Dopant Contrast in the Helium Ion Microscope: Contrast Mechanism

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Abstract. With the continued miniaturisation of semiconductor devices, there is an increasing need for nanoscale characterisation. Dopant mapping in a Low Voltage Scanning Electron Microscope (LV-SEM) was identified as a potential technique to fulfil this need, provided that a small enough probe size (~0.1 nm) could be achieved. It has been shown that He ion beams in Helium Ion Microscopes (HeIM) can be focussed to probe sizes as small as 0.24 nm. As the image in both LV-SEM and HeIM is formed by secondary electrons it is not surprising that HeIM exhibits dopant contrast as recently demonstrated. In this paper we describe similarities and differences between HeIM dopant contrast and SEM dopant contrast and explore implications for the contrast mechanism.

1. Introduction

The shrinking dimensions of electronic devices pose a challenge to the measurement of dopant concentrations with sufficiently high accuracy and spatial resolution for the analysis of two- and three-dimensional structures. Images formed by secondary electrons (SEs) generated in LV-SEM were proposed as a potential solution to this challenge, provided that a sufficiently small probe size could be achieved [1]. The smallest usable charged particle probe to generate secondary electron (SE) images of bulk specimens to date was not obtained in a Scanning Electron Microscope (SEM) but in a Helium Ion Microscope (HeIM) operated at 20 kV [2]. A result of several SEM dopant contrast studies was that increased primary beam energies lead to a reduction in SEM dopant contrast [3, 4, 5]. Therefore it was questionable if any dopant contrast could be observed in the HeIM. Initial results obtained in the first generation HeIM showed that doped areas could be identified but a direct correlation between dopant concentration and SE intensity, similar to that observed in SEM, was not found [6]. A further study employing a second generation HeIM with increased detection efficiency revealed that contrast similar to that in the SEM can be obtained [7]. This promising result opens up the question of why dopant contrast can be observed for high primary beam energies in the HeIM. Therefore, in this paper we investigate differences in dopant contrast behaviour in the HeIM and SEM in order to gain a better understanding of the contrast mechanism involved.
2. Investigation of SEM and HeIM dopant contrast characteristics

2.1. The influence of primary beam energy

Figure 1 a represents the contrast obtained on a cross section of a p-n junction, obtained by cleaving in air (for estimated oxide thickness see [8]), when imaged in the SEM using an Everhart-Thornley detector and an accelerating voltage, \( U \), where \( U = 2 \) kV. The bright layer reflects the extent of a p-doped area (boron doped to \( 5 \times 10^{18} \) atoms cm\(^{-3} \)) on an n-type substrate (arsenic doped to \( 1 \times 10^{19} \) atoms cm\(^{-3} \)). Figure 1 b was also obtained in the SEM but with \( U = 25 \) kV. The contrast (defined as the intensity difference between the p and n doped regions divided by the average intensity of these regions) is reduced compared to that in figure 1 a. A further reduction in contrast is visible in the SEM image collected with \( U = 30 \) kV figure 1 c.

![Figure 1: SEM images of p-n junction with indicated accelerating voltages, d) p-n contrast as a function of U in SEM, e-f) HeIM images with indicated accelerating voltages U. Changes in noise levels are due to changes in incident beam current, \( I_t \).](image)

The contrast as a function of \( U \) in the SEM when using an Everhart-Thornley detector. Maximum contrast is obtained at \( U = 2 \) kV (for silicon) as was previously found in [4]. The decline in contrast with larger \( U \) could be explained by increased incident beam currents, \( I_t \), obtained for larger \( U \) (see [9] for explanation). For example in the SEM used we measured...
$I_i(U=1\text{kV}) = 0.07\text{nA}$ compared to $I_i(U=10\text{kV}) = 0.34\text{nA})$. However, the maximum in the SEM contrast which was also reported in [5] cannot be explained purely as a result of changes in $I_i$, instead it is explained in [4] as a result of dynamic charging. In the SEM the escaping SEs lead to a positive charge near the surface, whereas trapped primary electrons can cause a negative charge deeper within the specimen. Through this process, an internal field is established that can result in acceleration of electrons towards the surface of the specimen [4]. The magnitude of this field in intrinsic silicon depends on the accelerating voltage [4] which affects the SE yield for a material of a given dopant type and concentration and is responsible for the observed dependence of dopant contrast on accelerating voltage. According to [4] the field strength is also influenced by the dopant atom type, with the positive surface charge present in p-type silicon increasing the field, and the negative surface charges in the n-type silicon reducing the field. Increased field strength accelerates electrons towards the surface of the specimen and results in higher yields for p-type silicon when compared to that of intrinsic silicon, likewise the reduced field strength in n-type silicon results in a smaller yield compared to intrinsic silicon at constant accelerating voltage. This is suggested as the cause for SEM dopant contrast [4], with a contrast magnitude that depends on accelerating voltage for a given difference in dopant concentrations.

