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High Breakdown Field P-type 3C-SiC Schottky Diodes Grown on Step-Free 4H-SiC Mesas

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Abstract. Step-free surface heteroepitaxy of 3C-SiC films with improved dislocation density on patterned 4H/6H-SiC substrate mesas has recently been reported. This paper details initial investigations of the performance of electrical devices implemented in stacking-fault-free 3C-SiC. Small-area p-type Schottky diodes with 50 nm Ti / 150 nm Ni contacts were fabricated on N_A = 1-5 x 10^{17} cm^{-3} unintentionally boron-doped 3C-SiC mesa films. Capacitance-voltage (CV) and current-voltage (IV) properties of the devices were measured at 24 °C, 200 °C, and 300 °C. CV measured doping profiles (verified also by secondary ion mass spectroscopy for two of the diodes) were essentially temperature independent. The IV characteristics show excellent rectification properties with low reverse leakage and relatively sharp reverse breakdown. Room temperature breakdown voltages (where current sharply increased to exceed 0.1 A/cm^2) from 96 V down to 53 V were observed, corresponding to peak electric fields near 2 MV/cm for N_A near 1 x 10^{17} cm^{-3} to above 3 MV/cm for N_A near 5 x 10^{17} cm^{-3}. These measured 3C-SiC electric fields are comparable to reported $<11\bar{2}0>$ and $<03\bar{3}8>$ 4H-SiC breakdown fields.

Introduction

Besides Si, SiC is the only other semiconductor that forms SiO_2 insulator when its surface is thermally oxidized. Inversion channel MOSFET switches are preferred because they are voltage dependent, they switch faster, the gate is well-insulated, and the device can be made normally off under zero applied gate bias. 3C-SiC inversion-mode MOSFET channel properties appear far superior to 4H-SiC MOSFET's, but excessive crystal defects in 3C-SiC have resulted in unacceptably poor blocking junction breakdown performance [1-3]. Step-free surface heteroepitaxy of 3C-SiC films with greatly improved dislocation density on patterned 4H/6H-SiC substrate mesas has recently been reported [4-6]. This paper details initial assessment of improved breakdown field performance demonstrated by p-type Schottky diodes implemented in stacking-fault-free 3C-SiC mesa films.

Experiment

The growth process for the heteroepilayer structure is the same as for "Sample B" described in [7]. The epi consisted of boron p-doped 3C-SiC layer residing on top of degenerately aluminium and boron doped 3C/4H layers. Boron doping was unintentional. These epi layers were grown on mesas etched into a p-type 5x10^{17} cm^{-3} 4H-SiC on-axis Si face substrate. The sample was thermally dry-oxidized (1150 °C for ~7 hours) to map the polytype and stacking-fault (SF) content of the film surface. The 4H-SiC oxidized 70 nm giving it a brown appearance, and the 3C-SiC oxidized 100 nm giving it a deep violet appearance. A few mesas with screw dislocations (< 5 %) grew entirely of the 4H-SiC polytype [8]. Patterned vias were buffered oxide etched (BOE) through the oxide. Small-area (up to 3 x 10^{-4} cm^2) 50 nm Ti / 150 nm Ni contacts were sequentially, without breaking vacuum, electron-beam deposited and patterned by lift-off on the 3C-SiC mesa surfaces. Fabrication concluded with wafer backside metallization as seen in Fig. 1.

The 3C-SiC p-type Schottky diodes were electrically tested in near-dark conditions on a computer-controlled probing station with a temperature-controlled hot chuck. A capacitance meter at 1 MHz frequency was used for CV measurements. Forward and reverse IV characteristics were measured with source-measure units, respectively. Acceptor doping versus depth profiles were calculated from CV data as described in [9], and secondary ion mass spectroscopy (SIMS) was performed by a commercial vendor [10].

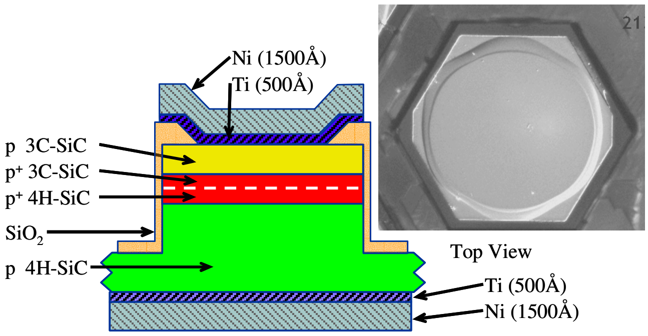

Fig. 1 Schematic cross section of the 3C-SiC Schottky diode and top view photograph of fabricated device.

