Temperature-dependent electrical properties of Au Schottky contact and deep level defects in n-type GaN

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The Au/n-GaN Schottky barrier diode (SBDs) has been characterized by current-voltage (I-V), capacitance-voltage (C-V) and deep level transient spectroscopy (DLTS) measurements in the temperature range of 85 K - 405 K. The estimated Schottky barrier height is 0.25 eV at 85 K and 1.06 at 405 K by I-V method, respectively. Calculations showed that the barrier height is 1.02 eV at room temperature by C-V method. Little variation with either temperature or frequency was observed, and the carrier concentration derived from these measurements confirmed the dopant concentration of ~ 6.2×10^{16} cm^{-3}. A dominant trap E_a, with activation energy of 0.92 eV is observed in n-type GaN grown by metalorganic chemical vapor deposition (MOCVD). The capture cross section of 1.9×10^{-15} cm^2 is estimated based on the well-known logarithmic dependence of DLTS peak height with different filling pulse width for trap E_a. The trap E_a (0.92 eV), which is commonly observed in thin GaN layer grown by various techniques, is believed to be associated with nitrogen interstitial defect.

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1. Introduction

Due to superior characteristics of gallium nitride (GaN) such as direct wide band gap (3.4eV at room temperature), high break down field and high saturation velocity, it is one of the promising materials for the fabrication of optoelectronic and high temperature/high-power microelectronic devices like light emitting diodes (LEDs) [1], laser diodes (LDs) [2], photo detectors [3], metal oxide semiconductor field effect transistors (MOSFETs) [4], hetero junction field effect transistors (HFETs) [5], high electron mobility transistor (HEMTS) [6] and Schottky rectifiers [7]. However, the performance of GaN devices can be limited by the deep levels present in the GaN band gap, which act as either carrier trap or generation/recombination centers. Although there has been a substantial knowledge about the presence of these deep level defects in GaN [8, 9], it is essential to understand these defects to address issues related to the performance and reliability of GaN devices.

Many researchers have characterized and reported the defect levels in GaN which was grown by hydride vapor phase epitaxy (HVPE) [10] and metalorganic chemical vapor deposition (MOCVD) [11, 12, 13]. Gotz *et al* [11] reported the two deep levels with activation energies 0.49eV and 0.18eV with trap concentration 6.3×10^{14} cm^{-3} for E_1 and 7×10^{13} cm^{-3} for E_2. Look *et al* [14] created a point defect in GaN by electron irradiation and reported electron traps at 0.18eV and 0.9eV by DLTS technique. He also reported that the electron traps at 0.18eV and 0.9eV could be related to nitrogen interstitial (N_I) or gallium interstitial complex (Ga_I -X). Goodman *et al* [15] identifies the nitrogen vacancy with activation energy of 0.20eV below the conduction band in n-GaN epitaxial lateral over growth metallo-organo vapor phase epitaxy (ELO-MOVPE). Look *et al* [16] identify the trap having the activation energy 90 ± 2 meV with effective capture cross section $\sigma = 3\pm 1 \times 10^{-22}$ cm^2 in GaN. Fang *et al* [17] observed a dominant trap with activation energy of 1.0 eV and apparent capture cross section 2×10^{-12} cm^2 in heterostructure AlGaN/GaN/SiC. Py *et al* [18] reported the four known levels with activation energy in the range 0.1 - 0.94 eV in n-GaN which was grown by hydride vapor phase epitaxy (HVPE) by deep level transient spectroscopy. In this paper we report on the temperature-dependent electrical properties of Au Schottky contacts and characterize deep level defects in n-type GaN.

