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Thermal and radiation response of 4H–SiC Schottky diodes with direct-write electrical contacts

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AQ1 Neil R. Taylor,[1,2] Yongchao Yu,[1] Mihee Ji,[1] Tolga Aytug,[1] Shannon Mahurin,[1] Richard Mayes,[1] Sacit Cetiner,[1] M. Parans Paranthaman,[1] Dianne Ezell,[1] Lei R. Cao,[2] and Pooran C. Joshi[1,a)]

AFFILIATIONS

[1]Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, Tennessee 37830, USA
[2]Nuclear Engineering, Department of Mechanical and Aerospace Engineering, The Ohio State University, 201 W. 19th Ave, Columbus, Ohio 43210, USA

[a)]Author to whom correspondence should be addressed: joshipc@ornl.gov

ABSTRACT

A high-sensitivity 4H–SiC temperature sensor and an alpha detector have been fabricated using additively printed metal contacts. The surface morphology and electrical conductivity of the printed electrodes were established prior to Schottky diode development. 4H–SiC Schottky diodes with direct-write printed silver contacts on the 5 μm-thick epilayer on 4H–SiC were characterized electrically in terms of the forward and reverse current–voltage and high-frequency capacitance–voltage characteristics. The turn-on voltage of the Schottky diodes, as established from the forward current–voltage characteristics measured up to a temperature of 400 °C, showed a linear temperature dependence. Schottky diodes with direct-write printed Ag electrodes were able to measure alpha particles emitted from Americium-241. The high temperature and radiation response of the Schottky diodes show their suitability for multi-modal sensor fusion on the 4H–SiC platform for harsh environment applications.

Highly linear temperature sensing instruments are important for almost all industrial and research applications. Industries such as aerospace, automotive, drilling, and nuclear all have interest in the development of advanced temperature sensors.[1–4] Within the nuclear industry, next generation of reactors is of great interest, and advanced sensors are required that can operate in harsh environments to achieve the desired safety and reliability. Thermocouples, resistance temperature detectors (RTDs), optical fibers, and semiconductor diodes are all possible solutions to provide robust high temperature sensing capabilities. Among the various temperature sensor types, semiconductor diode-based sensors offer the advantage of cointegration of sensors and integrated circuits (ICs).[5]

Wide bandgap (WBG) silicon carbide (SiC) offers a unique combination of structural, composition, and electrical characteristics for high temperature, high frequency, and harsh environment applications. It offers a wide bandgap (3.23 eV for 4H) compared to that of silicon (1.12 eV), as well as a high melting point (2730 °C), which allows it to operate at much higher temperatures than silicon. High thermal conductivity (3–5 W/cm K) and high breakdown field strength (2.0 MV/cm) of SiC material make it attractive for high power and high voltage applications.[6] SiC has been extensively studied, and fabrication techniques have been developed which allow for the high-quality crystal growth using chemical vapor deposition (CVD) of substrates and epitaxial layers. It has also been demonstrated to function in a wide variety of sensor modalities such as radiation, gas, temperature, and optical sensors.[4,7,8] Semiconductor-based temperature sensors have been fabricated and demonstrated on 4H–SiC[5,9,10] using microelectronic processing techniques. In the present work, we report on the direct-write printing of Ohmic and Schottky contacts to fabricate 4H–SiC-based temperature sensors and radiation detectors for advanced nuclear applications.

Typical fabrication of a semiconductor diode using microelectronics processing techniques involves device patterning using a mask and photolithography. After photolithography, the photoresist is developed and then metal is typically deposited by sputtering or electron-beam evaporation techniques. A final liftoff step is completed to remove excess metal and photoresist. The cleanroom fabrication does not lend itself well to rapid prototyping of sensor designs for

specific applications or integration scheme and requires the fabrication of photomasks for each sensor design one would want to produce. Even for a single layer design, the cleanroom fabrication can take hours to fabricate a set of sensors, while direct-write printing allows the fabrication of these detectors in under an hour depending on the design scheme. As is the focus of the present work, the digital direct-write printing technique allows selective deposition of a material without the usage of a mask.[11] It also enables a fast printing of neutron convertor materials onto a thin-film semiconductor (e.g., SiC) so that the conventional two-step process, with the first step being the deposit metal contact and the second step being coated neutron convertor materials, into one single step, which will drastically speed up the sensor optimization and final product fabrication time. This process can print functional material on a substrate such as a ceramic or semiconductor on either a flat or a curved surface with a linewidth control, which is fast approaching levels below 10 μm with the emerging printing techniques and concepts. The types of materials that can be printed include metals, polymers, semiconductors, dielectrics, and adhesives.

