Effect of thermal annealing on the transport properties of Ti/AlGaN/GaN low-barrier Mott diodes

© N.V. Vostokov, M.N. Drozdov, S.A. Kraev, O.I. Khrykin, P.A. Yunin

Institute of Physics of Microstructures, Russian Academy of Sciences,
603950 Nizhny Novgorod, Russia

E-mail: vostokov@ipm.sci-nnov.ru

Received March 2, 2022
Revised March 25, 2022
Accepted March 25, 2022

The influence of thermal annealing on the transport properties of Ti/AlGaN/GaN low-barrier Mott diodes with near-surface polarization-induced δ-doping has been studied. It is shown that annealing provides additional possibilities for controlling the effective barrier height of diodes, improving and fine-tuning their transport characteristics. Thermal annealing can be used to fabricate low-barrier diodes designed to operate at high temperatures.

Keywords: low-barrier diode, GaN, transport properties, thermal annealing.

DOI: 10.21883/SC.2022.07.54641.04

1. Introduction

Schottky (Mott) barrier diodes are the most common non-linear elements in uncooled receivers and RF/DC microwave converters [1,2]. Diodes are widely used in mixing and rectifier circuits. Somewhat less often, Schottky diodes are used as quadratic and video detectors [3]. To ensure high sensitivity in detection, diodes with lowered effective height of the Schottky barrier are needed, which makes it possible not to use the constant bias. This simplifies the design of the receiver and reduces the noise level due to the absence of permanent bias current. As an example, one can consider GaAs-based low-barrier Mott diodes with near-surface isotype δ-doping [4–6]. In the mixing mode of operation, lowering the effective barrier height of the diode makes it possible to reduce the required power level of the local oscillator [7,8], in a rectifying mode it increases the efficiency of RF/DC conversion at low microwave signal power [9,10].

The specificity of wide bandgap nitrides lies in the possibility of creating devices that operate at high temperatures, exposure to radiation and in aggressive environments. Thermodynamically stable phase of semiconductor compounds $(Ga, Al, In)N$ is the hexagonal wurtzite-type structure. The symmetry group of wurtzite allows the existence of a polar direction along the c-axis of the hexagonal lattice, with which the electric polarization is associated in the crystal. The polarization is directed from the nitrogen atom to the metal atom and increases in absolute value in the sequence GaN, InN, AlN. In the inhomogeneous sample and in the sample of finite dimensions, the presence of polarization leads to the appearance of electric field, band bending, and redistribution of charge carriers. In pseudomorphic heterostructures, to the spontaneous polarization of the semiconductor layers, their piezoelectric polarization associated with the elastic deformation of the crystal lattice of the pseudomorphic layer is added. Polarization effects in wide bandgap nitrides are much stronger than in other semiconductors and can be used as an additional degree of freedom in the development of instrumental heterostructures based on these materials [11].

In our recent work [12], the possibility of reducing the effective height of the Mott barrier to the AlGaN/GaN heterostructure with Ga-face polarity due to polarization-induced δ doping of the heterojunction was experimentally shown. The positive polarization charge arising in the plane of the AlGaN/GaN heterointerface due to the polarization jump forms a potential relief with the tunnel-transparent trapezoidal barrier near the interface with the metal, which reduces the effective height of the diode barrier. In this case, the polarization charge plays the same role as the charge of ionized δ-layer donors in GaAs based low-barrier Mott diodes [4]. The effect is demonstrated in Fig. 1, where the coordinate dependences of the position of the bottom of conduction band in diode heterostructures are schematically shown: curve *1* is plotted for conventional metal/GaN Mott diode; curve *2* is plotted for low-barrier metal/AlGaN/GaN diode. Using this approach, low-barrier Ti/AlGaN/GaN diodes with high values of ampere-watt sensitivity $\alpha = -R'/(2R)$ at low specific differential resistance R at zero bias, were fabricated [12]. This work is devoted to studying the effect of thermal annealing on the transport properties of such diodes.

2. Description of diodes and research methods

Heterostructures were grown under reduced pressure in an original metalorganic vapor phase epitaxy facility with inductive heated vertical quartz reactor [13]. As substrates, two-inch sapphire wafers with c-plane orientation (0001) in parallel to the wafer surface, were used. The sources

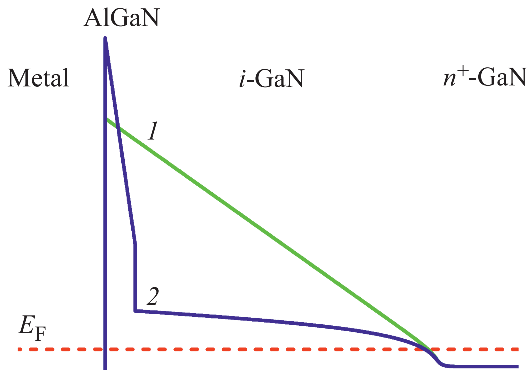

Figure 1. Band diagrams of diode heterostructures: *1* — metal/GaN; *2* — metal/AlGaN/GaN.

