Effect on 4H-SiC Schottky Rectifiers of Ar Discharges Generated in A Planar Inductively Coupled Plasma Source

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Abstract—**4H-SiC Schottky rectifiers were exposed to pure Ar discharges in a planar coil Inductively Coupled Plasma system, as a function of source power, of chuck power and process pressure. The reverse breakdown voltage (V_B) decreased as a result of plasma exposure due to the creation of surface defects associated with the ion bombardment. The magnitude of the decrease was a function of both ion flux and ion energy. The forward turn-on voltage (V_F), on-state resistance (R_{ON}) and diode ideality factor (n) all increased after plasma exposure. The changes in all of the rectifier parameters were minimized at low power, high pressure plasma conditions.**

Index Terms—**SiC, Plasma Etching, ICP Processing, Damage and Schottky Rectifier**

I. INTRODUCTION

SiC-based rectifiers are generating tremendous current interest for a broad range of applications, including broad band satellite transmission systems, advanced radar, high temperature sensors and traction motor control. [1-25] Most attention has been focussed on the 4H-SiC polytype because of its larger bandgap (3.25 eV) and higher mobility relative to the other polytypes. [5] Within the two basic classes of rectifiers, Schottky devices have the lowest on-state voltages and highest switching speeds, while p-i-n diodes have the higher reverse breakdown voltage and lower reverse leakage current. [15] Compared to Si rectifiers, SiC devices have on-state resistances approximately a hundred times lower or equivalently much larger breakdown voltage at the same on-state resistance. [26] While very high forward currents (up to 130 A) and breakdown voltages (4.9 kV) have been achieved for 4H-SiC Schottky rectifiers, [15] a lot of recent attention has been focussed on fabrication and materials technology for diodes in the 300-1000 V range. [15-17] Plasma processing is required both for dry etching of mesas and deposition of dielectrics for surface passivation and metal overlap edge termination. However little has been reported on the effects of plasma exposure on the electrical performance of 4H-SiC rectifiers.

In this paper, we describe the effect of Inductively Coupled Plasma (ICP) Ar discharges generated in a novel plasma source configuration, on the electrical properties of Ni/4H-SiC Schottky rectifiers. Both ion flux and ion energy are found to play a role in the extent of the observed changes in reverse breakdown voltage (V_B), on-state resistance (R_{ON}), ideality factor (n) and forward turn-on voltage (V_F).

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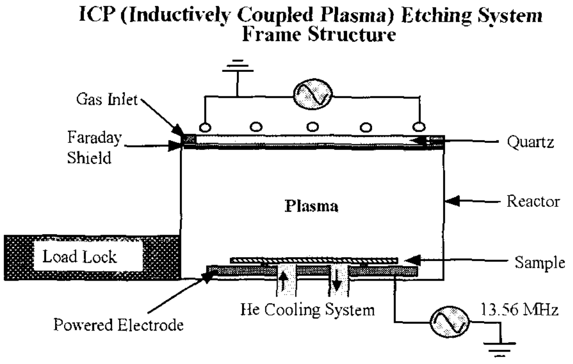

Fig. 1 Schematic of planar coil ICP reactor used in these experiments.

