A Comparative Study of n-p GaN/SiC Heterojunction and p-n Homojunction Diodes

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Abstract

A comparative study between GaN/SiC heterojunction and 6H-SiC homojunction diodes has been performed to understand the physical properties of n-p GaN/SiC heterojunction interface. The 6H-SiC homojunction diodes presented typical I-V characteristics with satisfactory breakdown voltage (≈ 800 V), however, the GaN/SiC heterojunction diodes showed an abnormal low forward turn-on voltage (≈ 1.8 V). The presence of a deep-level situated 1 eV below the p-SiC conduction band, is probably responsible for a tunneling-assisted current at low forward voltages, due to a high concentration of interface defects.

Introduction

The combination of electronic and physical properties of two wide band gap semiconductors such as GaN and SiC is very attractive for use in high power and high temperature semiconductor electronics. A first GaN/SiC high temperature heterojunction bipolar transistor (HBT) with high current gain was demonstrated a few years ago by Pankove *et al.* [1]. The understanding of the electrical characteristics of both GaN/SiC emitter-base heterojunction (HJ) diode and SiC base-collector homojunction diode are fundamental to the development of such device.

In this work we present a comparison between the physical properties of n-p GaN/SiC heterojunction and p-n 6H-SiC junction diodes, including current-voltage (I-V), capacitance-voltage (C-V) measurements, electroluminescence (EL) and photoluminescence (PL) spectra at room temperature.

Experimental procedure

Epitaxial n-type GaN ($0.5 \mu\text{m}$, $3 \times 10^{18} \text{ cm}^{-3}$) films were grown using metalorganic vapor deposition (MOCVD) on commercially available Si-face p-type 6H-SiC 3.5° off substrates ($1 \times 10^{18} \text{ cm}^{-3}$) [2]. Mesa-style $80 \mu\text{m}$ diameter HJ diodes were fabricated from these structures using reactive ion etching (RIE). Ohmic contacts of Titanium/Aluminium and Aluminium/Titanium were RF sputtered on the n-type GaN layer and p-type SiC substrate, respectively. The fabrication process was completed by rapid thermal annealing of the contacts. No passivation was used for the HJ diodes.

A similar process was used to fabricate $100 \mu\text{m}$ diameter 6H-SiC p-n homojunctions diodes on n⁺-p⁺ homoepitaxial layers ($5 \mu\text{m}$, $3.6 \times 10^{15} \text{ cm}^{-3}$ - $0.2 \mu\text{m}$, $8.5 \times 10^{18} \text{ cm}^{-3}$) grown on n⁺ ($2 \times 10^{18} \text{ cm}^{-3}$) SiC substrates [2]. In these diodes a wet thermal oxidation was performed for mesa passivation. Unpatterned Nickel was E-beam evaporated onto the n⁺ substrate, for the contact on p-type side, a Al/Ti contact, similar to the one used for the HJ diodes, was used.

Results and discussion

Typical semi-logarithmic I-V characteristics obtained on the 6H-SiC p-n diode at 442 and 294 K are shown in Fig. 1. At forward bias, the $\ln(J)$ vs V plot exhibited two linear regions. At

room temperature, in the low voltage region from 1.75 to 2.25 V, the extracted ideality factor (n) equals 2.0 to 2.1, indicating that carrier recombination mechanism dominates the current transport. Above 2.3 V, and before the effect of the series resistance ($\approx 5 \times 10^{-3} \Omega \cdot \text{cm}^2$) becomes predominant, the ideality factor was estimated to be 1.4 to 1.6, far from the theoretical value of 1 expected for pure diffusion current. The extrapolated saturation current densities are 1×10^{-21} and 3×10^{-27} , for recombination and diffusion currents respectively. The temperature dependence of the saturation recombination current density revealed an activation energy (E_a) of about 1.40 eV as shown in the Arrhenius plot of Fig. 2. This result is close to half bandgap of 6H-SiC ($E_g \approx 3.0$ eV), as predicted by the Shockley-Read-Hall theory [3].

Fig. 1- Semi-logarithmic plot of forward J-V for a 100 μm diameter 6H-SiC p-n diode at 294 and 442K. The inset shows the linear reverse J-V at 294K.

