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Ohmic Contact Resistance dependence on Temperature for GaN Devices

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Abstract. The temperature dependence of Ohmic contacts to GaN devices is investigated in this paper by measuring TLM contact resistances as a function of temperature. In particular, two types of Ohmic contacts are considered: (1) Contacts to highly doped implanted regions (such as MOSFET drain/source contacts or the back contact of Schottky diodes) and (2) contacts to 2 dimensional electron gas (2DEG) of an AlGaN/GaN heterojunction.

Introduction

It is not possible to realise a solid-state electrical rectifier or switch in SiC or GaN without at least one metal-semiconductor (M-S) Ohmic contact. The performance and understanding of the M-S contact is of great importance as it influences the overall performance of a semiconductor device. The transmission line method (TLM) is a well established technique first suggested by Shockley [1] to determine both the semiconductor sheet resistance (R_{sh}), the contact resistance (ρ_c) and the specific contact resistivity (R_c) of metal Ohmic contacts to semiconductors.

Experimental Details

N+ Contact. The starting material is a p-type GaN epilayer grown on a c-plane sapphire substrate, supplied by TDI Inc. The p-epilayer is 6 μm thick, Mg doped (Na = 1.9×10^{17} cm^{-3}). A high resistivity Zn compensated buffer layer was also grown between the sapphire substrate and the p-layer. A Si^+ implantation at 160 keV and with a dose of 3.0×10^{15} cm^{-2} was performed, resulting in a ~ 0.2 μm deep region. Various annealing was performed both with and without protection in an N_2 ambient to activate the implanted Si. The annealing temperatures were in the range of 1000-1200 °C. The annealing processes consisted of a two-step method; initially in a low temperature ambient for a number of minutes followed by a higher temperature ambient for a shorter time, within the tens of seconds range. Next, Ti and Al with 35 nm and 115 nm thicknesses were sequentially deposited by sputtering and patterned by a lift-off process, to form the TLM patterns.

HEMT Contact. AlGaN/GaN TLM structures were fabricated on a previously optimized stack to obtain a crack-free GaN layer up to 2–3 μm on commercial Si(111). This stack was comprised of 250 nm of GaN and 250 nm of AlN. Next, a 1.7 μm GaN layer was grown at 800 °C, followed by the active layers. The active layer of the HEMT consists of a 1 nm AlN spacer to reduce alloy scattering and to enhance the electron mobility and a 21 nm undoped AlGaN barrier with a 0.28 Al mole fraction. Finally, the structure was covered with an additional 5 nm of a GaN capping layer. The device isolation was achieved by means of a 150 nm deep mesa etch realised by Cl_2/Ar reactive ion etching. Source/Drain Ohmic contacts were formed by a Ti/Al/Ni/Au metallisation that was annealed for 30 s at 750 °C by rapid thermal annealing. HEMT devices include the additional step of the gate formation where the gate contact was made with a Ni/Au bi-layer.

Experimental Results

The basic idea of the TLM is to plot the resistance of metallic contacts with a constant width separated by varying lengths of semiconductor material. The slope of the resulting line is a function of the bulk film resistivity, while the intercept is the contact resistance, i.e., $R_T = R_{sh}Z^{-1}d + 2R_c \simeq R_{sh}Z^{-1}(d + 2L_T)$. The total resistance is measured for various contact spacings and plotted versus d as illustrated in Fig. 1. The slope leads to the sheet resistance. The intercept is $2R_c$ giving the contact resistance. In the simplest bilayer model for a homogeneous Ohmic contact to a semiconductor, the sheet resistance of the semiconductor below and between the TLM contacts is considered to be the same. This leads to the specific contact resistivity determination with R_{sh} known from the slope of the plot. Experimental TLM plots are presented for the N^+ and the HEMT contact Fig. 1.

