Large Area Silicon Carbide Power Devices on 3 inch wafers and Beyond

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ABSTRACT

Significant progress has been achieved in making large (3 inch and 100 mm) 4H-SiC substrates with much lower micropipe defect densities. With the recent availability of high quality 3 inch 4H-SiC substrates, the demonstration of large area power devices have been made possible in SiC Schottky diodes, PiN diodes, and thyristors. SiC Schottky diodes with a 1200 V rating have been achieved with 50 A forward currents. SiC PiN diodes have been demonstrated with 10 kV blocking voltages and current ratings of 50 A, with no forward voltage degradation over time. The largest devices to date have been 1770 V 4H-SiC thyristors that are 1 cm x 1 cm, with a forward current of 300 A.

INTRODUCTION

The commercial availability of relatively large, high quality wafers of the 4H polytype of silicon carbide (SiC) for device development has not only facilitated exciting breakthroughs in laboratories throughout the world, but has also led to an existing power device production capability. Silicon Carbide power devices offer tremendous potential over existing silicon power devices due to the much higher breakdown electric field in SiC. The first devices that are being manufactured in volume are SiC Schottky diodes, which are replacing Ultrafast Si PiN diodes in switch-mode power supplies, and is emerging in applications in motor controls and hybrid electric vehicles. Cree has based all of its SiC power device manufacturing on 3 inch diameter wafers over the last 3 years. The ever improving crystal quality of the 3 inch diameter 4H-SiC substrates has allowed excellent yields and reliability for these devices, which has enabled SiC to finally start to displace silicon.

Cree has a vertically integrated capability for the development and manufacture of SiC power device technologies including 3-inch 4H-SiC substrate production, SiC epitaxial growth, advanced SiC device fabrication and characterization, as well as device packaging and reliability testing capabilities. This paper will describe progress made in increasing the quality and size of n-type 4H-SiC wafers, and some of the resulting power device demonstrations achieved on 3 inch SiC wafers.

SILICON CARBIDE SUBSTRATES

To enable the commercialization of SiC, specific focus has been placed on achieving larger diameter high quality substrates, with a particular focus on reducing the micropipe defects that occur in the material. The micropipe has been seen by many as preventing the commercialization of SiC power devices. However, in SiC boules grown by the seeded sublimation method, recent production results show a steady reduction in the micropipe densities by over an order of magnitude in the last several years. The advances in micropipe defect density for our SiC substrates is illustrated in Fig. 1, with average production in the range of 7 micropipes/cm^2 on 3-inch diameter 4H-SiC wafers. This improved quality is what has allowed high volume production of SiC Schottky diodes on 3 inch SiC wafers with high yields. This has presented a cost structure that allows SiC to compete with mainstream Si PiN diodes in switch-mode power supply applications, where the increased power density allowed by SiC offsets the higher cost of the SiC component. However, to further reduce costs and drive market penetration, it is strategically important to push to larger wafer diameters without giving up yield.

Therefore, we are also developing 100 mm diameter wafers for future production. The quality of our “R&D best” 100 mm diameter wafers is quickly approaching the quality we are currently achieving on 3 inch wafers, as seen in Fig. 1. However, we still need to establish more of a production process for this material, and further develop the capability to grow very uniform epitaxy on these wafers.

SIC SCHOTTKY DIODES

Cree currently offers 600 V and 1200 V Schottky diodes with current ratings up to 10 A. These devices show tremendous advantages over silicon PiN diodes in terms of lower switching losses, higher temperature operation, higher

