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Numerical Design Study on the Optimal p-Emitter Thickness of 4H-SiC Bipolar Diodes

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Abstract

Numerical device simulations show that slight extensions of the p-emitter thickness in 4H-SiC high voltage blocking bipolar pin diodes lead to a significant lowering of the forward voltage drop under high injection conditions at room temperature. The advantage of higher recombination currents in the enlarged p-region resulting from an enhanced excess carrier density overbalances the higher series resistance of the high-doped p-region. Both effects have their origin in the incomplete ionization of the acceptor dopants in the p-emitter. Hence, they become less significant at higher temperatures. A temperature dependent optimal p-emitter thickness is identified.

1 Introduction

A well-known disadvantage of high voltage pin diodes made of 4H-SiC is the high forward voltage drop resulting from the high diffusion voltage and the high on-resistance. Previous investigations have shown that, unexpectedly, at room temperature (RT) the on-resistance of pin diodes equipped with a thick p-emitter is lower than for diodes with a thin p-emitter ($d_p < 1\mu m$) [1].

Implanted p-emitters are limited to a thickness less than $1\mu m$, whereas epitactically grown p-emitters are quite expensive. But manufacturing processes with consecutive n-epitactical growth and p-implantation provide more flexibility in the p-emitter thickness.

One the one hand, a thick p-emitter region leads to an enhanced recombination current in the anode region, but on the other hand constitutes an additional series resistance. The interplay of these two contrary effects for varying thickness of the p-emitter has been studied using numerical device simulation. The results are compared with the measured data reported in [1].

2 Device Structure and Simulation Model

The 4H-SiC pin diodes considered (cf. Fig. 1) have an Al-implanted anode with a p-doping of about $2 \cdot 10^{19} cm^{-3}$ and a thickness d_p varying from $0.4\mu m$ to $10.4\mu m$. The epi-layer is low-doped with a nitrogen concentration of about $10^{15} cm^{-3}$. Epi-layer and n-substrate are linked by an n-buffer. To economize on computational expense, the substrate was modelled as a simple electric resistor. We performed isothermal calibrated device simulations [2] at 300K (=RT) and at 450K using the simulator TeSCA (distributed by WIAS, Berlin). The underlying drift-diffusion model includes the incomplete ionization of the dopants in the carrier balance equations. The effective lifetime in the Shockley-Read-Hall recombination model was assumed to be $180ns$ at RT and $900ns$ at 450K, respectively.

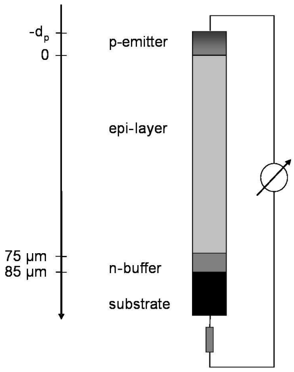

Figure 1: Structure of the investigated pin diodes.

3 Simulation Results

The forward characteristics of the devices investigated are displayed in Fig. 2. The forward voltage drop at 450K is much lower than that at RT mostly because of the considerably longer carrier lifetime at 450K. Evidently, the thickness of the p-emitter region has a significant effect on the forward conductance, which is much more pronounced at RT than at 450K. The forward voltage versus the p-emitter thickness at a nominal current level of $100A/cm^2$ is shown in Fig. 3.

At RT the forward voltage is strongly reduced by extending the width d_p of the p-emitter from $0.4\mu m$ to $5.4\mu m$, where it attains a minimum. Increasing d_p beyond the optimum value leads to a marginally higher forward voltage due to the slightly higher series resistance of the thicker emitter region. At 450K, the dependence of the forward voltage on d_p is much less pronounced, but yet there exists a very flat minimum at $d_p = 4.4\mu m$. For both temperatures, the voltage drop caused by the series resistance of the emitter is virtually negligible. For a doping concentration of $2 \cdot 10^{19} cm^{-3}$, we find an increase of the forward voltage U with d_p as $\frac{U}{d_p} = 6.7\frac{mV}{\mu m}$ at RT and $\frac{U}{d_p} = 2.3\frac{mV}{\mu m}$ at 450K (cf. Fig. 3).

Hence, the change of the forward voltage with d_p is primarily determined by the d_p-induced variation of the emitter efficiency alone, which is much more pronounced at RT than at 450K. This phenomenon will be explained in the following.

