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Sombel Diahm, Marie Laure Locatelli, Thierry Lebey, Christophe Raynaud, Mihai Lazar, et al.. Polyimide Passivation Effect on High Voltage 4H-SiC PiN Diode Breakdown Voltage. Materials Science Forum, 2009, MATERIALS SCIENCE FORUM, 615-617, pp.695-698. 10.4028/www.scientific.net/MSF.615-617.695 . hal-04368204

**HAL Id: hal-04368204**

**<https://hal.science/hal-04368204>**

Submitted on 31 Dec 2023

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# Polyimide Passivation Effect on High Voltage 4H-SiC PiN Diode Breakdown Voltage

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**Keywords:** 4H-SiC, PiN diodes, JTE, passivation, polyimide, breakdown voltage, environmental atmosphere.

**Abstract.** A polyimide (PI) has been used for the passivation of maximum 7.8 kV 4H-SiC P<sup>+</sup>N<sup>-</sup>N<sup>+</sup> (PiN) diodes with a 60 μm-thick base epilayer and a junction termination extension (JTE) periphery protection. The dielectric strength of PI films is studied versus area and temperature. The reverse electrical characterization of the PI-passivated PiN diodes is presented for different natures of the environmental atmosphere. The results are compared to those obtained from same devices passivated with a deposited SiO<sub>2</sub> thick film. The highest experimental breakdown voltages are obtained for PI-passivated PiN diodes immersed in PFPE oil, with a typical value of 5-6 kV, and a maximum value of 7.3 kV. Experimental observations are discussed in correlation with the PI film insulation properties.

## Introduction

Silicon carbide (SiC) is known as a suitable wide bandgap semiconductor for device operation under high temperature (above 400°C) and high voltage severe stresses. However, for extending the operating temperature range, which still remains limited nowadays at 175 °C, considerable progresses must be carried out at the level of packaging materials [1, 2]. Particularly higher performance has to be reached with appropriate high dielectric rigidity and high temperature surface insulation materials in order to avoid the formation of premature arcing. Polyimides (PI) appear as potential candidates for the passivation of high temperature SiC power devices due to their excellent electrical, thermal and mechanical properties [3]. This paper deals with the study of the effect of using a spin-coated PI film on the electrical characteristics of high voltage 4H-SiC PiN diodes. Equivalent components passivated with a good quality SiO<sub>2</sub> thick layer have been studied for comparison.

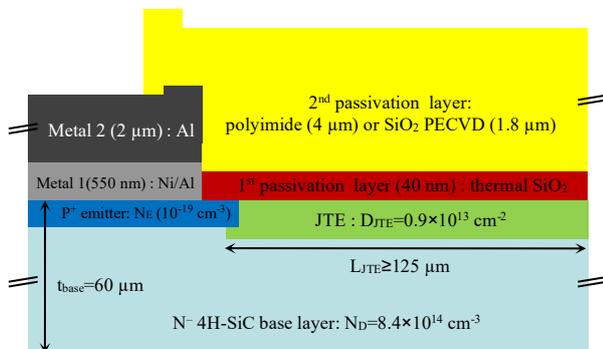


Fig. 1. Device structure with JTE periphery and passivation layers including technological parameters.

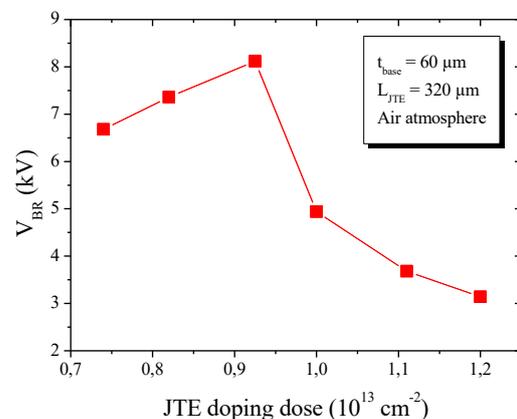


Fig. 2. Simulated breakdown voltage of PiN diodes versus the JTE implanted Al dose.

