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Kelvin probe force microscopy for characterizing doped semiconductors for future sensor applications in nano- and biotechnology

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ABSTRACT

Kelvin probe force microscopy (KPFM) is one of the most promising non-contact electrical nanometrology techniques to characterize doped semiconductors. By applying a recently introduced explanation of measured KPFM signals, we show the applicability of KPFM to determine and control surface-near electrostatic forces in planar doped silicon and in doped silicon nanostructures. Surface-near electrostatic forces may be used for the immobilization of nano- and biomaterials in future sensor applications in nano- and biotechnology. Additionally, the influence of the electrostatic potential distribution in doped semiconductor nanostructures, e.g. in horizontal Si nanowires, and its influence on the surface-near electrostatic forces are discussed. It is explained how drift and diffusion of injected electrons and holes in intrinsic electric fields influence the detected KPFM signal. For example KPFM is successfully employed to locate p^+p and n^+p junctions along B-doped and As-doped p-Si nanowires, respectively. As an outlook the physical immobilization and the transport of biomaterials above arrays of separately addressable doped semiconductor cells will be discussed.

1. Introduction

Biosensors possess an unprecedented potential for the immobilization, modification, transport, and detection of a wide range of analytes in health care, food industry, and environmental monitoring [1]. The interaction between analytes and biosensors can be driven by physical adsorption, chemical covalent immobilization, and by biological immobilization. The chemical covalent and the biological immobilization are considered to be practical and convenient, but are difficult to be controlled and sometimes deactivated. The most widely used biosensors are based on the functionalization of substrates so that only specific analytes bind to the functionalized substrate similar to a lock-and-key mechanism [2]. In this paper we focus on the detection, control, and application of surface-near electrostatic forces above doped semiconductors for future sensor applications in nano- and biotechnology. Electrically polarizable nano- and biomaterials may differ with respect to their size, shape, electrical polarizability, mass and their tendency to align in electric gradient fields. Therefore, the proposed electrical sensors may be used to immobilize and transport electrically polarizable nano- and biomaterials. Only recently a newly developed magnetic biosensor has been presented [3]. This biosensor benefits from the fact that biological fluids are inherently nonmagnetic and thus provide a low magnetic background. Magnetic detection can be done sensitively even in complex fluids such as whole blood, saliva, or tissue extracts. Furthermore, magnetic actuation by an external field can be used to accelerate the speed of reactions and provide force discrimination by removing non-specifically bound labels for increased selectivity. Typically, the range of surface-near magnetic stray fields above magnetic biosensors is comparatively as large as the range of surface-near electrostatic forces above doped semiconductors with an ultrathin insulating surface layer. A problem which cannot be solved completely is that the vast majority of biomaterials is not magnetizable and must be labelled for use with magnetic biosensors.

It has already been shown that electric gradient forces may be used to move single ions above a solid if an electrode is attached to the back side of the solid and if a positionable metallic

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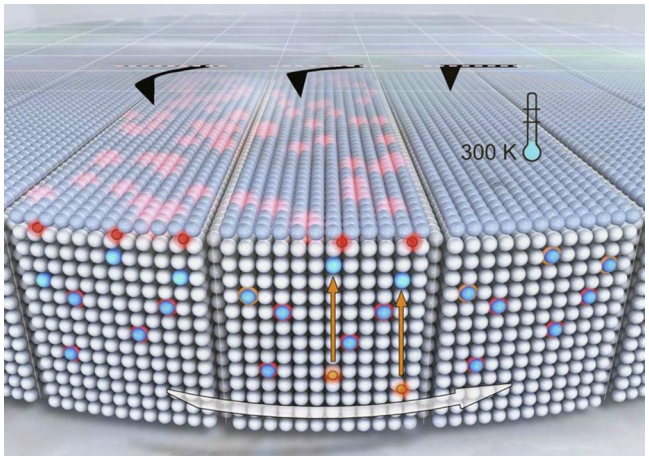

Fig. 1. Schematic illustration of a Kelvin probe force microscopy cantilever above a planar doped semiconductor with a thin oxide layer (grey–blue atomic layer) showing occupied surface states at the interface between the oxide layer and the semiconductor (animated in red) and the same number of unscreened ionized immobile dopant atoms (animated in light-blue).

