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

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A numerical analysis of the static forward and reverse characteristics of 6H-SiC PIN-diodes has been performed across a temperature range of 300 - 623 K. Using the device simulator Dessis$_{\text{-ISE}}$ we discuss the contributions of different physical mechanisms to the device behavior including field dependent recombination due to the Franz-Keldysh and the Poole-Frenkel effect. Numerical investigations of the blocking behavior at lower temperatures yield low activation energies of 0.2 - 1 eV for the measured reverse current.

I. Introduction

Silicon Carbide (SiC) 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 [1]. 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.

Pelaz et al. reported on the influence of the Poole Frenkel effect on PIN-diodes forward characteristics [3]. Up to now, the reverse characteristics couldn't be analysed in the low temperature range due to the extremly low density of minority carriers resulting from the wide band gap of SiC and the associated numerical instabilities. Using an advanced domain integration technique [4], the complete temperature range in reverse direction can now be analysed as well.

The device structure and the doping profile reported in Ref. [2] are shown in Fig.1. The strong field dependence of the reverse characteristics indicates that they are appearently dominated by field-assisted thermal generation processes as well until avalanche breakdown sets on at 710 V (Fig.6). This finding also suggests that other mechanisms like surface leakage are of minor importance [10].

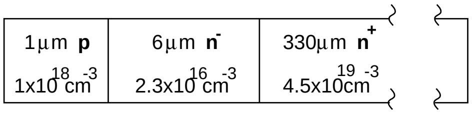

Fig. 1. *Schematic of the simulated 6H-SiC pin diode.*

Using the multi-dimensional device simulator Dessis$_{\text{-ISE}}$ [8] we discuss in this paper the contributions of different physical mechanisms to the forward and reverse characteristics and their temperature dependence in the range of 300 - 623 K. To account for the observed field dependence of recombination and generation, analytical formulas for field dependend lifetimes within the Shockley-Read-Hall (SRH) regime have been derived from a microscopic level modelling the Franz-Keldysh effect and the Poole-Frenkel effect. The difference between the simulation results and the measured data of the blocking behavior at low temperatures is discussed and activation energies for the measured reverse current densities are extracted using an apparent intrinsic density as fit parameter.

II. Modelling

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 Franz-Keldysh effect leads to a non-vanishing tunneling probability for electrons and holes due to a change of the density of states near the band edges because of strong electric fields (Fig.3). The Poole-Frenkel effect occurs in the case of charged recombination centers. The electronic structure of the localized states in the band gap are changed due to the bend of the band edges, thus lowering the thermal energy barrier for generation or recombination (Fig.2).

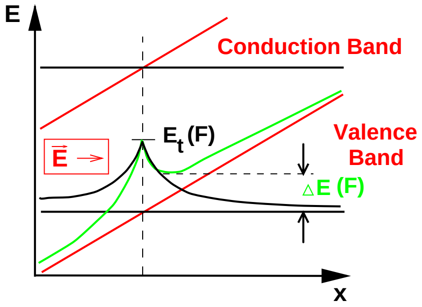

Fig. 2. *Energy band diagram illustrating the Franz-Keldysh effect.*

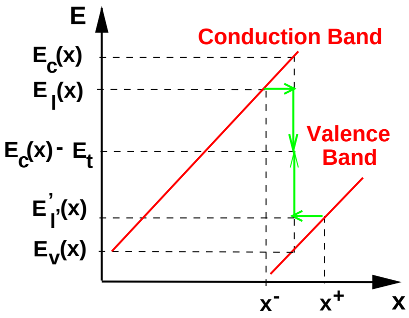

Fig. 3. *Energy band diagram illustrating the Poole-Frenkel effect.*

The SRH rate is determined by [5]:

$$R^{SRH} = \frac{np-n_i^2}{\tau_p(F)[n+n_i\, exp((E_t-E_i)/kt)]+\tau_n(F)[p+n_i\, exp((E_i-E_t)/kt)]}$$

where n and p are the electron and hole densities, n_i id the effective intrinsic carrier concentration, E_t and E_i are the trap energy and the intrinsic fermi level energy, respectively. The field dependence of the lifetimes

$$\tau_\alpha\,(F) = \frac{\tau_{\alpha,o}}{1+g(F)} \quad , \quad \alpha = n, p$$

is expressed by means of field-enhancement factors $g\,(F)$. The SRH-lifetimes in the absence of field influence are defined by

$$\tau_\alpha = \frac{1}{C_\alpha N_t} \quad , \quad \alpha = n, p$$

where N_t is the trap density and C_α is the XXX for electrons and holes, respectively.

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 [6]. 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 [7]. 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).

III. SIMULATION RESULTS

In Fig.4 the forward characteristic across the complete temperature range have been simulated accouting for phonon-assisted band-to-band Auger recombination and SRH recombination including the Franz-Keldysh effect and the Poole-Frenkel effect.

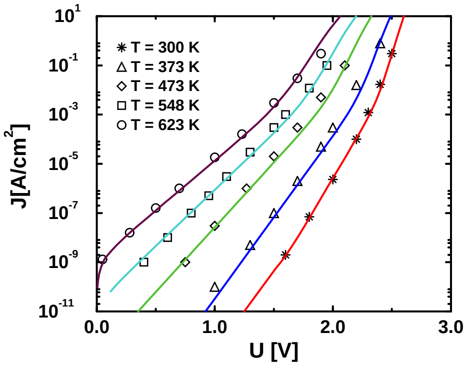

Fig. 4. *Forward characteristics across the complete temperature range.*

Due to the low electric fields and the non-degenerately doped material, only the

Poole-Frenkel mechanism influences the behavior resulting in a larger ideality factor in the recombination dominated range. The resulting SRH-lifetimes are $3 \times 10^{-7}\,s$ for electrons and holes, respectively. The remaining physical parameters, as far as known for 6H-SiC, were adapted from Ref. [9], otherwise Si default parameters were used [8].

