

Temperature Dependent Electrical Properties of n-Type 4H-SiC Substrates

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Abstract. High-quality, low resistivity n-type (nitrogen-doped) single crystal 4H-SiC wafers are needed to grow high-quality epitaxial SiC layers used for the active blocking layers of high-voltage power devices. The resistance of the substrate constitutes a portion of the device resistance for vertical devices, and therefore the SiC substrate properties must be fully characterized. In this study we report the 4H-SiC substrate electrical properties as a function of temperature measured using van der Pauw structures to measure resistivity from 4-point measurements, and carrier concentration and mobility from Hall effect measurements. We find that the SiC substrate resistivity has a minimum around 425K for typical substrate doping levels, due to a competition between the decreasing mobility and increasing carrier concentration with increasing temperature. The measured energy levels of the N donor (hexagonal / cubic sites) are extracted for a $5.8 \times 10^{18} \text{ cm}^{-3}$ N-doped substrate, and found to be 15 meV and 105 meV, respectively.

Introduction

High-quality, low resistivity nitrogen-doped single crystal 4H-SiC wafers of up to 200mm diameter have enabled high-volume manufacturing of 4H-SiC vertical power devices, such as Schottky diodes, MOSFETs, and JFETs. High-quality substrates are needed to grow high-quality epitaxial SiC layers used for the active blocking layers of these high-voltage power devices. The resistance of the substrate constitutes a portion of the device resistance for vertical devices, and therefore the SiC substrate properties must be fully characterized. Many studies of the SiC electrical properties as a function of nitrogen doping have been carried out [1-6], usually focusing on the epitaxial, lower-doped drift layers, which have been well characterized. An issue in SiC is that dopant activation is typically not 100%, and the activated dopants are not fully ionized at room temperature due to the rather large energy levels of the dopants, compared to dopants in Si. Thus, merely knowing the dopant concentration via SIMS measurements is not enough to characterize the material's electrical properties. In this study, commercial Wolfspeed 150mm N-doped substrates were characterized using Hall measurements, to extract the resistivity, carrier concentration, and mobility as a function of temperature. Thus the effects of the substrate properties can better be taken into account when considering device design and modeling.

Experimental

In this study we report the 4H-SiC substrate electrical properties as a function of temperature measured using van der Pauw structures to measure resistivity from 4-point measurements, and carrier concentration and mobility from Hall effect measurements, using an Ecopia HMS-5500 system with sample heating and cooling capability. Samples used were 1cm x 1cm pieces from double-side polished 150mm Wolfspeed SiC wafers, with known different resistivity values.

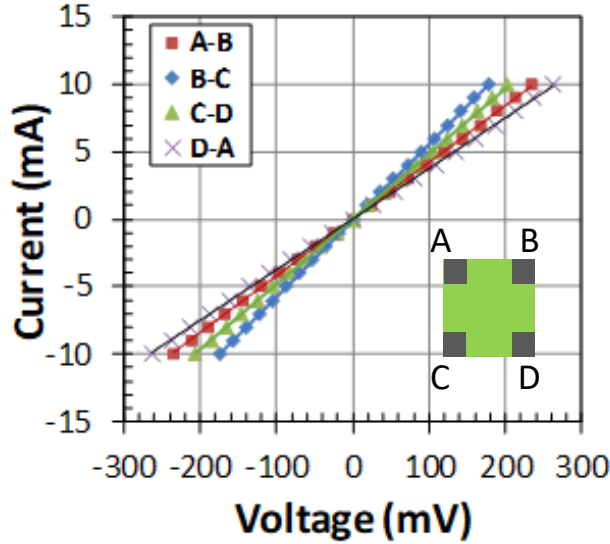


Fig. 1. I-V curves showing ohmic contact behavior at 300K for a 1x1cm² Si-face van der Pauw sample.

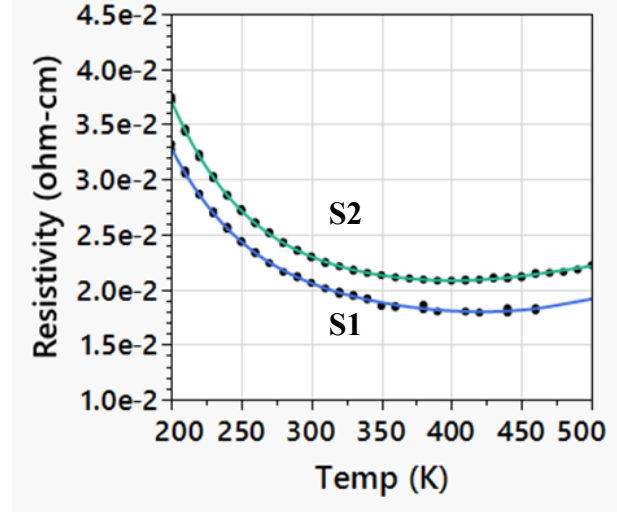


Fig. 2. Resistivity versus temperature for two Si-face SiC pieces with different doping levels.

