euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025

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Nanomechanical and -electrical characterisation of vertical nanowires for energy harvesting at the nanoscale

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Abstract

Nanowire-based energy harvesting from renewable sources including mechanical motion offers a potential solution for generating small amounts of power in remote areas. Reliable quality control of semiconductor nanowires (NWs) with high aspect ratios and diameters down to sub-100 nm demands quantitative characterisation of the mechanical and electrical properties of these NWs. This manuscript presents quantitative characterization of vertically aligned nanowires, using a nanoindentation instrument with electrical contact resistance (ECR) measurement capability. Reliable measurement results are expected to advance semiconductor NW fabrication techniques and validate modeling approaches, contributing to progress in energy harvesting technologies.

Keywords: Nanometrology, nanoelectromechanical measurement, energy harvesting, piezoelectric nanowires

1. Introduction

Energy harvesting from renewable sources, such as solar energy, waste heat, and mechanical motion, has gained significant attention as a viable solution for generating small amounts of electrical energy in remote or hard-to-reach areas. These energy harvesting systems are critical for powering low-energy devices such as sensors, medical implants, and wireless communication modules in locations where traditional energy sources are impractical.

Among the various energy harvesting technologies, nanowire (NW)-based systems have emerged as promising candidates due to their unique properties and ability to function efficiently at the nanoscale [1]. NW-based systems include photovoltaic solar cells for converting sunlight into electricity, thermoelectric devices for generating energy from waste heat, and electromechanical energy nanogenerators that convert mechanical motion into electrical power. Over recent decades, these systems have demonstrated encouraging progress, showcasing their potential for practical applications in sustainable energy solutions.

However, the nanoscale dimensions of the wires incorporated into these systems present significant challenges, particularly in testing and characterization. Quantitative measuring the mechanical and electrical properties of nanowires is crucial for optimizing their performance in energy harvesting devices.

Several methodologies and instruments have been developed for the mechanical characterization of small material volumes, including vertically aligned nanowires. Among these, the nanoindentation technique stands out due to its high force and depth resolution, minimal sample preparation requirements, and increasing popularity over the past decades [2]. More recently, the integration of advanced electrical contact resistance (ECR) measurement capabilities [3] with nanoindentation instruments has led to the emergence of conductive nanoindentation. This advanced technique enables simultaneous nanoelectrical and nanomechanical characterization of small material volumes, further expanding its applicability and significance in material research [4].

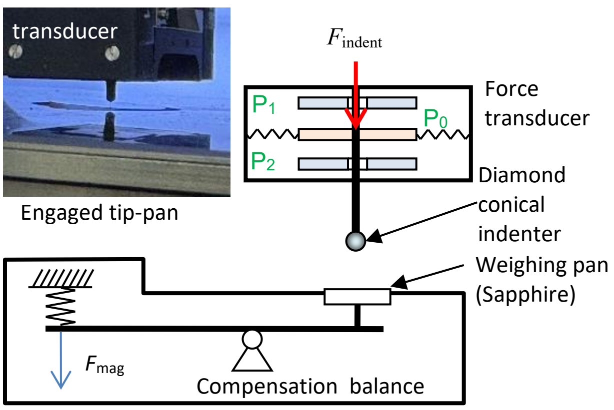
2. Quantantitive nanoelectromechanical measurements with conductive nanoindentation: Instrument characterisation

The nanoindentation instrument with nanoECR module (Hysitron TriboIndenter TI-950/980) used in this manuscript consists of

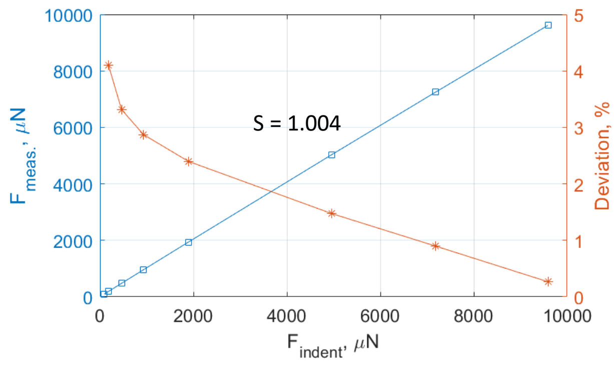
- a capacitive force transducer with an indentation force up to 10 mN,
- a conductive diamond (Berkovich) indenter, and
- a Keithley SourceMeter (2602B) with 4-wire mode for through-tip current measurements.

Quantitative nanomechanical and electrical measurements with this instrument require traceable calibration of all components involved. Among these, the traceable calibration of the force transducer is particularly critical [5].

As illustrated in Figure 1, a commercial precision compensation balance (YAD01IS, Sartorius AG) has been utilized for the in-situ calibration of the indentation force produced by the capacitive force transducer. The diamond conical indenter in use has a tip radius of 2 µm.



