Formation Process and Properties of Ohmic Contacts Containing Molybdenum to AlGaN/GaN Heterostructures

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DOI: 10.15598/aeee.v14i1.1587

Abstract. *Properties of wide bandgap semiconductors as chemical inertness to harsh conditions and possibility of working at high temperature ensure possible applications in the field as military, aerospace, automotive, engine monitoring, flame detection and solar UV detection. Requirements for ohmic contacts in semiconductor devices are determined by the proposed application. These contacts to AlGaN/GaN heterostructure for application as high temperature, high frequency and high power devices have to exhibit good surface morphology and low contact resistance. The latter is a crucial factor in limiting the development of high performance AlGaN/GaN devices. Lowering of the resistance is assured by rapid thermal annealing process. The paper present studies of Ti/Al/Mo/Au ohmic contacst annealed at temperature range from 825 °C to 885 °C in* N_2 *atmosphere. The electrical parameters of examined samples as a function of the annealing process condition have been studied. Initially the annealing temperature increase caused lowering of the contacts resistance. The lowest value was noticed for the temperature of annealing equal to 885 °C. Further increase of annealing temperature led to deterioration of contact resistance of investigated ohmic contacts.*

Keywords

AlGaN/GaN, ohmic contacts, RTA, RTP, surface morphology, Ti/Al/Mo/Au.

1. Introduction

The ohmic contacts in AlGaN/GaN semiconductor devices have crucial influence on device performance [1], [2], and [3]. At the high electron mobility transistor (HEMT) ohmic contacts govern transconductance and saturation current. The AlGaN/GaN HEMTs are capable of handling higher current densities than other III-V high electron mobility transistors due to higher two-dimensional electron gas (2DEG) density (10^{13} cm^{-2} or higher) accumulated on the AlGaN/GaN interface [4] and [5].

The thermal stability of AlGaN/GaN heterostructures and their chemical inertness engender difficulties in ohmic contact formation. Smooth surface morphology for high edge definition and minimal contact resistance are essential for desirable device behavior. To achieve a change from Schottky contact after deposition metallization to ohmic contact, samples were annealed at different temperatures. High annealing temperatures, usually over 800 °C, are required to establish good ohmic contact performance [6], [7], [8], [9], [10], [11], [12], and [13]. On the other hand, so high annealing temperature causes changes on the heterostructure and metal-semiconductor interface, which in turn leads to alteration of 2DEG parameter - carrier mobility [14].

At this stage of investigation we have to seek for compromise between appropriate ohmic contact performance and 2DEG parameters. In our studies, for Ti/Al/Mo/Au ohmic contacts, the temperature had to be above 800 degrees to reach this compromise. To minimize the deterioration of 2DEG parameters, the thermal annealing was led in time as short as possible to reach good ohmic performance.

Also, the high temperature annealing has strong influence on the microstructure and the surface morphology of the ohmic contact. The reasons of the impact of annealing temperature on the microstructure of Ti/Al/Ni/Au are the low melting temperature of aluminum (660 °C) and migration followed by coalescence of agglomerates [15].

In this study Ti/Al/Mo/Au metallization scheme have been used. The Ti/Al based ohmic contact is one of the most prevalent metallization schemes of ohmic contact to AlGaN/GaN heterostructures [6], [7], [8], [9], [10], [11], [12], and [13]. A titanium layer is essential as, at elevated temperatures, the Ti participates in the reaction with nitrides on the interface and forms TiN [8]. This reaction extracts nitrogen and generates N-vacancies. N-vacancies act as n-type dopants and create a highly doped layer underneath the metallization, leading to low-contact resistance of the Ti/Al based ohmic contact. The aluminum is the layer which is responsible for the formation of the ohmic contact to AlGaN/GaN heterostructures. In general, there is no standard annealing temperature that leads to low resistance ohmic contact. Research studies indicated on different temperature that exhibited successful ohmic contact formation [6], [7], [8], [9], [10], [11], [12], and [13].

Low resistance ohmic contacts to AlGaN/GaN are of great importance because an improvement of their electrical properties would lead to enhancement of the device performance. In this paper we report the influence of annealing temperature on the current-voltage characteristics and contact resistance R_c.