Samples shown here are from Si-face (0001) wafers with the standard 4° off-axis cut. SiC properties are expected to be isotropic within this plane [2]. Ni contacts (40nm) with a thin Au cap layer were evaporated onto the corners and annealed at 950 °C for 30sec. The contact size is small enough to not affect the values extracted from the Hall measurements by more than a few percent [7].

Results and Discussion

Figure 1 shows the set of I-V curves across each of the 4 contacts (A-D) of a Si-face 1cm x 1cm sample measured at 300K (room temperature) along with linear fits to each data set, indicating the ohmic behavior of the Ni contacts. Figure 2 shows the resistivity versus temperature for two differently doped Si-face substrates (note that the lines in Figs. 2, 3, and 5 are polynomial fits to the data to reveal trends). Both samples show that the substrate portion of device resistance will decrease as the die goes from room temperature to 175 °C (448K); 175 °C is a typical maximum rated temperature for packaged power devices. This is opposite to the behavior of the lower-doped epi drift region [5], but is expected for these very high SiC doping levels, similar to reports of epi-grown [5] or implanted [3] highly N-doped 4H-SiC. These substrate properties need to be accounted for when considering the temperature coefficient of resistance for a vertical power device on SiC. Note also that as the temperature decreases below room temperature, the resistivity increases as well; this also agrees with [5] for samples with relatively similar doping levels.

The Hall measurement results reveal that this nonlinear resistivity is due to competing effects of incomplete ionization, and the temperature and doping dependence of mobility, which are different at these high doping levels compared to low-doped drift epilayers. Figure 3 shows that the free carrier concentration increases with temperature, indicative of incomplete ionization. Secondary ion mass

spectrometry (SIMS) indicates sample S1 has a N content of $5.8 \times 10^{18} \text{ cm}^{-3}$, and S2 has a N content of $4.5 \times 10^{18} \text{ cm}^{-3}$; which should represent the maximum of the carrier concentrations in Fig. 3 if temperature were increased further. Using the neutrality equation as described in various references [1-6] and using a cubic to hexagonal site ratio of unity allows extracting the energy levels of the two dopant sites (hexagonal sites (h), and cubic sites (k)) predicted for N-doped 4H-SiC [1-6]. In the calculations we have used a compensation level of $5 \times 10^{13} \text{ cm}^{-3}$, a degeneracy factor of 2 [3], used 3 for the number of conduction band minima [5], and an electron effective mass of 0.40 eV [3,6]. For example, shown in Fig. 4 are fits for sample S1, from which the donor levels extracted are $E_{dh}=15 \text{ meV}$ and $E_{dk}=105 \text{ meV}$, for the hexagonal and cubic sites, respectively. We find that the energy level of the hexagonal site is much lower than that published for lower doped SiC epitaxial material (expected due to band narrowing and impurity band effects [6]), while the energy level of the cubic

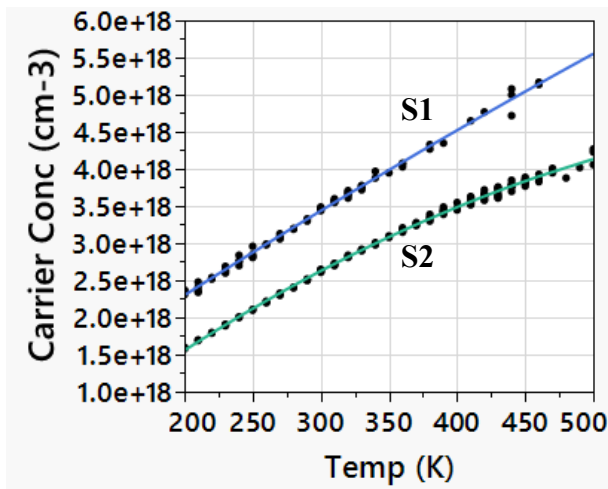


Fig. 3. Carrier concentration of the Si-face samples S1 and S2 from the Hall measurement.

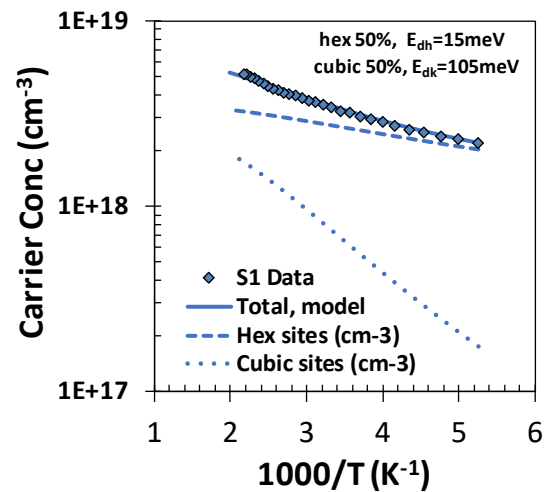


Fig. 4. Hall carrier concentration versus reciprocal temperature for sample S1.

site is not decreasing in a similar manner. This cubic site donor level fitting may be influenced by a potentially deeper 3rd level as mentioned in [2] (as shown by the measured carrier concentration in Fig. 4 exceeding the modeled value at low $1000/T$ values), so the cubic site fit shown here may be overestimating the depth of this donor.

