

# Achieving Peta-Ohm Resistance for Semi-Insulating 4H-SiC Devices by Atomic Layer Deposition

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Growing demands for precise current measurements, such as atto-ampere-level measurement of cross-cellular biological current transduction, have spotlighted a pressing need for low-noise resistors with ultra-high resistance immune to voltage fluctuations. Traditional semi-insulating materials, however, struggle to provide consistent resistance across varying voltages. To bridge this gap, we introduce a design that integrates semi-insulating 4H-SiC with atomic-level metal oxide interlayers and electrodes. The strategic adjustment of surface states via atomic-scale metal oxide layers optimizes the work functions on 4H-SiC surfaces, validated through density functional theory simulations. This design transcends conventional limitations, establishing an ideal Ohmic behavior and maintains Peta-Ohm-level resistance, unaffected by voltage variations. These on-chip devices with fine-tuned resistance are compatible with integrated circuit manufacturing processes, making them ideally suited for applications in precision electronics.

The resistance of an ideal conductor follows a linear ratio between current ( $I$ ) and voltage ( $V$ ), which implies that its resistance value remains constant irrespective of variations in applied voltage. Such linear relationship is also known as classical Ohm's, signifying that the ratio—defined by  $R = V/I$ —should remain unaltered over a broad varying voltage levels [1]. However, in practical scenarios, the resistance values of many resistors can deviate under different voltage conditions [2], due to material properties, temperature fluctuations, and manufacturing inconsistencies. Devices whose resistance alters with voltage are typically known as 'varistors' [3, 4]. Due to their fluctuating resistance, varistors are unsuitable for precision tasks or in advanced electronics requiring high accuracy, whereas circuits detecting precision currents necessitate high-resistance, voltage-stable resistors.

The lowest thresholds for measuring whimsical electrical currents are now extending from nano-amperes (nA) to atto-amperes (aA), and potentially even lower. Applications range from nA-level in molecule detection [5, 6] to pA-level in mass spectrometry [7, 8] and neutron flux leakage [9, 10], down to fA-level in biological current assessments [11–14]. In circuit design, incorporating a high-resistance resistor [15] exceeding tera-Ohms (T $\Omega$ ) is crucial for precise, high-speed precision current measurements, by efficiently converting current signals down to aA into detectable voltages [16–18], thus improving detection accuracy and analytical precision; see in Fig. 1(a).

For low current measurement in the above critical ap-

plication, current manufacturing of high-resistance resistors suffers from very limited choice of materials: sapphire, quartz, Teflon PTFE, polystyrene and polyethylene, just to name a few [19], compared in detail in Table S1 of Supplementary Material [20]. Organic materials Teflon PTFE [21, 22], polyethylene [23, 24] and polystyrene [25, 26] exhibit reduced environmental stability and can accumulate internal charges upon deformation. Ceramic insulators such as quartz can also suffer from noises associated with piezoelectrical effects which allow the device to build considerable charges [27, 28]. Sapphire is purported to display the most superior characteristics but variations in resistance illustrated in Fig. S1 [29, 30]. A high-resistance resistor with its image as shown in Fig. S2, acquired commercially, exhibited comparable irregularities, failing to follow the ideal Ohmic characteristic curve as outlined in Fig. 1(d). The limitations above show weak promise for precision current measurement down to atto-ampere levels with these materials. Another potential candidate, 4H polytype of silicon carbide (4H-SiC), has an exceptionally high resistivity, but suffers from numerous surface states and spontaneous polarization, the latter being caused by the internal electric fields due to the alignment of dipole moments within the material [31, 32]. This condition inevitably results in resistors made from 4H-SiC exhibiting resistance that varies with voltage. To date, there are no documented or available evidences of high-resistance resistors that exhibit voltage-invariant characteristics.