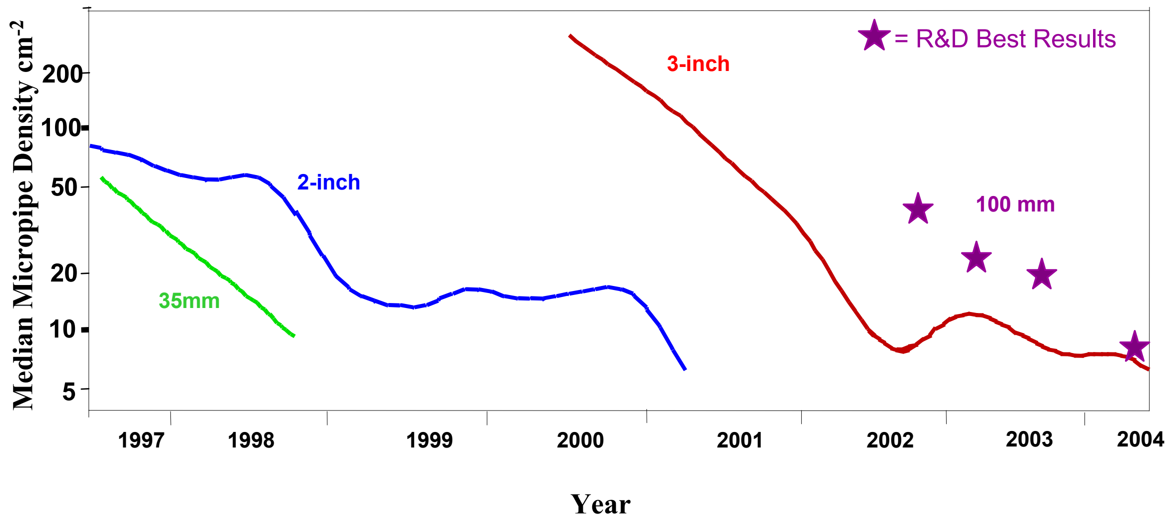

Figure 1: Progress in reduction of Cree's median micropipe density in production n-type 4H-SiC versus time. Also included are "R&D Best" results on 100 mm wafers.

switching frequency and improved efficiency. However, the recent improvements in material quality discussed above have allowed us to demonstrate much larger, higher current diodes on 3 inch diameter wafers. Figure 2 shows the I-V characteristics of 1200 V / 50 A Schottky diodes. The forward voltage drop (V_F) for 50 A is 1.7 V at room temperature (RT). Due to decreasing electron mobility with temperature, this V_F increases to about 3.3V at 200°C. The reverse bias leakage current for these diodes remains very low at full rated voltage from RT to 200°C, as shown in Fig. 3, increasing from 18 µA to 50 µA at 200°C.

SiC PiN Diodes

For higher voltage and higher current applications, SiC PiN diodes would be preferred. However, these devices have been plagued in the past by a V_F degradation phenomenon, which has resulted in insufficient reliability and stability for production. The degradation involves the growth of stacking faults from basal plane dislocations present in the substrate and epilayers [1]. As the stacking faults grow, the observed V_F increases because the stacking faults sufficiently kill the minority carrier lifetime so as to effectively prevent conductivity modulation through them. However, through improvements in the thick epitaxial layer growth process using hot wall CVD, we have achieved a >15X reduction in the density of basal plane defects in the blocking layer of the devices [2]. This has allowed us to demonstrate high voltage PiN diodes with large areas that show no V_F degradation.

We have achieved 10 kV / 50 A SiC PiN diodes, utilizing a 100 µm thick blocking layer, grown with the low basal plane dislocation process, and utilizing a guard ring based edge termination. The substrate used had a 0.6 cm^{-2} micropipe density and was 3 inches in diameter. The 50 A PiN diode had a die size of 8.7 mm x 8.7 mm chip, and an active conducting area (not including the edge termination region) of 0.50 cm^2.

Figure 4 shows the reverse blocking capability of a typical large PiN diode. Reverse blocking is measured out to 9 kV, where the leakage current exceeds the current compliance limit of the measurement test set-up. In terms of

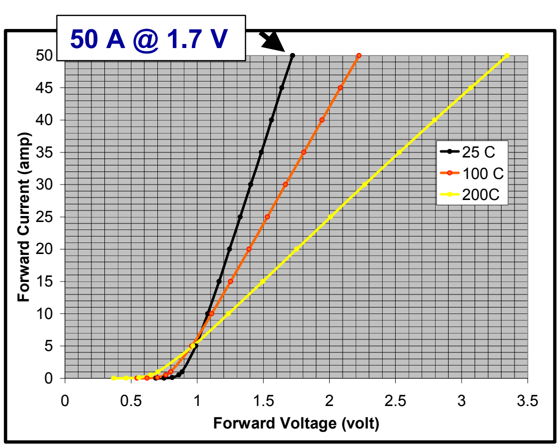

Figure 2: Forward I-V characteristics of the 1200 V, 50 A SiC Schottky diode, with a chip size of 5.6mm x 5.6 mm.

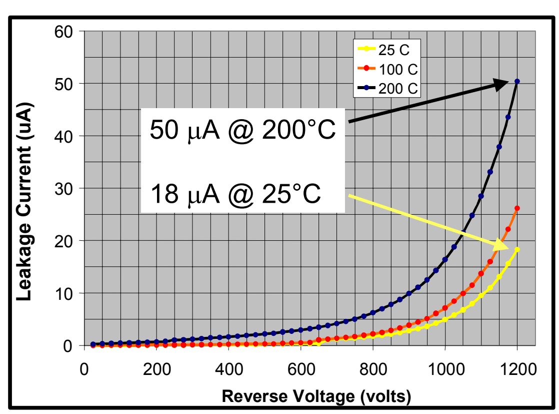

Figure 3: Reverse I-V characteristics of the 1200 V SiC Schottky diode at room temperature, 100°C, and 200°C.

