ELECTRICAL CHARACTERIZATION OF SPUTTER DEPOSITION INDUCED DEFECTS IN n-GaN

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ABSTRACT

We have used current-voltage (*I-V*) measurements to assess and compare the electrical characteristics of resistively evaporated and sputter deposited Au Schottky contacts on epitaxially grown GaN. These *I-V* measurements revealed that resistively deposited Au contacts exhibited excellent rectification properties: high barrier height, low reverse current and good ideality factor ($n = 1.04$). In contrast, sputter deposited contacts had poor characteristics: low barrier height, high reverse current and non-linear forward *I-V* characteristics. The cause of this is thought to be defects introduced at and near the surface during sputter deposition. Deep level transient spectroscopy (DLTS) showed that at least four defects, with energy levels at 0.22±0.02 eV, 0.30±0.01 eV, 0.40±0.01 eV and 0.45±0.10 eV below the conduction band, were introduced in the GaN during sputter deposition. The first of these defects has similar electronic properties as a radiation induced defect in GaN, speculated to be the nitrogen vacancy, while the second appears to be the same as a defect in the as-grown material. The latter two defects have not previously been observed in as-grown or processed epitaxial GaN.

INTRODUCTION

Gallium nitride is a direct wide band-gap semiconductor which has unique applications in blue, green and ultraviolet light emitting diodes, detectors and blue lasers [1]. Because of its low thermal generation rates and high breakdown fields, an inherent property of wide bandgap semiconductors, it also has recently also shown to be important in the field of high temperature and power electronics [2]. The fabrication of these electronic devices requires, among others, metallisation for ohmic or Schottky contacts on the GaN. The metallisation method chosen for this purpose has to fulfil several requirements, including good adhesion of the metal to GaN. Sputter deposition is a metallisation method which is frequently employed because sputter deposited layers exhibit better adhesion compared to layers deposited by other methods [3]. In addition, sputter deposition facilitates the stoichiometric deposition of compounds and controllable deposition of high melting point metals, and yields high deposition rates. However, due to the energetic particles involved, sputter deposition is damaging on an atomic scale and causes lattice disorder at and below to the semiconductor surface [4].

It has been reported that the barrier heights of sputter-deposited Schottky contacts on n-type Si [5] and n-type GaAs [6] are lower than those of similar contacts deposited by other less damaging processes (e.g. resistive evaporation), while for p-type Si [7] and p-type GaAs [8] the

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opposite was found. Using deep level transient spectroscopy (DLTS) [9], it was shown that this barrier height alteration was accompanied by the introduction of sputter deposition induced defects at and below the semiconductor surface, thought to be the cause of the barrier alteration [4]. No studies have yet been reported for GaN where the contact quality and metallization induced defects are investigated as function of the metallization process.

In this paper we report the current-voltage (*I-V*) characteristics of resistively evaporated and sputter deposited Au Schottky contacts on epitaxially grown GaN. We also report the properties of the defects, determined by DLTS, present in epitaxially grown GaN before and after sputter deposition of Au Schottky contacts thereon. We show that sputter deposition introduces at least four electron traps, two of which have not previously been observed in as-grown or in processed epitaxial GaN.

EXPERIMENTAL PROCEDURE

For this study we used epitaxial GaN with a free carrier density of $(2–3)\times10^{16}$ cm^{-3}, grown by organo-metallic vapor phase epitaxy (OMVPE). Before contact fabrication, the samples were cleaned [10] by first boiling them in aqua-regia and rinsing in de-ionised water, and then degreasing them by boiling in trichloroethylene followed by rinsing in boiling isopropanol and thereafter in de-ionised water. Finally, the samples were dipped in $HCl:H_2O$ (1:1) for 10 seconds. After this cleaning, Ti/Al/Ni/Au (150 Å/2200 Å/400 Å/500 Å) ohmic contacts [11] were fabricated on the GaN and annealed at 500 ^{o}C for 5 minutes in Ar. Prior to Schottky barrier diode (SBD) fabrication, the samples were again degreased and dipped in an $HCl:H_2O$ (1:1) solution. Following this, circular Au Schottky contacts, 0.6 mm in diameter and 1 μm thick, were sputter-deposited on the GaN through a metal contact mask, as close as possible to the ohmic contact to minimise the diode series resistance. Sputter deposition was performed in DC mode at a power of 0.141 kW in an Ar pressure of $4.8\text{x}10^{-3}$ mbar at a rate of 4.5 nm s^{-1}. For control purposes, Au SBDs were resistively deposited next to the sputter deposited SBDs.

