Silicon Nanowire Based Solar Cells on Glass: Concepts and experimental processing

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We will introduce different aspects of research in our group on: 'Materials developments and thin film solar cell device concepts with nanowires'. Special emphasis will be pointed to:

- the achievements essentially in silicon nanowire (SiNW) growth using the vapor-liquid-solid growth mechanism with chemical vapor deposition (CVD) and physical vapor deposition (PVD) using electron beam evaporation (EBE) and pulsed laser deposition (PLD) techniques;
- the use of SiNWs in novel thin film solar cell concepts on glass;
- in the context of applications, the role of gold as the SiNW growth catalyst in comparison to alternative metal catalysts (e.g. Al, In) will be discussed.

For the different research projects we will show how nanomaterial optimization profits from the combination of various techniques as electron microscopy (EM) techniques [such as transmission EM down to atomic resolution and analytical EM (using electron energy loss spectroscopy (EELS) and EDX) as well as scanning EM (including electron back scatter diffraction (EBSD) and EDX) in combination with an ion beam in a dual beam focussed ion beam (FIB) machine], Raman spectroscopy, optical characterization and numerical finite element modelling.

Making use of silicon nanowires (SiNWs) in solar cells essentially requires their integration onto cheap glass substrates. This is realized by two approaches:

(1) bottom-up gold nanoparticle (colloids or droplets formed by annealing of thin gold layers) catalyzed by vapor-liquid-solid (VLS) growth of SiNWs from silane (SiH_4) by chemical vapor deposition (CVD) at borosilicate glass compatible temperatures (< 650°C).
(2) top-down etching of silicon thin films on glass (cf. Fig. 1 and Fig. 2) and further formation of SiNWs.

For approach 1): The SiNWs grow in different directions on the glass substrate favouring, but not exclusively, low index growth directions (preferably <111>, <110>, <112>) as determined by electron backscatter diffraction (EBSD) measurements in a scanning electron microscope (SEM). SiNW widths between 10nm and 250nm are realized based on the gold droplet diameters and optical characterization in an Ulbricht sphere of the NW material suggests that the absorption by the silicon is highest for the NW with large diameters.
Passivation of SiNW surfaces is successfully carried out by atomic layer deposition (ALD) of aluminium oxide (Al_2O_3). Passivation and transparent conductive oxide contact formation by ALD is tested with doped ZnO:Al layers.
Axial and radial NW doping strategies using co-doping during CVD, ion-implantation and thermal activation of dopants as well as dopant diffusion from highly doped spin-on-glass suspensions will be presented and I-V-measurements will be carried out for single NWs in a scanning electron microscope (SEM) and for NW ensembles in a probe station. First NW solar cell parameters of contacted NW ensembles such as open circuit voltage (V_{OC}), fill factor (FF), short circuit current (I_{SC}) and efficiency (η) will be presented.
Additionally, characterization of structural properties of these SiNWs is carried out using electron microscopy (EM) techniques, including transmission EM.

For approach 2) The SiNWs are formed *via* electrochemical etching of the thin silicon film layer stack (~1.5µm thick) on glass with the doping structure p^+nn^+. This layer is multicrystalline or microcrystalline and is deposited by electron beam evaporation (EBE) or PECVD. The etching is carried out by silver nitrate and hydrofluoric acid. Low reflectance (< 10%, at 300-800 nm) and a strong broadband optical absorption (~ 95 % at 500 nm) have been measured for the resulting material. The highest obtained open-circuit voltage (V_{OC}) and short-circuit current density (j_{SC}) under AM1.5 illumination was 450 mV and 40 mA/cm^2, respectively. The power conversion efficiency of the SiNW array solar cell on glass was obtained to be of the order of 5%.

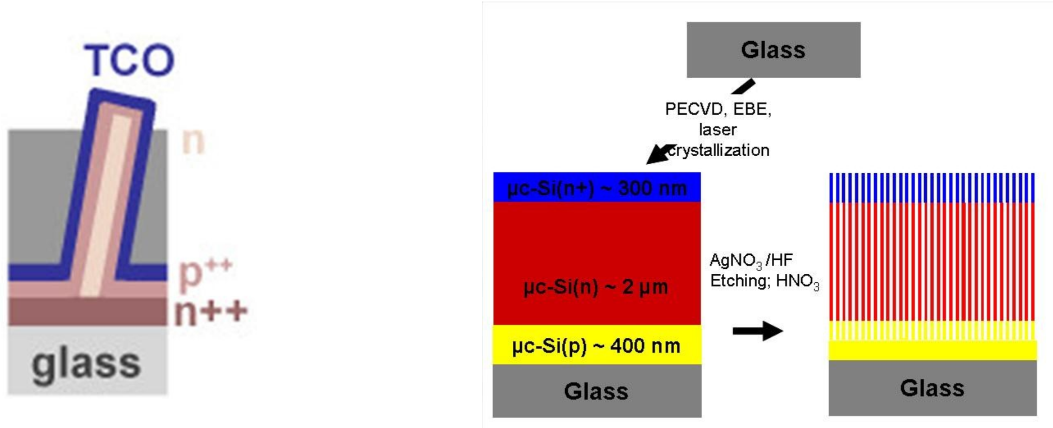

Figure 1. Schematic presentation of the formation procedure of SiNWs and their integration in a thin film solar cell concept: (left) bottom up by VLS growth; (right) top down by chemical etching of thin Si-layers on glass.

