

# Introduction to EBIC

## Application Note

The electron microscope is a versatile instrument particularly with regard to its use in the semiconductor field. The interaction of a focused electron beam with a specimen or device can be monitored in a variety of ways, allowing topographical, chemical, optical and electrical information to be obtained. This is because there are many different phenomena which take place as a result of the interaction. Some of these phenomena have a chance of leaving the specimen, e.g., x-rays, back scattered electrons, secondary electrons, Auger electrons, cathodoluminescence (CL). Others tend to stay in the specimen, e.g., heat, electrons and electron-hole pairs (a hole is the absence of an electron in a crystal and can be treated in a similar manner to an electron but of positive charge).

In a semiconductor either electrons or holes typically dominate as dictated by the concentration of ionized dopants, and the nomenclature is n type for electrons dominating and p type for holes. Minority carriers are therefore holes in n type and electrons in p type. Electron-hole pair generation is a local disturbance from the equilibrium concentration. As electron hole pairs are formed, the disturbance has the biggest impact for minority carriers, as the generation density is typically less than the majority carrier density.

The relaxation process back to equilibrium involves recombination. If recombination is radiative then this may exit the specimen in the form of cathodoluminescence. However, recombination can also be non radiative. Any form of recombination effectively removes the carriers and this therefore affects the measured signal.

For a standard electron-beam induced current (EBIC) experiment, an internal electric field in a semiconductor, for example associated with a p-n junction, causes charge separation and hence current flow. This allows the contacted specimen to act as the detector of the motion of electron-hole pairs. Their relative movement is measured in an external circuit (the EBIC amplifier). In this note, any specimen containing an internal junction is termed a device.

Hence, with EBIC microscopy, it is the local electrical behaviour of electrons and holes and minority carriers in particular which are studied. As the functioning of all semiconductor devices relies on the behaviour of electrons and holes and electric junctions or barriers, EBIC microscopy can be a powerful technique in characterizing materials and device properties.

To correctly interpret EBIC results, it is worth considering the generation, motion and collection of electron-hole pairs, and in particular minority carriers.

### Carrier generation

Electron-hole pair generation occurs via a series of inelastic scattering events. As the energy required to make an electron-hole pair (several eV) is much smaller than that required to create an x-ray (several keV), the generation volume for an EBIC signal is larger than that for x-ray generation. Although a small spot size is an important factor in influencing spatial resolution, the overriding factor for EBIC is the accelerating voltage as this determines the size of the generation volume.

### Drift and diffusion

Drift is the term given to the motion of carriers under the influence of an electric field. As electrons and holes are of opposite charge they move in opposite directions in the presence of an electric field. The electric field in question is usually strong and internal.

Away from electric fields carriers diffuse as a result of concentration gradients. As minority carriers are relatively few and far between, electron-hole pairs created by the electron beam perturb the minority rather than the majority carrier concentration. Hence a concentration gradient is created only of one carrier type, and it is the minority carriers which are subject to diffusion. This is fundamental to both the operation of many semiconductor devices and also the technique and interpretation of many EBIC applications. Carrier diffusion is principally characterized using one parameter the minority carrier diffusion length  $L$ . This is related to the minority carrier lifetime  $\tau$ , by the equation  $L = (D\tau)^{0.5}$  where  $D$  is the relevant carrier diffusion coefficient.

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### Carrier recombination

In a perfect, pure semiconductor the recombination route for electron-hole pairs depends only on the band structure, temperature, and to a smaller extent, the local injection density. In a crystal containing imperfections the situation is more complex as impurities and crystal defects have a strong influence on the local recombination behavior. The minority carrier lifetime in the bulk of a semiconductor away from defects is an average of the lifetimes associated with various recombination routes. At surfaces and defects, carrier lifetimes are often greatly reduced as defects provide a much more probable, non-radiative recombination route.

Hence despite the fact that CL relies on radiative recombination, and EBIC does not, the two techniques are related in that contrast features are governed by generation and recombination. More specifically EBIC is influenced by the combined probabilities of radiative and non-radiative recombination, whilst CL is influenced by their ratio.