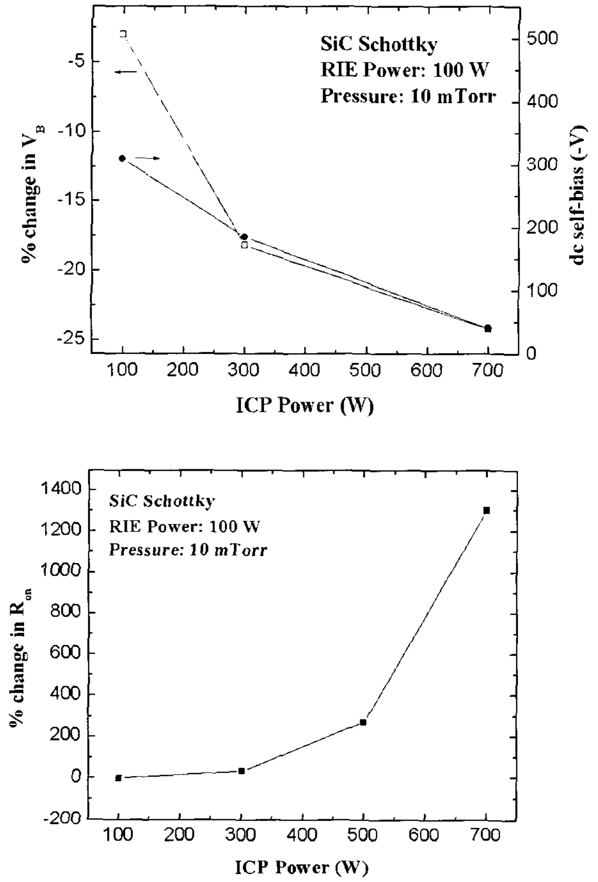

Fig. 2 Percentage change in V_B (top) and R_{ON} (bottom) of 4H-SiC rectifiers as a function of ICP source power during Ar plasma exposure at fixed rf chuck power (100 W) and process pressure (10 mTorr). The developed dc self-bias is also shown at top.

II. EXPERIMENTAL

10 μm of n-type ($n \sim 5 \times 10^{15}$ cm^{-3}) 4H-SiC was grown by vapor phase epitaxy on n^+ (10^{19} cm^{-3}) 4H-SiC substrates. Ohmic contact to the back of the substrate was provided by a full-area layer of e-beam deposited Ni annealed at 970 °C for 3 minutes. Front-side Schottky contacts were produced by a lift-off of e-beam evaporated Ni (1000 Å thick), with a contact diameter of 154 μm. The as-fabricated rectifiers showed R_{ON} of 4.4 mΩ-cm^2, V_F = 1.96 V and V_B = -330 V.

The devices were exposed to pure Ar discharges in a planar coil geometry ICP reactor manufactured by Cliotek, Inc., shown schematically in Figure 1. A key feature of this system is the ability to operate at very low source power (20 W) as well as chuck power (5 W), which allows one to design etch or deposition processes that end with very low ion energy and flux conditions to minimize damage. The ICP source power (13.56 MHz) was varied from 100-700 W, the rf chuck power (13.56 MHz) from 25-200 W and the process pressure from 10-40 mTorr. All exposures were 30 secs in duration and removed < 150 Å of the surface by sputtering. These plasma exposure simulate the ion bombardment received by the SiC surface during processes such as dry etching or plasma enhanced chemical vapor deposition and represent a worst-case scenario because there is no chemical etch component that would remove some of the damaged surface region on a deposition of dielectric to protect the surface from further ion bombardment.

III. RESULTS AND DISCUSSION

Figure 2 shows the percentage changes in V_B (top) and R_{ON} (bottom) as a function of ICP source power at fixed rf chuck power (100 W) and process pressure (10 mTorr). The reverse breakdown voltage decreases with increasing ion flux. Since the dc self-bias on the sample electrode also decreases with increasing source power, this indicates that increasing ion flux is a factor in degrading the breakdown voltage. Note however that the changes are ≤ 25% even at the highest source power employed. For SiC there is an empirical relationship between V_B and the doping in the epilayer, N_D, which is given by [26]

