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Low Resistance Non-Transparent ohmic Pt-contacts on p-GaN

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ABSTRACT

The metal – p-GaN junction for low resistance ohmic contacts is still a challenge to be applied in GaN-based opto electronics as well as in power and high frequency devices. Currently, we try to improve the performance of our blue laser diodes. In order to decrease heat generation during device operation it is necessary to ensure as small contact resistances as possible.
In this work, we achieved a specific contact resistance value of $R_C = 1.8 \pm 1.7 \cdot 10^{-5}\ \Omega cm^2$ for Pt-contacts on MOVPE-grown p-GaN. The Pt-layers were deposited by e-beam and thermally assisted vacuum evaporation after a standard cleaning process. For evaluation of R_c we used optimised circular TLM test patterns defined by photolithography. Best contacts were formed by annealing in Nitrogen athmosphere at 500°C.
We also investigated the dependence of the contact resistance on the Mg doping concentration. Therefore p-GaN layers with different Mg-concentrations were grown on SiC-substrates and Pt-contacts were processed. For those samples, we investigated the Mg-concentrations, verified by secondary ion mass spectroscopy (SIMS), the hole concentrations and mobilities in dependence of C(Mg), which we obtained from HALL-measurements, and the contact and sheet resistances, measured by circular TLM measurements.
The experiments showed that the optimum Mg-concentration for low contact resistances is ***higher*** than $2 \cdot 10^{19}$ cm^{-3} which was found to provide a maximum hole concentration near $7 \cdot 10^{17}$ cm^{-3}.
The influence of self-compensation in p-GaN in bulk and near interfaces will be discussed.

INTRODUCTION

The semiconductor material system Ga(In,Al)N can be used in many applications including opto electronic, power and high frequency devices. Because of its large band gap it is possible to realise light emitting devices in the ultra violet, blue and green colour range with potential to red. At OSRAM – Opto semiconductors in Regensburg, Germany, blue LEDs are produced in large scale since 1998. Meanwhile the product spectrum has extended by white LEDs using converter technology. For all devices, the n- and p-doped Ga(In,Al)N-layers are grown by MOVPE (**M**etal **O**rganic **V**apour **P**hase **E**pitaxy) on 2‘‘-SiC-substrates. We are also working on the performance improvement of blue laser diodes for applications like data storage, printing, projection displays and illumination. The current status of our laser diode lifetimes in continuous wave operation is several minutes which is mainly limited by the high operation temperature due to the threshold current density of about 7,5 kA/cm^2. To lower the heat generation, low series, interface and contact resistances inside the device are necessary. In this work we concentrate on the metal-p-GaN contact which is still one of the major heat sources in our laser diodes. After giving a short survey of the theoretical background, the C-TLM (circular transmission line method) measurement technique will be described including the sample preparation. Concerning the experimental results we present our actual value of $R_C = 1.8 \pm 1.7 \cdot 10^{-5}\ \Omega cm^2$ and the dependence of the contact resistance on the chemical Mg-concentration. All of the presented R_C–

investigations are done with Pt–metallisation, for which we got the lowest R_C-values compared to Pd- and Ni-metallisation in previous experiments. Various p-GaN contact resistance best values were published, for example $4.3 \cdot 10^{-4}\ \Omega cm^2$ for Pd/Au [1], $2.0 \cdot 10^{-5}\ \Omega cm^2$ for Pt [2] and $2.2 \cdot 10^{-6}\ \Omega cm^2$ for Pt/Ru [3], but untill now, the physical origin of the different results depending on the contact material are still not known exactly. In a conclusion we try to give an an explanation approach for our Pt-contact resistance results and an alternative defect model will be discussed.

THEORETICAL DESCRIPTION OF METAL-SEMICONDUCTOR-CONTACTS

The barrier height Φ_B, which is the offset between the contact material Fermi level and valence band of the Mg-doped p-GaN, is either defined by the difference of GaN electron affinity χ (4.1 eV [4]) plus band gap $E_{G(GaN)}$ (3.4 eV) and the metal work function Φ_M (5.65 eV for Pt [5]), according to *Schottky-Mott* model, or it is mainly defined by the occupation of interface states, which is called Fermi-level-pinning according to *Bardeen* model. In the latter case the barrier height is rather independent of the work function of the contact metal. For operation of the devices, holes have to be injected from the metal into the p-GaN-layer and therefore have to overcome this barrier. The current transport mechanisms for hole injection into the p-GaN-layer are thermionic emission of holes over the barrier, field emission which is quantum mechanical tunneling of holes through the barrier, generation of electron-hole-pairs within the depletion region and hopping of the holes from the metal to the p-GaN-valence band via defect states. A detailed discussion of the metal semiconductor contact is given in [6]. For the main two current transport mechanisms, the theoretical descriptions are given by the following formulas [7].