### Signal collection

A standard EBIC signal is a current flow in an external measurement circuit, (the EBIC amplifier). The signal does not require an external bias to be applied as this then is a measurement of conductivity. A true EBIC signal only forms and is measured when the specimen containing an internal electric field is connected to the external amplifier independent of any alternative earth path. As it is more practical to have the amplifier outside the microscope chamber vacuum, the contacted specimen is usually connected to an external amplifier using vacuum feed throughs. It is important not to confuse an absorbed current signal, where the specimen current is measured with respect to the stage earth, to an EBIC signal where the amplifier is connected to either side of an electric junction in a device independent of the stage or chamber earth.

### EBIC signal strength and contrast

If the rectifying junction of the specimen is not ideal and contains leakage paths or shunt resistances the measured EBIC signal may be less than that generated. This is because the generated signal may flow along a route alternative to the measurement circuit. More specifically, the amplifier circuit can only function quantitatively at higher gains if the rectification of the specimen is sufficient. This is not specific to EBIC but is true of any current measurement experiment from a diode. The specimen's diode characteristics are therefore important to quantify prior to interpreting the EBIC signal in a quantitative manner.

With a knowledge of carrier generation, drift, diffusion, recombination, and collection, it is possible to understand the various factors which govern the EBIC signal as the beam is scanned. Like other scanning techniques an advanced understanding of the result will necessarily need detailed knowledge concerning device configuration.

As each incident electron can generate many electron-hole pairs, the EBIC strength may be described as an EBIC gain. This is the ratio between the incident beam current (not the filament emission current) and the EBIC. This ratio is easy to measure using SmartEBIC™ software. The EBIC gain is not specific to a given specimen, as it will depend on the injection conditions. However, for set injection conditions, the EBIC gain can be quantitative between different parts of a specimen, or different specimens.

An EBIC collection efficiency is a more difficult ratio to work with because this relies on modelling the expected EBIC signal assuming 100% of carriers generated are collected. Simulations such as Monte-Carlo calculations can model the number of carriers generated taking into account losses from back-scattered signals, phonon production etc. The collection efficiency is then the ratio between the measured signal and the modelled signal.

EBIC contrast is simpler and is the relative difference in the strength of the EBIC signal as the beam moves from one part of the specimen to another with constant injection conditions. The EBIC contrast can be shown in an image or can be quantified further if the EBIC signal, (or EBIC gain) is quantified at every point in the image.

Although the polarity of the EBIC signal depends on the specimen and connections, the traditional manner of viewing an image is in absolute terms, where a larger signal is represented by a brighter part of the image. For this reason SmartEBIC is designed to work in bipolar mode with a simple software toggle switch to change polarity.

### EBIC experiments

SmartEBIC provides a simple routine to measure the diode characteristics of the specimen and specimen contacting in-situ. (This does not require the specimen to be under vacuum, although if the chamber door is open or if chamber-scope illumination is present, the specimen may act as a photocell. In such cases the I-V trace may have an offset associated with light induced electron-hole pairs).

This routine is invaluable not only in proving the contacts are suitable, but in characterizing the rectification. The diode characteristics of the contacted specimen gives the user a good indication of the possible gain and bias limitations for the amplifier, and the degree to which the measured EBIC signal is true to the generated signal. The I-V trace can be repeated at any time to reconfirm the specimen's contacting and junction status.

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### Characterizing junctions

Carrier drift is proportional to the electric field strength. This is typically strongest at the precise location where the material changes from n to p-type, e.g., where the band diagram (in real space) has the strongest gradient. At this point recombination is unlikely and carrier separation is very likely. Hence, in cross section, the peak EBIC signal maps the peak electric field and junction position. This precision is better with good focussing and lower kV, but does not have the resolution of secondary electron imaging because of the smearing effect of the generation volume.

Contrast features can be associated with both generation and collection phenomena. The former can be the result of surface features or subsurface voids or cracks. At the p-n junction, limitations to the collection efficiency will be mainly caused by recombination at the junction or surface. Junction recombination may be significant for heterojunctions (p-n junctions made from a sandwich of two different semiconductors). Recombination at the top surface will depend on the condition of the surface. This influence can be reduced by using a higher accelerating voltage but for bulk specimens, this reduces the spatial resolution.

