Ti/Al/X/Au Au-Contained Ohmic Contact Technique

Subjects: Physics, Applied

Contributor: Lin-Qing Zhang , Xiao-Li Wu , Wan-Qing Miao , Zhi-Yan Wu , Qian Xing , Peng-Fei Wang

AlGaN/GaN high electron mobility transistors (HEMTs) are regarded as promising candidates for a 5G communication system, which demands higher frequency and power. Source/drain ohmic contact is one of the key fabrication processes crucial to the device performance. Firstly, Aucontained metal stacks combined with RTA high-temperature ohmic contact schemes were presented and analyzed, including process conditions and contact formation mechanisms. Considering the issues with the Au-contained technique, the overview of a sequence of Au-free schemes is given and comprehensively discussed. In addition, in order to solve various problems caused by hightemperature conditions, novel annealing techniques including microwave annealing (MWA) and laser annealing (LA) were proposed to form Au-free low-temperature ohmic contact to AlGaN/GaN HEMT. The most popular metallization schemes of ohmic contact in AlGaN/GaN HEMT is Ti/Al/X/Au, where X can be Ni, Mo, Pt, Ta, Ir, etc.

AlGaN/GaN HEMT ohmic contact

1. Introduction

Traditional Si-based radio frequency (RF) and power devices, due to the physical limitation of Si material, cannot meet the requirements of higher-speed and higher-power in a 5G generation communication system. GaN-based HEMTs are regarded as promising candidates for high-frequency and high-power electronic devices due to their superior material properties [1][2][3][4]. The GaN-based materials are always heterogeneous and grown on other substrates, such as Si, SiC, and sapphire [5][6][7][8]. Among the heterojunction device structures, the AlGaN/GaN HEMT exhibits the best electronic characteristics [9][10][11]. Furthermore, the AlGaN/GaN-on-Si is the structure most commonly selected for power application for the following reasons [12][13][14][15]: the fabrication process is compatible with Si CMOS process flow, which helps to reduce the manufacturing cost. Realization of a large-size AlGaN/ GaN-on-Si wafer can also further reduce the cost. The regular epitaxial AlGaN/GaN layers are grown on a high-resistivity Si substrate by metal organic chemical vapor deposition (MOCVD), which is shown in **Figure 1**. From Si bottom to top, a GaN buffer layer with a thickness of about 3 μm is deposited for reducing stress caused by lattice mismatch. After that, the device layer is formed by depositing an unintentional doped (UID) GaN device layer (~100 nm), AlN interlayer (~1 nm), and $Al_xGa_{1-x}N$ barrier layer (~25 nm, x varies from 0.15–0.4). The two-dimensional electron gas (2DEG) is formed at the AlGaN/GaN interface due to the polarization effect [16][17]. Finally, the GaN cap layer (~3 nm) is deposited for protecting the device surface.

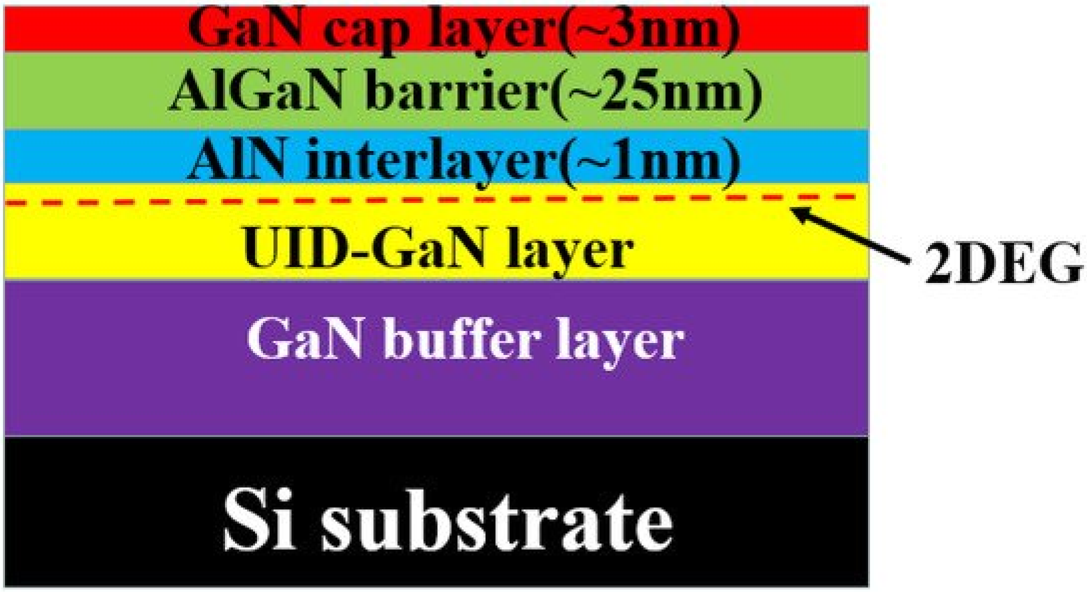

Figure 1. Schematic AlGaN/GaN-on Si device structure.

For RF application, the gate of the fabricated device is always formed in a T-shape for smaller gate resistance [18][19][20]. The process flow, which can be seen in **Figure 2**, consists of mesa isolation, source/drain ohmic contact formation, SiN passivation, T-shape gate formation, gate electrode deposition, via formation, and testing electrode deposition.

