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Capacitance–frequency (C-V–f) and conductance–frequency (G-V–f) characteristics of Au/n-GaN freestanding Schottky structure

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Abstract

In this paper, we have studied Au/n-GaN freestanding Schottky structures. The growth technique of GaN used is the HVPE (Hybrid Vapor Phase Epitaxy) method. The frequency dependent capacitance–voltage (C–V–f) and conductance–voltage (G–V–f) characteristics of Au/n-GaN freestanding/Ag Schottky diodes has been investigated in the frequency range of 100 Hz–1MHz at room temperature. The higher values of C and G at low frequencies were attributed to the native oxide layer thickness and surface states. From the C–f and G–f characteristics, the energy distribution of surface states (N_{ss}) and their relaxation time (s) have been determined in the energy range of (E_c-0.648) eV– (E_c-1.35) eV taking into account the forward bias I–V data. The values of N_{ss} and τ_{ss} change from 6.18×10^{13} eV^{1} cm^{-2} to 9.37×10^{12} eV^{1} cm^{-2} and 6.3×10^{4} s to 3.6×10^{7} s, respectively.

Keywords: C-G-f characteristics, Gallium nitride freestanding, Schottky structure, interface state density, time constant

1. Introduction

GaN material systems are finding applications, not only in blue emitting lasers and LEDs [1, 2], but also in an electronic device at high-power/high-frequency/high temperature, UV photodetectors and various gas sensors [1]. As a wide gap material, GaN exhibits a high breakdown voltage, a high thermal conductivity and a large saturation electron drift velocity, which are well suited for power device, microwave device and optoelectronic device applications [1]. Many of these devices use Schottky barriers [3].

The capacitance–frequency (C–f) and conductance–frequency (G–f) measurements provide the significant information about the density or energy distribution of the interface state at the interface metal/semiconductor. The effects of interface states on the capacitance–voltage characteristic of metal/semiconductor contact have been studied by several authors [4, 5].

In the present work, the capacitance–frequency (C–f), conductance–frequency (G–f) characteristics of the Au/n-GaN freestanding Schottky diodes have been investigated at room temperature and at various biases in dark.

The purpose of this paper is to characterize the density distribution and relaxation time of the interface states by capacitance–conductance–frequency (C–G–f) characteristics of Au/n-GaN freestanding Schottky structure.

2. Experiment

As we mentioned in our previous work [6] the freestanding GaN is provided by Lumilog Company. The GaN samples used in this work were grown by HVPE (Hybrid Vapor Phase Epitaxy) method. The substrate (n type) is unintentionally doped and has a thickness of 200 µm. The contact Schottky used is the gold (Au), was carried out by sputtering with area contact equals to 1.96×10^{-3} cm^2. The ohmic contact is formed on the rear face using the silver (Ag). Schematic diagram of GaN freestanding Schottky diode is shown in Figure1.

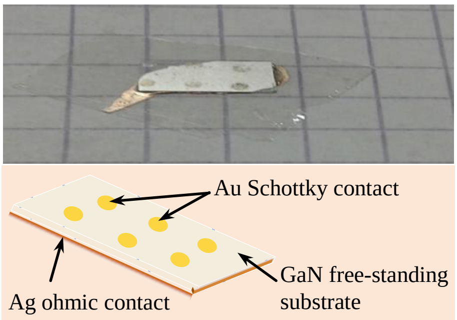

Figure 1. Schematic diagram of GaN freestanding Schottky diode.

To characterize our samples electrically, we used the measurements of current with a measuring instrument "HP 4155 B, Semiconductor Parameter Analyzer" and the measurements of capacitance with measuring instrument " HP4275A, Keithley Test System" at multi frequency.

3. Results and discussion

3.1. I-V characteristics of Schottky diode

The current-voltage (I-V) curve of Au/n-GaN Schottky diode is plotted at room temperature and is shown in Figure 2.

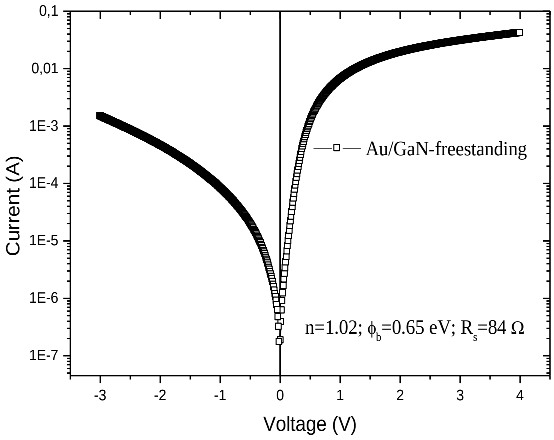

Figure 2. Current-voltage characteristic of the Au/n-GaN diode at room temperature [6].

