Modeling the temperature-dependent reverse breakdown behavior of GaAs PIN diodes

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Abstract— The demands on modern electronics are constantly increasing. In the field of power electronics, the semiconductor material gallium arsenide (GaAs) is gaining more and more popularity. In this work, a first GaAs PIN Diode for 900 V operation is under investigation. With the help of simulations and measurements, the temperature-dependent reverse breakdown behavior is investigated. An analytical model will be presented, which can reproduce this behavior.

Keywords— GaAs, PIN diode, reverse breakdown, HV measurements, analytical model

1. Introduction

Power electronic components are essential for a variety of applications in automotive, power supply or telecommunications [1]. A basic device is the PIN diode, which is used as a rectifier or in high frequency technologies [2]. In most cases, silicon (Si) is used to manufacture PIN diodes. In the area of power electronics, however, silicon reaches its limits. Currently the semiconductor materials gallium nitride (GaN) and silicon carbide (SiC) are dominating the market [3]. With regard to the material properties the compound semiconductor gallium arsenide (GaAs) has the potential to be a worthy alternative (see Table 1). One of the most important positive properties is the high electron mobility, which is 6-7X the value of Si and 10-12X the value of SiC. Using the high electron mobility and a low defect density a new high speed epitaxial process was developed. So it is possible to produce GaAs PIN diodes with a unique cost to performance ratio in comparison to SiC Schottky diodes or Merged PIN Schottky (MPS) diodes.

Table 1 Material properties of Si, GaAs, GaN and SiC [3].

	Si	**GaAs**	**GaN**	**SiC**
Bandgap energy [eV]	1.12	1.4	3.49	3.26
Breakdown field [MV/cm]	0.3	0.4	3.5	3.0
Electron mobility at 300 K [cm^2/V·s]	1400	8500	900	700
Saturated electron velocity [107 cm/s]	1.0	1.3	1.3	2.0
Relative dielectric constant	11.8	12.8	9.0	10.0
Thermal conductivity [W/cm·K]	1.5	0.5	1.7	3.5

In this work the temperature dependent reverse breakdown behavior of GaAs PIN diodes is investigated with simulations and measurements. Based on these results an analytical model is developed.

2. Results and discussion

A. TCAD simulations

We performed 2D TCAD simulations at different temperatures and reverse bias for a 900 V GaAs PIN diode. With rising temperature the leakage current increases due to additional thermally activated charge carriers. This is a typical behavior of all semiconductor diodes, since the intrinsic conductivity increases with increasing temperature. Furthermore the breakdown voltage increases with rising temperature, assuming that no self-heating takes place (see Fig. 1).

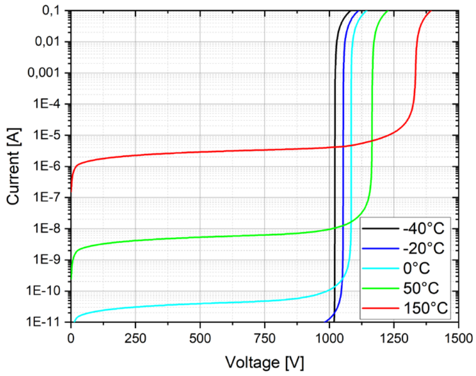

Fig. 1 Simulated IV-characteristic of a reverse biased 900 V GaAs PIN diode [4].

B. High-voltage measurements

The measured first generation diodes were fabricated at 3-5 Power Electronics and are specified up to 900 V [4]. The high voltage measurements were done in a wide temperature range from -40 °C to +150 °C, which is a typical range for automotive applications. The measured IV-curves are shown in Fig. 2.

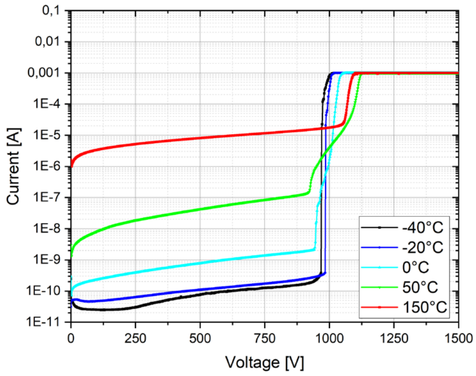

Fig. 2 Measured IV-characteristic of a reverse biased 900 V GaAs PIN diode. Current limited to 1 mA due to equipment compliance.