Results

Doping. For the majority of devices the CV measurements indicated that the doping was nearly uniform as a function of depth for the more lightly doped top epilayer. The 3C-SiC devices that contained stacking faults or did not yield uniform CV-extracted doping versus depth profile are excluded from the data set of this initial report. The CV characteristics and calculated doping versus depth profiles did not change significantly with measurement temperature (Fig. 2). The CV-extracted doping values varied from approximately $1\text{x}10^{17}$ cm^{-3} to $5\text{x}10^{17}$ cm^{-3} across the sample.

Several devices were selected for aluminum and boron profiling by SIMS. The CV-measured doping profile and corresponding boron SIMS profiles for the lightly-doped top epilayer of one of these devices are shown in Fig. 3. All aluminum SIMS profiles showed concentrations of $1\text{x}10^{16}$ cm^{-3} for the top epilayer. Fig. 3 shows reasonable agreement between total acceptor doping concentrations measured by CV and SIMS. The temperature invariance of the CV data and consistency with SIMS results suggests that incomplete ionization and/or series resistance effects did not significantly compromise CV measurement of acceptor doping concentration N_A [11]. SIMS measurements at much greater depth than shown in Fig. 3 confirmed the degenerate aluminum doping for the buried p^+ layers on both sides of the 3C/4H heterojunction.

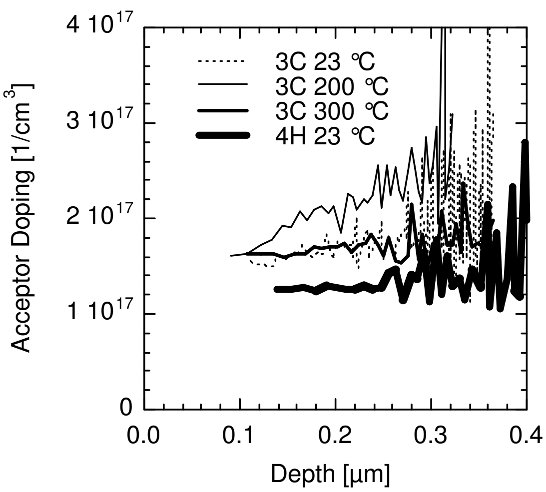

Fig. 2 CV measured doping of 3C-SiC p-type Schottky diode at 23°C, 200°C, and 300°C compared with a 4H-SiC Schottky diode at 23°C grown on the same wafer.

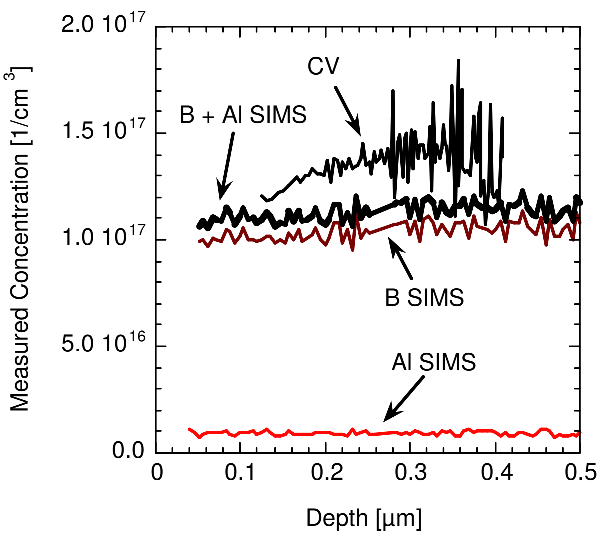

Fig. 3 Comparison of CV and SIMS for 3C SiC Schottky diode (see text).

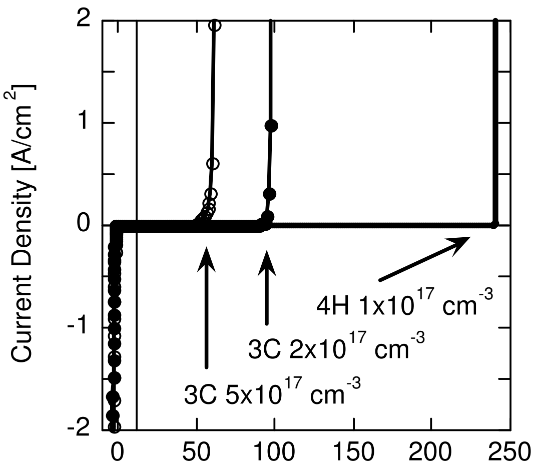

Fig. 4 Linear scale IV characteristics of two p-type 3C-SiC and one 4H-SiC Schottky diodes.

