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Revised Channel Mobility Model for Predictive TCAD Simulations of 4H-SiC MOSFETs

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Keywords: TCAD, 4H-SiC MOSFET, channel mobility.

Abstract. We present a revised channel mobility model for 4H-SiC MOSFETs. Mobility measurements are performed on 4H-SiC lateral MOSFET test structures in the temperature range of 25-175 °C. We observe that the temperature and P-well concentration dependence of channel mobility cannot be predicted by popular mobility models available within commercial TCAD tools. A careful investigation revels that channel mobility components need to be revised and replaced using a comprehensive model that accurately describes the predominant scattering mechanisms. We present a well calibrated channel mobility model for 4H-SiC using a revised treatment of bulk, surface roughness and surface phonon components. An excellent agreement with measured data is obtained using this model, making it more suitable for predictive device simulation using TCAD tools.

Introduction

The promising properties of 4H-SiC based MOSFETs, such as low on-state resistance (R_{ON}), faster switching and ability to operate at higher temperature than Si counterparts, make them a very attractive option for a wide range of applications in the power electronics market [1]. Further, the progress in crystal growth techniques has enabled manufacturing of 200mm wafers allowing for cost effectiveness of 4H-SiC power MOSFETs. Technology Computer Aided Design (TCAD) simulations are useful to accelerate the development cycles for next generation of power MOSFETs. Channel mobility is one of the key factors in improving R_{ON}, but the limiting factors that determine the realistic channel mobility values in 4H-SiC MOSFETs are contentious [2-4]. We observe that the existing TCAD channel mobility models are not adequate in describing both the temperature & P-well concentration dependence simultaneously, and therefore lacks in their predictive capability for new device designs. We present a revised channel mobility model that is well calibrated and shows an excellent match with the available measured data from lateral 4H-SiC MOSFETs.

Experimental results

Lateral MOSFETs used in this paper are test structures designed over a wide range of average P-well doping concentrations (between ~ 4E16 up to ~1E18). Figure 1 shows the schematic structure of the lateral MOSFET and Table 1 lists the average P-well concentrations for the six lateral MOSFETs fabricated. Temperature dependent drain current (I_d) versus gate bias (V_g) characteristics are measured for each P-well concentration and are shown in Figure 2. The drain current increases with decreasing P-well doping concentrations and with increasing temperature for a given concentration, as illustrated in these figures. The field effect channel mobility is calculated using the derivatives of the I_d-V_g characteristics and are shown in Figure 3, for their P-well concentration & temperature dependence, respectively. The peak channel mobility decreases with increasing P-well concentration whereas it increases with increasing temperature for all the measured structures.

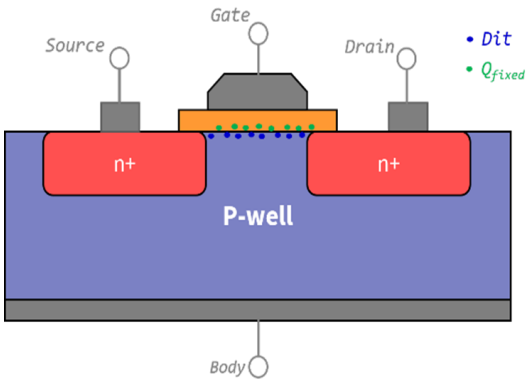

Table 1: Average P-well concentration

P-well	Concentration (cm^{-3})
1	1.0E18
2	8.5E17
3	6.3E17
4	5.3E17
5	4.5E17
6	3.6E17

Fig. 1. Schematic diagram for a Lateral MOSFET structure and associated table for average P-well concentrations.

