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Scanning Microscopy

Volume 10 | Number 1 Article 3

2-1-1996

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Koschinski, P.; Dworak, V.; West, P. E.; and Balk, L. J. (1996) "Development of an Scanning Tunneling Microscopy-Based Electron Beam Induced Current (EBIC) Microscope," *Scanning Microscopy*: Vol. 10 : No. 1 , Article 3.
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Scanning Microscopy, Vol. 10, No. 1, 1996 (Pages 33-38) 0891-7035/96$5.00+.25
Scanning Microscopy International, Chicago (AMF O'Hare), IL 60666 USA

DEVELOPMENT OF AN SCANNING TUNNELING MICROSCOPY-BASED ELECTRON BEAM INDUCED CURRENT (EBIC) MICROSCOPE

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(Received for publication September 13, 1995 and in revised form February 1, 1996)

Abstract

Measurements of electron beam induced currents (EBIC) can either be performed in a scanning electron microscope (SEM) or in a scanning tunneling microscope (STM), since both microscopes are very similar in their basic assembly. However, a straightforward application of an STM in EBIC-measurements, i.e. the use of a microscope tip as a fine source for low energetic electrons is not possible due to the specific demands on the instrument in an EBIC application. The present paper gives a compilation of these demands and describes their conversion into an optimized STM-EBIC microscope.

Key words: Electron beam induced current, scanning tunneling microscope .

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Introduction

The measurement of electron beam induced currents (EBIC) in a scanning electron microscope (SEM) has been proven to be a valuable means in the analysis and characterization of semiconducting materials and semiconductor devices [4]. The advantageous features of this measurement technique are a high sensitivity for electronic properties as relevant for devices like the internal potential distribution within a device and a high spatial resolution. In order to improve the spatial resolution and to gain access to surface related electronic properties like surface states, which mainly determine the behaviour of modern devices this measurement technique has been successfully applied to a scanning tunneling microscope (STM) [2]. The microscope tip is used as an electron source for primary electrons (PE) in the energy range of some ten electron volts, leading to EBIC measurement results with an improved spatial resolution in comparison to conventional SEM-EBIC measurements. In order to benefit from this technique a special STM based equipment optimized for STM-EBIC measurements is required, since, e.g. the magnitudes of the induced currents in an STM are far less than that obtained in conventional scanning electron microscope measurements, and since there is an influence of the biased tip on the measurement [3]. The present work gives a detailed discussion about STM-EBIC specific demands on the measurement set-up and presents technical solutions fulfilling these demands. The resulting optimized instrument is described, and various examples are given demonstrating the capability of the instrument.

Measurement of Induced Currents in an STM

The experimental configuration as used for STM-EBIC measurements is very similar to that used for conventional SEM-EBIC measurements. Figure 1 depicts the experimental configuration. The configuration consists of an STM, a current amplifier and a digital control unit. The microscope tip is scanned across the sample surface by the movement of a piezoelectric scanner, which is driven by the digital control unit. The build-in feedback loop of the instrument ensures a constant emission current of electrons from the

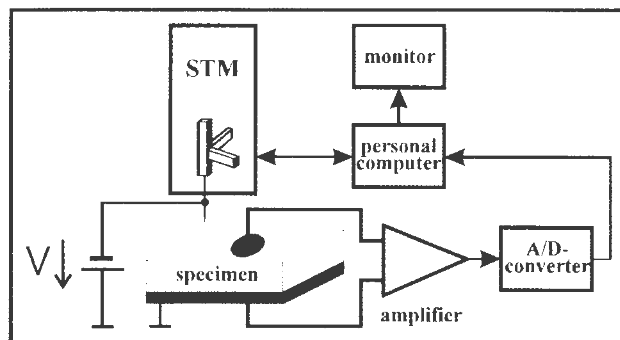

Figure 1. STM-EBIC experimental configuration .

tip by changing the sample-tip distance. From the variation of the sample-tip distance the topographic information can be deduced. A detailed description of STM-techniques can be found in e.g. [5] In order to enable an emission from the tip a voltage has to be applied between tip and sample which must be sufficiently high in order to ensure a generation of electron-hole-pairs (e-h-pairs). If the sample exhibits internal electrical fields, e.g. by a Schottky-contact present, the e-h-pairs are separated by this field leading to a current in the external circuit, which can be amplified by the current amplifier. Subsequently the current value is converted in a form suitable for further numerical processing by a digital to analogue converter. The current value is displayed on a computer monitor as a grey scaled picture, in which each pixel corresponds to a tip position on the sample surface. By scanning the tip across the sample surface both informations, topography and induced current can be measured simultaneously and displayed on the monitor.

