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Effect of rapid thermal annealing on deep level defects in the Si-doped GaN

V. Rajagopal Reddy *, M. Sivapratap Reddy, P. Koteswara Rao

Department of Physics, Sri Venkateswara University, Tirupati 517 502, India

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ABSTRACT

Rapid thermal annealing effects on deep level defects in the n-type GaN layer grown by metalorganic chemical vapor deposition (MOCVD) have been characterized using deep level transient spectroscopy (DLTS) technique. The samples were first characterized by current–voltage (*I*–*V*) and capacitance–voltage (*C*–*V*) measurements. The measurements showed that the barrier height of the as-grown sample to be 0.74 eV (*I*–*V*) and 0.95 eV (*C*–*V*) respectively. However, the Schottky barrier height of the sample annealed at 800 °C increased to 0.84 eV (*I*–*V*) and 0.99 eV (*C*–*V*) respectively in nitrogen atmosphere for 1 min. Further, it was observed that the Schottky barrier height slightly decreased after annealing at 900 °C. DLTS results showed that the two deep levels are identified in as-grown sample (*E*1 and *E*3), which have activation energies of 0.19 ± 0.01 eV and 0.80 ± 0.01 eV with capture cross-sections 2.06×10^{-17} cm^2 and 7.68×10^{-18} cm^2, which can be related to point defects. After annealing at 700 °C, the appearance of one new peak (*E*2) at activation energy of 0.49 ± 0.02 eV with capture-cross section $\sigma_n = 5.43 \times 10^{-17}$ cm^2, suggest that *E*2 level is most probably associated with the nitrogen antisites. Thermal annealing at 800 °C caused the *E*1 and *E*3 levels to be annealed out, which suggest that they are most probably associated with the point defects. After annealing at 900 °C the same (*E*1 and *E*3) deep levels are identified, which were identified in as-grown n-GaN layer.

1. Introduction

III–V nitrides have recently been the focus of intense research activity due to their applications in the fabrication of ultraviolet and blue light emitting diodes and lasers [1]. In addition GaN is a very favorable material for high temperature and high power electronic devices applications because of its large direct band gap and high saturation velocity. The applications include blue/ultraviolet light emitting devices (LEDs) [1,2], sun blind solar detectors [3], metal-semiconductor field effect transistors (MESFETs) [4] and high electron mobility transistors (HEMTs) [5]. Nevertheless, due to the lattice mismatch between GaN epilayer and the commonly used sapphire substrate [6], they inherently suffer from the draw back of having substantially high density of dislocations. The presence of threading dislocations, intrinsic point defects and point – defect clusters can act as non-radiative carrier recombination sites or levels reducing light-emission effectiveness [7]. Besides their influence on optical performance, dislocations can act as accepter-like centers, which can capture electrons. They can lead to the formation of defect clouds along the dislocation lines [8]. This behavior reduces the carrier mobility due to scattering effect and could affect the performance of electronic devices. It is therefore obvious that the formation of these dislocations as well as the electrically active defects must be minimized using the optimized growth conditions and suitable scattering substrates. Further reduction in the density/concentration of the dislocations related to the deep levels as well as point defects can be achieved by means of post growth processing steps such as thermal annealing [9].

Many researchers have characterized and reported the defect levels in GaN, which was grown by various techniques [10–16]. Soh et al. [10] reported three electron traps at $E_C - E_T \sim 0.10$–0.11, 0.24–0.27 and 0.59–0.63 eV in undoped GaN, Si-doped GaN and crack-free undoped GaN grown on cracked Si-doped GaN/AlGaN templates while additional levels at $E_C - E_T \sim 0.18$ and 0.37–0.40 eV are also observed in the Si-doped GaN. Muret et al. [11] reported the electronic properties of deep defects in n-type GaN having the activation energies in the range 0.94–1.30 eV and apparent capture cross section from 10^{-15} to 10^{-12} cm^2 by Fourier transform deep level transient spectroscopy (FTDLTS). Py et al. [12] characterized the deep levels in undoped n-GaN, which was grown by hybride vapor phase epitaxy. They reported the four known levels with activation energies in the range 0.17–0.94 eV. Fang et al. [13] characterized the AlGaN/GaN/SiC Schottky diodes, with and without Si_3N_4 passivation by deep level transient spectroscopy (DLTS). They reported the dominant trap A_1, with activation energy 1.0 eV and the apparent capture cross section of 2×10^{-12} cm^2 in both unpassivated and passivated SBDs. Tokuda et al. [14] reported the two electron traps with activation energy of ($E_C - 0.23$ eV) and

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* Corresponding author.
E-mail address: reddy_vrg@rediffmail.com (V.R. Reddy).

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($E_C - 0.58$ eV) respectively in n-type GaN grown homoepitaxially by MOCVD on free standing GaN substrate by DLTS technique. Nakamura et al. [15] studied inductively coupled plasma (ICP) induced defects in n-type GaN using current–voltage (*I*–*V*) characteristics and deep level transient spectroscopy (DLTS) measurements. Emiroglu et al. [16] observed that a meta stable hole trap in n-type GaN by DLTS and reported that it is unstable after thermal stress. In the present work, we have investigated the thermal annealing effects on the electronic properties of deep level defects in n-type GaN as-grown by metal organic chemical vapor deposition (MOCVD) on c-plane Al_2O_3 substrate (see Tables 1 and 2).