We unveil in this work the development of 4H-SiC re-

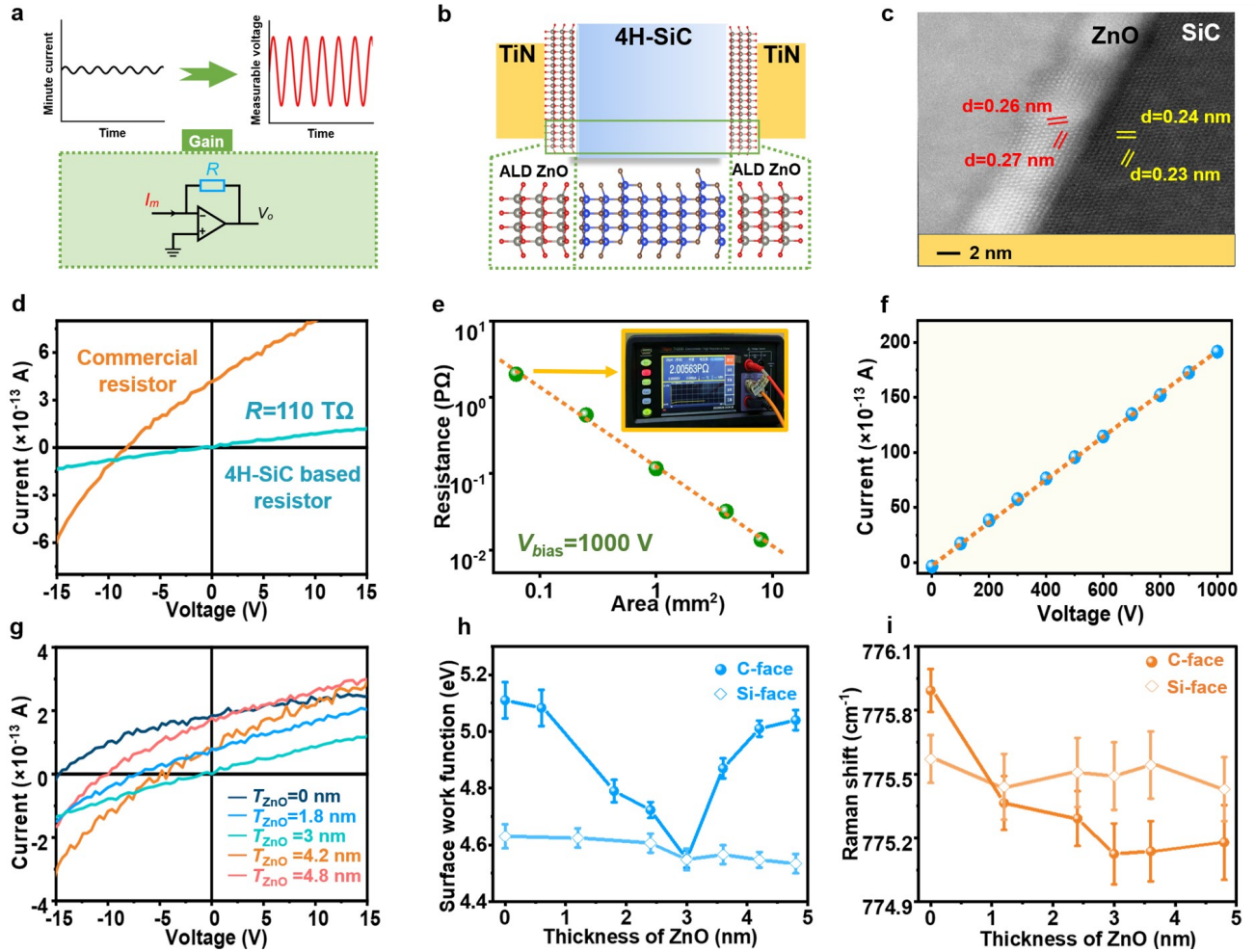


FIG. 1. (a) Simplified working principle of precision current measurement, utilizing a high-resistance resistor as a gain to amplify weak current signals into detectable voltage signals. (b) Device diagram illustrating the atomic-level engineering of 4H-SiC resistor. (c) In-situ cross-sectional TEM image near the interface of the 4H-SiC/ZnO resistor structure on the C-face. (d)  $I$ - $V$  measurement comparing the performance of 4H-SiC resistor and commercial resistor. (e) Linear dependence of resistance on cross-sectional area for 4H-SiC resistor (inset: resistance testing image of an area of  $0.0625$  mm<sup>2</sup> using a high-resistance meter). (f)  $I$ - $V$  measurement of a  $52.4$  T $\Omega$  4H-SiC resistor under the bias from 0 to 1000 V. (g)  $I$ - $V$  measurement for 4H-SiC resistors with increasing ALD ZnO thickness on the C-face while maintaining a 3 nm thickness on the Si-face. (h,i) Atomic-level ZnO thickness dependent surface work functions and Raman shift on the C-face and Si-face, respectively.

