

Direct and rapid SEM imaging of dopant areas in semiconductor devices

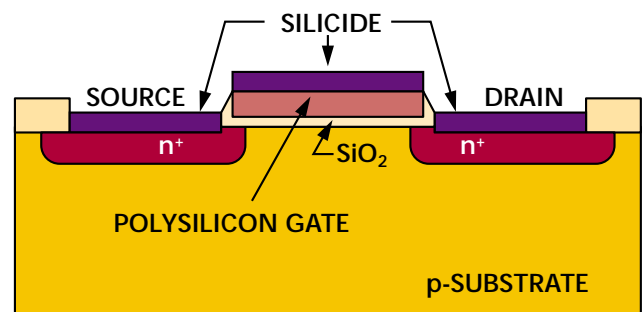
More from low kV

The semiconductor industry is always keen to find ways to rapidly check production techniques or device failure. One of the areas of interest is the actual junction of a device and hence the areas that are doped with n or p material. Imaging of these areas has been the subject of investigation for a long time. Traditional methods that are used on a regular basis involve chemical junction delineation followed by standard SEM imaging, or AFM/STM profiling. In addition EBIC has been applied to visualise the active junction area. These methods of imaging of the doped areas are indirect and involve additional steps in specimen preparation. These all require both time and care: for example etch rates will depend on the presence of metals and metal ions taking part in the electro-chemical reaction (e.g. Cu) and this makes it difficult to image all doping levels in one step. A capability to directly image the doping areas would therefore be advantageous. Direct imaging of the doping areas using modern immersion type SEM imaging is now shown to be possible.

Semi-conducting materials are doped with impurity atoms to change the properties of the material and create junctions. These properties, and others, can be combined and exploited to form devices that can be used in numerous commercial applications. One most common device is the metal-oxide-semiconductor field-effect transistor (MOSFET). This is a four-terminal device (including base contact) and the n-type MOSFET consists of a p-type semiconductor substrate doped (ion implanted) with two n⁺ regions known as source and drain. The contact on the insulator is called the gate and

is metallic. Heavily doped poly-silicon, or a combination of silicide and poly-silicon makes up the rest of the gate electrode. MOSFETs on a silicon integrated circuit are surrounded by thick oxide called the field oxide to insulate them from adjacent devices.

Although semiconductors can be doped in a controlled way, the doping distribution may not always turn out as planned. Dopants often diffuse into other regions of the device, which will cause the device to fail in its operation. It is necessary for the semi-conductor industry to obtain dopant profiles for device failure analysis and to provide analytical support for process and product development. The most common methods used to characterise doping profiles are Secondary Ion Mass Spectroscopy which maps the chemical concentration of dopants, and Spreading-Resistance or Capacitance Voltage Profiling which map electrically active dopants.



Cross-sectional diagram of an n-type MOSFET

However these techniques are essentially one dimensional only and therefore difficult to apply to real situations where it is necessary to profile device junctions vertically as well as laterally. The methods most successful for two-dimensional profiling are based on etching and imaging of the etched structure.

Direct imaging using SEM

Dopant profiling with the Scanning Electron Microscope refers to the direct mapping of electrically active dopants in semiconducting materials using secondary electrons (SE). The dopant region has not been prepared in any other way than made accessible to the electron beam for example by making a cross-section. So sample preparation is really very straightforward, only requiring a cleaved cross-section. This is fairly simple to obtain for most semiconductors. After cleaving, the sample should be immediately transferred to the SEM. In this way both oxidation and possible contamination are kept to a minimum. It is best to use freshly cleaved material, and preferably scan the region of interest only once. In this way it is possible to get reproducible results. Secondary electron images show different contrast on differently doped materials: p-type dopants show up as bright areas (compared to the substrate) whereas n-type dopants show up as dark areas. In addition, highly doped regions show greater contrast than low-doped regions i.e. the signal is a function of the dopant concentration.

The nature of the contrast and the explanation of the physics is subject of further theoretical investigations. Although progress has been made, an overall theoretical model that (quantitatively) describes and explains the contrast is not yet available. A theoretical explanation is very useful since a more detailed understanding can also help to target further practical and instrumental improvements for this method.

One of the most important considerations for the usefulness of this technique for industrial implementation, is the sensitivity, although the sensitivity limits necessary for any dopant profiling technique are becoming less stringent as device dimensions decrease. A technique should be capable

of imaging dopant concentrations at least as low as $10^{17}/\text{cm}^3$. Experimentally it has been shown that the lower limit (with 6 % contrast) for dopants in Si is in the range of 3×10^{15} dopants/ cm^3 . This has been demonstrated by imaging lightly doped p-type layers in an n+ substrate. It shows the enormous sensitivity of the SEM technique.

