Semiconductors, 2022, Vol. 56, No. 14

Temperature stability features of ohmic contacts resistance to GaAs and GaN based nanoheterostructures

© V.I. Egorkin, V.E. Zemlyakov, A.V. Nezhentsev, A.A. Zaitsev, V.I. Garmash

National Research University of Electronic Technology,
124498 Zelenograd, Moscow, Russia

E-mail: alekseyy_nejencev@rambler.ru

Received January 13, 2021
Revised July 26, 2021
Accepted August 17, 2021

The temperature stability of Ge/Au/Ni/Au ohmic contacts to GaAs nanoheterostructures and Ti/Al/Ni/Au ohmic contacts to GaN nanoheterostructures on silicon substrate was investigated. It has been established that optimization of the RTA process made it possible to obtain ohmic contacts with field emission current flow mechanism. The thermal stability of ohmic contacts for transistors and mesa resistors demonstrated the threshold behavior of the heat treatment temperature. The optimum process parameters for temperature stability and minimum contact resistance were defined.

Keywords: ohmic contact, gallium arsenide, gallium nitride.

DOI: 10.21883/SC.2022.14.53873.9603

1. Introduction

High-electron-mobility transistors based on gallium arsenide (GaAs) and gallium nitride (GaN) have progressed rapidly in the last twenty years and are becoming the base components of modern microwave electronics and power electronics. In order to ensure reliable operation of semiconductor devices, one needs to make the parameters of transistors and mesaresistors temperature-independent. Since Ohmic contacts are integral components of transistors and mesaresistors based on semiconductor lines, a thorough understanding of the temperature dependence of resistance of an Ohmic contact is critical to the design of reliable devices [1,2].

The most widespread metallic designs for the fabrication of Ohmic contacts to epitaxial gallium arsenide layers are those based on an eutectic alloy of germanium and gold (AuGe). Such contacts are formed by special thermal processing at temperatures $\sim 380^\circ$C (rapid thermal annealing, RTA). Liquid-phase reactions occurring in this process shape the electric properties of a contact. The thermal stability of AuGe-based Ohmic contacts to gallium arsenide is achieved through the use of metallization with refractory materials [3–5], or by optimizing the regimes of thermal processing [6,7].

Metallization based on Ti/Al is typically used as a contact one to GaN-based nanoheterostructures [8–11]. It is believed that the contact resistance decreases after annealing due to the formation of a TiN layer at the metal–semiconductor interface. This results in the emergence of nitrogen vacancies acting as a donor impurity in the semiconductor [12]. The technology for GaN-based heterostructure growth on a silicon substrate has progressed considerably over the last ten years [13–15]. Since silicon features a high thermal conductivity, the parameters of heat dissipation are significantly better than those of gallium arsenide. This makes it possible to fabricate high-power gallium nitride transistors. High-temperature thermal processing is performed in fabrication of Ti/Al-based Ohmic contacts to gallium nitride. Thermal-field emission is distinguished in studies focused on the current transport mechanism [1,16–18].

A potential barrier forms in the process of deposition of metallization layers at the metal–semiconductor interface. In the case of an Ohmic contact, it does not exert any appreciable influence (either its height or its width are insignificant). The temperature dependence of the contact resistance is governed by the current transport mechanism in an Ohmic contact. A total of three mechanisms are distinguished: thermionic emission, field emission, and thermal-field emission [19,20].

Having plotted the experimental temperature dependence of the contact resistance, one may determine the mechanism of current flow in an Ohmic contact. If this mechanism is field emission, the resistance is independent of temperature. According to literature data, the primary current transport mechanism in Ohmic contacts to GaAs and GaN is thermal-field emission (with metallic conductivity) [20,21]. Therefore, the optimum parameters of fabrication of Ohmic contacts to GaN- and GaAs-based nanostructures, where the current flow is governed by the field emission law, need to be determined in order to achieve high thermal stability levels.

In the present study, Ti/Al/Ni/Au (20/100/40/50 nm) and Ge/Au/Ni/Au (5/10/10/150 nm) metallizations for the fabrication of Ohmic contacts to gallium nitride and gallium arsenide, respectively, were examined. The influence of temperature on the resistance of an Ohmic contact was studied, and the mechanism of current transport through the metal–semiconductor interface was identified.