## Experimental part

4H-SiC PiN diodes ( $\varnothing=250\ \mu\text{m}$ ) has been realized in a  $60\ \mu\text{m}$ -thick  $\text{N}^-$  epilayer ( $N_D=8.4\times 10^{14}\ \text{cm}^{-3}$ ), with a Al-implanted  $\text{P}^+$  emitter ( $N_E=10^{19}\ \text{cm}^{-3}$ ), and a Al-implanted JTE periphery ( $L_{\text{JTE}}\geq 125\ \mu\text{m}$  and  $D_{\text{JTE}}=0.9\times 10^{13}\ \text{cm}^{-2}$  for an implanted-Al dose of  $1.1\times 10^{13}\ \text{cm}^{-2}$  and given a 80% electrical activation [4]) as shown in Fig. 1. The common post-implantation annealing was performed at  $1650\ \text{C}$  for 30 min in Ar atmosphere. The maximal breakdown voltage of these PiN JTE diodes has been derived from ionization integral calculations realized by numerical 2D-simulations, taking into account the Konstantinov's ionization coefficients [5] and varying the JTE doping dose (cf. Fig. 2). A 7.8 kV value corresponds to the doping dose of  $0.9\times 10^{13}\ \text{cm}^{-2}$  as in [6]. The primary passivation layer is a thin oxide of  $40\ \text{nm}$  in thickness grown by dry oxidation at  $1150\ \text{C}$  for 2 h followed by a post oxidation annealing at  $1150\ \text{C}$  for 1 h in  $\text{N}_2$ . The second passivation layer has been realized either with spin-coated PI cured at  $400\ \text{C}$  for 1 h in  $\text{N}_2$  atmosphere ( $e=4\ \mu\text{m}$ ), or with PECVD deposited  $\text{SiO}_2$  layer ( $e=1.8\ \mu\text{m}$ ), for comparison. The  $\text{SiO}_2$  thickness was limited due to the low deposition speed ( $\sim 330\ \text{nm/h}$ ). Electrical properties of PI films have been investigated through metal-insulator-metal (MIM) capacitors with different electrode diameters from 0.3 to 5 mm. The dielectric breakdown field of PI has been measured using a Keithley 2410 source meter with a 1100 V voltage source. Electrical characterizations of PiN diodes have been performed using a 12.5 kV FUG voltage source connected in series with a Keithley 485 picoammeter and a protection resistance of  $20\ \text{M}\Omega$ . The voltage has been applied to the devices using a Signatone probe station with high voltage needles.

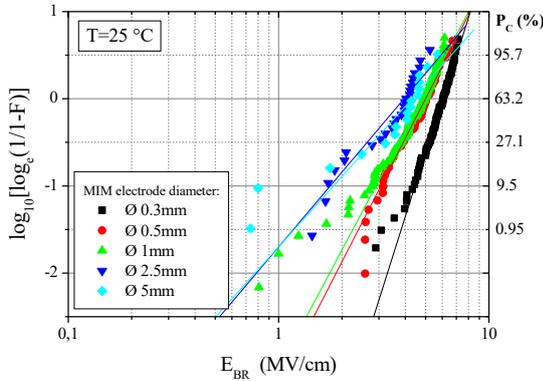


Fig. 3. Weibull cumulative probability of failure of PI films versus  $E_{\text{BR}}$  for different MIM electrode diameters.

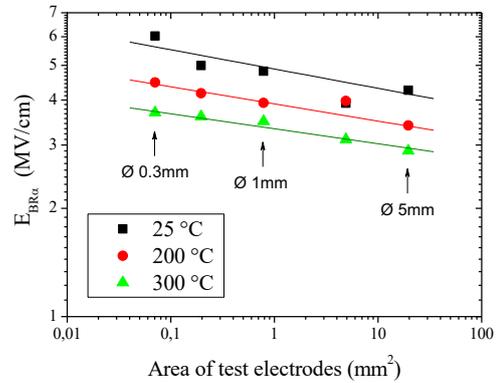


Fig. 4. Evolution of the mean dielectric strength of PI films versus MIM electrode area up to  $300\ \text{C}$ .

