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Dopant imaging of power semiconductor device cross sections

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ABSTRACT

Several Scanning Probe Microscopy (SPM) methods allow to image dopant profiles in a range from 10^{14} cm^{-3} to 10^{19} cm^{-3} on semiconducting samples. In our work we present Scanning Capacitance Force Microscopy (SCFM) and Kelvin Probe Force Microscopy (KPFM) experiments performed on cross sections of silicon (Si) and silicon carbide (SiC) power devices and epitaxially grown calibration layers. The contact potential difference (CPD) shows under illumination a reduced influence on surface defect states. In addition results from numerical simulation of these microscope methods are discussed.

1. Introduction

The characterization of power electronic device cross-sections is an essential part of manufacturing and optimization processes. One of the most important information is the mapping of the targeted dopant concentrations, since they determine the electronic performance of the device. It is found that Secondary Ion Mass Spectroscopy (SIMS) is difficult to be applied in the case of power semiconductor devices because of the low dopant concentrations (as low as 10^{14} cm^{-3}) and narrow dimensions in the μm range. In this contribution, a dedicated Scanning Probe Microscope (SPM) [1], operated under ultra-high vacuum conditions, is applied for this purpose. An image of the scanning probe microscope instrument is shown in Fig. 1. The most important operation modes are Scanning Spreading Resistance Microscopy (SSRM) [2], Kelvin Probe Force Microscopy (KPFM) [3] and Scanning Capacitance Force Microscopy (SCFM) [4]. On the one hand, SSRM is found to be a robust method for silicon samples. This SPM technique measures the local spreading resistance at relatively high loading forces. The main disadvantage is the destructive nature of this imaging mode, where high normal forces of about 50 μN are required to penetrate through the native oxide layer of the semiconductor surface. On the other hand, KPFM and SCFM are non-contact methods, which are sensitive enough to observe dopant concentrations in the range of 10^{14} cm^{-3} to 10^{19} cm^{-3}. KPFM is found to be influenced by surface defects [5], which can lead to partial pinning of the Fermi level and subsequently a reduced contact potential difference (CPD) is observed. The band bending due to defects can be reduced by suitable sub-bandgap illumination of the tip-surface interface [6].

2. Experimental results

To demonstrate the capability of our instrument, we performed dopant imaging on Si-based high-voltage super-junction device structures [7]. These structures were manufactured by a demanding and complex trench-etching followed by epitaxial refill process. The trenches have a depth of 60 μm, a width of 3 μm and are boron-doped with concentrations in the range of 10^{14}–10^{15} cm^{-3} to get p-type conductivity. We found that SSRM provides valuable quantitative information about the doping level by comparison of the measured data at the region of interest to previously calibrated epitaxially grown layers [8]. Furthermore, the trenches were investigated by the non-contact method, KPFM, as shown in Fig. 1b) and c). KPFM measures the contrast in the CPD signal by applying a bias voltage V_{CPD} to compensate electrostatic forces, which is sensitive to defect structures at the surface. A decrease of the defect density by suitable sample preparation and the reduction of the surface band bending by illumination with sub-bandgap irradiation are feasible strategies to minimize band bending and to optimize the CPD contrast mechanism [9,10]. SCFM seems to be a valuable method to visualize differently doped regions, but still needs further sophisticated modelling to obtain quantitative results. Fig. 2c) shows a Synopsys

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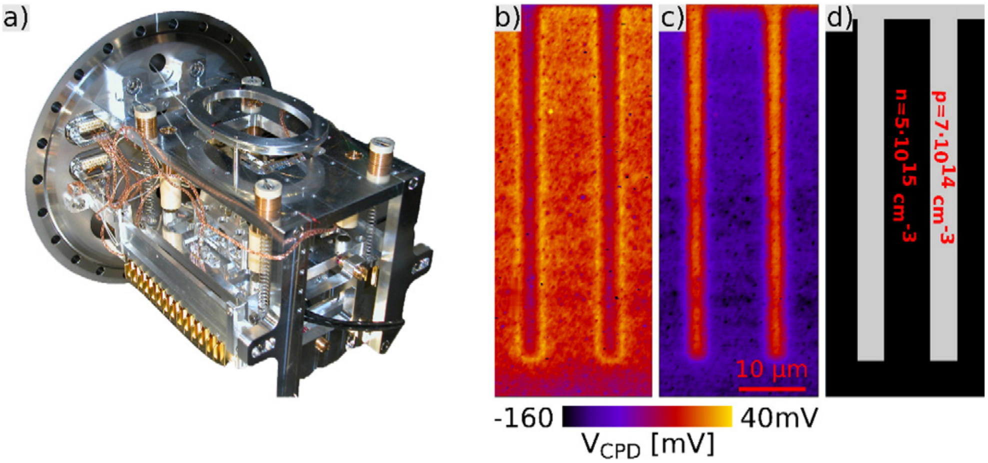

