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Cross Section Potentiometry of Doped Silicon Structures Using SFM

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The surface work function measurement of doped silicon structures by using an adapted commercially available SFM (scanning force microscope) is presented. The investigation of a well defined ion-implanted sample for testing the measurement method is described. Deviations of the measured work function values from the theoretical expectations are discussed and interpreted. Furthermore the cross-sectional measurement of a microcrystalline silicon p–i–n diode structure for photovoltaic applications is presented. Contrast can be achieved due to different dopants and the built-in electric drift field between p- and n-doped regions. The potential to judge the quality of diode structures and to suggest improvements for the deposition process is stated.

1. Introduction

In the last years Scanning Force Microscopy (SFM) has emerged as a powerful tool for the investigation of material surface characteristics. The surface topography can be sampled easily obtaining height information of surface features in a nondestructive way [1]. But also other physical or chemical characteristics can be measured by modifying and expanding the classical SFM experiment. In this work, measurement of surface work function differences on a nanometer scale is presented. The experiment is based on a modification of the classical Kelvin probe experiment utilizing the fact that forces in the nN range can be detected by SFM accurately. Novel materials for photovoltaic purposes were investigated. The application of this method on semiconductor samples has shown the potential of dopant profiling and the possibility to investigate the potential distribution in cross-sectioned diode structures.

2. Physical Principles and Experimentals

The basis of the experiment is an Atomic Force Microscope (AFM) which can be operated in noncontact mode. In AFM noncontact mode the height information is obtained by means of a mechanically excited oscillating tip at a frequency ω_1. Approaching the surface attractive and repulsive forces act on the tip and induce damping of the amplitude and shift of the resonance frequency. Keeping the amplitude or the resonance

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frequency constant means having a constant tip–sample distance. In this way the surface topography can be tracked with subnanometer accuracy.

For the measurement of work function differences a voltage with a dc and a sinusoidal ac part (frequency ω_2) is applied between the conducting tip and the sample (see also [2 to 4]). The electrostatic force between the plates of a capacitor, which in our case is the tip–sample system, is given by

$$F = \frac{1}{2}\,\left(U_{\mathrm{dc}} + U_{\mathrm{ac}}\sin\left(\omega_2 t\right)\right)^2\,\frac{\partial C}{\partial z}\,. \tag{1}$$

U_{dc} is the sum of all dc voltages including the one corresponding to the work function difference between tip and sample. Expanding expression (1) results in three terms for the electrostatic force between tip and sample,

$$F = \frac{1}{2}\left(U_{\mathrm{dc}}^2 + \frac{1}{2}\,U_{\mathrm{ac}}^2\right)\frac{\partial C}{\partial z} \tag{2}$$

$$+\ \frac{\partial C}{\partial z}\,U_{\mathrm{dc}}\,U_{\mathrm{ac}}\sin\left(\omega_2 t\right) \tag{3}$$

$$-\ \frac{1}{4}\,\frac{\partial C}{\partial z}\,U_{\mathrm{ac}}^2\cos\left(2\omega_2 t\right). \tag{4}$$

The most important term of the upper expression is (3). If U_{dc} equals zero, term (3) vanishes. This means that the electrostatic force inducing an oscillation of the tip at frequency ω_2 vanishes if the externally applied dc voltage is equal to the voltage corresponding to the work function difference but with opposite sign. Term (2) of the upper expression shows that there is a force acting on the tip which is not dependent on the electrical excitation frequency. This force results in a constant bending of the cantilever. Term (4) provides information about the capacity of the tip–sample system.

The basis of the Kelvin experiment realized at our institute is a commercially available Topometrix TMX Explorer 2000. The excitation frequency ω_1 for noncontact AFM is mostly chosen to be the fundamental resonance which is in the range of 80 to 200 kHz depending on the kind of cantilever. The oscillation of the cantilever is detected with a laser beam reflected from the backside of the cantilever and a four zone photodetector. The tips have a conductive coating which is essential for measuring work function differences. The tip radius is a critical parameter in the experiments since it defines the area of the capacitor and hence the strength of the reaction of the tip on the electrical excitation. Tips with a radius from 25 nm (PtIr coating) to 100 nm (diamond coating) are used in the experiments. All experiments are carried out in ambient air. The modified Kelvin experiment (nanopotentiometry) described above was developed and added to the commercial instrument. The electrical excitation of the tip is sinusoidal and chosen in a frequency range below the fundamental resonance. The amplitude of the voltage necessary for the electrical excitation depends strongly on the kind of sample and is in the range of volts. The response of the cantilever is detected via the same laser system necessary for the noncontact topography measurement. A PAR 124 A lock-in amplifier is used to measure the amplitude of the oscillating cantilever at the electrical excitation frequency ω_2. The lock-in output is fed into a PI regulator which generates and adds a dc voltage to the sinusoidal excitation to make the oscillation of the cantilever at the frequency ω_2 disappear (see expression (3)). The generated dc voltage is recorded by an AD converter and represents the work function difference between tip and sample. In this experiment a resolution of work function differences in the meV range can be achieved.