sistors that for the first time achieve Peta-Ohm (P $\Omega$ )-level resistance with characteristics that remain constant across varying voltages. These resistors are crafted from a semi-insulating 4H-SiC wafer, atomic-scale zinc oxide (ZnO) interlayers through atomic layer deposition (ALD), and titanium nitride (TiN) electrodes through magnetron sputtering, as illustrated in Fig. 1(b), and In-situ Transmission Electron Microscopy (TEM) analysis as illustrated in Fig. 1(c). By integrating a 3 nm thick ZnO layer onto both the C-face and Si-face, we have successfully developed high-resistance resistors that maintain a constant resistance across varying voltages and display an ideal  $I$ - $V$  curve intersecting the origin, demonstrating ideal Ohmic behavior as shown in Fig. 1(d), starkly contrasting with commercial devices. The

realized resistor, exhibiting a 110 T $\Omega$  resistance, features a small cross-sectional area of just about  $1$  mm<sup>2</sup> and a thickness close to  $500$   $\mu$ m. Importantly, we demonstrated that the device's resistance is adjustable by modifying its cross-sectional area, as evidenced in Fig. 1(e), where an increase in area from  $0.065$  mm<sup>2</sup> to  $8$  mm<sup>2</sup> correspondingly reduces the resistance from  $2$  P $\Omega$  to  $13.6$  T $\Omega$ ; see in Fig. S3(a) for the corresponding  $I$ - $V$  curves. The developed high-resistance 4H-SiC resistors exhibit outstanding manufacturing compatibility and provide the versatility to tailor resistance by adjusting the cross-sectional area, showing a resistance of  $2$  P $\Omega$  with only a cross-sectional area of about  $0.065$  mm<sup>2</sup> and a thickness of approximately  $500$   $\mu$ m.

It is noted that when our device's resistance exceeds

740 T $\Omega$ , the measured  $I$ - $V$  curve spans the second to fourth quadrants, indicating that the resistance value surpasses the internal resistance of the parameter analyzer. In practice, we tested the resistance value of the 2 P $\Omega$  resistor using a high-resistance meter, as shown in Fig. S3(b), confirming its consistency with the resistance value calculated based on area. This kind of resistor maintains its exceptional Ohmic performance with a stable resistance under a bias of up to 1000 V, as demonstrated in Fig. 1(f); detailed characterization methodologies demonstrations can be found in Supplementary Material [20]. In addition to ZnO, our investigations extended to alumina (Al<sub>2</sub>O<sub>3</sub>) and titanium oxide (TiO<sub>2</sub>) as the interlayer, description of which will be provided subsequently (Fig. S4).

The thickness of the ZnO interlayer significantly impacts the performance of the resistors, as depicted in Fig. S5, which shows the  $I$ - $V$  curves of devices with and without ZnO on both the Si and C faces. It is observed that without any ZnO modification and only with the Si-face is modified with a 3 nm ZnO layer, the  $I$ - $V$  curves exhibit nonlinearity, similar to those of commercial resistors. However, introducing a 3 nm ZnO layer to just the C-face begins to display an ideal zero-crossing Ohmic performance. Furthermore, we kept the Si-face ZnO thickness constant at 3 nm and carried out the  $I$ - $V$  curves for several groups of devices by varying the thickness of ZnO on the C-face (Fig. S6 and Fig. 1(g)), suggesting the impact acted strongly depends on the modification on the C-face. The voltage shift from 0 V at zero-current conditions systematically changes with the ZnO layer thickness ( $T_{\text{ZnO}}$ ) on the C-face (Fig. S7). The voltage shift reaches zero at a 3 nm thickness of the ZnO layer, further suggesting that this thickness eliminates additional bias caused by surface charges on only the C-face. To evaluate the above thickness dependence, Kelvin Probe Force Microscopy (KPFM) was employed to track variations of the work function across different  $T_{\text{ZnO}}$  on both C-face and Si-face, with findings illustrated in Fig. S8 and Fig. 1(h). Specifically, the work function on the C-face decreased initially from 5.11 eV to 4.55 eV for a 3 nm ZnO layer and subsequently increases, while it remained consistently around 4.6 eV on the Si-face, independent of  $T_{\text{ZnO}}$  adjustments. Additionally, Raman spectroscopy detected shifts in the surface electron states on the C-face due to ZnO thickness changes, marked by alterations in the  $E_2$  transverse optical phonon peak (from 775.9 cm<sup>-1</sup> to 775.1 cm<sup>-1</sup>), with no significant change on the Si-face (Fig. 1(i) and Fig. S9). Moreover, Fourier transform infrared (FT-IR) spectroscopy, investigating interfacial reactions, identified a shift from 931 cm<sup>-1</sup> to 933 cm<sup>-1</sup> in the FT-IR spectra on the C-face after depositing a 3 nm-thick ZnO layer, as indicated in Fig. S10. This collective evidence from the similar trends of the voltage shift, work function variation, Raman shifts, and alongside FT-IR shifts suggests that ZnO modification signif-

icantly affects the interfacial molecular structure, chemical interactions, and the distribution of energy levels at the microscopic scale, responsible for the ideal Ohmic characteristic of the proposed 4H-SiC resistor.

