Influence of combined AFM/current measurement on local electronic properties of silicon thin films

B. Rezek ∗, T. Mates, E. Šípek, J. Stuchlík, A. Fejfar, J. Kočka

Institute of Physics, Academy of Sciences of the Czech Republic,
Cukrovarnická 10, 162 53 Praha 6, Czech Republic

Abstract

Hydrogenated microcrystalline silicon (µc–Si:H) thin films were prepared by plasma enhanced chemical vapour deposition and transferred without breaking vacuum into an ultra high vacuum (10−10 mbar) atomic force microscope (AFM). The AFM is used to characterize surface morphology and electronic properties with high lateral resolution. This combined AFM/current measurement leads to a modification of the local electronic properties. This modification is detected as a significant decrease in local current compared to that in newly scanned regions. Kelvin probe microscopy shows that the contact potential difference is reduced by 0.25 eV in the area with decreased conductivity. This area with decreased conductivity remains on the surface for at least several hours. When the cantilever is kept fixed at a particular point on the surface the current exhibits a long–term decay (≈ 10 min). This effect is suggested to be due to a local change of a gap state distribution.

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1 Introduction

Microcrystalline silicon thin films exhibit pronounced inhomogeneities at a microscopic level, which significantly influence their performance in solar cells and other devices [1]. Simultaneous measurement of atomic force microscopy

∗ Corresponding author.
Email address: rezek@fzu.cz (B. Rezek).
URL: www.fzu.cz/~rezek (B. Rezek).
(AFM) and local currents enabled the establishment of a direct correlation between the microstructure and the local electronic properties of such films [2]. This approach revealed a pronounced inhomogeneity in hydrogenated microcrystalline silicon thin films (μc–Si:H) prepared by plasma enhanced chemical vapour deposition (PECVD) [2,3] and made possible an accurate evaluation of the microscopic crystalline patterns produced in hydrogenated amorphous silicon thin films (a–Si:H) by interference laser crystallization [4]. The large difference of conductivities between the amorphous and the microcrystalline phase, together with the high lateral resolution of AFM enabled the study of crystallites as small as few tens of nanometers. In the contact mode of AFM, the surface corrugation is followed independently of local electronic properties. Thus the electronic properties are directly correlated with the morphology. This is a great advantage compared to studies by scanning tunnelling microscopy, where it is difficult to distinguish whether variations in tunnelling current reflect electronic or topographic features [5].

In this contribution, we report that scanning the surface of silicon thin films by the combined AFM/current technique can lead to a local change of electronic properties. This change in local properties is detected as a decrease in local current and as a difference in surface potential in the scanned area compared to newly measured regions.

2 Experimental

Thin films of nominally undoped μc–Si:H were deposited by radio frequency (13.56 MHz) PECVD using 4.5% dilution of silane gas in hydrogen. The films, of 200 nm thickness, were prepared on a nickel–chromium (NiCr) layer, which had been evaporated on a Corning 7059 glass substrate and serves as a bottom contact to the silicon layers. After the deposition, the samples were transferred into an ultra high vacuum AFM stage (base pressure of $10^{-10}$ mbar) without breaking vacuum ($p < 10^{-7}$ mbar). Auger spectroscopy showed no contamination of the sample surface after the transfer.

An AFM by Omicron Vakuumphysik was used to investigate the samples. During the AFM scan of the surface morphology the cantilever was operated in the region of repulsive forces. Under these conditions, the tip of the cantilever is kept in close mechanical and electrical contact with the sample. At the same time, a dc bias was applied, and the current flowing between the tip and the bottom electrode was registered. In addition, in selected points, the surface potential was detected at the same place by retracting the cantilever 50 nm above the surface and using the technique of Kelvin probe microscopy [6,7]. In this manner, the spatially resolved maps of surface morphology, local current, and contact potential difference were measured simultaneously. Highly doped
silicon cantilevers were used for current and potential measurements.

The time evolution of the local current was investigated at a fixed point on the surface. In this case, the cantilever was not scanning across the surface, but was kept fixed in one spot. The contact was maintained by the feedback control loop. A bias voltage of 10 V was applied to the sample and the current decay was registered.

3 Results

As the maps of local current were rendered, repeated scanning of the same area resulted in a decreased current and contact potential difference compared to newly measured regions. This effect is illustrated by Fig. 1 where images of surface morphology (a), local current (b), and contact potential difference (c) were acquired with a silicon cantilever using 3.5 V bias on the sample. The size of images is $3 \times 3 \mu m$. Prior to this scan, a smaller $1.5 \times 1.5 \mu m$ area was scanned several times at the same bias voltage. This area now appears as a dark square in the center of the current and surface potential images. In surface morphology no difference was detected. Similar behavior has been observed also on a-Si:H films.