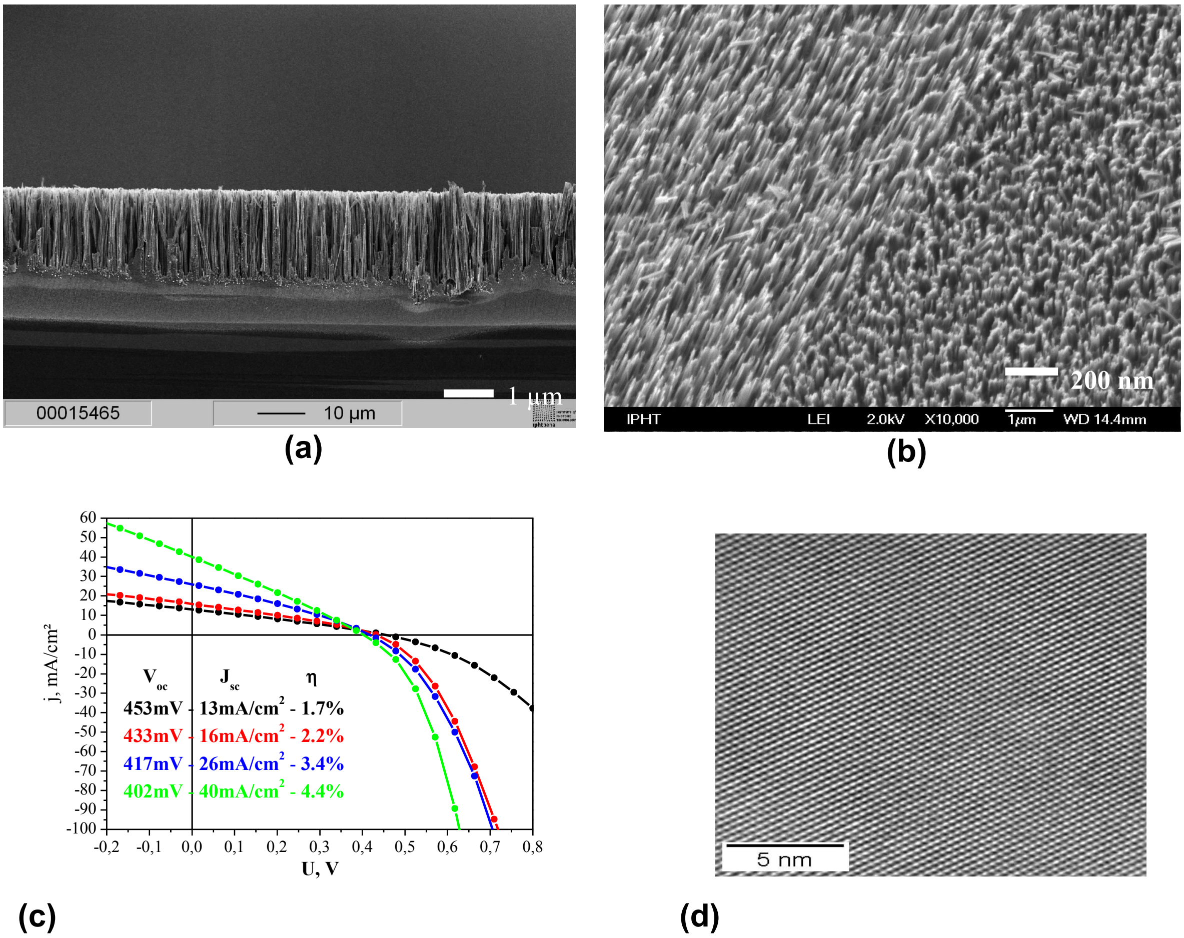

Figure 2. (a) Cross section SEM image of the $AgNO_3$/HF etched p^+nn^{++}-µc-Si surface; (b) planar SEM micrograph of etched crystallites; grain boundaries are discernible; (c) Current-voltage characteristics in illuminated case (AM1.5); (d) high resolution TEM image of the SiNW. The selected area indicates that the wire is single crystalline all along its length and <112> oriented.