Lund University 2015-12-14

Fabrication of band-engineered diodes using compositionally graded $InAs_{1-x}P_x$ heterostructured nanowires

Physics of Low-Dimensional Structures and Quantum Devices

Albin Linder
Daniel Svedbrand
Edvin Winqvist

Supervisor: Ali Nowzari

Introduction

The goal of this project was to fabricate diodes using nanowires with changing material composition instead of using conventional p-n junctions. The doping methods used to create p-n junctions become less desirable at smaller scales due to lack of adequate control over the process. Therefore there is an ambition toward research on alternative methods that can replace p-n junctions in switching devices such as MOSFETs.

The nanowires used for this project are made of InAs where a part of the wire has a gradually increasing concentration of phosphorous. The diodes were fabricated by placing nanowires on a substrate and electrically connecting them by depositing metal electrodes. The IV characteristics were then obtained by measurements using a precision probe station.

Theory

Diodes are conventionally fabricated using a p-n junction. By gradually changing the composition along the axis of a nanowire to materials with a higher band gap, a similarly structured band diagram as in a p-n junction can be obtained. This idea can be implemented in an InAs nanowire considering the fact that InAsP has a higher bandgap than InAs, therefore by introducing phosphorous (P) along the wire during growth, a nanowire structured as in Fig. 1a) can be obtained, resulting in a bandgap as depicted in Fig. 1c). Due to limitations in control over the precursors during growth, it can be difficult to get a linear concentration increase and a simple approach to circumvent this complication is to increase the concentration in small increments, resulting in a sawtooth-shaped band structure, see Fig. 1b) with resulting band structure 1d).

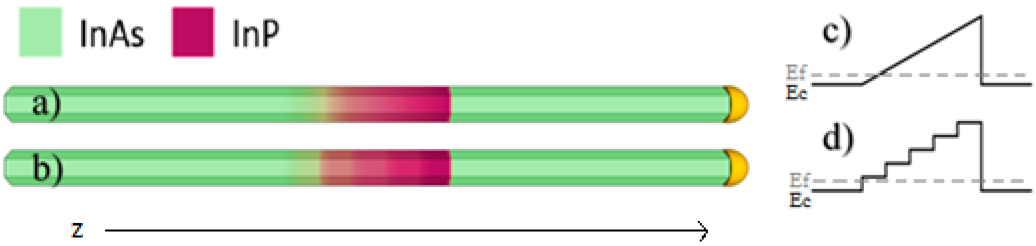

Figure 1: a) Ideal case of a nanowire with linearly increasing P concentration, b) nanowire with discrete increments of P concentration, c) conduction band structure of the nanowire shown in a), d) conduction band structure of the nanowire shown in b).

Although the nanowires were not intentionally doped, InAs leads are degenerately n-type due to unintended carbon impurity incorporation during growth acting as donors and charge accumulation due to Fermi level pinning at the surface of InAs. The Fermi level in InAs has been reported to be pinned 0.1 eV above the conduction band minimum.[1] The Fermi level pinning facilitates the formation of ohmic contact in n-type InAs.

The nanowires were fabricated with the intention of having five segments of 30 nm each with a gradually changing composition from $InAs_{0.5}P_{0.5}$ to $InAs_{0.3}P_{0.7}$. In the last segment, the bandgap difference with InAs is estimated to be 0.69 eV, of which 0.46 eV is the conduction band offset.[2] Considering that the Fermi level is pinned 0.1 eV above the conduction band, the diode barrier height is subsequently estimated to be 0.36 eV.

At forward biases smaller than the barrier height, electrons are injected across the barrier by thermionic emission only, see Fig. 2a). At forward biases larger than the barrier height, the barrier is effectively eliminated resulting in a large drift current, as in Fig. 2b). At reverse bias electrons may only travel from right to left as depicted in Fig. 2c) by thermionic emission, or by tunneling through the barrier, resulting in a very small reverse current. The same behavior is expected from the engineered sawtooth-shaped bands.

