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Title	Metal contacts to p-type GaN by electroless deposition
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Publication date	2007-09-01
Original Citation	Lewis, L., Casey, D., Rohan, J. F. and Maaskant, P. P. (2007) 'Metal contacts to p-type GaN by electroless deposition', Proceedings of SPIE, 6797, Manufacturing LEDs for Lighting and Displays; Berlin, Germany, 10-11 September, 67970J, doi: 10.1117/12.758947
Type of publication	Conference item
Link to publisher's version	10.1117/12.758947
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Download date	2026-11-15 11:45:51
Item downloaded from	https://hdl.handle.net/10468/7690



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Metal contacts to *p*-type GaN by electroless deposition

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ABSTRACT

Initial results are presented on the electroless deposition of metal contacts to *p*-type gallium nitride (GaN). Deposition procedures were developed for the deposition of both nickel and tungsten-cobalt (W-Co) contacts onto *p*-type GaN. Attempts to deposit platinum on *p*-type GaN failed, despite the fact that electroless platinum deposition was successfully achieved on other substrate types. Nickel contacts were overlaid with gold and annealed in oxygen ambient to form ohmic contacts with specific contact resistivity values down to $2x10^{-2}$ Ωcm^2. Measurements at elevated temperatures up to 140^0C showed that the specific contact resistivity was almost independent of temperature. The tungsten-cobalt contacts showed rectifying behaviour even after annealing at 650^0C. This makes this contact type a possible candidate for Schottky contacts in high temperature applications.

Keywords: *p*-type GaN, ohmic contact, electroless deposition

1. INTRODUCTION

Gallium nitride material is widely used for light emitting diode (LED) devices, laser diodes (LDs) as well as Schottky diode rectifiers and hetero-junction transistors. All these devices require high quality metal contacts: both ohmic contacts and Schottky contacts. Ohmic contacts need to have a low specific contact resistivity value (ρ_c), especially when the contacts are to operate at high current densities, as the voltage that is dropped across the contact will be the product of the current density and the specific contact resistivity. Devices that operate with a current density of 1 $kA.cm^{-2}$ across the ohmic contact will need to have contacts with $\rho_c<1x10^{-3}$ $\Omega.cm^{-2}$ if the voltage drop across the contact is to stay below 1V. For Schottky diode contacts the long-term stability of the contacts is an issue, especially in high-power, high-temperature applications. The standard deposition methods for metals on semiconductor wafers are (electron beam) evaporation and sputtering. These methods have the advantages of good process reproducibility and good thickness uniformity. However, there is still room for improvement in the contact quality, especially when it comes to the specific contact resistivity of ohmic contacts to *p*-type GaN, and the long-term stability of Schottky contacts when these are to operate at elevated temperatures ($T>300^0C$).

Electroplating is a technique that has some unique features that could result in superior contact quality: it allows for the co-deposition of metals (e.g. Ni-P, Ni-B, W-Co, W-Ni), in-situ cleaning of the semiconductor surface (by reversal of the electrodes), and it is capable of producing good metal-to-metal adhesion even when the metals are not all part of the same processing step. It is also a technique that can be used for selective deposition, thus reducing waste of precious metals. The method is generally cheap and it is already widely used to deposit thick layers of silver or gold for bond pad metallisations.

Electroless deposition methods have the added advantage that they do not require any electrical contacts. Metal seed layers deposited by electroless deposition can be used to facilitate subsequent electroplating processes, as illustrated in Figure 1: the electroplated metal can be patterned by allowing the metal to plate only within windows opened up in a photo resist layer. This provides metal features with well-controlled sidewall profiles. The seed layer is removed from the un-plated areas at the end of the process.

An examination of the literature reveals that various attempts have been made to electroplate metal contacts onto GaN. Hasegawa et al.[1] looked at electroplated Schottky contact metals on *n*-type GaN. They also examined pulsed anodic etching of GaN and pulsed electro-deposition[2] of Pt, Ni, Co, Ag, and Sn. They found that a 15min dip in NH_4OH at 50^0C was beneficial as a surface pre-treatment. Cocojari et al.[3] studied platinum Schottky contacts on *n*-type GaN for application in frequency multipliers. De Lucca et al.[4] studied the electro-deposition of platinum as a means of forming

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ohmic contacts on *p*-type GaN. Ying Che Sung et al.[5] from Arima in Taiwan have patented a contact scheme involving electroplated beryllium-gold onto *p*-type GaN. Upon annealing, the beryllium acts as a *p*-type dopant.