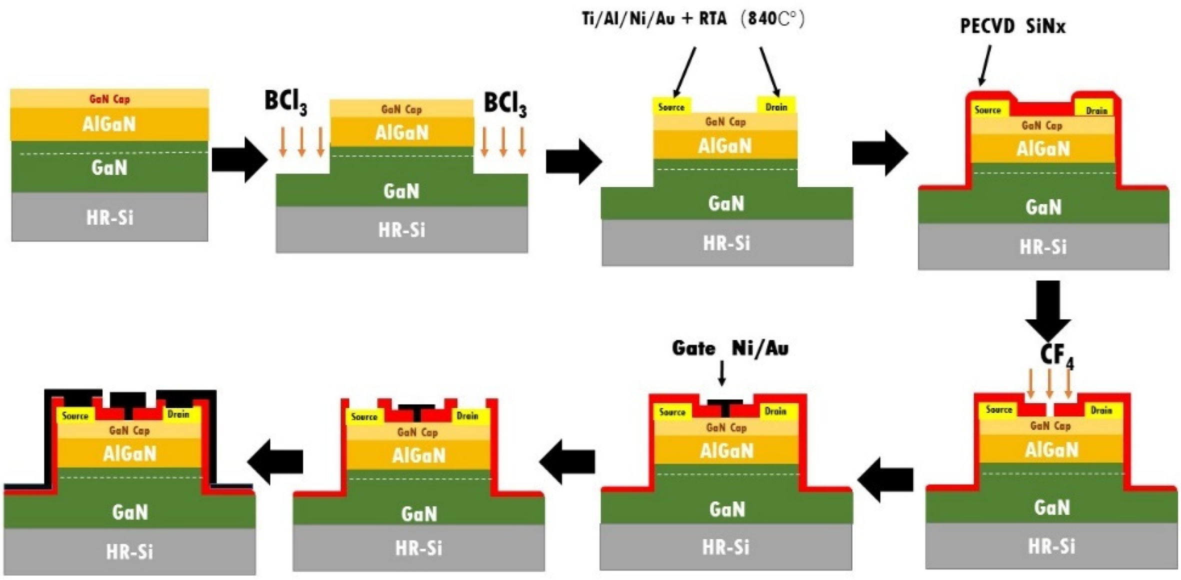

Figure 2. Schematic process flow of T-shaped AlGaN/GaN HEMT.

For power application, the gate is fabricated in a regular shape, as shown in **Figure 3**. The fabrication process consists of mesa isolation, source/drain ohmic contact formation, gate electrode deposition, SiN passivation, via formation, and testing electrode deposition.

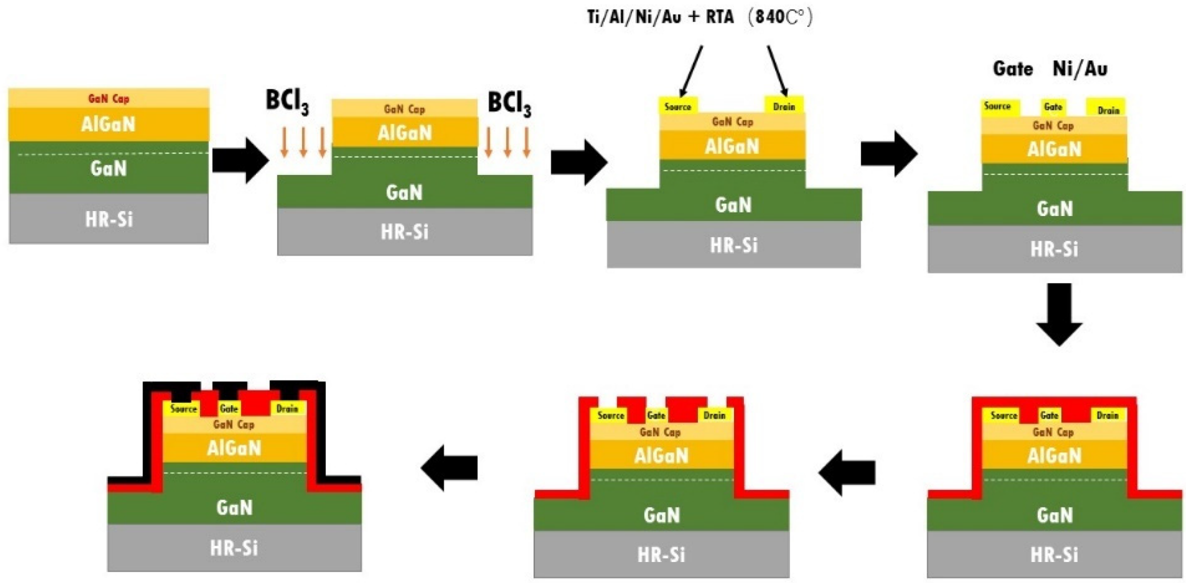

Figure 3. Schematic process flow of regular AlGaN/GaN HEMT.

The quality of source/drain ohmic contact has a great impact on the performance of AlGaN/GaN HEMT, such as on-resistance (R_{on}), output current (I_{DS}), extrinsic transconductance (G_m), and current gain cut-off frequency (f_T) [11][21][22][23][24][25]. Always, the source/drain regions form ohmic contact to reduce R_{ON} and improve output current and f_T characteristics. Thus, the source/drain ohmic contact technique should be investigated. Over the years, researchers have systematically investigated ohmic contact to n^+-GaN and AlGaN/GaN for achieving low contact resistance (R_C).