We analyze the experimental I-V characteristic by the forward bias thermionic emission theory which is given as follows [7]:

$$I_{TE} = I_{TE0} exp\left(\frac{q(V-R_sI)}{nkT}\right) \quad (1)$$

where I_{TE0} is the saturation current, R_s is the series resistance of structure, n is the ideality factor, T is the temperature, k is the Boltzmann constant and q is the electron charge.

The saturation current I_{TE0} is expressed by:

$$I_{TE0} = SA^*T^2 exp\left(-\frac{q\phi_b}{kT}\right) \quad (2)$$

where A^* is the effective Richardson constant ($A^* = 120(m_n^*/m_0)$ =26.4 A cm^{-2} K^{-2} for n-GaN based on effective mass of 0.22 m_0 for [8], m_0 is free electron mass, ϕ_b is the barrier height and S is the contact area.

The ideality factor is deduced from the following relation:

$$n = \frac{q}{kT}\frac{d(V)}{d(lnI)} \quad (3)$$

The barrier height ϕ_b is given by:

$$\phi_b = \frac{kT}{q} ln\left(\frac{SA^*T^2}{I_{TE0}}\right) \quad (4)$$

The saturation current (I_s), ideality factor (n), barrier height and series resistance (R_s) determined from the I-V characteristic are respectively: 1.98×10^{-7} A, 1.02, 0.65 eV and 84 Ω for Au/n-GaN diode [6].

3.2. Capacitance-frequency (C-f) and conductance-frequency (G/ω-f) characteristics

According to Nicollian and Goetzberger [9, 10] and Werner et al. [11] the surface state capacitance (C_{ss}) and conductance (G_{ss}) for a MS and MIS structures can be described as:

$$C_{ss} = \frac{AqN_{ss}}{\omega\tau_{ss}} arctan(\omega\tau_{ss}) \quad (5)$$

$$C_{ss} = \frac{AqN_{ss}}{2\tau_{ss}} Ln(1+\omega^2\tau_{ss}^2) \quad (6)$$

where τ_{ss} is time constant of the N_{ss} and it can be written as:

$$\tau_{ss} = \frac{1}{V_{th}\sigma N_d} exp\left(\frac{qV_d}{kT}\right) \quad (7)$$

where σ is the cross-section of interface states, V_{th} is the thermal velocity of carrier N_d is the doping concentration and V_d is the diffusion potential defined by:

$$V_d = \phi_b - \frac{kT}{q} ln\left(\frac{N_C}{N_d}\right) \quad (8)$$

with Nc the effective density of electrons.

At low frequencies, the experimental capacitance obtained from the C-f measurements approximately equals to the sum of space-charge capacitance C_{sc} and the interface capacitance C_{ss} [12, 9].

Accordingly, the capacitance of the devices depends on frequency and it can be described as [9, 10]:

$$C = C_{sc} + C_{ss} \quad \text{(at low frequency)} \tag{9}$$

$$C \approx C_{sc} \quad \text{(at high frequency)} \tag{10}$$

The interface state density for small values of $\omega\tau_{ss}$ is equals to [10, 9]:

$$N_{ss} = \frac{C_{ss}}{qA} \tag{11}$$

The interface-state capacitance C_{ss} is obtained from the vertical axis intercept of C_{ss}–f plots.

For n-type semiconductors, the energy of the interface states E_{ss} with respect to the bottom of the conduction band at the surface of the semiconductor is given by [10, 13]:

$$E_c - E_{ss} = q(\phi_b - V) \tag{12}$$

Figures 3 and 4 show the experimental forward bias capacitance and conductance (C-V and G-V) characteristics at different frequencies and at room temperature, respectively.

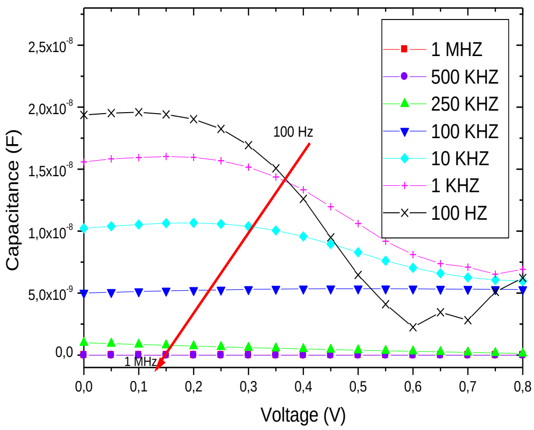

Figure 3. Frequency dependence of the measured capacitance-voltage (C-V) characteristics of the Au/n-GaN Schottky diode from 100 Hz to 1 MHz.