## Results and discussion

The intrinsic dielectric breakdown strength ( $E_{\text{BR}}$ ) of PI films has been previously measured using MIM capacitors [7]. Fig. 3 and 4 show respectively the Weibull probability of failure versus  $E_{\text{BR}}$  for different MIM diameters at  $25\ \text{C}$ , and the evolution of the mean dielectric strength versus MIM electrode area up to  $300\ \text{C}$ . PI film  $E_{\text{BR}}$  remains high in the whole temperature range.  $E_{\text{BR}}$  decreases with increasing the electrode area, due to the higher probability to find defects in the film under the test electrode. At  $25\ \text{C}$ , the mean breakdown field remains around  $5\ \text{MV/cm}$ . So according to these results, a  $4\ \mu\text{m}$ -thick PI film should be able to withstand vertically applied voltages up to 2 kV. In comparison, the  $E_{\text{BR}}$  of the deposited oxide has been evaluated and was in the range of  $6\text{--}8\ \text{MV/cm}$  at  $25\ \text{C}$  (not shown here). So, a  $1.8\ \mu\text{m}$ -thick  $\text{SiO}_2$  film should be able to withstand vertically applied voltages at maximum 1.4 kV.

Fig. 5 shows the reverse  $I(V)$  characteristics of several PI-passivated PiN diodes in air. In this condition, a maximum voltage of 2.4 kV has been obtained mainly due to air ionization with visible arcing ( $E_{\text{BRair}}\approx 3\ \text{kV/mm}$ ). The consequence of the air arcing appears at the edge of the PI film around the PiN diode electrode where some degradations have been observed. Fig. 6 presents a sketch with the localization of the breakdown in the environment of PI-passivated PiN diodes supported by pictures taken before and after the measurements in air.

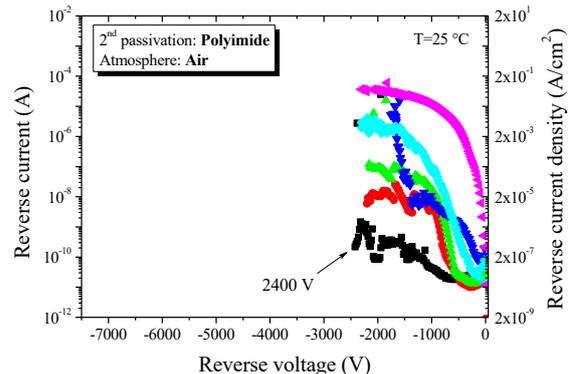


Fig. 5. Reverse characteristics of PiN diodes passivated with PI (performed in air atmosphere).

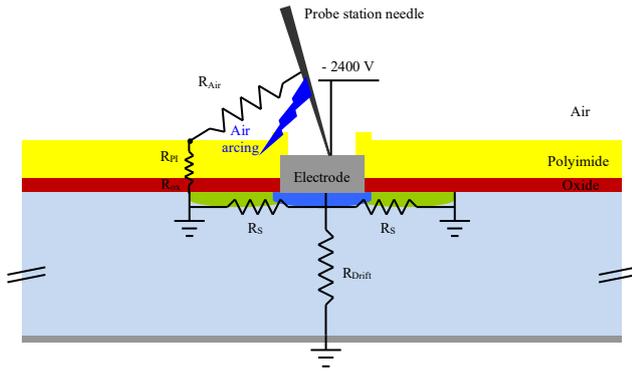


Fig. 6a. Sketch of a PiN diode and typical breakdown issues during measurements in air atmosphere.