$$V_B = 1.75\times10^{15} N_D^{-0.75}$$

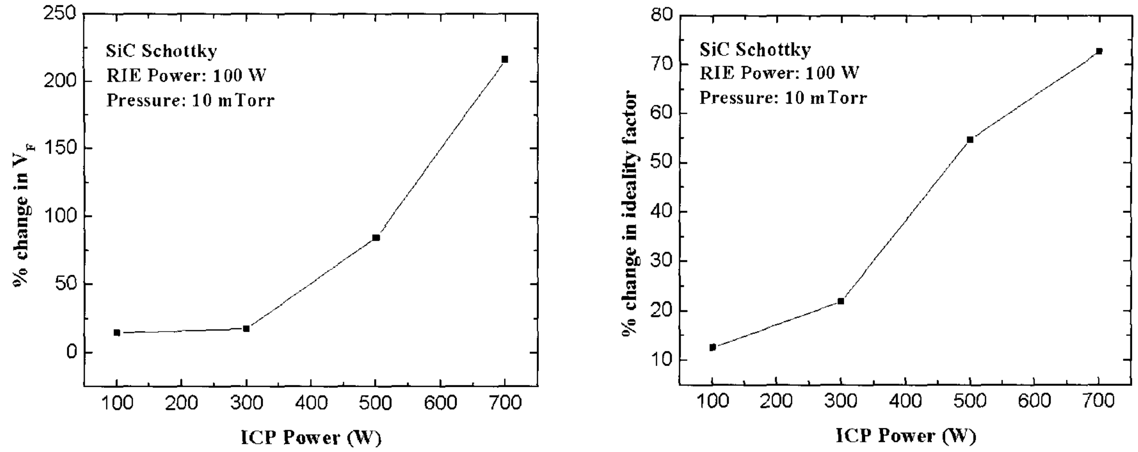

Fig. 3 Percentage change in V_F (top) and n (bottom) of 4H-SiC rectifiers as a function of ICP source power during Ar plasma exposure at fixed rf chuck power (100 W) and process pressure (10 mTorr).

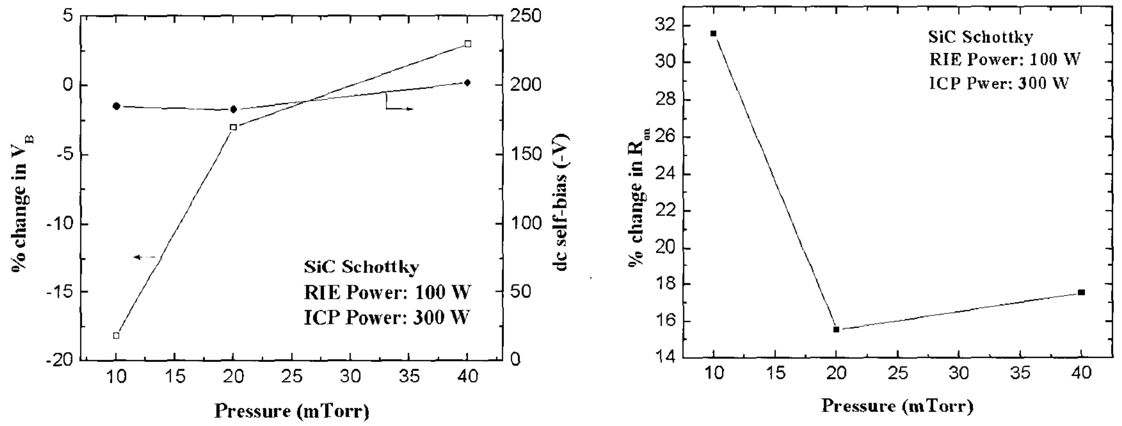

Fig. 4 Percentage change in V_B (top) and R_{ON} (bottom) of 4H-SiC rectifiers as a function of process pressure during Ar plasma exposure at fixed ICP source power (300 W) and rf chuck power (100 W). The developed dc self-bias is also shown at top.

One of the expected effects of Ar plasma exposure on the exposed SiC around the contact periphery is a decrease in N_D through creation of deep trap states. However this would lead to an increase in V_B, which is the opposite of what is observed experimentally. Therefore, we suggest that the main effect of the plasma exposure under our conditions is an increase in surface defects that initiate breakdown at much lower values than expected from the bulk doping of the SiC epilayer.

The on-state resistance can be written [6]

$$R_{ON} = \frac{4V_B^2}{\mu \in E_C^3}$$

where μ is the electron mobility, ∈ the permittivity of 4H-SiC and E_C the critical field for breakdown. Since V_B decreases with increasing source power, we would also expect a decrease in R_{ON} unless E_C is also decreasing. Figure 2 (bottom) shows large increases in R_{ON} as the source power is increased, which is consistent with the creation of surface states that promote early breakdown of the damaged rectifier.

