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TCAD Modelling of Anisotropic Channel Mobility in 4H-SiC MOSFETs

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Abstract. Channel mobility is one of the most critical parameters in 4H-SiC based Power MOSFETs and contributes a significant fraction of device on-state resistance. Experimentally, it has been shown that the a-face channel mobility is much higher compared to the Si-face, making a-face a very attractive option for a wide range of applications in the power electronics market. However, modelling of the a-face channel mobility using Technology Computer Aided Design tools is not well established due to the complex nature of channel mobility due to a variety of scattering mechanisms involved. In this paper, we present a well calibrated a-face channel mobility model that shows an excellent match with the available experimental data and further provides critical insights into the anisotropic nature of channel mobility in 4H-SiC MOSFET structures.

Introduction

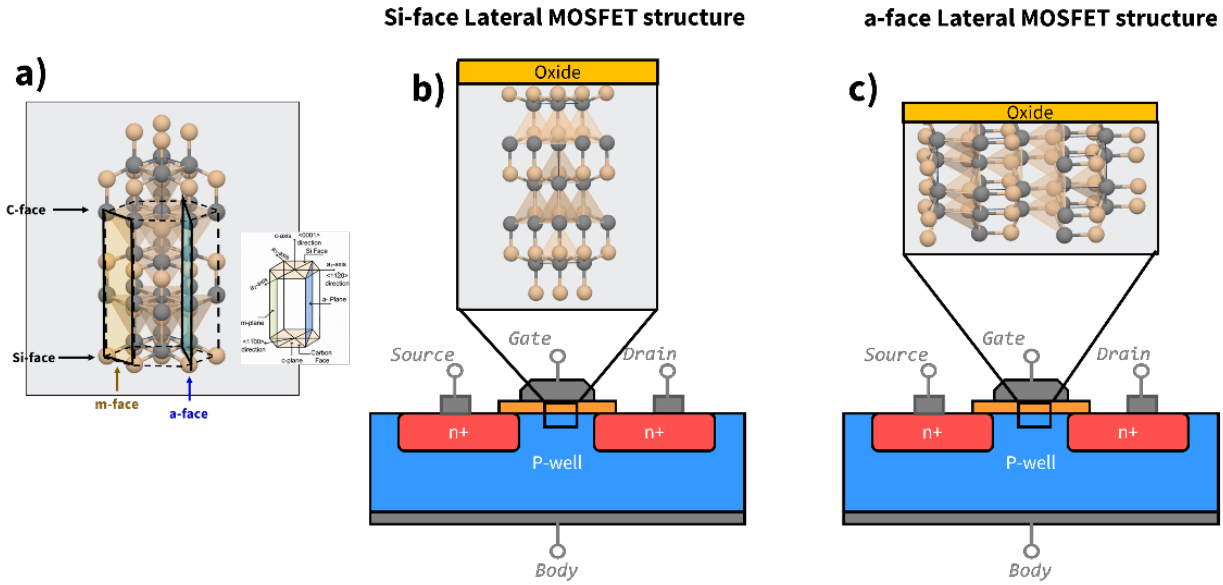

Fig. 1. a) Hexagonal crystal structure of 4H-SiC showing various faces b) Schematic of lateral MOSFET created using Si-face orientation c) Schematic of lateral MOSFET created using a-face orientation

Channel mobility is one of the most critical parameters in 4H-SiC based Power MOSFETs and contributes a significant fraction of device on-state resistance (RON). 4H-SiC has a hexagonal crystal structure and the bulk mobility is anisotropic, larger in the (0001) direction (parallel to the a-face or m-face), and lower perpendicular to that (along Si-face directions) as illustrated in Figure 1. Such an anisotropic nature is also observed in channel mobilities when channels are formed along these crystallographic orientations. Experimentally, it has been shown that the a-face channel mobility is much higher compared to the Si-face, making a-face a very attractive option for a wide range of

applications in the power electronics market [1,2]. However, to the best of our knowledge, Technology Computer Aided Design (TCAD) modelling of the a-face channel mobility is not well established in the literature [3,4]. Thus, here we present a well calibrated a-face channel mobility model that shows an excellent match with the available experimental data and further provides critical insights into the anisotropic nature of channel mobility in 4H-SiC MOSFET structures.