3. Experiments and Results

The major interest of our group is the characterization of silicon for photovoltaic purposes. As an application of nanopotentiometry we have investigated different dopants in silicon. The basic idea in dopant profiling by means of nanopotentiometry is that the position of the Fermi level within the forbidden band gap – and therefore the work function – depends on the kind of dopant (donor or acceptor) and its concentration [4 to 6]. Simple calculations show that a Fermi level shift of about 1 meV corresponds to a variation of the dopant concentration of less than 10% in the range of 10^{14} to 10^{18} cm^{-3} [4]. We investigated a 1 Ω cm p-type silicon wafer which underwent a stripe like As implantation with an acceleration voltage of 30 keV and a dose of 10^{14} cm^{-2}. One sample was annealed in order to recrystallize the amorphized implant region and one was measured without annealing. As can be seen in Fig. 1 the annealed sample has a smaller work function contrast than the sample which has not been annealed. This can be explained by the fact that additionally to the doping a heterojunction effect (crystalline/amorphous silicon) is measured in the sample which has not been annealed. Nevertheless the work function contrast seems to be smaller than one would expect from the implant parameters. The implanted structure is buried beyond a p-doped region near the surface. So screening of the As doping can take place. Also band bending at surfaces is a known problem which can also screen the surface-near crystal bulk properties.

Another application of nanopotentiometry is the investigation of novel silicon based thin film materials for photovoltaic purposes. Microcrystalline silicon thin films are of special interest in photovoltaic research. The material can be deposited in a low temperature process (below 600°C) on glass substrates with only a small amorphous fraction. The big advantage of this material compared with amorphous silicon is the stability of the electrical performance in photovoltaic applications. Since the quality of the thin films depends strongly on the deposition parameters it is helpful to investigate the electrical characteristics especially on a microscopic level. In Fig. 2 a cross-sectioned

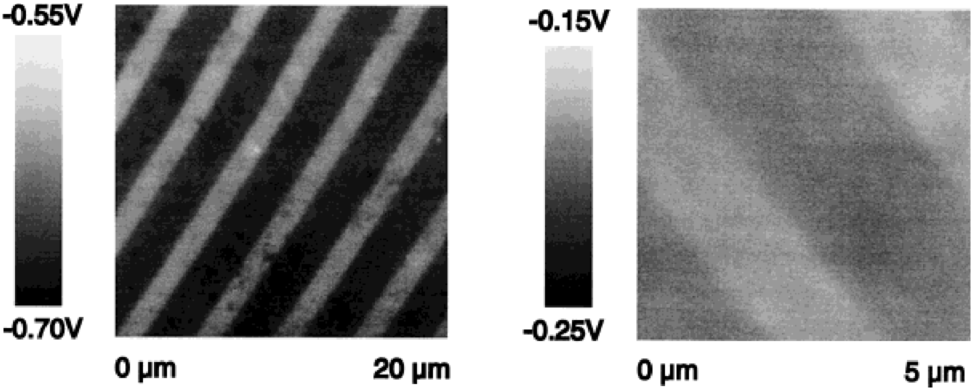

Fig. 1. As-implanted 1 Ω cm p-type silicon wafer (30 keV, 10^{14} cm^{-2}). The dark regions are doped with As. Left: without annealing; right: with annealing

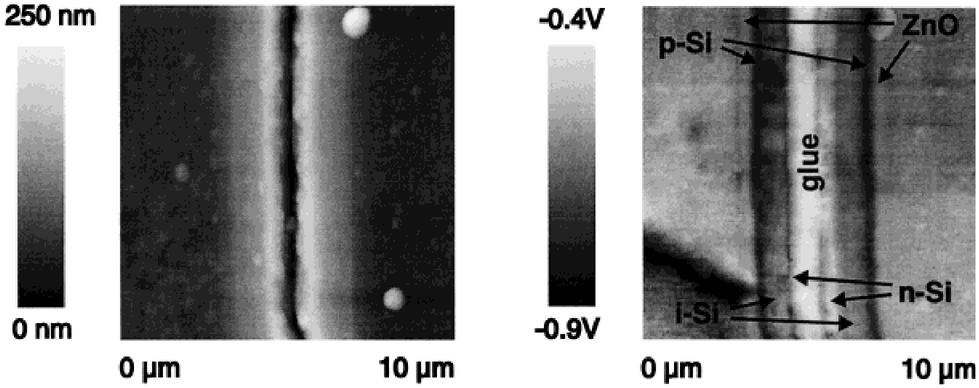

Fig. 2. Cross-sectional view of a microcrystalline silicon p–i–n diode structure. Left: topography; right: nanopotentiometry

p–i–n diode structure made of microcrystalline silicon is shown. Before cross-sectional preparation two p–i–n devices are glued together on their frontsides in order to prevent damaging of the area of interest by polishing and to obtain two operating diodes in one preparation step. In the nanopotentiometric picture, contrast is visible due to different layers. Having a closer look to the structure the built-in electric field between the p- and the n-layer can be seen as a gradually change from dark to light grey. From this kind of measurement the quality of the p–i–n diode structure is derived and suggestions for improvements are possible.

4. Conclusions

The measurement of work function differences on a nanometer scale using a commercially available SFM equipment is described. The application on novel silicon based photovoltaic materials is discussed. The possibility to investigate dopant distributions and the quality of microcrystalline silicon diode structures is demonstrated.

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