Nanowires: A Cathodoluminescence Study

III-V Semiconductor Nanowires at Low-Temperature

As features of modern electronics shrink, the demands of the spatial resolution of the characterization techniques increase. One family of potential building blocks for future devices is nanowires. We show how low-temperature cathodoluminescence can be used to study variations in the emission from two types of nanowires: Nanowires with a GaInAs segment in an otherwise GaAs core and radial InAs quantum wells on an InP core.

Introduction

Semiconductor Nanowires (NWs) have been predicted to be used in future optical and electrical devices. The NWs typical have diameters of 10-100 nm and lengths ranging from 1-20 µm. Despite a large lattice mismatch, the small diameter means that materials can be combined that are not possible in bulk. To optimize the performance of potential devices, it is important to study the optical properties of the NWs. The approach we have used here is to study the optical properties of GaAs- and InP-based NWs using low-temperature cathodoluminescence (CL) with a spatial resolution better than 100 nm. A paradox of this technique is that the higher the material quality, the lower the spatial resolution. The spatial resolution comes from local excitation and global detection. A high material quality usually leads to a longer diffusion length, which in turn leads to lower resolution in the images.

Single-size diameter of the gold particles in the range 30 to 80 nm were used to seed the NWs [1]. Two types of structures are presented here: 1) GaAs-based structures, where the core is GaAs, including a short segment of GaInAs. The NWs were capped with a thin (10-40nm) shell of AlGaAs to passivate the surface. 2) InP-based structures covered by a sequence of radial layers: A thick InP layer, a thin InAs layer and a second thick InP layer. The InAs layer serves as a radial quantum well (RQW). The crystal structure of the InP core can be controlled by introducing dopants during growth [2]. The core can therefore either be pure zincblende (ZB), pure wurtzite (WZ) or a mixture of both. By interrupting the dopants during the core growth, it is possible to vary the crystal structure in segments.
It is therefore possible to create a core with a controlled superlattice of segments of, for instance pure WZ and a mixed WZ/ZB structure. We have used typical segment lengths of about 200 nm.

The CL studies were performed in a scanning electron microscope (SEM) with a liquid He cryostage. The emission was dispersed through a monochromator and detected by a photomultiplier tube. Monochromatic CL and SEM images were recorded simultaneously. The NWs were studied either as grown in side view by cleaving the substrate and mounting the sample with the fresh cleave facing upwards, or by breaking off the NWs and transferring them to a non-emitting Si substrate. The former gives access to the entire length of thousands of NWs. However, the emission from substrate can interfere with that from the NWs as a fraction of the electrons can be scattered to the substrate and result in secondary emission unrelated to the nanowires. The transfer to a different substrate can be used to isolate single NWs. All CL images are monochromatic and were recorded at 7-8 K. They are presented with the contrast expanded where black means no emission and the brightest color represents the highest intensity in the individual images.

**Results and Discussion**

NWs with an axial GaInAs segment in an otherwise GaAs core can be used to study diffusion along the core of the NW. Figure 2 shows an SEM image of a typical single NW together with three monochromatic CL images. 2e shows the emission from the core and 2d the emission from the segment. The segment emission shows a decrease in intensity towards the top and the core emission shows a similar increase towards the top. This is caused by diffusion from the GaAs core to the segment. From images like this one, the diffusion length of electron-hole pairs can be determined. Uncapped GaAs NWs show a diffusion length of about 100 nm. When capped by an AlGaAs shell, the diffusion length is improved to about 1 μm as
a consequence of reducing the influence of non-radiative recombination of the GaAs surface [3]. The abrupt transition below the segment in figure 2d has a different origin. As the GaInAs segment is grown, a thin layer grows radially, forming a RQW. This RQW is closer to the GaAs core than the segment, and the RQW will capture the carriers from the core before they can reach the segment, leading to a short diffusion length along the core. Here, the capture can be evidenced by the emission from the RQW, as illustrated in figure 2c. The emission energy of the segment is higher than that of the RQW, so the In content is higher in the RQW than that in the segment, giving some indications of the differences between the In incorporation during the axial and radial growth [4].

Figure 3 shows a NW with an InAs RQW grown on a pure WZ InP core, whereas the RQW in figure 4 was grown on a core with a regular superlattice of WZ/ZB structure [5]. The growth of a pure WZ core results in a core with smooth side facets, whereas the side facets on the ZB core are more irregular. The RQW on the pure WZ core is well defined and shows thickness fluctuations differing by a single InAs layer (monolayer) in thickness, leading to a local change in the emission intensity, as shown in figure 3c and d. The two images show complementary contrasts, which can be interpreted in terms of a map of different thicknesses of the RQW. In contrast, the RQW on the WZ/ZB core shows a stripy emission pattern, where the bright areas correspond to the flat QW on the six WZ segments in figure 4c. The RQW thickness on the ZB segments is severely distorted with island formation, in a Stranski-Krastanow growth mode. This leads to the formation of quantum dots (QDs), emitting at a lower energy, as these are thicker, less confined in the radial direction. The emission from these QDs shows up in the dark segments in figure 4c and the bright segments in 4d.

In addition, figure 1 shows a combination of monochromatic images (color coded) of the QW emission. The differently colored segments correspond to different thicknesses.

**Summary**

Cathodoluminescence is a very useful tool to study the optical properties of semiconductor nanowires on a submicron scale. We have demonstrated that it is possible to study thickness variations on the scale of atomic layers and on a length scale of better than 100 nm. Using axial variations in the composition, it is possible to study diffusion of carriers.

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Authors
Prof. Anders Gustafsson (corresponding author via e-mail request)
David Lindgren
Lund University
Solid State Physics
Lund, Sweden
www.nano.lth.se/anders.gustafsson

Contact

Lund University - Department of Food Technology
PO-Box 118
22100 Lund
Sweden