Without changing any parameters, the reverse characteristic for 623 K was simulated with the standard SRH model (Fig.5), using different generation models: The standard SRH 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").

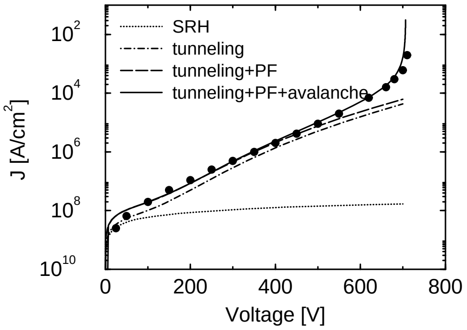

Fig. 5. *Influence of different generation models on the reverse current density.*

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.6. The influence of the energy level of the recombination center has been analysed as well. It was found to be of minor influence as well as the temperature dependence of the lifetimes due to a change of C_α.

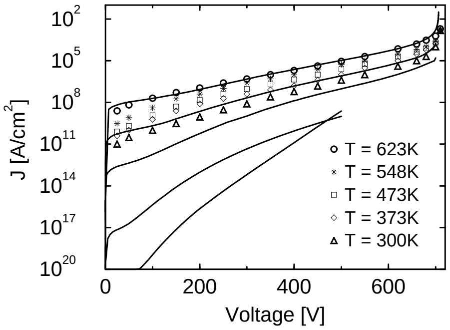

Fig. 6. *Comparison of measured and simulated reverse current densities at different temperatures.*

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.7.

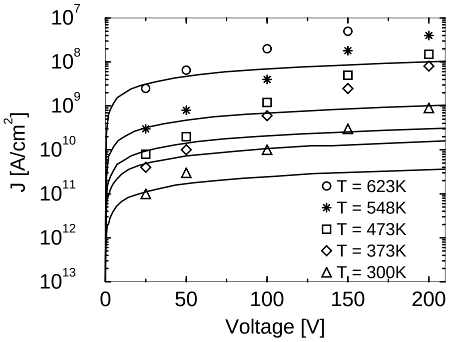

Fig. 7. *Fit of the low-field reverse characteristics assuming constant lifetimes and adjusting $n_i^{app}(T)$ for each temperature.*

The extracted values of the apparent intrinsic density are plotted in Fig.8 as function of $1/T$. Assuming an activation law as $n_i^{app}(T) = n_{i,0}^{app}\exp(-E_{act}/kT)$ one can distinguish a high- and a low-temperature activation energy (dashed lines). The fitted values are $945\,\mathrm{meV}$ and $190\,\mathrm{meV}$, 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. An experimental characterisation of electron-hole generation in SiC has yield similar activation energies for defect-related generation [10].

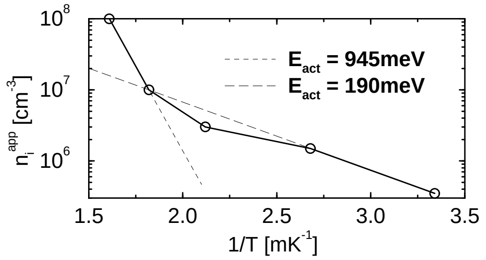

Fig. 8. *Arrhenius plot of the extracted apparent intrinsic density.*

IV. Conclusion

A complete numerical investigation of the static behavior of a wide band gap material such as SiC can be performed based on drift-diffusion simulations. Accounting for field-dependent generation-recombination mechanisms, a good agreement between measured and simulated data has been achieved for forward bias across a temperature range of $300 - 623\,K$ and reverse bias at $623\ K$. On the other hand, the field-dependend recombination-generation mechanisms cannot explain the large measured reverse current densities at lower temperatures far away from the theoretical values. By using an apparent intrinsic density as fit parameter it has been found, that these reverse currents are activated with Energies within a range of $0.2 - 1\,eV$.

V. Acknowledgement

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References

[1] J. B. Casady, R. W. Johnson, Solid-State Electronics, Vol. 39, No. 10, 1409, (1996)

[2] J. A. Edmond, D. G. Waltz, S. Brueckner, H.S. Kong, J. W. Palmour and H. Carter Jr., Proc. 1^{th} Int. High Temperature Electronics Conf., Albuquerque, N ew Mexico, 500, (1991)

[3] L. Pelaz, J.L. Orantes, J. Vincente, L.A. Bailón, J. Barbolla, IEEE Transactions on Electron Devices, Vol. 41, No. 4, 587, (1994)

[4] P. D. Yoder, K. Gärtner, and W. Fichtner, J. Appl. Phys., Vol. 79, No. 4, 1951, (1996)

[5] W. Shockley, W.T. Read Jr., Phys. Rev., Vol 87, 835 (1952), R.N. Hall, Phys. Rev., Vol 87, 387, (1952)

[6] A. Schenk, Solid State Electronics, Vol 35, No. 11, 1585, (1992)

[7] J. Frenkel, Phys. Rev., Vol 54, 647, (1938)

[8] ISE Integrated Systems Engineering AG, CH, DESSIS user manual 3.0, (1996)

[9] M. Ruff, H. Mitlehner, and R. Helbig, IEEE Transactions on Elelctron Devices, Vol. 41, No. 6, 1040, (1994)

[10] Y. Wang, J.A. Cooper JR., M.R. Melloch, S.T. Sheppard, J. of Electronic Materials, Vol. 25, No. 5, 899, (1996)