2. Experimental details

Gallium nitride (GaN) samples used in this study were grown by metalorganic chemical vapor deposition (MOCVD) on c-plane Al_2O_3 substrate and were followed by the growth of 2μm n-type GaN with Si. The n-GaN layer was first ultrasonically degreased with warm trichloro ethylene followed by acetone and methanol for 5min each. This degreased layer was then dipped into boiling aquaregia [HNO_2: HCl =1:3] for 10 min to remove the surface oxide and the sample was rinsed in deionized water. Ohmic contact Ti (20nm)/Al (40nm) was deposited on a portion of the sample by electron beam evaporation system under the vacuum of 6×10^{-6} mbar. Then the sample was annealed at 750 ºC for 2 min in nitrogen atmosphere. Schottky contacts are formed by the evaporation of gold (Au) as dots with a diameter of 1mm through stainless steel mask with a thickness of 60 nm. The current – voltage (I-V) characteristics were first measured in the temperature range 85 to 405K by the step of 40K in the dark. Then, capacitance - voltage (C-V) and DLTS measurements were carried out by automated DLS-83D system (Semi Lab, Lock-in amplifier based system which facilitated measurement at pulse frequency in the mHz range).

3. Result and discussion

Typical current-voltage characteristics of gold (Au) Schottky contact on n-GaN in the temperature range of 85K - 405K are shown in Fig. 1. The current flow through the diode can be described by thermionic emission (TE) theory and I-V relationship of a Schottky diode is given by [19]

$$I = I_S \exp\left(\frac{qV}{nkT}\right)\left[1-\exp\left(\frac{-qV}{kT}\right)\right] \quad (1)$$

where

$$I_S = AA^{**}T^2 \exp\left(\frac{-q\phi_{bO}}{kT}\right) \quad (2)$$

where, I_S is the saturation current, q is the electron charge, V is the applied voltage, T is the absolute temperature, n is ideality factor, k is Boltzmann's constant , A is the diode area, A^{**} is the effective Richardson constant (26.4 A cm^{-2} K^{-2} for n-GaN) [20] and Φ_{b0} is the Schottky barrier height (SBH). The value of Φ_{b0} can be deduced directly from the I-V curves, if the Richardson constant A^{**} is known. The I-V measurement were made to determine the saturation current I_S from which the barrier height was defined in terms of the thermionic emission theory

$$\phi_{b0} = \frac{kT}{q}\ln\left(\frac{AA^{**}T^2}{I_S}\right) \quad (3)$$

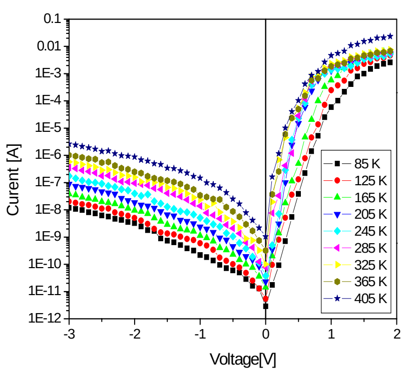

Fig. 1. Typical forward and reverse current-voltage (I-V) characteristics of Au Schottky contact on n-type GaN in the temperature range of 85-405 K.

Equation (1) shows that the logarithmic plot of *I/ [1-exp (-qV/kT)]* against V as shown in Fig. 2 is a linear and I_S was obtained from the y-axis intercept at zero voltage. Using these I_S value the barrier height is determined from the equation (3). The calculated barrier height is 0.25 eV at 85K and 1.06 eV at 405K respectively. It is observed that the leakage current at -1V is 2.18 $\times 10^{-10}$ A at 85K and 1.47 $\times 10^{-7}$ A at 405K respectively. Many models have been proposed to explain the excess leakage current in Schottky diodes on GaN or AlGaN/GaN, including the thin surface barrier model [21] and the field-emission/trap-assisted tunneling model [22]. However the detailed analysis of the I-V curves is beyond the scope of this paper.

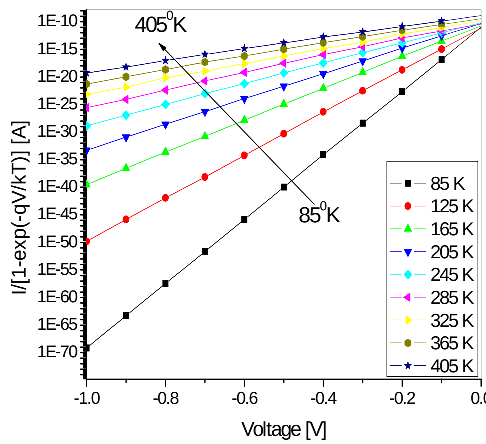

Fig. 2. ln I/[1-exp(-qV/kT)] versus V plot for Au Schottky contact on n-GaN in the temperature range 85- 405K.