2. Ti/Al/X/Au Au-Contained Ohmic Contact Technique

Considering the wide bandgap of (Al)GaN, two methods are adopted to form good quality ohmic contact: (1) reduce the barrier height(Φ_B) by selecting the appropriate metal and (2) increase the possibility of tunneling by forming an n^+-(Al)GaN surface. The energy band diagram of metal/(Al)GaN by two methods are shown in **Figure 4**.

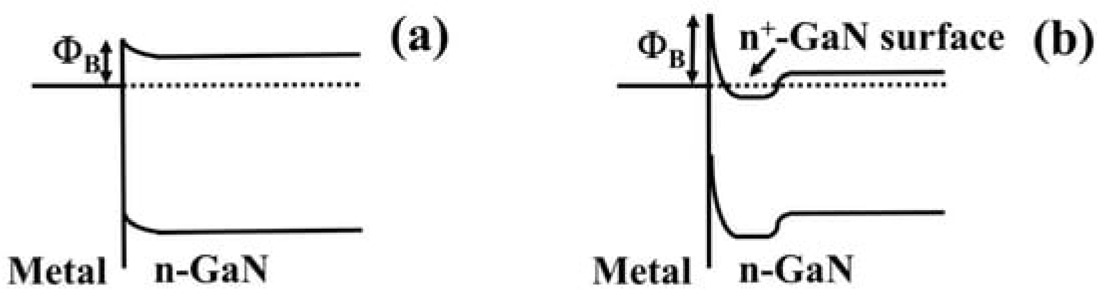

Figure 4. Energy band diagram of metal/(Al)GaN by reducing the barrier height(Φ_B) (**a**) and increasing the possibility of tunneling by forming n^+-(Al)GaN surface (**b**).

For the first method, researchers selected Al, Ti, Au, Ni, Mo, Pd, Pt, Cr, etc. as contact metals and investigated their contact characteristics with (Al)GaN [26][27][28][29][30][31][32][33][34]. The work function (W_m), specific contact resistivity (ρ_c), and Φ_B characteristics of different metal materials can be seen in **Table 1**.

Table 1. W_m, ρ_c, Φ_B characteristics of different metals to (Al)GaN.

Metal	W_m (eV)	ρ_c ($\times 10^{-6}$ Ω/cm^2)	Φ_B (eV)	Refs.
Al	4.28	8	0.8	[26][33]
Ti	4.33	3	0.58	[26][27][28][29][31]
Au	5.1	2.35	0.9	[26][31][32]
Ni	5.15	6.99	1.4	[26][29][32]
Mo	4.6	5.3	0.81	[30]
Pd	5.12	9.78	1.9	[26][34]
Pt	5.65	11	1.6	[26][29]
Cr	4.5	11.8	0.39	[29]

The results indicate that it is challenging to form good quality ohmic contact between single layer metal and (Al)GaN due to the higher W_m of the selected metal material. Also, the Ti, Al, etc. single layers are prone to oxidation during the high-temperature annealing process. Thus, a multilayer metal stack combined with a high-temperature annealing scheme became the common choice for GaN-based devices' source/drain ohmic contact formation [35]. The multilayer metal stack, as shown in **Figure 5**, always consists of four metal layers: the barrier layer, coating layer, diffusion barrier layer, and cap layer. The most popular metal scheme is Ti/Al/X/Au, where X can be Ni, Mo, Pt, Ta, Ir, etc. During the annealing process, the barrier layer Ti reacts with the AlGaN layer to form TiN [36]. TiN carries out lower work function [37], which lowers the Schottky barrier height and therefore helps in ohmic contact formation. Also, the created N vacancies formed in the reaction process make the AlGaN layer underneath the contact metal n^+-doped, which makes electron tunneling easy for ohmic contact formation [38]. Coating layer Al reacts with Ti under the high-temperature atmosphere to form Al_3Ti, which helps in ohmic contact formation [39]. The diffusion layer Ni, Mo, Pt, and Ta etc., which owns high melt point prevents Au indiffusion and Al outdiffusion [40]. Furthermore, the surface morphology of the contact metal can be affected by the metal layer. Au, which acts as a cap layer, prevents the Ti, Al layer oxidation within the high-temperature annealing atmosphere. Also, the Au layer improves the contact conductivity [41].

