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Avalanche diodes with low temperature dependence in 4H-SiC suitable for parallel protection

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Abstract. Avalanche diodes have been fabricated on 4H-SiC substrate. These diodes show an abrupt avalanche voltage of about 59 V which corresponds to the calculated theoretical one using our previously determined impact ionization coefficients. This avalanche voltage increases by as small as 3.7 mV/K over the investigated temperature range (150K-420K).

Introduction

Avalanche diodes (or Zener diodes) are widely employed for voltage regulation or parallel protection against electrostatic discharge or lightning. Two mechanisms of breakdown are present in this kind of diode: avalanche breakdown and Zener (tunneling) breakdown. Thanks to its wide bandgap, high breakdown field, and high thermal conductivity, Zener diodes fabricated on 4H-SiC can operate at higher Zener voltages and higher temperatures than conventional Si-based Zener diodes. Some authors reported on 4H-SiC Zener diodes having mixed avalanche-Zener breakdown around 20 V [1-3]. Vassilevski et al. presented a diode having pure avalanche breakdown of 280 V [4]. In this paper, we present the fabrication and characterization of avalanche diodes with avalanche breakdown voltage of about 59 V and the ionization coefficients used for the simulation of this breakdown voltage.

Device fabrication

A 4H-SiC epitaxial wafer from Cree Inc. was used to fabricate the diodes. The active part of the structure consists of a p⁺ layer (2.2 μm) and a p-type transition layer (0.1 μm) grown on n⁺-type substrate (see Fig. 1). 43 circular mesa terminated diodes with an area of about 0.8 mm² were formed on 1x1 cm² samples. The termination was realized by reactive ion etching (RIE) with a typical SF₆ process like the one investigated in [5]. As passivation, an 1.6 μm thick PECVD oxide was deposited and thermally treated in O₂ atmosphere at 950°C and in N₂ atmosphere at 1050°C for 1 hour each. To realize low resistive contacts, a Ni-based metallization for the cathode and an Al-based one for the anode were annealed at 1000°C. Al was used as over metallization on the anode side, Ni/Au on the cathode side.

Experimental result and discussion

In order to determine exactly the layer widths and the doping levels of the diodes, capacitance-voltage (C-V) measurements were performed with a HP 4194A impedance/gain-phase analyzer in

combination with the C-V simulation by Sentaurus software [6]. A typical C-V characteristic measured from the diodes at room temperature is shown in the Fig. 2. These measurements confirmed a very thin lowly p-type doped layer between two heavily doped layers. C-V simulations performed using Sentaurus gave the best fit to the experimental C-V curve with a p⁺-p-n⁺ structure having doping concentration of $6.5 \times 10^{18} \text{ cm}^{-3}$, $5.8 \times 10^{17} \text{ cm}^{-3}$ and $6.5 \times 10^{18} \text{ cm}^{-3}$ respectively. The width of the thin p-layer in the structure simulated is $0.104 \text{ } \mu\text{m}$. This result is in very good agreement with the secondary ion mass spectrometry (SIMS) measurements performed later, assuming a doping activation of 80%.

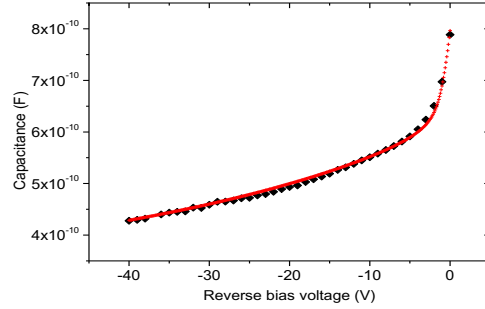
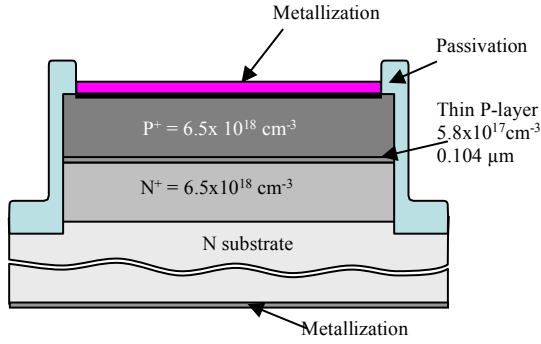


Fig.1. The schematic structure of the diodes $S \approx 0.8 \text{ [mm}^2\text{]}$.

