High Temperature Reliability of SiC n-MOS Devices up to 630 °C

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Abstract. SiC based field-effect devices are attractive for electronic and sensing applications above 250 ºC. At these temperatures the reliability of the insulating dielectric in metal-oxide-semiconductor (MOS) structures becomes an important parameter in terms of long-term device performance. We report on the reliability of n-MOS SiC capacitors following thermal stress cycling in the 330 to 630 ºC range. As the primary mode of oxide breakdown under these conditions is believed to be due to electron injection from the substrate, the gate leakage current was measured as a function of temperature. The gate dielectric was grown using dry oxidation with a post oxidation NO passivation anneal. For large area, 1 mm diameter, 6H-SiC capacitors we obtain current densities as low as 5nA/cm^2 at 630 ºC. In addition, gate leakage measurements from arrays of 300 to 1000 μm diameter devices fabricated on different 1cm^2 6H-SiC substrates are presented. These are encouraging results for the long-term reliability of SiC field-effect sensors.

Introduction

For high temperature electronic and sensing applications, SiC based field-effect devices show great promise, particularly above 250 ºC, which represents an upper bound for Si based structures [1]. We are developing catalytic gate SiC sensors (Pt-SiO_2-SiC) for detection of hydrogen containing species at elevated temperatures [2]. For real-time sensing applications we find these sensors have a millisecond response time to gas change from oxygen to hydrogen. This fast response requires sensor operation at 630 ºC [3]. At these temperatures the reliability of the insulating dielectric in metal-oxide-semiconductor (MOS) structures becomes an important parameter in terms of long-term device performance [4].

Experimental

Device Fabrication. The n-MOS capacitors were fabricated on 1cm^2 6H-SiC (0001) Si face substrates with a 3 μm thick, 2.1 x 10^{16} N/cm^3 epitaxial layer grown on an n$^+$ (1.0 x 10^{18} N/cm^3) wafer. The gate oxide was grown via dry oxidation at 1150 ºC, followed by a 900 ºC Ar anneal and a 2 hour 1175ºC post oxidation NO passivation anneal. The oxide thickness is ~39 nm, as determined via spectroscopic ellipsometry. The gate metal is 100 nm of Pt sputtered at 350 ºC in a 5 mTorr Ar atmosphere. Shown in Fig. 1 is a micrograph of a SiC sample consisting of an array of 52 gates with nominal diameters ranging from 200 to 1000 μm. A large area back contact, either a 75 nm thick Au film or a thermally cured colloidal Ag paste, provides a common ground plane for all the gates on the chip.

High Temperature Electrical Characterization Techniques. The SiC sample was mounted on an alumina header. The electrical connections between the Pt gates and the measurement equipment were made via ultrasonic wire bonding. Three platinum microheaters (Heraeus) were attached to

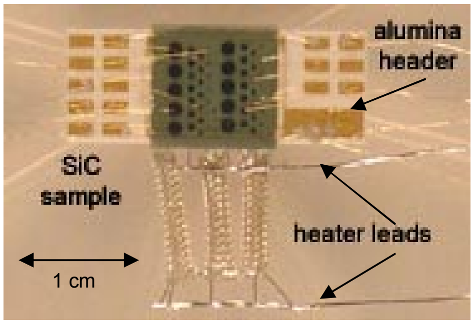

Fig. 1: Micrograph of a 6H-SiC sample (1cm x 1cm) with an array of 52 n-MOS devices mounted on a thermally conducting, electrically insulating alumina header. Nominal gate diameters are: 200, 300, 500 and 1000 µm. The gates are numbered by column from right to left, 1 refers to the 200 µm devices on the far right and 8 the 1000 µm devices on the far left. The sample can be heated up to 630 ºC via the three Pt micro-heaters attached to the back of the header. Experimental data is only presented for the 300 – 1000 µm gates.

the backside of the thermally conducting alumina header to locally heat the SiC sample to 630 ºC. The header also provides the necessary electrical insulation from the heater current for precision electrical measurements using a commercial (Keithley Models 90 and 82) current-voltage (I-V) and capacitance-voltage (C-V) system. At 630 ºC our noise is ±5pA and ±2pF respectively.