Problems Associated with the Measurement of Electron Beam Induced Current in an STM

Even though the basic experimental configuration is not too complex, a straightforward application of an STM in electron beam induced current investigations is not possible. There are several difficulties which must be circumvented when using an STM in EBIC-measurements. The following compilation gives a brief insight in the problems associated with STM-EBIC.

In STMs the voltage applied between tip and sample is in the range of some volts, since for tunnneling no higher voltages are necessary. These voltages are not high enough to emit electrons from the tip with a kinetic energy sufficiently high for the formation of electron-hole-pairs in the semiconductor sample. However, with higher voltages applied to the tip ionization processes can occur. Impact ionization of ambient gas molecules by the accelerated electrons can be excluded since the mean free path length of the emitted electrons is much greater than the tip-sample distance [6], but, due to the high electrical field strength between tip and sample, field ionization of the ambient gas molecules will occur, leading to statistical fluctuations of the emission current [1]. The fluctuations can not be compensated by the feedback loop because they lead to spikes in the emission current, causing unpredictable variations of the generation of e-h-pairs which finally influence the induced current.

Since all scanning probe microscopes are optimized for an application in near field microscopy, in which the area under investigation is usually some square nanometers, the scan range is limited to some microns depending on the scanner used. One advantage of SEM, the fast change from a macroscopic view to a microscopic view by simply changing the magnification, is not available in scanning probe microscopes. It is therefore extremely time consumptive to find the sample structures of interest, e.g. the space charge region of a pn-junction in an STM, since the sample can not be translated under the tip while the scan is in progress.

If the applied voltage to the tip exceeds the operating voltage of the emission current amplifier monitoring the emitted current form the tip, the amplifier is highly endangered to be damaged if the tip has direct contact to the sample which leads to an extremely high current.

Finally, a conventional STM is not capable of measuring induced currents since it is equipped only with one current amplifier for the emission current. Therefore an additional current amplifier must be implemented into the instrument.

Realized STM-EBIC Microscope

From the problems listed in the section above demands can be deduced which can be addressed to an STM if the instrument is applied to induced current measurements.

The voltage applied to the tip must be increased. Practical values are in the range between 10 V and 100 V. In order to avoid field ionization of ambient gas molecules the whole equipment should be operated under vacuum conditions. The possibility of finding the sample structures of interest can be improved by allowing a sample shift while the scan is in progress preferably with nanometer accuracy. The STM should be equipped with an input protection circuit for the emission current amplifier and with an additional current amplifier for the measurement of induced currents. The option of biasing the sample as necessary for special EBIC-measurements should be implemented, too.

All the demands have been transformed into a working STM-EBIC microscope realized in a TopoMetrix scanning tunneling microscope. Figure 2 shows the schematic set-up of the STM-EBIC microscope. In order to avoid field ionization the instrument excluding electronics has been brought into a vacuum chamber allowing a minimum operating pressure of approx. $1.0 \cdot 10^{-5}$ mbar.

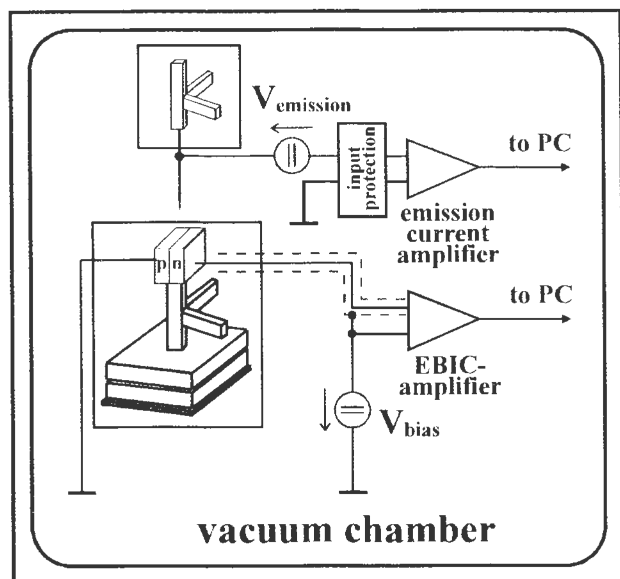

Figure 2. STM-EBIC microscope: schematic set-up.