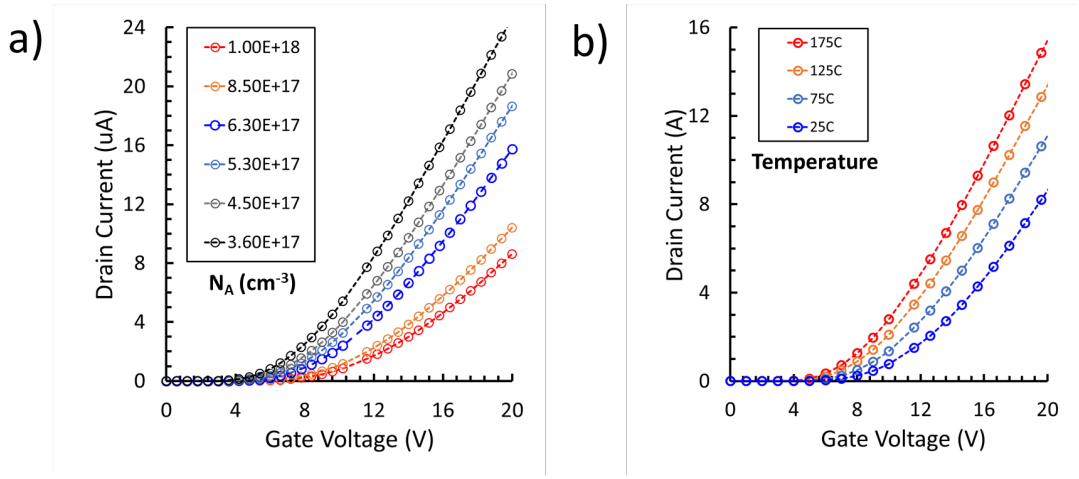

Fig. 2. a) Measured I_d-V_g characteristics for all P-well concentrations, b) representative temperature dependence of drain current for the highest P-well concentration (~1E18).

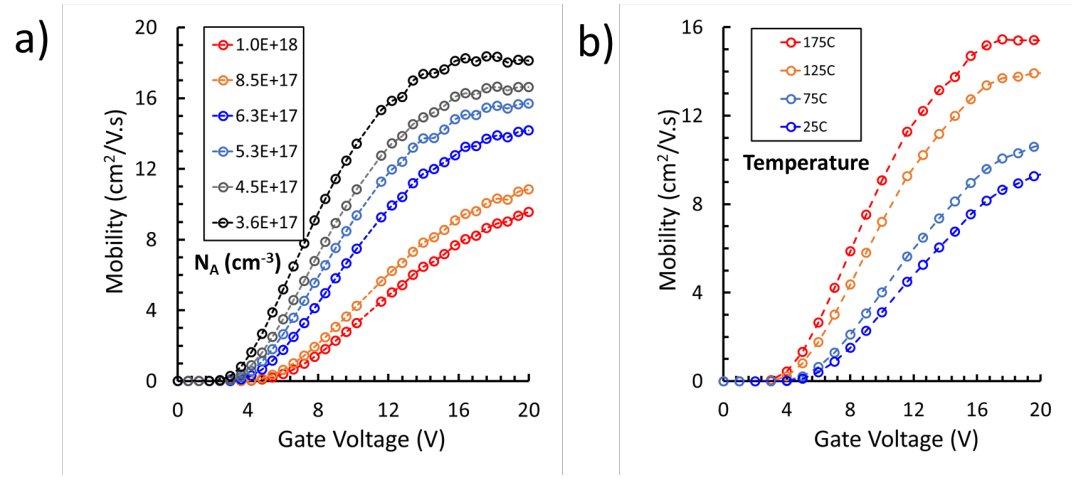

Fig. 3. a) Calculated field effect channel mobility using I_d-V_g characteristics for all P-well concentrations; the peak mobility decreases with increasing P-well concentration. b) Representative temperature dependence of channel mobility for the highest P-well concentration (~1E18).

Results and Discussion

Results using existing channel mobility model

TCAD simulations are performed using the Silvaco Victory Process and Victory Device tools [5]. The channel mobility model consists of bulk, Surface Roughness (SR), Surface Phonon (SP), and Remote Coulomb Scattering (RCS) terms combined using the Matthiessen's rule. One of the popular

channel mobility models for 4H-SiC is proposed by V. Uhnevionak et. al. [6] and is also available in commercial TCAD tool. V. Uhnevionak et. al. performed a very similar experiment of measuring the channel mobility across varying P-well concentrations and temperatures, using 4H-SiC lateral MOSFETs. We tested this model with a revised calibration of parameters, however, noticed following limitations. Figures 4 a), b) show the results for the temperature dependence of peak mobility – measured for another Lateral MOSFET structure with p-Well concentration of 4E16, and c) shows overall fitting across a wide-range of P-well concentrations. Here we observe that, although a qualitative match in Region I (initial portion of channel mobility up to 8 V of V_g) is observed, the model does not predict the increasing peak mobility with increasing temperature as observed in measurement. Secondly, the calculated field effect channel mobility curves, using a recalibrated set of model parameters, also do not show a quantitative agreement with measurements across the P-well concentrations. Thus, due to lack of quantitative match with measurements and due to inability in predicting the temperature dependence of the peak mobility, the model needs to be revised.

