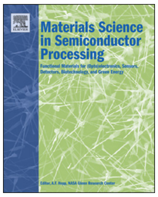
Materials Science in Semiconductor Processing 17 (2014) 94–99

Contents lists available at ScienceDirect

Materials Science in Semiconductor Processing

journal homepage: www.elsevier.com/locate/mssp



Electrical characterization and DLTS analysis of a gold/n-type gallium nitride Schottky diode

A. Elhaji [a], J.H. Evans-Freeman [b], M.M. El-Nahass [c,*], M.J. Kappers [d], C.J. Humphries [d]

[a] Materials and Engineering Research Institute, Sheffield Hallam University, UK
[b] College of Engineering, University of Canterbury, New Zealand
[c] Department of Physics, Ain Shams University, Cairo, Egypt
[d] Department of Materials Science and Metallurgy, University of Cambridge, UK

ARTICLE INFO

Available online 26 September 2013

Keywords:
Nitrides
MOVPE
GaN
Schottky diode
DLTS

ABSTRACT

This work describes a comparison of current density–voltage (J–V) and capacitance–voltage (C–V) properties measured as a function of temperature; deep trap properties are measured by deep level transient spectroscopy (DLTS) of Schottky diodes fabricated on n-type gallium nitride (GaN grown by metal organic vapor phase epitaxy (MOVPE). Unexpected behavior in the standard Richardson plot was observed in the temperature range 165–480 K, reflecting a range of Schottky barrier heights and a variation of ideality factor. This was explained by applying a Gaussian spatial distribution of barrier heights across the Schottky diode. C–V measurements were carried out in the temperature range 165–480 K to compare the temperature dependence of the barrier height with those obtained by the Gaussian distribution method. DLTS and high-resolution Laplace DLTS (LDLTS) show a majority carrier peak centered at 450 K.

1. Introduction

The gallium nitride (GaN) system and related materials have been the focus of intense research for both optoelectronic and electronic applications. They have offered several opportunities, from visible light-emitting diodes (LEDs) to laser diodes, solar-blind ultraviolet (UV) detectors to microwave power electronics and then to solid-state UV light sources and white lighting and also in high power/high temperature electronics. Due to their wide band gaps, the effects of deep level centres on the III-nitride material devices may be more pronounced than in narrower band gap semiconductors. The advantages associated with a large band gap include higher breakdown voltages, ability to sustain large electric fields, lower noise generation and high temperature operation [1–5]. In addition, nitrides are ideal for applications in displays and high density data storage [4]. An understanding of the nature of defects in GaN materials is very important not only for improving material quality but also for improving the device performance in this material system. On the other hand, Schottky contacts are essential components of both high power GaN rectifiers and high electron mobility transistors.

Zhou et al. [6] reported that the vertically depleting Schottky rectifiers exhibited a higher reverse breakdown voltage than the lateral device, which is possibly due to the more uniform field distribution a vertical device can provide. In addition, the Schottky rectifiers also exhibited ultrafast reverse recovery characteristics ($<$ 20 ns).

Recently, Donoval et al. [7] performed temperature dependent measurements of the forward I–V characteristics on the Ni/InAlN/GaN Schottky diodes at various temperatures in the range of 300–820 K. They found that the tunneling current dominates in the whole temperature range, while the thermionic emission becomes comparable to the tunneling current only at highest temperatures used. The barrier height of

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* Corresponding author. Tel.: +20 1224168621.
E-mail address: prof_nahhas@yahoo.com (M.M. El-Nahass)

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http://dx.doi.org/10.1016/j.mssp.2013.08.006

the Ni/InAlN/GaN Schottky diodes, evaluated from the thermionic emission current, shows a slightly negative temperature coefficient and its value at 300 K is 1.47 eV.

Lin [8] studied the electronic transport and Schottky barrier heights of Pt/n-type GaN Schottky diodes in the extrinsic region (100–300 K). The anomalous behavior of the barrier height and of the ideality factor was clarified as a result of tunneling transport at low temperature (owing to a marked decrease in effective density of states in the conduction band at low temperature), and discussed in terms of the thermionic field emission model. Investigations on GaN and $Al_xGa_{1-x}N$ hetero-structures have revealed that the high leakage current in reverse-bias is owing to tunneling current as a result of high-density defects and dislocations, which are the principal tunneling pathways in GaN film grown hetero-epitaxially on foreign substrates [9,10]. On the other hands, Arslan et al. concluded that the leakage current is mainly due to Frenkel–Poole emission at a temperature higher than 250 K and carrier transport via conductive dislocations is the dominant source of reverse bias leakage current in GaN hetero-structures [11].