2. Experimental details

Gallium nitride (GaN) samples used in the present work were grown on Al_2O_3 substrate by metalorganic chemical vapor deposition (MOCVD) and was followed by the growth of 2 µm n-type GaN with Si. To evaluate the thermal stability of deep levels in GaN, rapid thermal annealing (RTA) was carried out at 700, 800 and 900 °C in N_2 ambient for 1 min, and the results were compared with the as-grown sample. The n-GaN layer was first ultrasonically degreased with organic solvents such as warm trichloroethylene followed by acetone and methanol for 5 min each. This degreased layer was then dipped into boiling aquaregia [HNO_3:HCl = 1:3] for 10 min to remove the surface oxide and the sample was rinsed in deionized water. Contacts were deposited on the sample surface for electrical measurements. In the case of the ohmic contact Ti (25 nm)/Al (100 nm) was deposited on a portion of the sample by electron beam evaporation system under the vacuum of 4×10^{-6} mbar. Before the Schottky contact using Au was fabricated the sample was annealed at 650 °C for 3 min in nitrogen ambient by rapid thermal annealing system. The stainless steel mask was used to deposit circular dots with a diameter of 0.7 mm. The thickness of the Schottky contact is 50 nm. For all the samples current–voltage (*I*–*V*) with low leakage current and low series resistance were observed. Then capacitance–voltage (*C*–*V*) characteristics were measured at room temperature. Finally 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) in the temperature range 100–400 K by placing the sample inside the liquid–nitrogen cryostat to evaluate trap parameters.

3. Results and discussion

Forward and reverse current–voltage (*I*–*V*) characteristics of as-grown and annealed n-type GaN samples measured at room temperature are as shown in Fig. 1. As we can see in Fig. 1, the Schottky contacts on as-grown layers display good reproducible behavior current–voltage characteristics. The diodes exhibits a current rectification of about four orders of magnitude at ±1 V, and a low leakage current density 2.67×10^{-5} A/cm^2 under reverse bias of 1 V. However, the Schottky contacts on annealed layers at 700, 800 and 900 °C the leakage current densities are 8.43×10^{-6} A/cm^2, 2.40×10^{-7} A/cm^2 and 1.71×10^{-7} A/cm^2 respectively. The forward *I*–*V* characteristics were analyzed using standard thermionic emission relation for electron transport from a metal-semiconductor with low doping concentration and the equation is given by [17]

$$I_d = I_s \exp\left(\frac{qV_d}{nkT}\right)\left[1 - \exp\left(\frac{-qV_d}{kT}\right)\right] \tag{1}$$

where V_d is the voltage across the diode ($V_d = V - IR$), R is the series resistance, n is the ideality factor, and I_s is the saturation current and given by

$$I_s = AA^{**}T^2 \exp\left(\frac{-q\phi_b}{kT}\right) \tag{2}$$

where A^{**} is the effective Richardson constant, A is the area of the diode and ϕ_b is the Schottky barrier height. The value of ϕ_b can be deduced directly from the *I*–*V* curves by knowing the effective Richardson constant (A^{**}). The theoretical value of A^{**} is 26.4 A cm^{-2} K^{-2} based on the effective mass ($m^* = 0.22m_o$) of n-GaN [18] and is used

Table 2
The trap parameters for as-grown and annealed samples of n-GaN layer.

Trap	*E*1	*E*2	*E*3
As-grown			
$E_C - E_T$ (eV)	0.19 ± 0.01	–	0.80 ± 0.01
σ (cm^2)	2.06×10^{-17}	–	7.68×10^{-18}
N_T (cm^{-3})	1.55×10^{16}	–	4.03×10^{16}
700 °C annealed			
$E_C - E_T$ (eV)	0.19 ± 0.01	0.49 ± 0.02	0.80 ± 0.01
σ (cm^2)	2.06×10^{-17}	5.43×10^{-17}	7.68×10^{-18}
N_T (cm^{-3})	1.55×10^{16}	4.13×10^{15}	4.03×10^{16}
800 °C annealed			
$E_C - E_T$ (eV)	–	0.49 ± 0.02	–
σ (cm^2)	–	5.43×10^{-17}	–
N_T (cm^{-3})	–	4.13×10^{15}	–
900 °C annealed			
E_C–E_V	0.19 ± 0.01	–	0.80 ± 0.01
σ (cm^2)	2.06×10^{-17}	–	7.68×10^{-18}
N_T (cm^{-3})	1.55×10^{16}	–	4.03×10^{16}

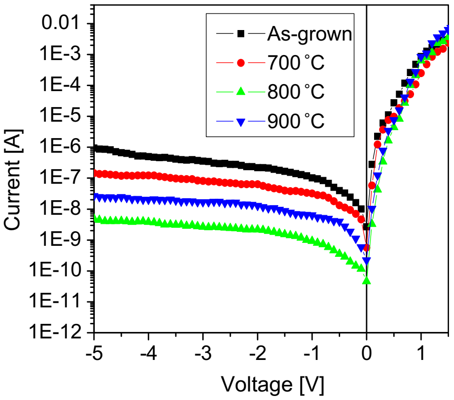

Fig. 1. The current–voltage (*I*–*V*) characteristics of Au Schottky contact on as-grown and annealed n-type GaN layer measured at room temperature.

Table 1
The Schottky barrier heights, ideality factor and series resistance as-grown and annealed samples of n-GaN layer.

Sample	Schottky barrier height (SBH) ϕ_b (eV)		Ideality factor	Series resistance
	I–*V*	*C*–*V*	‘*n*’	R_S
As-grown	0.74	0.95	1.22	97
700 °C	0.78	0.92	1.17	54
800 °C	0.84	0.99	1.10	47
900 °C	0.79	0.91	1.20	55