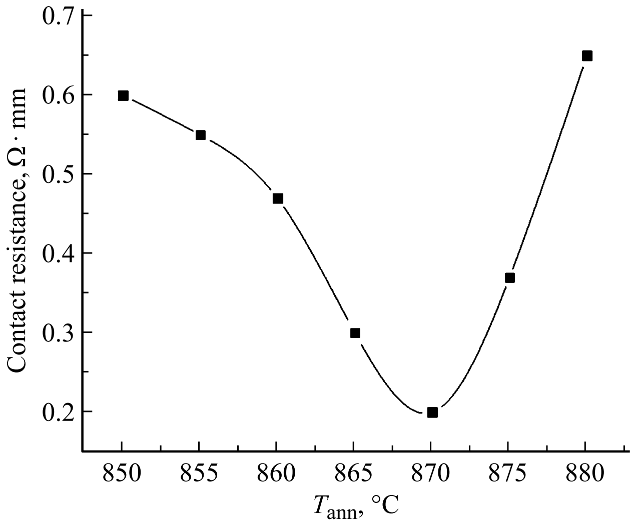

Figure 1. Dependence of the resistance of Ohmic contacts to GaN based on the Ti/Al/Ni/Au metallization on the RTA temperature. The annealing time is 30 s.

2. Experiment

Contact photolithography was used to fabricate the samples for examination; the resist mask was formed in accordance with [22]. Ti/Al/Ni/Au and Ge/Au/Ni/Au metallizations were deposited using an electron-beam deposition setup produced by Kurt J. Lesker. Thermal processing of Ohmic contacts to gallium nitride and gallium arsenide was performed in a Unitemp 1200 industrial RTA furnace and a proprietary thermal processing setup [23], respectively.

The temperature dependence of the contact resistance was examined using a probe station with a heated stage in ambient environment. A resistive heater positioned below the measurement stage was used. The temperature was measured with a thermocouple in contact with the stage.

Samples of Ohmic contacts to gallium arsenide were fabricated in accordance with the process parameters given in [24]. The RTA duration was 1 min at temperatures $T_{\text{ann}} = 278$, 398, and 450°C.

The dependence of the resistance of contacts based on the Ti/Al/Ni/Au metallization on the RTA temperature was studied in detail (Fig. 1). The contact resistance reached a minimum of 0.2 Ω · mm at a temperature of 870°C.

The samples fabricated at RTA temperatures of 850, 870, and 880°C were then subjected to heating, and the contact resistance was monitored in the process.

3. Results

It can be seen from Fig. 2 that the resistance of Ohmic contacts to gallium arsenide formed at an RTA temperature of 398°C is almost independent of the measurement temperature. The resistance of Ohmic contacts fabricated at 278°C decreases at higher measurement temperatures, while the resistance of contacts formed at 450°C increases slightly with temperature.

The resistance of Ohmic contacts to GaN nanoheterostructures based on the Ti/Al/Ni/Au metallization decreases at higher temperatures if the RTA temperature is < 860°C. When the RTA temperature increases to 870 and 880°C, the temperature dependence of the contact resistance becomes much weaker. Since the contact resistance and the semiconductor structure itself degrade at higher temperatures of thermal processing, RTA temperatures in excess of the above values were not examined.

It can be seen from Figs. 2 and 3 that the resistance of Ohmic contacts formed at the optimum RTA parameters is minimized and remains constant as the temperature

