Supplementary Material

Fabrication and Testing of High-temperature Schottky Diodes

Helei Dong, Liangjie Guo, Chengwei Zhen, Tengteng Dong, He Fu, Xin Tian, Siyu Liang, Rui Feng, Qiulin Tan

Fabrication of Thin-Film Schottky Diode

Chottky diode devices are prepared using techniques such as photolithography, electron beam evaporation, and magnetron sputtering. However, since the substrate may contain inorganic contaminants such as dirt or organic contaminants such as bacteria or dander, this can lead to the electrode structure being damaged during subsequent photolithography processing. Therefore, the substrate must be pretreated before preparing the device.

Place the Al2O3 substrate in a clean glass dish and introduce acetone solvent for physical cleaning. Use an ultrasonic cleaner to clean the glass dish for 5 min at high intensity. After ultrasonic cleaning the substrate, place it in an ethanol solution again and perform the same steps as above. After another ultrasonic cleaning, rinse the substrate repeatedly with deionized water until it is pure, and then blow it dry with nitrogen.

Anode Fabrication

In the process of preparing the anode, the surface of the Al2O3 substrate is first mirror-polished to ensure its flatness, and then a positive photoresist RZJ-304 produced by Suzhou Ruihong is applied by spin coating. This process involves setting specific rotational speed parameters—an initial speed of 500 r/min for 5 s, followed by high-speed spin coating at 3000 r/min for 30 s—to achieve uniform photoresist coating. The spin-coated substrate is preheated at 100 °C for 1 minute to promote the adhesion and curing of the photoresist. The spin-coated substrate is then UV-photolithographed using a mask based on the design shown in Fig.1b. An exposure dose of 80 units is used to ensure accurate pattern transfer. After exposure, the substrate is developed for 20 seconds, rinsed with deionized water (15 seconds per side), and blown dry with nitrogen. It is then post-heated at 120 °C for 1 minute to further cure the pattern.

After that, the bottom electrode of the diode is prepared on the substrate by electron beam evaporation. To enhance the adhesion strength between the bottom electrode and the Al2O3 substrate, a 15 nm thick titanium (Ti) layer is first evaporated on the substrate, taking advantage of its good adhesion to Al2O3. Then, a 50 nm thick platinum (Pt) layer is evaporated on top as the anode electrode material. After the electrode is prepared, a stripping process is carried out to remove the photoresist from the unilluminated part. This involves dipping the substrate in acetone for 3 minutes, followed by 30 seconds of oscillation using an ultrasonic oscillator, and then an additional 3 minutes of static immersion. Finally, the substrate is rinsed with deionized water and blown dry with a nitrogen gun, and placed on a clean filter paper for subsequent use. This process ensures the accurate preparation of the anode electrode pattern, laying the foundation for further electronic device manufacturing.

Fabrication of the semiconductor layer

The substrate should be prepared for the anode by sputtering a SiC semiconductor layer, as outlined in Step 1. It is imperative that this process be conducted under low vacuum conditions at 0.44 Pa. Subsequently, a uniform coating must be applied, the mask template must be aligned according to the design, and a second photolithography must be performed. Subsequent to the development and drying of the photolithographed substrate, it is imperative to adhere to the parameters delineated in Step 1. The culmination of this process entails the etching and peeling of the substrate to achieve the desired semiconductor shape. A series of etching tests were conducted to ascertain the optimal conditions for the etching process. The tests involved the use of concentrated hydrochloric acid (concentration 36%-38%) and deionized water at a ratio of 50:1, with an etching rate of 50 nm and a duration of 100 s.

Following the preparation of the platinum (Pt) electrode, it is essential to promptly deposit the a-IGZO semiconductor layer. The primary composition of the Pt layer deposited by electron beam evaporation is nanoparticles, and Pt is the second most reactive metal after silver (Ag) in air. Prolonged exposure to air may cause oxidation of the Pt layer, which could affect the formation of the Schottky barrier between Pt and SiC and adversely impact device performance.