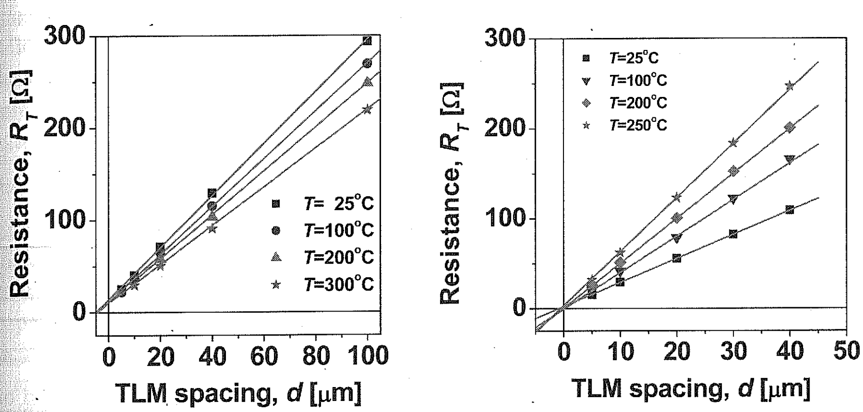

Fig.1. (left) TLM-T plot for a N^+ contact and, Z=300μm (right) TLM plot for a HEMT based contact, Z=150 μm.

Fig. 2 presents the sheet and the contact resistance extracted for a typical TLM structure measured in the temperature range of 25 - 300 °C. For the N^+ contact, it is clearly observed that both, R_{sh} and R_c decrease with T. Conversely, R_{sh} increases with T in contacts made to AlGaN/GaN. A more physical insight of the reason below this temperature dependence is given in the next section. It was observed also that R_c has a weaker dependence on the temperature, also displaying a slight increase of the contact resistance if the metal stack remains intact. The relevant change in the contact resistance value could not be spotted from the intercept point variation in Fig. 1. In addition, the slope (sheet resistance) is not affected by the metal degradation. In the case of HEMT we were confident that the sheet resistance remains unaffected just up to 250 °C (this is the reason of the different legend temperature range values in Fig. 1).

At room temperature, the contact resistance obtained for the N^+ contact is much higher (2 Ωmm) when compared with the value for the HEMT based contact (0.3 Ωmm). This is due to the different current transport mechanism being much more efficient for an optimised HEMT based contact. It is believed that this is caused by a direct link between the metal stack and the electrons in the 2DEG channel. The N^+ sheet resistance is quite large which could be due to a poor activation of dopants below the contact. The sheet resistance of 400 Ω/sq is consistent with a 2DEG sheet concentration of 10^{12} cm^2 and mobility of 1400 cm^2/Vs.

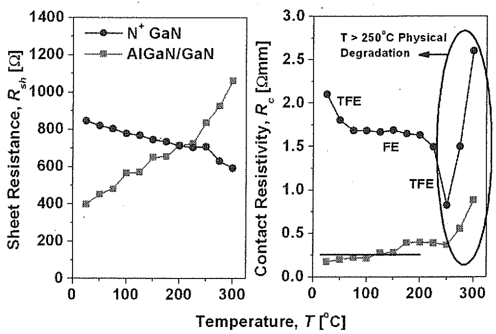

Fig. 2. Experimental R_{sh} and R_c *vs* T in the temperature range 25-300 °C for an ohmic contact to an implanted N^+ GaN and to AlGaN/GaN. An Ohmic M-S contact follows a TFE or FE mechanism depending on the semiconductor effective doping.

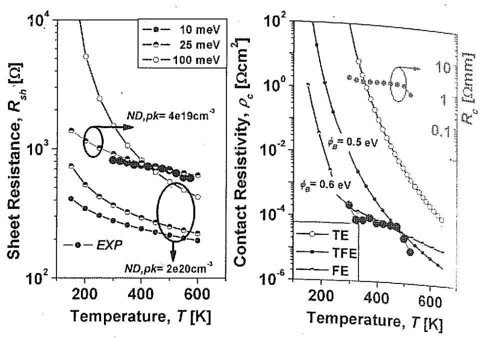

Fig. 3. Experimental and simulation characteristics vs the temperature of the Si implanted N^+ GaN region [2] (a) sheet resistance and, (b) metal-semiconductor contact resistance to the Si implanted N^+ GaN well. E_d=10, 25 and 100 eV are the simulated donor levels with a peak value concentration of $N_{D,pk}$=2e20 cm^{-3}. ϕ_B is the barrier height.