Room temperature current-voltage (*I-V*) measurements were used to assess the quality of the Schottky contacts. The sputter deposition induced defects were characterised by DLTS using a Stanford Research lock-in amplifier (model SR830), which facilitates transient analysis at pulse frequencies of as low as 1 mHz. The energy level, E_T , in the bandgap and apparent capture cross section, s_a , of a defect, the combination of which is referred to as its DLTS "signature", were determined from Arrhenius plots of T^2/e vs $1/T$, where e is the emission rate at a temperature T.

RESULTS AND DISCUSSION

I-V Measurements

I-V measurements showed that resistively deposited Au SBDs exhibited excellent rectification properties (Fig. 1). The forward *I-V* curves of these diodes are linear for at least seven decades of current and the ideality factor calculated, assuming thermionic emission, was 1.04. The barier height of these diodes is (0.96±0.02) eV and the current at a 1 V reverse bias, I_R, is $< 10^{-11}$ A. In contrast, Fig. 1 shows that the sputter deposited contacts exhibit poor rectification characteristics: non-linear forward *I-V* characteristics and high reverse currents (□ 2×10^{-4} A). Because the forward log(*I*) vs *V* characteristics of the sputter deposited diodes were non-linear, no ideality factor was calculated. The barrier height estimated from the reverse *I-V*

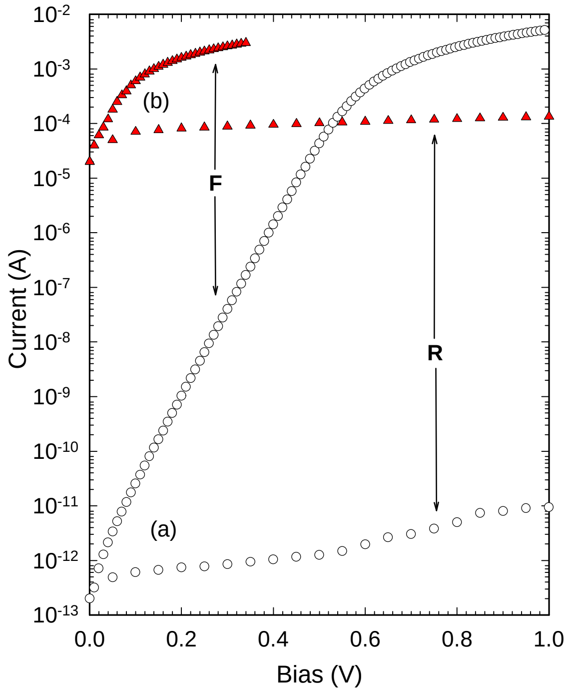

Figure 1: Room temperature forward (F) and reverse (R) *I-V* curves of Au contacts deposited on n-GaN by: (a) resistive evaporation (circles); (b) sputter deposition (triangles).

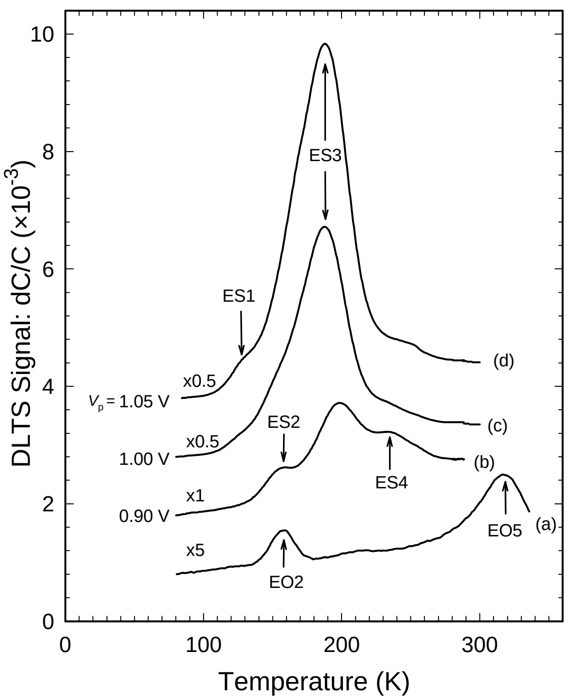

Figure 2: Curve (a): DLTS spectrum of resistively deposited SBD on epitaxial *n*-GaN. Curves (b) - (d) are for a sputter deposited SBD using a lock-in frequency of 46 Hz, a filling pulse width of 0.2 ms, a reverse bias of 1 V and filling pulse amplitudes, V_p, as indicated.

characteristics (assuming thermionic emission) of these diodes was (0.47±0.03) eV, which is significantly lower than the barrier height of resistively deposited contacts. These *I-V* measurements confirm that, as for Si [5] and GaAs [6], sputter deposition of Schottky contacts on n–GaN yields diodes with a drastically reduced barrier height and inferior rectification characteristics. It should be pointed out, however, that sputter-deposited Au contacts adhered much better to the GaN than resistively evaporated Au contacts.