Cathode Fabrication

The cathode preparation process commences with the initial step, which encompasses photolithography and development, followed by subsequent thermal treatment. Subsequently, silver (Ag) is deposited as the top cathode electrode on the prepared semiconductor layer using magnetron sputtering technology. The power output is set to 100 watts, with a duration of two minutes, in order to form a 32-nanometer cathode film. Given the stability concerns associated with the semiconductor layer, which is susceptible to chemical reactions and may compromise device performance, it is imperative that cathode deposition be executed expeditiously following the completion of the preparation process. Furthermore, it is imperative to regulate the sputtering thickness of the cathode to below 100 nm. This is to avert the consequences of protracted sputtering, which can result in the infiltration of nano-aluminum particles into the semiconductor layer. Such infiltration can precipitate short circuits and device failure.

The prepared diodes are illustrated in Fig.1c. Throughout the entire preparation process, it is imperative to maintain environmental cleanliness and ensure constant temperature and humidity conditions. These are general requirements in microelectromechanical systems (MEMS) semiconductor processes and are critical for ensuring the successful preparation and stable performance of the devices

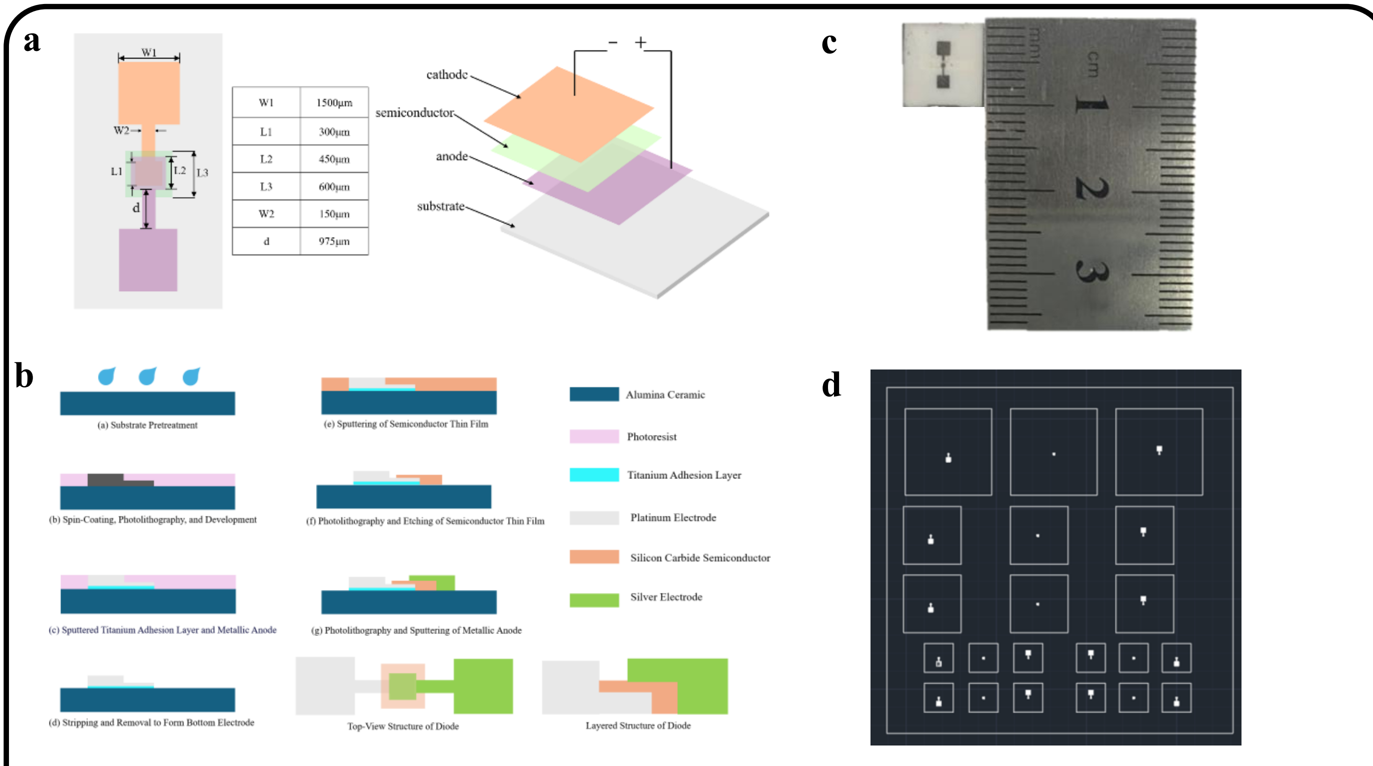

Fig. 1 Preparation of Thin Film Schottky diodes a. 3D View of Schottky Diode and Structure of Schottky Diode**. b** Fabrication Flowchart of Thin-Film Schottky Barrier Diode **c** Diode physical diagram**. d .** Photolithography mask