of gallium, aluminum, and nitrogen were trimethylgallium, trimethylaluminum, and ammonia. Monosilane diluted with hydrogen provided donor doping of GaN. Before the formation of the working layers of the heterostructure, the low-temperature GaN nucleating layer was grown. Then followed: heavily doped n^+-GaN layer $2\,\mu$m thick; undoped i-GaN layer 120 nm thick; undoped $Al_xGa_{1-x}N$ layer $d = 0-3$ nm thick. Analysis of the chemical composition of the heterostructures was carried out by secondary ion mass spectrometry (SIMS) in the TOF.SIMS-5 (IONTOF) facility. The thicknesses of the $Al_xGa_{1-x}N$ layers in heterostructures are comparable to the depth resolution in layer-by-layer SIMS analysis. Therefore, the Al content in the layers and their thickness were determined from the totality of data using the SIMS profile reconstruction technique [14] and simulation of the current-voltage ($I-V$) characteristics of diodes. This procedure is described in more detail in [12]. Barrier contacts of Ti/Au diodes (50 nm/100 nm) were formed on the surface of heterostructures by electron-beam vaporization. To measure the volt-ampere characteristic, contacts with diameter of $5\,\mu$m were used. Ohmic contact to the n^+-GaN layer was formed by fusing the indium drop deposited onto the semiconductor surface. $I-V$ characteristics were measured using the 4200-SCS parameter analyzer (Keithley Instruments). Thermal annealing of the diodes was carried out in the AccuThermo AW410 facility (Allwin21 Corporation) in an atmosphere of high-purity argon.

3. Results and discussion

Fig. 2 shows the $I-V$ characteristics of three diodes: D1, D2 and D3. D1 is ordinary Ti/GaN Mott diode. The barrier height of the diode determined from the $I-V$ characteristics is 0.52 eV, the non-ideality factor is 1.09. The addition of an $Al_xGa_{1-x}N$ layer with $x \approx 0.15$ and the thickness of $d \approx 1$ nm to the structure at the interface with the metal leads to the increase in the forward current of the diode by much orders of magnitude — diode D2. This diode has a high value of $\alpha = 9$ A/W at zero bias for the small value of $R = 4 \cdot 10^{-4}\,\text{Ohm} \cdot \text{cm}^2$. Diode D3 is similar to D2 but with more thick $Al_xGa_{1-x}N$ layer and more high content of Al: $d \approx 2.3$ nm, $x \approx 0.3$. Unlike diode D2, the $I-V$ characteristic of diode D3 is close to symmetrical one near zero bias (value α is close to zero). This is due to the fact that the bias voltage is mainly impressed between the metal and the degenerate two-dimensional electron gas (2DEG) formed near the AlGaN/GaN heterointerface [12]. As it turned out, diode D3 can be made as rectifying one using thermal annealing. Let's consider the effect of annealing on transport characteristics via example of this diode.

Fig. 3 shows dependences of R and α of diode D3 on voltage before and after successive annealing processes. Annealing for 5 min at temperature of 300°C led to the increase in the resistance and rectifying $I-V$ characteristic of the diode ($\alpha = 4$ A/W at zero bias) due to the growth

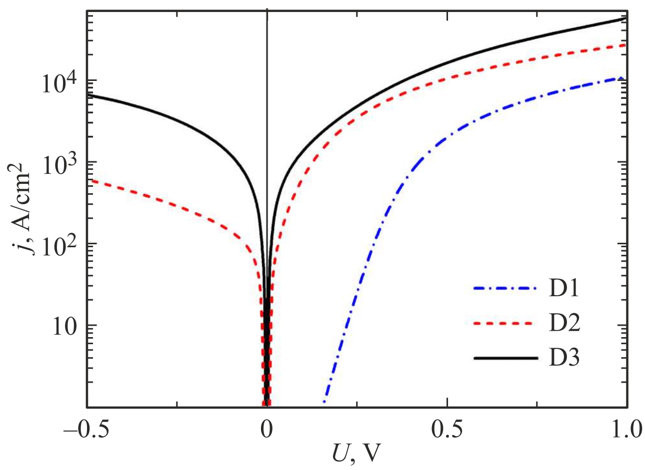

Figure 2. $I-V$ characteristics of diodesD1, D2 and D3.

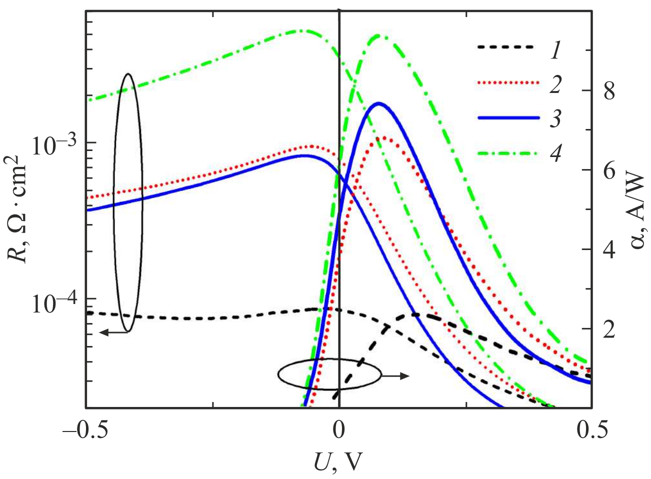

Figure 3. Dependences of specific differential resistance and ampere-watt sensitivity of diode D3 on voltage before and after successive annealing processes. Curves *1* — before annealing; curves *2, 3* and *4* — after annealing at temperatures of 300, 500, and 700°C, respectively.