Experimental Details

a-face lateral MOSFETs used in this paper are special test structures which are fabricated on p-type epilayers, grown on a-face cut 4H-SiC substrates [1]. P-type doped epitaxial layers, having p-well concentrations of about 1e16cm-3, are grown on the a-face (11-20) cut 4H-SiC substrate. Gate oxide was deposited with a CVD process, followed by nitric oxide (NO) passivation anneals. Poly-Si was deposited and patterned for the gate electrodes, with ohmic contacts formed to N+ implanted source and drain regions. These lateral MOSFETs are all long-channel devices (Lg > 50 um) to ensure accurate field-effect (FE) mobility extraction. Temperature dependent drain current (Id) versus gate bias (Vg) characteristics are shown in Fig. 2a). The channel FE mobilities as a function of temperature for a-face lateral MOSFETs is calculated using the derivatives of the Id-Vg characteristics and are shown in Fig. 2b). Next, we also plotted the temperature dependence of the peak channel mobility as shown in Fig. 2c) and observed opposite trends for Si-face and a-face. For Si-face, the peak channel mobility increases with increasing temperature whereas for the a-face a decrease in peak channel mobility with increasing temperature.

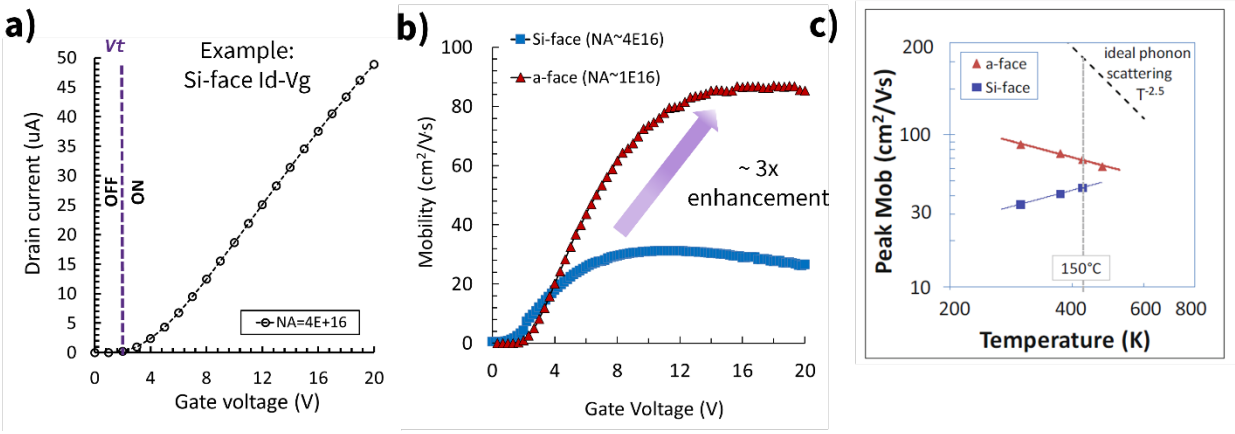

Fig. 2. a) Id-Vg measurement on Si-face lateral MOSFET b) Extracted field-effect channel mobilities for the Si-face and a-face showing strong enhancement in peak mobility for similar P-well concentrations c) Corresponding temperature dependence of the peak value of channel mobility for the Si-face and a-face.

Channel Mobility and it's Components

Modelling channel mobility is a complex task due to a variety of scattering mechanisms that compete and dictate the total channel mobility along with its temperature dependence. The standard channel mobility model consists of bulk, Surface Roughness (SR), Surface Phonon (SP), and Remote Coulomb Scattering (RCS) terms combined using Matthiessen's rule. This is illustrated in Figure 3. By reviewing literature, we observed that the standard mobility models developed for Silicon technology perform poorly in describing the physics of SiC MOS interface. As shown by earlier literature and our previous work on modelling Si-face channel mobility term [3,4,6], it is not possible to describe the temperature and P-well surface concentration dependence of channel mobility using semi-empirical parameters developed for the Silicon technology. Thus, a straightforward adoption of the available mobility models misses on critical customizations that are necessary to describe the