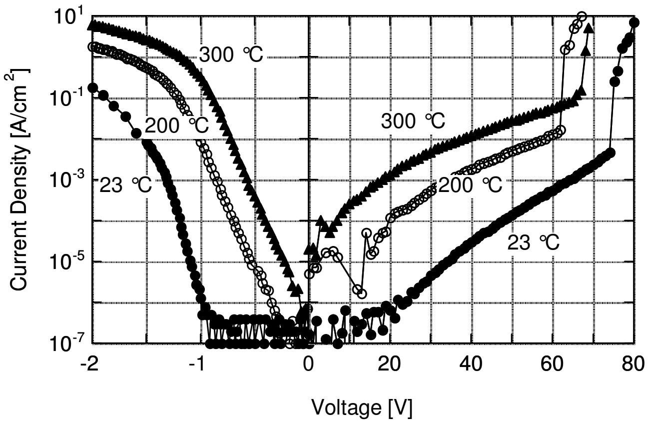

Fig. 5 Log-scale IV characteristics of a 1.7 X 10^{17} cm^{-3} p-type 3C-SiC Schottky diode at 23°C, 200°C, and 300°C. The area of the device was 10^{-4} cm^2. Note the difference in the scale for forward and reverse voltage.

Current-Voltage. Linear current-scale IV characteristics at room temperature from two representative SF-free 3C-SiC diodes and a 4H-SiC diode are shown in Fig. 4. Representative logarithmic current scale IV characteristics of a 1.7×10^{17} cm^{-3} 3C-SiC device at 23 °C, 200 °C, and 300 °C are illustrated in Fig. 5. The IV characteristics generally show excellent rectification properties with low reverse leakage and relatively sharp reverse breakdown. As expected, the leakage current of the 3C-SiC diodes increased with ambient temperature. Breakdown voltages from 96 V down to 53 V were observed for SF-free diodes.

The current at higher forward biases (> 1.5 V) increases with temperature, presumably as a result of increasing p-type dopant ionization with temperature in quasi-neutral epilayer and substrate device regions. Exponential IV behavior is observed at all three temperatures. However, the forward current ideality factors (1.8 at 23 °C, 1.7 at 200 °C, and 1.4 at 300 °C) were significantly above the nominal value of unity. Also, the exponential forward current regions measured at room temperature exhibited some variation as a function of voltage sweep rate parameters. A similarly high room-temperature ideality factor of 1.6 was extracted from a 4H diode on the sample. Further study beyond the scope of this initial report is needed to ascertain physical reasons for non-ideal forward IV behavior.

Breakdown Field. For this study, the reverse breakdown voltage V_B was defined at room temperature as the voltage at which the reverse current exceeded 0.1 A/cm^2, which generally corresponds to where the room temperature current most sharply increased with reverse voltage (Fig. 5). The peak electric E_B field in semiconductor diodes at breakdown voltage can be estimated using the well-known procedure described in [12] with doping N_A extracted from CV measurements and the IV measured breakdown voltage V_B at 0.1 A/cm^2. The calculated breakdown field of the stacking-fault-free 3C-SiC devices are plotted Fig. 6 as solid circles, with values ranging from near 2 MV/cm for N_A near 1 x 10^{17} cm^{-3} to above 3 MV/cm for N_A near 5 x 10^{17} cm^{-3}. Even if the observed breakdown was due to leakage instead of avalanche, the 3C-SiC avalanche breakdown field must exceed the values shown in Fig. 6. For comparison, Fig. 6 also shows previously measured diode breakdown fields along <0001>, $\langle 11\bar{2}0 \rangle$, and $\langle 03\bar{3}8 \rangle$ 4H-SiC [13, 14], and 3C-SiC grown on silicon substrates [15]. The breakdown electric field of the p-type 3C-SiC Schottky diodes measured in this work is comparable to measured breakdown fields previously reported along $\langle 11\bar{2}0 \rangle$ and $\langle 03\bar{3}8 \rangle$ for 4H-SiC [14]. As a further check, we applied identical measurement and calculation procedures to one of the very few 4H diodes on the sample. As expected, the 4H result ($N_A = 1.2 \times 10^{17}$ cm^{-3}, V_B = 240 V, E_B = 3.3 MV, plotted as the open triangle in Fig. 6) matches the reported <0001> 4H-SiC breakdown field [13].