Discussion

N+ Contact. The implanted GaN layer sheet resistance is determined with:

$$R_{sh}^{-1}(T) = q\int_z^t \left[n(z,T) \times \mu_n\left(n(z),T\right) \right] dz \qquad (2)$$

Numerical computation of the integral for each temperature [2] leads to the determination of the theoretical sheet resistance vs T of the implanted GaN layer between TLM strips shown in Fig. 3 (a). The experimental value sheet resistance is significantly higher than the theoretical value (Fig. 3(a)) if it is considered the donor level energy commonly reported in literature (E_d = 10-25meV). The decrease of the sheet resistance with the temperature is given by the fact that more free electrons are available when the temperature increases, diminishing the effect of the freeze-out of carriers at room temperature. Metal-Semiconductor transport mechanisms, specifically thermionic emission (TE) and thermionic field emission (TFE) are strongly affected by the lattice temperature because thermionic emission over the potential barrier into the metal has an exponential dependence on the thermal energy, which varies as a function of $1/kT$. In contrast, if complete ionization of carriers is considered, the tunnelling mechanism based on field emission (FE) or tunnelling is virtually independent of temperature [2]. If partial activation of impurities is considered then FE is also dependant upon temperature as is shown in Fig. 3(b). Tunnelling is improved with temperature as more dopants become active thus further reducing the barrier thickness. We suggest that the experimental temperature dependence of the contact resistance could be explained by a combination of FE and TFE depending on the temperature range. Both FE and TFE may coexist with the mechanism displaying the lowest resistance becoming dominant at a given temperature. (is that right? being dominant the one with the lower resistance for a given temperature.)

HEMT Contact. It could be considered that sheet resistance between the TLM contacts is equivalent to the sheet resistance of the 2DEG channel [3]. Therefore, $R_{sh} \approx \left(q\mu_{2DEG} n_s\right)^{-1}$ where μ_{2DEG} is the channel mobility and n_s is the 2DEG sheet charge concentration. The temperature dependence is then given by the mobility properties in the 2DEG. In the AlGaN/GaN heterojunction the lattice vibrations due to polar-optical phonons on the non-intentionally doped GaN layer are the mobility limitation factor at elevated temperatures. This polar-optical phonon mobility depends on temperature (mainly because phonons follow the Bose-Einstein distribution function of occupancy) and 2DEG sheet charge density [3]. Regarding the first type of implanted Ohmic contacts, the theory of their interface to a bulk semiconductor is very similar to that of the Schottky interface. This is because all Ohmic contacts inevitably form initially as Schottky barriers. Methods are deployed in order to manipulate the band structure so that the tunnelling transport mechanism can dominate. For example, it is believed that Ti reacts with GaN and forms TiN at elevated temperatures, extracting N from GaN and generating N-vacancies in the GaN layer. N-vacancies act in turn as an effective n-type dopant, which enables the tunnelling contact mechanism [4]. The lowering of the Schottky-barrier to SiC or GaN via intermediate metallic nitrides or silicides has also been widely reported [5], [6]. TiN, for example, is believed to have a lower work function than Ti, and therefore, a lower contact resistance can be achieved [4]. Analogously, TEM and XRD analysis links the formation of silicides at the metal–SiC interface with the ohmicity of the contact. The silicides formed were Ti_3SiC_2 for Al/Ti contacts and $NiSi_x$ for Al/Ni contacts [7]. In contrast, a direct electron path mechanism has been suggested as the main Ohmic contact mechanism in the AlGaN/GaN heterojunction [4]. Reportedly, metal-nitride (such as TiN) clusters penetrating through the thin AlGaN barrier layer (which could also be recessed to improve the contact resistivity) are the direct link between the 2DEG and the metal stack which is the source/drain of the HEMT transistor. This would explain the more metallic-like dependence and the reduced R_c of just 0.3 Ωmm.

Summary

The temperature analysis of R_{sh} and R_c will advance our understanding of the physical mechanisms taking place at the M-S interface. In the case of implanted contacts a reduction of both R_{sh} and R_c (2/0.7 Ωmm – 25°C/250 °C) with T was observed which is explained in terms of a partial activation of dopants. Here, tunnelling increases with temperature as more dopants become active thus further reducing the barrier thickness. Conversely, R_{sh} increases with T in contacts made to AlGaN/GaN. The temperature dependence is explained here by the mobility properties in the 2DEG. In the AlGaN/GaN heterojunction, lattice vibrations due to polar-optical phonons in the non-intentionally doped GaN layer strongly increase with temperature and hence limit the mobility at elevated temperatures. It was observed that R_c has a weaker (0.2/0.4 Ωmm – 25°C/250 °C) dependence on the temperature with a slight increase of the contact resistance if the metal stack remains intact.

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