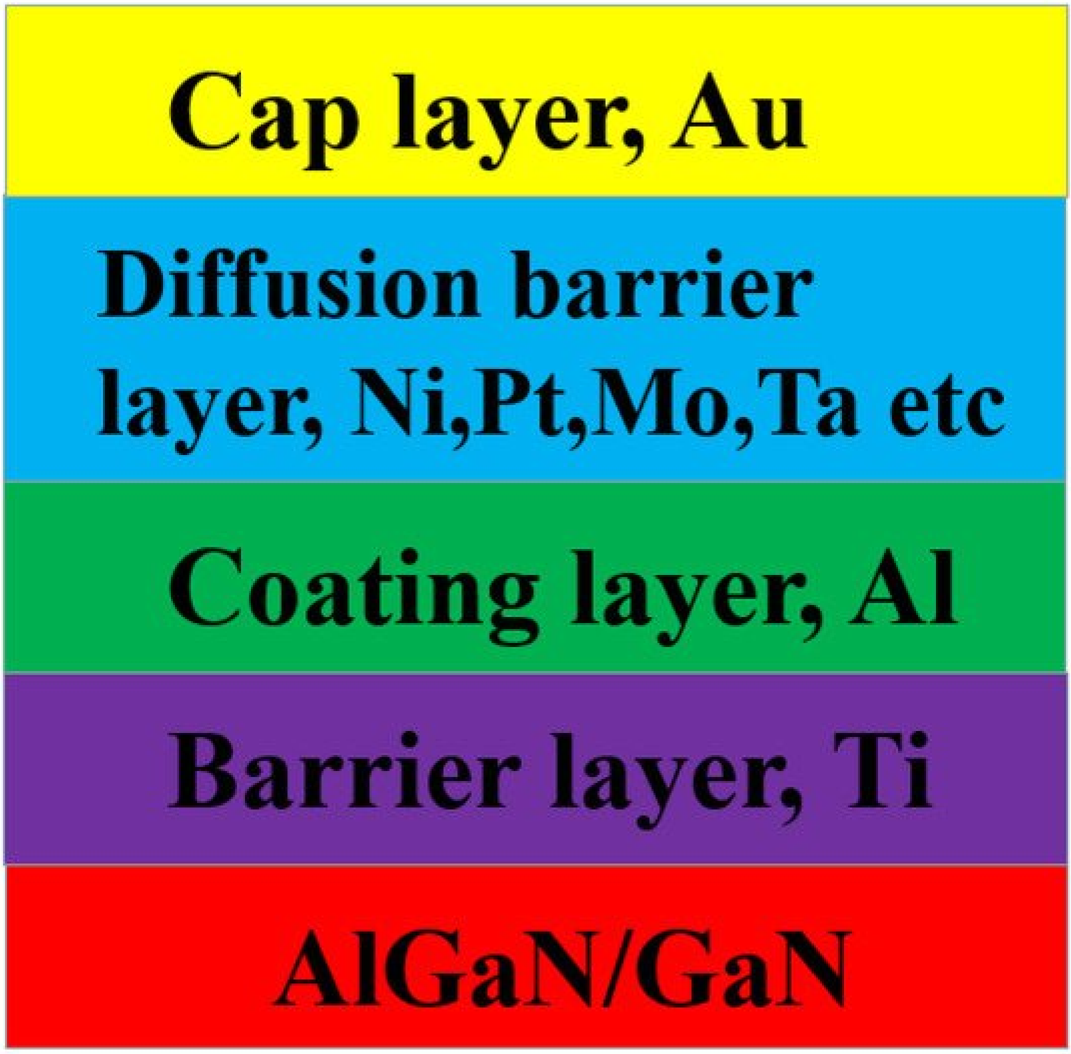

Figure 5. Schematic structure of metal stacks used for forming ohmic contact to AlGaN/GaN HEMT.

Ohmic contact resistance R_C, ρ_c, surface morphology, and thermal stability are the important indexes of ohmic contact quality. The R_C value can be affected by the selected metal stack, the metal thickness, ohmic recessing of the AlGaN layer, surface pre-treatment prior to ohmic metallization, annealing time and temperature, n-type doped in the semiconductor, etc. [40][42][43][44][45][46][47][48][49][50][51]. These affecting factors were investigated and optimized by universities and research institutions. Jacobs B et al. [42] have systematically studied the influence of the metal stack, Ti, Al, Ni thickness, Ti/Al ratio, and annealing condition on R_C. In their results, the achieved optimized R_C is 0.2 Ω·mm with Ti thickness of 30 nm, Ti/Al ratio of 6, Ni thickness of 40 nm, and annealing temperature of 900 °C for 30 s. Yan et al. [47] demonstrated that the R_C can be further reduced by a multi-step annealing process. With the improvement of AlGaN/GaN material growth, ohmic contact formation for metal and AlGaN/GaN becomes challenging. Buttari D et al. [48] developed a low-damage Cl_2 reactive ion etching (RIE) recess etch on an AlGaN layer (7nm), decreasing R_C from 0.45 Ω·mm to 0.27 Ω·mm. By Si ion implantation in the source/drain region, Nomoto K et al. [49] proved that the on-resistance can be decreased dramatically. By etching holes that were 0.8 μm × 0.8 μm in size and etching a depth of 10 nm, Wang et al. [50] developed a pattern of square holes technique in the source/drain AlGaN layer and achieved an R_C as low as 0.1 Ω·mm, as shown in **Figure 6**. The fabricated

AlGaN/GaN HEMTs exhibits comparable output current, peak transconductance and threshold voltage characteristics with conventional AlGaN/GaN HEMTs. Before ohmic contact metal deposition, Fujishima T et al. [51] developed a $SiCl_4$ and BCl_3 plasma treatment on the source/drain surface and achieved low R_C values of 0.41 Ω·mm and 0.17 Ω·mm, respectively. By optimizing the affecting factors of Ti/Al/X/Au schemes, the achieved R_C can be as low as 0.3 Ω·mm, and even much lower. The obtained low R_C can meet the requirements for the RF and power applications of AlGaN/GaN HEMT by using Ti/Al/Ni/Au metal schemes.