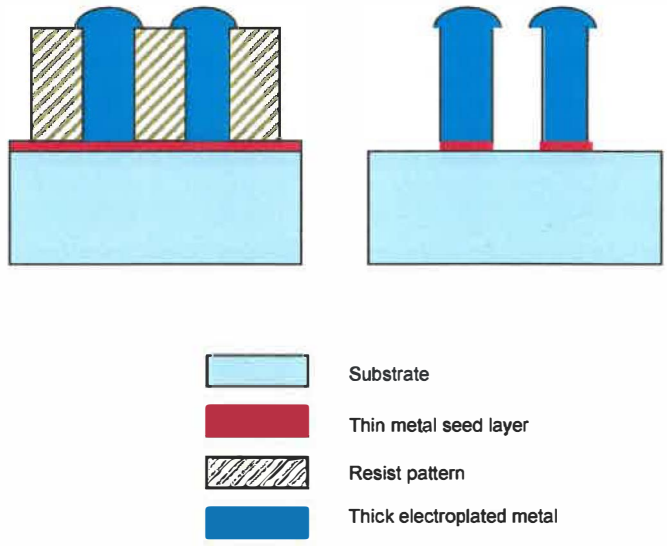


Figure 1: A schematic of a selective electroplating process, using an electroless deposited metal seed layer

2. EXPERIMENTAL RESULTS

A. Electroless platinum and electroless palladium deposition trials

Figure 2 shows the result of an electroless platinum deposition onto a copper-coated substrate. The surface finish and adhesion of this deposit were good. However, no deposition could be obtained onto either *p*- or *n*-type GaN.

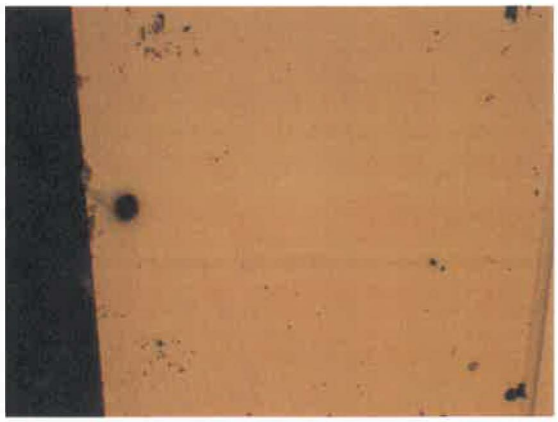


Figure 2: An example of the platinum deposition achieved on a copper coated substrate.

A number of experiments were also carried out with different palladium bath compositions, but these baths were not sufficiently stable and as yet no deposition has been achieved.

B. **Electroless W-Co**

Tungsten has been tested as an ohmic contact metal to *n*-type 3C-SiC[6]. No interaction between the contact metal and the SiC was observed there. Figure 3 shows a micro-graph of our electroless W-Co deposit. The deposit was quite uniform and had a cobalt content of about 28%. The contacts were rectifying on both *p*- and *n*-type GaN. The contacts were still rectifying after annealing at 550^{0}C for the *p*-type contacts and after annealing at 650^{0}C for the *n*-type contacts, so that this W-Co contact looks suitable for use as a stable Schottky contact to either *p*- or *n*-type GaN.

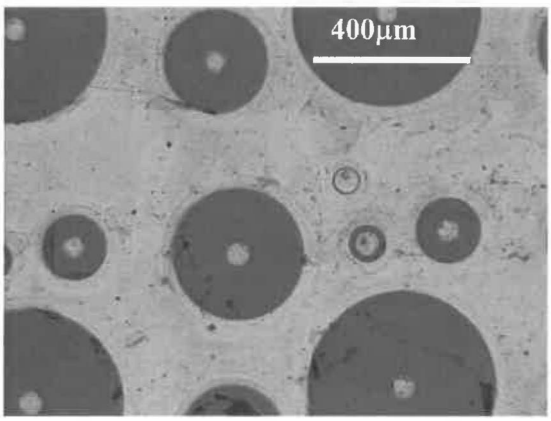


Figure 3: A set of electroless deposited tungsten-cobalt contacts on gallium nitride; light colour is metal (some resist residue is still present)

C. **Electroless Ni-Au**

The Ni-Au ohmic contact scheme to *p*-type GaN is well established. Both metals can be deposited from electroless baths. The nickel deposit (see Fig. 4) is of high quality with excellent adhesion. Deposition times of between 10 and 25 seconds yield nickel thicknesses of between 70nm and 180nm. The deposition rate can be controlled by adjustment of pH and temperature. To achieve uniform deposition, the sensitisation and cathodisation processes were optimised as well as the bath composition.

