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Spatially localized current-induced crystallization of amorphous silicon films

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Abstract

Field-enhanced metal-induced solid phase crystallization (FE-MISPC) at room temperature is employed to create microscopic crystalline regions at predefined positions in hydrogen-rich amorphous silicon (a-Si:H) films. Electric field is applied locally using a sharp conductive tip in atomic force microscope (AFM) and nickel electrode below the a-Si:H film. The process is driven by a constant current of −50 pA to −500 pA while controlling the amount of transferred energy (1–300 nJ) as a function of time. Passing current leads to a formation of nanoscale pits in the a-Si:H films. Depending on the energy amount and rate the pits exhibit lower or orders of magnitude higher conductivity as detected by current-sensing AFM. High conductivity is attributed to a local crystallization of the films. This is confirmed by micro-Raman spectroscopy.
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1. Introduction

Hydrogenated amorphous silicon (a-Si:H) is a material of extraordinary interest in industrial environment for several decades. It offers an increasing range of applications in photovoltaics, optoelectronics, xerography, sensor devices, and other fields [1]. Amorphous structure, for which lack of long-distance order and existence of coordination defects are typical, gives rise to specific features such as continuous density of electronic states and enhanced light absorption [2].

Fabrication of a-Si:H in thin films enables to reduce material and energy costs as well as using of substrates with various interesting properties such as flexibility or transparency. Therefore, crystallization of amorphous silicon films is traditionally studied as an alternative method for producing large area electronics such as displays and solar cells. Crystallization is typically induced by laser annealing [3] or high temperature furnace annealing [4]. Presence of silicide forming metals such as nickel [5] or application of electric field [6,7] was found to reduce the crystallization temperature.

Nowadays, production of silicon nanocrystals becomes increasingly important as they are attractive for nanoelectronic, optoelectronic, and biologic applications [8]. Usually they are generated by electrochemical etching of bulk silicon into so-called porous silicon [9]. Producing the nanocrystals in well defined locations or creating arranged microscopic patterns is still challenging though.

In this contribution, we induce field-enhanced [6,7] metal-induced [5] solid phase crystallization (FE-MISPC) at room temperature by a sharp tip in atomic force microscope (AFM). Hereby we create localized microscopic crystalline regions at predefined positions in a matrix of a-Si:H films. We characterize the dynamics of the local crystallization process, its thresholds, and resulting changes of local microstructural, electronic, and material properties.

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2. Experimental

The a-Si:H films are deposited by plasma-enhanced chemical vapor deposition (PE-CVD) in the thickness of 200 nm on a Corning 7059 glass substrate coated with 40 nm thin nickel film. Substrate temperature of 50 °C and 0.02% dilution of SiH_4 in helium result in a high hydrogen content (20–45 at.%) in the films [10].

The FE-MISPC is accomplished by applying the electric field locally using a sharp conductive tip in atomic force microscope (AFM). The tips are Pt/Cr coated doped silicon cantilevers with a spring constant of 0.2 N/m. The AFM tip is brought into contact with the a-Si:H film using loading forces of 10–20 nN.

Sample design and experimental setup are shown schematically in Fig. 1. The FE-MISPC process is driven by a constant current I_C from −50 pA to −500 pA which is applied by an external source unit. The current source is connected to the bottom nickel electrode. Electrons must be sourced to nickel in order to facilitate the FE-MISPC process [6].

In principle, one can use also a voltage source to initiate the FE-MISPC process. However, particular threshold voltages are significantly fluctuating. Applying constant current enables better control of the process.

Note that the sourced constant current I_C is not the current which flows through the sample. The sourced current is also charging the parallel capacitance C_P which arises mostly from the wire leads and is typically 10–50 pF. Therefore, the sample current I_S is measured independently by an additional picoampermeter in the tip-sample branch.

The voltage V required to maintain the current is monitored as a function of time t and the amount of energy E transferred to the a-Si:H films by the current flow is controlled in the range of 1–300 nJ. The transferred energy is calculated as

$$E = \int V(t) I_S(t)\,\mathrm{d}t. \quad (1)$$

The energy E is calculated from the time-point when the sample current I_S exceeds 50% of the constant current I_C. The higher the current amplitude the shorter the time required to transfer the specified amount of energy. Setting different levels of the constant current I_C can be thus used to study dynamics of the FE-MISPC process. However, based on Eq. 1 the energy transfer time is rather determined by temporal variations of the sample current I_S and the voltage V developed on the current source. Therefore, as the characteristic parameter of the particular FE-MISPC process we define average energy transfer rate $r_a = E/t_{tot}$, where t_{tot} is the total time over which the energy was transferred. In this work, the r_a was between 0.5–30 nJ/s.

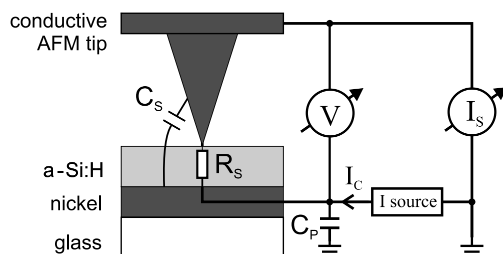

Fig. 1. Schematic drawing of the experimental setup and electrical circuit.

Microscopic morphology and local conductivity of the films after FE-MISPC process are characterized by current-sensing AFM, using the contact force of 10–20 nN and sample bias voltage of −25 V during scanning. Micro-Raman spectroscopy is applied for detection of local crystallinity of the films using an excitation laser wavelength of 785 nm. The laser focus size and depth was slightly below 1 μm.

3. Results

Fig. 2 shows typical current–voltage ($I_S(V)$) characteristics of the tip-sample system. The current starts rising slowly from −15 V and then abruptly from about −25 V. The tendency is strongly non-linear, resembling a discharge characteristics. These values are typical for a new AFM tip. Depending on the tip wear and condition, the threshold voltage fluctuates up to 100 V or more.

Typical course of the single FE-MISPC process as a function of time is shown in Fig. 3. When the constant cur-

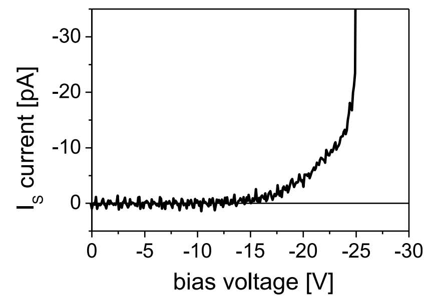

Fig. 2. Typical $I_S(V)$ characteristics of the tip-sample system.

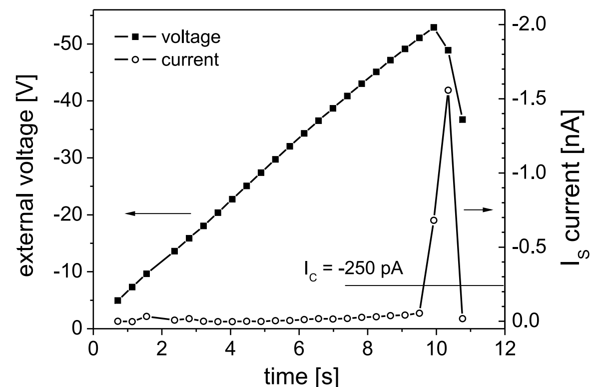

Fig. 3. Typical profile of external voltage V and sample current I_S as a function of time in the course of FE-MISPC process. Constant current applied from an external source was −250 pA.

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