At this low pressure field ionization has not been observed and consequently the emission current is stabilized. The emission current amplifier has been equipped with an input protection, which allows a shortening between tip and sample without any damage to the amplifier. The increase of the emission voltage has been achieved by creating a series connection between the emission current amplifier and a voltage source (battery) allowing emission voltages in the range from 1V up to 100 V. Great care has been taken for the shielding of this series connection since the emission current amplifier is very sensitive against external distortions. The amplifier for the amplification of the induced current signal has been mounted to close proximity to the sample to avoid any distortions reducing the signal to noise ratio of the current signal. Due to the use of an operational amplifier as current amplifier a biasing of the sample with simultaneous measurement of the current is possible. A precise shifting of the sample even when the scan is in progress can be performed by the use of a so called tripod-scanner as specimen holder. By invoking the tripod-scanner a translation of the sample is possible with an accuracy of some ten nanometers.

Measurement Results

The following micrographs show measurement results obtained in the developed STM-EBIC microscope on various samples. Figure 3 shows the experimental set-up used for EBIC investigations on a silicon sample with a layer n-doped by ion implantation with a thickness of 0.7 μm. Figure 4 depicts the topography micrograph of the cross-section of the silicon sample. The micrograph shows an increase of the topography due to a formation of an inclined plane by sample preparation. The corresponding STM-EBIC micrograph (Figure 5) shows an induced current signal in the doping region probably indicating the presence of internal electrical fields due to doping inhomogeneities in depth as expected for ion implantation. The spatial resolution of the measurement can be estimated to be 300 nm.

Figure 6 depicts the experimental configuration as used for EBIC-measurements on a Si-Schottky-diode. The Schottky-diode was fabricated by evaporating an aluminium dot onto the p-doped semiconductor. The Schottky-diode has not been biased for the measurement. Figure 7 reveals the topography micrograph of the sample showing clearly the edge of the aluminium dot. The corresponding STM-EBIC micrograph (Figure 8) indicates electrical fields present at the edge of the Schottky-contact by an increase of the induced current in the vicinity of the contact. Furthermore a decrease of the magnitude of the induced current occurs when the tip comes in close proximity to the contact. This effect also has been observed in numerical simulations of induced currents, too, and can therefore be understood as an interaction of the electrical fields introduced to the semiconductor by the biased tip and the internal electrical fields present due to the Schottky-contact. The reachable spatial resolution in this measurement is approximately 300 nm.

Conclusions

The present work demonstrates that the measurement of electron beam induced currents in a scanning tunneling microscope can provide information of the electrical situation within a semiconductor sample. The capabilities inherent in this technique can only be exploited to full extend when an STM is adopted to the demands that this technique put on the instrument. The reachable spatial resolution with an optimized instrument is in the range of some hundred nanometers.

Acknowledgments

The authors would like to thank A. Ketterson and T. Moore, Texas Instruments, and J. Carrejo, Motorola, for supplying the semiconductor samples. The work was financially supported by the Deutsche Forschungsgemeinschaft within Sonderforschungsbereich 254.

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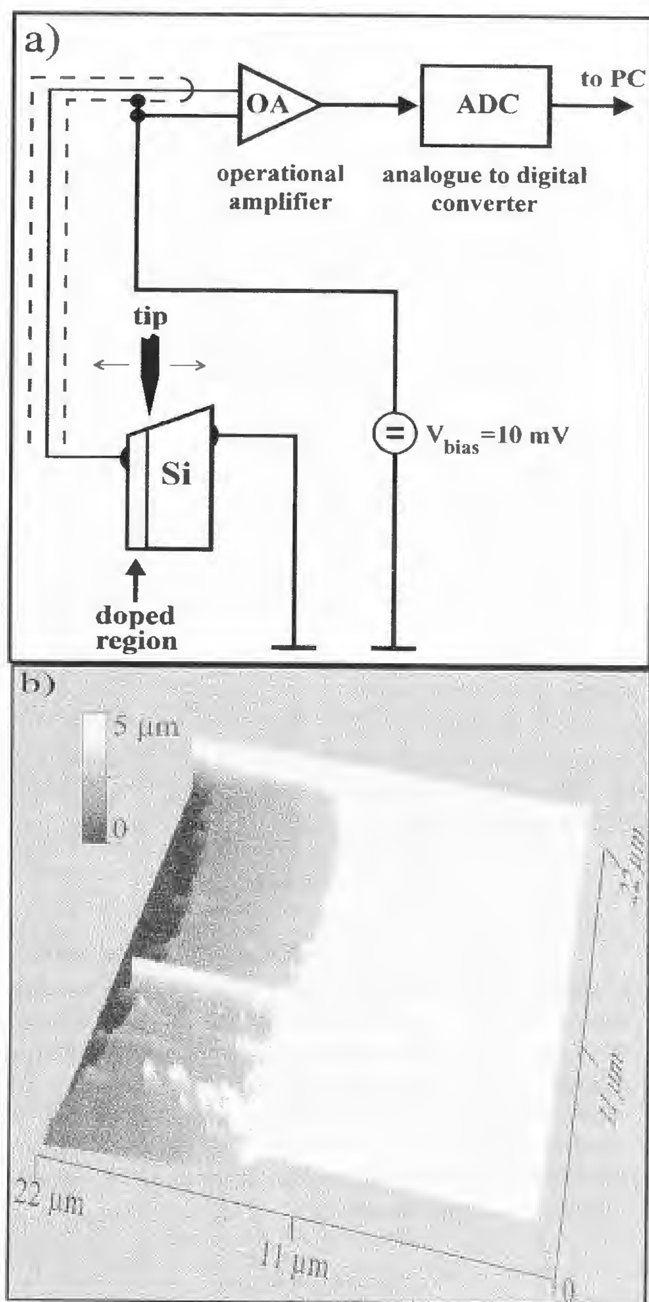

