Analysis of the ohmic contacts of Ti/Al/Ni/Au to AlGaN/GaN HEMTs by the multi-step annealing process*

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Abstract: The multi-step rapid thermal annealing process of Ti/Al/Ni/Au can make good ohmic contacts with both low contact resistance and smooth surface morphology for AlGaN/GaN HEMTs. In this work, the mechanism of the multi-step annealing process is analyzed in detail by specific experimental methods. The experimental results show that annealing temperature and time are very important parameters when optimizing the Ti/Al layer for lower resistance and the Ni/Au layer for smooth surface morphology. It is very important for good ohmic contacts to balance the rate of various reactions by adjusting the annealing temperature and time. We obtained a minimum specific contact resistance of 3.22×10^{-7} $\Omega\cdot cm^2$ on the un-doped AlGaN/GaN structure with an optimized multi-step annealing process.

Key words: AlGaN; GaN; high electron mobility transistor; annealing; ohmic contact

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1. Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) are outstanding devices for applications requiring high frequency, high power and high temperature performance. Owing to the combination of high breakdown electric fields (3.3 MV/cm) and high electron saturation drift velocity (1.5×10^7 cm/s), AlGaN/GaN HEMTs have already shown excellent performance, including a unity current gain cut-off frequency (f_T) that has exceeded 200 GHz[1], a maximum power gain cut-off frequency (f_{max}) that has reached 400 GHz[2], and an output power density in excess of 40 W/mm at 4 GHz. However, in spite of the latest developments in AlGaN/GaN HEMTs technology, a distance still exists between the theoretical expectations and the experimental results. Parasitic resistance of the source and drain is one of the important factors impacting the performance of the devices[3, 4]. Ohmic contacts with low resistance are therefore essential to fully exploit the potential of AlGaN/GaN HEMTs.

Because of the wide band gap of AlGaN, it is difficult to get good ohmic contacts on an AlGaN/GaN structure. Some methods, such as reducing the thickness of the barrier layer[4, 5] or removing AlGaN and re-growing heavily doped material (e.g. InGaN[6]), can effectively make lower contact resistance. However, these processes are complex and hard to control. Typically, depositing a multi-layer metal stack followed by rapid thermal annealing (RTA) at high temperatures is the simplest way to realize ohmic contacts on an AlGaN/GaN structure. A multi-layer metal stack Ti/Al/Ni/Au on an AlGaN surface is the most widely utilized among many contact metallization schemes. In general, Ti/Al layers can reduce contact resistance by reacting with nitrides at the metal/AlGaN interface, forming thin TiN and Al–Ti–N layers with a low work function and leaving a lot of N vacancies, which act as donors[7, 8]. Ni, as a barrier layer, limits the interdiffusion between the upper and lower metals during RTA. The final layer, Au, is adopted to avoid oxidation and decrease the total contact resistance. The annealing temperature and time will determine the performance of the ohmic contacts. Despite traditional single-step annealing under high temperature, a kind of multi-step annealing process of Ti/Al/Ni/Au was developed. The specific contact resistance can be reduced by one order of magnitude by changing the annealing process from one single step to three steps. Compared with single-step annealing, the advantage of the multi-step annealing method is it can enhance the reaction between the metal and the semiconductor without degrading the surface morphology[9]. Although the multi-step annealing process is simple and effective, its mechanism has not yet been

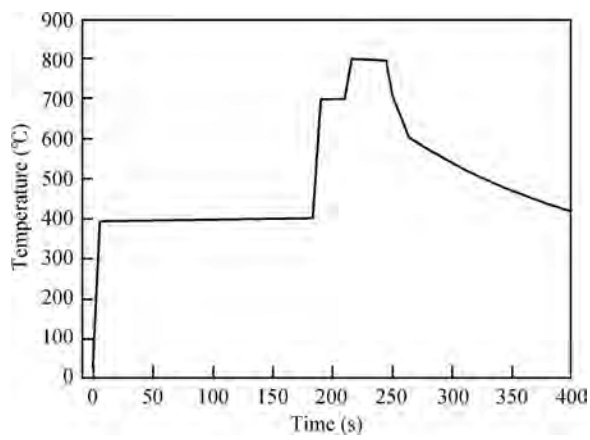

Fig. 1. The process of multi-step annealing.

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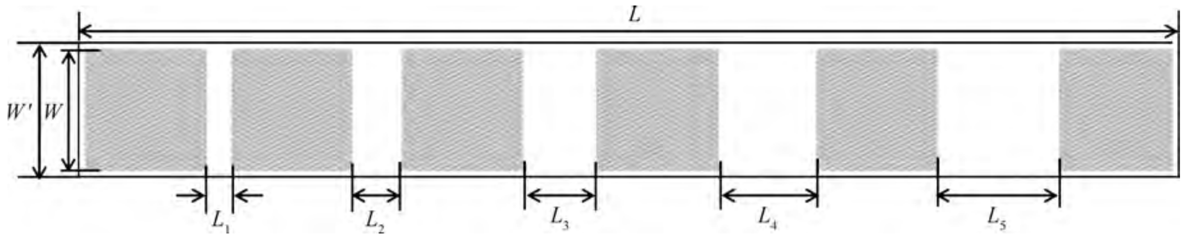

Fig. 2. Image of the TLM test pattern. $W = 100$ μm; $W' = 110$ μm; $L = 910$ μm; $L_1 = 20$ μm; $L_2 = 40$ μm; $L_3 = 60$ μm; $L_4 = 80$ μm; $L_5 = 100$ μm.

fully discussed.