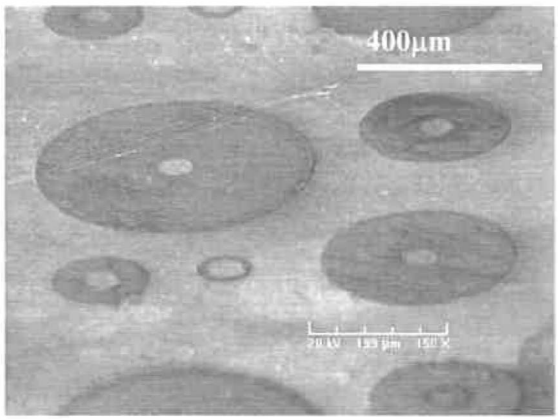


Figure 4: Nickel plating on GaN (SEM micrograph; 70 degree angle)

Following the nickel deposition, a gold layer was deposited from a (electroless) replacement type bath specifically designed for use with nickel. Immersion causes some nickel to be replaced by gold. The gold finish on the samples showed increased surface roughness in comparison to the underlying nickel. The adhesion also deteriorated after

immersion in the gold bath. The thickness of the metals contacts ranged from 80 nm to 200 nm in thickness with a gold content of between 25 and 40% (by volume). Some variation in the thickness of the contacts was present for nominally similar deposition trials. Such thickness variations were of the order of 50 nm.

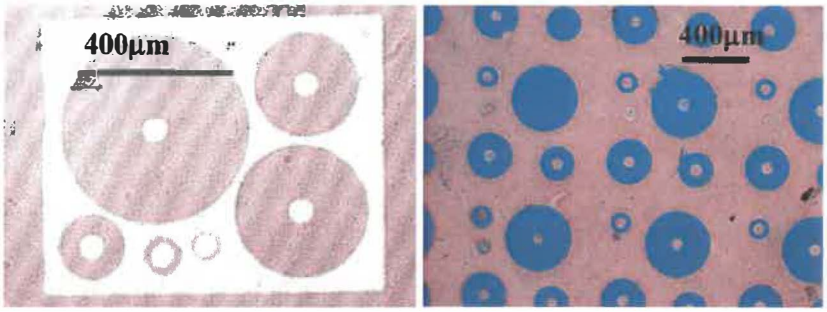


Figure 5: Concentric TLM patterns consisting of electroless deposited nickel (left) and the same with a gold over layer (right)

Once the deposition processes had been optimised, we investigated the possibility of forming ohmic contacts to both *p*- and *n*-type GaN, by subjecting the samples to different heat treatments. Ohmic contacts to *n*-type GaN could only be achieved with Ni-Au contacts after annealing at 800^{0}C.

In order to assess the electrical quality of the contacts, we employed circular transmission line method (c-TLM) patterns, defined by a photo resist lift-off process. A typical set of c-TLM contacts is shown in figure 5a. We employ 50 µm diameter inner contacts and a set of six outer contacts, which are nominally 60, 80, 140, 220, 280 and 400 µm in diameter.

We use the c-TLM technique because it does not require semiconductor etching to eliminate edge effects, as would be the case with linear TLM patterns; we have noticed that we can evaluate *p*-type contacts on LED material, rather than on thick, specially grown *p*-GaN test layers, provided that we keep the bias voltage low, typically below 1V. Under those conditions the current is contained to the uppermost (*p*-GaN) layer and does not spread to the underlying layers[7]. A set of measurements across the six different gap sizes is plotted and fitted to the following formula [7], which describes the resistance across the gap (R_{PP}) as a function of R_{SH} (the sheet resistance of the semiconductor layer), ρ_c (the specific contact resistivity of the metal to semiconductor contact), and r_i and r_o (the radii of the inner and outer metal contacts):

$$R_{PP} = \frac{R_{SH}}{2\pi}\ln\left(\frac{r_o}{r_i}\right) + \frac{\rho_c}{2\pi L_t}\left(\frac{1}{r_i} + \frac{1}{r_o}\right) \qquad (1)$$