As expected from the simulations, the leakage current increases with increasing temperature. An increase in the breakdown voltage with increasing temperature, as can be seen in the simulation, cannot be confirmed in the measurements. The reason for this is the edge termination of the device which leads at higher temperature to a breakdown at the edge of the device [5].

C. Comparison between simulation and measurement

Due to the edge effect, a comparison between measurement and simulation is only possible for the lower temperatures of -40 °C and -20 °C, since there the breakdown takes place at the p/n-junction and not at the edge (see Fig. 3).

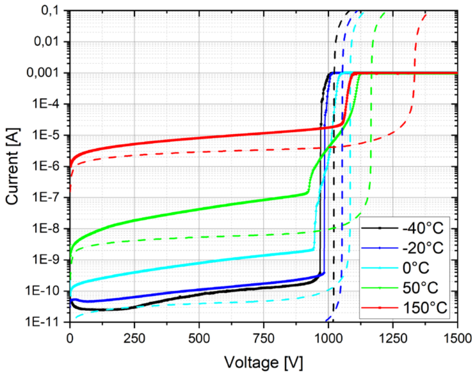

Fig. 3 Comparison between measured (solid line) and simulated (dashed line) IV-characteristics for a reversed biased 900 V GaAs PIN diode.

Causes for deviations can be related to the technology or to the simulation models for GaAs. Since this work was carried out on diodes of the first generation [4] problems such as the edge effect cannot be ruled out. This is no longer a concern in the latest diodes [6], which will be part of future work. Additionally the models for the avalanche breakdown are only valid in certain temperature ranges or have been calibrated for those. In order to enable a wide temperature range for applications in the automotive industry, corresponding models must be further developed.

D. Analytical model

Based on the simulations and measurements of the GaAs diodes an analytical model has been developed which can reproduce the behavior in reverse bias. The critical point is the temperature dependence of the saturation current and the breakdown voltage itself. With the help of the multiplication coefficient M [7], the total current I can be described as follows:

$$I = I_S \cdot M \qquad (1)$$

The saturation current IS is strong temperature dependent, for this reason an exponential approach is chosen:

$$I_S = I_0 \cdot 2^{(c \cdot T)} \qquad (2)$$

The constants I0 and c are fit parameters and T is the temperature. The multiplication coefficient was modeled with the following approximation after Miller [8]:

$$M = 1 \,/\, (1 - |V/V_{BD}|^n) \qquad (3)$$

The fit parameter n is between 2 and 6. From the TCAD simulations it can be seen that the breakdown voltage increases almost linearly with increasing temperature:

$$V_{BD} = m \cdot T + b \qquad (4)$$

Slope m and interception point b of the linear function can be determined by fitting. Since only a few measurement data show a sharp breakdown, the simulation data were used in the first step. Fig. 4 shows a fit of (4) as well as the respective breakdown voltages for the corresponding temperatures.

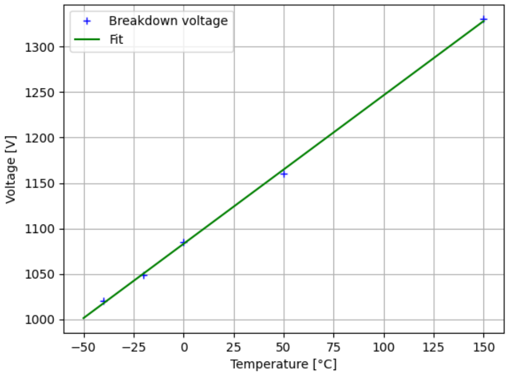

Fig. 4 Plot of the breakdown voltages from the TCAD simulations for the individual temperatures (blue markings) and the linear fit function (green).

The determination of the saturation current in the reverse direction turned out to be much more difficult. The simulations suggest that there are different temperature ranges for the saturation current in the reverse direction. To describe this behavior using (2), separate fits were carried out for low and high temperatures (see Fig. 5). Using different fits for higher and lower temperatures it is possible to have a relatively simple model capable of describing the temperature-dependence of the breakdown voltage.