2. Experimental Details

The AlGaN/GaN heterostructure applied in this study consisted of AlGaN/GaN grown by metalorganic vapor phase epitaxy (MOVPE) on sapphire substrate. Prior to metal deposition, the native oxide (Ga_2O_3) was removed from all samples surfaces by etching in HCl:H_2O (1:1) solution, followed by a deionised water rinsing and drying in N_2 flow. Then, the samples were immediately loaded into the vacuum chamber of an evaporation system. The metallic contact consisting of Ti/Al/Mo/Au (23/100/40/190 nm) was deposited on the substrate under vacuum conditions with a base pressure lower than 10^{-6} mbar. The metal layers were deposited by using an electron beam evaporator (Ti, Al, Mo) and resistance heater (Au). The transfer length method (TLM) mesa isolation was achieved by means of a 80 nm deep mesa etch performed by Cl_2/BCl_3/Ar reactive ion etching. The Ti/Al/Mo/Au ohmic metallizations were annealed at various temperatures in rapid thermal annealing (RTA) system. The temperature of each annealing process was changed over the range

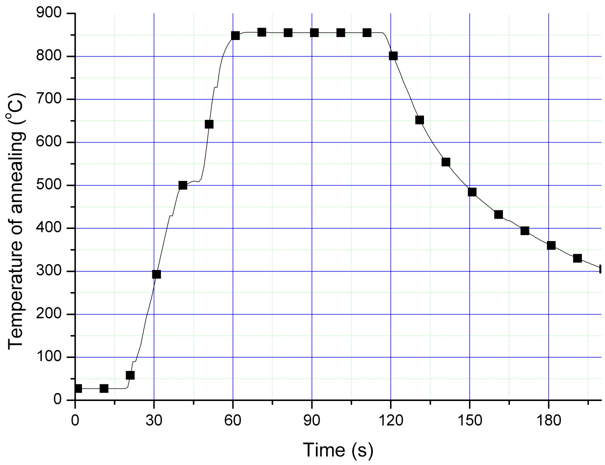


Fig. 1: Temperature characteristic of thermal annealing at 855 °C.

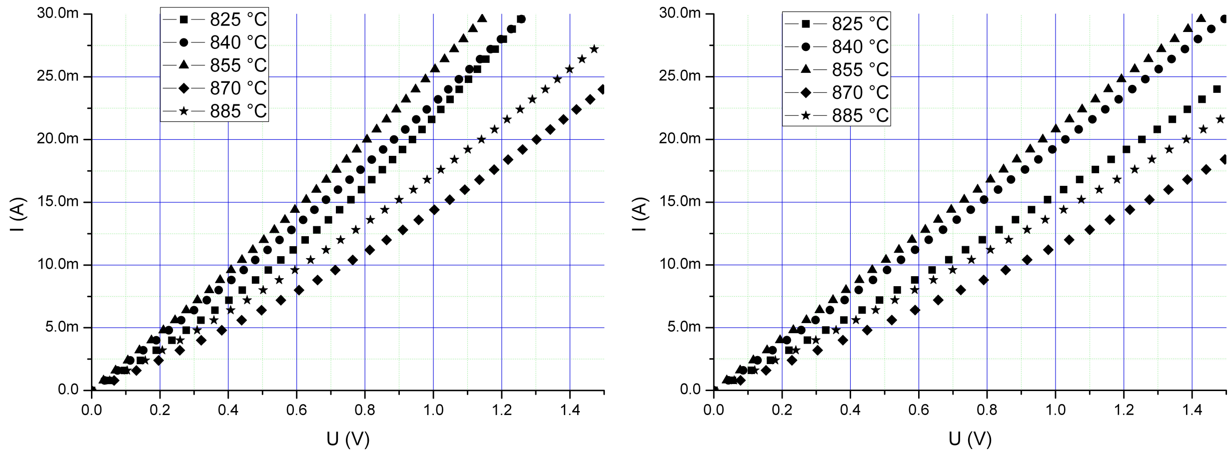
from 825 °C to 855 °C and the annealing time of 60 seconds was kept for all samples (Fig. 1).