Results from X-ray diffraction (XRD) analysis reveal that the surface of the 4H-SiC wafer is characterized by a single crystalline phase with an orientation aligned along the [0001] direction (Fig. S11) [33]. This orientation shows the abrupt C-termination or Si-termination on the surfaces, leading to the formation of a dangling bond due to the unpaired electrons at the surfaces (Fig. 2(a)). This condition fosters surface states and the spontaneous polarization effect [34], which negatively impacts the creation of ideal resistors, resulting in significant differences in the work functions between the C-face and Si-face,  $W_{F,C} = 5.11$  eV and  $W_{F,Si} = 4.63$  eV; which has already been demonstrated in Fig. 1(h). The energy levels of the three sites of 4H-SiC, i.e., the C-face, Si-face and interior, are also plotted in Fig. 2(a). The energy levels for the conduction band minimum (CBM,  $E_C$ ) and the valence band maximum (VBM,  $E_V$ ) of the 4H-SiC interior are 3.6 eV and 6.9 eV, respectively [35]. The characteristic of high purity semi-insulation of 4H-SiC leads to an intrinsic semiconductor property, determining the interior Fermi level of 5.25 eV of 4H-SiC interior located at the mid-gap [36]. The discrepancy of Fermi levels between the three sites of 4H-SiC serves as the direct evidence of the polarity attributed to spontaneous polarization [31, 32]. Existing studies have shown that surface states on the C-face and Si-face also affect the rectifying performance of Schottky diodes made from 4H-SiC [37–39]. The Fermi level of TiN electrodes was tested to be 4.58 eV, as indicated in Fig. 2(a) and Fig. S12. Here, the energy levels for CBM and VBM of the ALD processed ZnO were 4.5 eV and 7.77 eV, respectively [40].

We then conducted Density Functional Theory (DFT) calculations to investigate the impact of introducing a ZnO layer on the characteristics of the 4H-SiC resistor, utilizing the atomic configurations of 4H-SiC and ZnO as depicted in Fig. 2(a) for modeling. The work functions on the C-face and Si-face were extracted from the computed electrostatic potential distribution of a pure 4H-SiC layer (Fig. S13(a)). The predicted  $W_{F,C} = 5.61$  eV and  $W_{F,Si} = 4.36$  eV indicates that the  $W_F$  of the C-face is notably higher than that of the Si-face, consistent with experimental observations. Additionally, the spatial Projected Density of States (PDOS) distribution, depicted in Fig. S13(b), reveals prevalent localized surface states at both the C-face and Si-face, suggesting the possible presence of Fermi level pinning effects at the conductor/4H-SiC interfaces [41, 42]. Previous studies have already demonstrated the presence of Fermi levels at 4H-SiC surfaces aligning with the surface Fermi levels despite variations in electrodes [32, 43]. Building upon this, the energy diagram of the pure 4H-SiC resistors with TiN electrodes was depicted in Fig. 2(b), establishing an