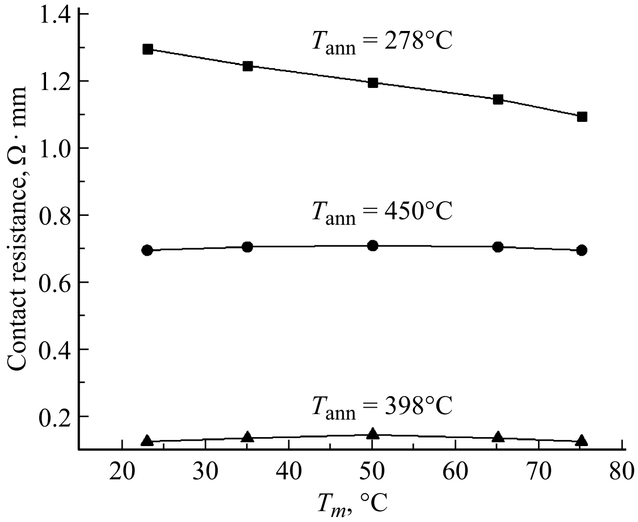

Figure 2. Dependence of the resistance of Ohmic contacts to GaAs fabricated at different RTA temperatures T_{ann} based on the Ge/Au/Ni/Au metallization on measurement temperature T_m.

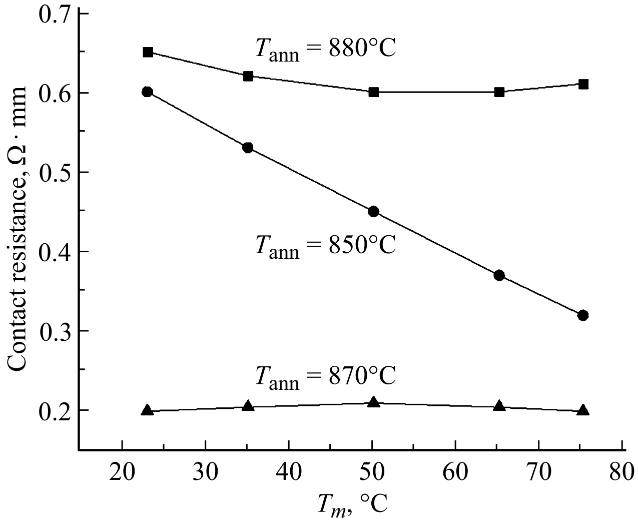

Figure 3. Dependence of the resistance of Ohmic contacts to GaN fabricated at different RTA temperatures T_{ann} based on the Ti/Al/Ni/Au metallization on measurement temperature T_m.

increases in the indicated range. Theoretical models suggest that the mechanism of current transport through the metal–semiconductor interface (specifically, field emission) is what ensures the high thermal stability of optimized Ohmic contacts. The temperature dependence of the contact resistance of samples annealed at suboptimum parameters is indicative of current transport in accordance with the thermal-field emission mechanism. Thus, optimizing the RTA methods, one may alter the current transport mechanism and switch from thermal-field emission to field emission.

4. Conclusion

The possibility of fabrication of thermally stable Ohmic contacts was demonstrated in the process of examination of the influence of temperature on the resistance of Ohmic contacts to GaAs and GaN. It was found that Ohmic contacts with a current transport mechanism governed by the field emission law may be formed by optimizing the RTA methods. An Ohmic contact to GaAs based on the AuGe metallization has the lowest and temperature-independent contact resistance ($0.13\,\Omega\cdot\text{mm}$) if it is fabricated by RTA performed for 60 s at a temperature of 398°C. Ti/Al-based Ohmic contacts to GaN formed at an RTA temperature of 870°C within 30 s are thermally stable. The minimum resistance for the Ti/Al/Ni/Au metallization was $0.2\,\Omega\cdot\text{mm}$. The thermal stability of Ohmic contacts of transistors and mesaresistors exhibits a threshold behavior with thermal processing temperature and features an optimum in terms of thermal stability and contact resistance.