the height of Ti/AlGaN barrier and, as a consequence, the disappearance of 2DEG. Such increase in the height of the Schottky barrier as a result of annealing structures with Ti/(Al)GaN contacts at temperatures of $< 400^\circ$C is described in the literature and is associated with the chemical interaction of the interphase oxide layer with titanium, which leads to the formation of a closer contact [15,16]. Subsequent annealing of the diode for 5 min at temperature of 500°C led to further increase α, but to decrease R ($R = 6 \cdot 10^{-4}\,\mathrm{Ohm}\cdot\mathrm{cm}^2$, $\alpha = 5\,\mathrm{A/W}$ at zero bias) due to diffusion of nitrogen into the metal, formation of heavily doped nitrogen vacancies in the near-contact layer of the semiconductor and decrease in the effective barrier height of the diode [16,17]. After annealing for 1 min at temperature of 700°C, the diode resistance increased again, which may be due to the degradation of the polarization properties of the AlGaN layer due to chemical interaction with titanium.

4. Conclusion

The studies performed show that thermal annealing can have the strong effect on the differential resistance and nonlinear properties of Ti/AlGaN/GaN low-barrier Mott diodes with near-surface polarization-induced δ-doping. This provides additional opportunities for controlling the transport characteristics of diodes and fine-tuning them. Annealing can be used for „quenching“ of low-barrier diodes designed to operate at high temperatures.

Funding

The study has been performed under the state assignment of the Institute for Physics of Microstructures of the Russian Academy of Sciences (subject No. 0030-2021-0023). The equipment of the Center for Collective Use „Physics and Technology of Micro- and Nanostructures“ physically based at the Institute of Physics of Microstructures of the Russian Academy of Sciences was used.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] F. Sizov. Semicond. Sci. Technol., **33** (12), 123001 (2018).
[2] L.-G. Tran, H.-K. Cha, W.-T. Park. Micro and Nano Syst. Lett., **5**, 14 (2017).
[3] E.R. Brown. Solid-State Electron., **48** (10–11), 2051 (2004).
[4] V.I. Shashkin, A.V. Murel, V.M. Daniltsev, O.I. Khrykin. FTP, **36** (5), 537 (2002) (in Russian).
[5] V.I. Shashkin, Y.A. Drjagin, V.R. Zakamov, S.V. Krivov, L.M. Kukin, A.V. Murel, Y.I. Chechenin. Int. J. Infr. Millim. Waves, **8** (11), 945 (2007).
[6] P.V. Volkov, N.V. Vostokov, A.V. Goryunov, L.M. Kukin, V.V. Parshin, E.A. Serov, V.I. Shashkin. Pis'ma v ZhTF, **45** (5), 56 (2019) (in Russian).
[7] V.R. Zakamov, V.I. Shashkin. Radiotekhnika i elektronika, **56** (8), 1009 (2011). (in Russian).
[8] S.A. Korolyov, A.P. Shikov, A.V. Goryunov, V.I. Shashkin. IEEE Sens. Lett., **4** (5), 3500404 (2020).
[9] C.H.P. Lorenz, S. Hemour, K. Wu. EEE Trans. Microw. Theory Techn., **64** (7), 2146 (2016).
[10] B. Kapilevich, V. Shashkin, B. Litvak, G. Yemini, A. Etinger, D. Hardon, Y. Pinhasi. IEEE Microw. Wirel. Compon. Lett., **26** (8), 637 (2016).
[11] *Polarization Effects in Semiconductors: From Ab Initio Theory to Device Applications*, ed. by C. Wood and D. Jena (N.Y., Springer, 2008).
[12] N.V. Vostokov, M.N. Drozdov, O.I. Khrykin, P.A. Yunin, V.I. Shashkin. Appl. Phys. Lett., **116** (1), 013505 (2020).
[13] O.I. Khrykin, A.V. Butin, D.M. Gaponova, V.M. Daniltsev, M.N. Drozdov, Yu.N. Drozdov, A.V. Murel, V.I. Shashkin. FTP, **39** (1), 21 (2005) (in Russian).
[14] P.A. Yunin, Yu.N. Drozdov, M.N. Drozdov, O.I. Khrykin, V.I. Shashkin Surf. Interface Anal., **49** (2), 117 (2017).
[15] M.T. Hirsch, K.J. Duxstad, E.E. Haller. Electron. Lett., **33** (1), 95 (1997).
[16] S. Arulkumaran, T. Egawa, H. Ishikawa, M. Umeno, T. Jimbo. IEEE Trans. Electron Dev., **48** (3), 573 (2001).
[17] Q.Z. Liu, S.S. Lau. Solid-State Electron., **42** (5), 677 (1998).