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Effect of anode area on the sensing mechanism of vertical GaN Schottky barrier diode temperature sensor

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Effect of anode area on temperature sensing ability is investigated for a vertical GaN Schottky-barrier-diode sensor. The current-voltage-temperature characteristics are comparable to each other for Schottky barrier diodes with different anode areas, excepting the series resistance. In the sub-threshold region, the contribution of series resistance on the sensitivity can be ignored due to the relatively small current. The sensitivity is dominated by the current density. A large anode area is helpful for enhancing the sensitivity at the same current level. In the fully turn-on region, the contribution of series resistance dominates the sensitivity. Unfortunately, a large series resistance degrades the temperature error and linearity, implying that a larger anode area will help to decrease the series resistance and to improve the sensing ability.

1. Introduction

Gallium nitride (GaN) based Schottky barrier diodes (SBDs) are key components for the next-generation high power and high switching frequency devices, which are commonly adopted in switching power supply, wireless communications, drivers, and so on.[1–4] Compared with the planar SBDs fabricated on the AlGaN/GaN structure, vertical devices can achieve high power density and high breakdown voltage by simply increasing the drift layer thickness other than extending the gate-to-drain distance.[5–10] Therefore, vertical devices are preferable to sink chip size and decrease the cost. Especially, with the tremendous progress in high quality GaN substrates, vertical GaN SBDs have attracted a great deal of attention in recent years.

On the other hand, GaN devices commonly generate heat during static on-state and on/off switching.[11] This heat dissipation will drastically increase the junction temperature especially for vertical devices which handle higher power densities. Generally, electrical parameters of SBDs are temperature-dependent and will be degraded under a relatively high temperature.[12] Hence, temperature monitoring plays a key role in ensuring safe operation or quality control. However, the accuracy and reliability of the conventional thermocouples or resistive temperature sensors do not meet the request of high temperature environment.

Alternatively, GaN based Schottky barrier diodes (SBDs) are a kind of promising candidates for *in situ* temperature sensor applications due to the wide bandgap, good linearity, and long-term stability. In our previous study, latera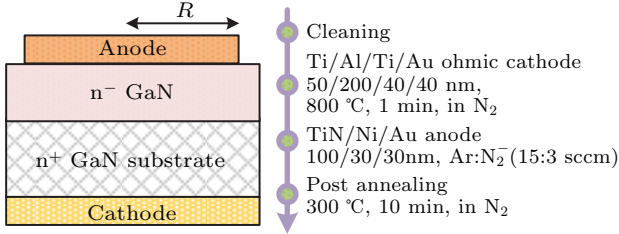l, quasi-vertical and vertical GaN-compatible temperature sensors were fabricated and evaluated with thermally stable TiN anode.[13–16] When the SBD works in sub-threshold region, the forward voltage at a fixed relatively small current level decreases linearly versus temperature. It was demonstrated that the sensitivity of the lateral and quasi-vertical SBD is dependent on the anode area. However, the effect of anode area of a vertical diode on the sensing characteristics is not investigated extensively. In this work, vertical GaN SBDs with various anode sizes are proposed to investigate the effect of anode area. It is found that a large anode area helps to decrease the series resistance and to enhance the sensitivity. The current density and series resistance dominate the sensitivity in sub-threshold region and fully turn-on region, respectively.