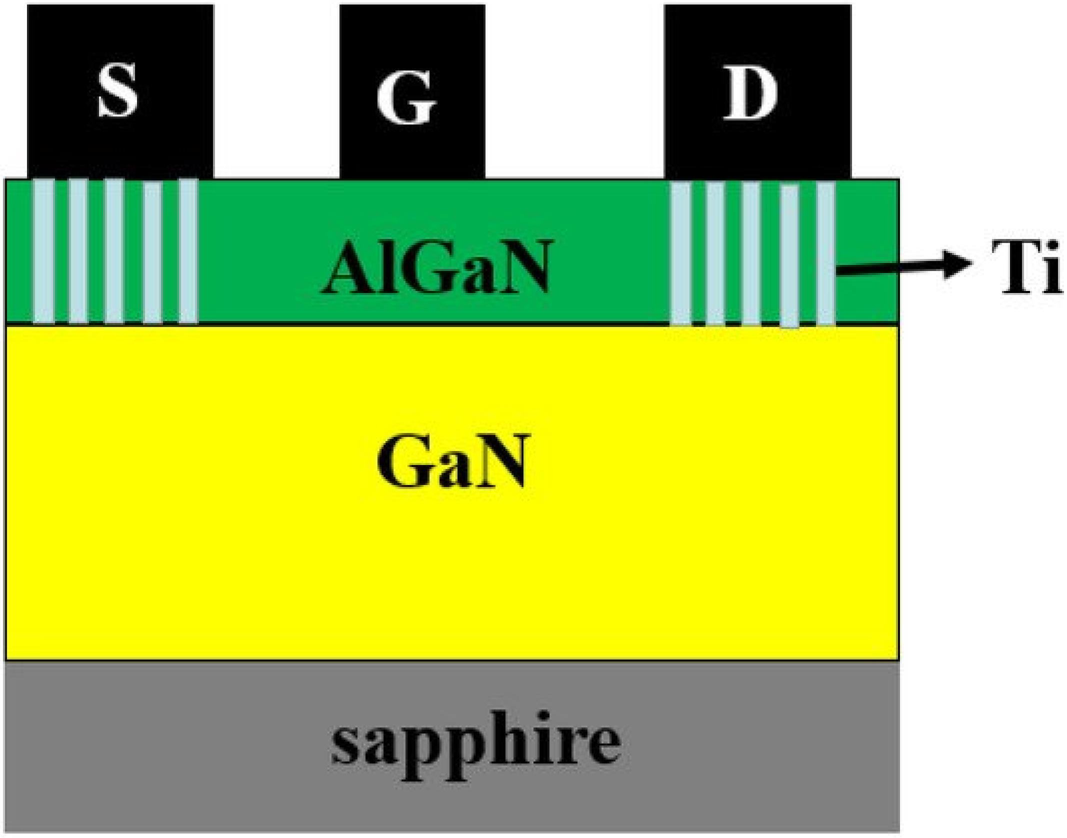

Figure 6. Schematic structure of AlGaN/GaN HEMT with holes etching in the ohmic region.

Universities and industries have conducted studies on the ohmic contact formation mechanism. Two methods are regarded as the mechanism to form ohmic contact to AlGaN/GaN HEMT: (1) a field emission (FE) tunneling mechanism [52][53][54] via the formation of a thinner high doping or a lower barrier; and (2) a spike mechanism [55][56] by TiN direct electron path formation along the dislocation. In the FE tunneling mechanism, Ti reacts with the GaN or AlGaN layer to form TiN. N should be extracted from GaN or AlGaN, generating a highly n-doped interface region, which is responsible for the occurrence of FE tunneling. The work function of TiN (3.74 eV) is lower than Ti (4.33 eV), which is believed to lower the Schottky barrier for low-resistance ohmic contact formation. In the spike mechanism, the TiN projections forming along the dislocation places penetrate through the AlGaN layer under a high temperature, which sets up a direct electron path connecting the 2DEG and the ohmic metal. This method is believed to be more efficient in electron transferring than the FE tunneling mode. With the improvement of AlGaN/GaN material growth, the spike phenomenon, which penetrates through the whole AlGaN layer, becomes less likely to happen. The cross-sectional diagrams of both physical models are shown in **Figure 7**, which reveals the ohmic contact formation mechanism.

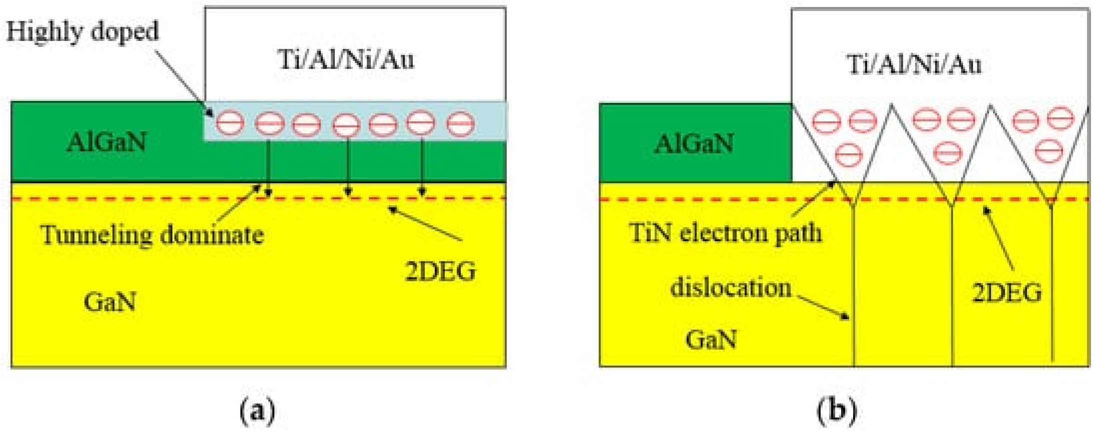

Figure 7. Physical models of Ti/Al/Ni(x)/Au ohmic contact to AlGaN/GaN HEMT: FE tunneling mechanism (**a**) and spike mechanism (**b**).