thermionic emission:
$$R_c = \frac{h^3}{q^2 \cdot 4\pi m^* k \cdot T} \cdot \exp\left(\frac{q\Phi_B}{kT}\right) \qquad (1)$$

field emission:
$$R_c = C \cdot \exp\left[\frac{4\pi\sqrt{\varepsilon m^*}}{h}\left(\frac{\Phi_B}{\sqrt{N_A}}\right)\right] \qquad (2)$$

R_C is the contact resistance, h the Planck constant, q the electronic charge, m* the effective hole mass, k the Boltzmann constant, T the absolute temperature, ε the dielectric constant of p-GaN, Φ_B is the barrier height and N_A the net acceptor concentration. The pre-exponetial factor C has a weak temperature dependence [8].

In a previous work [9], we investigated Pt, Pd and Ni – contacts on MOVPE-grown p-GaN test structures by temperature dependent contact resistance measurements. The results showed a weak temperature dependence which was independent of the contact material. For this reasons we believe that for our contacts the dominating current transport mechanism is the quantum mechanical tunneling of the holes through the barrier.

To get low contact resistances it is therefore important, to warrant an as high net acceptor concentration as possible near the metal-p-GaN-interface leading to a low barrier width.

MEASUREMENT TECHNIQUE

In this work, we determine our contact resistances by the circular TLM measurement technique (transmission line method). Therefore, test structures consisting of semiinsulating GaN and a 1 µm thick Mg-doped p-GaN layer were grown on SiC substrates by MOVPE. For contact metallisation, Platinum was deposited by vacuum evaporation, because of its high metal work function of 5.65 eV [5]. The circular TLM patterns were then defined by photolithography leading to a geometry of circular contact pads with a radius of 100 µm and spacings of 2, 4, 8, 16, 32 and 64 µm to a large area contact. Two probe measurements were performed to the different contact spacings and the experimental values were fitted by the analytical formula [7]

$$R = \frac{R_S}{2\pi} \cdot \left[\ln\left(\frac{r_o}{r_i}\right) + \sqrt{\frac{R_C}{R_S}} \cdot \left(\frac{1}{r_o} + \frac{1}{r_i}\right) \right] \qquad (3)$$

yielding to the sheet resistance R_S of the p-GaN layer in Ω/square and the contact resistance R_C of the metal-p-GaN contact in Ωcm^2. The different spacings of the c-TLM patterns are defined by the outer and inner radii r_o and r_i.

EXPERIMENTAL RESULTS

Effect of annealing on Pt-contact

In Fig. 1 the experimental values for the two probe resistance measurements versus the spacings of one sample - as-processed and annealed – and the corresponding fit curves are plotted.

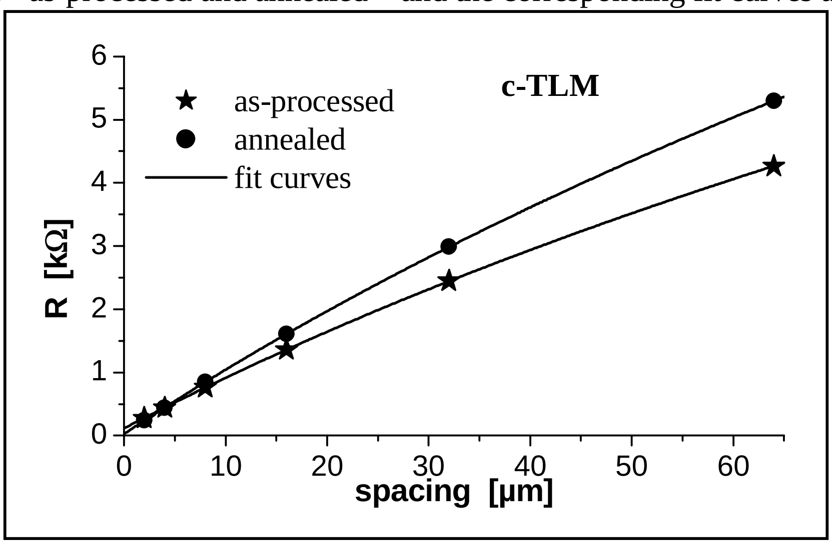

Figure 1. Experimental values and theoretical fits for Pt-contact resistance determination of an as-processed and annealed sample