unique material properties of 4H-SiC crystal. In this work, we take on this challenge and have developed a new set of semi-empirical parameters for the 4H-SiC-oxide interface. Here we start with the approach originally proposed by C. Lombardi et. Al. [6] and later significantly revise the proposed semi-empirical formulation to describe experimental data. Our TCAD simulations are performed using the Silvaco Victory Process and Victory Device tools. The interface trap density is estimated using high-low C-V measurements and was used as input for the RCS portion. An extensive calibration of SR, SP and RCS model terms was performed to match the experimental data for measured a-face channel mobility.

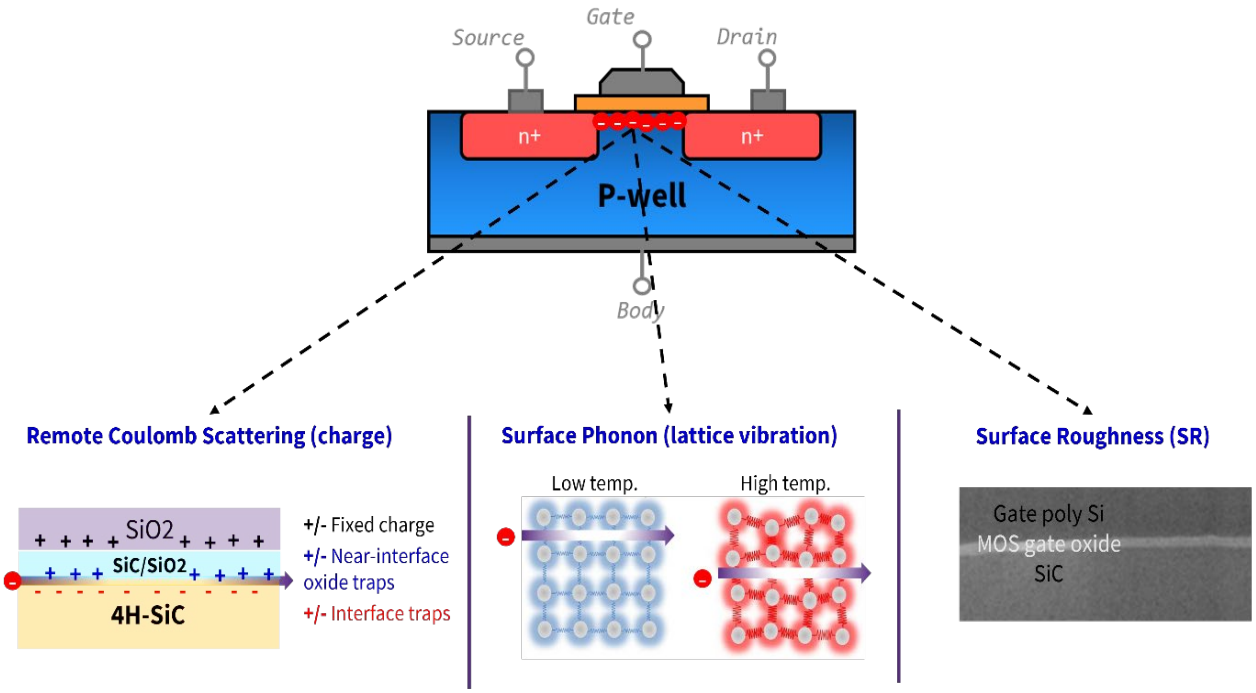

Fig. 3. Schematic illustration of the channel mobility components: the electrons flowing across source to drain experience three primary scattering mechanisms and these are termed as Remote Coulomb Scattering (RCS) due to the charges present at the oxide interface, Surface Phonon (SP) due to atomic rearrangement of the atoms at the interface, and the Surface Roughness (SR) term that represent reduction of the electron mean free path due to geometrical roughness at the interface.