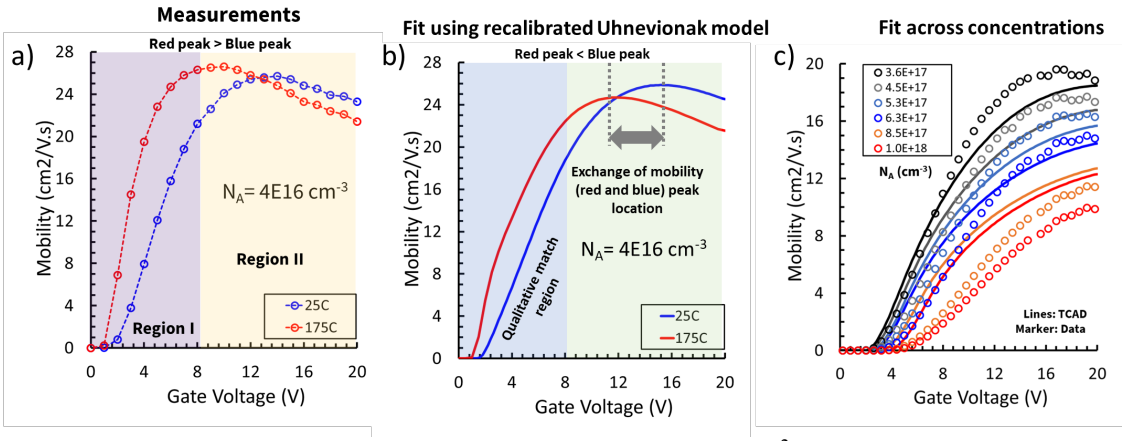

Fig. 4. a) Measured field effect channel mobility (N_A = 4E16cm^{-3}), b) corresponding field effect channel mobility calculated using recalibrated Uhnevionak model and c) fit using recalibrated Uhnevionak model across the P-well concentrations (~ 3.6E17 up to 1E18).

Results using revised channel mobility model

The channel mobility model consists of four components – bulk, SP, SR and RCS. Previously, the bulk component has been modeled using the well-known Caughey-Thomas model [3]. However, we observed that the Caughey-Thomas bulk mobility model needs to be replaced by a revised bulk mobility model for 4H-SiC [7] based on the Klaassen approach [8-9]. The revised bulk mobility model more accurately describes the temperature dependence of electron mobility. The other important components of channel mobility are the SR and SP terms, which we model here using the Lombardi CVT approach, which was originally proposed for Silicon [10]. We performed an extensive recalibration of the SR and SP model parameters against measured hardware data, which leads to a different set of parameters developed for 4H-SiC. The RCS component is universal in nature and only the model parameters needs to be calibrated. The RCS terms need interface trap density and fixed charges as inputs. The interface trap density near the conduction band is measured using the high-low C-V technique. The fixed charge at the interface depends on the P-well surface concentration and is treated as a calibration parameter.

The results with a revised channel mobility model are shown in Figure 5. As evident from these results, we obtain an excellent match with the measured data across a wide range of P-well doping concentrations and across the multiple temperatures (ranging between 25-175 °C). Thus, our revised channel mobility model shows predictive capability for both varying P-well concentrations and measurements performed across multiple temperatures, simultaneously. Such an excellent fit indicates the predictive ability of our revised channel mobility model, as the single set of well-calibrated mobility model parameters allows an excellent matching across the concentrations and multiple temperatures.