The reverse characteristics vs temperature were tested up to 100 V, and no significant variations in the reverse currents were detected (not shown). When immersed in silicon oil, the 6H-SiC p-n diodes exhibited good rectification characteristics for reverse voltages up to

Fig. 2- Arrhenius plot of saturation recombination current density of a 6H-SiC p-n junction diode.

Fig. 3- C-V characteristics of a 6H-SiC p-n diode and GaN/6H-SiC n-p HJ diode.

800 V at room temperature as shown in the inset of Fig. 1.

The C-V characteristics of both types of diodes (HJ and homo) are shown in Fig. 3. The intercept $1/C^2$ with the voltage-axis gives the built-in potential (Φ_{bi}) around 2.1 (HJ) and 2.6 V (homo), respectively. From the drift-diffusion theory [4], one would expect the value of Φ_{bi}

for this HJ to be about 2.8 eV, significantly higher than the one we have measured. Anomalous low Φ_{bi} values have been reported previously in GaN/SiC n-p HJ diodes [5].

Fig. 4- Semi-logarithmic plot of forward and reverse J-V for an 80 μm diameter GaN/6H-SiC HJ diode at several temperatures.

also, a too high saturation current density of about $1 \times 10^{-16} \text{ A/cm}^2$ is observed at room temperature. The change in ideality factor with temperature is not well understood at this time but suggest that mechanisms other than thermal recombination-generation are involved. Carrier generation mechanisms induced by a high density of morphological defects (scratch, micropipe, misfit dislocations, stacking fault) and also carrier tunneling are expected to be the dominant leakage mechanisms for the HJ diodes samples presently available. These diodes presented high leakage currents of 1 mA/cm^2 at -20 V with catastrophic reverse failures between -40 and -50 V .

The 6H-SiC p-n junction diodes showed typical blue light emission, when forward biased, as shown in Fig. 5. The

Fig. 5 – Comparison between the EL spectrum of the p-n 6H-SiC diode and the PL spectrum from the same p-n homojunction, excited with a HeCd laser at room temperature.

The HJ diodes presented an orange-red light emission with maxima at 1.88 eV in the forward biased region as shown in Fig. 6. In the same figure, the PL spectra from the HJ and p-type 6H-SiC substrate shows at room temperature a broad emission band at 1.98 eV when excited by 390 nm light. This result shows that the p-SiC is responsible for the EL emission. At 10K

Forward and reverse I-V characteristics at 478 K and room temperature are shown in Fig. 4 for the HJ diodes. The turn-on voltage at room temperature of about 1.8 V is in agreement with the measured Φ_{bi} . We have tried to draw activation energy plots of either reverse currents at fixed bias voltage or saturation current densities extrapolated from I-V forward characteristics. None of them yielded linear Arrhenius-like results as expected. The ideality factor changes with temperature and,

electroluminescence spectrum is dominated by the free exciton recombination peak at 425 nm (2.9 eV) as previously reported [6,7]. Donor-acceptor recombination (N and Al) as well as deep acceptor centers are probably involved in the yellow-green emission. The room temperature PL emission of the 6H-SiC p-n homojunction is dominated by the near band edge recombination peak at $\sim 3.0 \text{ eV}$.

the PL of p-type 6H-SiC is dominated by near band edge emission (DAP N-Al). This is strongly quenched above 60 K while a band at 1.8 eV increases and progressively shifts to the room temperature value of 1.98 eV. Preliminary results of the PL temperature dependence suggest that a level about 1 eV below the conduction band acts as an effective electron trap, leading to the PL and EL emissions. Since Vanadium is a usual SiC contaminator it is possible that the related deep levels (630-780 meV) are involved in the radiative emission [8]. A tunneling assisted current to this deep level [9] in forward bias regime below the turn-on voltage is improbable, since the depletion layer for this range of voltages is large enough (590 to 190 Å) to prevent such tunneling, unless the presence of some interface defects can locally reduce the depletion layer or create field enhancement by sharp edge effects.

Fig. 6- Comparison between the EL spectrum of the GaN/6H-SiC HJ diode and the PL spectrum from the same HJ and p-type substrate, excited with a Xe lamp (390 nm) at room temperature.

Conclusion

We found that the low turn-on voltage in the GaN/SiC HJ diodes is probably related to the presence of a deep-level in the p-SiC substrate. Further work will be necessary to well understand the tunneling-assisted current mechanism at low forward voltages, and also to improve the GaN/SiC interface growth.

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