In this work, the mechanism of the multi-step annealing process has been experimentally investigated by transmission line method (TLM) and scanning electron microscopy (SEM) measurements. A two opposite mechanisms theory was proposed. The minimum specific contact resistance obtained was 3.22×10^{-7} $\Omega\cdot$cm^2 on the un-doped AlGaN/GaN structure by an optimized multi-step annealing process.

2. Experimental

AlGaN/GaN heterostructure materials were grown by PAMBE (plasma assisted molecular beam epitaxy) on a 2-inch sapphire substrate. The active layers of the device consist of a 20 nm un-doped $Al_{0.24}Ga_{0.76}N$ layer and a 500 nm un-doped GaN layer. The measured room temperature Hall mobility and sheet carrier concentration are 1180 cm^2/(V$\cdot$s) and 1.1×10^{13} cm^{-2}, respectively. Device processing was initiated with mesa isolation by ICP-RIE. The surfaces of the samples were then treated by HCl : H_2O = 1 : 6 solution to remove the native oxide layer. A metal electrode pattern is formed by e-beam evaporated Ti(20 nm)/Al(120 nm)/Ni(55 nm)/Au(45 nm) and lift-off. The as-deposited samples are introduced into a rapidly thermal processing (RTP) system for annealing in N_2 ambient. Figure 1 shows a typical scheme of the multi-step annealing process. The annealing temperature first rises to 400 ℃ and is sustained for 3 min, then it increases to 700 ℃ rapidly and is annealed for 20 s. Finally the temperature rises to 830 ℃ and is annealed for 30 s[9]. In order to investigate the multi-step annealing mechanism, a series of comparative experiments were performed systematically by changing the annealing time for 400, 700 and 830 ℃. Two-point current–voltage characteristics and surface morphology were measured for analysis of the ohmic contacts. The specific contact resistance was recorded by TLM measurement using an Agilent B1500 semiconductor characterization system. Figure 2 shows an image of the TLM pattern, the contacts of which are rectangular (100×100 μm^2), and separated by 20, 40, 60, 80 and 100 μm.

3. Results and discussion

Figure 3 shows the dependence of ρ_c on the annealing time of 0, 90, 180, 270 and 360 s at 400 ℃ in the first step. As shown in Fig. 1, the ρ_c is reduced slightly, while the time increases from 0 to 180 s. With a further increase in annealing time, the ρ_c does not change very much. As we know, Al has the lowest melting point, 660 ℃, among the Ti/Al/Ni/Au metal stack. During the first annealing step, all of the metals are solid and will not diffuse or react severely. The first annealing step is supposed to eliminate the effects of contamination and allow the substrate temperature to reach 400 ℃ uniformly. Prolonging the annealing time will not affect the performance of the ohmic contacts significantly.

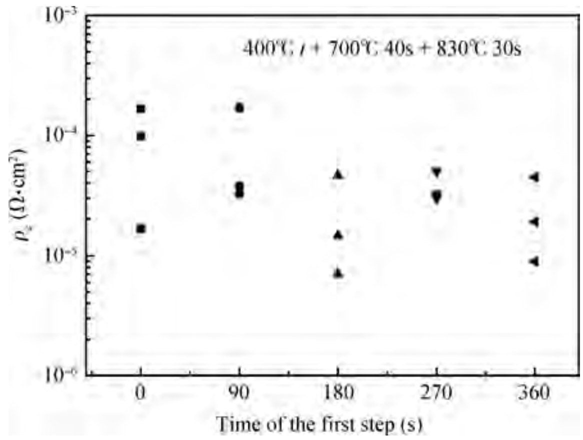

Fig. 3. Dependence of ρ_c on the annealing time of the first step.

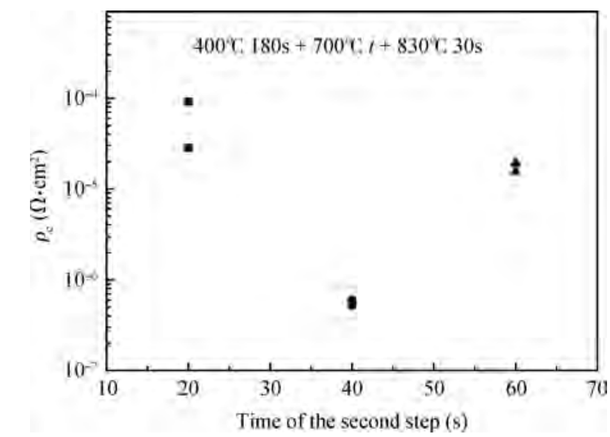

Fig. 4. Dependence of ρ_c on the annealing time of the second step.

