Temperature Diagnosis of Bulk GaN-based Schottky Diode by Raman Spectroscopy

Hui Xu[1], Siddharth Alur[1], Yaqi Wang[1], An-Jen Cheng[1], Kilho Kang[1], Claude Ahyi[1], John Williams[1], Minseo Park[1]*, Chaokang Gu[2], Andrew Hanser[3], Tanya Paskova[3], Edward A. Preble[3], Keith R. Evans[3], and Yi Zhou[4]

[1]Department of Physics, Auburn University, Auburn, AL 36849
[2]Department of Chemistry and Biochemistry, Auburn University, Auburn, AL, 36849
[3]Kyma Technologies, Inc., 8829 Midway West Road, Raleigh, NC 27617
[4]Department of Electrical Engineering, University of California, Los Angeles, CA 90095
*corresponding author

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Abstract

Intensive research has been focused on the GaN based electronic devices due to their intrinsic properties such as large band gap, high critical breakdown field and high electron saturation velocity, which provide great potential for high power and high frequency applications. Schottky diodes are useful components for high power electronics because of their fast switching. However, a significant limitation of device performance is the self-heating problem. Therefore, accurate determination of the device temperature is very important. In our experiment, we fabricated vertical Schottky rectifiers based on freestanding GaN substrate, where semi-transparent Ni was patterned on the Ga-face as the Schottky contact and full backside ohmic contact Ti/Al/Pt/Au was deposited on the N-face. Afterwards, Raman spectra were collected as a function of forward bias. The Raman E2 peak was found to shift and broaden systematically with device operating power. We conclude that micro-Raman spectroscopy is a great non-contact tool to monitor the thermal characteristics of electronic devices under operation.

INTRODUCTION

Since the operation of GaN-based light-emitting diode (LED) was demonstrated, nitride-based semiconductor has attracted scientific and commercial interests. For example, green nitride-based LEDs are widely applied in traffic signals. Due to their unique material properties, there are many promising applications for GaN, especially in high power and high frequency area. Thanks to recent technology, great improvement has been made to GaN based devices, although difficulties still exist. Self-heating is one of the issues. In the case of high electron mobility transistor (HEMT) at high bias, temperature increase due to self-heating can negatively affect the device performance [1]. Raman Spectroscopy is used by several groups for temperature measurement of HEMT [2, 3]. Schottky diodes are preferred in high power electronics, which also suffer from self-heating problem. However, no report has been published for temperature diagnosis of bulk GaN based Schottky diodes which are under operation.

EXPERIMENT

Our devices were fabricated based on the bulk GaN wafer with a thickness of 500 µm, and the wafer was produced at Kyma Technologies, Inc. The samples were initially immersed in acetone, TCE and methanol in an ultrasonic bath. Afterwards, they were treated with heated HCl solution to remove the native oxide. A 4-layered metal stack Ti/Al/Pt/Au was sputtered on the full backside (N-face GaN) of the wafer. Subsequently, the ohmic contact was annealed at 750^{o}C for 30s in the nitrogen atmosphere. Semi-transparent metal Ni was patterned on the front Ga side as circular Schottky contacts. Then, the current-voltage (I-V) and capacitance-voltage (C-V) curves were measured to characterize the Schottky diodes. From the C-V curve, the carrier concentration was determined to be ~3×10^{16} cm^{-3}. The 441.6 nm line (80 mW) from HeCd laser was used to collect Raman spectra when the devices were heated through applied bias and hot plate.

RESULTS AND DISCUSSION

Figure 1 is the low field I-V curve with a forward voltage up to 2 V and figure 2 is the high field I-V curve with a forward voltage up to 20 V.