Funding

The research results presented above were obtained as part of a project of the National Research University of Electronic Technology (MIET) with state support established under decree No. 218 of the Government of the Russian Federation dated April 2010 for the cooperation of Russian organizations for higher education, state academic institutions, and organizations implementing complex projects on high-technology manufacturing. The MIET project title is „Development of the Manufacturing Technique and Engineering Preparation for the Manufacture of Transistor Chips Based on Gallium Nitride Heterostructures on Silicon Substrates 150 mm in Diameter for Power Conversion Modules“. Agreement No. 075-11-2019-068 dated November 26, 2019.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] F. Iucolano, G. Greco, F. Roccaforte. Appl. Phys. Lett., **103** (20), 201604 (2013).
[2] Z.H. Liu, S. Arulkumaran, G.I. Ng. Appl. Phys. Lett., **94** (14), 142105 (2009).
[3] T.C. Shen, G.B. Gao, H. Morkoc. J. Vacuum Sci. & Technol. B: Microelectron. and Nanometer Structures Processing, Measurement, and Phenomena, **10** (5), 2113 (1992).
[4] P.H. Hao, L.C. Wang, F. Deng, S.S. Lau, J.Y. Cheng. J. Appl. Phys., **79** (8), 4211 (1996).
[5] A.M. Crook, E. Lind, Z. Griffith, M.J. Rodwell, J.D. Zimmerman, A.C. Gossard, S.R. Bank. Appl. Phys. Lett., **91** (19), 192114 (2007).
[6] M. Murakami. Sci. Technol. Adv. Mater., **3** (1), 1 (2002).
[7] A. Callegari, E.T.S. Pan, M. Murakami. Appl. Phys. Lett., **46** (12), 1141 (1985).
[8] Z. Fan, S.N. Mohammad, W. Kim, Ö. Aktas, A.E. Botchkarev, H. Morkoç. Appl. Phys. Lett., **68**, 1672 (1996).
[9] A.N. Bright, P.J. Thomas, M. Weyland, D.M. Tricker, C.J. Humprhreys, R. Davies, J. Appl. Phys., **89**, 3143 (2001).
[10] A. Motayed, R. Bathe, M.C. Wood, O.S. Diouf, R.D. Vispute, S.N. Mohammad. J. Appl. Phys., **93**, 1087 (2003).
[11] M.W. Fay, G. Modlovan, N.J. Weston, P.D. Brown, I. Harrison, K.P. Hilton, A. Masterton, W. Wallis, R.S. Balmer, M.J. Uren, T. Martin. J. Appl. Phys., **96**, 5588 (2004).
[12] J.S. Kwak, S.E. Mohney, J.Y. Lin, R.S. Kern. Semicond. Sci. Technol., **15**, 756 (2000).
[13] C.L. Wu, J.C. Wang, M.H. Chan, T.T. Chen, S. Gwo. Appl. Phys. Lett., **83** (22), 4530 (2003).
[14] T.A. Rawdanowicz, J. Narayan. Appl. Phys. Lett., **85** (1), 133 (2004).
[15] J. Komiyama, Y. Abe, S. Suzuki, H. Nakanishi. Appl. Phys. Lett., **88** (9), 091901 (2006).
[16] T.V. Blank, Yu.A. Gol'dberg. Semiconductors, **41** (11), 1263 (2007).
[17] F. Iucolano, F. Roccaforte, A. Alberti, C. Bongiorno, S. Di Franco, V. Raineri. J. Appl. Phys., **100** (12), 123706 (2006).
[18] N. Thierry-Jebali, O. Ménard, C. Dubois, D. Tournier, E. Collard, C. Brylinski, F. Cayrel, D. Alquier. Mater. Sci. Forum (Trans. Tech. Publications Ltd), **711**, 208 (2012).
[19] A.A. Lakhani, R.C. Potter, D.M. Beyea. Semicond. Sci. Technol., **3** (6), 605 (1988).
[20] G.S. Marlow, M.B. Das, L. Tongson. Solid-State Electron., **26** (4), 259 (1983).
[21] T.V. Blank, Yu.A. Gol'dberg, O.V. Konstantinov, V.G. Nikitin, E.A. Posse. Tech. Phys., **52** (2), 285 (2007).
[22] A.V. Nezhentsev, V.E. Zemlyakov, V.I. Egorkin, V.I. Garmash. Elektron. Tekh., Ser. 2: Poluprovodn. Prib., №2–3, 96 (2015) (in Russian).
[23] V.I. Egorkin, V.E. Zemlyakov, A.V. Nezhentsev, V.I. Garmash. Russ. Microelectron., **46** (4), 272 (2017).
[24] V.I. Egorkin, V.E. Zemlyakov, A.V. Nezhentsev, V.I. Garmash. Semiconductors, **52** (15), 1969 (2018).