Experimental results and discussion

In order to verify the performance and nonlinear characteristics of the Schottky diode at high temperatures, the diode is tested at temperature using a device temperature test system consisting of a Keithley 4200A-SCS parameter analyzer, a Lakeshore Model CRX-6.5K high and low temperature probe station, a Lakeshore 336 temperature controller, a pump and a refrigeration cycle. As shown in Fig.2a， When the probe contacts the object to be tested, the temperature sensor on the probe can accurately measure the temperature, enabling real-time measurement. The internal temperature measurement error does not exceed 0.5°C within a range of room temperature to 600°C.

In a high-temperature test environment, the oxidation protection of metal components and test probes is particularly critical. Therefore, vacuum refrigeration technology is introduced to ensure that the sample chamber is always maintained in a high vacuum during the test. The conversion of the mechanical pump to a molecular pump can improve the vacuum rate, and then the test chamber is subjected to a cold cycle treatment, which can ensure the temperature balance of the test system during testing at different temperatures, and ensure that the system is not damaged due to excessive temperature differences.

The data from the parameter analyzer Keithley 4200A-SCS was recorded every 50 ℃ based on a set temperature step of 21 ℃. The recorded data is plotted in Fig.2b, which shows a set of I-V characteristic curves of the diode in the temperature range of 21-600 ℃.

As can be seen from Fig.2b, the current-voltage curve exhibits a nonlinear characteristic, and as the temperature increases, the curve gradually shifts from right to left. Plot the measured voltage versus temperature curve, as shown in Fig.2c. When the temperature rises to 600 degrees Celsius, the Schottky diode voltage gradually decreases with increasing temperature, gradually decreasing from 0.65V to 0.1V. and the voltage attenuation rate is calculated to be 0.92mV/°C. The resistance change curve obtained by plotting and calculating is shown in Fig.2d. The resistance decreases from 3.61kΩ to 1.53kΩ, and the average resistance attenuation rate is calculated to be 3.43Ω/°C.

According to the slope of the current change, the voltage has a smaller slope at 0-0.25 V and a larger slope at 0.25-1. In order to facilitate data comparison, the measured current-voltage curve from room temperature to 600°C is converted into a junction current-voltage (J-V) characteristic curve. According to the formula for junction current density[1]:

$$J = A * T^2 \exp\left(\frac{-q\phi_{BO}}{kT}\right)\left[\exp(\frac{qV}{nkT}) - 1\right] \quad (1)$$

When the forward voltage is low (approximately 0–0.25 V), as the temperature increases, the slope of the I-V curve in the low-voltage range gradually decreases. The term q/nkT in Equation 1 represents the slope of the curve, and as T increases, this term decreases. By performing segmented linear fitting on the curves in Fig 2b, the temperature-dependent slope curves of the two sets of curves are fitted within the forward voltage ranges of 0–0.25 V and 0.74–1 V. The temperature-dependent slope curves of the 21–600°C range are shown in Fig 2e.

The slope of the I-V curve in the forward voltage range of 0-0.25V is significantly higher than that in the range of 0.74-1V. As the forward voltage increases, the I-V curve of the diode tends to the ideal diode characteristic when the voltage is in the 0.74-1V range, and the fit of the curve improves accordingly with increasing temperature. This is because the equivalent resistance of the diode decreases at high temperatures, thereby reducing the impact of resistance on the performance of the entire device. Although increasing temperature causes the resistivity of the metal cathode and anode to increase, the resistance of the semiconductor layer tends to decrease. In this experiment, the diode's equivalent resistance decreases, which indicates that the effect of temperature on the resistivity of the semiconductor layer is more significant than its effect on the metal electrodes. When the forward voltage exceeds the diode's turn-on voltage, the slope of the curve decreases significantly compared to the first half, and the slope can be regarded as the reciprocal of the equivalent resistance, which means that the diode's equivalent resistance increases in the second half, and the resistance plays a major role in reducing the current at this time.

Verification shows that as the temperature of the diode increases, the I-V characteristic curve becomes nonlinear and shifts to the right. The diode's ideality factor gradually decreases with increasing temperature, while the barrier height gradually increases with increasing temperature. This characteristic meets the performance requirements for operation at high temperatures, confirming the correctness of the diode operating at high temperatures.