Fig. 1. (a) AFM with a 100 × 100 µm^2 closed loop scanner operating in UHV conditions with full optical access [1]. KPFM images of a silicon test structure (b) without and (c) with irradiation (about 20 mW, λ = 475–525 nm) by sub-bandgap photons, respectively. The p-doped trenches with approximate concentrations of 5–7·10^{14} cm^{-3}are surrounded by the n-type substrate as shown schematically in (d).

Sentaurus TCAD simulation of the hole density in the vicinity of a probing metallic tip on a silicon surface. The depletion zone below the probing tip leads to a change of the capacitance as a function of dopant density. The radius of curvature of the probing tips is about 50 nm as shown in the corresponding SEM pictures in Fig. 2a) and b). In addition, SiC-device structures were investigated with the abovementioned methods. In this case, SSRM was found to be difficult to be applied because of the extreme hardness of SiC (close to diamond), which makes it difficult to form a stable electronic contact between the diamond-coated tip and the SiC surface.

2.1. KPFM method

Kelvin Probe Force Microscopy (KPFM) relies on the measurement of electrostatic forces between probing tip and sample as a function of applied voltage V_{CPD} [3]. For compensated contact potential, the electrostatic force is at its minimum. Ideally, the contact potential difference (CPD) is influenced by the shift of the Fermi energy,

$$V_{CPD} = \frac{1}{q}\left(\chi + \frac{E_g}{2} + k_B T \cdot \ln\left(\frac{N_A}{n_i}\right) - \phi_m\right)$$

for *p*-doping and

$$V_{CPD} = \frac{1}{q}\left(\chi + \frac{E_g}{2} - k_B T \cdot \ln\left(\frac{N_D}{n_i}\right) - \phi_m\right)$$

for *n*-doping, where χ is the electron affinity, E_g is the band gap, k_B is the Boltzmann constant, T the temperature, q the elementary charge, n_i the intrinsic carrier density, ϕ_m the work function of the metallic tip and N_D is the donor density and N_A the acceptor density. However, the Fermi level can be influenced by interface trap states or surface defects, which leads to band bending and a reduction or increase of the CPD for p- and n-type semiconductors, respectively. In extreme cases, the Fermi level is pinned and the CPD would be independent of dopant concentration.

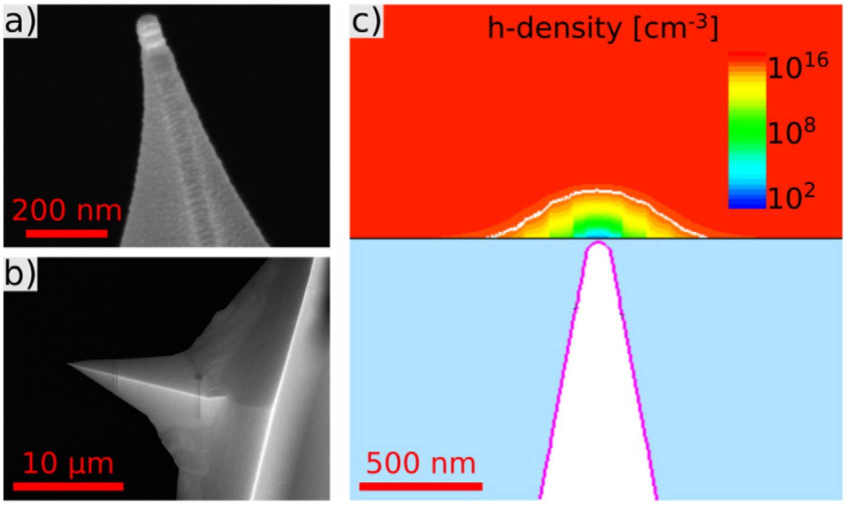

Fig. 2. (a) and (b) SEM images of a Pt/Ir coated AFM tip used for KPFM and SCFM measurements. (a) Exhibits the radius of the tip apex of approximately 50 nm. (c) Synopsys Sentaurus TCAD simulation of the hole density in the vicinity of the metallic probing tip on a silicon surface. The bulk density is p = 10^{16} cm^{-3}. The depleted zone at an applied voltage of 5.8 V extends about 200 nm into the semiconductor resulting in a measurable capacitance by the SCFM approach.