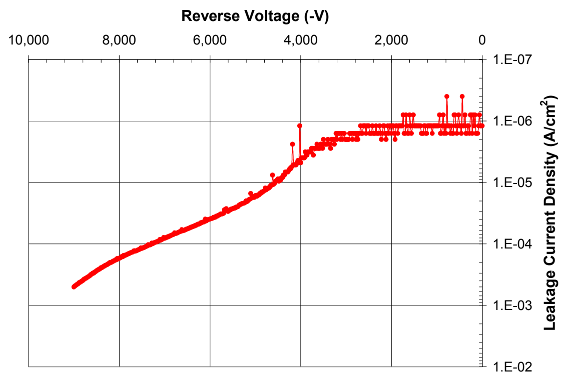

Figure 4: Reverse J-V characteristic of a 50 A diode (8.7 mm x 8.7 mm) showing >9 kV blocking (solid curve) that is current compliance limited. The dashed line extrapolates the reverse blocking to 10 kV.

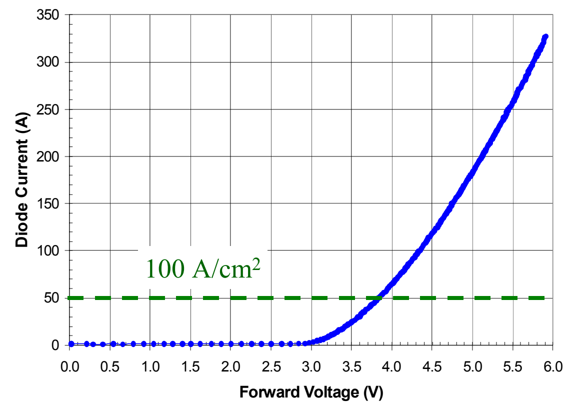

Figure 5: Pulsed forward I-V characteristic of a large 10 kV diode with a 3.9 V forward drop at 50 A and 5.9 V forward drop at 328 A, indicating a high level of conductivity modulation.

leakage current density, the 0.5 mA/cm^2 corresponds to a minimal value that is well below the typical current densities allowed in reverse operation. Hence, a 10 kV blocking is implied for these large devices. A low forward voltage drop of 3.9 V is observed at 50 A (100 A/cm^2) indicating a high degree of conductivity modulation (Fig. 5). As mentioned above, these devices utilized the low basal plane defect epitaxy process, and as a result 60-80% of these die have no measurable V_f drift, versus only about 20% for our older standard process.

PiN diodes are capable of handling very high current densities and we have measured this large device out to a pulsed current of 328 A (656 A/cm^2) at a low forward drop of 5.9 V. For a single chip, this demonstrates over 3 MW of pulsed power!

SiC Thyristors

With the improvements observed in SiC PiN diodes for very high voltage, high current applications, it is also desirable to make a complementary switching device. One attractive device for high voltage, high current switching is the thyristor. Due to its heavy conductivity modulation resulting from minority carrier injection from both sides of the junction, the thyristor is capable of very high current densities.

The largest devices fabricated on high quality 3 inch 4H-SiC wafers to date have been 1 cm x 1 cm thyristors. A full wafer of devices is shown in Fig. 6, and the device layout is shown in Fig. 7. In forward bias, these devices blocked 1770 V, as shown in Figure 8, with a leakage current density

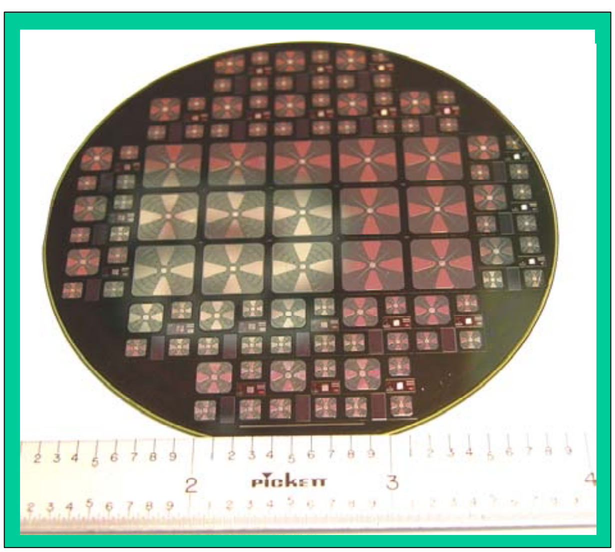

Figure 6: Picture of a 3 inch SiC wafer with fifteen 1 cm^2, and many smaller, thyristors.