References

1. Chen, K.J.; Häberlen, O.; Lidow, A.; lin Tsai, C.; Ueda, T.; Uemoto, Y.; Wu, Y. GaN-on-Si power technology: Devices and applications. IEEE Trans. Electron Devices 2017, 64, 779–795.
2. He, J.; Cheng, W.C.; Wang, Q.; Cheng, K.; Yu, H.; Chai, Y. Recent Advances in GaN-Based Power HEMT Devices. Adv. Electron. Mater. 2021, 7, 2001045.
3. Mishra, U.K.; Shen, L.; Kazior, T.E.; Wu, Y.F. GaN-based RF power devices and amplifiers. Proc. IEEE 2008, 96, 287–305.
4. Palacios, T.; Chakraborty, A.; Rajan, S.; Poblenz, C.; Keller, S.; DenBaars, S.P.; Speck, J.S.; Mishra, U.K. High-power AlGaN/GaN HEMTs for ka-band applications. IEEE Electron Device Lett. 2005, 26, 781–783.
5. Pengelly, R.S.; Wood, S.M.; Milligan, J.W.; Sheppard, S.T.; Pribble, W.L. A review of GaN on SiC high electron-mobility power transistors and MMICs. IEEE Trans. Microw. Theory Tech. 2012, 60, 1764–1783.
6. Pérez-Tomás, A.; Fontserè, A.; Llobet, J.; Placidi, M.; Rennesson, S.; Baron, N.; Chenot, S.; Moreno, J.C.; Cordier, Y. Analysis of the AlGaN/GaN vertical bulk current on Si, sapphire, and free-standing GaN substrates. J. Appl. Phys. 2013, 113, 174501.
7. Liang, Z.; Du, H.; Yuan, Y.; Wang, Q.; Kang, J.; Zhou, H.; Zhang, J.; Hao, Y.; Wang, X.; Zhang, G. Ultra-thin AlGaN/GaN HFET with a high breakdown voltage on sapphire substrates. Appl. Phys. Lett. 2021, 119, 252101.

8. Ishida, M.; Ueda, T.; Tanaka, T.; Ueda, D. GaN on Si technologies for power switching devices. IEEE Trans. Electron Devices 2013, 60, 3053–3059.
9. Wośko, M.; Szymański, T.; Paszkiewicz, B.; Pokryszka, P.; Paszkiewicz, R. MOVPE growth conditions optimization for AlGaN/GaN/Si heterostructures with SiN and LT-AlN interlayers designed for HEMT applications. J. Mater. Sci. Mater. Electron. 2019, 30, 4111–4116.
10. Baliga, B.J. Power semiconductor device figure of merit for high-frequency applications. IEEE Electron Device Lett. 1989, 10, 455–457.
11. Tang, Y.; Shinohara, K.; Regan, D.; Corrion, A.; Brown, D.; Wong, J.; Schmitz, A.; Fung, H.; Kim, S.; Micovic, M. Ultrahigh-speed GaN high-electron-mobility transistors with fT/fmax of 454/444 GHz. IEEE Electron Device Lett. 2015, 36, 549–551.
12. Su, M.; Chen, C.; Rajan, S. Prospects for the application of GaN power devices in hybrid electric vehicle drive systems. Semicond. Sci. Technol. 2013, 28, 074012.
13. Freedsman, J.J.; Egawa, T.; Yamaoka, Y.; Yano, Y.; Ubukata, A.; Tabuchi, T.; Matsumoto, K. Normally-off Al2O3/AlGaN/GaN MOS-HEMT on 8 in. Si with low leakage current and high breakdown voltage (825 V). Appl. Phys. Express 2014, 7, 041003.
14. Egawa, T. Heteroepitaxial growth and power electronics using AlGaN/GaN HEMT on Si. In Proceedings of the 2012 International Electron Devices Meeting, San Francisco, CA, USA, 10–13 December 2012.
15. Then, H.W.; Radosavljevic, M.; Agababov, P.; Ban, I.; Bristol, R.; Chandhok, M.; Chouksey, S.; Holybee, B.; Huang, C.Y.; Krist, B.; et al. GaN and Si Transistors on 300mm Si (111) Enabled by 3D Monolithic Heterogeneous Integration. In Proceedings of the 2020 IEEE Symposium on VLSI Technology, Honolulu, HI, USA, 16–19 June 2020; pp. 1–2.
16. Asbeck, P.M.; Yu, E.T.; Lau, S.S.; Sullivan, G.J.; Van Hove, J.; Redwing, J. Piezoelectric charge densities in AlGaN/GaN HFETs. Electron. Lett. 1997, 33, 1230–1231.
17. Katz, O.; Horn, A.; Bahir, G.; Salzman, J. Electron mobility in an AlGaN/GaN two-dimensional electron gas. I. Carrier concentration dependent mobility. IEEE Trans. Electron Devices 2003, 50, 2002–2008.
18. Jessen, G.H.; Fitch, R.C.; Gillespie, J.K.; Via, G.; Crespo, A.; Langley, D.; Denninghoff, D.J.; Trejo, M.; Heller, E.R. Short-channel effect limitations on high-frequency operation of AlGaN/GaN HEMTs for T-gate devices. IEEE Trans. Electron Devices 2007, 54, 2589–2597.
19. Ranjan, K.; Arulkumaran, S.; Ng, G.I.; Vicknesh, S. High Johnson’s figure of merit (8.32 THz· V) in 0.15-µm conventional T-gate AlGaN/GaN HEMTs on silicon. Appl. Phys. Express 2014, 7, 044102.