### Characterizing depletion regions

In the depletion region carrier separation and the EBIC signal strength still depends primarily on the strength of the electric field. For a given potential change across a junction, high dopant conditions result in narrow depletion regions and high electric fields. The situation is reversed for low dopant regions. It is important to note that the EBIC collection efficiency depends on both the electric field strength and the relative dimensions of the depletion region compared to that of the generation volume. Hence although a narrow depletion region may be associated with a strong electric field, it may be narrower than the generation volume. This provides an example of why it is worth understanding the basic device structure in order to devise experimental conditions and correctly interpret results.

Recombination at defects is less likely in a depletion region, although this depends on the electric field strength. If a reverse bias is applied to a junction, the depletion region is extended. SmartEBIC provides the ability to choose a bias condition and automatically apply a suitable offset current to allow microscopy under certain bias conditions. This offset allows the EBIC amplifier to be used at a high gain suitable for monitoring the effect of the electron beam, whilst ignoring the bias induced leakage current. In this way the dimensions of the depletion region can be altered in order to further characterize the junction. EBIC can therefore be useful in characterizing depletion regions and defect structures and inhomogeneities therein.

### Remote from electric fields and defects

The collection efficiency is determined by two distinct processes, the probability of diffusion to the depletion region and the probability of collection by drift once it reaches the depletion region. The latter is usually much more probable. If low injection conditions exist (injected hole pair concentration is less than the majority carrier concentration), then minority carrier diffusion governs the first process. Minority carrier diffusion is characterized by a single parameter  $L$ . The diffusion length can be measured from EBIC experiments in both plan view and cross section experiments.

Measurements in cross-section mode are common and relatively easy to perform. Measurements in plan view are not straight forward as they require the collection efficiency as a function of accelerating voltage, and the subsequent fitting of the results. An example of the use of the technique described by Wu and Wittry is given in the following web publication; <http://scholarworks.rit.edu/cgi/viewcontent.cgi?article=1355&context=other>.

For cross section measurements the beam is scanned in a straight line perpendicular to the collecting junction. As diffusion follows the equation  $e^{-x/L}$  the reciprocal to the slope of a EBIC linescan plotted on a natural logarithmic axis gives  $L$ . This calculation assumes that the diffusion dominates over drift, that the generation volume is a point source and that other losses, for example at the surface are negligible. For such experiments it is important that the user understands the likely size of the depletion region, and the importance of the size of the generation volume with regard to the assumptions made. In short, a high kV experiment which results in a large generation volume should not be used to measure a diffusion length of dimensions smaller than the generation volume otherwise errors will dominate.

SmartEBIC software provides a simple routine to extract the parameter  $L$  from cross sectional linescans, but the user must take care with the assumptions made in the experiment.

### Close to defects

Defects are usually associated with reduced carrier lifetimes. As recombination occurs the EBIC collection efficiency falls and hence causes contrast on an image. A defect may reduce EBIC locally for several reasons. If it is an inclusion or void, it will reduce the generation of carriers.

If it is a crystallographic imperfection or extended defect such as a dislocation or grain boundary, its strength as a recombination center will depend on its electrical activity, e.g., how it locally alters the band structure of the semiconductor and behaves as a black-hole for carriers to recombine.

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### Close to defects (continued)

The black hole analogy may help the visualization of carriers being lost to recombination. However, recombination may not be inevitable for a carrier near a recombination center and hence the defect can be considered a shade of grey rather than black. Also, the amount of EBIC signal lost to recombination at a defect is a complicated function of the generation function, and the relative position, size and defect strength (shade of grey) of the recombination center. It is also a function of the proximity of any electric fields and the diffusion length as this dictates the likelihood of carriers reaching the defect.

There is much work in the literature covering this field. Although complicated, much can be understood simply by measuring the EBIC contrast. This is especially true if care is taken to standardize conditions between experiments. For example when comparing the EBIC contrast of dislocations between different specimens, it is important that beam conditions are the same and that dislocations are at similar depths if a quantitative comparison is required to their recombination strengths. As grain boundaries are planar, this variable is lost and hence a direct comparison can be made between different grain boundaries simply by comparing EBIC contrast values.

The quantitative nature of the SmartEBIC system helps in the process of characterizing defects. For example with a simple image, a defect may look dark and to expand over a large area. However, this depends on the dynamic range of the image. With a quantitative EBIC map, the strength and spatial extent of the defect can be more thoroughly understood.