The current in a Schottky rectifier is described through thermionic emission model by the following equation:

$$I = AA^{*}T^{2}\exp\left(-\frac{q\Phi_B}{k_B T}\right)\exp\left[\frac{qV}{nk_B T}-1\right] = I_0\exp\left[\frac{qV}{nk_B T}-1\right]$$

For $qV > 3k_BT$ the above equation can be simplified [4]:

$$I = I_0 \exp\left[\frac{qV}{nk_BT}\right]$$

where A is the device area, A* is the effective Richardson constant, for GaN, 26.4 A cm^{-1} K^{-2}, T is the temperature, k_B is Boltzmann constant, q is the electron charge, Φ_B is the barrier height, and n is the diode ideality factor, V is the forward current. A linear region can be found at lnI vs. V plot; therefore the ideality factor is determined to be 1.02. Also using the intercept at y axis, barrier height is calculated to be 0.54eV.

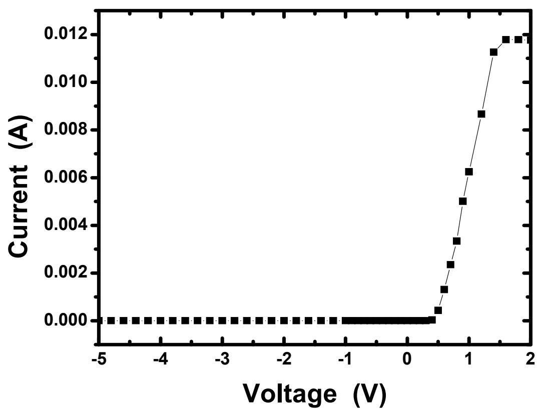

Figure 1: Low field I-V curve

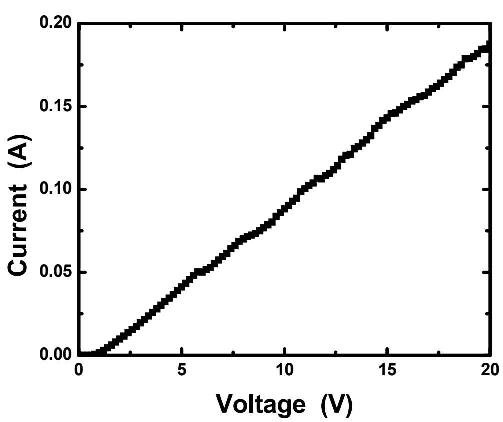

Figure 2: High field I-V curve

C-V measurement can give a good evaluation of barrier height:

$$\frac{A^2}{C^2} = \frac{2(\psi_{Bi} - V - k_BT/q)}{q\varepsilon\varepsilon_0 N}$$

where C is the capacitance, ε is the dielectric constant of GaN, ε_0 is the vacuum permittivity, and N is the electron concentration.

$$\Phi_B = \psi_{Bi} + \frac{k_BT}{q} ln \frac{N_c}{N}$$

where N_C is the effective density of state in conduction band. By using this equation the barrier height is determined to be 0.6eV.

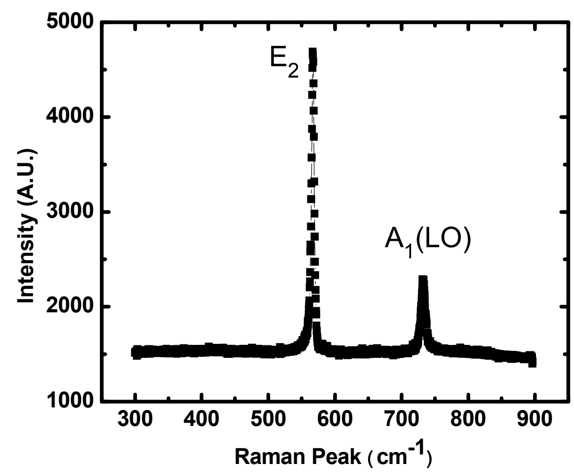

Figure 3: Micro-Raman spectrum

Based on Raman selection rules, E_2 and A_1(LO) modes are allowed. Figure 3 shows a typical Raman peaks for our bare GaN sample. The reason to choose E_2 peak is because of their high intensity and sensitivity to strain.

Figure 4 shows the Raman E_2 peak and relative FWHM against forward power. The corresponding forward voltages are 0, 10 V, 15 V, 20 V. Notice that systematic changes occurred during the measurement. As we can see, Raman E_2 peak shifted to a lower wave number and corresponding FWHM broadened, according to the forward bias change. It is assumed that self-heating increased the temperature of the devices.

