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Investigation of Mobile Ion Effects on SiC MOSFET Threshold-Voltage Instability Using Experimental Data and Numerical Modeling

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Next-generation power devices, based on wide-bandgap semiconductors that can be operated at high temperatures and large power densities, are necessary to meet performance and reliability goals for future power conditioning systems, ranging in applications from motor drives and electric vehicles to grid-level power transformers. Silicon Carbide (SiC) MOSFETs are being investigated as a very attractive candidate. However, the oxidation process is more complicated than Si, largely due to the presence of carbon and 4H polytype crystal structure, which when combined with the necessarily thick oxide for power devices, produces oxide defects that are a major obstacle to achieving the full performance of SiC power MOSFETs. These defects include significant numbers of interface traps and near-interface oxide traps [1]. Additionally, bias-temperature stresses (BTS) show evidence of mobile ion contamination in the gate oxide [2], corroborated by triangular voltage sweep (TVS) measurements to quantify the amount of charge [3]. Mobile ions may include traditional elements or carbon-related complexes [4] and are likely a result of the fabrication process for SiC MOS. Deconvolving the different effects of various oxide defects through standard experimental means has proven challenging given the complex dependencies on bias, temperature, and time. Efforts have been made to simulate the effects of interface and oxide traps [5],[6], but they do not consider mobile ions in the calculations. Given the strong dependence of oxide trap charging on time, a time-dependent (TD) mobile ion model is necessary to study both effects when simultaneously present. To better understand the influence of mobile oxide charge, we developed a numerical simulator that emulates the time-dependent diffusive and field driven transport of mobile impurity ions in the gate oxide of SiC power MOSFETs.

There has been much interest in the effects of mobile ions on SiC MOSFETs, particularly since it was found that the presence of sodium in the gate oxide could dramatically increase MOSFET field effect mobilities [7]. Unfortunately, this improvement is unstable when devices are subjected to BTS and the presence of mobile charge in the oxide is a major problem for devices that are intended to operate at temperatures of 150 °C and higher. Even without the purposeful introduction of ions into the oxide, typical mobile ion-like charge densities in SiC MOS devices have been found to range from 10^{11} to 10^{13} cm^{-2} [3-4,8-9], levels which will cause unacceptably high hysteresis in device characteristics. Additionally, mobile ions will act in opposition to charge trapping effects, which may explain why threshold instabilities have been observed to reduce as the temperature is increased [2,3], and could lead to problems accurately assessing the reliability of SiC MOS devices [10].

Figure 1 shows both experimentally measured and numerically simulated gate current of a SiC MOS capacitor during an example TVS measurement. From the TVS measurement performed at 150 °C, total mobile ion density was estimated to be $N_p \cong 1.2 \times 10^{12}\ \mathrm{cm}^{-2}$. Even when a simple simulation is performed that includes no additional effects (such as interface or oxide traps), basic agreement is obtained although the experimental data is broader and shows additional features.

We can also study how a charge distribution at steady-state reacts to an abrupt change in bias, simulating a BTS. Figure 2 shows time slices of the distribution as it transitions across the oxide. By the end, the distribution has entered a new state of equilibrium. The redistribution of charges moves the position of the charge centroid, which determines the net voltage shift of the device's terminal characteristics. Figure 3 shows how the charge centroid evolves during the initial stages of a typical BTS applied to a SiC MOS device; the ionic current induced by the movement in this charge distribution is also shown. Most of the movement occurs over 1-2 decades of time, after which the effect saturates and the charge is located almost entirely on the opposite side of the oxide. The ionic current is reasonably constant throughout until it quickly drops at the end of the transition.

References

[1] K. Matocha and V. Tilak, “Understanding the inversion-layer properties of the 4H-SiC/SiO2 interface,” *Materials Science Forum*, vol. 679-680, no. ,pp. 318-325, March 2011.

[2] A.J. Lelis, D. Habersat, R. Green, and N. Goldsman, “Temperature-dependence of SiC MOSFET threshold-voltage instability,” *Materials Science Forum*, vol. 600-603, pp. 807-810, September 2008.

[3] D.B. Habersat, A.J. Lelis, and R. Green, “Detection of mobile ions in the presence of charge trapping in SiC MOS devices,” *Materials Science Forum*, vol. 717-720, pp. 461-464, May 2012.

[4] A. Chanthaphan et al., “Investigation of unusual mobile ion effects in thermally grown SiO2 on 4H-SiC(0001) at high temperatures,” *Applied Physics Letters*, vol. 100, pp. 252103, June 2012.

[5] S. Potbhare et al., “A physical model of high temperature 4H-SiC MOSFETs,” *IEEE Transactions on Electron Devices*, vol. 55, pp. 2029-2040, August 2008.

[6] A.J. Lelis, D.B. Habersat, R. Green, and N. Goldsman, “Two-way tunneling model of oxide trap charging and discharging in SiC MOSFETs,” *Materials Science Forum*, vol. 717-720, pp. 465-468, May 2012.