Results and Discussion

High temperature C-V measurements. Figures 2 and 3 show representative 1MHz C-V measurements of the n-MOS devices at 630 ºC. As discussed above, this temperature was chosen for device evaluation to optimize the sensor response time. Complete C-V characteristics from deep depletion into accumulation were obtained and the accumulation capacitance agrees well with the measured oxide thickness. Our ability to bias the capacitor far into accumulation at 630 ºC provides evidence of the high temperature stability of the insulating layer of the MOS capacitors. As the signal to noise ratio of the sensor is proportional to the slope of the C-V characteristic near mid-gap gate bias [2], the focus of our reliability measurements has been on 500 - 1000 µm diameter gates.

Gate Leakage Current Measurements from 330 to 630 °C We have shown that the optimum gate bias point for Pt-SiO_2-SiC sensors in terms of sensor response time, sensor to sensor repeatability and high temperature stability of the gate oxide is near mid-gap [2,4]. Oxide leakage

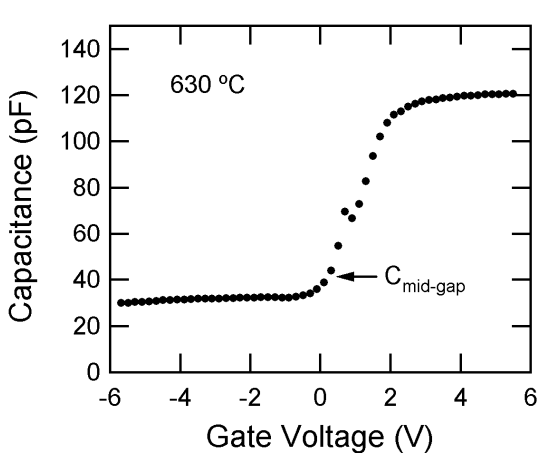

Fig. 2: 1 MHz capacitance-voltage characteristic of a 300 µm diameter n-MOS device at 630 °C. For gas sensing, the optimal gate bias is near mid-gap [2].

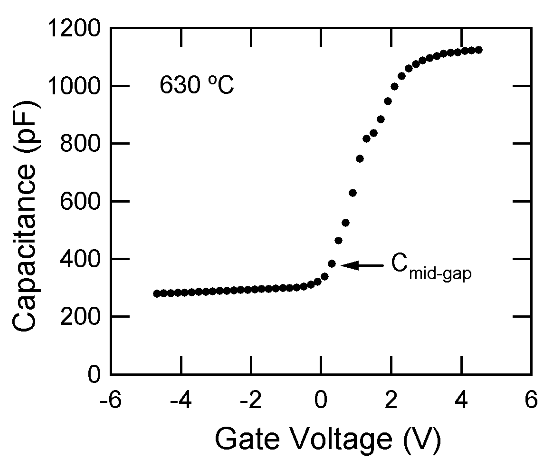

Fig. 3: 1 MHz capacitance-voltage characteristic of a 1000 µm diameter n-MOS device at 630 °C.