2. Experiments and characterization

The vertical GaN SBDs (Fig. 1) were fabricated on a commercial free-standing wafer. The epitaxial structure and the main processes were similar with our previous work.[15] The electrode material and the sputtering conditions are listed in Fig. 1. To improve the high temperature interface reliability, we adopted a thermally stable TiN as the anode electrode. Compared with the Ni and NiN anodes in our previous work,[14–17] the work function of TiN is approximately 4.7 eV. The relatively small Schottky barrier height (SBH, $\Phi_b \sim 0.6$ eV) is beneficial to decrease the turn-on voltage (V_{on}) and on-state power loss.[17] On the other hand, the TiN can effectively suppress the interface reaction between GaN and the conventional metal anode. Good Schottky contact properties are maintained even after the 800 °C annealing for several minutes.[18] Those results demonstrate that TiN is promis-
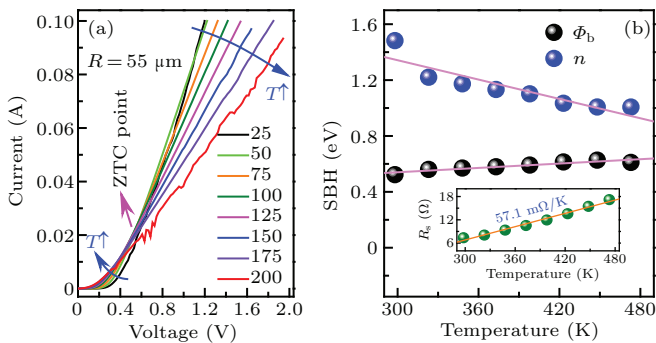
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ing for GaN SBD temperature sensor applications. Herein, we focus on evaluating the effect of anode area on the sensitivity. A series of SBDs with different anode radii ($R =$ 55 μm, 70 μm, and 85 μm) were fabricated. To investigate the temperature sensing ability and the mechanism, current-voltage-temperature (I–V–T) characteristics were measured from 25 °C to 200 °C with steps of 25 °C.

Fig. 1. Schematic view of the vertical GaN SBD temperature sensors with different anode radii (R). The corresponding main fabrication processes are also listed.

3. Results and discussions

The typical I–V–T characteristics of SBD with an anode radius of 55 μm were recorded, as shown in Fig. 2(a). The V_{on} extracted by linear fitting the forward region is about 0.47 V, which is consistent with previous reports.[14,17] In addition, the I–V–T curves show a zero-temperature coefficient (ZTC) point. Obviously, the variation of current versus temperature are different in the bias regions above and below the ZTC point (approximately 0.6 V). For the small forward voltage (V_F) region (below ZTC point), the voltage at a specific current value decreases gradually with the increasing temperature (negative coefficient). Noticeably, above the ZTC point (relatively high V_F region), the voltage at a specific current value increases gradually with the increasing temperature (positive coefficient).

Fig. 2. The I–V–T characteristics (a) of vertical GaN SBD with an anode radius of 55 μm. (b) The relationship between key parameters and temperature.

Theoretically, the I–V–T curves of the SBD follow the thermal emission (thermionic emission, TE) model. The forward current I_D under $V_F > 3kT/q$ reads[17]
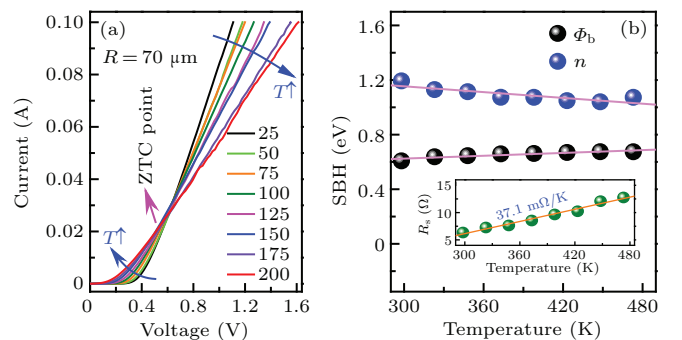
$$I_D = A_e A^* T^2 \exp\left(-\frac{q\Phi_b}{kT}\right) \exp\left(\frac{q(V_F - I_D R_s)}{nkT}\right). \quad (1)$$
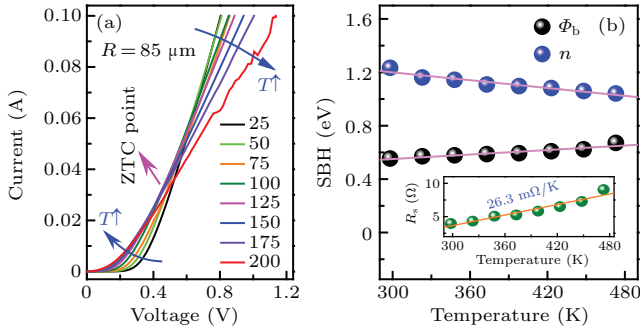
The V_F is then solved as

