High resolution dopant profiling in the SEM, image widths and surface band-bending

K.W.A. Chee, C. Rodenburg*, C. J. Humphreys
University of Cambridge, Department of Materials Science and Metallurgy, Pembroke Street, Cambridge, CB2 3QZ, UK.
*University of Sheffield, Department of Engineering Materials, Mappin Street, Sheffield, S1 3JD, UK.

E-mail: kwac2@cam.ac.uk

Abstract. To study the mechanisms of dopant contrast in secondary electron (SE) imaging in the SEM, we have measured the image widths of a series of thin p-doped layers in Si, from 1 nm upwards. We have used computer modelling to simulate the effects of surface band-bending due to a realistic density of surface states on the Si, and we have also calculated the magnitude of the external patch fields. We have found a good correlation between the intensity widths and slopes of experimentally measured SE images of thin p-doped layers and the calculated widths and slopes of the energy distributions across these layers at a depth of 5-10 nm below the surface. This is consistent with the mean escape depth of SEs in Si being about 7 nm. We conclude that doping contrast in the SEM is mainly a function of bulk built-in voltages modified by surface band-bending effects within about 5-10 nm of the surface.

1. Introduction
Doping differences in semiconductors produce clearly observable secondary electron (SE) image contrast in the SEM. It has been demonstrated that the SE emission intensity is sensitive to the number of ionised dopants, rather than the total number of dopant atoms [1-2]. In general, the p-doped region gives a higher SE yield than the n-doped region. The dopant contrast mechanism is due to the built-in electric field across a p-n junction, modified by the effects of surface band-bending and external patch fields [3-8]. We have explored the relative contributions of these factors by experimentally measuring the SE intensity profile across a Si sample consisting of differently doped regions and by comparing this with the calculated electrostatic potential distribution across the same sample using detailed computer simulations in solving Poisson’s equation for our semiconductor specimen.

2. SE imaging experiments
The silicon specimen was CVD grown with six B-doped layers each having a p-type doping concentration of 1×10^19 cm^-3, and layer widths of 1, 2, 3, 5, 10 and 30 nm grown on a Sb-doped (5×10^18 cm^-3) n-type substrate. The capping layer and the spacer layers between the thin p-type layers are undoped (fig.1). The specimen was cleaved in air along a direction perpendicular to the [001] growth direction to expose a {110} plane and imaged immediately after cleaving. The SE imaging

1 To whom any correspondence should be addressed.
was performed on a FEI XL30 sFEG-SEM at a beam accelerating voltage of 1 kV using a beam diameter of 4 nm, which is the smallest probe size possible having a sufficient beam current of ~ 7 pA in order to provide a high resolution image. An objective aperture of 30 m diameter was used, and the operating pressure in the vacuum chamber using oil-free pumps was $3 \times 10^{-6}$ mbar.

![Fig. 1 SE image of the Si specimen containing six p-doped layers on an n-doped substrate. The layer thicknesses (1, 2, 3, 5, 10 and 30 nm) increase from left to right.](image1)

![Fig. 2 Contrast profile (normalized to n-doped region) as a function of distance from the surface, relating to the SE image in figure 1.](image2)

Using the TTL detector activated in the UHR mode and operating at a working distance of ~ 3 mm, the SE image (fig. 1) was obtained at a magnification of 20000× (scanned field area of ~ 6.1 m × ~ 4.2 m) at a scan period of ~ 10 s/frame. The extractor bias was 20 V and the deflector voltage was 60 V. The settings we have used have been optimised for dopant contrast in high resolution imaging [8-9]. As shown in figures 1 and 2, all the p-doped layers are distinguishable in the SE image, including the 1-nm thick layer. The image widths of the thin layers are wider than the actual widths for reasons which will be given later. However, it is significant that a doped layer as thin as 1 nm can be detected using a 1 kV incident electron beam of diameter 4 nm. The contrast profile in figure 2 is calculated using the standard definition [8, 10]:

$$\text{Contrast}, \ C = \frac{I - I_{\text{sub}}}{I_{\text{sub}} - I_{\text{ref}}} \times 100 \% \ , \quad (1)$$

where $I_{\text{sub}}$ is the intensity from the substrate and $I_{\text{ref}}$ is the reference intensity obtained from the beam-blanked image.