Figure 3 shows the percentage changes in V_F (top, measured at 100 A.cm^{-2}) and ideality factor (bottom) as a function of source power at fixed rf power (100 W) and pressure (10 mTorr). Note that the changes in both parameters are ≤ 20% provided the source power is left below 300 W, corresponding to a dc self-bias ≤ -185 V. At higher source powers both V_F and n are severely degraded even though the self-bias under these

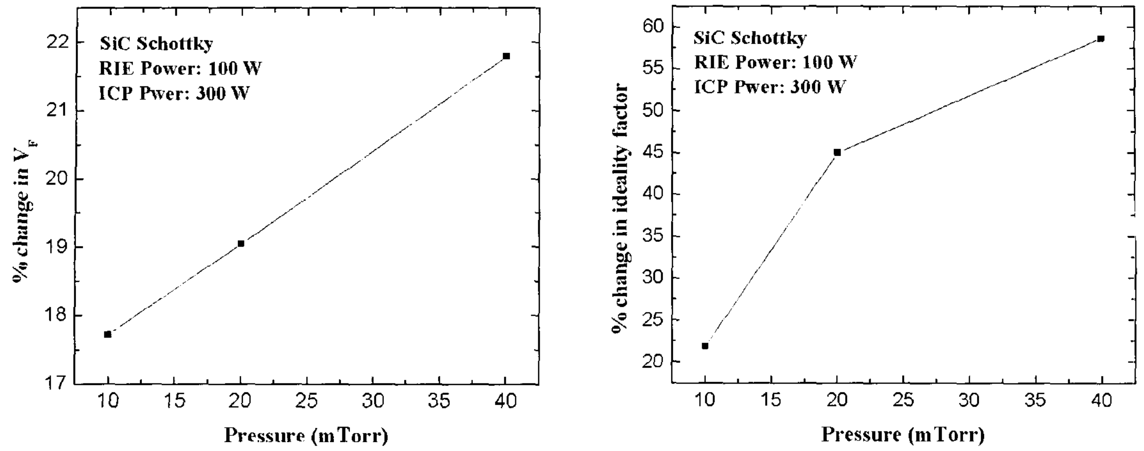

Fig. 5 Percentage change in V_F (top) and n (bottom) of 4H-SiC rectifiers as a function of process pressure during Ar plasma exposure at fixed ICP source pressure (300 W) and rf chuck power (100 W).

conditions is low (-41 V at 700 W source power). The average energy of the incident Ar^+ ions is roughly given by the sum of the dc self-bias and the plasma potential (approximately –25V in this system). Therefore even though the ion energy is low at high source powers, the ion flux is sufficient to create significant degradation in the rectifier characteristics. The forward voltage drop for a Schottky rectifiers is related to the barrier height (ϕ_B) and R_{ON} through the relation [22]

$$V_F = \frac{nkT}{e}\ln\left(\frac{J_F}{A^{**}T^2}\right) + n\phi_B + R_{ON}J_F$$

where k is Boltzmann's constant, T the absolute temperature, e the electronic charge, J_F the forward current density and A^{**} is Richardson's constant for 4H-SiC. Therefore V_F can be degraded by increases in ideality factor and on-state resistance along with a reduction in forward current due to introduction of trap states.

The changes in rectifier performance were also dependent on the applied rf chuck power, or equivalently on ion energy. The changes in V_B, V_F, R_{ON} and n were ≤ 20% for V_B and V_F, ≤ 30% for R_{ON} and ≤ 40% for n over the range of these parameters that we investigated.

Figure 4 shows the percentage changes in V_B (top) and R_{ON} (bottom) as a function of process pressure at fixed source power (300 W) and rf power (100 W). Note that the decreases in both parameters are largest at the lowest pressure. This is consistent with the fact that at low pressures the incident ions have a lower probability of collisions with gas molecules or they traverse the sheath region and therefore they impact with their full energy. A major advantage of the planar ICP source is its ability to operate at higher pressures (≥ 40 mTorr) relative to the more normal 10 mTorr range of conventional cylindrical coil sources. The ideality factor of the rectifiers was still more degraded at higher pressures, while V_F showed very small changes with pressure (Figure 5).

IV. SUMMARY AND CONCLUSIONS

4H-SiC power rectifiers were exposed to Ar discharges in a planar coil ICP reactor as a function of various plasma parameters. The reverse breakdown voltage decreases with increasing ion flux, which is controlled by the source power, whereas V_F, R_{ON} and n all increase under the same conditions. These results are consistent with creation of surface states that promote reverse breakdown at lower applied voltages. The same trends were observed with increasing of chuck power, which controls the incident ion energy. The increases in V_B and R_{ON} are minimized at high operating process pressure, as expected since these conditions reduce the effectiveness of the ion bombardment experienced during the plasma exposure. Damage during actual etch or deposition process would be lower than produced during the Ar plasma exposure, but clearly process conditions that utilize low ion energies and fluxes are desirable at the end of an etch cycle or the beginning of a deposition cycle in order to minimize ion-induced damage.