Fig. 2. Measured (◆) and simulated (+) capacitance-voltage characteristics.

Current-voltage (I-V) measurements have been realized in the temperature range of 150K-420K using a Keithley 2410 Sourcemeter and a cryogenic probe station incorporating a liquid nitrogen flow cryostat system. The diodes show stable operation under avalanche breakdown voltage of about 59 V. In the experimental setup (SMU compliance = 20 mA), they are able to operate at a power density of 150 W/cm^2 . As seen in Fig. 3 and Fig. 4, the breakdown voltage changes very slightly from 59 V to 60 V in the investigated range of temperature which corresponds to a ratio of $\Delta V/\Delta T = 3.7 \text{ mV/K}$ or a positive temperature coefficient γ of the breakdown voltage of $6.27 \times 10^{-5} \text{ K}^{-1}$ calculated as follows:

$$\gamma = \frac{V_z(T_2) - V_z(T_1)}{V_z(T_1)} \times \frac{1}{T_2 - T_1} = 6.27 \times 10^{-5} \text{ (K}^{-1}\text{)} \quad (1)$$

Where $V_z(T_2)$ and $V_z(T_1)$ are the breakdown voltages measured at temperature T_2 and T_1 respectively.

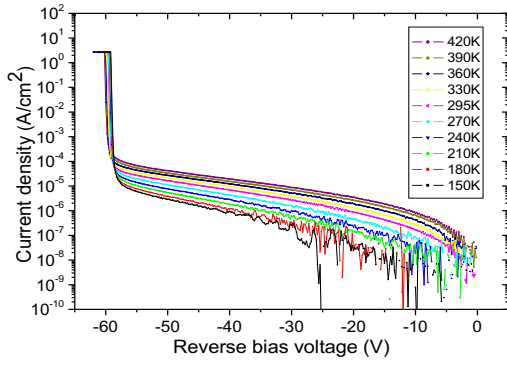


Fig. 3. Reverse current–voltage characteristics in the investigated range of temperature (150K - 420K). SMU current compliance is 20 mA.

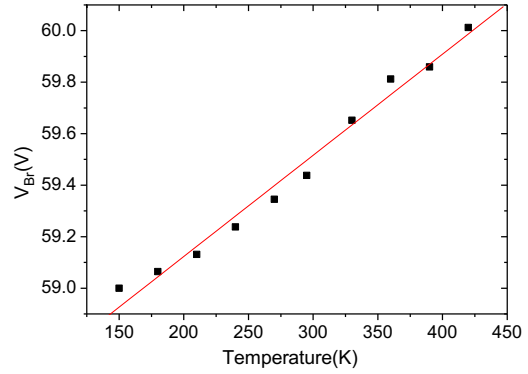


Fig. 4. Temperature dependence of breakdown voltage.