### 3. Finite-element modelling and discussion

Finite-element simulations were performed using ATLAS software to solve Poisson’s equation for the Si sample used in the experiments above. The bottom of the substrate was grounded. A surface state density of $1.6 \times 10^{12}$ cm$^{-2}$ was used in the simulations as determined in [7]. The surface states were simulated in a uniform 1 nm silicon layer on the surface of the semiconductor and were assigned an energy level at the mid-gap position for silicon (0.55 eV), which is a known surface state level [6]. The two-dimensional plot of the electrostatic potential distribution is shown in figure 3. The built-in potentials across the p-n junction and across the p-i junctions are clear. Above the surface, in the vacuum, the potential is ranging, giving rise to so-called patch fields. Figure 4 shows the calculated energy distributions across the specimen at various depths below the surface (5 nm, 15 nm and 0.5 μm,
the latter being essentially in bulk material), and at 5 nm above the surface. It is of interest to note that
the widths of the calculated energy distributions across the p-doped layers are significantly wider than
the actual widths of the doped layers, for the thinner layers. Since the secondary electrons are
scattered by the crystal potential, and \( E = -eV \), where \( E \) is the energy and \( V \) the potential, this explains
why the SE image widths of the thin p-doped layers are significantly wider than the actual widths of
the layers.

Fig. 3 Two-dimensional electrostatic potential
distribution plot in and above the silicon
specimen obtained using finite-element analysis
solutions of Poisson’s equation.

Fig. 4 Energy distributions across sections 5 nm,
15 nm and 0.5 \( \mu \)m below, and 5 nm above the
semiconductor specimen.

Fig. 5 Measured SE intensity from the
semiconductor specimen in figure 1.

Fig. 6 Carrier concentrations across the Si
specimen at a depth of 5 nm below the surface.
We have compared the measured SE intensity (fig. 5) across the p-doped layers in figure 1 with the calculated energy distributions across these layers (fig. 4). We have calculated the energy distributions across the doped layers for a wide range of depths above and below the specimen, and only reproduce some of these for clarity in figure 4. We find that the experimental SE intensity distribution (fig. 5) corresponds most closely to the calculated energy distribution at a depth of 5-10 nm below the surface. At this depth both the widths and the relative heights of the experimental and theoretical curves agree reasonably well. The above result is consistent with the fact that the majority of SEs escaping from Si come from a depth of about 7 nm [10-11]. These SEs therefore experience the potential distribution within a surface layer about 7 nm deep.

Figure 6 shows calculated carrier concentrations for the Si specimen in figure 1, at a depth of 5 nm below the surface. Comparing figures 5 and 6, it is clear that the measured SE intensity is reasonably closely related to the hole concentration at this depth. It is not related to the density of acceptor atoms, which have a width of 1 nm for the narrowest doped layer.

4. Summary and Conclusions

We have shown that the image intensity widths and slopes of thin p-doped layers of Si using SE imaging in the SEM correspond closely with the widths and slopes of the energy distribution across these layers, at a depth of 5-10 nm below the surface. This suggests that doping contrast in the SEM is a function of bulk built-in voltages modified by band-bending effects within 5-10 nm of the surface, consistent with the average escape depth of SEs in Si being about 7 nm.

5. Acknowledgements

A.Chee acknowledges ORSAS, Cambridge Commonwealth Trust, Trinity Hall Cambridge and FEI Company for sponsorship. C. Rodenburg thanks the Royal Society for their support.

6. References

[1] Turan R, Perovic D D and Houghton D C 1996 Appl. Phys. Let. 69(11), p 1593
[2] Castell M R, Perovic D D and Lafontaine H 1997 Ultramicroscopy 69(4), p 279
[3] Perovic D D, Castell M R, Howie A, Lavoie C, Tiedje T and Cole J S W 1995 Ultramicroscopy 58(1), p 104
[4] Perovic D D, Turan R and Castell M R 1998 Proc. Int. Centennial Symposium on the electron, Cambridge, U.K. (IOM Communications), p 258
[5] Howie A 1995 J. Microsc. 180, p 192
[6] Sealy C P, Castell M R and Wilshaw P R 2000 J. Electron Microsc. 49(2), p 311
[7] Chee K W A, Rodenburg C and Humphreys C J 2007 Proc. Microsc. Semicon. Mat. (in press)
[8] Elliott S L, Broom R F and Humphreys C J 2002 J. Appl. Phys. 91(11), p 9116
[9] Kazemian P, Mentink S A M, Rodenburg C and Humphreys C J 2006 J. Appl. Phys. 100(5), p 054901
[10] Goldstein J, Newbury D, Joy D, Lyman C, Echlin P, Lifshin E, Sawyer L and Michael J 2003 Scanning Electron Microscopy and X-ray Microanalysis 3rd ed (Kluwer Academic / Plenum Publishers, New York)
[11] Howie A 2000 Microsc. Microanal. 6, p 291