Results and Discussion

We tested our revised channel mobility model on channel mobility curves obtained specially created lateral MOSFET test structures having a-face and Si-face orientations. The TCAD predicted and experimentally measured temperature dependence of channel mobility curves is shown in Figure 4. As evident from Figure 4 a) and 4 b), we obtain an excellent match with the measured mobility curves across multiple temperatures (ranging between 25-200°C). The Si-face lateral MOSFET has P-well surface concentration of about ~1E18/cm^3, whereas P-well surface concentration for a-face lateral MOSFET is about 1E16/cm^3. From the comparison of the simulated and measured channel mobility curves, our revised a-face channel mobility model shows predictive capability across multiple lattice temperatures.

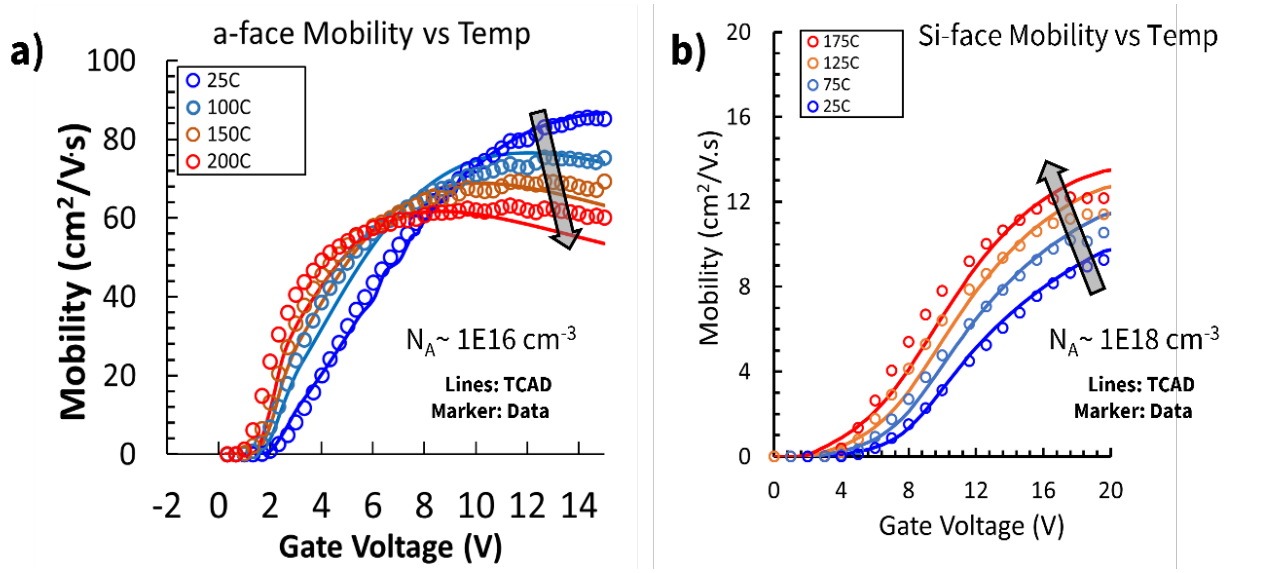

Fig. 4. a) TCAD predictions for a-face channel mobility and its temperature dependence – the markers represent the measurement, and the lines show TCAD result b) TCAD predictions for Si-face channel mobility and its temperature dependence.