For comparison, GaN Raman E_2 peak at several different temperatures were also probed. It is shown in figure 5. A hot plate was used to heat the devices. Before each measurement, the devices stay heated for 10min in the purpose to make the temperature uniform through the whole sample. Since the energy band gap of GaN (~3.4 eV) is greater than the energy of the incident laser light with a wavelength of 441.6 nm, absorption of the laser light energy by the sample can be neglected [5].

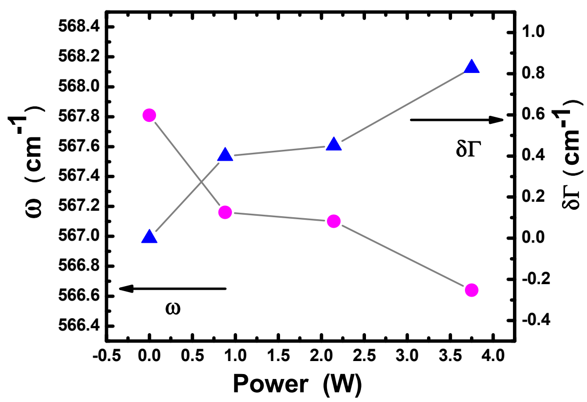

Figure 4: Power dependent Raman E_2 and FWHM

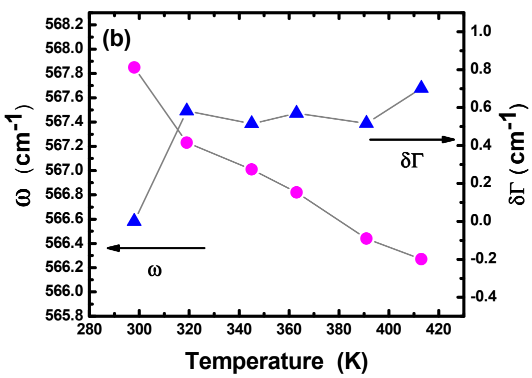

Figure 5: Temperature dependent Raman E_2 and FWHM

With increasing temperature, all the Raman peaks shifted to lower wave numbers. The peak shift is described by the following equation [6]:

$$\omega = \omega_0 - \frac{\alpha}{e^{\beta\hbar\omega_0/k_BT} - 1}$$

where α, β are fitting parameters, ω_0 is the 0K Raman frequency. There are mainly two reasons leading to the Raman frequency shift. One is the thermal expansion causing the frequency change; the other is the anharmonic coupling of phonon with other phonons [7]. Using the curve in figure 5 for calibration, it is found that our biased device has a temperature increase from room temperature to 371K.

Continuous broadening of FWHMs was observed in both cases. Equation:

$$\Gamma(T) = \Gamma_0[1 + \frac{2}{e^{\hbar\omega_0/2k_BT} - 1}]$$

was used by Liu *et al.* [8] to depict the relationship of FWHM and temperature, where Γ_0 is the FWHM at 0 K.

Because of the lack of inversion symmetry, GaN is well known as a piezoelectric material. Which means it is possible that when an electric field is applied on the device, strain will be produced. Therefore it is necessary to confirm that the Raman peak shift observed comes from thermal effect, but not from the piezoelectric effect. It is reported that the strain in GaN is proportional to the applied electric field. The maximum voltage in our experiment is 20V, which lead to a maximum electric field of 400V/cm. According to the work done by Sarua *et al.* [9] this electric field corresponds to a strain in the order of 10^{-7}. It has been pointed out that 1 GPa biaxial stress will shift the Raman peak by 4.2 wave number [10]. Considering our data, it is expected that the devices in our experiment will shift ~ 0.001 cm^{-1}, which is much smaller than the shift observed.

CONCLUSIONS

Vertical Schottky diodes were fabricated based on bulk GaN wafer. Raman peak shift and FWHM broadening were observed when the devices were biased. Moreover, Raman spectra were collected when the devices were under direct heat. Therefore, Raman spectroscopy offers a non-contact temperature diagnosis for devices.

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