There is a fundamental difference in charging in the SEM and HeIM, as in the latter, the charge implanted due to the primary beam is positive, as is the charge deposited close to the surface due to the escape of SEs. However, as the SE yield for He ion impact is in the order of several SEs per incident He ion [10], more positive charge is deposited close to the surface through the escape of SEs than is deposited by the primary He ions. As a result, there will be an internal field present in HeIM similar to that suggested to form in the SEM and one may expect dopant contrast of a similar magnitude. In addition, as the SE yield for He ion impact in the range between $U = 10-40$ kV is reported to increase with increased $U$ [11], we would expect HeIM contrast to increase with increasing $U$ (an opposite trend to that in the SEM (shown in figure 1 d)).

Figure 1 e and f are images taken in an Orion Plus HeIM, where SEs are generated by a primary beam consisting of He ions accelerated to $U = 31$ kV (figure 1 f) and 25 kV (figure 1 e). As can be seen in figures 1 e and f, the contrast in the HeIM is of similar magnitude to that of 25 kV SEM (figure 1 b). In addition, the contrast in the HeIM at the higher accelerating voltage of $U = 31$ kV is increased compared to that obtained at $U = 25$ kV. This result supports the theory of dynamic charging as a contributor to dopant contrast in images generated by SEs.

2.2. Influence of charging

The importance of charging in relation to dopant contrast has been discussed above. In SEM, the influence of charging cannot be investigated independently from the influence of the primary beam energy (charge neutrality can only be achieved by adjusting the primary beam energy).
However, HeIM allows the investigation of the effect of charging by neutralising the build-up of positive charge due to the impacting He ion beam through the use of an electron flood gun. The SE image obtained in the HeIM without the use of a flood gun is presented in figure 2 a. It is a cross-section of silicon containing seven boron doped layers (with dopant concentrations of $4 \times 10^{15}$, $6.5 \times 10^{16}$, $8 \times 10^{17}$, $4 \times 10^{18}$, $9 \times 10^{18}$, $2 \times 10^{19}$, $5 \times 10^{19}$ cm$^{-3}$ from left to right) on an n-type substrate (arsenic doped $1 \times 10^{19}$ atoms cm$^{-3}$). The specimen was completely insulated from the specimen holder through the use of 1mm thick glass slides. At the top of the image in figure 2 a, the four highest doped layers can be distinguished. The contrast for the highest doped layer relative to the n-type substrate is ~30 %. As scanning progresses (towards bottom part of the image) the intensity is considerably reduced as a result of the build up of positive charge at the surface. The accumulation of positive charge prevents the escape of low energy SEs leading to the observed darkening effect. Nevertheless, the dopant contrast for the p-type layer with the highest dopant concentration is still visible at the bottom of the image and as a result of the charge build up, the contrast for this layer relative to the n-type substrate has increased to ~50%. This increase in dopant contrast as a result of charge accumulation during progressive scanning is consistent with the increased contrast as a result of increased acceleration voltage in the HeIM, as the latter is also related to an increase in surface charge (due to a yield increase). Both of these results demonstrate that charging does contribute to dopant contrast and should not be ignored. To collect dopant contrast images with minimum influence of charging, an electron flood gun was used to collect the image shown in figure 2 b. The flood gun was pulsed at the end of each line during image acquisition and then turned off before commencing the next line. The electron flood gun energy was 400 eV with a pulse time of 1000 μs. The fact that there is no notable reduction in intensity with progressing scanning in figure 2 b demonstrates successful charge compensation to some degree. Analysis of the dopant contrast of the highest doped layer reveals that some charging still remains as the contrast increases from 23% at top of the image to 27% at the bottom of the image.

3. Conclusion
We have investigated the influence of primary beam energy on dopant contrast obtained in HeIM and SEM, as well as the influence of charging in the HeIM. Our results indicate that charging can alter dopant contrast significantly. Notably, charging in the HeIM can be controlled in the HeIM by the use of an electron flood gun.

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References
[1] Castell M R, Muller D A and Voyles P M 2003 Nature Mat. 2, 129
[2] Hill R, Notte J and Ward B 2008 Phys. Procedia. 1, 135
[3] Sealy C P, Castell M R and Wilshaw P R 2000 J. Electron. Microsc. 49, 311
[4] Chakk Y and Horvitz D 2006 J. Mater. Sci. 41 4554
[5] Elliott S L 2001 PhD Thesis, University of Cambridge p.42
[6] Jepson M A E, Inkson B J, Rodenburg C and Bell D C, 2009 EPL 85 46001
[7] Jepson M A E, Inkson B J, Liu X, Scipioni L and Rodenburg C 2009 EPL 86 26005
[8] Dapor M, Jepson M A E, Inkson B J and Rodenburg C 2009 Microsc. Microanal. 15 237
[9] Kazemian K, Rodenburg C, Humphreys C J 2004 Microelectronic Engineering 73–74 948
[10] Ramachandra R, Griffin B and Joy D 2009 Ultramicroscopy 109 748
[11] Yamanaka T, Inai K and Ohva K 2009 Proc. SPIE 7272 72722L