Electrical multi-probe studies on nanowires for solar energy conversion

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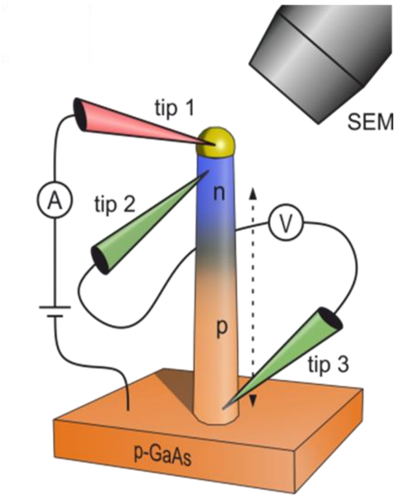
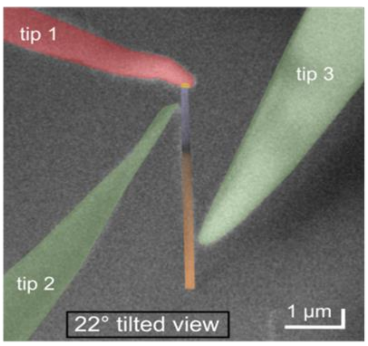
Abstract

For an improved understanding of the preparation of axial and radial III-V nanowire (NW) structures a suitable electrical NW analysis with highest spatial resolution is necessary. We thoroughly investigated the electrical properties of free-standing GaAs-NWs with axial pn-junction applying a 4-point-prober. This UHV-based multi-tip scanning tunneling microscope (MT-STM) is in vacuo combined with a state-of-the-art NW preparation. 2- and 4-point I-V characteristics of the diode are recorded non-destructively, enabling the calculation of the local ideality factor. 4-point-probe measurements at different NW positions result in an axial resistance profile, allowing the determination of the doping concentrations of p- and n-doped parts. Investigation of oxide-free NWs enables the determination of very low doping concentrations which would not be accessible for oxidized samples. At the pn-junction a ~500 nm narrow region of low conductance was detected, indicating a compensation effect of dopants during growth. By recording electron beam induced current (EBIC) images, the position of the charge separating contact has been identified.

Results

Catalysis-assisted vapor-liquid-solid growth mode offers the opportunities to prepare corresponding axial and radial III-V nanowire (NW) structures in a bottom-up approach, which combine promising photovoltaic performance and multiple scientific and economic benefits. For reasons of miniaturization and reduced material consumption as well as for improved performance, considerable research effort has already focused on the development of solar energy conversion devices based on NWs [1,2]. Nonetheless, precise and well-defined axial and/or radial doping profiles are essential, but the preparation and analysis of suitable doping profiles in NWs is still challenging. In order to improve the capability for accessing their properties, highly accurate characterization and preparation techniques are required to create and to resolve adequate spatially distributed doping concentrations at the nanoscale.