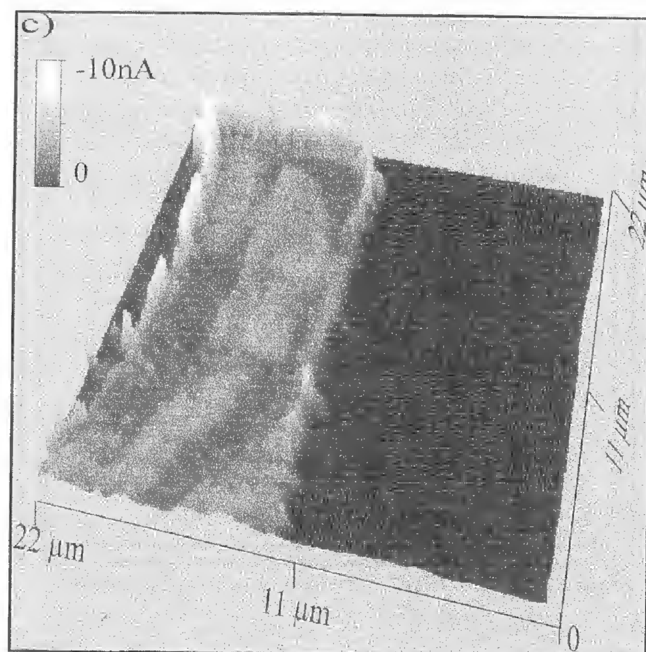

Figure 3. (a) Experimental set-up used for STM-EBIC measurements on doped silicon, (b) topography micrograph of the n-doped silicon sample, (c) STM-EBIC micrograph of the n-doped silicon sample.

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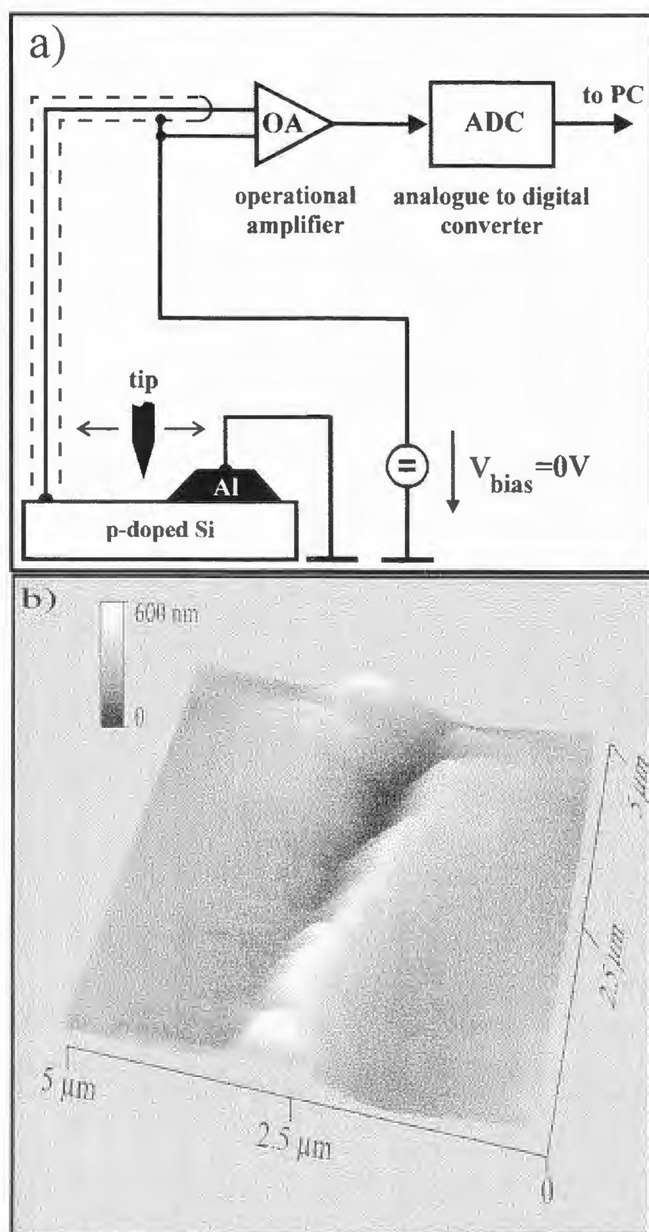
Discussion With Reviewers