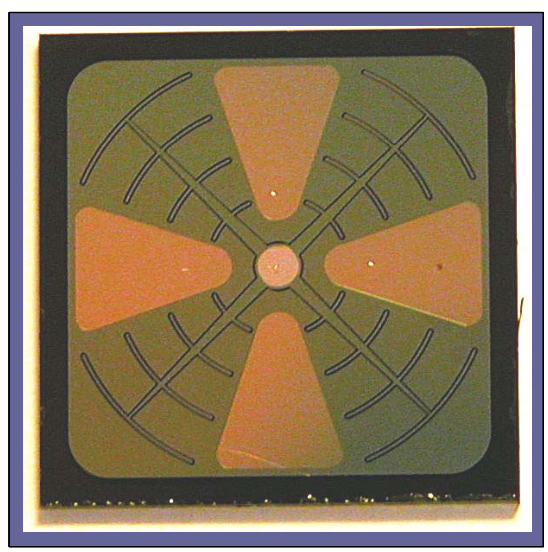

Figure 7: Picture of a 1 cm^2 SiC thyristor chip.

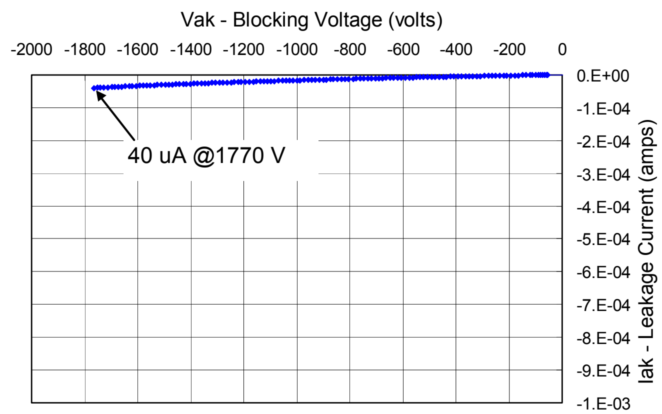

Figure 8: Forward blocking voltage of a 1 cm^2 4H-SiC thyristor device.

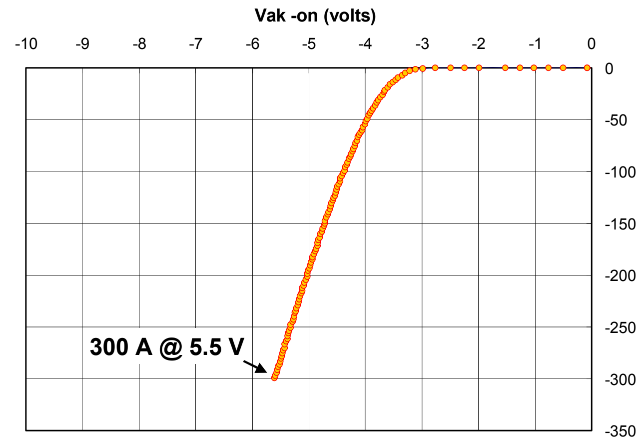

Figure 9: The forward I-V characteristics of the 1 cm^2 thyristor at room temperature. A gate current of 100 mA was used.

of only 40 $\mu A/cm^2$. A gate turn-on current of only 100 mA was required to obtain a low voltage breakover, and a forward current of 300 A (300 A/cm^2) was achieved at a V_f of 5.5 V, as shown in Figure 9.

CONCLUSIONS

The quality and diameter of 4H-SiC substrates is rapidly improving, allowing the demonstration of large area power devices on 3 inch diameter wafers. An average wafer production density of 7 micropipes/cm^2 on 3-inch diameter 4H-SiC wafers is achieved, and substrates with micropipe densities less than 1 cm^{-2} have been used for a variety of large area device demonstrations, with die sizes ranging from 5.6 mm x 5.6 mm to 1 cm x 1 cm. Schottky diodes capable of 1200 V and 50 A have been demonstrated. Large area bipolar devices have been demonstrated with no V_f degradation, as shown by 10 kV, 50 A PiN diodes. The largest devices fabricated to date are 1 cm x 1 cm 4H-SiC thyristors with a current capability of 300 A. The next step is to migrate to 100 mm diameter wafers, which have been demonstrated to have micropipe densities as low as 7 cm^{-2}.

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ACRONYMS

PiN: p-type – insulator – n-type
RT: Room temperature
SiC: Silicon Carbide
V_F: Forward voltage drop