Numerical values of the surface corrugation, local current, and potential on the fresh and previously scanned surface are shown in the accompanying spatial profiles (d), (e), and (f). These profiles were taken along the line indicated by an arrow in the Fig. 1(a). The spatial profiles (e) and (f) show that the current decreased by approx. one order of magnitude and the contact potential difference was reduced by 0.25 V in the region previously scanned. No change is visible in the surface morphology profile (d). Fluctuations in the profiles are not due to noise but reflect the granular structure of the film.

The smallest area modified so far was $250 \times 250 \text{ nm}$. The minimal achievable size is still to be investigated.

The evolution of the local current as a function of time at a fixed location is shown in Fig. 2. The bias voltage of 10 V gave rise to rather large currents (in the order of 100 nA) which made the decay more noticeable. Within the first 10 minutes a pronounced current decrease is observed (see Fig. 2(a)). After a pause of about twenty seconds the measurement was repeated for another 10 min. When the bias is applied for the second time at the same spot, the current starts at the level it had when the previous measurement was finished, and than slowly decreases with time (see Fig. 2(b)). The overall decay is non-exponential. Compared to this long-term decay the current images correspond to the situation $5–10 \text{ ms}$ after bias voltage application.
Fig. 1. Images of surface morphology (a), local currents (b), and surface potential (c) acquired simultaneously by AFM with a conductive cantilever on a µc–Si:H film. The sample was biased at 3.5 V. The dark square in the center of images (b) and (c) is the result of a previous AFM/current measurement at that area. Numerical values of the surface corrugation (d), local current (e), and surface potential (f) on the fresh and already scanned surface can be seen in the accompanying profiles along the line indicated by an arrow in the image (a). The spatial profiles show reduced current and contact potential difference in the dark region while no change is visible in the surface morphology.

4 Discussion

The observed decrease of local current with measurement time is not related to the particular cantilever used. The decrease of current could be reproduced with silicon, metal coated, and diamond coated cantilevers as well. In this study uncoated cantilevers were preferred to metal coated cantilevers because the coating is known to wear off rapidly in contact mode and the coating may be deposited on the surface [8]. Degradation of the cantilever tip during
Fig. 2. Evolution of local current as a function of time $I(t)$ at a fixed location on the $\mu c$–Si:H sample, which was biased at 10 V: (a) first and (b) second measurement at the same spot.

measurement can be also excluded since both high and low current levels are detected in a single image (see Fig. 1(b)).

The effect does not seem to be due to chemical modification (oxidation) of the sample surface because no change was detected in the surface morphology. In–situ deposition and operation under ultra high vacuum makes the explanation that the current decreases due to a formation of a very thin invisible $\text{SiO}_2$ layer [9], or due to the charge trapping in the native oxide layer [10] unlikely. The field induced oxidation by a local probe is usually connected with pronounced modification of morphology [11]. The decay of the current at the fixed point excludes mechanical modifications of the sample (for instance by abrasion) under influence of raster scanning.

Transient electronic phenomena can play an important role in intrinsic $\mu c$–Si:H and influence the local current response. When surface morphology and local current are registered simultaneously, the voltage bias is applied prior to the scanning and then held constant between cantilever and the sample as the image is rendered. Nevertheless as the cantilever scans across the surface, the material feels the voltage as being applied just at a particular measurement point.

The time evolution of the local current, shown in Fig. 2, is similar to the current decay observed macroscopically on amorphous silicon where it has been attributed to a transient change of occupation of electronic states in the mobility gap [12]. Thus it seems that the reported effect is due to a charge trapping of carriers in the gap states. Such charging effects are indeed observed in surface potential image (see Fig. 1(c)) where the decrease in contact potential difference indicates a shift of a Fermi level with respect to the surface not previously scanned.
Yet when the bias voltage is switched off the sample does not recover. \( I(t) \) in the second curve in Fig. 2 just continues to decay and the area with decreased conductivity persists on the surface for a long time. The boundaries of the area remain sharp although hazing due, for example, to carrier diffusion from the surroundings might be expected. In addition, the decrease of current is observed in both bias polarities and the current could not, so far, be reset by any variations in bias voltage.

Reversible modification of a subsurface space charge region by transfer of free carriers presumes, however, that the distribution of gap states does not change. The change of gap state distribution could explain why the area of decreased current does not recover and remains stable for a long time.

The origin of the possible change in the gap states distribution is still unclear. We speculate that it is perhaps connected to a structural relaxation of the material in response to local charging, which could lead to the creation of additional defect states in the mobility gap.

5 Conclusions

To conclude, scanning the surface of microcrystalline silicon by the combined AFM/current technique leads to a local modification of electronic properties which can be detected as decreased local current and contact potential difference (compared to a newly scanned region) and which persists on the sample surface for at least several hours. We suggest that this effect is connected with the trapping of charge and/or the creation of defect states in the mobility gap of \( \mu c\text{-Si:H} \) which result in a rather stable modification of the electronic properties in that particular location. This may be an interesting feature for application in microelectronics.
References