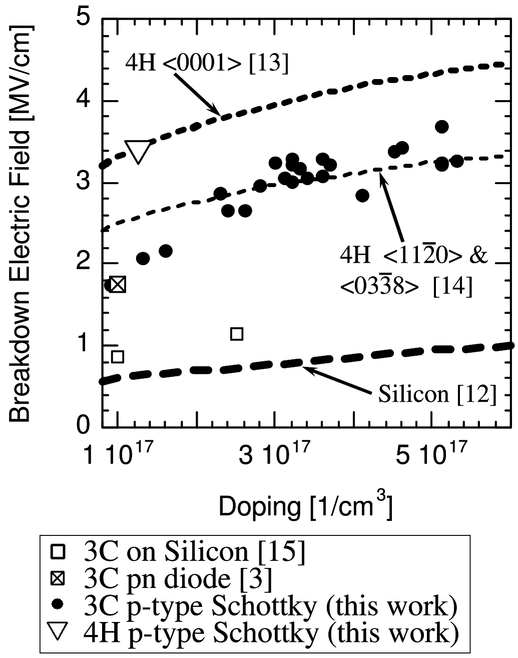

Fig. 6 Breakdown electric field vs. doping at 23°C.

Summary Discussion

Reverse breakdown voltages in excess of 100 V have been previously reported for 3C-SiC Schottky diodes [15, 16]. However, these devices all used thick, very lightly doped epilayers so that the peak electric field was kept to less than 20% of the breakdown fields measured in this report. Furthermore, these works also defined breakdown as occurring at significantly higher current density than the 0.1 A/cm^2 used in this work. The 3C-SiC Schottky diode results of this paper are comparable within measurement error to 3C-SiC p^+n junction devices previously reported by our group using a different 3C epilayer growth approach [3].

While the initial 3C breakdown field results reported here are highly promising, the data set only covers 1-5x10^{17} cm^{-3} boron-doped epilayers. Further measurements over wider doping density and with epilayers dominated by other dopants (i.e., nitrogen and aluminum) will enable a more complete and useful understanding of 3C-SiC breakdown behavior.

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References

[1] J. Wan, et.al.: IEEE Electron Device Letters Vol. 23, (2002), p. 482
[2] T. Ohshima, et. al.: Japanese Journal of Applied Physics Vol. 42 (2003), p. L625
[3] P. G. Neudeck, et. al.: IEEE Transactions on Electron Devices Vol. 41 (1994), p. 826
[4] P. G. Neudeck, et al.: Materials Science Forum Vol. 389-393 (2002), p. 311
[5] P. G. Neudeck, et al.: Materials Science Forum Vol. 433-436 (2002), p. 213
[6] P. G. Neudeck and J. A. Powell: "Homoepitaxial and Heteroepitaxial Growth on Step-Free SiC Mesas," in *Recent Major Advances in SiC* (Springer-Verlag, Germany 2003), p. 179
[7] A. J. Trunek, et. al.: Comparative Growth Behavior of 3C-SiC Mesa Heterofilms With and Without Extended Defects, presented at this conference, (2003)
[8] M. Dudley, W. M. Vetter, and P. G. Neudeck: Journal of Crystal Growth Vol. 240 (2002), p. 22
[9] D. K. Schroder: *Advanced MOS Devices* (Addison-Wesley, Reading, MA 1987)
[10] Charles Evans & Associtates, Sunnyvale, CA, http://www.cea.com
[11] A. V. Los and M. S. Mazzola: Journal of Electronic Materials Vol. 30 (2001), p. 235
[12] B. J. Baliga: *Modern Power Devices, 1st ed.* (John Wiley & Sons, Inc., New York 1987), p. 67
[13] A. O. Konstantinov, et. al.: Applied Physics Letters Vol. 71 (1997), p. 90
[14] S. Nakamura, et. al.: Journal of Applied Physics Vol. 80 (2002), p. 3355
[15] C. W. Liu and J. C. Sturm: Journal of Applied Physics Vol. 82 (1997), p. 4558
[16] Y. Ishida, et. al.: Materials Science Forum Vol. 389-393 (2002), p. 459