DLTS Measurements

Fig. 2 depicts the DLTS spectra of control (resistively deposited) and sputter-deposited diodes. Curve (a) shows that the control sample contained two defects, labelled EO2 and EO5, with energy levels at 0.27±0.01 eV and 0.61±0.02 eV below the conduction band, respectively. In this defect labelling nomenclature, "E" implies electron trap and "O" that the material was grown by OMVPE. From the literature it appears that EO2 and EO5 are the same as the E1 and E2, respectively, observed by Hacke *et al* in n-GaN grown by hydride vapor-phase epitaxy [12]. These two defects also have similar sigantures as E_2 and E_1, respectively, detected by Götz *et al* in MOCVD grown GaN [13]. Curves (b) - (d) in Fig. 2 show that after sputter deposition, defects labelled ES1, ES2/EO2, ES3 and ES4 are detected. These curves also show that the peak heights of the sputter induced defects increase strongly with increasing filling pulse height, indicating an increase of the concentration of the sputter induced defects towards the Au/GaN interface. This trend was also previously observed for defects introduced by sputter deposition of Schottky contacts on Si [5] and GaAs [6]. Note that EO5 is absent in the spectra of sputter deposited SBDs. The reason for this is that the energy level of EO5 is 0.61 eV below the conduction band whereas the barrier height of the sputter deposited SBDs is only 0.47 eV. Therefore, during the quiescent DLTS bias the EO5 level remains below the Fermi level [14] and, consequently, it does not emit carriers.

For determining the defect signatures, the overlapping peaks in Fig. 2 had to be separated. To achieve this, we followed two strategies. Firstly, we recorded spectra at fixed values of the quiescent bias, V_r, and filling pulse amplitude, V_p, but at different filling pulse durations, t_p, in the range 20 ns < t_p < 100 µs. Secondly, we kept V_r and t_p constant and recorded spectra while increasing V_p in steps of 0.05 V up to the flatband condition. Some of these spectra are depicted in Fig. 3. The ES2/EO2 peak was found to be well defined for 50 ns < t_p < 5 µs (curve (b)), whereas the ES4 peak is best defined for 500 ns < t_p < 5 µs (curve (c)). The ES3 peak only appears for t_p □ 10 µs (curve (d)). Spectra recorded at different $V_{p,}$ while V_r and t_p were kept constant, revealed the presence of another defect, ES1, for V_p □ 1.25 V (curve (f) in Fig. 3).

The separation between the ES1 and ES2/EO2 peak positions was more clearly observed at low pulse frequencies and therefore the signature of ES1 was determined using frequencies of below 10 Hz. The defect signatures of ES2/EO2, ES3 and ES4, were determined using pulse widths where their peak shapes were optimised as described above and frequencies of 1 - 220 Hz. From Fig. 3, where we compare the signatures of the sputter induced defects to those of radiation-induced defects and defects in as-grown OMVPE GaN, it seems that two of the defects observed after sputter deposition may be the same as other defects previously reported in GaN.

Firstly, the signature of ES1, with a level at E_C - 0.22±0.02 eV, is similar to that of the ER3 defect with a level at E_C - 0.20±0.01 eV, which was observed after 5.4 MeV He-ion irradiation and 2 MeV proton irradiation of the same epitaxial GaN [15]. ER3, in turn, is thought to be the same as a defect, labelled *E*, with a level at E_C - 0.18 eV, observed by Fang *et al* [16] after electron irradiation of MBE-grown GaN. These authors pointed out that, should the capture cross section of this defect be temperature activated, then its actual position in the bandgap may be close to that of V_N (E_C - 0.07) [16], but no firm identification has yet been made. Secondly, ES2, with a level at E_C - 0.30±0.01 eV, has almost the same DLTS "signature" as EO2, with a level at E_C - 0.27±0.01 eV, which is

