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## Report:

The goal of this experiment was the study of the non-linear piezoelectric (flexoelectric) properties of GaN nanowires by *in situ* three-points bending using the *in situ* AFM "SFINX" in combination with simultaneous electrical measurements and µLaue diffraction.

Gallium nitride nanowires with a diameter of few hundred nanometers and lengths of several tens of micrometers were grown by MOVPE. These wires were placed across holes which were prepared by electron beam lithography in a $SiO_2$ layer forming self-suspended nano-bridges. For the *in situ* flexoelectric studies the wires were contacted electrically by electron beam lithography (see Fig. 1(a)). However, during transportation and handling of the sample part of the electrical connections were lost. Thus, *in situ* three-points bending tests on non-contacted self-suspended GaN nanowires were performed as well as on Au nanowires grown by physcial vapor deposition placed across Si micro-trenches.

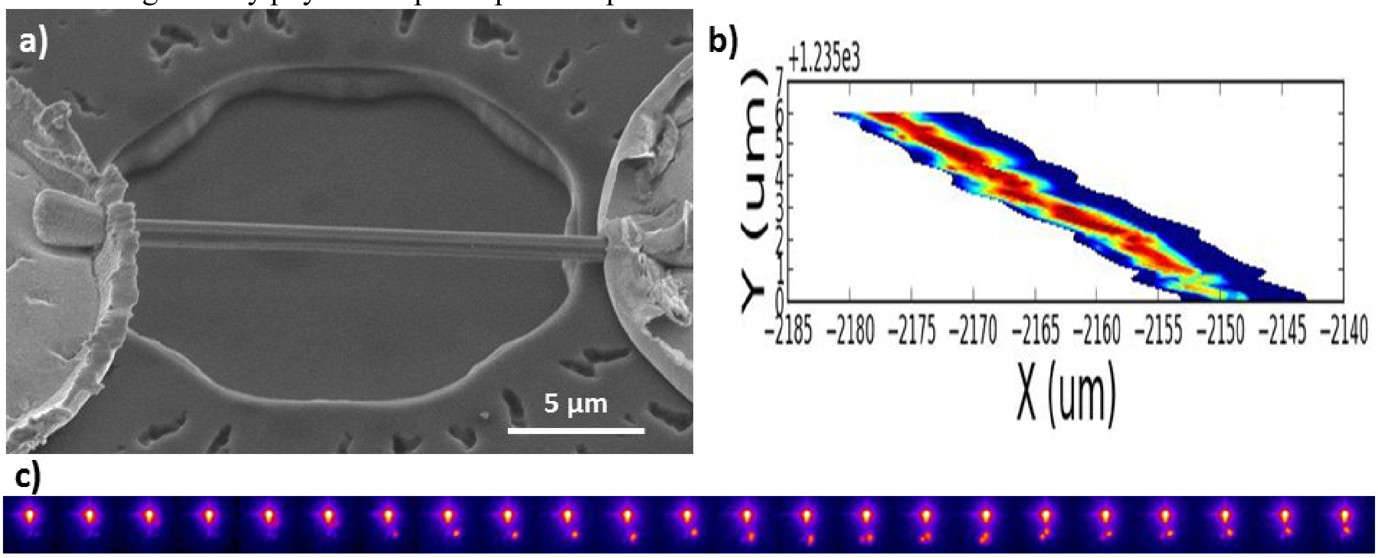


**Fig. 1: a) SEM image of an electrical contacted self-suspoended GaN nanowire. b) Ga-K fluroescence for a GaN Nanowire recorded by the newly developed KB scanning method. c) Seuqence of Si(001) and GaN (111) µLaue spots recorded by the KB scan along a mechanically loaded GaN nanowire.**

### GaN nanowires

During the experiment 32-02-760 we have developed a new technique, the KB-scan, which allows for measuring the complete profile of a mechanically deformed nanowire *in situ* by tilting the KB stage, thus, scanning the X-ray beam along the wire. However, for strongly bent wires the deformed structure may get out

of the focused X-ray beam. Moreover, the beam focus deteriorates for larger tilting angles. We improved this scanning technique by moving the KB mirrors horizontally as well as vertically (instead of tilting the stage), hence, mapping a deformed structure in two dimensions. Figure 1(b) presents the Ga-K fluorescence map for a mechanically deformed Ga nanowire recorded by the new 2D KB mapping technique. Besides the fluorescence yield µLaue diffraction patterns were recorded simultaneously along the wire. The Si004 and GaN 111 Laue spots along the bent nanowire are displayed in Fig. 1(c). From the displacement of the Laue spots on the detector the deformation of the GaN nanowire was inferred. The bending angle along the nanowire is presented in Fig. 1(d). Due to the comparatively large diameter of the nanowire and the rigidity of GaN, the bending angle amouns to < 0.5°.