The first term in equation (1) represents the lateral resistance in the semiconductor, while the second term represents the resistance of the inner and outer contacts, where $2\pi L_t r_i$ corresponds to the effective current carrying area on that contact and similarly $2\pi L_t r_o$would be the effective current carrying area on the outer contact (disc perimeter times lateral current penetration—also called: current spreading—length).
L_t is the lateral current spreading length. It is linked to R_{SH} and ρ_c by equation (2) [7]:

$$L_t = \sqrt{\frac{\rho_c}{R_{SH}}} \qquad (2)$$

For good quality contacts on *p*-type GaN, this current spreading length is very short (even sub-micron) due to the high sheet resistance of a typical *p*-type GaN layer. For valid TLM measurements, one needs to have good linearity on the I-V curves across all the different gap sizes and additionally a good fit of the set of resistance values to equation (1). Furthermore, we have shown in previous work[8] that it is necessary to accurately measure the dimensions of the contact

radii, as a small error in these values can lead to a large error in the extracted ρ_c value, especially on contacts to *p*-type GaN that have a good specific contact resistivity: $\rho_c < 1 \times 10^{-3} \Omega.cm^2$. Significant differences between the nominal contact size on the lithographic mask and the actual contact size can readily occur due to under- or over-exposure of the resist pattern.

Ni-Au contacts were formed on LED material with a 150 nm thick *p*-type layer with a hole concentration of about 2 x 10^{17} cm^{-3}, a quantum well (QW) region and a 4μm thick *n*-type layer, with a doping level of about 2 x 10^{18} cm^{-3}. A number of different contact thicknesses were deposited. All these deposits were annealed for 60s at 500°C in an O_2 atmosphere. Figure 6 shows the current voltage characteristics across the different gap sizes and also the best fit of the R_{PP} values to equation (1), for two different samples, labelled A and B.

When the actual contact dimensions are taken into account, the extracted ρ_c values for these two samples are 2.2 x 10^{-2} Ωcm^2 for sample A and 8.6 x 10^{-2} Ωcm^2 for sample B. The extracted sheet resistances were 280 kΩ for sample A and 300 kΩ for sample B, corresponding to *p*-layer resistivity values of 4.2 Ωcm and 4.5 Ωcm, respectively.

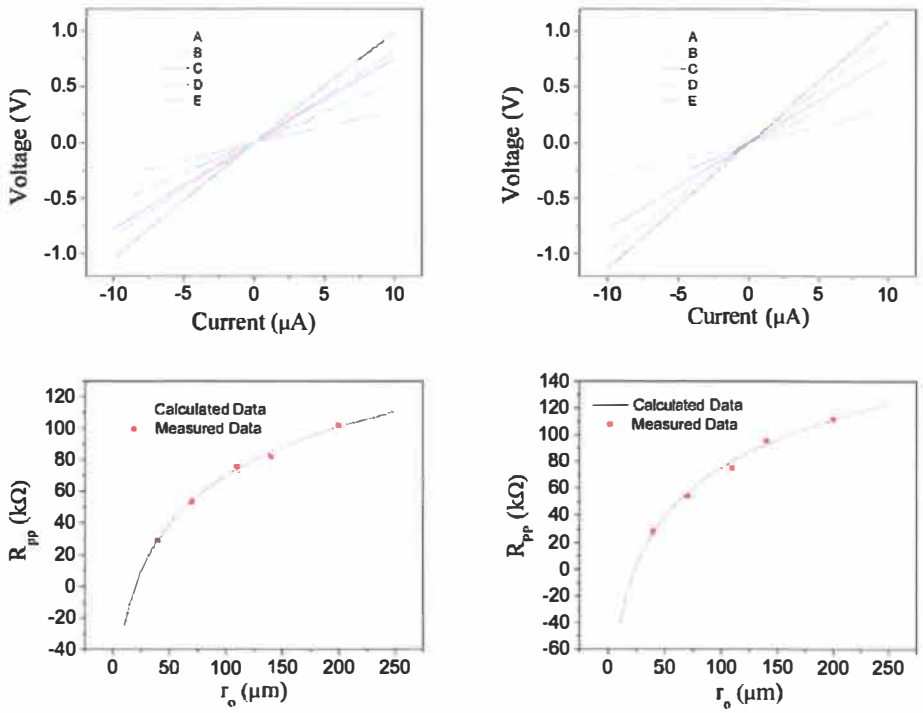


Figure 6: I-V characteristics measured across a set of five TLM patterns (the sixth pattern is missing) and the associated fitting to equation (1) for two of our best samples: A and B. Ni-Au contacts to *p*-type GaN, annealed for 60s at 500°C in O_2