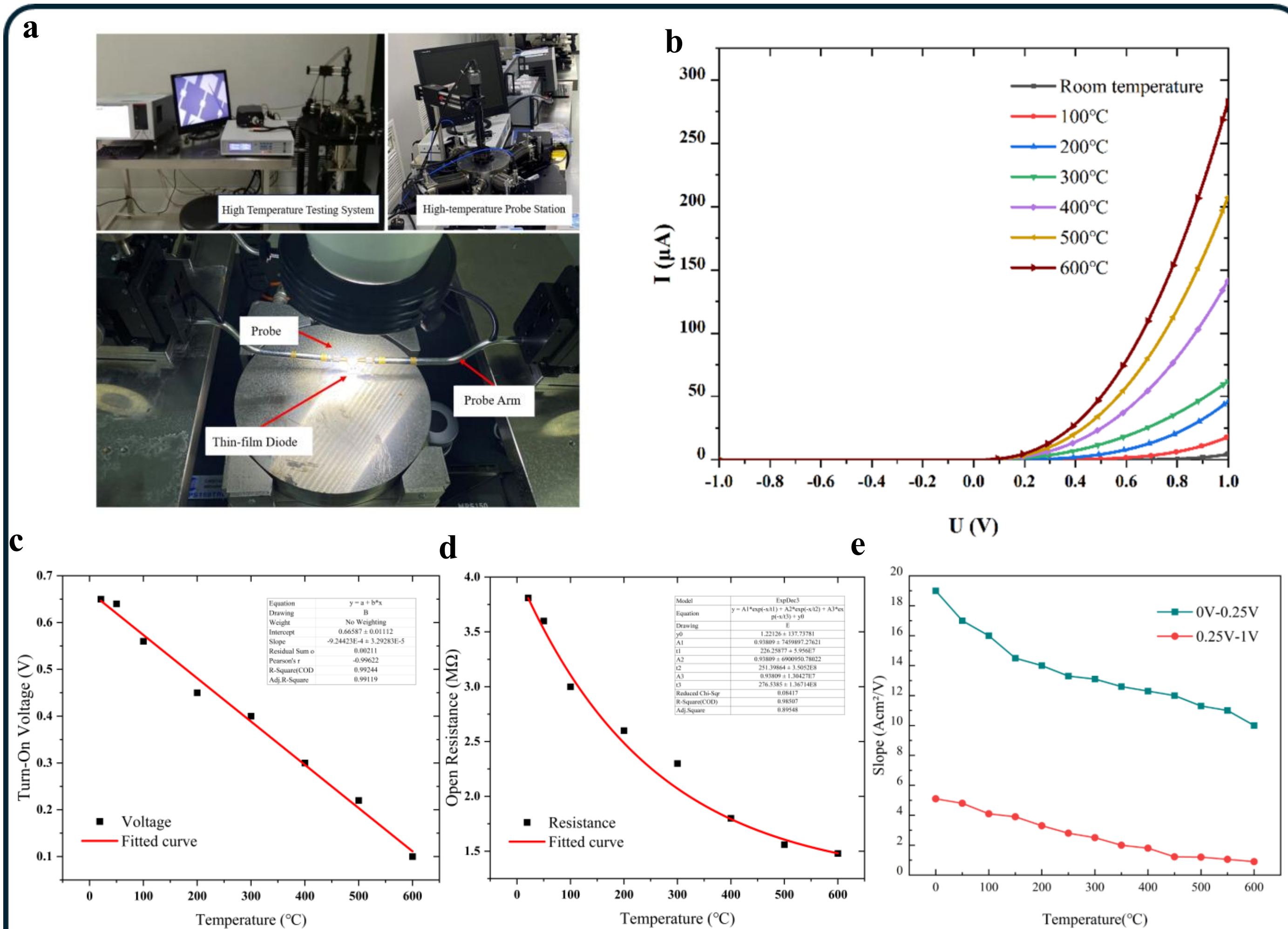

Fig. 2 Test and Analysis a. Thin-film diode high-temperature characteristic test system. **b** Schottky Diode I-V Characteristic Curves **c** Schottky diode turn-on voltage. **d** .Schottky diode turn-on resistance. **e** Diode current density at different voltages.

References

1 Fei.Lu. Preparation and high-temperature characterization of Al2O3-based thin-film type a-IGZO Schottky barrier diodes .2018