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1.2 kV PiN Diodes with SiCrystal epiwafer

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Abstract. Silicon carbide devices limitations often originate from the quality of the substrate material. Therefore it is interesting to investigate devices fabricated on alternative source materials. Currently, CREE is the world market leader of SiC wafers. Nowadays, some new companies begin to propose alternative material. The European manufacturer SiCrystal furnishes now some epiwafers for the fabrication of 1,2kV devices. In this paper we present 4H-SiC 1.2 kV PiN diodes with a JTE termination realized on a SiCrystal epiwafer. The devices exhibit a blocking voltage of 1.2 kV, a current density of 420 A.cm⁻² and a specific differential series resistance of 4.4 m Ω .cm². The yield of fabricated diodes with a breakdown voltage greater 600 V is superior to 75%.

Introduction

Since the first commercial SiC devices are available on the market, silicon carbide is increasingly considered for the design of future power systems. With its advantageous physical and electrical properties, it is theoretically possible to realize SiC power devices with a breakdown voltage greater than 10 kV [1]. A bandgap being three times higher than that silicon's one and a thermal conductivity superior to that one of copper, SiC power devices are eligible to work at high temperature. Moreover, the volume of power systems, including electronic devices and cooling system would be reduced with SiC components.

Currently, the development of SiC devices is limited by the quality of the base material. Micropipes and dislocations are the most important defects. The high density of defects limits the realization of large devices which in turn limits the maximum current.

The work presented in this paper deals with the realization of a high voltage bipolar diode on an n^+ substrate with an n^- epilayer purchased from SiCrystal [2]. The structure is a PiN diode protected by a junction termination extension (JTE) [3]. First, the conception and the fabrication are described. Then, electrical characterizations are presented and discussed.

Design and fabrication

Design. The base material is an n-type substrate with a doping concentration of 6×10^{18} cm⁻³ covered by an 11 µm thick n-type epilayer doped at 5×10^{15} cm⁻³. Thickness and doping level are specified with a tolerance of ± 15 % and ± 50 %, respectively. The diodes anode is formed by ion implantation of aluminium [4]. The diode structure is presented in figure 1. The length of the JTE L_{JTE} varies in the range 125 µm to 500 µm. The SiCrystal data sheet proves their epiwafers to be suitable for diodes with a blocking voltage of 1.2 kV. This suggestion implies a certain safety margin. Simulations made with MEDICITM show that the theoretical blocking capability of the diodes is 1.6 kV (with Konstantinov ionization coefficient [5]) in one dimension. Implanting the optimal dose of 1×10^{13} cm⁻² in the JTE box (figure 1) and having a JTE length superior to 150 µm, the attainable breakdown voltage is calculated to be 1.57 kV. This result is obtained with the

nominal doping concentration of 5×10^{15} cm⁻³ in the epilayer. Taking into account the tolerance of the doping, in the worse case, the concentration of donors is 7.5×10^{15} cm⁻³. In this case, the simulated blocking voltage is 1.3 kV, which approaches the value specified by SiCrystal. The device fabrication requires a mask set of 7 levels which is described in table 1.

Fabrication. The source material is a quarter of a two inch SiCrystal epiwafer (50 mm). After chemical cleaning, a thick photoresist of 4 μ m is deposited. The first photolithography step is performed to pattern alignment marks. These marks are subsequently etched in an RIE reactor [6]. To form the anode, a 2 μ m thick aluminium layer is used as implantation mask (photo lithography with the second mask). The anode is formed with four successive high energy implantations of aluminium as described elsewhere [4]. Then the formation of the JTE is realized by the same ion implantation process. In order to activate the dopants, a high temperature annealing is performed at 1650°C during 30 minutes in argon atmosphere. The first passivation layer is a thin oxide grown by dry oxidation at 1150°C during 2 hours followed by a post oxidation annealing at 1150°C under nitrogen atmosphere during 1 hour. After opening the oxide above the anode, the metals Ni (50nm)/Al (500nm) [7] are deposited by resistance heating and the contacts are patterned by a lift-off process. The cathode metallization on the backside is formed by a bilayer Ti/Ni. Ohmic behaviour is effectively obtained after annealing at 1000°C for 2 minutes. Then, the second passivation is realized. It is a 2 μ m thick SiO₂ layer [8] deposited by sputtering. To finish, the thick oxide is etched above the anode and a 2 μ m thick Al over layer is deposited on the first contact.



Figure 1. Detailed schematic of the fabricated diode corresponding to all mask levels.





Table 1. Set of mask description.

Table 2. *Diodes description*.

Characterization results and discussion

Electrical characterization of the fabricated diodes was performed twice for both conducting and blocking state. The first characterization was performed after the contact annealing. Only part of the diodes was tested at this time. Note that the components just had the thin oxide as passivation. The second characterization was performed at the end of all processes and this time all the diodes were characterized. The mask layout is composed of several cells with a dimension of 10×6 mm². In each cell, there are several diodes with different sizes. The diode diameters are: 250, 400 and 1000 µm. In addition, for the same emitter size, the length of the JTE varies (table 2).