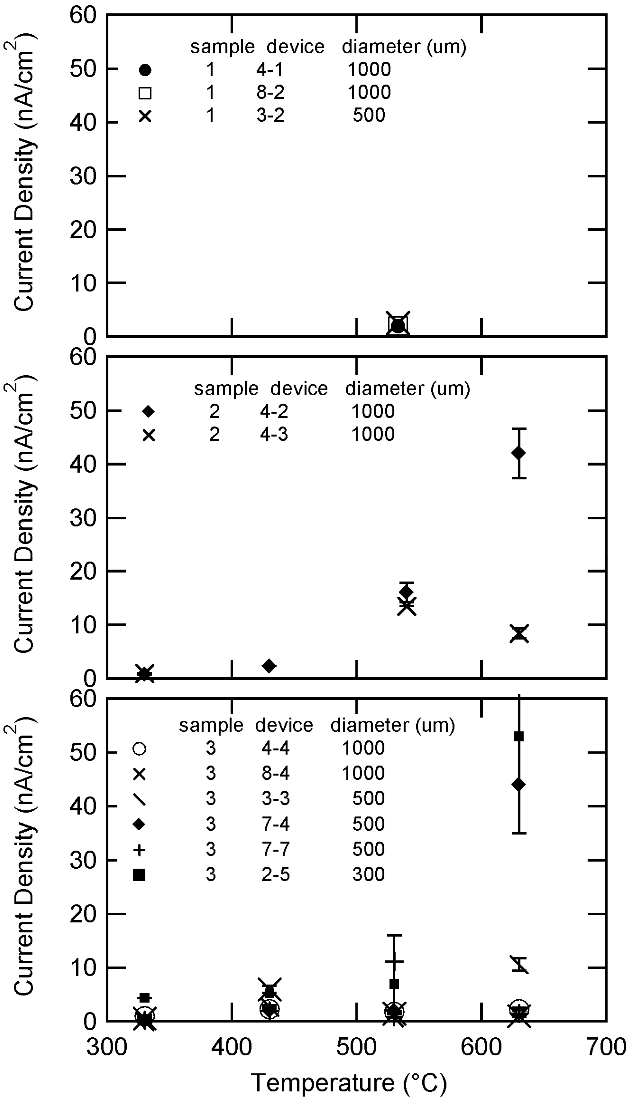

Fig. 4: Gate leakage current density as a function of temperature for n-MOS capacitors. (a) The devices in sample 1 were measured after 5 hours of continuous heating at 530 ºC; note that all three data points lie on top of each other. (b) and (c) Data on Samples 2 are 3 were obtained at 330, 430, 530-540 and 630 °C. The error bars on the current density measurement on all the gates are smaller than the symbol itself for T ≤ 500 °C. All the devices were biased near midgap to optimize sensor performance.

measurements were made on three independently processed samples subjected to different thermal stress cycles. Shown in Fig. 4a are the results from sample 1 after 5 hours of heating at 530 ºC. We find no degradation in performance during continuous operation at this temperature. Despite the different physical locations of the three gates on the 1cm^2 chip (from Fig. 1 device 4-1 is from the middle column and 8-2 from the far left column) all three have the same current density within the error bars of our measurement. Plotted in Figures 4b and 4c are the gate current densities of several gates from sample 2 and sample 3 measured at T = 330, 430, 530-540 and 630 °C. In the 300-450 °C temperature range, all 10 devices consistently exhibit current densities below 5nA/cm^2, irrespective of size or location on the chip. Above 450 °C there is a larger spread in the data with measurements ranging from 3-53 nA/cm^2. We attribute the higher current density of the 300 μm device to the limitations of our measurement system, as the absolute value of the leakage current for the smallest gates is ~5x smaller than that of the 1 mm devices. Note that the leakage current densities of two of the 1 mm diameter capacitors from sample 3 (gates 4-4 and 8-4) are below 4nA/cm^2 even at the highest temperature of 630 °C. In addition, four of the seven gates of diameter ≥ 500 μm have leakage current densities <10nA/cm^2 over the entire temperature range.

Our goal is to develop reliable field-effect gas sensors for long-term operation in chemically corrosive high temperature environments; thus, the stability of the gate dielectric is of paramount importance. The primary mode of oxide breakdown at elevated temperatures is attributed to electron injection from the substrate [5,6]. Therefore, we have chosen to concentrate on the 6H polytype, as opposed to 4H-SiC, because the band alignment between SiO_2 and 6H-SiC provides a larger barrier (by ~0.25 eV) for electron injection from the conduction band of the semiconductor into the insulator [7].

To the best of our knowledge, these are the first oxide reliability measurements at 630 °C. Mean times to failure (MTTF) of >10 hours at a field of 7 MV/cm at 300 °C for 4H-SiC n-MOS capacitors were reported [8]. Extrapolating these results to the electric field of our MOS sensors biased at midgap corresponds to well over 100 year operation at 300 °C. For n-type 6H-SiC MOS capacitors at 450 °C, current densities <100 nA/cm^2 (for oxide fields up to 8.9 MV/cm) and a 12 MV/cm dielectric breakdown strength have been reported [9].

Our results are encouraging in regards to the long-term reliability of SiC field-effect sensors. We have shown that 5nA/cm^2 leakage current densities on 1mm diameter gates are achievable up to 630 ºC. Continuous operation at elevated temperature does not affect the capacitors. Measurements are in progress to determine the operational stability and measurement stability of the SiC sensors at 630 ºC for time periods of several weeks [10]. Within our sample set (eleven devices of 300-1000 μm diameter from three independently processed 1cm^2 substrates) we observed no correlation on device performance due to gate size or gate position on the substrate. The measurement techniques described in this paper are relevant for reliability studies of SiC power devices, as they provide a platform for accelerated aging as well as time-dependent dielectric breakdown measurements at high temperature.

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