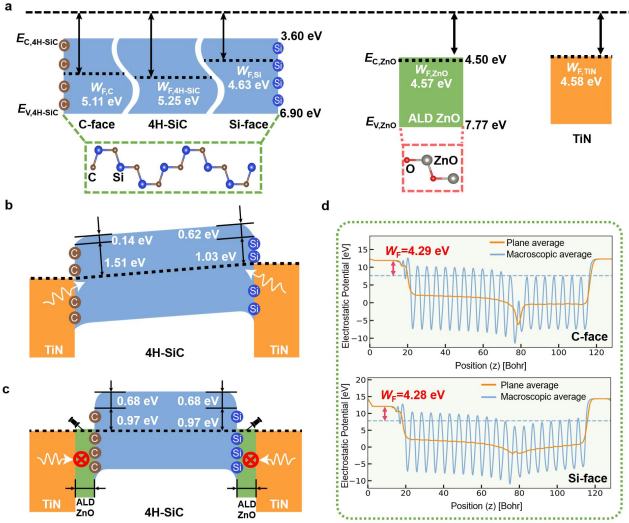


FIG. 2. (a) Energy level diagram illustrating the Fermi level and band gap of 4H-SiC, ALD ZnO, and TiN. The dashed boxes depict the atomic configurations of 4H-SiC and ZnO. (b) Band diagram of pure 4H-SiC resistors with TiN electrodes. (c) Band diagram of 4H-SiC resistors with 3 nm ALD ZnO interlayers. (d) DFT computed electrostatic potential distribution at C-face (upper) and Si-face (lower), with the dashed line representing the Fermi level of the structure. Surface  $W_F$  denotes the potential difference between the vacuum level near the surface and the Fermi level. Computed atomic models are shown in Fig. S14.

Ohmic conductor/semiconductor contacts on both sides while considering the Fermi level pinning effect, with barrier heights of 0.14 eV and 0.62 eV, respectively. The notable difference in surface potential between the C-face and Si-face induced a potential disparity, consequently causing a voltage shift across the 4H-SiC resistor without any modifications.

By introducing ALD processed ZnO as interlayers into the 4H-SiC resistors, the localized surface states on the 4H-SiC surfaces undergo remarkable changes. Attributed to the different surface Fermi levels of 4H-SiC, nonuniform amounts of charges have transferred on the C-face and Si-face after contacting with atomic-level ZnO, causing uneven modification effect at each side, specific discussion in Supplementary Text 4 and Fig. S14 [20]. The DFT calculations presented in Fig. 2(d) indicate the computed work functions on the C-face and Si-face with 3 nm ALD ZnO interlayers, yielding  $W_{F,C} = 4.29$  eV and  $W_{F,Si} = 4.28$  eV. It is evident that the simulated work function of the C-face experiences a significant decrease from 5.61 eV to 4.29 eV after the incorporation of a 3 nm ZnO layer, while the work function of the Si-face undergoes only a minor alteration (from 4.36 eV to 4.28 eV) following the addition. These simulated rules of changes after modification align perfectly with the patterns observed in the experimental results shown in Fig. 1(h). These findings showcase the work function tuning

effect achieved by ALD processed ZnO from a theoretical perspective.

The surface states of the ALD processed ZnO composite, and its work function characteristic will determine the electrical properties upon contact with the conductor. When employing different electrodes (such as Ag, Au, Cu, and ZrN, uniformly applied to both faces, with KPFM measurements depicted in Fig. S15(a-d)) or electrode pair (Ag on the Si-face and TiN on the C-face), with identical 3 nm ZnO interlayers on both faces, all configurations persist in displaying ideal Ohmic properties, as evidenced in Fig. S15(e) and (f), respectively. These tests imply that there is no bending of energy levels due to differences in work functions between the conductors and the composite surfaces, hence suggesting a Fermi level pinning effect on the composite C-face and Si-face. On the other hand, introducing interlayer blocks the wavefunction penetration from the conductors to the semiconductors, benefiting the Fermi level pinning effect acting between the composite and the conductors. The overall effect also guarantees significant versatility in selecting electrode materials for our high-resistance devices. By the Fermi level pinning effect, ideal Ohmic characteristics arise due to the almost identical work functions realized by applying a 3 nm ZnO layer, leading to a completely flattened Fermi level with uniform barrier heights of 0.68 eV on both faces, as showcased in Fig. 2(c). This illustrates the absence of any internal electric field within the device under no bias conditions, which accounts for the device's stable resistance characteristic regardless of applied voltage. Moreover, when the interlayer is altered to ALD processed  $Al_2O_3$ , it similarly demonstrates the capability to modify surface work functions, facilitating the development of a resistor that exhibits a voltage-independent characteristic, in contrast, ALD processed  $TiO_2$  does not present this effect, as indicated in Fig. S4. This divergence is attributed to the distinct electron distributions in the interlayer materials, leading to different charge transfer dynamics at the composite surface.