A. Cavallini: Could the authors give a deeper insight into the problem of the voltage applied between tip and sample in an STM-EBIC? How did they find the optimum range (10-100 V) reported in their paper?

Authors: Due to the small distance between tip and sample, extremely high electrical field strengths occur. These high electrical fields lead eventually to a direct ionization of ambient gas molecules by a direct tunneling process of electrons from the tip to the gas molecules or atoms [1]. This statistically ionization leads to a fluctuation of the emission current and therefore to a non-constant generation of electron-hole pairs and finally to a reduction of the signal to noise ratio of the measured induced current. In order to avoid this effect, the instrument should be operated at least under rough vacuum conditions.



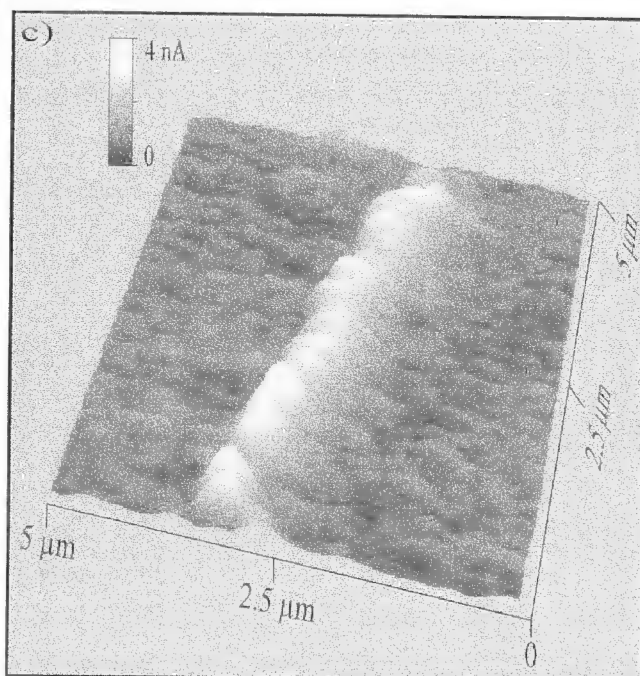


Figure 4. (a) Experimental set-up used for STM-EBIC measurements on a Al-Si-Schottky-diode, (b) topography micrograph of the Al-Si-Schottky-diode, (c) STM-EBIC micrograph of the Al-Si-Schottky-diode.

Impact ionization of the gas molecules or atoms can be neglected due to the high mean free path length of the electrons in the energy range used [6].

The proposed energy range of 10 eV to 100 eV is a compromise between required generation rate and minimum tip sample interaction. The generation rate of electron-hole pairs, and consequently the maximum induced current, depends on the energy of the impinging electrons. Therefore, the higher the emission energy of the electrons, the higher the induced current can be expected. For a sufficiently high signal to noise ratio, a high generation rate or high emission voltage is necessary. On the other hand, a high emission voltage leads to a significant change of the internal electrical situation of the sample due to the field effect occurring in STM-EBIC. The energy range between 10 eV and 100 eV can be regarded as the one providing a sufficient induced current with minimum tip sample interaction. However, in special cases, the emission voltage used should be adopted to the sample.