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REFERENCES

[1] N. V. Dyakonova, P.A Ivanov, V.A. Kozlov, M.E. Levinshtein, J.W. Palmour, S.L. Rumyantsev and R. Singh, IEEE Trans. Electron Dev. 46, 2188 (1999).

[2] D. Alok and B.J. Baliga, IEEE Electron Dev. Lett. 44, 1013 (1997).

[3] P.G. Neudeck, J. Electron. Mater. 24, 283 (1995).

[4] M.G. Spencer, J. Palmour and C. Carter, IEEE Trans. Electron. Dev. 49, 940 (2002).

[5] J.B. Casady, A.K. Agarwal, S. Seshadri, R.R. Siergiej, L.B. Rowland, M.F. MacMillan, D.C. Sheridan, P.A. Sanger and C.D. Brandt, Solid-State Electron. 42, 2165 (1998).

[6] M. Trivedi and K. Shenai, J. Appl. Phys. 85, 6889 (1999).

[7] D. Peters, R. Schoener, K.H. Holzein and P. Friedrichs, Appl. Phys. Lett. 71 2996 (1997).

[8] C. I. Harris and A. O. Konstantinov, Physica Scripta T79 27 (1999).

[9] V. Khemka, R. Patel, T.P. Chow and R.J. Gutmann, Solid-State Electron. 43, 1945 (1999).

[10] B.J. Baliga, IEEE Electron Dev. Lett. 5, 194 (1984).

[11] K.J. Schoen, J.M. Woodall, J.A. Cooper, Jr. and M.R. Melloch, IEEE Trans. Electron. Dev. 45, 1595 (1998).

[12] M. Mehrotra and B.J. Baliga, Solid State Electron. 38, 703 (1995).

[13] B.J. Baliga and H.R. Chang, IEEE IEDM Tech. Dig. 658-661 (1987).

[14] A. O. Konstantinov, N. Nordell, Q. Wahab, and U. Lindefelt, Appl. Phys. Lett. 73, 1850 (1998).

[15] R. Singh, J.A. Cooper, Jr., M.R. Melloch, T.P. Chow and J.W. Palmour, IEEE Trans. Electron Dev. 49, 665 (2002).

[16] M.C. Tarplee, V.P. Madangarli, Q. Zhang and T.S. Sudarshan, IEEE Trans. Electron Dev. 48, 2659 (2001).

[17] P. Alexandrov, J.H. Zhao, W. Wright, M. Pan and M. Weiver, Electron. lett. 37, 1261 (2001).

[18] P.G. Neudeck and C. Fazi, IEEE Electron Dev. Lett. 18, 96 (1997).

[19] J.B. Casady, in Processing of Wide Bandgap Semiconductors (William Andrew, Norwich, NY, 2000).

[20] C. I. Harris and A. O. Konstantinov, Physica Scripta T79 27 (1999).

[21] K.V. Vassilevski, A.B. Horsfall, C.M. Johnson, N.G. Wright and A.G. O'Neill, IEEE Trans. Electron. Dev. 49, 947 (2002).

[22] D.T. Morisette, J.A. Cooper, Jr., M.R. Melloch, G.A. Dolny, P.M. Shenoy, M. Zafrani and J. Gladish, IEEE Trans. Electron Dev. 48, 349 (2001).

[23] Q. Zhang and T.S. Sudarshan, Solid-State Electron. 45, 1847 (2001).

[24] D.C. Sheridan, G. Niu, J.N. Merrett, J.D. Cressler, C. Ellis and C.C. Tin, Solid-State Electron. 44, 1367 (2000).

[25] V. Saxena, J.N. Su and A.J. Steckl, IEEE Trans. Electron Dev. 46, 456 (1999).

[26] B.J. Baliga, Power Semiconductor Devices (PWS, Boston 1996).

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