It is known that two mechanisms of breakdown can be present in Zener diodes: avalanche breakdown and Zener (tunneling) breakdown. For the silicon and germanium diodes, the breakdown is due to tunneling effect when the breakdown voltage is less than $V_{Br}^T < 4 \times E_g$ and is caused by avalanche multiplication when the breakdown voltages is in excess of $V_{Br}^A > 6 \times E_g$. Where E_g is the semiconductor band gap in eV. For voltages between V_{Br}^T and V_{Br}^A , both mechanisms of breakdown are present [7]. If these values of breakdown voltage are applied to Zener diodes in 4H-SiC which has a energy band gap of 3.26 eV, the breakdown voltage of a mixed avalanche-tunneling Zener diode can be in the range of about (13 V-20 V). 4H-SiC Zener diodes are indeed reported with breakdown voltages due to a mixed avalanche-tunneling breakdown of 23 V [1], 19 V [2], and 22 V [3]. Since the band gap in SiC decreases with increasing temperature [8], the breakdown voltage due to the tunneling effect has a negative temperature coefficient. On the other hand, it is demonstrated that the breakdown voltage due to avalanche multiplication in SiC has a positive temperature coefficient [9,10]. So when the two mechanisms of breakdown are competitive, the temperature dependence of Zener diodes can reach to a very small value as the result in [2]. Since the breakdown voltage of the diodes presented is about three times higher than that in the Zener diodes having mixed avalanche-tunneling breakdown [1-3] and they have a positive temperature coefficient, we suggest that breakdown voltage is mainly due to avalanche breakdown. In comparison with mixed avalanche-tunneling breakdown Zener diodes in 4H-SiC which have the breakdown voltages of about 20 V, the advantage of pure avalanche breakdown diodes is that one can obtain intended breakdown voltage with comparable very low temperature dependence. The temperature coefficient of some 4H-SiC Zener diodes is summarized in the table 1.

Table 1. Zener voltages and temperature coefficients.

Ref.	V [V]	γ [K ⁻¹]
[1]	23	5.7×10^{-5}
[2]	19	2×10^{-5}
[3]	22	8×10^{-5}
[4]	280	3×10^{-4}
Our work	59	6.27×10^{-5}

In all cases, the temperature dependence of 4H-SiC Zener diodes is appreciably lower than that of Si Zener diodes with the same breakdown voltage and is about 10^{-3} K^{-1} . In order to investigate this breakdown, simulations were performed using Sentaurus with our impact ionization coefficients and published data [11-13]. Our impact ionization coefficients in 4H-SiC are

experimentally determined by the optical beam induced current (OBIC) method. The empirical law of impact ionization coefficient (Eq.2) proposed by Chynoweth [14] has been used in our extraction procedure:

$$\alpha_{n,p} = a_{n,p} \times \exp\left(-\frac{b_{n,p}}{E}\right) \quad (2)$$

Where $\alpha_{n,p}$ represent the ionization coefficients for electrons and holes respectively, E is the electric field and [a, b] _(n,p) are fitting parameters. We have determined the following values:

$$a_n = 0.46 \times 10^6 \text{ cm}^{-1}; b_n = 1.78 \times 10^7 \text{ Vcm}^{-1}$$

$$a_p = 1.56 \times 10^7 \text{ cm}^{-1}; b_p = 1.72 \times 10^7 \text{ Vcm}^{-1}$$

The details of this study are reported elsewhere [15]. The data used in the simulation for the comparison are the most popular data [11] and the latest data published [12, 13] in 4H-SiC. The results of voltages and electric fields at breakdown as simulated by Sentaurus are reported in table 2. A good agreement between experimental and simulated breakdown voltage using our extracted data is observed.

Table 2. Simulated voltage and electric field at breakdown.

Ref.	V [V]	E [MV/cm]
[11]	51.9	4.35
[12]	43.3	3.83
[13]	46.0	3.99
Our work	59.5	4.79

Conclusions

Due to its wide band gap, high breakdown field, and high thermal conductivity, Zener diodes fabricated in 4H-SiC can not only operate at higher temperatures and higher voltages but also exhibit a temperature coefficient appreciably lower than that in Si-based Zener diodes. Zener diodes in 4H-SiC have been fabricated and are able to operate at a Zener voltage of 59 V with a very low temperature coefficient of $6.27 \times 10^{-5} \text{ K}^{-1}$. This temperature coefficient is 10 times lower than that in Si-based Zener diodes of the same breakdown voltage therefore these Zener diodes in 4H-SiC are of great advantage for applications requiring high thermal stability (as parallel protection). The diodes fabricated are able to operate in avalanche mode at high power density, making those devices suitable for ESD protection. Furthermore, simulations using our impact ionization parameters give a good agreement with the experimental data. This indicates that these coefficients can be used in device design to predict breakdown voltages due to avalanche multiplication, taking into account temperature effect.

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