The capacitance-voltage characteristics of Au Schottky contact on n-GaN were measured at temperatures ranging from 85 to 405 K. Little variation with either temperature or frequency was observed. Fig. 3 shows only one C-V curve which is measured at room temperature to check the quality of the Schottky diode. The barrier height was obtained by the following capacitance and voltage relation [20]

$$\frac{1}{C^2} = \left(\frac{2}{\varepsilon_s qNA^2}\right)\left(V_{bi} - \frac{kT}{q} - V\right) \quad (4)$$

where ε_s is the permittivity of the semiconductor (ε_s = 9.5 ε_0) and V is the applied voltage. From the plot of $1/C^2$ versus V gives the x-intercept V_0 related to the built in potential by the relation $V_{bi} = V_0 + kT/q$, where T is the absolute temperature. The barrier height is given by the equation $\Phi_b = V_0 + V_n + kT/q$, where $V_n = (kT/q) \ln(N_c/N_d)$. The density of states in the conduction band edge is given by $N_c=2(2\pi m^*kT/h^2)^{3/2}$, where $m^*=0.22m_0$ and its value is 2.6×10^{18} cm^{-3} for GaN [23]. The calculated barrier height and carrier concentration of Au Schottky contact are 1.02eV and 6.2 $\times10^{16}$ cm^{-3}.

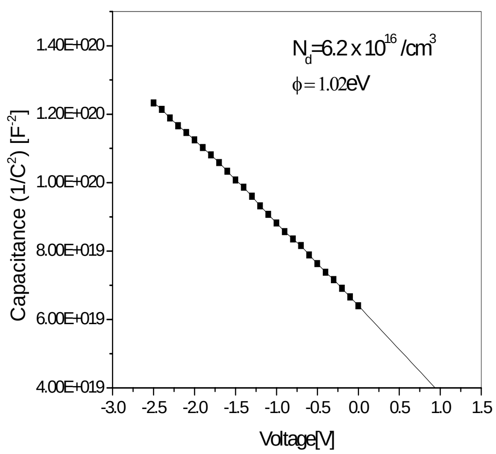

Fig. 3. The capacitance - voltage (C-V) characteristics of Au Schottky contact on n-GaN at room temperature.

To investigate whether there are electrically active as-induced defects generated in the band-gap, we performed deep level transient spectroscopy (DLTS) measurements. Any deep level can be experienced as either capture or emission of carrier, with transition probabilities per unit time depending on the free carrier concentrations, capture cross section of the trap, ionization energy and temperature. According to the value of applied voltage for the electron trap studied here in the space charge zone of Schottky diode on n-type GaN in the dark, either emission or capture of electrons toward or from the bottom E_C of the conduction band is relevant. When the Fermi level just coincides with the trap level E_T, the capture coefficient equals the emission rate e_n resulting at equilibrium which is given by [24]

$$e_n = \sigma_n v_{th} N_C \exp\left(\frac{E_T - E_C}{kT}\right) = \frac{1}{\tau_e} \qquad (5)$$