$$V_F = n\Phi_b + \frac{nkT}{q}\left[\ln\left(\frac{I_D}{A_e A^*}\right) - 2\ln(T)\right] + I_D R_s, \quad (2)$$

where A_e, T, q, n, k, A^* and R_s are the Schottky anode area, Kelvin temperature, electronic charge, ideality factor, Boltzmann constant, Richardson constant (26.9 A·cm^{-2}·K^{-2} in our calculation) and series resistance, respectively. Based on Eq. (2), the key parameters (Φ_b, n, and R_s) of the SBD versus temperature with an anode radius of 55 μm are fitted and plotted in Fig. 2(b). It is demonstrated that the Φ_b increases from 0.52 eV to 0.62 eV linearly with the increasing T, while the n decreases from 1.4 to 1.0 linearly. In addition, we also find that the R_s increases from 7.3 Ω to 17.2 Ω with temperature in a slope of 57.1 mΩ/K. The variation of Φ_b and n versus temperature are not consistent with the TE model, in which those values should be constants. The possible reason is attributed to the spatial fluctuation of Φ_b at interface, namely, the barrier height inhomogeneous effect.[19] The carrier at relatively high temperature gains more energy and then overcomes the high barrier patch, resulting in a high average barrier height.

To evaluate the effect of anode radius on the electrical properties, the I–V–T characteristics of SBDs with anode radii of 70 μm and 85 μm are shown in Figs. 3(a) and 4(a), respectively. The I–V–T characteristics of both diodes are comparable with that of the small anode one, except the forward voltage that reaches the compliance current. By fitting the I–V–T curves, the Φ_b of the 70 μm SBD increases from 0.61 eV to 0.67 eV, while the n decreases from 1.2 to 1.0 linearly with the increasing T (Fig. 3(b)). The Φ_b of the 85 μm SBD increases from 0.56 eV to 0.67 eV, while the n decreases from 1.2 to 1.0 linearly with the increasing T (Fig. 4(b)). Those values and the variation trends are comparable to each other, implying that other factors are the root causes. It is worth noting that the slopes of R_s are 37.1 mΩ/K and 26.3 mΩ/K for the 70 μm (inset of Fig. 3(b)) and 85 μm (inset of Fig. 4(b)) diodes, respectively. This indicates that the R_s presents an obvious effect at the voltage region above the ZTC point.

Fig. 3. The I–V–T characteristics (a) of the vertical GaN SBD with an anode radius of 70 μm. (b) Relationship between key parameters and temperature.

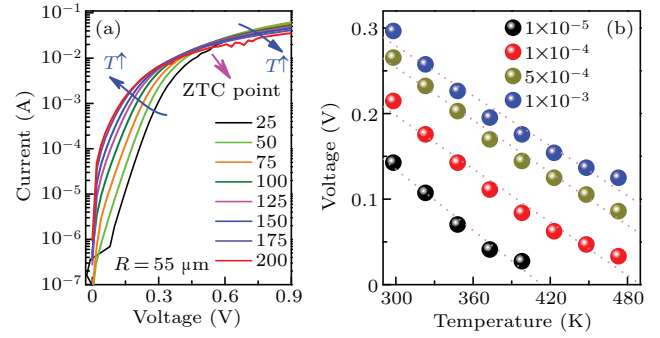**Fig. 4.** The $I–V–T$ characteristics (a) of the vertical GaN SBD with an anode radius of 85 μm. (b) Relationship between key parameters and temperature.

Fig. 5. (a) The sub-threshold region $I–V–T$ characteristics of the vertical GaN SBD with an anode radius of 55 μm. (b) The $V_F–T$ relationship at different current levels.