To study the influence of the annealing process parameters on the properties of the Ti/Al/Mo/Au metallization, the electrical parameters (I-V characteristic and contact resistance Rc) were measured. For contact resistance Rc measuring we adopted the TLM (four probes mode) test structure. The distance between contact were 31, 20, 10 and 6 μm. The current-voltage (I-V) characteristics were measured on the two neighboring contacts from TLM test structure.

3. Result and Discussion

Figure 2 shows the current-voltage characteristics of Ti/Al/Mo/Au metallization as a function of annealing temperature. When the distance between measured neighboring pads is lower (Fig. 2(a) - 6 μm, Fig. 2(b) - 10 μm) the current at a given voltage as expected increases. However, the decreasing of distance between pads is reflected at more visible non-linearity of I-V characteristics (Fig. 2). It could mean, that on the m-s interface remains a barrier. The influence of temperature of RTA annealing process shows, that the smallest total resistance RT at given voltage was achieved at 855 °C (Fig. 2). First, at given voltage with increase of annealing temperature up to 855 °C the total resistance RT decreased.

However, increase of annealing temperature above the temperature of 855 °C caused the increase of total resistance RT. But the shape of I-V characteristic remains slightly non-linear. Figure 3 shows the contact resistance Rc of Ti/Al/Mo/Au metallization as a function of annealing temperature. For calculation of contact resistance, we adopted the TLM method. The resistance for given distance between pads and anneal-



(a) distance between measured metal pads: 5 μm

(b) distance between measured metal pads: 10 μm

Fig. 2: Current-Voltage characteristic of Ti/Al/Mo/Au contact after annealing at various temperatures.

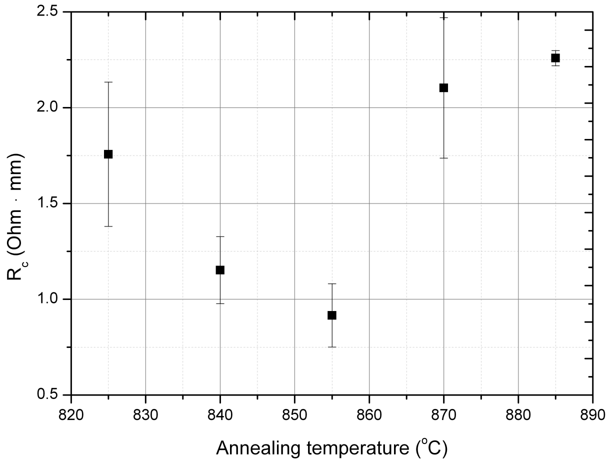
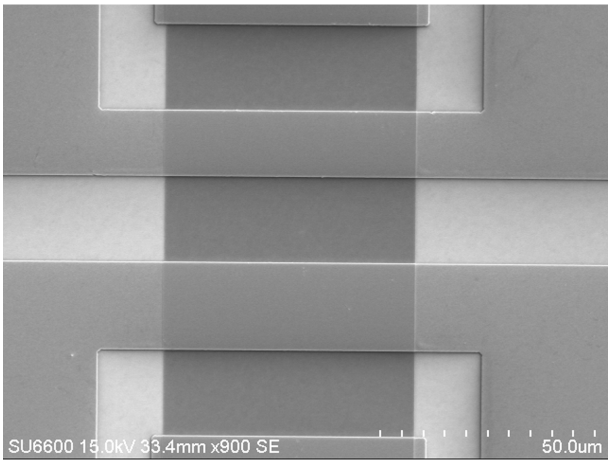


Fig. 3: Contact resistance Rc as a function of annealing temperature of Ti/Al/Mo/Au contacts for AlGaN/GaN heterostructures.