here σ_n is the capture cross-section, v_{th} is the thermal velocity of an electron defined as $v_{th}= (3kT/m_{eff})^{1/2}$, N_C is the effective density states at the bottom of the conduction band, k is the Boltzmann's constant and T is the absolute temperature, τ_e is the emission time constant, which is the reciprocal of the emission time e_n. In order to characterize the deep level defects, DLTS measurement were performed over the temperature range 85-405K using automated DLTS system. Typically, a quiescent reverse bias of V_r = -1V was employed with filling –pulse voltage V_p = 0V and filling pulse width t_p = 0.1ms. Fig. 4 shows DLTS spectrum measured with lock-in frequency of 120 Hz. Only one prominent deep level in the as-grown GaN that peaked at 361 K is observed and labeled as 'E_a' is shown in figure 4. The basic DLTS analysis relies on spectrum which is obtained from the plot of the possible correlation of the emission transient (formerly box-car or lock-in) as either a function of the temperature [25] or the rate window [26], the other parameters being constant. From several such spectra, the product $e^{-1}_n v_{th}N_C$ can be calculated and plotted as a function of 1000/T, leading usually to a straight line an Arrhenius plot. Fig. 5 shows an Arrhenius plot for one deep level (at 361K). It can be seen from figure 5 that the Arrhenius analysis the activation energy for the trap E_a was determined to be 0.92eV. We interpret the Ea as corresponding to the defect level with activation energy of 0.95eV which is similar to that reported by Goodman *et al* [27] and 0.879eV reported by Lee *et al* [28]. Fang et al [29] reported that the electron trap might be a N_I related defect created by the reaction N_N $V_N + N_I$ [30] having the activation energy of 0.85eV. Auret *et al* [31] also reported the electron trap with activation energy of 0.92 eV with capture cross section of 7.9 $\times 10^{-14}$ cm^2 which is similar to the estimated activation energy (0.92 eV) of our samples.

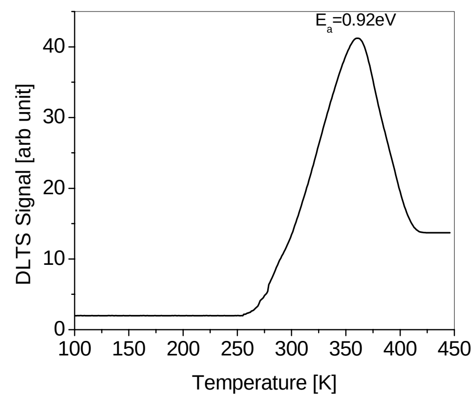

Fig. 4. DLTS spectrum of an Au Schottky contact on n-GaN grown by MOCVD. (V_r = -0.5V, V_p=0V, t_p=100 µs, f = 120Hz).

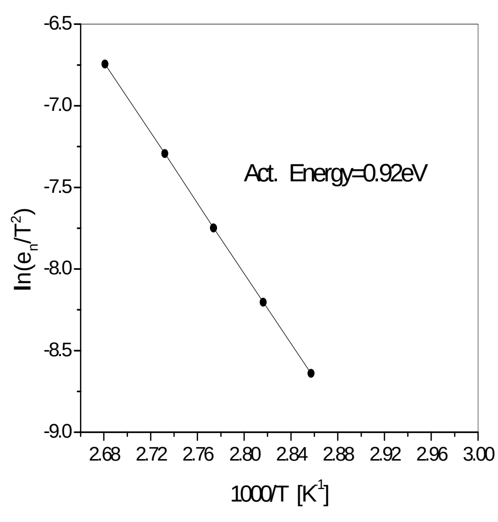

Fig. 5. The Arrhenius plot of ln(e_n/T^2) versus 1000/T of Au Schottky contact on n-GaN.

The carrier capture cross section of semiconductor deep level defect contains useful information on the nature of the defect. This parameter directly determined by measuring the capture time constant τ_c of the deep level [32]

$$\tau_c = \frac{1}{\sigma_n v_{th} n} \tag{6}$$

where σ_n is the cross section, v_{th} is the thermal velocity of electron and n is the free carrier concentration at the measurement temperature. τ_c is often measured by monitoring the deep level transient spectroscopy (DLTS) peak height as a function of filling pulse width t_p [33] (as shown in the figure 6), the slope of the plot $ln(1-N(t_p)/N_T)$ versus t_p as shown in figure 7 giving τ_c^{-1} where $N(t_p)/N_T$ is the peak amplitude. The above plot is usually found to be non linear due to different capture rate of the free carrier tail extending into the depletion region. The initial part of the plot, which is fairly linear, gives a reliable estimate of the τ_c [34]. The capture cross section of E_a as determined from the figure 7 is 1.9×10^{-15} cm^2. We interpreted the estimated capture cross section of our samples which were grown by MOCVD which is found to similar to the capture cross section ($\sigma_a = 4.3 \times 10^{-15}$ cm^2) reported by Goodman *et al* [15] and reported by Py *et al* [18] ($\sigma_a = 1 \times 10^{-16}$ cm^2).