20. Androse, D.R.; Deb, S.; Radhakrishnan, S.K.; Sekar, E. T-gate AlGaN/GaN HEMT with effective recess engineering for enhancement mode operation. Mater. Today Proc. 2021, 45, 3556–3559.
21. Tasker, P.J.; Hughes, B. Importance of source and drain resistance to the maximum fT of millimeter-wave MODFETs. IEEE Electron Device Lett. 1989, 10, 291–293.
22. Li, L.; Nomoto, K.; Pan, M.; Li, W.S.; Hickman, A.; Miller, J.; Lee, K.; Hu, Z.Y.; Bader, S.J.; Lee, S.M.; et al. GaN HEMTs on Si with regrown contacts and cutoff/maximum oscillation frequencies of 250/204 GHz. IEEE Electron Device Lett. 2020, 41, 689–692.
23. Shinohara, K.; Corrion, A.; Regan, D.; Milosavljevic, I.; Brown, D.; Burnham, S.; Willadsen, P.J.; Butler, C.; Schmitz, A.; Wheeler, D.; et al. 220GHz fT and 400GHz fmax in 40-nm GaN DH-HEMTs with re-grown ohmic. In Proceedings of the 2010 International Electron Devices Meeting, San Francisco, CA, USA, 6–8 December 2010.
24. Brown, D.F.; Shinohara, K.; Corrion, A.L.; Chu, R.; Williams, A.; Wong, J.C.; Rodriguez, I.A.; Grabar, R.; Johnson, M.; Butler, C.M.; et al. High-Speed, Enhancement-Mode GaN Power Switch with Regrown n+ GaN Ohmic Contacts and Staircase Field Plates. IEEE Electron Device Lett. 2013, 34, 1118–1120.
25. Zhang, L.Q.; Huang, H.F.; Liu, X.Y.; Shi, J.S.; Liu, Z.; Zhao, S.X.; Wang, P.F. Two-dimensional device simulation for radio frequency performance of AlGaN/GaN HEMT, Semiconductor Technology International Conference. In Proceedings of the 2015 China Semiconductor Technology International Conference, Shanghai, China, 15–16 March 2015; pp. 1–3.
26. Rickert, K.A.; Ellis, A.B.; Kim, J.K.; Lee, J.L.; Himpsel, F.J.; Dwikusuma, F.; Kuech, T.F. X-ray photoemission determination of the Schottky barrier height of metal contacts to n-GaN and p-GaN. J. Appl. Phys. 2002, 92, 6671–6678.
27. Hirsch, M.T.; Duxstad, K.J.; Haller, E.E. Effects of annealing on Ti Schottky barriers on n-type GaN. Electron. Lett. 1997, 33, 95–96.
28. Binari, S.C.; Dietrich, H.B.; Kelner, G.; Rowland, L.B.; Doverspike, K.; Gaskill, D.K. Electrical characterisation of Ti Schottky barriers on n-type GaN. Electron. Lett. 1994, 30, 909–911.
29. Lee, M.L.; Sheu, J.K.; Lin, S.W. Schottky barrier heights of metal contacts to n-type gallium nitride with low-temperature-grown cap layer. Appl. Phys. Lett. 2006, 88, 032103.
30. Reddy, V.R.; Ramesh, C.K.; Choi, C.J. Structural and electrical properties of Mo/n-GaN Schottky diodes. Phys. Status Solidi A 2006, 203, 622–627.
31. Wu, Y.F.; Jiang, W.N.; Keller, B.P.; Keller, S.; Kapolnek, D.; Denbaars, S.P.; Mishra, U.K.; Wilson, B. Low resistance ohmic contact to n-GaN with a separate layer method. Solid-State Electron. 1997, 41, 165–168.

32. Schmitz, A.C.; Ping, A.T.; Khan, M.A.; Chen, Q.; Yang, J.W.; Adesida, I. Metal contacts to n-type GaN. J. Electron. Mater. 1998, 27, 255–260.
33. Luther, B.P.; Mohney, S.E.; Jackson, T.N.; Asif Khan, M.; Chen, Q.; Yang, J.W. Investigation of the mechanism for Ohmic contact formation in Al and Ti/Al contacts to n-type GaN. Appl. Phys. Lett. 1997, 7, 57–59.
34. Ping, A.T.; Khan, M.A.; Adesida, I. Ohmic contacts to n-type GaN using Pd/Al metallization. J. Electron. Mater. 1996, 25, 819–824.
35. Fan, Z.; Mohammad, S.N.; Kim, W.; Aktas, Ö.; Botchkarev, A.E.; Morkoç, H. Very low resistance multilayer Ohmic contact to n-GaN. Appl. Phys. Lett. 1996, 68, 1672–1674.
36. Wang, L.; Mohammed, F.M.; Adesida, I. Differences in the reaction kinetics and contact formation mechanisms of annealed Ti/Al/Mo/Au Ohmic contacts on n-Ga N and AlGaN/GaN epilayers. J. Appl. Phys. 2007, 101, 013702.
37. Luther, B.P.; Mohney, S.E.; Jackson, T.N. Titanium and titanium nitride contacts to n-type gallium nitride. Semicond. Sci. Technol. 1998, 13, 1322.
38. Kim, J.K.; Jang, H.W.; Lee, J.L. Mechanism for Ohmic contact formation of Ti on n-type GaN investigated using synchrotron radiation photoemission spectroscopy. J. Appl. Phys. 2002, 91, 9214–9217.
39. Van Daele, B.; Van Tendeloo, G.; Ruythooren, W.; Derluyn, J.; Leys, M.R.; Germain, M. The role of Al on Ohmic contact formation on n-type GaN and AlGaN/GaN. Appl. Phys. Lett. 2005, 87, 061905.
40. Mohammed, F.M.; Wang, L.; Selvanathan, D.; Hu, H.; Adesida, I. Ohmic contact formation mechanism of Ta/Al/Mo/Au and Ti/Al/Mo/Au metallizations on AlGaN/GaN HEMTs. J. Vac. Sci. Technol. B Microelectron. Nanometer Struct. Processing Meas. Phenom. 2005, 23, 2330–2335.
41. Qin, Z.X.; Chen, Z.Z.; Tong, Y.Z.; Ding, X.M.; Hu, X.D.; Yu, T.J.; Zhang, G.Y. Study of Ti/Au, Ti/Al/Au, and Ti/Al/Ni/Au ohmic contacts to n-GaN. Appl. Phys. A Mater. Sci. Processing 2004, 78, 729–731.
42. Jacobs, B.; Kramer, M.; Geluk, E.J.; Karouta, F. Optimization of the Ti/Al/Ni/Au ohmic contact on AlGaN/GaN FET structures. J. Cryst. Growth 2002, 241, 15–18.
43. Kong, X.; Wei, K.; Liu, G.; Liu, X. Role of Ti/Al relative thickness in the formation mechanism of Ti/Al/Ni/Au Ohmic contacts to AlGaN/GaN heterostructures. J. Phys. D Appl. Phys. 2012, 45, 265101.
44. Feng, Q.; Li, L.M.; Hao, Y.; Ni, J.Y.; Zhang, J.C. The improvement of ohmic contact of Ti/Al/Ni/Au to AlGaN/GaN HEMT by multi-step annealing method. Solid-State Electron. 2009, 53, 955–958.