The p-GaN sheet resistance increased from 52.2 ± 1 kΩ to 65.5 ± 2 kΩ by an contact annealing treatment of 13 minutes at 500°C in Nitrogen atmosphere. The corresponding Pt-p-GaN-contact resistance decreased from $2.4 \pm 0.7 \cdot 10^{-4}\ \Omega cm^2$ down to $1.8 \pm 1.7 \cdot 10^{-5}\ \Omega cm^2$, which is our actual contact resistance best value. Annealing temperatures of 300°C and 400°C didn`t result in a significant decrease of R_C. For higher annealing temperatures like 600°C, we observed resistance values which could not be fitted adequately by the theoretic formula (3) to evaluate the absolute contact resistance value. Further investigations are necessary to understand this sample behaviour.

Dependence of R_C on Mg-doping concentration

For the investigation of the contact resistance dependence on the Mg-doping concentration three special epitaxial runs were performed yielding the test structures with semiinsulating GaN and about 1 µm thick Mg-doped p-GaN-layers. For these runs it was our target to realise a gradient of Mg-incorporation over the 2‘‘- wafer by appropriate gas flux and temperature distribution during the growth.

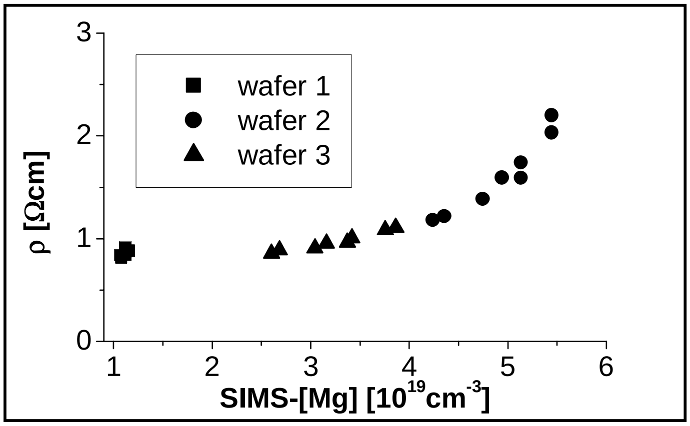

Figure 2. Specific p-GaN resistance versus Mg-concentration

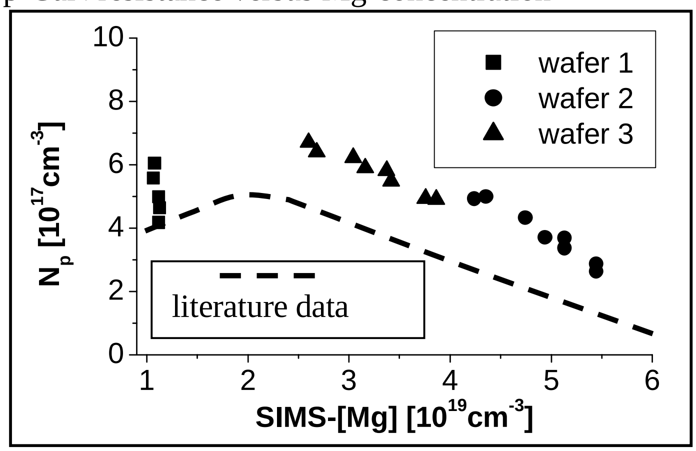

Figure 3. Hole concentration versus Mg-concentration

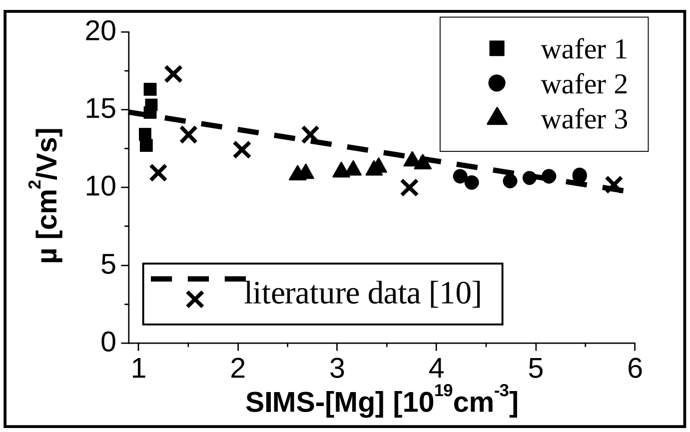

Figure 4. hole mobility versus Mg-concentration

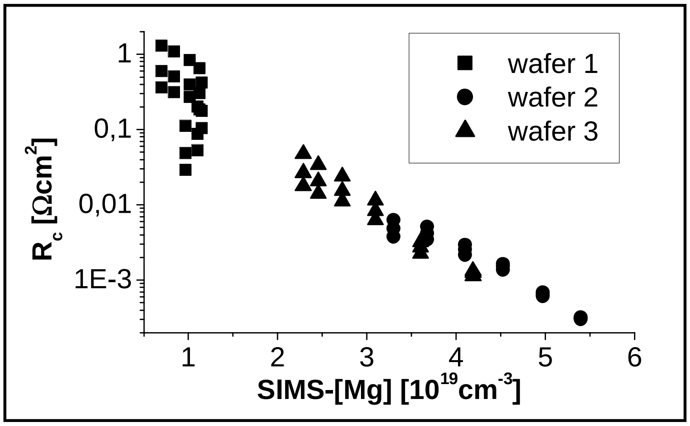

Figure 5. Pt-contact resistance versus Mg-concentration

SIMS-measurements were undertaken to determine the chemical Mg-concentration in the test structures and the exact thickness of the p-GaN layer at several points of the wafer. The specific resistance of the p-GaN, its free hole concentration and the corresponding mobility was obtained by HALL-measurements of sawed 5 x 5 mm^2 samples with Pt-contacts evaporated through a shadow mask. For the Pt contact resistance measurements, the Pt metallisation was structured by photolithography to define the circular TLM patterns. For all samples the exact measurement positions on the wafer were determined, which allowed to correlate the electrical characteristics with the chemical Mg doping concentration.
Figures 2, 3 and 4 show the specific p-GaN resistance ρ, the hole concentration N_P at room temperature and the hole mobility μ obtained by HALL-measurements versus the SIMS-Mg-concentration. The different symbols represent values from three wafers, each of a different epitaxial run. In fig. 2, the specific p-GaN resistance ρ increases with increasing Mg doping, which is mainly dominated by the decrease of mobile holes shown in fig. 3. The hole mobility (fig. 4) is rather independent of the doping within the investigated concentration range (the hole concentration and the mobility values of the wafer 1 are afflicted with high errors because of non-ohmic