An example that shows dopant levels of different concentration is shown in the following layered test structure (figure 1). In this image the concentration of the dopant reduces from left to right (white bands). Another way of showing dopant areas is to translate the grey levels to intensity profiles. After the SE images have been collected these can be converted into contrast profiles by taking line scans across the image and integrating over

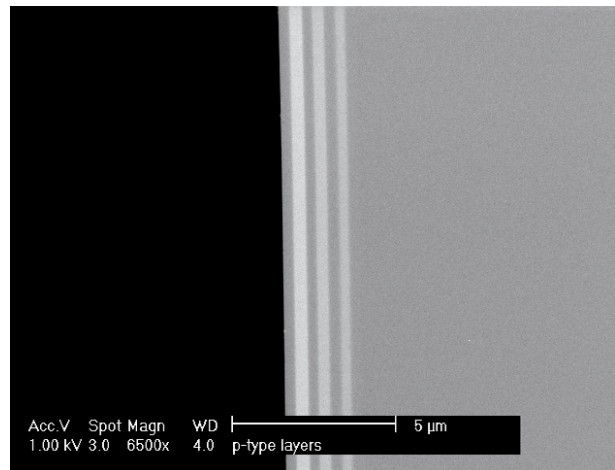


Figure 1: Test structure p-doped layers with decreasing concentration

the entire image, then converting into contrast (C) using for example the following equation:

$$C = 100 * (I_d - I_{sub}) / (I_{sub} - I_{ref})$$

Where I_d is the intensity of the intentionally doped layer, I_{sub} is the intensity of the substrate and I_{ref} is the reference intensity obtained when the beam-blanking facility is switched on. The latter provides a background value for normalisation and to compensate for the actual image contrast and brightness setting chosen by the user.

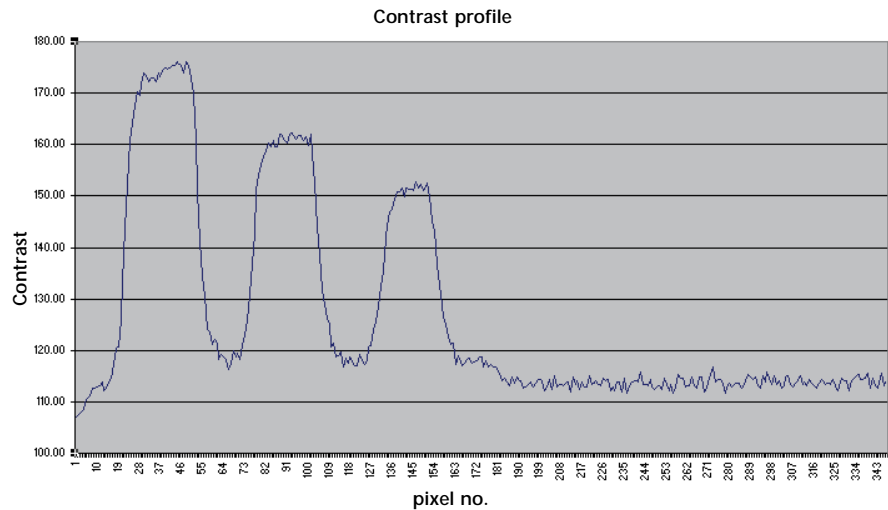


Figure 2: Normalized intensity profile related to figure 1.

Direct imaging with XL30 S FEG and Sirion

The optimum dopant contrast is observed when applying a field emission gun on an immersion based column in combination with a tunable in-lens secondary electron detector. The Schottky field emission gun provides a high beam current in a small geometric spot and at low incident electron energies (~1 kV). At this low energy the secondary electron yield is high and in most cases charging in other areas is minimised. FEI's immersion lens systems have a dedicated detection system that can be further optimised to show the dopant contrast. The in-lens detector is normally used to show either SE or BS images, with a possible BS energy threshold. For further optimisation of the electron signal detection, a special detector mode was designed that allows a further

enhancement of the contrast generated by the dopant areas. This dedicated mode provides one additional parameter that can be SW controlled by the user. It has been shown that applying this extra dopant imaging parameter (DIP) is a great way to improve the contrast of the image, in particular for n-type material. A few examples on cross-sections for actual MOSFET devices are shown in figures 3,4,5 and 6.