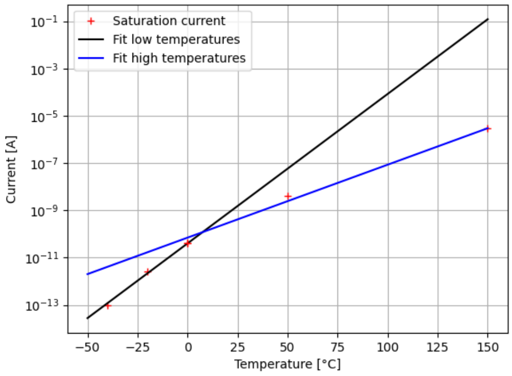

Fig. 5 Saturation current from the TCAD simulations as a function of the temperature (red markings) and the two fit functions for low temperatures (black) and high temperatures (blue).

In addition, a fit was made for the coefficient n in (3) to calculate the multiplication coefficient M. After fitting all the necessary parameters TCAD simulations and the analytical model can be compared. The results are shown in Fig. 6.

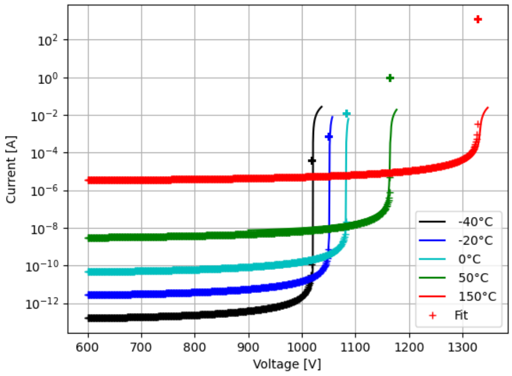

Fig. 6 Comparison between simulated (solid line) and analytically fitted (symbols) IV-characteristics of a GaAs diode in reverse direction for different temperatures.

Simulation and analytical model are in good agreement. Since real diodes are exposed to thermal destruction beyond the breakdown voltage, the focus of this paper was to model the temperature-dependent behavior until breakdown.

The analytical model can also be used to map the measurement data. However, a new parametrization is required due to the differences between measurements and TCAD simulations as shown in Fig. 3. Furthermore, we limit the model to the temperature range of -40 °C to -20 °C since the breakdown mechanism changed for higher temperatures in our experiments. In addition, we had to skip the temperature dependency of the saturation current due to resolution limitations of the applied measurement equipment. According to Fig. 7, measurement data and the analytical model are in good agreement at -40 °C and -20 °C. The steep rise at breakdown is significantly smoother in the analytical model.

The analytical model enables a quick simulation of the IV-characteristic of a GaAs diode in reverse direction including temperature dependency in the saturation current and in the breakdown voltage. To optimally meet user's/customer's needs, model extensions to capture the impact of geometry are in development, also for next generations of GaAs diodes with new developed edge termination [6].

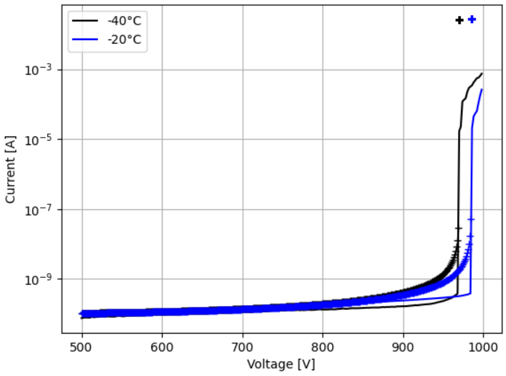

Fig. 7 Comparison between measured (solid line) and analytically fitted (symbols) IV-characteristics of a GaAs diode in reverse direction for different temperatures.

3. Conclusion

In this work the temperature-dependent behavior of GaAs PIN diodes has been investigated with TCAD simulations and measurements. Because of the edge termination the measurements for higher temperatures do not show a sharp breakdown.

Based on the results from simulations and measurements an analytical model has been developed. The model describes the temperature-dependent behavior of a reverse biased GaAs PIN diode. The model was parameterized by fitting the breakdown voltage VBD and the saturation current IS. In comparison with simulations and measurements, the model shows a good agreement. An extension of the model with geometry parameters is conceivable to describe the physics of the PIN diode even better.

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