Analysis of Channel Mobility Components

Next, we perform a component-wise analysis of total channel mobility that unravels the complex but interesting interplay among a variety of scattering mechanisms. Figure 5 a) shows the mobility components for the Si-face with a P-well concentration of 1E18 cm^{-3} towards illustration. Here, following the Matthiessen's rule, we observe that the total channel mobility is determined by the RCS and SP terms which are predominant scattering mechanisms. Further, at very high gate biases the channel mobility is limited by the SP term alone. The mobility components for a-face and Si-face are shown in Figure 5 b) and 5 c), respectively. Note, here we have excluded the total channel mobility in this graph for adding clarity – but since these components are added using the Matthiessen's rule, the lowest value is dominant contributor towards the total channel mobility as a function of applied E-field. The solid lines in this plot represent the mobility components at room temperature and the dashed lines represent the components at 200°C. First, we observe that our revised channel model predicts that the peak value of channel mobility is determined by the cross-over between the RCS and SP terms across the temperature range considered (between 25-200°C). Next the peak channel mobility is determined by the cross-over between the RCS and SP terms which are the lowest components as a function of applied E-field/gate bias. The higher density of interface traps (D_{it}) present at the Si-face results in stronger Coulomb scattering and thus limiting RCS component. Similarly, for Si-face, the stronger surface phonon scattering also limits the peak channel mobility. In contrast to these observations, for a-face, we observe that the RCS mobility is much higher due to lower interface trap density (D_{it}) along the a-face orientation. Furthermore, the SP limited mobility is also higher for a-face compared to Si-face – which explains the enhancement of peak channel mobility going from the Si-face to a-face. The temperature dependence of the peak channel mobility can be understood as follows. For both the Si-face and a-face the SP mobility is reduced with increasing temperature. However, for the Si-face the RCS slope at 200°C is strongly enhanced and the cross-over indicates higher peak channel mobility at 200°C compared to 25°C. Whereas, for the a-face, the RCS mobility is weakly enhanced at 200°C compared to 25°C and the cross-over is dominated by the reduction of SP mobility with increasing temperatures.

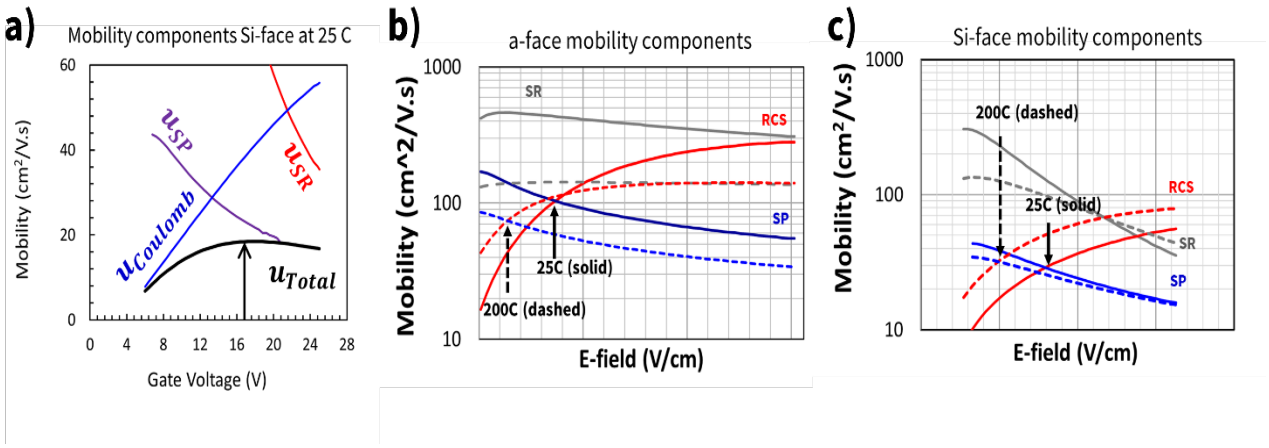

Fig. 5. a) Mobility components for Si-face at 25°C – the peak value of the total channel mobility is determined by the cross-over of the RCS and SP terms b) Mobility components for Si-face at 25°C (solid lines) and 200°C (dashed lines) c) Mobility components for a-face at 25°C (solid lines) and 200°C (dashed lines) – note the total mobility term is not shown in the graph for clarity.

Conclusions

In this paper, we presented TCAD modelling of the channel mobility for lateral MOSFET test structures created using the Si-face and a-face orientations. A revision of standard mobility model is necessary to capture the unique material properties of 4H-SiC crystal. We developed channel mobility models for both the Si-face and a-face orientations. The TCAD results are in excellent agreement with measured data and successfully predict the channel mobility curve along with their temperature dependence. The mobility component analysis further reveals the complex interplay among the various scattering mechanisms that are responsible for determining the total channel mobility. In conclusion, our revised channel mobility models allow us to predict the anisotropic nature of channel mobility and thereby perform predictive TCAD simulations of 4H-SiC MOSFETs.

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