Images shown below and on the next page were recorded with an XL30 S FEG and for a Sirion instrument it is expected that the imaging is even further improved because of the stronger beam at low kV, and hence the better S/N will result in a better contrast. This makes the

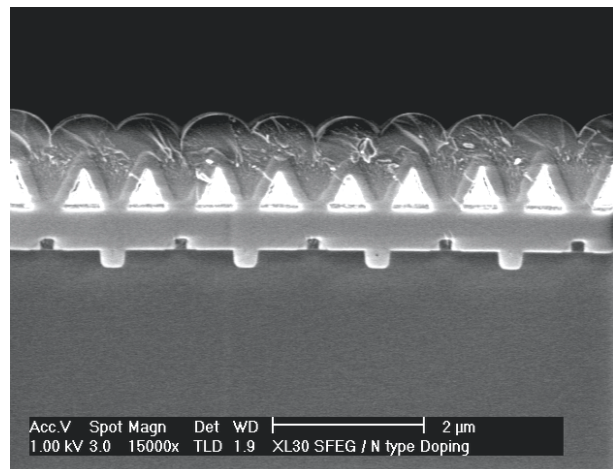
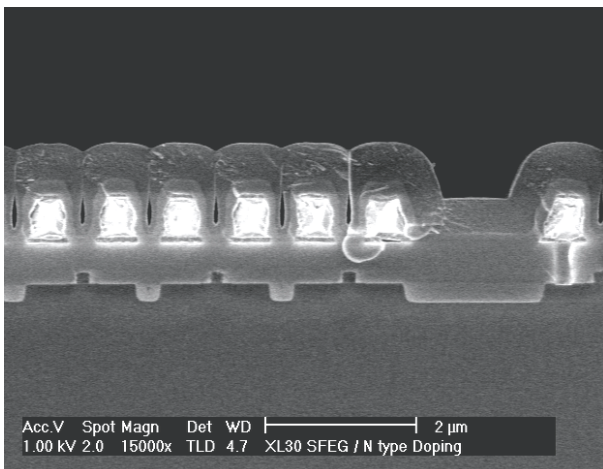


Figure 3 and 4: Cross-section view of n-doped MOSFET structure .

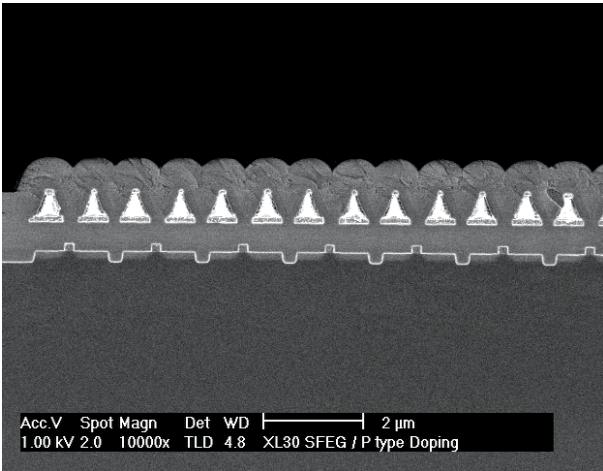


Figure 5: Cross-section view of p-doped MOSFET.

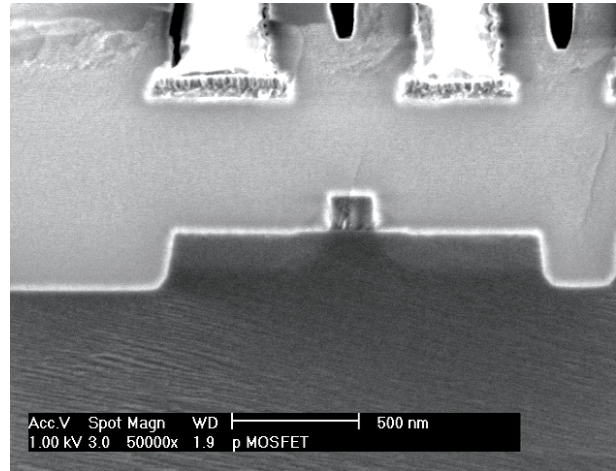


Figure 6: topographical information from the cleave is also visible. No other specimen preparation.

Sirion even more suited for this kind of application. From the images above and on the previous page it is apparent, that p-doped imaging is easier and shows better contrast than n-doped imaging. Especially for imaging n-doped material the tuning of the extra parameter of the detector will help to visualise the doped areas. Using the DIP, the instrument is capable of showing the contrast for both types of dopants very quickly. The additional digital imaging capability also helps to quickly translate image grey level information into graphs with normalised contrast values. Profiles can be collected relatively quickly and easily, with the necessary spatial resolution and sensitivity, but without the need for any surface chemical treatments or complicated sample preparation.

Reference:

The work described in this application note has been carried out in strong co-operation with the department of Materials Science and Metallurgy at the University of Cambridge. For further reading, consult S.L. Elliot, R.Broom, C.J. Humphreys, J.Appl.Phys. (2002) in press. The further development of the dopant imaging parameter has been done in collaboration with C.J. Schönjahn and C.J. Humphreys.

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