In this paper, we demonstrate the temperature response and radiation detection characteristics of 4H–SiC Schottky diodes fabricated using the aerosol jet technique. Silver contacts were printed on 4H–SiC substrates to form Schottky and Ohmic contacts using nanosilver conductive inks (Source: Clariant, Prelect TPS 50 G2). The electrical contacts were printed using an Optomec Aerosol Jet 200 series system operated in ultrasonic mode to aerosolize the inks into the necessary mist for printing. As shown in Fig. 1(a), a carrier gas is flown through the atomizer to pick up the nanoparticles and carry them to the deposition head. At the deposition head, a second gas, the sheath gas, is used to focus the nanoparticles through the aerosol nozzle for a controlled deposition onto the substrate. The printing process is controlled by a 2D/3D motion control system. The desired digital design can be produced CAD software and filled with the print pattern according to specific parameters. The program can control the print speed, line overlap, sheath gas flow velocity, carrier gas flow velocity, and number of printed layers. The gas flow rates and nozzle selection allow for the adjustment of the printed linewidth and the amount of material deposited. All these parameters affect the overall print quality including the thickness, coverage, and overspray. Table I lists the typical printing parameters used for the deposition of silver Schottky contacts.

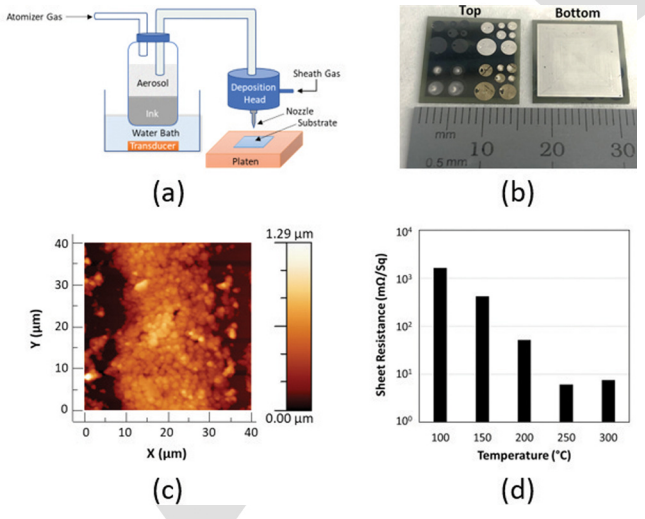

FIG. 1. (a) Schematic of the Aerosol jet printing system, (b) printed Schottky contacts on the 4H–SiC epitaxial side and the Ohmic contact on the bulk side, (c) surface morphology of printed contacts, and (d) printed silver conductivity.