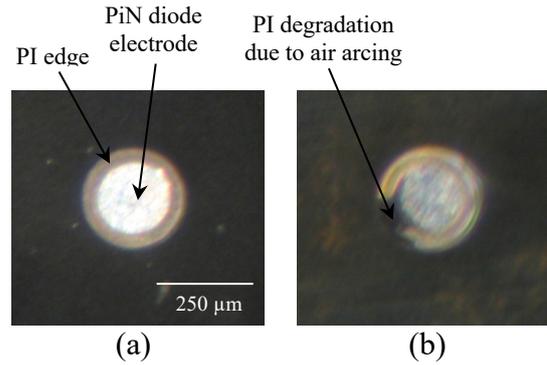


Fig. 6b. Surface state of PiN diodes passivated with PI before (a) and after (b) high voltage measurements in air.

In order to avoid high voltage issues due to air arcing, another series of measurements has been performed immersing the sample in a perfluoropolyether (PFPE Galden® fluid;  $E_{BR, PFPE} \approx 16 \text{ kV/mm}$ ) oil bath of several mm-deep. The typical results are presented on Fig. 7a and a comparison is made with identical diodes from another part of the same initial wafer but passivated with PECVD  $\text{SiO}_2$  (cf. Fig. 7b). PI-passivated diodes exhibit higher maximum voltage (5.96 kV) than those with PECVD  $\text{SiO}_2$  (4.82 kV). One reason to explain it could be the lower passivation thickness for the latter diodes.

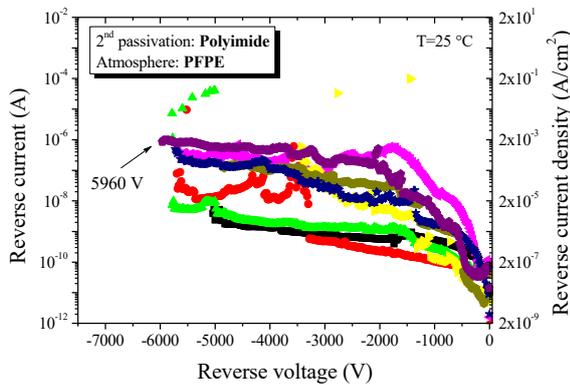


Fig. 7a. Reverse characteristics of PiN diodes passivated with PI (performed in PFPE environment).

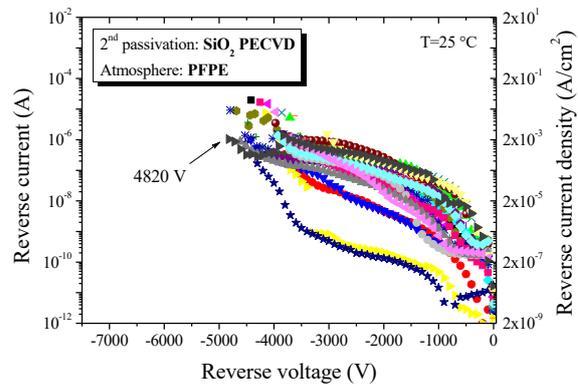


Fig. 7b. Reverse characteristics of PiN diodes passivated with  $\text{SiO}_2$  PECVD (performed in PFPE environment).

However, the breakdown still occurs suddenly, and in the device environment, without destruction of the diode. Fig. 8 proposes a sketch of the localization of the breakdown in the PI film supported by pictures taken before and after measurements in PFPE. It has been observed that the breakdown always occurs relatively far ( $L \geq 1 \text{ mm}$ ) from the tested PiN diode, in the PI film, probably where a defect in the insulating layer was located inducing a lower  $E_{BR}$ , as shown above in Fig. 3. Considering the reverse voltages involved (6 kV) and the distance between the crater and the device, the 2<sup>nd</sup> passivation layer is certainly at the origin of the failure (the breakdown voltage of PFPE being around 16 kV for  $L=1 \text{ mm}$ ). The PiN diodes appear as not destroyed because the devices can be retested other times showing breakdown voltage similar values.