### Specimen configurations

EBIC is typically performed in plan view or cross section, but for some devices where both plan view and cross section measurements are required the specimen can be tilted. SmartEBIC system provides a specimen holder which allow the specimen to remain contacted but to tilt (controlled ex-situ) between 0 and 90 degrees on a mini sub stage. Alternatively, for some microscopes the SEM stage can be tilted.

### Plan View

The electric junction is normally in the plane of the specimen and perpendicular to the ebeam. This configuration is useful for examining recombination centers such as dislocations and grain boundaries, and also junction and doping homogeneity. For semiconductors which do not have a p-n junction, a Schottky barrier can be created on the specimen surface. This is a surface film of metal deposited on the semiconductor. In addition the surface preparation of the semiconductor is critical. Inappropriate surface preparation can impede this approach.

A Schottky barrier behaves similarly to a p-n junction because the metal film causes an internal electrical field. The type of metal (its work function) needs to be chosen to match the semiconductor and doping type. This creates a depletion region and hence collects minority carriers. For EBIC the specimen also requires an Ohmic contact away from the Schottky barrier. For plan view EBIC studies the metal needs to be thin enough to allow the incident electrons to penetrate.

Plan view EBIC can often result in a large DC signal but with small contrast features. SmartEBIC system provides a simple AutoScaling routine which, once the user has specified the region of interest (ROI), calculates and applies the best offset current and gain for the signal to match the input's dynamic range. This best utilizes the analog inputs and ensures that contrast features, even when enhanced, do not result in unwanted digitization features.

### Cross section

In cross section studies the junction is typically in the plane of the electron beam. This configuration is often used to locate and characterize junctions, and measure diffusion lengths.

A lateral EBIC linescan can be used to estimate the minority carrier diffusion length  $L$ . As mentioned above,  $L$  is an important property because it governs the scale over which minority carriers have influence, (away from electric fields). SmartEBIC system allows the linescan to be profiled from a quantitative area scan, or performed live as a slow linescan with user specified pixel dwell time. A slow linescan will be important for low signal levels when the amplifier is at a high gain setting. SmartEBIC system automatically suggests suitable pixel dwell times dependent on the amplifier setting.

The relative usefulness of either configuration is very specimen dependent. Indeed a half way house where the junction or specimen surface is inclined and hence electron beam can also be useful and can be obtained by bevel etching the specimen.

### Other specimen configurations

SmartEBIC system provides three electrically isolated, BNC vacuum feed throughs. The fourth feed-through has a core cable which is connected to the electrically isolated specimen mount, and the outer sheath is connected to the microscope chamber via the feed through flange. This is intended for beam current measurements. However, in this configuration any imaging application may have noise associated with the chamber earth and which is not associated with SmartEBIC hardware.

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### Other specimen configurations (continued)

The default SmartEBIC connections involve 4 pins and these can be connected together with the BNC feed through connections using simple solder in other configurations to give more flexibility, e.g., for three terminal devices, or for devices which require power to cool a substrate.

Experiments which require precision in-situ contacting will require hardware in addition to the standard SmartEBIC hardware. Please contact Gatan for more information.

### Low signal issues

SmartEBIC system is designed to work in DC mode and be sensitive to low current applications. This means that care is taken to minimize extraneous noise without resorting to the use of filters (which exist on the amplifier and are not programmable from the software). Furthermore if the beam current feed-through is used, the measured current is smaller and the system can be used for absorbed current imaging applications. (See below).

If extraneous electrical noise (e.g., at TV frequency) from environmental effects is problematic, then SmartEBIC and DigiScan™ systems have the line sync. option with a user specified frequency. For low signal applications one option to circumvent noise problems is to record a dark reference image where there is no beam on the specimen. This is then subtracted from the result. The line sync. option ensures that the dark reference is synchronous with the result image. Another alternative is to use AC EBIC which requires a beam blanker, see below.