Fig. 6. (a) The production of SBH and n versus temperature. (b) The relationship between sensitivities and current density.
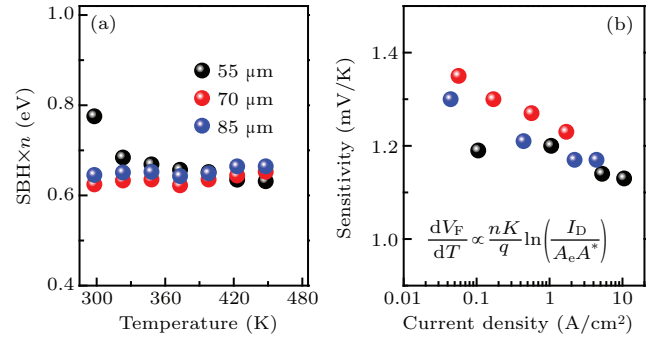
The relationship between forward voltage and temperature is commonly used for determining the sensitivity. Furthermore, the sub-threshold region is preferable for temperature sensing application due to the relatively small power loss. When we choose a specific current (1×10^{-5}, 1×10^{-4}, 5×10^{-4}, or 1×10^{-3} A in our experiment), the corresponding forward voltage on the $I–V–T$ curves shifts negatively with the increasing temperature (Fig. 5(a)). The variation of this forward voltage versus temperature is then plotted in Fig. 5(b). Under four selected current levels, the corresponding forward voltage decreases with increasing temperatures, implying that the slope is negative (Fig. 5(b)). Based on the absolute slope of the fitting line, the measured sensitivities S_m are deduced to be 1.19, 1.2, 1.14, and 1.13 mV/K at 1×10^{-5}, 1×10^{-4}, 5×10^{-4}, and 1×10^{-3} A, respectively. Based on Eq. (2), the V_F is determined by three main parts. Firstly, we confirm that the production $n\Phi_b$ shows slight dependence on temperature (Fig. 6(a)), which is ascribed to the opposite variation trends of Φ_b and n. Secondly, the voltage drop contributed by the R_s ($I \times dR_s/dT$) is smaller than 0.05 mV/K due to the small current in sub-threshold region. In addition, the non-linear part of $\ln T$ can also be ignored in relatively small temperature range.[20] Hence, the sensitivity dV_F/dT is correlated with the current density I_D/A_e as

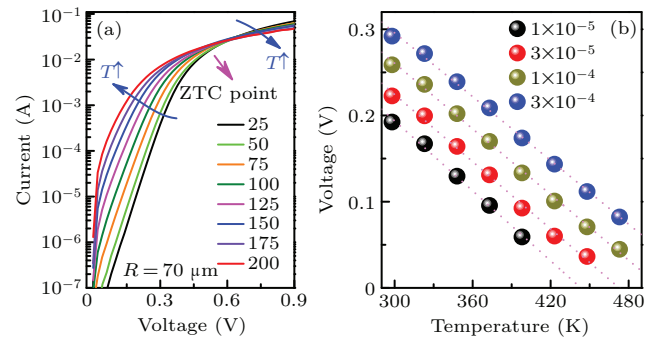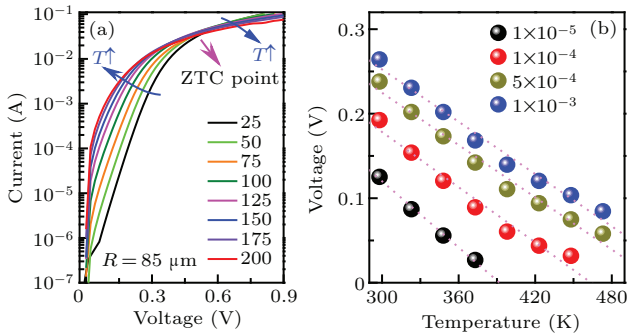$$\frac{dV_F}{dT} \propto \frac{nK}{q} \ln\left(\frac{I_D}{A_e A^*}\right). \quad (3)$$

Therefore, the sensitivity is mainly determined by the ideality factor n, current level I_D and anode area A_e, but is not related with the wafer structure and diode geometry (circular, finger, dot, etc.). The above discussion is confirmed by the decreasing trend of sensitivity versus current level, which is proportional to the logarithms of current density (Fig. 6(b)). Because an ideal SBD follows the TE model, the change of anode material (variation in Φ_b and reverse leakage current) has no direct effect on the sensitivity. In addition, although the interface reaction for the metal anode on GaN generates a relatively higher n and contributes to the sensitivity, the degradation of reliability is unsuitable for high temperature applications.