**Au nanowires**

While Au nanowires were elastically bent in former experiments, the plastic regime was reached in the present work. Several *in situ* loading-unlaoding cycles were performed where 2D KB scans were recorded measuring the complete nanowire profile under stress as well as after relaxation. This cycling allowed us to access the nucleation of the very first dislocations and, thus, to study the onset of plasticity. The bending angle all along the nanowire inferred from the *in situ* scans for the pristine wire, first loading and unloading as well as the second loading and unlaoding cycle is presented in Fig. 2(a) demonstrating a purely elastic behavior for the first loading and plasticity for the second loading (finite bending angle after retraction of AFM-tip). The µLaue diffraction pattern displayed in Fig. 2(b) shows splitted Laue spots evidencing dislocations stored in the wire after the second loading. The splitting angle indicates that of the order of 20 dislocations are stored in the wire. The activated slip system was determined by calculating the inverse pole figure presented in Fig. 2(c).

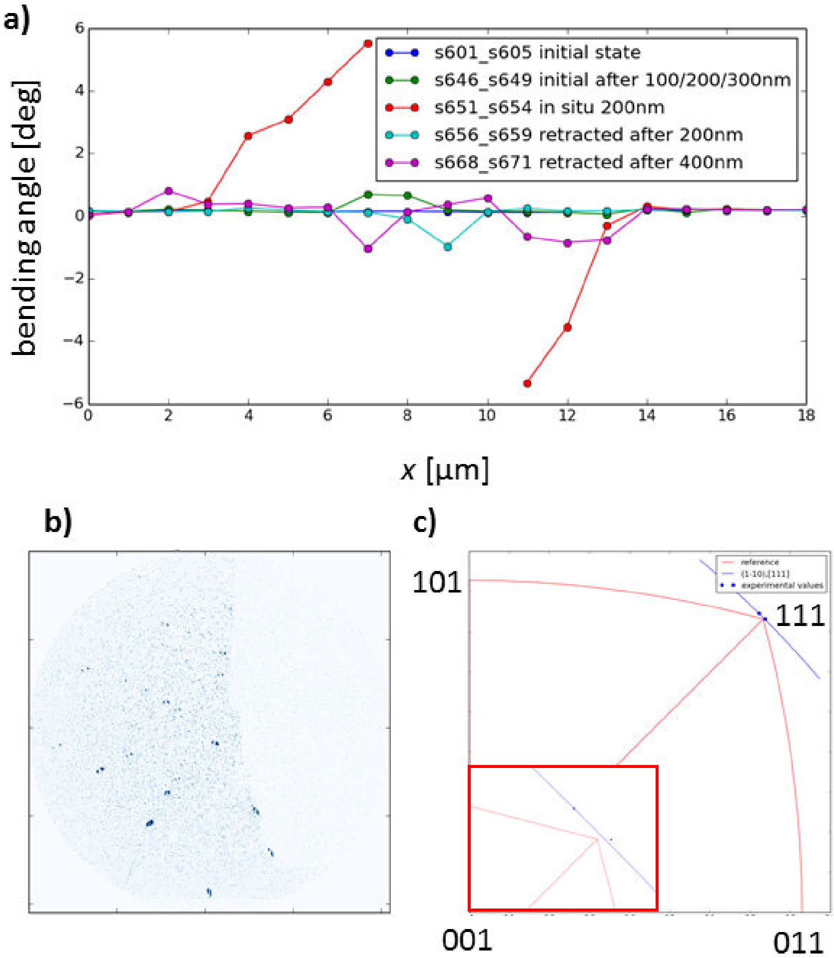


**Fig. 2: a) Bending angle along mechanically loaded Au nanowire inferred from *in situ* µLaue diffraction. b) µLaue diffraction pattern and c) corresponding inverted pole figure for a Au nanowire after onset of plasticity.**

Originally we intended to deform electrically contacted GaN nanowires studying their piezotronic properties. Although we could not perform the intended studies due to contacting issues, we were able to deform for the first time semiconducting nanowires, to develop a new *in situ* mapping technique by scanning the KB mirrors and, thus, the focused X-ray beam in two dimensions, and to study the onset of plasticity in single Au nanowires.

**Publication(s):**

**- Abstract accepted for an oral contribution at the ECI Nanomechanical Testing in Materials Research and Development conference, Albufeira (Portugal), Oct 2015, T.W. Cornelius, C. Leclere, Z. Ren, A. Davydok, O. Thomas, *In situ nano-mechanical tests in the light of µLaue diffraction***

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