Next, we re-measured the contacts on sample A, while this sample was held at 140°C. The results of this test are shown in figure 7. The ohmic nature of the contact is not affected by the temperature rise, but there is a sharp drop in the voltage values recorded. The extracted ρ_c value for the c-TLM measurement at 140°C was $\rho_c = 2.5 \times 10^{-2}$ Ωcm^2, which is close to the value measured at room temperature: $\rho_c = 2.2 \times 10^{-2}$ Ωcm^2. The extracted sheet resistance was 70 kΩ, corresponding to a *p*-layer resistivity of 1.1 Ωcm, down from 4.2-4.5 Ω.cm at room temperature. The almost unchanged value of ρ_c indicates that carrier transport is through a tunnelling mechanism and as such is independent of temperature. The reduction in sheet resistance is attributed to an increased acceptor activation level at the higher temperature.

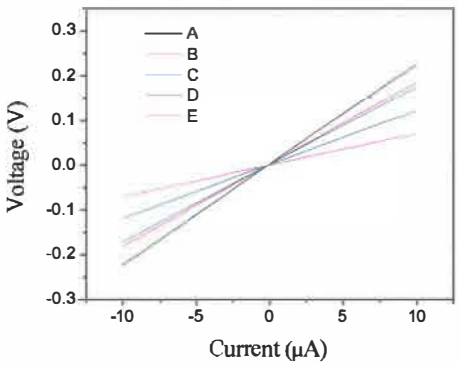


Figure 7: I-V characteristics measured across a set of five TLM patterns (the sixth pattern is missing) on sample A at 140^{0}C

3. PROCESS OPTIMISATION

We have demonstrated the possibility of employing an electroless deposition method to form ohmic contacts to *p*-type GaN. During the course of the experiments a number of optimisation steps were employed to try and achieve lower ρ_c values. We found that a thorough cleaning of the wafer prior to the electroless process was necessary to achieve uniform metal coverage. We obtained best results with solvent cleaning followed by a brief dip in aqua regia. Also of interest is the deposition rate of the metals. Initial trials show that slower depositions at lower temperatures yield better contacts. We also observed that thinner layers yielded lower ρ_c values. Another factor affecting the final results is the annealing temperature. A set of nominally identical samples were annealed at different temperatures in the range of 400^{0}C to 600^{0}C. While the I-V characteristics were linear on all these samples, the extracted ρ_c values showed some variation. A plot of the results is shown in figure 8.

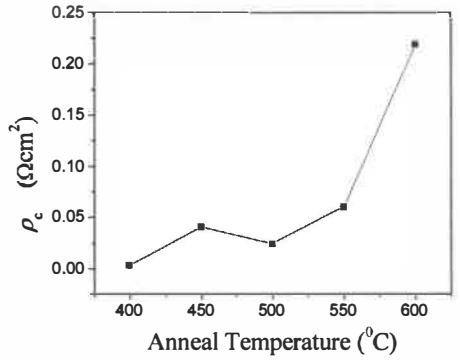


Figure 8: The specific contact resistivity as a function of the annealing temperature (electroless deposited Ni-Au contacts to *p*-type GaN, annealed for 60s in O_2)

5. CONCLUSIONS

We have explored electroless deposition processes for metal contacts to GaN, both for Schottky contact and ohmic contact applications. W-Co contacts show potential for Schottky contacts to either *p*-type or *n*-type GaN, while the Ni-Au contacts can be used as ohmic contacts to *p*-type GaN. The specific contact resistivity value obtained with the Ni-Au ohmic contacts (ρ_c =2.2 x 10^{-2} Ωcm^2) would be adequate for applications running at low current density, such as standard LEDs. The ohmic contacts could be further improved through optimisation of the surface preparation prior to metal deposition and through the use of higher doped *p*-GaN layers. The contact resistivity is almost independent of temperature indicating a carrier transport mechanism dominated by tunneling. The deposition process itself is low cost and fast in comparison to other deposition methods.

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