-based lamella preparation, are now placing this into easy reach.

Perhaps given the past developments, the first technique to make this transition is EBIC, which gives rise to the aptly named Scanning Transmission Electron Beam Induced Current (STEBIC), see Figure 6. It's conceptually similar with EBIC in SEM, with the notable difference that the charge carriers are confined within the thickness of the lamella, which results in a much-desired increase in spatial resolution, at the expense of increasing complexity in sample preparation and modelling [5].

ELECTRON HOLOGRAPHY

Within TEM-based techniques, most explored is however Electron Holography. Electron Holography is able to reveal electric, and magnetic fields with a high spatial resolution that approaches atomic detail[6]. In contrast with the other techniques presented here, numerical reconstruction is used in order to retrieve maps of electric fields from experimental holograms. Electron Holography also provides the ability to characterise space charge layers, such as those formed at grain boundaries.

EQUIPMENT

In terms of provision of equipment, all these techniques have undergone a transition from the hands of pioneering microscopist or analysts, into commercial supply and support. Electrical performance of current equipment far surpasses that of the early days – imaging speed and beam currents are no longer major limiting factors. Recent development focus has been moving towards ease of use, automation and service, with an ever-increasing role played by software.

Necessary equipment primarily consists of dedicated calibrated electronics and quantitative software, with the variations required by each method. For current techniques, this means one or more dedicated preamplifiers, a second-stage amplifier for digitisation, embedded voltage source for biasing, current source for compensation, an imaging unit for scanning and image acquisition. All these are available as turn-key solution for most SEM, FIB-SEM and (S)TEMs.

For SEMs, hardware typically includes a dedicated nanoprober, which may be removable to allow use of the microscope for other techniques, and may further include beam blanker, plasma cleaner, heating/cooling stages and other such dedicated equipment. For TEMs, a biasing holder is used to provide electrical connections to the specimen, and Electron Holography further requires a biprism.

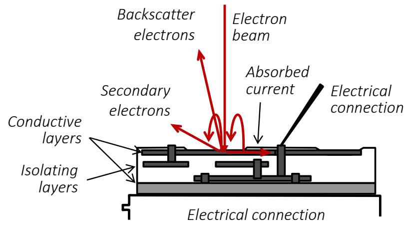
Software for electrical analysis follows a well-established tradition for quantitative work, which exceeds the requirements for general imaging, where pixel values do not present a physical value or indeed have a physical unit. This is required not only for an adequate comparison between devices or processing parameters, but also for modelling.

Modelling for electrical analysis may include a wide range of parameters, including the interaction between the electron beam and the specimen, electrical fields at junctions, recombination activity of defects. This enables a very revealing comparison between calculated and measured parameters, which has been amply explored to extract diffusion lengths of minority carriers, edges of depletion regions, recombination strength, amongst others.

The modelling approach has been extended to account for temperature and charge density, and thus provide further information on nature and density of physical defects and corresponding energy levels.

VC takes advantage of changes in the yield of secondary electrons, backscatter electrons or absorbed electrons in the presence of surface electric fields.

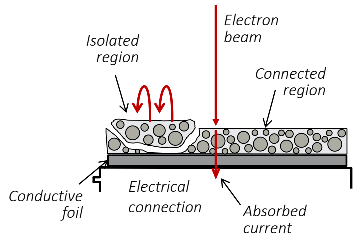
Surface fields spread across entire conductive networks or areas, and therefore VC has a degree of resistance contrast, but lacks spatial resolution



Typical setup for VC for CMOS devices, including electrical connection for voltage source (biasing)

Surface electric fields may arise because of charging from the beam, or an applied voltage

Two false-colour SE images of a chip operating in-situ, showing Voltage Contrast on tracks due to biasing (plan view, 650 µm image width)