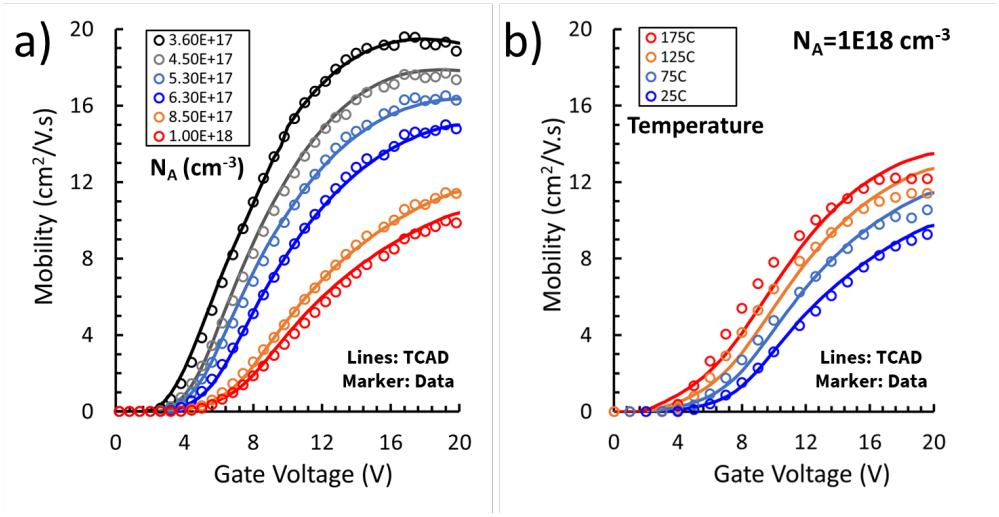

Fig. 5. a) Mobility match across a wide range of P-well concentrations (~ 3.5E17 up to 1E18) using the revised channel mobility model and b) mobility match across temperatures for a representative highest concentration case (N_A = 1E18 cm^{-3}).

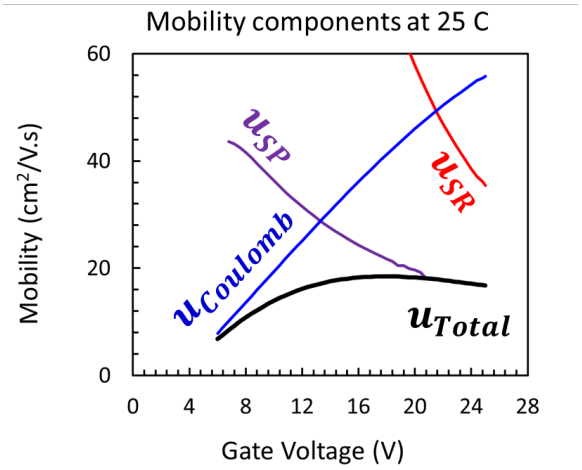

Fig. 6. Calculated channel mobility components of the field effect channel mobility. The SP and RCS mechanisms are predominant scattering mechanisms that determine peak mobility value.

Channel mobility components derived from revised channel mobility model

A careful component wise analysis of the revised channel model reveals that the peak value of channel mobility is determined by the cross-over between the RCS and SP terms (see Figure 6). This is different from earlier reports [6,11,12] which indicate that RCS and SR are predominant scattering mechanisms that limit the channel mobility in 4H-SiC MOSFETs. Our component-wise analysis, however, agrees with the recently reported Hall mobility measurements on 4H-SiC lateral MOSFET structures [13]. Further, our revised model predicts the contribution of interface traps needs to be lowered to improve the peak channel mobility, which agrees with widely reported process improvements. The reduction of the interface trap density changes the slope of the RCS component allowing for an improved peak channel mobility and corresponding reduction in channel resistance contribution to the total on-state resistance of power MOSFETs.

Conclusions

In this paper, we presented a revised channel mobility model for 4H-SiC power MOSFETs. We obtain an excellent match with the measured data across a wide range of P-well doping concentrations and across the multiple temperatures (ranging between 25-175 °C). The component-wise analysis

indicate that the RCS and SP terms are predominant scattering mechanisms that limit the channel mobility in 4H-SiC MOSFETs. Our findings although different from earlier reports, agrees well with the recent Hall measurements on 4H-SiC lateral MOSFETs and provide crucial insights into the engineering approaches for improving the channel mobility.

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