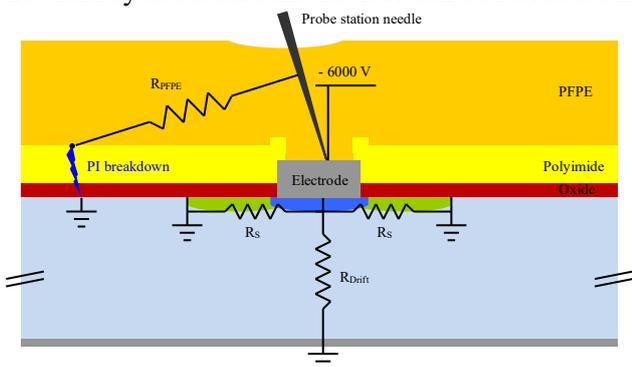


Fig. 8a. Sketch of a PiN diode and typical breakdown issues during measurements in PFPE environment.

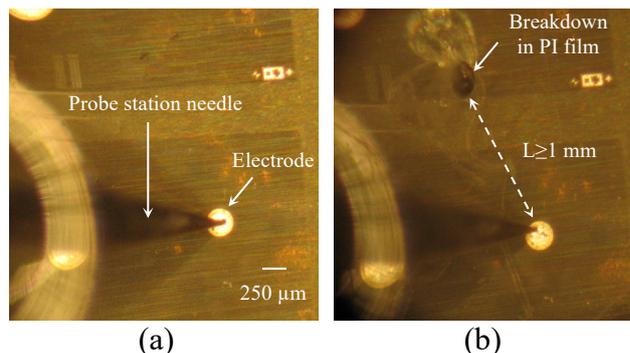


Fig. 8b. PI-passivated PiN diode before (a) and after (b) high voltage measurements in PFPE environment.

A different behavior could also be observed as shown Fig. 9. In this PI-passivated diode, the reverse characteristic exhibits a maximum voltage of 7.3 kV (cf. Fig. 9a), after a current knee. In this case, the post breakdown degraded zone is observed in the diode area, as shown Fig. 9b. No weak point in the surrounding dielectric PI passivation of this device, and SiC avalanche breakdown within it, might explain such a result. PiN diodes with a PI passivation have therefore exhibited 93% of their maximum blocking voltage in the best observed case. Other authors have reported comparable values [6, 8-10].

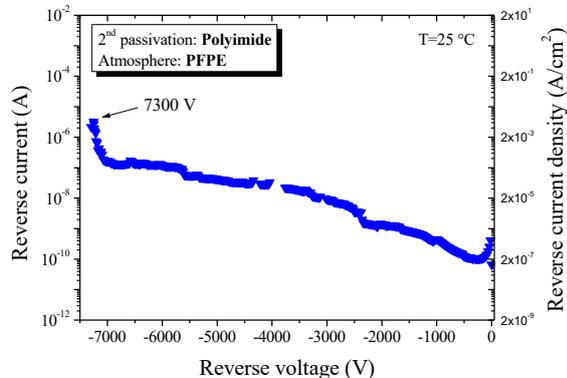


Fig. 9a. Reverse characteristic up to the breakdown of a PI-passivated PiN diode with a higher insulating quality (performed in PFPE environment).



Fig. 9b. PI-passivated PiN diode after the breakdown at 7300 V (performed in PFPE environment).

## Summary

A polyimide (PI) has been evaluated for the passivation of high temperature SiC power devices and compared to a SiO<sub>2</sub> passivation layer. First, MIM capacitors have been characterized to determine the dielectric strength of PI films versus test electrode area and temperature. Then, the PI passivation layer has been evaluated on 4H-SiC PiN diodes owning a maximum avalanche breakdown voltage of 7.8 kV. Whereas the blocking voltage of PI-passivated PiN diodes is around 2.3 kV in air atmosphere, this value increases up to 6 kV when tested in PFPE oil against 4.8 kV for those passivated with SiO<sub>2</sub>. Moreover, these voltage limitations appear as a consequence of the 2<sup>nd</sup> passivation breakdown. However, a PI-passivated PiN diode has exhibited a breakdown voltage of 7.3 kV without PI failure. This voltage represents 93% of the maximum value expected. These results show that to achieve the maximum breakdown voltage it is necessary to increase the 2<sup>nd</sup> passivation layer thickness which is easier by depositing PI than SiO<sub>2</sub>.

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