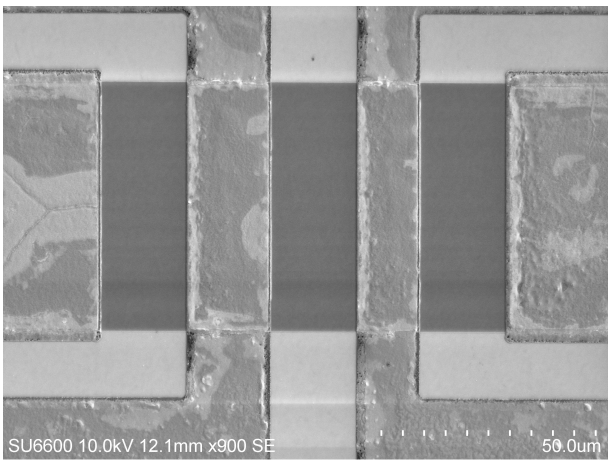
ing temperature was calculated from I-V characteristics at given voltage (0.2 V). Also for those contacts the resistance RC have the smallest value at 855 °C.

SEM was used to characterize the film smoothness and edge acuity. As shown in Fig. 4(b), the surface of ohmic contacts changed after annealing at high temperature (855 °C) but is still smooth enough and the edge acuity is proper for a variety of applications in semiconductor devices. Rough surface of ohmic contacts is disadvantageous for reliability and stability [11].

The roughness appeared due to the Al in the ohmic contact scheme. Impact of annealing temperature on the microstructure of studied Ti/Al/Mo/Au was not so large as on the Ti/Al/Ni/Au ohmic contacts (Fig. 5) examined earlier [15], [17], but it is still easily observed. At the ohmic contact with Ni barrier (Ti/Al/Ni/Au) the primary mechanism responsible for the poor morphology and the heterogeneous chemical composition of the ohmic contact is the formation of Al droplets



(a) before annealing



(b) after annealing at 855 °C RTA 60 s

Fig. 4: SEM micrographs of ohmic contacts.

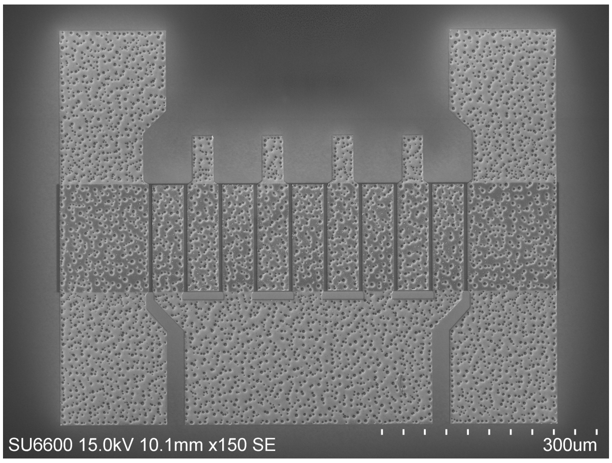


Fig. 5: SEM micrographs of ohmic contacts containing Ni barrier (Ti/Al/Ni/Au) instead of Mo.

above 660 °C (melting point of Al), [17]. On the final roughness and morphology of ohmic contacts influence not only presence of Al layer but also the thicknesses and composition of the rest layers of ohmic metallization. In particular the type of barrier layer for gold [17]. Comparison of two technologies, with Ni (Fig. 5) and Mo (Fig. 4) layers, shown the better properties of the molybdenum layer.

Because Al plays an essential role in the ohmic contact formation, it would be a challenge to avoid of its application. SEM micrographs of Ti/Al/Mo/Au ohmic contacts annealed at various temperature (not shown) did not show large differences in the topography, only sometimes some cracks of Mo layer have been observed (Fig. 4). It was observed that a smooth surface, superior edge acuity and lowest contact resistance of 0.92 Ω·mm were obtained for the sample annealed at 855 °C.

4. Conclusion

It has been demonstrated the influence of temperature of rapid thermal annealing process on the ohmic contact performance of Ti/Al/Mo/Au metallization to AlGaN/GaN heterostructures. For all studied samples, a lower contact resistance of 0.92 Ω·mm, a good surface morphology and edge acuity were achieved when annealing the samples at 855 °C for 60 s. However, the I-V characteristics still remain slightly non-linear. It means, that the metal-semiconductor Ti/Al/Mo/Au-AlGaN/GaN contacts still have a barrier. Further temperature increase of thermal annealing process did not influence on the shape of I-V characteristic. What is more, it caused the increase of contact resistance RC. Our results indicated, that further optimization of this Ti/Al/Mo/Au contact has to be made.

