IMAGING ELECTRIC FIELDS AT NANOMETER LENGTH SCALES

Semiconductor p-n junctions are basic building blocks for devices like transistors, solar cells, avalanche photodetectors or light emitting diodes. To implement the junction, the electrical properties of semiconducting materials are engineered by adding just very few (less than 1%!) dopant atoms that donate or accept an electron to the conduction or from the valence band, respectively. In this way, the density of mobile charges in the semiconducting material can be tuned over several orders of magnitude.

It is very well known that a transition from a region with one type of dopant (donors or acceptors) to the other kind will generate a depletion region with almost no free charges but an electric field, a so-called p-n junction, giving rise to interesting properties such as rectifying current voltage characteristics and potentially light emission, for example in light emitting diodes. However, challenges remain to control and measure the electrically active doping levels in semiconducting materials with nm precision.
One aspect of a p-n junction is its abruptness: how fast the transition from one dopant atom to the other is made. This property influences the electric field strength present at the junction and thereby the characteristics of a device made from the junction.

Transmission Electron Microscopy (TEM) is interesting with regards to dopant characterization due to its high spatial resolution from few nm to atomic spatial resolution, as well as the penetration through the sample (hence transmission). When an electron probe traverses a region in the sample containing an electric field in the plane of the sample, the electrons are deflected by the field. This beam deflection can be measured very precisely if an image of the transmitted probe is made at each scan location of the probe on the sample, while scanning the sample point by point with a nm sized probe and making nm sized scanning steps. This technique is referred to as 4D-STEM, see Fig. 1. Because the technique is sensitive only to the projected electric field, only electrically active dopants will be contributing to the signal. However, material contrast does contribute to the signal, but is invariable with applied bias.

In this work, in collaboration with colleagues at CEA Grenoble in IRIG and LETI at the Nano Characterization platform (PFNC), we have performed such experiments on a p-n junction in silicon, using a very high quality and fast direct electron detector, as well as electrical contacts to the p-n junction thin film sample. The contacts to the sample allow measuring the internal field as a function of applied external bias voltage, see Fig. 2. From the measured electric field map at each applied bias voltage, we can calculate the charge density map. We have then compared the measured electrical properties (electric field and charge density) with calculated ones assuming either a perfectly abrupt transition from p to n dopants, or a linearly graded one. Our analysis showed that the junction under study could be rather well approximated by a linear graded junction. This work shows that quantitative electrical information at nm length scale is possible by 4D-STEM and that this powerful technique allows to probe the doping profile in semiconductors determining their electrical properties. This work was carried out at the TEM in PFNC in CEA. The installation of two new state of the art TEM's both at Institut Néel and at the PFNC will certainly boost this activity and will allow obtaining even better-quality electrical field maps on semiconducting samples, further improving signal to noise as well as spatial resolution.

Figure 1

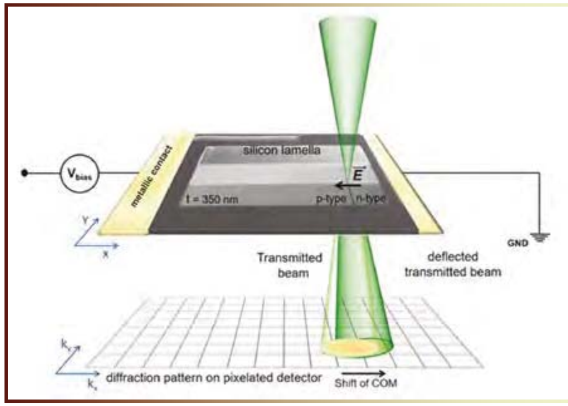
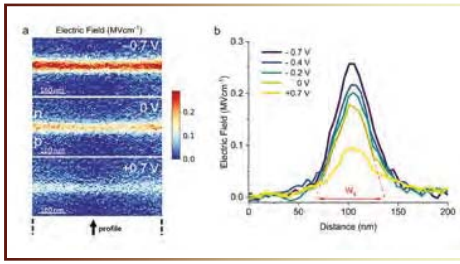


Figure 2



Captions

Figure 1: Concept of a 4D-STEM experiment performed in a silicon p-n junction with electrical contacts.

Figure 2: (a) In situ biased 4D-STEM electric field maps of the silicon p-n junction for different applied bias voltage. (b) Profiles of the electric field obtained from (a) by integration along the entire map length, as indicated in (a). The measured depletion length for zero bias is indicated by W_d.

FURTHER READING

Assessment of Active Dopants and p–n Junction Abruptness Using In Situ Biased 4D-STEM
B.C. da Silva, Z.S. Momtaz, E. Monroy, H. Okuno, J.L Rouvière, D. Cooper & M.I. den Hertog
Nano Letters 22,23, 9544–9550 (2022) - https://dx.doi.org/10.1021/acs.nanolett.2c03684

The influence of illumination conditions in the measurement of built-in electric field at p–n junctions by 4D-STEM
B.C. da Silva, Z.S. Momtaz, L. Bruas, J.L Rouvière, H. Okuno, D. Cooper & M.I. den Hertog
Applied Physics Letters 121, 123503 (2022) - https://dx.doi.org/10.1063/5.0104861

Martien den Hertog , *martien.den-hertog@neel.cnrs.fr*
Jean Luc Rouviere (IRIG), *jean-luc.rouviere@cea.fr*
David Cooper (LETI), *david.cooper@cea.fr*

Post-Doc
Bruno Cesar da Silva