Fig. 7. (a) The sub-threshold region $I–V–T$ characteristics of the vertical GaN SBD with an anode radius of 70 μm. (b) The $V_F–T$ relationship at different current levels.
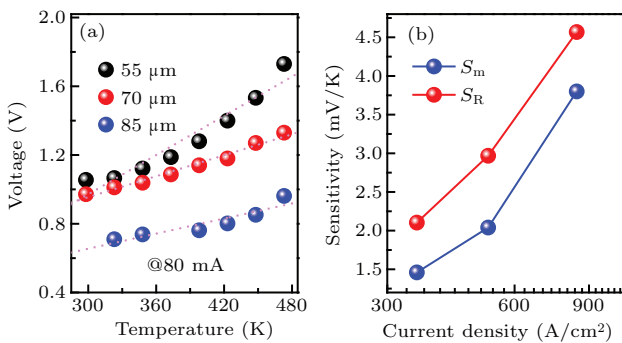
To evaluate the effect of anode area on the sensitivity, the sub-threshold region of $I–V–T$ characteristics for the SBDs with anode radii of 70 μm and 85 μm are also plotted in Figs. 7(a) and 8(a), respectively. Then, the corresponding $V_F–T$ relationships at different currents with the fitting line are plotted in Figs. 7(b) and 8(b), respectively. Obviously, good linearity can be observed for all the $V_F–T$ curves, and the deduced sensitivities are summarized in Fig. 6(b). On the one hand, the production of Φ_b and n shows slight dependence on temperature (Fig. 6(a)). On the other hand, the voltage drop contributed by the R_s (S_R, the production of dR_s/dT and current) is smaller than 0.04 mV/K. Therefore, the sensitivity is also proportional to the logarithms of current density (Fig. 6(b)). Therefore, when the sensor works at a specific current (sub-threshold region), a relatively larger anode area helps

to realize a smaller current density and to obtain a higher sensitivity.

Fig. 8. (a) The sub-threshold region I–V–T characteristics of the vertical GaN SBD with an anode radius of 85 μm. (b) The V_F–T relationship at different current levels.

Unlike the sub-threshold region, the voltages at a specific current increase with the increasing temperature in the fully turn-on region, showing a positive slope above the ZTC point (Fig. 9(a)). At a current of 80 mA, the S_m values are deduced to be 3.81 mV/K, 2.04 mV/K, and 1.46 mV/K for the SBD with anode radii of 55 μm, 70 μm, and 85 μm, respectively. However, the S_R values contributed by the R_s are calculated to be 4.56 mV/K, 2.97 mV/K, and 2.1 mV/K (Fig. 9(b)). Therefore, the S_m is dominated by the S_R in this region. We realize that the series resistance degrades the temperature error and linearity,[13] implying the fully turn-on region is not suitable for temperature sensor application. It is worth noting that a larger anode area helps to decrease the R_s and to improve the sensing ability.

Fig. 9. (a) The V_F–T relationship in fully turn-on region for the SBD with different anode radii. (b) The relationship between sensitivities and current density.

4. Conclusions

In summary, we have fabricated vertical GaN SBD temperature sensors using a thermally stable TiN anode. Based on the I–V–T characteristics, the effect of anode area on the sensitivity is investigated. It is demonstrated that the I–V–T characteristics are comparable to each other for the diode with different anode areas, presenting a ZTC point and a typical

barrier inhomogeneous behavior. In addition, the R_s increases with temperature in slopes of 57.1 mΩ/K, 37.1 mΩ/K, and 26.3 mΩ/K for 50 μm, 70 μm, and 85 μm diodes, respectively. When the voltage is below the ZTC bias point (sub-threshold range), the forward voltage decreases linearly versus temperature with a negative slope. The sensitivity deduced from the absolute value of slope is dominated by the current density, which follows the TE model. A large anode area helps to enhance the sensitivity at the same current level. When the voltage higher than the ZTC point (fully turn-on range), the forward voltage increases linearly with temperature in a positive slope. Then, the contribution of series resistance dominates the sensitivity. Under this condition, a larger anode area helps to decrease the series resistance and to improve the sensing ability.

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