Provided that an ideal transistor is used in the precision current measurement circuit, our 4H-SiC resistor, serving as a feedback resistor in the amplifying circuit, theoretically has the capability to amplify a precision current of 1 fA into a voltage signal of 52.4 mV (Fig. 1(a)). To further demonstrate the potential of our resistors, an effective test circuit for precision current measurement was proposed, aimed at measuring the photocurrent response signal of a photodetector under extremely weak light intensity. The schematic diagram of the circuit connection was shown in the inset of Fig. 3(a). By employing series voltage division, the weak current signal in the circuit was converted into a voltage signal detectable by a spectrum analyzer through the resistor with internal resistance similar to that of the photodetector. Given that the photodetector exhibits an ultra-low dark current of

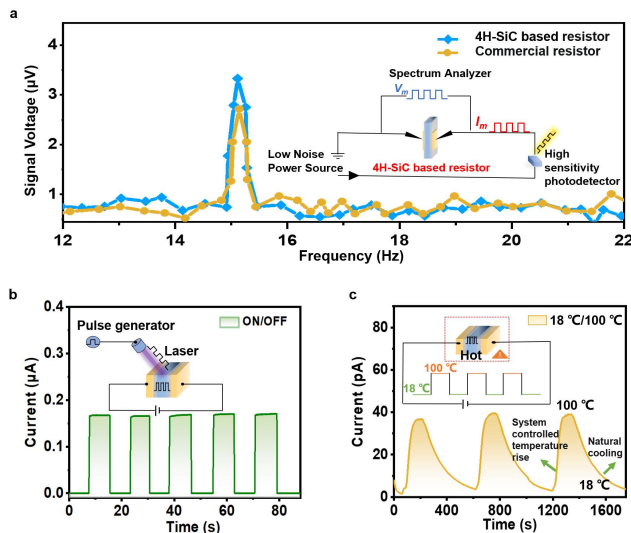


FIG. 3. (a) Measurement of weak photocurrent response signal of photodetector using a 4H-SiC resistor and a commercial resistor with a resistance of  $10\text{ T}\Omega$ . (inset: schematic diagram illustrating the circuit connection for weak photocurrent response signal measurement using 4H-SiC resistors.) (b) Photoresistivity characteristic of 4H-SiC resistor with the periodic light switching. (c) Thermoresistivity characteristics of 4H-SiC resistor with periodically varying temperature.

60 fA and a high internal resistance, our 4H-SiC resistor, alongside the largest available commercial resistor with the same resistance of  $10\text{ T}\Omega$ , respectively, were selected for use in this scheme. When a bias voltage of 5 V was applied to the circuit and the photodetector was illuminated with pulsed light at a frequency of 15 Hz and an intensity of  $38\text{ nW/cm}^2$ , a corresponding signal voltage was measured. The results in Fig. 3(a) indicated that the capability of 4H-SiC resistors reaches or even surpasses the level of commercial resistors. However, due to the limitations of the internal resistance of the utilized spectrum analyzer, this test circuit can only detect signals up to the current level.

The high-resistance resistors we developed can also be utilized for sensing light and heat signals. For photoresistivity, as demonstrated in Fig. 3(b), when exposed to pulsed modulated 360 nm laser irradiation under a bias voltage of 20 V, the resistance of the device exhibited stable dark resistance and periodic variation as the laser was turned on and off. The linear decrease in resistance with increasing light intensity is advantageous for the development of highly sensitive ultraviolet photodetector (Fig. S16(a)). Regarding thermoresistivity, as shown in Fig. 3(d), by modulating the temperature using a temperature controller to  $100\text{ }^\circ\text{C}$  and allowing it to naturally cool back to room temperature over multiple cycles, the measured current exhibited periodic changes over time under a bias voltage of 20 V. Additionally, the resistance value decreases linearly as the temperature in-

creases from room temperature to  $100\text{ }^\circ\text{C}$  (Fig. S16(b)). The movie S1 in Supplementary Material [20] captured the real-time variation of resistance with temperature. Moreover, as shown in Fig. S17, a comparison of the  $I$ - $V$  curves of commercial resistors and 4H-SiC resistors at different temperatures was conducted. The data shows that as temperatures rise, the  $I$ - $V$  curves of commercial resistors consistently do not intersect the origin. In contrast, our specially designed 4H-SiC resistors maintain their ideal  $I$ - $V$  curve, even at increased temperatures up to  $60\text{ }^\circ\text{C}$ .

Our research demonstrates for the first time the feasibility of tuning Peta-Ohm level resistance of semi-insulating 4H-SiC resistors via the incorporation of atomic-level metal oxide interlayers. Our devices exhibited performance closely matching that of commercial high-resistance resistors in low-current amplification circuits, though the ultimate potential of our resistors is somewhat hindered by the internal resistance of the source meter. Additionally, we have illustrated the device's promising applications as a highly sensitive photodetector and as a thermal sensor. This advancement signifies a promising step forward for integrated 4H-SiC devices, and this innovation is expected to drive substantial progress in the field of precision measurement technology.

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