45. Yu, H.; McCarthy, L.; Rajan, S.; Keller, S.; Denbaars, S.; Speck, J.; Mishra, U. Ion implanted AlGaN-GaN HEMTs with nonalloyed ohmic contacts. IEEE Electron Device Lett. 2005, 26, 283–285.
46. Brown, D.F.; Williams, A.; Shinohara, K.; Kurdoghlian, A.; Milosavljevic, I.; Hashimoto, P.; Grabar, R.; Burnham, S.; Bulter, C.; Willadsen, P. W-band power performance of AlGaN/GaN DHFETs with regrown n+ GaN ohmic contacts by MBE. In Proceedings of the International Electron Devices Meeting, Washington, DC, USA, 5–7 December 2011.
47. Yan, W.; Zhang, R.; Du, Y.; Han, W.; Yang, F. Analysis of the ohmic contacts of Ti/Al/Ni/Au to AlGaN/GaN HEMTs by the multi-step annealing process. J. Semicond. 2012, 33, 064005.
48. Buttari, D.; Chini, A.; Meneghesso, G.; Zanoni, E.; Moran, B.; Heikman, S.; Zhang, N.Q.; Shen, L.; Coffie, R.; DenBaars, S.P.; et al. Systematic characterization of Cl2 reactive ion etching for improved ohmics in AlGaN/GaN HEMTs. IEEE Electron Device Lett. 2002, 23, 76–78.
49. Recht, F.; McCarthy, L.; Rajan, S.; Chakraborty, A.; Poblenz, C.; Corrion, A.; Speck, J.S.; Mishra, U.K. Nonalloyed ohmic contacts in AlGaN/GaN HEMTs by ion implantation with reduced activation annealing temperature. IEEE Electron Device Lett. 2006, 27, 205–207.
50. Wang, C.; He, Y.; Zheng, X.; Zhao, M.; Mi, M.; Li, X.; Mao, W.; Ma, X.; Hao, Y. Low ohmic-contact resistance in AlGaN/GaN high electron mobility transistors with holes etching in ohmic region. Electron. Lett. 2015, 51, 2145–2147.
51. Fujishima, T.; Joglekar, S.; Piedra, D.; Lee, H.S.; Zhang, Y.; Uedono, A.; Palacios, T. Formation of low resistance ohmic contacts in GaN-based high electron mobility transistors with BCl3 surface plasma treatment. Appl. Phys. Lett. 2013, 103, 083508.
52. Bright, A.N.; Thomas, P.J.; Weyland, M.; Tricker, D.M.; Humphreys, C.J.; Davies, R. Correlation of contact resistance with microstructure for Au/Ni/Al/Ti/AlGaN/GaN ohmic contacts using transmission electron microscopy. J. Appl. Phys. 2001, 89, 3143–3150.
53. Boudart, B.; Trassaert, S.; Wallart, X.; Pesant, J.C.; Yaradou, O.; Théron, D.; Crosnier, Y.; Lahreche, H.; Omnes, F. Comparison between TiAl and TiAlNiAu ohmic contacts to n-type GaN. J. Electron. Mater. 2000, 29, 603–606.
54. Mohammad, S.N. Contact mechanisms and design principles for nonalloyed ohmic contacts to n-GaN. J. Appl. Phys. 2004, 95, 4856–4865.
55. Wang, L.; Mohammed, F.M.; Adesida, I. Formation mechanism of Ohmic contacts on AlGaN/GaN heterostructure: Electrical and microstructural characterizations. J. Appl. Phys. 2008, 103, 093516.
56. Vertiatchikh, A.; Kaminsky, E.; Teetsov, J.; Robinson, K. Structural properties of alloyed Ti/Al/Ti/Au and Ti/Al/Mo/Au ohmic contacts to AlGaN/GaN. Solid-State Electron. 2006, 50, 1425–1429.

Retrieved from https://encyclopedia.pub/entry/history/show/59199