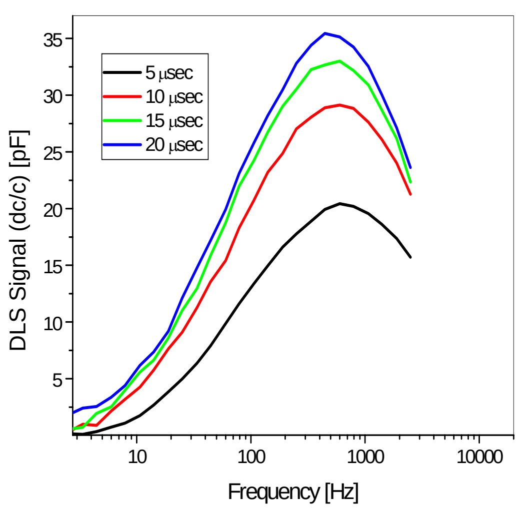

Fig. 6. Capture cross section measurement of DLTS spectra with different filling pulse width (5μs, 10μs, 15μs, 20μs,) graph of Au /n-GaN Schottky barrier diode.

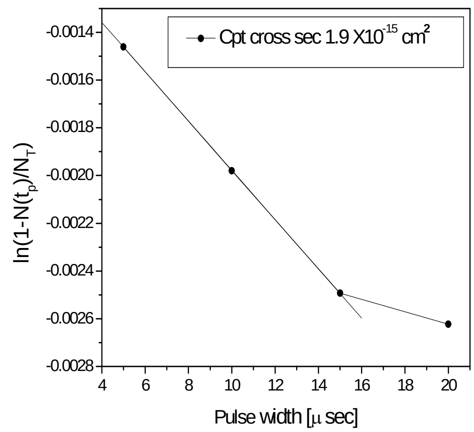

Fig. 7. The capture cross section plot of ln $(1-N(t_p)/N_T)$ versus Pulse width of Au/n-GaN Schottky diode.

The exact origin of the deep level remains an open question. Our observed level Ea is interpreted as corresponding to the 0.95 eV level measured by Goodman *et al* [27], and the 0.879eV level measured by Lee *et al* [28] and the 0.92 eV level measured by Auret *et al* [31]. They have suggested that the Ea level may be associated with a native defect in GaN and it has been assigned to nitrogen interstitial. In comparing DLTS measurements it would not be unexpected for electronic levels in GaN to grow by a variety of techniques. Conversely, the presence and concentration of defect levels associated with impurities might be expected to vary in metals grown by different techniques.

4. Conclusions

We have investigated the electrical properties of Au/n-GaN Schottky diode in the temperature range of 85 K - 405 K. Little variation with either temperature or frequency was observed, and the carrier concentration derived from these measurements confirmed the dopant concentration of ~ 6.2×10^{16} cm^{-3}. Measurements showed that the barrier height of Au/n-GaN Schottky diode is 0.25 eV at 85 K and 1.06 eV at 405 K by I-V method, and 1.02 eV at room temperature by C-V method. Based on temperature-dependent I–V characteristics, it was observed that the barrier height is increased with increase in temperature. Deep level transient spectroscopy was used to characterize electronic defects in n-type GaN. A dominating trap E_a with activation energy of 0.92eV, which is commonly observed in thin GaN layer grown by various techniques, has been found in n-type GaN grown by metalorganic chemical vapor deposition. The capture cross section 1.9×10^{-15} cm^2 was extracted based on the logarithmic dependence of DLTS signal with filling pulse width for the trap E_a. The trap E_a is believed to be associated with nitrogen interstitial native defect. Level E_a

is interpreted as corresponding to electronic state previously observed in GaN grown by HVPE and MOCVD.

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