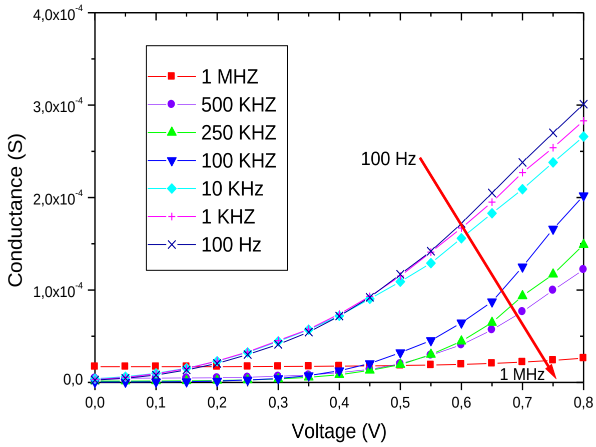

Figure 4. Frequency dependence of the measured conductance-voltage (G-V) characteristics of the Au/n-GaN Schottky diode from 100 Hz to 1 MHz.

Figure 3 shows the measured capacitance with applied bias voltage for the frequency range of 1 MHz to 100 Hz. As can be seen from Fig. 3, the capacitance value at the forward bias decreases with the bias voltage from about 0.00 V to 0.8 V at all frequencies. A very small variation in capacitance (capacitance decreases with increasing frequency) has been observed in deep depletion of the characterized diode. The observed trend in characteristics occurs because at low and intermediate frequency the interface traps and time constant or relaxation time of these interface traps follow the a.c. signal and resulted in to excess capacitance, which further depends on the frequency. However, at high frequency, interface traps level does not follow a.c. signal [14-24]. Therefore the contribution probability of interface trap level in to the total capacitance is almost negligible or very less. In this case, Schottky barrier diode characteristics are influenced by space charge capacitance only.

As seen from Figure 4, the conductance increased with the bias voltage from about 0.00 V to 0.8 V at all frequencies. Furthermore, the conductance value increases with decreasing frequency at a given bias voltage.

Figures 5 and 6 show the measured capacitance and conductance values, respectively, as a function of frequency, in the voltage range of 0.0–0.7 V with steps of 0.1 V. It can be seen from Figures 5 and 6, both the values of capacitance and conductance are higher at the low frequencies with respect to the high frequencies. These behaviors can be attributed that at low frequencies, the charges at surface states can easily follow an a.c. signal and the number of them decreases with increasing frequencies. The higher values of C and G at low frequencies were attributed to the insulator layer and surface states.

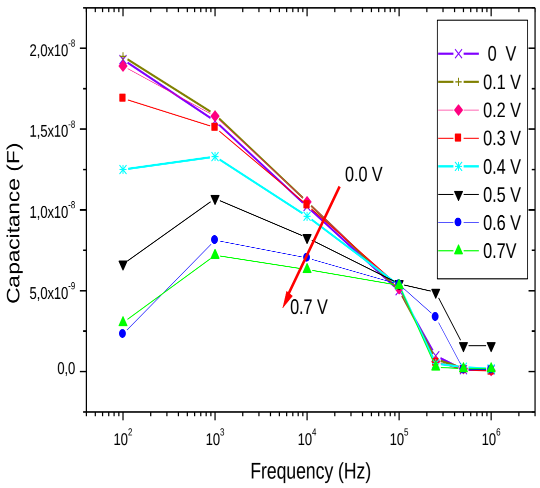

Figure 5. Capacitance-frequency characteristics with bias as a parameter for the Au/n-GaN Schottky diode.

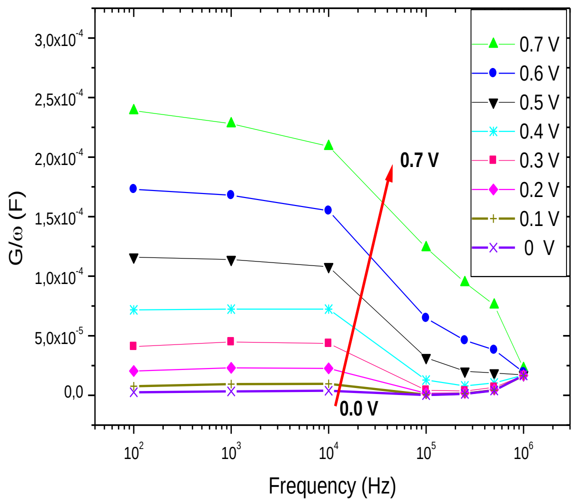

Figure 6. Measured G_{ss}/ω-f with bias voltage as parameters for the Au/n-GaN Schottky diode.