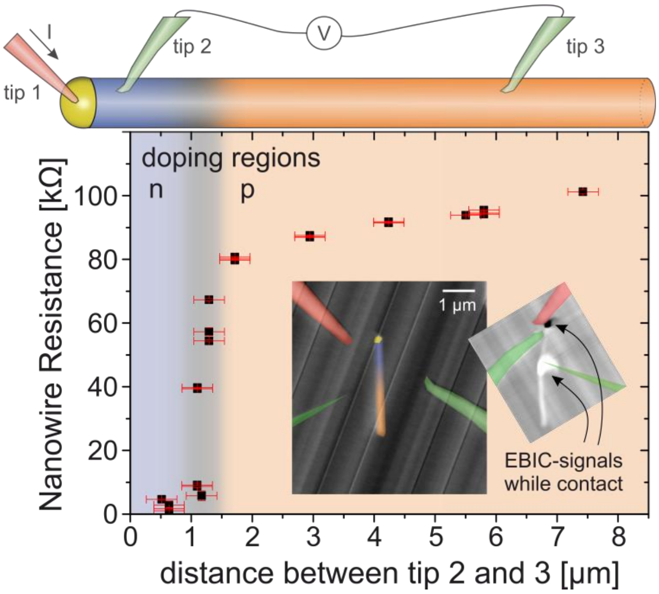


Transmission line measurements [3] are most frequently used to investigate the electrical properties of NWs [4,5]. Here, IV-curves between adjacent evaporated ohmic contacts are recorded. Substantial disadvantages of that approach include the tedious and difficult contact preparation, the detachment of the NWs from the growth substrate, missing information about the electrical connection to the substrate and the doping level at the base of the NWs, and specific care must be taken to preserve the doping profile or even the NW composition upon creation of the ohmic contacts [6]. The development of multi-probe techniques increased the spatial resolution, which allowed detailed electrical investigations on the nanoscale. Starting with electrical transport phenomena on planar samples [7], recently this technique was demonstrated also on NWs [8]. An integrated scanning electron microscope (SEM) is used to visualize the NWs as well as the prober (tungsten tips). Piezoelectric nanopositioner on each tip ensure a highly precise movement in order to contact a single free-standing NW. This setup enables 4-point-probe measurements on single upright NWs (Fig. 1). For that, GaAs NWs with various doping profiles and axial pn-junctions were grown by metal-organic vapor phase epitaxy (MOVPE) via the vapor liquid solid (VLS) growth mode.

Fig. 1. Schematic procedure of MT-STM measurement. (top) Transferring the NW-sample to UHV environment in MT-STM, positioning the W-tips at one freestanding NW and applying 4-point probe measurements on NW. (bottom) False color SEM image of tip configuration in MT-STM (22° tilt view)

During growth of the NW-base, DEZn was offered for p-doping. Trimethylgallium (TMGa), tertiary butylarsine (TBAs), diethylzinc (DEZn) and tetraethyltin (TESn) were applied as liquid precursors, for Ga, As, Zn (p-dopant) and Sn (n-dopant) supply, respectively. By using gold particles with a diameter of around 100 nm, which were deposited on p-doped GaAs(111)B substrates before loading them to the MOVPE reactor, the NW diameter was defined. Subsequently, DEZn was switched off and TESn was offered for the n-doping of the NWs-top. After growth, the sample was transferred contamination-free to ultrahigh vacuum (UHV) [9] and in-vacuo to the purpose-built multi-tip scanning tunneling microscope (MT- STM) [10] in order to perform electrical measurements.

Fig. 2 displays the IV characteristic and resistance profiling along the axial pn-junction of GaAs nanowires. Applying a transport model [11,12] allows the determination of the doping profiles. The base of the NW exhibits a doping concentration of around 1.2 x 10^{19} cm^{-3}; a much lower doping of around 2 x 10^{17} cm^{-3} was extracted for the n-type segment. Oxidized NWs with the same diameter would be fully depleted, due to their surface states and a doping level extraction would be impossible. Visualization of the contacted NW in "sample current" mode enables access to EBIC signals (inset Fig. 2). At the pn-junction, a strong signal is visible confirming the charge carrier separation at the junction.



In summary, we successfully studied UHV-transferred, as-grown free-standing GaAs-nanowires with axial pn-junction by MT-STM. While 2-point I-V characteristics show a diode behavior, 4-point probe measurements of pn-junctions exhibit more detailed insights. Based on the resistance profiles of single NWs the doping concentration of p- and n-doped segments is extracted. In between, a region of low conductivity was measured, suggesting the compensation of dopants during NW-growth. The utilization of our MT-STM and the precise determination of doping profiles along nanostructures are essential to improve the preparation and the development of NW device structures for efficient solar energy conversion.

Fig. 2. Non-destructive, 4-point-probe resistance profile of an axial p-i-n-junction in a freestanding nanowire. The schematic measurement setup on top of the figure shows the positioning of the tips on the NW. Tip 3 is stepwise moved along the NW while measuring the potential difference to tip 2. By dividing the potential difference with the current through the NW (measured by tip 1) the resistance is calculated. Between the n- and p-doped regions an increased resistance is measured, which we explain by the compensation of dopants during growth.

The insets show sample current images before and during contact. Electron-beam induced current signals appear if one tip is in contact with a NW, confirming the charge carrier separation at the pn-junction.

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