## EBIC distinguished from related techniques

### Electron beam induced current (EBIC)

Carriers are created using the electron beam, but current only flows in the form of EBIC if an internal electric field in the specimen exists to separate the carriers and cause them to flow in an external circuit (the ammeter). The EBIC can and often is much larger than the incident beam current as each injected electron creates many electron-hole pairs. The technique does not work on non semiconducting material and requires some electrical junction in the device. SmartEBIC is designed primarily for EBIC studies, but the equipment is versatile as explained below.

### AC EBIC

AC EBIC is usually performed with a modulated injection source. This is obtained using an electrostatic beam blanker in the microscope column. Suitable modulation frequencies are governed by the amplifier gain and scanning speed. AC EBIC may be performed for specimen or injection conditions with low signal levels, or in situations where environmental noise is problematic. A lock-in amplifier is used to increase signal to noise ratios. The lock-in amplifier is given a reference signal from the signal generator running the beam blanker. The output of the lock-in amplifier is used for imaging. For some specimens where there is a transient response in the current, e.g., when studying current flow through pin-holes in oxide insulators on semiconductors, the lock-in technique may also be useful as the out of phase component can be utilized.

SmartEBIC system can be sold to work in AC mode with additional equipment, but the autoscaling and quantification routines are limited as the software is not configured to communicate with the lock-in amplifier.

### Single contact EBIC (SCEBIC)

This technique may be suitable for defect analysis in high integration circuits where access to devices is limited by interconnects without destructive FIB work. The amplifier connects the device substrate to microscope ground. Image contrast occurs as a result of transient phenomena as the beam is scanned whereby excess charges generated by the beam are stored and discharged in the junction. This technique may be suitable for certain specimens but as a technique it is not mature.

### Electron beam induced voltage (EBIV)

This technique requires a voltmeter to be connected across the device instead of an ammeter. The separation of charge creates a potential difference as the voltmeter restricts the current flowing in the manner which would occur in an EBIC experiment. Although the DigiScan can be used to map the voltage from the voltage amplifier can be used, standard SmartEBIC software is not configured for automatic communication with a voltmeter. The signal can be quantified if the user requests a voltage map, but must manually relate the gain of the voltage amplifier to quantify the result.

### $\beta$ conductivity

This is similar to EBIC but a bias is applied to the specimen and a conductivity is measured rather than an EBIC current. SmartEBIC system allows EBIC to be performed with a positive or negative bias applied with a suitable offset calculated and applied automatically. This must be within the source current limitation for a given gain setting and so is dependent on the diode characteristics of the specimen.

### Remote EBIC (REBIC)

This technique is sometimes performed on insulators (where normal EBIC is not possible). It is useful for examining grain boundaries. Contrast is both positive and negative but is only recorded if the electron beam traverses a planar junction which isolates the two probes and which is associated with an electric field. Either side of the electrical junction is connected to an ammeter but current only flows as the electric field of the junction acts to separate charge. SmartEBIC system is suitable for REBIC studies but the signal size is very dependent on the specimen grain boundary and injection conditions.

### Absorbed current imaging

For absorbed current imaging, only one connection is required to the specimen and a current is measured with respect to microscope ground. This current is very small and is slightly smaller than the incident beam current. This technique does not require semiconducting specimens or electrical junctions in the specimen.

SmartEBIC system is suitable for measuring Absorbed Currents given suitable contacting conditions. Note any electrical noise in the chamber earth may cause noise in the image, and this cannot be controlled by SmartEBIC hardware.

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### Cathodoluminescence (CL)

Cathodoluminescence is a related technique when applied to semiconductors characterization. The CL is due to radiative recombination and the CL contrast is associated by the ratio of radiative to non radiative processes. EBIC contrast is dominated by the sum of radiative and non radiative recombination events. Both techniques have similar spatial resolution and when performed in tandem can provide much information by distinguishing different recombination events.

To measure CL, Gatan has a range of products including MonoCL4™ for spectral CL. The MonoCL4 product range or other CL products involving DigiScan digital beam control are compatible with SmartEBIC and significant cost savings can be achieved by combining these products. SmartEBIC hardware is not compatible with MonoCL2™.

### Voltage contrast

Voltage contrast is an imaging technique using secondary electron. This technique does not require the use of current amplification.

It provides information about the electrical properties of devices as the SE yield and signal measured by the detector is influenced by the local potential of the material. Combined EBIC and Voltage contrast techniques can be performed and can be beneficial in failure analysis.