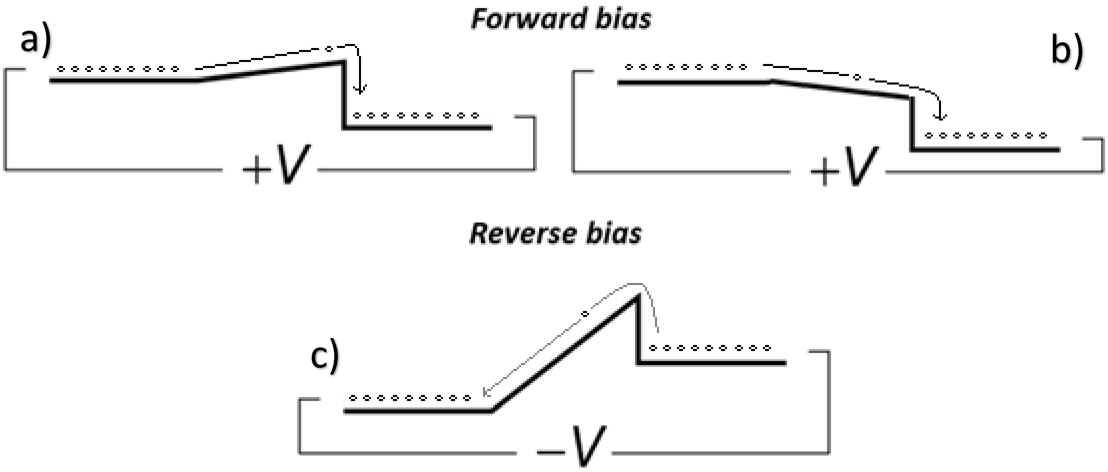

Figure 2: Currents through the diode under different bias conditions. a) a small forward bias allows a small current by thermionic emission, b) a larger forward bias will cause a large drift current as the barrier is no longer in effect, c) only a very small current from thermionic emission or tunneling through the barrier can occur at reverse bias.

The rectification ratio of a device is given by the ratio between the current generated at a certain forward bias and the corresponding current at the reverse bias of the same magnitude. The rectification ratio is a figure of merit of diodes, showing how effective a diode rectifies.

Method

The nanowires were grown prior to the start of the project using an MOCVD machine. The $InAs_{1-x}P_x$ composition change was done in five steps, changing the P concentration between 50 and 70 percent. A substrate with 24 metal pad pairs was also prepared before the project for electrically contacting the nanowires. Fig. 3a) is a schematic of how the growth of the segments has been done in steps by changing the phosphorous content of the precursors released into the chamber. Fig. 3b) is an SEM image of the nanowires grown on an InAs substrate.

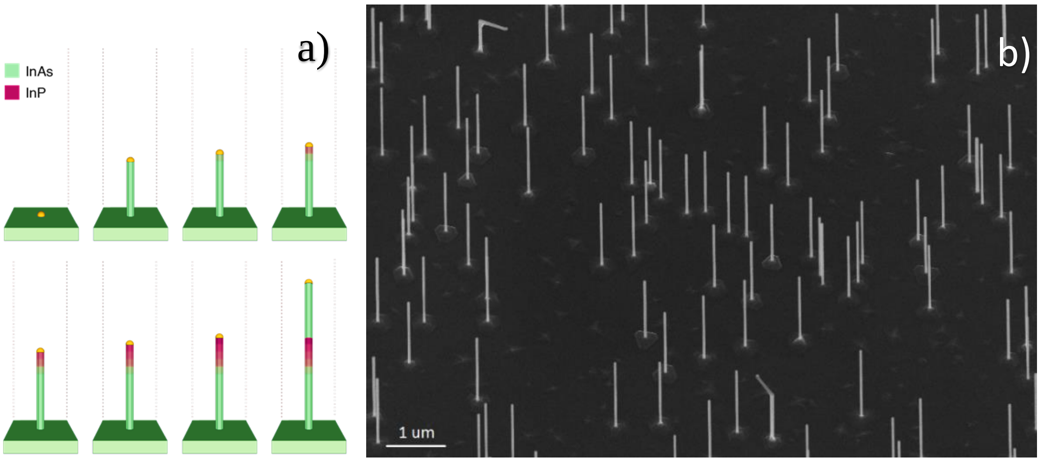

Figure 3: a) Step-wise growth process of the nanowires, b) SEM image of nanowires after growth.