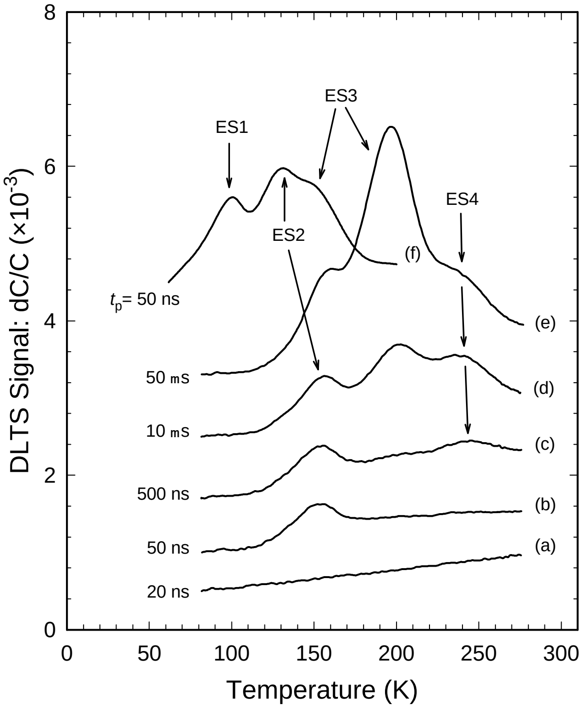

Figure 3. DLTS spectra of a sputter deposited Au Schottky contact on epitaxial GaN recorded using V_r = 1 V and different pulse widths, as indicated in the figure. Spectra (a) - (e) and (f) were recorded at V_p = 1.1 and 1.2 V, respectively, and lock-in amplifier frequencies of 46 Hz and 1 Hz, respectively.

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present in as-grown GaN. If these defects are the same, then it implies that sputter deposition resulted in an increase of the EO2 (ES2) concentration towards the GaN surface.

The ES3 and ES4 defects, with levels at E_C - 0.40±0.01 eV and E_C - 0.45±0.10 eV, have not been observed before in irradiated or in as-grown epitaxial n-GaN. Their signatures also do not correspond to those of defects introduced by nitrogen implantation of GaN, where it was suggested that one of the defects thus introduced may be a N interstitial [17]. These observations suggest that ES3 and ES4 are not related to the simple radiation induced point defects detected up to now. This can be explained by the fact that sputter deposition introduced several defects, other than the point defects introduced by high-energy irradiation. The formation of such complex type defects is the result of energetic particles, like Ar ions, entering the GaN during sputter deposition and losing energy at a high enough rate to create defects in close proximity of each other which can combine or interact.

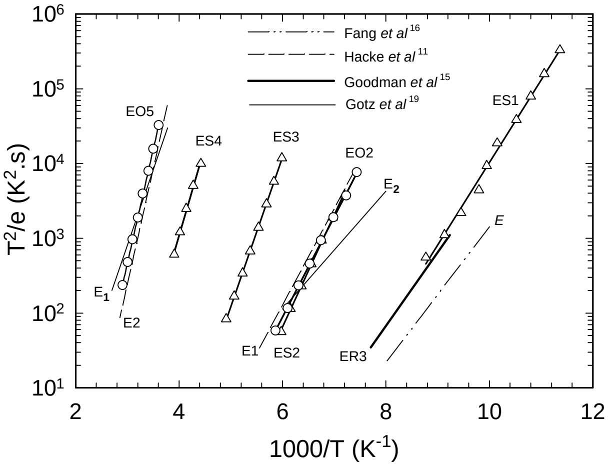

Figure 4: DLTS Arrhenius plots of defects in as-grown and particle-processed epitaxial GaN. Open circles and triangles are for defects present before and after sputter deposition, respectively, detected in the present study.

The peak shape and electronic properties of ES4 were found to be strongly dependent on the pulse height. Increasing the pulse height resulted in a broadening of the peak and a shift to lower temperatures. The same behaviour could not be induced when maintaining a fixed pulse level, and increasing the reverse bias, ruling out the possibility of this behaviour being due to electric field assisted emission. This behaviour of ES4 is similar to that of defects introduced during low energy Ar ion bombardment of GaAs where it was shown that those defects are located close to the surface and have a band-like energy distribution [18].

CONCLUSIONS

We have shown that sputter deposition of Au Schottky contacts on n-GaN results in SBDs with poor rectification properties and introduces electron traps, labelled ES1 - ES4. ES1, is located at E_C - 0.22±0.02 eV and has a similar DLTS signature as the *E* and ER3 defects, introduced in epitaxial GaN by high energy electron and He-ion irradiation, respectively. ES2 seems to be the same as the EO2 defect in as-grown GaN. The concentrations of ES1 - ES4 increase strongly towards the interface, indicating that this is the region where most of the sputter-induced damage resides. The ES3 and ES4, with energy levels at E_C - 0.40±0.01 eV and E_C - 0.45±0.10 eV, respectively, have not previously been observed in as-grown or particle bombarded GaN. Finally, it should be stressed that the sputter-deposited Au contacts adhered considerably better to GaN than resistively evaporated Au contacts.

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