Dopant profiling in semiconductor nanowires by Atom Probe Tomography

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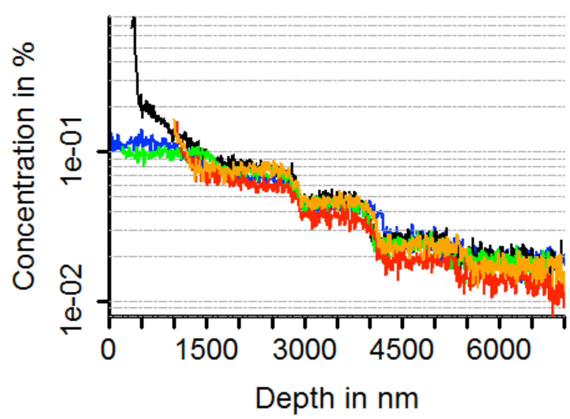
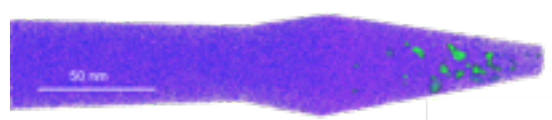
The controlled incorporation of doping atoms is essential for nearly all semiconductor devices. Devices such as transistors, light-emitting diodes, solar cells etc. are all impossible without the application of doping atoms that locally control the Fermi-level and the internal potential landscape. In such devices precise control over 3D distribution of the various doping species is thus critical for their functionality. Nanowires comprise a relatively new class of highly interesting 3D semiconductor nanostructures in which doping also plays a crucial role. For their application in devices such as solar cells and light emitting diodes it is also crucial to control the doping profiles in them. Due to their small size and special geometry it is very difficult to determine doping profiles in a straightforward manner. Cross-sectional STM, which has an unprecedented capacity to determine the distribution and properties of doping atoms in epitaxially grown semiconductors is unfortunately not yet readily applicable for the study of doping atoms in nanowires. More standardized techniques such as SIMS and EDX are also not applicable for a study of doping profiles in semiconductor nanowires.





b)

Figure 1. a) Si-doping profiles observed by Atom Probe Tomography in InP nanowires. b) Si doping clusters as indicated by the green iso-surfaces observed in a strongly doped InP nanowire.

At present the best and probably only technique that allows addressing this problem is Atom Probe Tomography. We have developed an improved approach [1] in which we have been able to measure doping concentrations with Atom Probe Tomography down the ppm-level or a doping level slightly below 10^{17} atoms/cm^3. We have used this approach to examine Si (n-type) and Zn (p-type) doped InP nanowires and have been able to extract the doping profiles and check the dopant incorporation efficiency, see Figure 1a. Measurements like these allow to determine the doping efficiency. We noticed that this can vary from nanowire to nanowire and that at high doping concentrations the growth of the nanowire can become unstable. Under these conditions a strong local variation of the doping concentration can occur resulting in dopant clusters, see Figure 1b. Finally we have used the Atom Probe Tomography technique to analyze details in the doping profiles that allow us to retrieve important details in the incorporation process of doping atoms in nanowires. Figure 2 shows an example of a Si doping profile along the growth axis of the nanowire. The length and the height of both doping segments was supposed to be equal but as shown strong deviations can occur. Finally we have used Atom Probe Tomography to determine the background impurity level in core/shell GaP/Si nanowires.

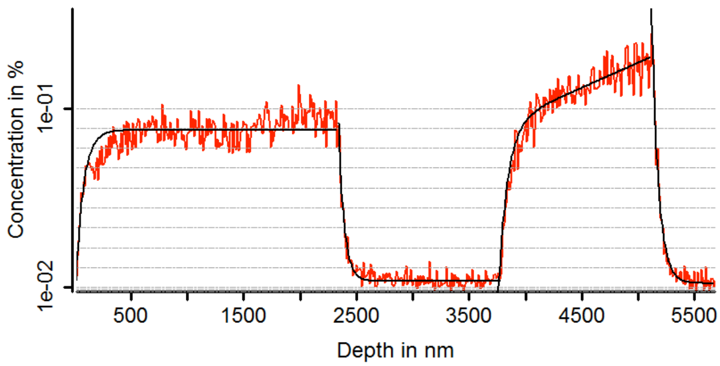


Figure 2. Si-doping profile in an InP nanowire as obtained by Atom Probe Tomography. Muraki-type fits where used to describe the quality of the doping interfaces.

References:

[1] S. Koelling, A. Li, A. Cavalli, S. Assali, D. Car, S. Gazibegovic, E.P.A.M. Bakkers and P.M. Koenraad, "Atom-by-Atom Analysis of Semiconductor Nanowires with Parts Per Million Sensitivity" Nano Letters DOI: 10.1021/acs.nanolett.6b03109.

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