In situ electron microscopy correlating site-specific mechanical, electrical and optical properties of nanowires

Lunjie Zeng[1], Jonatan Holmér[1], Rohan Dhall[2], Christoph Gammer[3], Andrew M. Minor[2,4], Wolfgang Jäger[1,5], and Eva Olsson[1]

1 Department of Physics, Chalmers University of Technology, 412 96 Gothenburg, Sweden

2 National Center for Electron Microscopy, Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States

3 Erich Schmid Institute of Materials Science, Austrian Academy of Sciences, 8700 Leoben, Austria

4 Department of Materials Science and Engineering, University of California, Berkeley, California 94720, United States

5 Institute for Materials Science, Christian-Albrechts-University Kiel, 24143 Kiel, Germany

Corresponding authors: lunjie@chalmers.se, eva.olsson@chalmers.se

Nanostructures often possess unique mechanical, electrical and optical properties, showing promise as building blocks in devices such as nanoscale sensors, transistors and solar cells. The understanding of the structure-property relation of individual nanostructures is of critical importance for the further development of these devices. In situ electron microscopy is well suited for studying the direct correlation between microscopic structure and properties of nanoscale objects, thanks to the advances in electron optics, detector technologies, as well as in situ sample holder design. Especially, in situ electron microscopy enables correlative measurements on crystal and electronic structure, mechanical behavior, electrical transport and photoresponse on the same nanostructure. Here, we show that such correlative measurements are powerful for the understanding the properties of individual semiconductor nanowires [1–5].

In InAs nanowires, a direct correlation between mechanical and charge transport properties has been unveiled by in situ transmission electron microscopy (TEM) [1]. Uniaxial tensile stress was applied on the individual nanowires through a push-to-pull mechanism (Figure 1). Meanwhile, strain mapping was performed by using scanning TEM – Nanobeam electron diffraction (STEM-NBED or 4D STEM). The electrical measurements were carried out on the nanowires under stress. The quantitative stress, strain and charge transport measurements reveal a significant reduction of resistivity in the nanowires due to stress and strain, resulting in an enhanced piezoresistive response of the nanowires compared to bulk InAs. A strong nanoscale inhomogeneity in strain distribution is observed. It is believed to have a reverse effect on the conductivity by increasing the scattering of charge carriers.

In GaAs nanowires, a direct experimental evidence of uniaxial strain-induced modifications of hole mobility has been found, using in situ TEM [2]. The conductivity of the nanowires varied with applied uniaxial tensile stress, showing an initial decrease of ~5-20% up to a stress of 1~ 2 GPa, subsequently increasing up to the elastic limit of the nanowires. This anomalous change in conductivity is attributed to a hole mobility variation due to changes in the valence band structure caused by stress and strain. The corresponding lattice strain in the nanowires was quantified by in situ 4D STEM and showed a complex spatial distribution at all stress levels. Meanwhile, a significant red shift of the band gap induced by the stress and strain was unveiled by monochromated electron energy loss spectroscopy (EELS). The effect of bending deformation on charge transport in individual GaAs nanowires has also been studied [3]. The current-voltage (I-V) characteristics of the nanowires change from linear to nonlinear as bending deformation is applied. The nonlinearity increases with strain. The response of I-V characteristics to bending deformation can be explained by strain induced valence band shift, which results in an energy barrier for charge carrier transport along the nanowire.

The photovoltaic property of individual GaAs nanowires with build-in p-i-n junction has been investigated using a in situ scanning tunneling microscope – scanning electron microscope (STM-SEM) setup [4,5]. Photocurrent and electron beam induced current (EBIC) in the nanowires were used to characterize the performance of the individual nanoscale solar cells. The STM-SEM setup also enables the mechanical manipulation of the nanowires. It is found that tensile strain modifies light absorption in the nanowires through band gap engineering, whereas the strain does not significantly affect charge generation and separation processes.

These in situ electron microscopy measurements enable an improved understanding of the intriguing interplay between atomic structure, electronic structure, charge transport and photocurrent in individual free-standing nanostructures. The results provide information for a basic understanding of the properties of these nanostructures and for tailoring device performances. The techniques used in the studies can also be applied to study other nanostructures.

References:

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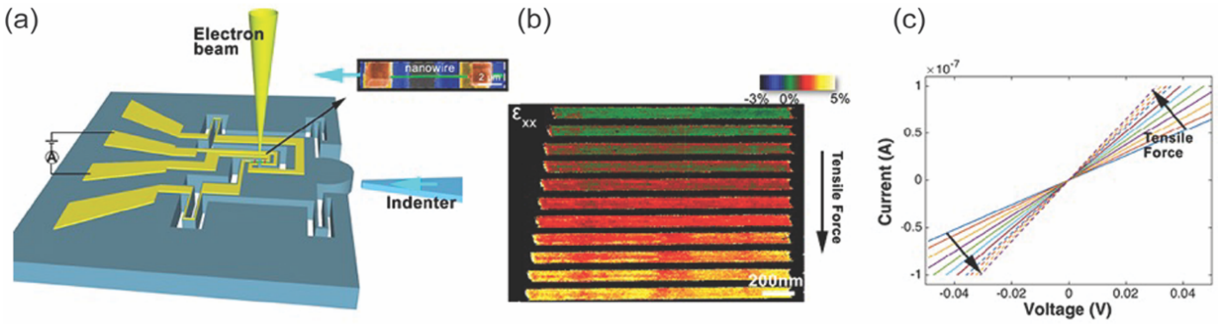

Figure 1. An example of the in situ TEM measurements on individual nanowires: (a) A schematic of an experimental setup used for the study. Tensile stress can be applied on a nanowire. Meanwhile, TEM, mechanical and electrical measurements are performed on the nanowire. (b) 4D STEM strain maps of the nanowire as a function of applied stress. (c) Changes in I-V characteristics of the nanowire due to applied stress.