Picture: Sander Münster, 3DKosmos.

conductive tip of an atomic force microscopy is scanned over the solid [4]. As shown by Chiou et al. [5] electrically polarizable nano- and biomaterials may be moved outside a solid carrier between the surface of the carrier and a large-area front side electrode on the μm length scale by dielectrophoresis. There the front side electrode is mounted at a distance from the surface of the carrier and does not touch the solid carrier. Note that dielectrophoresis does not use surface-near electrostatic forces, but the electrical gradient established between two electrodes. Nesterov et al. [6] describe an arrangement with a array of electrodes on a chip which allows the generation of a specific pattern of gradient forces when large voltages of up to 100 V are applied between at least two electrodes of the array. The electrical field lines are mainly formed in parallel to the micro-chip. Due to the strong electric field at the edges of the electrodes, it is expected that nano-sized biomaterials are destroyed at the edges of the electrodes. In contrast, the surface-near electrostatic forces above doped semiconductors can be controlled by a small voltage not larger than the bandgap of the semiconductor. For example, in order to control surface-near electrostatic forces above planar doped silicon with a backside electrode, a maximum voltage of 1.1 V has to be applied.

In this paper we present a solid carrier without front electrode for the locally controlled immobilization and transport of electrically polarizable nano- and biomaterials using surface-near electrostatic forces (Section 2). As shown in Sections 2–4 Kelvin probe force microscopy (KPFM) is one of the most promising non-contact electrical nanometrology techniques to determine surface-near electrostatic forces above planar doped silicon and above doped horizontal silicon nanowires. As an outlook the physical immobilization and transport of biomaterials on a rectangular array of separately addressable doped semiconductor cells will be discussed in Section 5.

2. Surface-near electrostatic forces

The starting point for the development of new solid carriers for the immobilization and transport of nano- and biomaterials is a doped semiconductor (Fig. 1). Optional on the semiconductor surface, a thin insulating layer can be deposited. The occupied surface states at the interface between the oxide layer and the semiconductor (animated in red) and the unscreened ionized immobile dopant atoms (animated in light-blue) form an asymmetric electric dipole with the electric field gradient normal to the semiconductor surface. As explained in the following the surface-near electrostatic forces may be detected by KPFM measurements because the electric field gradient influences the oscillation at the operation frequency f_{ac} of the conductive cantilever. This operation frequency is used as the KPFM feedback signal (left, Fig. 1). By applying the appropriate KPFM bias mobile majority charge carriers are injected into the semiconductor surface (animated in orange) and screen the unscreened ionized immobile dopant atoms (centre, Fig. 1). Without the electric field gradient normal to the semiconductor surface, the asymmetric electric dipole and the oscillation of the conductive cantilever at the operation frequency f_{ac} is not influenced by surface-near electrostatic forces (right, Fig. 1). To date, KPFM is a standard electrical nanometrology technique applied in various research fields, e.g. to investigate the interface dipole layer formed between a metal surface and alkali chloride thin films [7], surface defects in chalcopyrite solar cell devices [8] and other semiconductors [9,10], dopant profiles in semiconductors [11–13], especially with atomic resolution [14], and doping junctions in semiconductors [13,15–18]. KPFM has also been applied in the field of biotechnology research comprising organic solar cells as well as biomolecules and their interaction. Due to its non-destructive character and high lateral resolution, i.e. 2 nm achieved by means of UHV KPFM reported by Spadafora et al. [19], KPFM qualifies in particular for the investigation of nanostructures. Recently, low temperature UHV KPFM measurements have been performed with a CO-terminated tip on a naphtalocyanine molecule and the charge distribution within a single-molecule charge-transfer complex has been imaged [20]. In this work, a Level-AFM from Anfatec Instruments AG is employed for detecting surface-near electrostatic forces above doped semiconductors by KPFM measurements. It is demonstrated, that the transport of majority charge carriers to the measurement position during the KPFM measurement is crucial for the correct interpretation of the recorded KPFM bias. This knowledge allows a quantitative correlation of the probed lateral KPFM bias variation with the dopant distribution in planar doped semiconductors (Section 3) and in doped semiconductor nanowires (Section 4).

3. Planar doped semiconductors

In contrast to state of the art solid carriers for nano- and biomaterials [5] that make use of chemical covalent or biological immobilization, surface-near electrostatic forces of the carrier presented in Fig. 2 are not affected by the environment close to the surface. That is because those surface-near electrostatic forces are chemically and biologically isolated from the environment. The direction of the surface-near electric gradient field is indicated by the direction of the arrows and depends on the charge of occupied surface states at the interface between the oxide layer and the semiconductor. The strength of the surface-near electric gradient field depends on the equal number of occupied surface states and unscreened ionized immobile dopant atoms. Close arrows indicate a strong electric gradient field (Fig. 2). The proposed new carrier is a doped semiconductor with surface-near electrostatic fields and utilizes electrical polarizability of nano- and biomaterials for immobilization and transport of electrically polarizable nano- and biomaterials. The electrical polarizability is a measure of the displacement of a positive relative to a negative charge and for the formation of electric dipoles. For more complex nano- and biomaterials also electric multipoles may form. Electric forces are long-range and strongest on the nanometer-length scale. Without external electric fields the orientation of electrically polarizable nano- and biomaterials is determined by dipole–dipole interactions. Electric dipoles or multipoles act as a torque in a uniform