[7] E.Ö. Sveinbjörnsson et al., “High Channel Mobility 4H-SiC MOSFETs,” *Materials Science Forum*, vol. 527–529, pp. 961–966, October 2006.

[8] X. Zhu et al., “The effect of nitrogen plasma anneals on interface trap density and channel mobility for 4H–SiC MOS devices,” *Solid-State Electronics*, vol. 57, no. 1, pp. 76–79, Mar. 2011.

[9] T. Okayama, S.D. Arthur, J.L. Garrett, and M.V. Rao, “Bias-stress induced threshold voltage and drain current instability in 4H–SiC DMOSFETs,” *Solid-State Electronics*, vol. 52, no. 1, pp. 164–170, Jan. 2008.

[10] R. Green, A. Lelis, and D. Habersat, “Application of reliability test standards to SiC Power MOSFETs,” *2011 IEEE International Reliability Physics Symposium (IRPS)*, vol. 49, p. EX.2.1 –EX.2.9, April 2011.

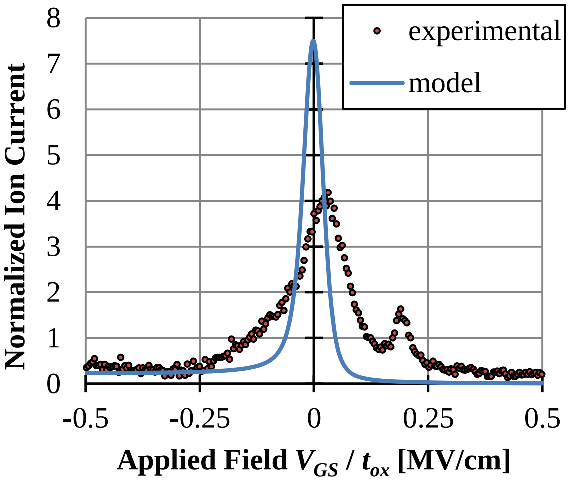

Fig. 1. Triangular voltage sweep measurement (dots) and simulation (line) data of a SiC MOS capacitor at 150°C. Area under the curve is total ion density, $N_p \approx 1.2 \times 10^{12}$ cm^{-2}.

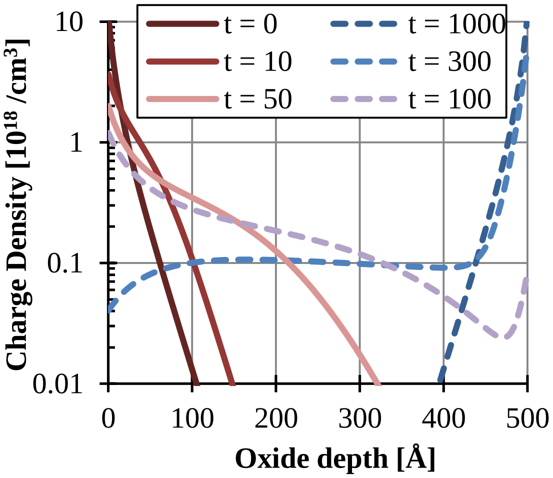

Fig. 2. Time-dependent movement of a 10^{12} cm^{-2} mobile ion population in 500 Å of SiO$_2$ following an abrupt switch from +1 V to -1 V applied bias. The charge distribution at various time steps is shown, and basically moves from left to right as time increases. $\mu = 10^{-13}$ cm^2/V s, $T = 150$ °C, and time from start t is in seconds.

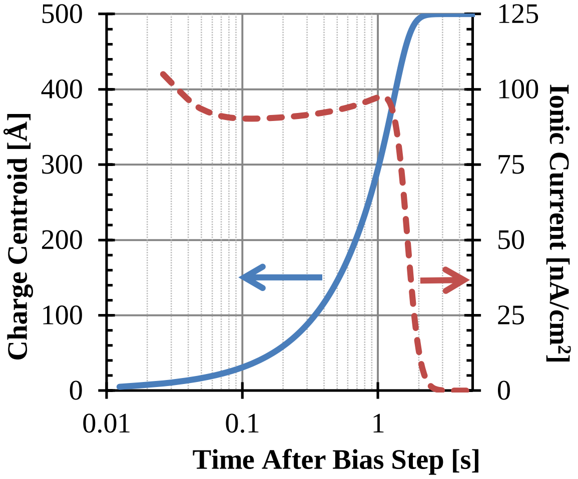

Fig. 3. Plot of the charge centroid (solid, left axis) and ionic current (dashed, right axis) versus time after an abrupt switch from -15 V to +15 V for a 10^{12} cm^{-2} mobile ion population in 500 Å-thick SiO$_2$ ($\mu = 10^{-12}\text{cm}^2/\text{Vs}$, $T = 150$°C).