A. Cavallini: The authors say that there are ionization processes when the voltage is higher than the conventional voltage (some volts) used in STM measurements. To avoid ionization processes, their equipment is used under vacuum conditions. That is, however, considered a strong disadvantage of SEM in respect to STM. Do the authors believe that to work in vacuum is the only way to overcome the ionization problems?

Authors: The problem of field ionization does not require the utilization of ultra high vacuum technology. According to our experience, even rough vacuum conditions can improve the emission current stability significantly. Another approach for solving this problem can be the replacement of the ambient air by specific gases which are used as an insulator with high breakdown voltage in high voltage environments, like SF_6. If such gases are used, the ionization can be reduced, too.

A. Cavallini: How did the authors estimate the spatial resolution of their measurements?

K. Luo: How did the authors arrive at the reported lateral resolution of 300 nm? Can the authors address the factors that limit the resolution? What is the typical distance between the tip and the sample? This distance may be considerably greater than the tunneling distance in an STM, and if so, how would the distance affect the resolution and what is the highest possible resolution of their microscope?
Authors: The spatial resolution of the measurements are derived by examination of linescans extracted from our measured micrograph. A precise determination of the reachable spatial resolution can only be performed if a test structure, e.g., a layer structure consisting of alternating pn-junctions of various extends, is available. Since we do not possess such a structure until now, we are forced to estimate the resolution from the micrographs.

The resolution itself is limited by the electronic properties of the sample, e.g., surface diffusion lengths or charge carrier lifetimes, and by the experimental parameters used for the measurements. A detailed discussion of the influence of the experimental parameters on the resolution can only be given when the behaviour of the injected electrons in the sample, i.e., the spatial distribution of the generated electron-hole pairs is known. Unfortunately, this distribution is not known for low energetic electrons until now.

K. Luo: In field emission experiments, it is important for the authors to provide information regarding the tip status. For example, what type of tips were used in their EBIC measurements? What is the typical tip diameter? What are the effects on the stability of the emission current by the contamination or oxide layer on the tip surface?
Authors: We used a commercially available etched tungsten tip with diameter of 40 nm. Since field emission is very sensitive against surface contamination and since tungsten is usually covered by an oxide layer, the tips were prepared before they were used. We removed the oxide layer by sputtering the tip with argon ions, and subsequently we coated the tips with a thin (< 10 nm) gold layer. This preparation procedure improves the emission stability significantly in comparison to the untreated tip.

K. Luo: When 10-100 V is applied to produce a high electrical field under a sharp tip, one would expect changes in both the tip and the sample surfaces. Material transfer between the tip and sample may also occur. Did the authors ever observe any deposition from the tip to the sample surfaces, for example?
Authors: We did not observe material transfer between tip and sample. However, a detailed investigation of material transfer requires very sensitive analytical techniques. From our experience, a degradation of the tip can he observed leading to a loss of spatial resolution after several scans, indicating a possible change of the tip surface structure.

K. Luo: Usually, there is a passivation layer of insulation such as SiO_2 deposited on the surface of microelectronic devices or chips. Would the STM-based EBIC microscope still be able to apply to such a system and measure the induced current?
Authors: The instrument is developed for investigations of devices and materials under development, not for commercially available devices which are usually passivated by thick, artificially grown oxide layers. Of course, neither these layers can be passed by the electron nor a controlled field emission of electrons is possible under these circumstances. In contrast, an investigation of semiconductors with a natural thin oxide layer is possible.

K. Luo: An electrical field is created near the sample surface when biased. Are there any electromagnetic interaction forces between the field and tip? How would they influence the measurement?
Authors: The main force present between tip and sample is the electrostatic coulomb force due to the electric field. That means that there are attractive or repulsive forces acting on the free charge carriers in the sample, thus changing the charge carrier densities within the sample. This interaction influences the measurement. A detailed description of the interaction can be found in ref. [3]. The electrostatic forces lead to an attractive force between tip and sample, too. This attractive force does not influence the measurements.

K. Luo: How fast can the tripod scanner operate? What is the largest travelling distance or the largest view it can provide?
Authors: The scan speed of the scanner is mainly limited by the cut-off frequency of the system's feedback loop. An acceptable scan speed is approximately one image in thirty minutes. The area that can be scanned depends on the scanner used. The largest area that our scanner can cover is 25 μm x 25 μm. With other scanners, up to 150 μm x 150 μm can be scanned.