The characterization bench used to test the devices is composed of a probe station connected with a Keithley 2410 source meter unit. This instrument allows a characterization in a voltage range from 0 to 1.1 kV and a maximum current of 1 A for an output power of 20 W.

Conducting state. During the first series of characterization, no precaution was taken into account to stick the sample on the probe station, it was just put on the metal chuck. The first characterization is presented in figure 2a. The smallest diodes with a 250 μ m large anode reach the highest current density with a value of about 420 A.cm⁻² at a bias of 5 V. Although the current is higher in the largest diodes, the current density decreases drastically to 100 A.cm⁻² at 5 V. The variation of the current density with respect to the anode diameter is probably due to the thin metallization which induces the current spreading phenomenon. This leads to an inhomogeneous potential distribution of the anode in that way that the potentials of the emitter vary with the distance to the needle probe. Nevertheless, the best devices are the smallest diodes (diameter of

 $250 \,\mu\text{m}$) with a specific differential series resistance R_d of $4.4 \,\text{m}\Omega.\text{cm}^2$ while the largest components exhibit an R_d of $17 \,\text{m}\Omega.\text{cm}^2$.

Before the second series of characterization, a thick oxide was deposited as passivation layer and a thick aluminium layer was applied to the original contacts. After several measurements up to a bias of 5V (fig. 2b), we noticed that the current is lower than in the first test. Even more problematic was the non homogeneity of the curves, which means that the devices did not exhibit typical diode characteristics with a continuity shape. This behaviour is probably due to insufficient etching of the second passivation, which causes a thin insulating layer to remain between the two metallization layers. The presence of such an oxide interlayer would induce the bad contact behaviour which is observed in the electrical characteristics. On the other hand, this faulty behaviour does not seem to affect the reverse characteristics shown in the next paragraph.



Figure 2. SiC PiN diodes forward characteristics a) without second passivation and overmetallization b) after all process steps.

Blocking state. During the first series of characterization, the sample just had a thin oxide as passivation. Therefore, it was not possible to go to higher voltages without the risk of destroying of the devices by arcing. To avoid this phenomenon, the sample was immerged in Galden[®].

The first series of measurements (fig. 3a) show breakdown voltages greater than 800 V, while some diodes even blocked the maximum voltage of the instrument (1.1 kV). This means that the best diodes are at least close to or probably higher than the blocking voltage of 1.2 kV, specified by the wafer manufacturer. Furthermore the characteristics show an increase in leakage current with diode diameter. This phenomenon could be explained not only by a higher recombination rate but also by the presence of defects in the wafer. The probability of a device to be settled on a defect increases with its size. The substrate used for the epiwafers is specified with a micropipe density $< 30 \text{ cm}^{-2}$.



Figure 3. SiC PiN diodes reverse characteristics a) without second passivation and overmetallization b) after all the technological steps. c) Comparison of the reverse characteristics of two distinct diodes before and after second passivation and over-metallization.

Concerning the second series of characterizations (fig. 3b), the devices could be tested in air because of the thick passivation they had. The breakdown voltages are in the range of 600 V to 1050 V. As described in table 3, the yield for diodes with a breakdown voltage greater than 50% of the theoretical maximum value (600 V) is superior to 75 %. Figure 4 shows the repartition of the diodes according to their breakdown voltages. The total average of the blocking voltage is about

850 V. Diodes larger than 10^{-2} cm⁻² (anode and JTE) yield is 60% while smallest diodes (4.5×10^{-3} cm⁻²) yield is 83%. These yields are closed to the expected values since the micropipes density represents a probability of 45 % and 14 % respectively for a diode to be settled on a defect.

Breakdown voltage [%Vbrmax]	Percent of diodes
0-25	20.3
25-50	4.5
50-75	44.4
75-100	30.8



Table 3. Percentage of diodes versus percentage of specified blocking voltage $V_{brmax} = 1.2 \text{ kV}$.

Figure 4. Repartition of the breakdown voltage of all diodes realized on the sample.

Comparing all blocking characteristics before and after the second passivation and overmetallization, the breakdown voltage is seen to decrease. By observing the reverse characteristics of two distinct diodes shown in figure 3c, the reduction of the blocking capability is about 200V. This alteration is attributed to a bad quality of the second oxide layer deposited by sputtering and it probably shows a high positive charge density due to contamination in the reactor that would reduce the effect of the JTE protection so the breakdown voltage becomes lower. This suspicion is supported by SIMS analysis of the deposited SiO₂ layer which revealed the presence of a high concentration of aluminium. This contamination is due to the reactor which is used to deposit oxide and aluminium.

Conclusion

In this work, 1.2 kV 4H-SiC PiN Diodes were fabricated on an epiwafer from SiCrystal. The first series of characterisations, performed before the final process steps (second passivation and overmetallization), revealed good diodes with a current density of 420 A.cm⁻² at 5V, a specific differential series resistance of 4.4 m Ω .cm² and a blocking capability of at least 1.2 kV. In addition, in spite of the reduction of the blocking voltage caused by the second passivation layer, the yield is about 75% for devices with a breakdown voltage greater than 50 % of the maximum value.

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