4 Analysis of the Emitter Efficiency

The electron diffusion length in the p-emitter amounts to $5.4\mu m$ at RT, and $10.4\mu m$ at 450K. Hence, a considerable fraction of electrons is able to diffuse from the middle

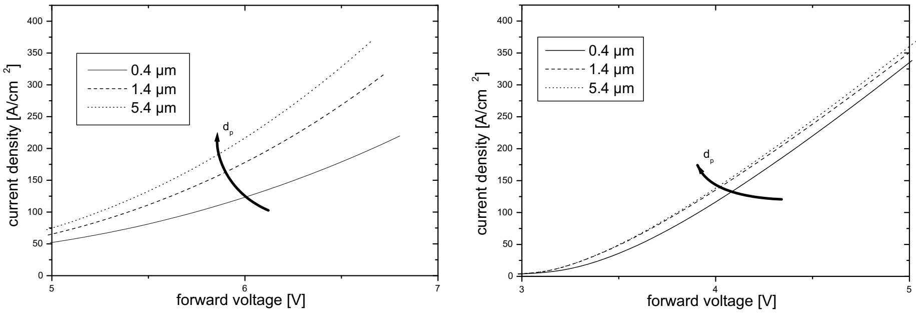

Figure 2: I-V characteristics of the simulated pin diodes at RT (left) and at 450K (right)

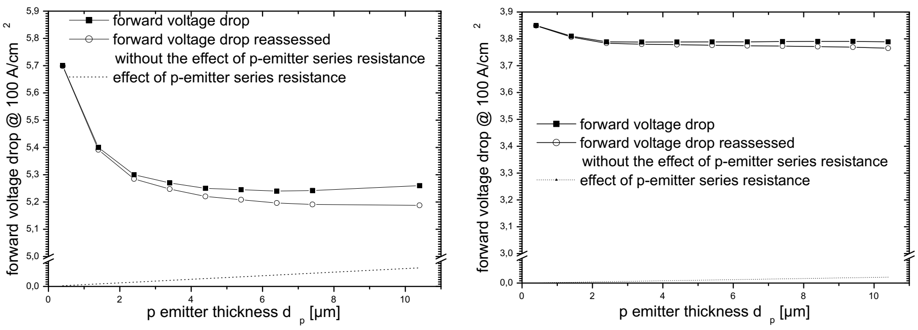

Figure 3: Effect of the p-emitter thickness on the forward voltage drop at $100A/cm^2$ at RT (left) and at 450K (right)

region deeply into the p-emitter (cf. Fig. 4).

But the acceptors in the p-emitter are only partially ionized; hence, the equilibrium concentration p_0 of the holes is, at RT, only 0.97% of the doping level (i.e. $p_0 = 1.95 \cdot 10^{17} cm^{-3}$). At 450K, 6.2% of the acceptors are ionized (i.e. $p_0 = 1.25 \cdot 10^{18} cm^{-3}$).

Consequently, at RT and at a sufficiently high current level ($100A/cm^2$) electrons diffusing into the p-emitter may reach the order of magnitude of the equilibrium concentration of the holes in the vicinity of the pn-junction. In order to compensate the charge of the excess electrons in the p-emitter, the hole concentration has to rise up accordingly.

At 450K, this phenomenon does not occur, because the equilibrium concentration of the holes is substantially higher than that of the diffusing electrons. Therefore, even under high injection conditions in the pin diode, a significant increase of the hole concentration is not observed.

As the recombination is proportional to the product of electron and hole concentrations and the electron and the hole concentrations in the p-emitter region are equally increased at RT, the recombination current flowing through the p-emitter region rises quadratically with the excess concentration, whereas at 450K, it rises approximately linearly, only.

We postulate thermal equilibrium at the anode contact, which sets the boundary value of the electron concentration profile. The wider the space between anode contact and pn-junction, the higher is the peak concentration of the diffusing electrons and the compensating holes at the pn-junction. However, increasing in the p-emitter thickness beyond the diffusion length of the electrons in the p-emitter does not lead to any further enhancement of the recombination current.

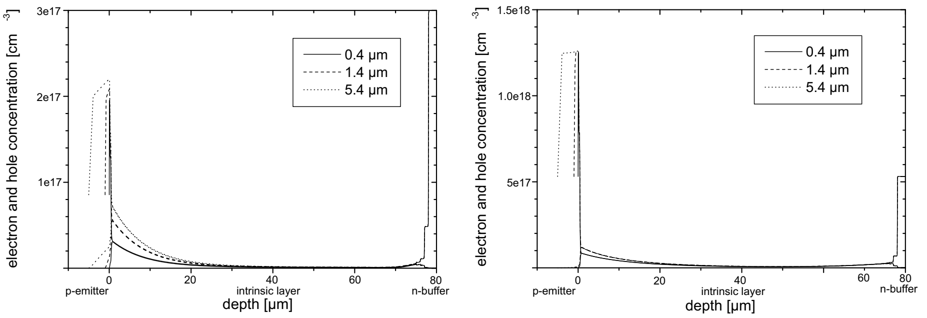

Figure 4: Electron and hole concentration in the pin diodes for a current level of $100A/cm^2$ at RT (left) and at 450K (right)

The simulated results are confirmed by the measured data reported in [1]. Minor discrepancies for very thin p-emitters at RT are explained by self-heating effects at the pn-junction neglected in our isothermal simulation.

5 Conclusion

Extending the width of the p-emitter region of SiC pin diodes effects a significant lowering of the forward voltage drop at RT in consequence of an enhanced recombination current in the p-emitter. Since this phenomenon has its origin in the incomplete ionization of the acceptors in the emitter, it becomes much less significant at higher temperatures.

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References

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