The characterization and the understanding of the properties of metal/GaN contacts is also an important issue, because the performance of GaN-based devices can often be limited by the quality of the Schottky and Ohmic contacts which can be related to the density of deep states in the semiconducting material. Deep Level Transient Spectroscopy (DLTS) has been used by a number of investigators to characterize electronic trap states in GaN grown by hydride vapor phase epitaxy (HVPE) [12] and metal organic chemical vapor deposition (MOCVD) [13,14]. Three distinct deep levels are consistently observed for n-type GaN, with activation energies ranging between 0.18 and 0.27 eV, 0.49 and 0.598 eV, and 0.665 and 0.67 eV, respectively [12–14]. Two additional deep levels with activation energies of 0.14 eV and 1.63 ± 0.3 eV was observed in n-type GaN grown by MOCVD [12]. Wang et al. [15] reported that n-type GaN grown by reactive molecular-beam epitaxy has a total of five donor like deep levels electronic defects with activation energies $E_1 = 0.234 \pm 0.006$ eV, $E_2 = 0.578 \pm 0.006$ eV, $E_3 = 0.657 \pm 0.031$ eV, $E_4 = 0.961 \pm 0.026$ eV, and $E_5 = 0.240 \pm 0.012$ eV. But only four levels with activation energies in the range 0.17–0.94 eV were observed in n-GaN grown by Hydride Vapor Phase Epitaxy by DLTS measurements in the temperature range 100–600 K [16]. Ito et al. [17] demonstrated that GaN films grown on AlN/sapphire template using metal organic vapor phase epitaxy (MOVPE) have high crystalline quality. They also observed four deep traps with energy levels $E_1 = E_c - 0.21$ eV, $E_2 = E_c - 0.57$ eV, E_4 and $E_5 = E_c - 1.2$ eV in n-GaN films grown on both AlN templates and on conventional LT-BL/sapphire.

Recently, a metastable hole traps in n-type GaN grown by MOVPE and subjected to thermal stress above approximately 540 K was reported: this persists for up to a week and can be characterized by DLTS [18]. The DLTS is used for studying the charge carrier traps in and their concentration in the semiconductors. It has also explores defects locate in a space charge (depletion) region in the Schottky diodes or p–n junctions [19,20].

Systematic researches on the electrical behavior of Schottky contacts on GaN are essential to obtain worthy information of the electrical parameters barrier height, ideality factor, and Richardson's constant and of the current transport mechanisms. The work presented here describes a comparison of *J-V* and *C-V* measurements of n-type GaN Schottky diodes in the temperature range 165–480 K. The forward bias *J–V–T* measurements are used to clarify the current transport mechanism and inhomogeneity in the barrier and to estimate the Schottky diode parameters and relates the findings to the presences of an electrically active deep states characterized by DLTS and high resolution Laplace DLTS (LDLTS), to try and correlate the presence of deep levels in the semiconductor with junction properties.

2. Experimental procedure

The GaN layers were grown on a *c*-plane sapphire substrate by metal-organic vapor phase epitaxy (MOVPE) using a Thomas Swan closecoupled 2 × 6″ showerhead reactor equipped with a Laytec Epicurve TT in situ wafer curvature monitoring system. Trimethyl gallium (TMG), silane (50 ppm SiH_4 in H_2) and ammonia (NH_3) were used as precursors and hydrogen was used as the carrier gas.

A GaN nucleation layer was grown at 540 °C, followed by a GaN epilayer with a nominal thickness of 3.1 μm grown at 1020 °C, with the top 1.6 μm doped with Si to provide an electron density of at least 3.1×10^{17} cm^{-3} at 300 K. The film was cleaned and dry etched in Ar plasma (100 W for 3 min) before deposition of Ni/Au (20 nm/20 nm, annealed at 500 °C for 5 min) and Schottky Al/Au (20 nm/200 nm) contacts by thermal evaporation in a dot and ring pattern. The Schottky contacts had an area of 1.962×10^{-7} m^2. The Hall-effect measurements showed that the grown n-type GaN sample had a carrier concentration of $\sim 2 \times 10^{17}$ cm^{-3} and a mobility of 250 cm^2/V s. The Schottky contacts had an area of 1.962×10^{-7} m^2. *J-V* and *C-V* measurements were carried out to determine the diode parameters. The *I–V* characteristics were recorded using an automated system based on a Keithley 6487 picoammeter. DLTS and LDLTS were carried out between 100 and 500 K and at a rate window 80 s^{-1}. LDLTS outputs are plotted as spectral intensity as a function of emission rate where the peak height is directly proportional to the trap concentration [21].

3. Results and discussion

3.1. Temperature dependent current density–voltage characteristics

Fig. 1 shows the ln *J–V* characteristics for Au/n-type GaN Schottky diodes measured at temperature range of 165–480 K. The temperature-dependence *J-V* measurements of Schottky diodes provide a useful method to investigate the physical mechanisms associated with the reverse and forward-biased current in the material [22,23]. Thermionic emission (TE) theory is normally used to obtain the Schottky barrier diodes parameters but there have been reports of certain anomalies at lower temperatures deviating from the theory [24,25]. These results have been adequately elucidated by incorporating the concept of barrier inhomogeneities and introducing a Gaussian distribution function with a mean and a standard deviation for the description.