(a) Schematic of the in-situ indentation force calibration setup



(b) Preliminary force calibration result

Figure 1. Traceable calibration of the indentation force using a precision compensation balance.

Figure 1(b) illustrates the first calibration result cross the full force range of 10 mN. The data indicate that the nanoECR force transducer exhibits a relatively high degree of linearity.

3. Experimental results

The well calibrated conductive nanoindentation instrument has then been used to characterise the depth-dependent electrical conductive resistance of the highly doped bulk silicon sample (Si<100>, As-doped, doping concentration up to 8.2 x 10^{19}) prepared by the IHT, TU Braunschweig. Figure 2 shows the measured through-tip current (i_c) with respect to the indentation depth up to 100 nm. It can be seen that the measured i_c becomes clearly evident, when the indentation depth h ≥ 30 nm.

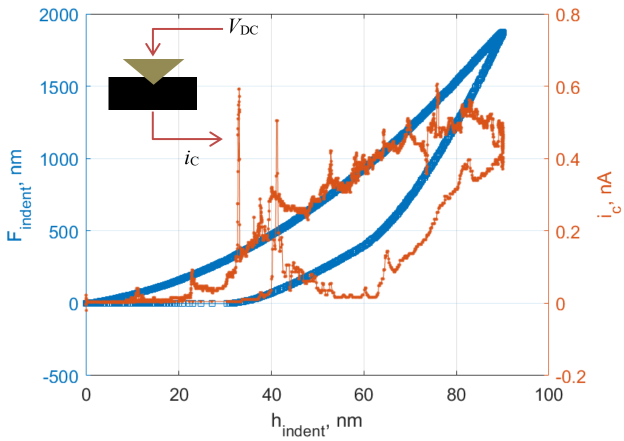
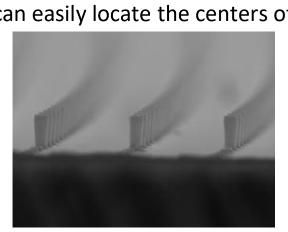
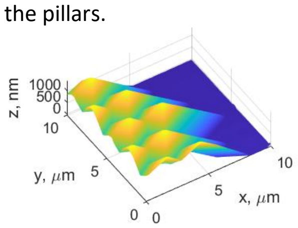


Figure 2. Simultaneous mechanical and electrical characterisation of highly doped Si <100> with an offset voltage V_{DC} of 1 V.

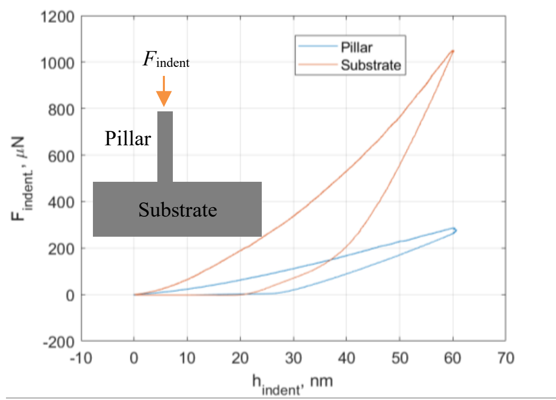
Owing to its in-situ topography scanning capability, the conductive nanoindentation instrument is also able to characterise vertically aligned nanowires. Figure 3(b) shows the topography of the nanopillars (Si<111>, $Ø_D$ = 500 nm, L = 1.3 µm) measured with a Berkovich indenter. From these images, one can easily locate the centers of the pillars.



(a) SEM image of the nano-pillars under measurement



(b) Pillar topography imaged by the nanoECR instrument



(c) Comparison between the indentation curves obtained on pillars and on substrate

Figure 3. Determination of the mechanical properties of nanopillars with the nanoindentation instrument.

Figure 3(c) shows typical indentation curves measured on the pillars' top surface and the silicon substrate. To extract the real mechanical properties of nanopillars, the body stiffness of nanopillars needs to be taken into consideration [6-7].

5. Summary and outlook

This manuscript presents our efforts in the quantitative nanoelectromechanical characterization of small volumes of semiconductor materials for energy harvesting, including vertically aligned nanowires, using a well-calibrated nanoindentation instrument with nano-ECR measurement functionality. The traceable and reliable measurement results of the nanowires are expected to significantly contribute to the advancement of semiconductor nanowire fabrication techniques and support the validation of various modeling approaches.

First experimental results have confirmed the capabilities of our measurement system. To ensure quantitative electrical measurements, the sensitivity and uncertainty of the ECR measurement module will be further characterized using an in-house-developed resistance array.

The traceable characterization of the mechanical and electrical properties of ZnO nanowires, fabricated at the IHT of TU Braunschweig [8,9], is further being planned.

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