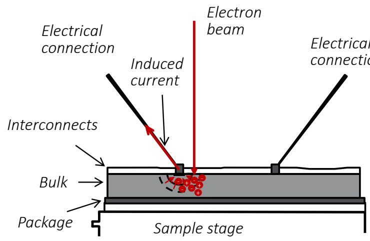
Electrically isolated regions tend to charge under the beam, giving rise to surface electric fields and therefore voltage contrast

A degree of resistance quantification may be obtained by measuring the absorbed current, however charging must be controlled

FIGURE 4 ***The Voltage Contrast (VC) technique***

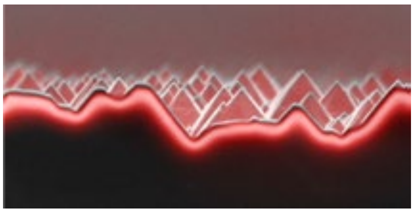
EBIC relies on collection of charge carriers induced into the device due to energy loss from the primary beam. Induced electrons, or holes, are collected only in the presence of an electric field, typically a pn junction.

It also reveals electrical activity of defects inside the field, such as grain boundaries or dislocations.

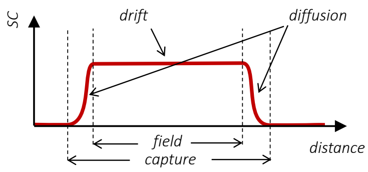


Schematic of plan-view setup showing device with two electrical connections, induced charge and collection at the internal electric field

Electron-hole pairs are induced in the entire bulk, but only collected at the probed junction



Colour mix of black-white SE and black-red EBIC signals showing electric field in a textured solar cell (cross-sectional view, 45 µm image width)



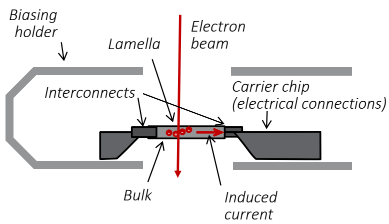
Typical line scan profile across an electric field, showing current collected at junction

Unsharp edges are given by diffusion of charge outside the field

FIGURE 5 ***The Electron Beam Induced Current (EBIC) technique***

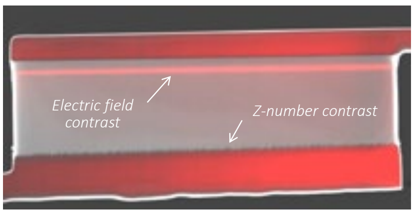
STEBIC is an advanced variant of EBIC, where a thin lamella is extracted from the device in order to limit the motion of charge carriers and increase spatial resolution.

It provides direct correlation with other high-resolution TEM techniques, such as HAADF or EELS.

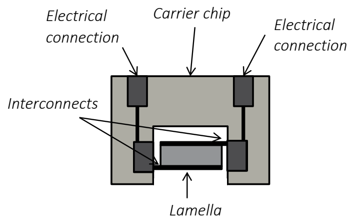


Schematic of STEBIC setup, showing biasing holder with charrier chip for electrical connections, and lamella specimen placed above a window.

Lamella is prepared using FIB-SEM with in-situ lift out



Colour mix of black-white HAADF and black-red STEBIC of induced current in a GaAs pn junction, and absorbed current in interconnects (cross-sectional view, 30 µm image width)



Electrical connections from the carrier chip to the lamella are made using GIS deposited interconnects

Final thinning is made with the lamella mounted on the carrier chip

FIGURE 6 ***The Scanning Transmission Electron Beam Induced Current (STEBIC) technique***

SUMMARY AND CONCLUSIONS

As concluding remarks, development of all these concepts, techniques and equipment in electron microscopy is driven in part by the need for increased resolution, which continues to bring in electrical analysis traditionally done with probing stations and optical technology.

Arguably a more important trend is the increasing role and application of electronic devices, where electrical analysis is just as important as physical characterisation and microanalysis.

As always, the ability of microscopy to bring images to previously invisible concepts and theories is finding successful audience, now within the electronic and electrical industry.

Article and references available online at: analyticalscience.wiley.com/publication/microscopy-and-analysis