From the C-f and G-f characteristics, the energy distribution of surface states N_{ss} (eV^{-1} cm^{-2}) (Figure 7) and their relaxation time τ_{ss} (s) (Figure 8) have been determined in the energy range of (E_c-0.648) eV–(E_c-1.35) eV taking into account the forward bias I-V data. The values of N_{ss} and τ_{ss} change from 6.18×10^{13} eV^{-1} cm^{-2} to 9.37×10^{12} eV^{-1} cm^{-2} and 6.3×10^{-4} s to 3.6×10^{-7} s, respectively. The value of N_{ss} and τ_{ss} decreases with interface energy from top of conduction band toward mid-gap of GaN. That is, the slow state density distribution decreases exponentially with bias from the metal Fermi level to the mid gap of the GaN. As mentioned in ref. [25], the interface states do not show any peak, this indicates that we deal with an interface state continuum.

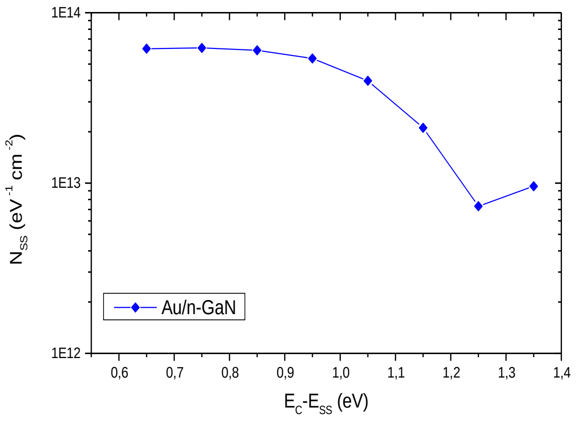

Figure 7. Interface state density versus (Ec-Ess) curves for the Au/n-GaN Schottky diode at room temperature.

The relaxation time of the states shows an exponential decrease with bias from the metal Fermi level to the mid gap of the GaN.

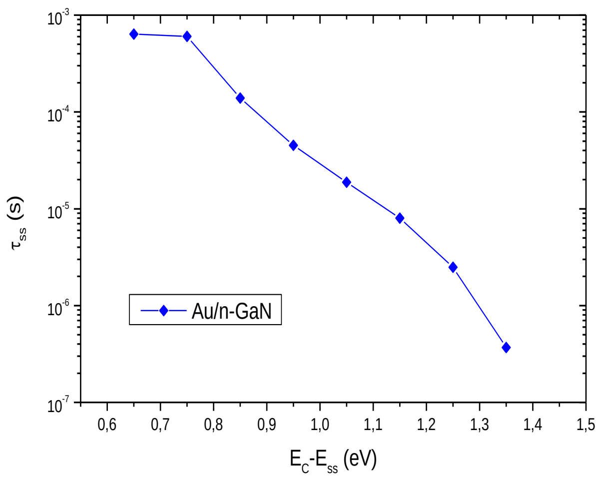

Figure 8. Relaxation time versus (Ec-Ess) curves for the Au/n-GaN Schottky diode at room temperature.

4. Conclusion

In this study the current-voltage (I-V), capacitance-frequency (C-f) and conductance-frequency (G-f) characteristics of the prepared Au/n-GaN freestanding Schottky barrier diode have been investigated with different bias voltages at room temperature. The values of ideality factor and barrier height have been calculated from the forward bias I-V characteristics as 1.02 and 0.65 eV, respectively, at room temperature. The higher values of C and G/ω at low frequencies were attributed to the localized surface states at metal-semiconductor interface. The energy distribution of surface states (N_{ss}) and their relaxation time τ_{ss} (s) have been determined in the energy range of (E_c- 0.648)-(E_c-1.35) eV taking into accounts the forward bias I-V data. The value of N_{ss} and τ_{ss} decreases with interface energy from top of conduction band toward mid-gap of GaN. These changes in N_{ss} and τ_{ss} range from 6.18×10^{13} eV^{-1} cm^{-2} to 9.37×10^{12} eV^{-1} cm^{-2} and 6.3×10^{-4} s to 3.6×10^{-7} s, respectively.

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