Acknowledgment

This work was co-financed by the European Union within European Regional Development Fund, through grant Innovative Economy (POIG.01.01.02-00-008/08-05), National Science Centre under the grant no. DEC-2012/07/D/ST7/02583, by National Centre for Research and Development through Applied Research Program grant no. 178782, program LIDER no. 027/533/L-5/13/NCBR/2014, by Wroclaw University of Technology statutory grants and Slovak-Polish International Cooperation Program no. SK-PL-2015-0028.

References

[1] QUIAO, D., Z. F. GUAN, J. CARLTON, S. S. LAU, G. S. SULLIVAN, L. JIA, L. S. YU, P. M. ASBECK, S. S. LAU, S. H. LIM, Z. L. WEBER, T. E. HAYNES and J. B. BARNER. Ta-based interface ohmic contacts to AlGaN/GaN heterostructures. *Journal of Applied Physics*. 2001, vol. 89, iss. 10, pp. 5543–5546. ISSN 0021-8979. DOI: 10.1063/1.1365431.

[2] JACOBS, B., M. C. J. C. M. KRAMER, E. J. GELUK and F. KAROUTA. Optimisation of the Ti/Al/Ni/Au ohmic contact on AlGaN/GaN FET structures. *Journal of Crystal Growth*. 2002, vol. 241, iss. 1-2, pp. 15–18. ISSN 0022-0248. DOI: 10.1016/S0022-0248(02)00920-X.

[3] MAHAJAN, S. S., A. DHAUL, R. LAISHRAM, S. KAPOOR, S. VINAYAK and B. K. SEHGAL. Micro-structural evaluation of Ti/Al/Ni/Au ohmic contacts with different Ti/Al thicknesses in AlGaN/GaN HEMTs. *Materials Science and Engineering B*. 2014, vol. 183, iss. 1, pp. 47–53. ISSN 0921-5107. DOI: 10.1016/j.mseb.2013.12.005

[4] AMBACHER, O., J. SMART, J. R. SHEALY, N. G. WEIMANN, K. CHU, M. MURPHY, W. J. SCHAFF, L. F. EASTMAN, R. DIMITROV, L. WITTMER, M. STUTZMANN, W. RIEGER and J. HILSENBECK. Two-dimensional electron gases induced by spontaneous and piezoelectric polarization charges in N- and Ga-face AlGaN/GaN heterostructures. *Journal of Applied Physics*. 1999, vol. 85, iss. 6, pp. 3222–3233. ISSN 0021-8979. DOI: 10.1063/1.369664.

[5] SMORCHKOVA, I. P., C. R. ELSASS, J. P. IBBETSON, R. VETURY, B. HEYING, P. FINI, E. HAUS, S. P. DENBAARS, J. S. SPECK and U. K. MISHRA. Polarization-induced charge and electron mobility in AlGaN/GaN heterostructures grown by plasma-assisted molecular-beam epitaxy. *Journal of Applied Physics*. 1999,

vol. 86, iss. 8, pp. 4520–4526. ISSN 0021-8979. DOI: 10.1063/1.371396.

[6] RUVIMOV, S., Z. LILIENTAL-WEBER, J. WASHBURN, D. QIAO, S. S. LAU and P. K. CHU. Microstructure of Ti/Al ohmic contacts for n-AlGaN. *Applied Physics Letters*. 1998, vol. 73, iss. 18, pp. 2582–2584. ISSN 0003-6951. DOI: 10.1063/1.122512.

[7] WANG, L., F. M. MOHAMMED, B. OFUONYE and I. ADESIDA. Ohmic contacts to n/*pm* GaN capped AlGaN/AlN/GaN high electron mobility transistors. *Applied Physics Letters*. 2007, vol. 91, iss. 1, pp. 012113-1–012113-3. ISSN 0003-6951. DOI: 10.1063/1.2754371.