All devices were fabricated on 4H–SiC wafers (source: NOVASiC) with a 5 − μm-thick epilayer ($n \sim 5 \times 10^{15}\,\mathrm{cm}^{-3}$) grown on high-conductivity 4H–SiC ($\rho \sim 0.02\,\Omega\,\mathrm{cm}$). Silver contacts were printed on both the epitaxial and bulk sides of 13 mm × 13 mm square dies to form Schottky and Ohmic contacts, as verified by the electronic characteristics. Circular contacts ranging from diameters of 1–3 mm were printed on the epitaxial side. On the epitaxial wafer contacts, additional 0.5 mm diameter silver contact pads were printed on top of the larger metal contacts. These contact pads were printed to act as a robust contact point for making electrical connection to the contact with micropositioners. The wafers were held at a temperature of 70 °C during printing to aid in the evaporation of the ink solvent. After printing, the ink was cured for an hour on a hot plate at 250 °C. Figure 1(b) shows the printed silver top-contacts in the top right corner of the left die and the silver Ohmic backside contact on the right die. The direct-write printing approach allows for multi-material printing on the same layer. Figure 1(b) demonstrates the possibility of multi-material printing as attempted for platinum (bottom left), gold (bottom right), and nickel (top left) contacts. The metal contact morphology was examined using an Atomic Force Microscope to determine the thickness and roughness of the printed metal-line. As shown in Fig. 1(c), the printed metal linewidth is about 30 μm with an average height of 0.47 μm and an RMS roughness of about 0.13 μm. The metal lines were overlapped 50% to print the target electrode size. The printed metal-line showed a high electrical conductivity, as shown in Fig. 1(d), which improved with an increase in thermal curing temperature. At a curing temperature of 250 °C, the metal-lines showed a sheet resistance value below 0.01 Ω/□. The metal conductivity did not change significantly with a further increase in curing temperature to 300 °C. To analyze the device characteristics for harsh environment applications, the temperature-dependent electrical properties of the fabricated Schottky diodes were evaluated from room temperature up to 400 °C, while radiation detection characteristics were established by exposing to alpha radiation from the Americium-241 (Am-241) emitter of 1.0 μCi.

The devices were characterized electrically and tested for temperature sensing capabilities. The samples were placed upon a Signatone S-1160 Series Probe Station and Signatone S-1060 Hot Chuck. The hot chuck utilizes a DC power source to supply 0–120 V and 0–7.5 A to power the hot chuck. The power supply uses a PID Athena microcontroller to control the temperature setpoint. The probe station and hot

TABLE I. Printing parameters for silver Schottky contacts.

Control parameter	Value
Nozzle diameter	150 μm
Print speed	6 mm/s
Line width	30 μm
Sheath flow	16 sccm
Ultrasonic atomizer flow	50 sccm

chuck are housed within a Signatone Dark Box to reduce EM interference and avoid any current generation from incident light on the device. Micropositioners were used to make connection to the device contacts, and measurements were performed using a Keithley 4200 A-SCS Parameter Analyzer to collect forward current–voltage (FIV), reverse current–voltage (RIV), and capacitance–voltage (C–V) data. These measurements detail the behavior of the device acting as a diode and determine its capability to act as a temperature sensor and as a radiation detector.

The hot chuck was used to vary the device temperature in the range of 20 − 400 °C to examine the effect of temperature on the electrical conductivity characteristics of the Schottky diodes with printed contacts. FIV and RIV measurements were conducted to quantify the turn-on voltage and overall current flow through the device. The turn-on voltage and current flow values at various temperatures were used to determine if the contacts have a linear response to measurement temperature. Figure 2 shows FIV plots across the investigated temperature range for a 4H–SiC Schottky diode. The RIV plot at varying temperatures showed a relatively high breakdown voltage exceeding −200 V up until the 400 °C measurement. For a semiconductor diode, the forward current behavior of the device can usually be simplified to the thermionic emission theory and follows

$$I = I_s\left(e^{\frac{qV}{nkT}} - 1\right), \tag{1}$$

where q is the electronic charge, V is the applied voltage, n is the ideality factor, k is the Boltzmann constant, T is the temperature, and I_s is the saturation current. The current flowing through the device is highly dependent on the temperature, which forms the basis of the temperature sensor. To accurately determine the turn-on voltage of the diode at these temperatures, a forward current density threshold of 2.83×10^{-7} A/cm^2 was chosen as the turn-on current. The voltage at which each contact reached this current threshold at various temperatures is plotted in Fig. 3. A least-squared fitting method was applied to determine the linearity of the I–V response at various temperatures. All the devices, with various electrode diameters in the range of 1–3 mm, showed a very linear response with r^2 values greater than 0.9. The calculated sensitivity of these devices was about 3.3 mV/°C. The high sensitivity of the printed devices matches well with the values reported for the devices fabricated by surface micro-machining[9] and thermal evaporation techniques.[12]