The Hall mobility at these high doping levels decreases at low temperatures, as shown in Fig. 5, consistent with other reports [4,5] for highly doped SiC; not fitting the Caughey-Thomas mobility model at low temperatures (which does not allow for mobility decrease at low temperatures). We use a Hall scattering factor (r_H) of unity, as described by Pernot et al. [4], for the Hall mobility determination. An interesting result of this behavior of a resistivity minimum (and mobility peak) versus temperature is shown in Fig. 6, showing the Hall mobility as a function of the temperature-dependent free carrier concentration. For two differently doped SiC samples, at a similar free carrier concentration, the mobility can be very different (due to being at different temperatures). This is a result of the temperature dependence of the dopant ionization and the carrier scattering mechanisms.

Because current in a vertical power device also flows along the [0001] direction, perpendicular to the Si-face plane, we also measured m-face van der Pauw samples. These were found to have essentially identical behavior to the Si-face samples for similar doping. As these samples are expected to be anisotropic [2] because they contain both [0001] and [11-20] in-plane directions, we cannot say

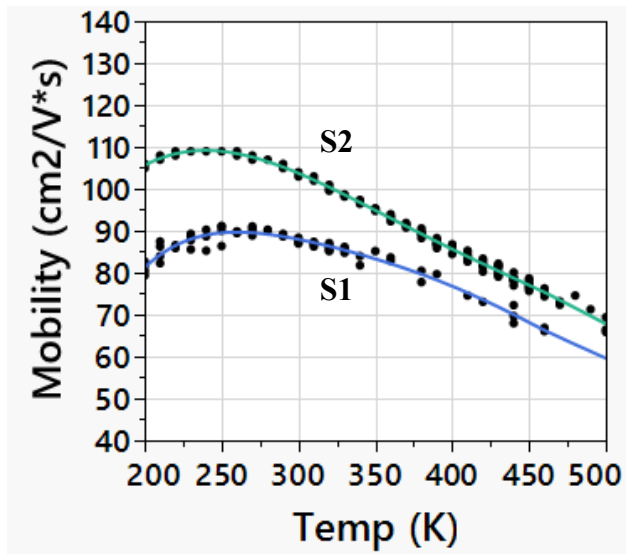


Fig. 5. Hall mobility versus temperature for the Si-face samples S1 and S2.

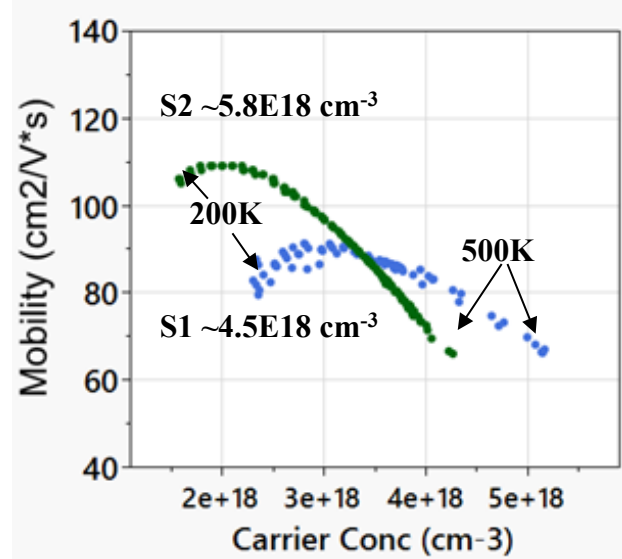


Fig. 6. Hall mobility vs free carrier concentration for the Si-face samples, in the T range of 200-500K.

conclusively what are the electrical properties in the [0001] direction, but we can confirm that the resistivity is not higher in that direction. More studies with structures such as Hall bars are needed to resolve the question of mobility anisotropy in highly-doped SiC substrates.

Summary

Substrates for SiC power devices are highly N-doped in order to have good electron conductivity. Resistivity and Hall measurements as a function of temperature reveal nonlinear behavior. At high temperature the increase in carrier concentration is indicative of incomplete ionization at room temperature; the dopant energy levels of the N donor (hexagonal / cubic sites) are extracted for a $6 \times 10^{18} \text{ cm}^{-3}$ N-doped substrate, and found to be 15 meV and 105 meV, respectively. The increase in resistivity at low temperature is due to the mobility decrease caused by impurity scattering, and the reduction in free carrier concentration. This behavior follows the expected trends for very highly doped SiC, and is important to consider when determining the effects of the SiC substrate resistance on device properties.

References

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