The SmartEBIC amplifier can be used to apply a voltage (up to +5V) to a device within the current source limitations of the amplifier. If higher voltages are required the SmartEBIC electrical contacting apparatus can be used together with an alternative bias source. SmartEBIC system can be used to measure the voltage contrast quantitatively by bypassing the EBIC amplifier, see below.

### Other mapping techniques

SmartEBIC system is suitable for other mapping technique where there is a need for a quantification of an analog input voltage. For example with current transport measurements in high T<sub>c</sub> superconductors, ESEM applications, or advanced techniques quantifying doping contrast in semiconductors.

## References

- "Electron Beam Induced Currents in Semiconductors", J I Hanoka and R O Bell, *Ann. Rev. Mat. Sci.* 1981, 11:353-80.
- "The experimental requirements for quantitative measurement of carrier recombination at defects in semiconductors using the EBIC technique", P R Wilshaw, *Ultramicroscopy* 31 (1989), 177-182.
- "The effect of different transition metals on the recombination efficiency of dislocations", T S Fell and P R Wilshaw, *Journal de Physique IV, Colloque C6, supplement au Journal de Physique III, Vol1, Dec 1991, C6-211.*
- "EBIC contrast of defects in semiconductors", P R Wilshaw, T S Fell and M D Coteau, *Journal de Physique IV, Colloque C6, supplement au Journal de Physique III, Vol1, Dec 1991, C6-3.*
- "Conventional EBIC versus MOS/EBIC study of electrically active defects in Si and SOI", I Bondarenko, H Kirk, O Kononchuk, and G Rozgonyi, *Material Science and Engineering B42, (1996) 32-37.*
- "EBIC investigation of defects in SOI materials using a Schottky diode and buried oxide capacitor", P Duval, G C M Silvestre and R A Moore, *Materials Science and Engineering B46, (1997) 38-42.*
- "Electrical and optical characterisation of extended defects in SIMOX structures", Y H Qian, J H Evans, L F Giles, A Nejm and P L F Hemment, *Semiconductor Science and Technology*, 11 (1996) 27-33.
- "Minority carrier recombination and internal quantum yield in GaAs:Sn by means of EBIC and CL", N Puhlmann, G Oelgart, V Gottschalch and R Nemitz, *Semiconductor Science and Technology*, 6 (1991) 181-187.
- Review of EBIC microscopy, H J Leamy, *Journal of Applied Physics* 53, 6 R51 (1982).
- "Investigation of minority-carrier diffusion lengths by electron bombardment of Schottky barriers", C J Wu and D B Wittry, *Journal of Applied Physics*, 49 (5) 2827.
- "Cathodoluminescence and EBIC of 2D junction laser structures on patterned (311)A GaAs substrates", C E Norman, A J North, J H Burroughes, R Burke and D A Ritchie, *Inst. Phys. Conf. Ser. No 157, (1997), 647.*
- "Novel applications of EBIC and CL to regrown, modulation doped structures on patterned substrates", C E Norman, M L Leadbeater, T M Burke and D A Ritchie, *Inst. Phys. Conf. Ser. No. 164, (1999) 677.*
- "Minority carrier recombination and internal quantum yield in GaAs:Sn by means of EBIC and CL", N Puhlmann, G Oelgart, V Gottschalch and R Nemitz, *Semiconductor Science and Technology*, 6 (1991) 181-187.
- Review of EBIC microscopy, H J Leamy, *Journal of Applied Physics* 53, 6 R51 (1982).
- "Investigation of minority-carrier diffusion lengths by electron bombardment of Schottky barriers", C J Wu and D B Wittry, *Journal of Applied Physics*, 49 (5) 2827.
- "Cathodoluminescence and EBIC of 2D junction laser structures on patterned (311)A GaAs substrates", C E Norman, A J North, J H Burroughes, R Burke and D A Ritchie, *Inst. Phys. Conf. Ser. No 157, (1997), 647.*
- "Novel applications of EBIC and CL to regrown, modulation doped structures on patterned substrates", C E Norman, M L Leadbeater, T M Burke and D A Ritchie, *Inst. Phys. Conf. Ser. No. 164, (1999) 677.*