High-frequency (1 MHz) capacitance–voltage (C–V) measurements were conducted on the Schottky diodes to gain an understanding of the metal/4H–SiC interface. The doping density and Schottky barrier height (SBH) can be extracted from the C–V characteristics using the following equation:

$$\frac{1}{C^2} = \frac{2}{qN_D\varepsilon_s\varepsilon_o A^2}(V_{bi} - V), \tag{2}$$

where C is the diode capacitance, A is the electrode area, q is the electronic charge, N_D is the doping concentration, ε_s is the permittivity of the semiconductor, ε_o is the permittivity of free space, V_{bi} is the built-in potential, and V is the applied bias voltage. The doping density was

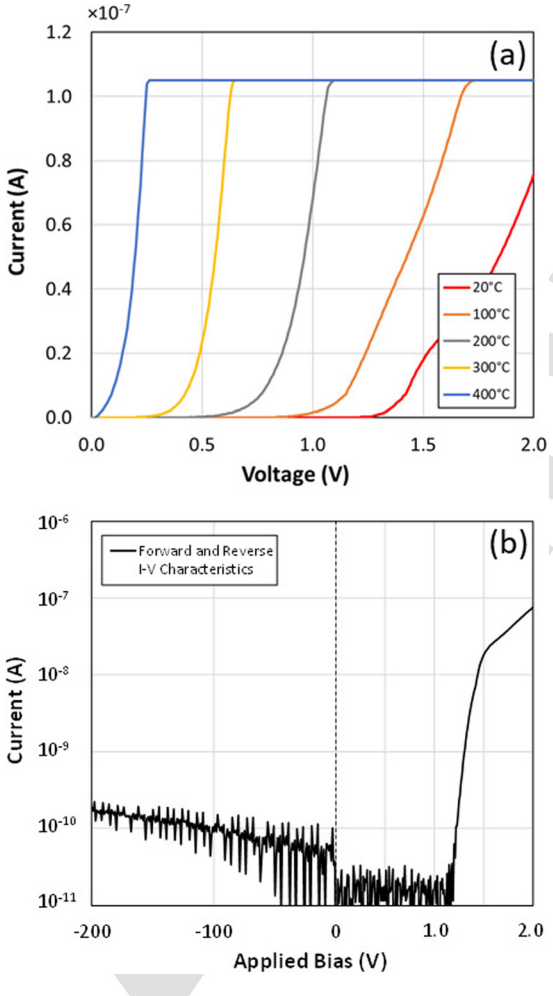

FIG. 2. (a) Temperature dependence of forward electrical conductivity characteristics of Schottky diodes and (b) typical forward and reverse bias characteristics at room temperature.

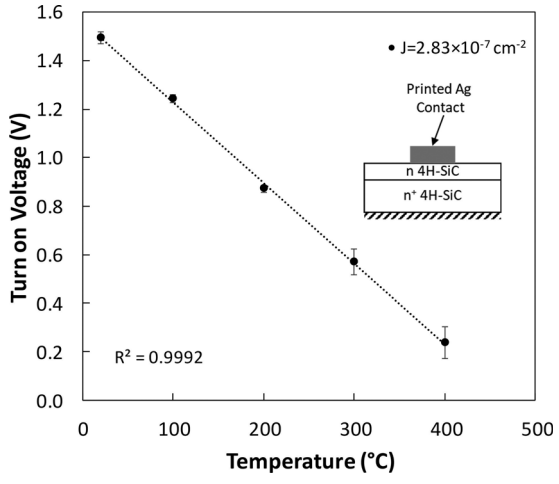

FIG. 3. Turn-on voltage vs temperature response of Schottky diodes with printed silver contacts.

