Temperature-Dependent Study of 6H-SiC PiN-Diode Reverse Characteristics

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Silicon Carbide is a promising material for special semiconductor applications, such as high-power and high-temperature devices. To date, much effort has been devoted to improving the process and device technology. With the progress in this field, the need for accurate modeling of device characteristics arises. This implies the formulation of proper physical models and their validation.

We report on investigations of the reverse characteristics of a 6H-SiC pin diode using the multi-dimensional device simulator DESSIS$_{-ISE}$ [1] discussing the contributions of different physical mechanisms to the blocking behavior and their temperature dependence in the range of 300 - 623,K. The device structure and the doping profile reported in Ref. [2] are shown in Fig.1.

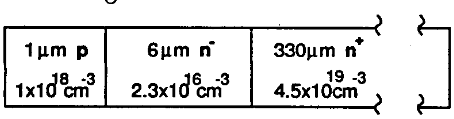

Figure 1: *Schematic of the simulated 6H-SiC pin diode.*

The strong field dependence indicates that it is appearently dominated by field-assisted thermal generation processes until avalanche breakdown sets on at 710 V (Fig.3). This finding also suggests that other mechanisms like surface leakage are of minor importance. A similar behavior of the reverse current is known from silicon pn junctions in the regime of field-enhanced SRH recombination. In principle, the field dependence of SRH lifetimes can originate from both the Franz-Keldysh effect (band-state field effect) and from the Poole-Frenkel effect (bound-state field effect). The latter occurs in the case of charged recombination centers. Field-enhancement factors are implemented in DESSIS$_{-ISE}$ based on the theory of tunnel-assisted multiphonon capture and emission, in which the band-state field effect is exploited [3]. In a similar way we derived the corresponding expressions for the case, when the field effect is caused by the lowering of the Coulomb barrier in the vicinity of donor- or acceptor-like recombination centers [4]. The lifetimes are reduced by a factor

$$g(F) = \left(\frac{E_t(0) + \epsilon_R}{E_t(F) + \epsilon_R}\right)^{3/2} e^{\frac{\Delta E_{PF}[E_t(0)+\epsilon_R]}{2\epsilon_R kT}}$$

where $E_t(0) - E_t(F) = \Delta E_{PF}$ is the reduction of the thermal depth of the recombination center, ΔE_{PF} denotes the barrier lowering according to the 1D Poole-Frenkel model: $\Delta E_{PF} = q(qF/\pi\epsilon)^{1/2}$, and ϵ_R is the lattice relaxation energy. The reduction factor is applied either to τ_n (donor-like center) or to τ_p (acceptor-like center).

In Fig.2 reverse characteristic for 623 K was simulated with the standard SRH model ("SRH", lifetimes $3 \times 10^{-7}\,s$), using different generation models: The standard SRH

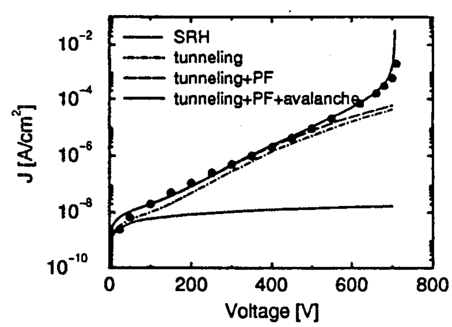

Figure 2: *Influence of different generation models on the reverse current density.*

model, the tunnel-assisted SRH model ("tunneling", lattice relaxation energy $592\,meV$), both tunnel-assisted SRH recombination and Poole-Frenkel effect in combination ("tunneling+PF"), and additionally impact ionization included ("tunneling+PF+avalanche"). The remaining physical parameters, as far as known for SiC, were adapted from Ref. [5], otherwise Si default parameters were used [1]. In the high-temperature regime, the simulated slope is in excellent agreement with the measured characteristics. As expected, the influence of the Poole-Frenkel effect is small in the high-field range.

It is important to note that these results rely on the assumption of thermal excitation of free electrons and holes via deep centers in the wide-gap material as described by the ideal diode theory. In the reverse-biased diode the generation current is proportional to the ratio $n_i/\tau_{n,p}$, hence the temperature dependence of the reverse current is governed by that of the intrinsic density $n_i(T)$. Lowering the temperature to 300 K reduces n_i to $10^{-6}\,cm^{-3}$. As a consequence, the current decreases to a value as low as $10^{-20}\,Acm^{-2}$. The striking discrepancy to the measured data is shown in Fig.3. One should note that the simulation of these extremely small currents becomes only possible thanks to an advanced domain integration technique [6].

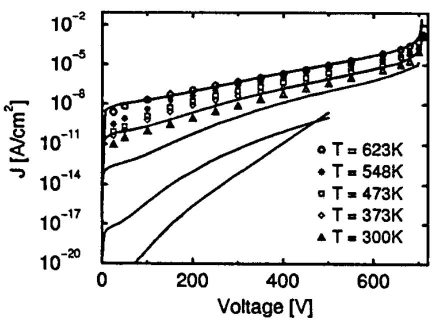

Figure 3: *Comparison of measured and simulated reverse current densities at different temperatures.*

The disagreement of the 300 K data by more than 10 orders of magnitude raises serious questions about the actual conduction mechanism, the validity of the standard SRH formula in this context, and the origin of an "intrinsic density". Since the generation of the free carriers which conduct the large measured current is restricted to the depletion zone for the large measured current (again provided that no other leakage mechanism is present), we adhered to the assumption that the generation rate is still determined by n_i^{app}/τ, but readjusted the value of the apparent intrinsic density $n_i^{app}(T)$ for each temperature. This fit is presented in Fig.4. The extracted values of

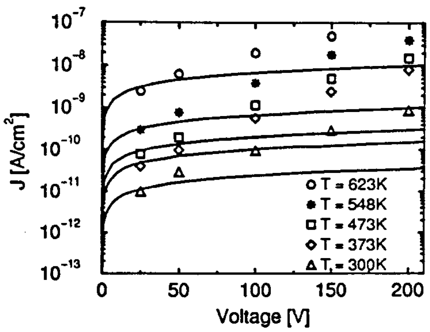

Figure 4: *Fit of the low-field reverse characteristics assuming constant lifetimes and adjusting $n_i^{app}(T)$ for each temperature.*

the apparent intrinsic density are plotted in Fig.5 as function of $1/T$. Assuming an activation law as $n_i^{app}(T) = n_{i,0}\exp(-E_{act}/kT)$ one can distinguish a high- and a low-temperature activation energy (dashed lines). The fitted values are 945 meV and 190 meV, respectively. The tendency of a decreasing E_{act} with decreasing temperature with values much lower than $E_g/2$ suggests a low-temperature conduction mechanism different from the normal transport in the bands. This implies a nonvanishing density of states in the gap, the origin of which still has to be clarified.

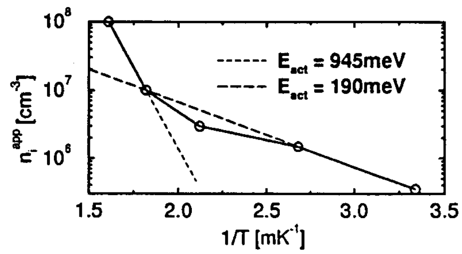

Figure 5: *Arrhenius plot of the extracted apparent intrinsic density.*

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