behaviour of the HALL-contacts). The experimental results concerning the Pt contact resistance, obtained by the c-TLM measurements are plotted in figure 5 and show an exponential decrease with increasing Mg concentration. The three values for each Mg-concentration represent the integral contact resistances determined by the different measurement currents of 0.5, 1 and 1.5 mA with the highest value for the lowest current density. The bigger the difference of these three values the higher the non-linearity of the contacts with respect to the current voltage characteristic.

DISCUSSION

The increase of the specific resistance (see fig. 2) of the p-GaN-layer due to the decrease of hole concentration with increasing Mg-doping concentration shown in figures 3 and 4 can be explained by the well-known self-compensation effect in MOVPE-grown Mg-doped p-GaN layers [10]. In such GaN-layers, the concentration range around $2 \cdot 10^{19}$ cm^{-3} is a limit for Mg-incorporation as shallow acceptors. Further Mg-atoms form deep donors which are believed to be Mg – Nitrogen vacancy complexes. Those deep donors compensate the Mg-acceptors resulting in the decrease of free holes and therefore the increase of the specific resistance. The exponential

decrease of the contact resistance can`t be easily explained by a narrowing of the barrier width, because the self-compensation should also affect the negative space charge density and therefore normally, one would expect an increase of the contact resistance. An alternative model is the formation of deep defects in the lower half of the band gap, which can act as donors and as acceptors. In the p-GaN bulk layer, those defects compensate the Mg-acceptors in the same way as conduction band near donors but in the contact region, the defects are occupied by electrons because they lie below the Fermi level and therefore increase the negative space charge density resulting in the lowering of the barrier width which increases tunneling probability and therefore decreases the contact resistance.
Also the results concerning our actual best value of $1.8 \pm 1.7 \cdot 10^{-5}$ Ωcm^2 show the increase of the sheet resistance in combination with an decrease of the contact resistance received by an annealing treatment of 13 minutes at 500°C in Nitrogen atmosphere (fig. 1). This behaviour can be explained as follows: During sample preparation, named deep defects are formed on the p-GaN surface between the contact areas by the plasma structuring of the Pt-metallisation. Due to the temperature treatment, those defects diffuse in the p-GaN bulk and under the contact pads, resulting in the observed sheet resistance increase in combination with the decrease of contact resistance. The existence of such kind of deep defects which is also addressed by another group [11] has to be verified in future.

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