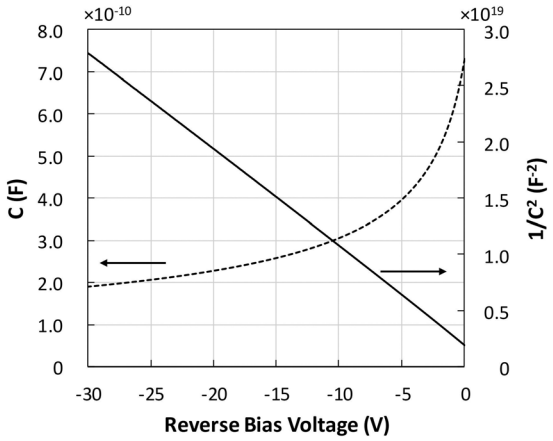

FIG. 4. High frequency capacitance–voltage characteristics of Schottky diodes.

calculated from the slope of the $C^{-2} - V$ plot as shown in Fig. 4. The linearity of the $C^{-2} - V$ plot indicates uniform doping in the depletion region of the semiconductor. The calculated donor doping concentration was $3.56 \times 10^{15}\text{cm}^{-3}$. The build-in potential value, as determined from the intercept of the $C^{-2} - V$ plot, was found to be 0.41 V.

These devices were also tested for their radiation detection capability to act as a dual-mode sensor. Figure 5 shows the radiation response of the Schottky diodes measured over a voltage range of up to −220 V. The devices were tested in a vacuum chamber with a 1 μCi Am-241 button source positioned approximately 2 cm above the detector. The detector experienced a fluence of approximately $(1.7 \pm 0.1) \times 10^3 \text{alphas/cm}^2\,\text{s}$. The energy deposited in the detector continues to increase up to the final bias voltage of −220 V. The increase in energy deposition and the subsequent charge collection are attributed to the increase in the bias-dependent depletion depth, and the induced charge on the metal contact could be explained by

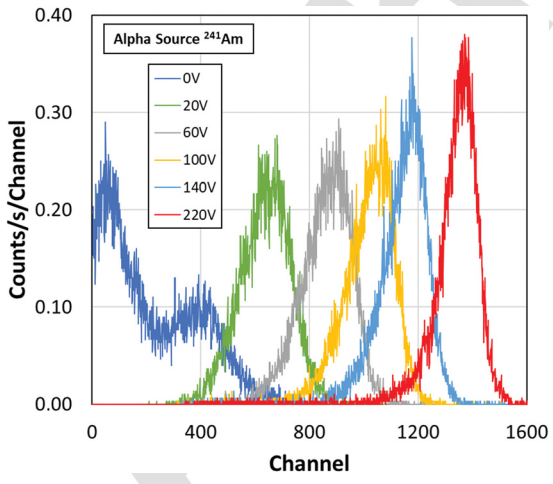

FIG. 5. Alpha spectra of the Am-241 source acquired on Schottky diodes with a 2 mm diameter silver contact at varying bias from 0 to −220 V.

proximity sensing,[13] i.e., charge can be induced on the printed metal electrode, even if the metal is not physically in contact with the semiconductor. The device never reaches saturation due to the depletion region of the device never reaching the full penetration depth of the alpha particles. SRIM calculations have shown that the range of a 5.486 MeV alpha particle in SiC is approximately 18.9 μm. The depletion depth calculated using the doping concentration and a voltage of −220 V is less than 7 μm. The spectral response at zero bias, i.e., voltaic mode, however, corroborates the formation of the SBH due to electronic state Fermi-level pinning at the metal-semiconductor interface[14] or interface dipole formation.[15] The observed alpha-radiation response shows that a combination of the direct-write printing technique and 4H–SiC material can be used for multi-modal sensor system development for high temperature and harsh environment applications. The radiation response of these detectors can be further tuned by increasing the epilayer thickness and reducing the epilayer dopant concentration to fully attenuate the incident alpha particles.

Direct-write printing of electrical contacts on 4H–SiC material shows promise for multimodal sensor development for high temperature and harsh environment applications. The 4H–SiC Schottky diodes fabricated using printed silver contacts exhibited excellent on-state characteristics with a linear temperature response of 3.3 mV/°C up to 400 °C. The Schottky diodes also showed a clear response to the alpha source with a Gaussian shape of the peaks as expected from an alpha particle source. The observed thermal and alpha radiation responses of 4H–SiC Schottky diodes show the potential of digital printing techniques for multi-modal sensors and integrated sensor system development.

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DATA AVAILABILITY

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