The substrate with the metal contacts was cleaned in acetone and Isopropyl Alcohol (IPA) using an ultrasonic bath. The nanowires were broken off the wafer and then transferred to a silicon substrate coated with SiO_2 containing the metal pads for contacting. SEM images of the nanowires in between the 24 metal pad pairs were taken. The images were then used to map out contacts between each pair of metal pads and also selecting defect free nanowires using an image processing code developed in MATLAB. A PMMA A5 resist was spun on the substrate at 5000 rpm for 60 seconds, followed by baking the substrate at 180°C for 5 minutes. This will coat the substrate with a resist layer of approximately 290 nm in thickness. The files created by the software were then used in an EBL process where a pattern for the contacts were burned into the resist.

The sample was rinsed in a buffered oxide etch (1:10) solution for 1 minute to remove native oxides, and then quickly placed in a metal evaporator. A 25 nm layer of Ni and a 75 nm layer of Au were evaporated onto the sample. It was then placed in acetone for several hours for the resist to be dissolved and the lift-off process to happen. Finally, the sample was rinsed in IPA to remove acetone residues after the lift-off. Fig. 4 is a schematic of the fabricated diode under the measurement setup.

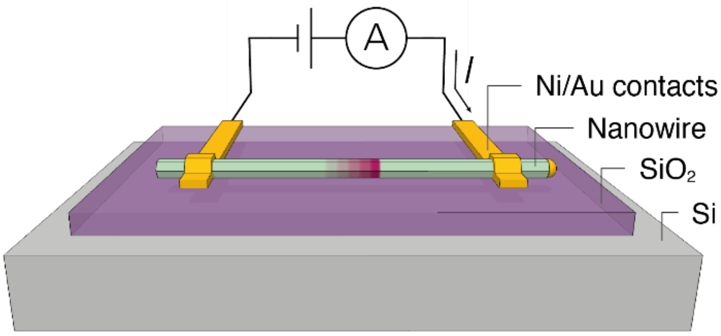

Figure 4: Schematic of a nanowire with attached contacts after all the processing steps.

Results and discussion

After the processing was complete, optical microscope images were taken of the sample and can be compared to images of an unused substrate, as seen in Fig. 5.

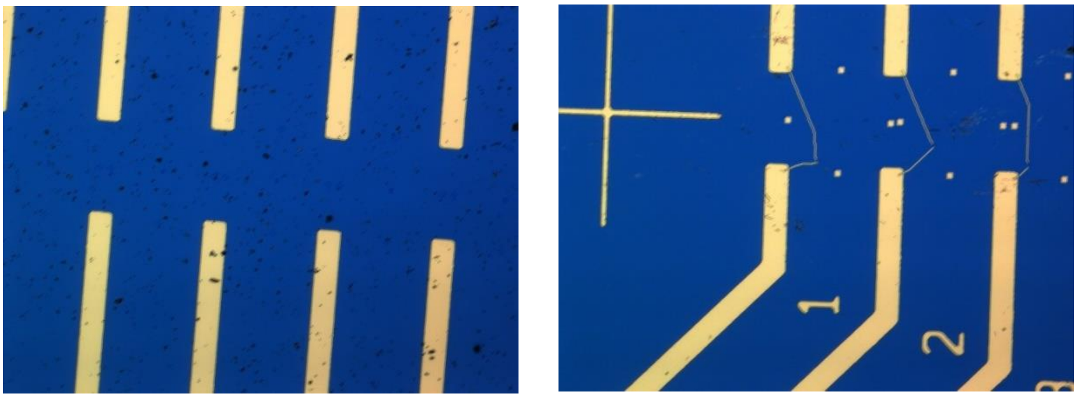

Figure 5: Optical microscope images of the substrate (a) before and (b) after processing.

Out of the 24 connected nanowires only the first one measured showed a diode-like IV curve, see Fig. 6. The other 23 measurements resulted only in noise as if no nanowire was correctly connected.