[8] RUVIMOV, S., Z. LILIENTAL WEBER, J. WASHBURN, K. J. DUXSTAD, E. E. HALLER, Z. F. FAN, S. N. MOHAMMAD, W. KIM, A. E. BOTCHKAREV and H. MORKOC. Microstructure of Ti/Al and Ti/Al/Ni/Au Ohmic contacts for nGaN. *Applied Physics Letters*. 1996, vol. 69, iss. 11, pp. 1556–1558. ISSN 0003-6951. DOI: 10.1063/1.117060.

[9] WANG, L., F. M. MOHAMMED and I. ADESIDA. Dislocation-induced nonuniform interfacial reactions of Ti/Al/Mo/Au ohmic contacts on AlGaN/GaN heterostructure. *Applied Physics Letters*. 2005, vol. 87, iss. 14, pp. 141915-1–141915-3. ISSN 0003-6951. DOI: 10.1063/1.2081136.

[10] FAY, M. W., G. MOLDOVAN, N. J. WESTON, P. D. BROWN, I. HARRISON, K. P. HILTON, A. MASTERTON, D. WALLIS, R. S. BALMER, M. J. UREN and T. MARTIN. *Journal of Applied Physics*. 2004, vol. 96, iss. 10, pp. 5588–5595. ISSN 0021-8979. DOI: 10.1063/1.1796514.

[11] YANXU, Z., C. WEIWEI, F. YUYU, D. YE and X. CHEN. Effects of rapid thermal annealing on ohmic contact of AlGaN/GaN HEMTs. *Journal of Semiconductors*. 2014, vol. 35, iss. 2, pp. 026004-1–026004-4. ISSN 1674-4926. DOI: 10.1088/1674-4926/35/2/026004.

[12] LALINSKY, T., G. VANKOL, Z. MOZOLOVA, J. LIDAY, P. VOGRINCIC, A. VINCZE, F. UHEREK, S. HASCIKL and I. KOSTIC. Nb-Ti/Al/Ni/Au Ohmic Metallic System to AlGaN/GaN. In: *International Conference on Advanced Semiconductor Devices and Microsystems*. Smolenice Castle: IEEE, 2006, pp. 151–154. ISBN 1-4244-0369-0. DOI: 10.1109/ASDAM.2006.331176.

[13] FLOROVIC, M., J. KOVAC, P. KORDOS, J. SKRINIAROVA, T. LALINSKY, S. HASCIK, M. MICHALKA, D. DONOVAL and F. UHEREK. Electrical properties of ohmic contacts for Al0.3Ga0.7N/GaN semiconductor devices. In: *International Conference on Advanced Semiconductor Devices and Microsystems*. Smolenice: IEEE, 2008, pp. 103–106. ISBN 978-1-4244-2326-2. DOI: 10.1109/ASDAM.2008.4743291.

[14] MACHERZYNSKI, W. and B. PASZKIEWICZ. Study of interface reactions between Ti/Al/Ni/Au metallization and AlGaN/GaN heterostructures. *Central European Journal of Physics*. 2013, vol. 11, iss. 2, pp. 258–263. ISSN 1895-1082. DOI: 10.2478/s11534-012-0158-0.

[15] MACHERZYNSKI, W., A. STAFINIAK, A. SZYSZKA, J. GRYGLEWICZ, B. PASZKIEWICZ, R. PASZKIEWICZ and M. TLACZALA. Effect of annealing temperature on the morphology of ohmic contact Ti/Al/Ni/Au to n-AlGaN/GaN heterostructures. *Optica Applicata*. 2009, vol. 39, iss. 4, pp. 673–679. ISSN 1899-7015.

[16] MACHERZYNSKI, W., K. INDYKIEWICZ and B. PASZKIEWICZ. Chemical analysis of Ti/Al/Ni/Au ohmic contacts to AlGaN/GaN heterostructures. *Optica Applicata*. vol. 43, iss. 1, pp. 67–72. ISSN 1899-7015.

[17] MACHERZYNSKI, W. and B. PASZKIEWICZ. Development of diffusion barriers for Ti/Al based ohmic contact to AlGaN/GaN heterostructures. In: *The Ninth International Conference on Advanced Semiconductor Devices and Microsystems*. Smolenice: IEEE, 2012, pp. 203–206. ISBN 978-1-4673-1195-3. DOI: 10.1109/ASDAM.2012.6418532.

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