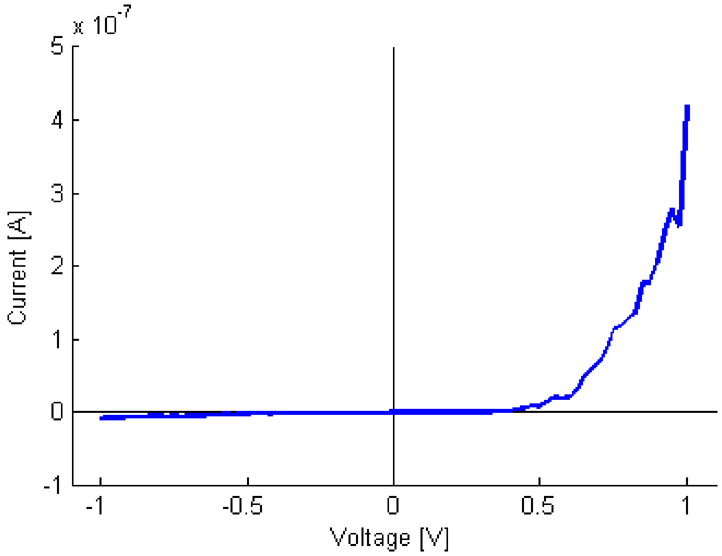

Figure 6: IV characteristics for the functional nanowire.

As seen in Fig. 6 the IV characteristics shows diodic behavior with a threshold voltage of about 0.4 V. This value closely corresponds to the theoretical barrier height of 0.36 V. The diode has a rectification ratio of 55 implicating that the device is clearly a diode. The reverse current is expected to decrease if a surface passivation procedure is included in the processing, which would subsequently increase the rectification. It is also possible that the segments of increasing phosphorous concentration are thinner than expected, which would result in a thinner potential barrier and during reverse bias increase the tunnelling current and reduce the rectification.

The reason that rectification was seen only from one nanowire was due to the fact that the other nanowires were not contacted correctly at the expected positions, due to a software bug that happened after the software crashed while designing the EBL patterns. SEM imaging of the substrate confirmed this by showing that the rest 23 pads were not connected to any nanowire at all. Only the first contact was in the right place, shown in Fig. 7.

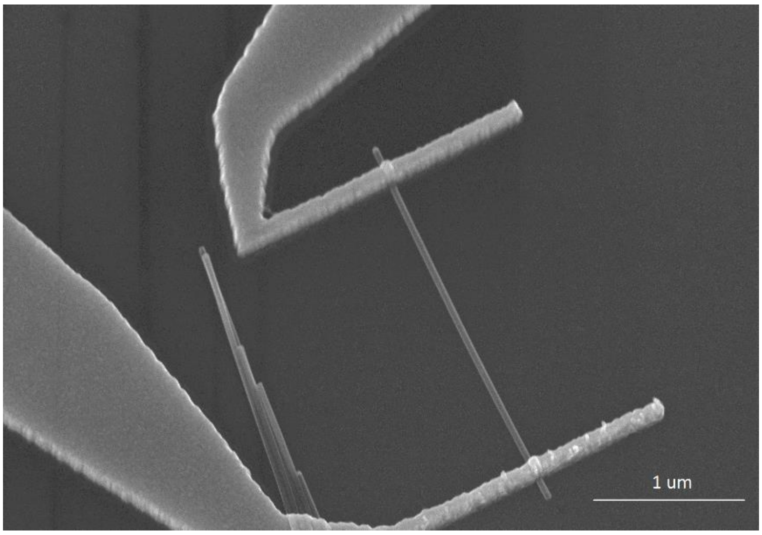

Figure 7: SEM image of the functional nanowire.

Fig. 7 shows that the contact placement on the nanowire is positioned precisely as defined in the MATLAB program. Since only one nanowire was connected, it is hard to statistically talk about the nanowires, but as a proof of concept, it can be claimed that a device was fabricated and measured that works as expected.

Only one nanowire worked, but it shows that it is possible to create band engineered nanowire diodes that mimic the band structure and properties of a p-n junction diode using the MOCVD method utilized in this work. In addition the concept of band engineering can be applied to design a range of other non-switching electronic and optoelectronic devices.[3]

References

[1] Persson, A. I., Björk, M. T., Jeppesen, S., Wagner, J. B., Wallenberg, L. R. & Samuelson, L. $InAs_{1-x}P_x$ *Nanowires for Device Engineering.* Nano Lett. 2006 Vol. 6, No 3 403-407

[2] Mead, C. & Spitzer, W. *Fermi level position at semiconductor surfaces.* Phys. Rev. Lett. 10, 10-11 (1963)

[3] Capasso, F. *Band-gap engineering: From physics and materials to new semiconductor devices.* Science 235.4785 (1987): 172-176