Figure 4 shows the dependence of ρ_c on the annealing times of 20, 40 and 60 s at 700 ℃ in the second step. It shows that the annealing time has a large impact on the performance of the ohmic contacts. Ti and AlGaN start reacting over 700 ℃ to form TiN with low resistivity and work function. Meanwhile, Al diffuses inward slowly, reacts with Ti/AlGaN and forms Al_3Ti and AlN. The formation of TiN and AlN generates N vacancies which act as donors. Thus, the interfacial region between the metal and semiconductor becomes heavily

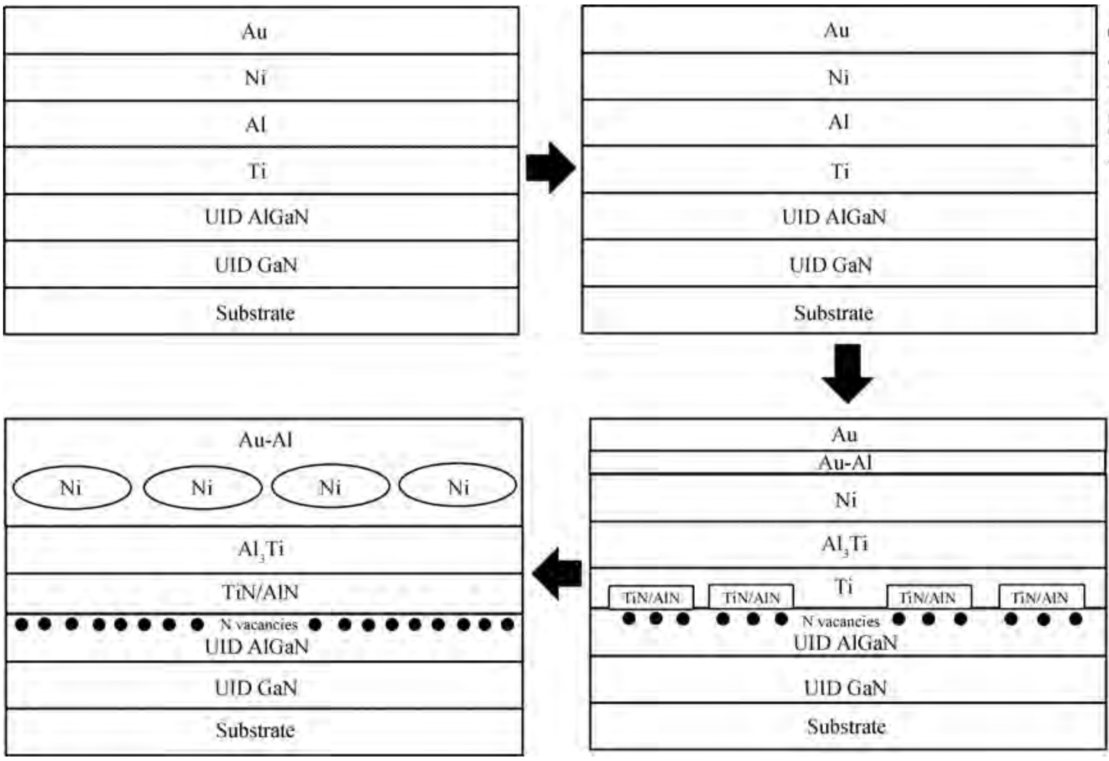

Fig. 5. The metal alloy process in rapid thermal annealing.

doped, providing the conditions for electron tunneling[7]. Al_3Ti not only has low resistivity and a high melting point, but also protects Ti from oxidation[10]. These phenomena are beneficial in forming ohmic contacts. However, Al will diffuse outward when the annealing time increases, and Al and Au will react and form an Al–Au alloy in spite of the blocking of Ni. The Al–Au alloy has a very low re-melting point of 525 ℃ and will deteriorate the performance of the ohmic contacts greatly[11]. The lowest ρ_c is obtained at an annealing time of 40 s, and the performance of the ohmic contacts will get worse if the annealing time is shorter or longer. Therefore, it can be assumed that two opposing mechanisms coexist. One is beneficial to form good ohmic contacts, while the other is detrimental. When the annealing time is less than 40 s, the positive mechanism plays a major role in the contact resistance ρ_c, which becomes lower as time increases. When the annealing time exceeds 40 s, the negative mechanism will overwhelm the positive one. In this case, prolonging the annealing time can make the ohmic contacts worse. Figure 5 briefly represents the metal alloy process in rapid thermal annealing (RTA).

Figure 6 shows the dependence of ρ_c on the annealing time of 15, 30 and 45 s at 830 ℃ in the third step. The result is similar to the result of the second step. At an annealing temperature of 830 ℃, ohmic contacts are beneficial from the very intense reaction among Ti, Al and AlGaN. However, at such a high temperature, it is difficult for Ni to block the diffusion of metals perfectly. The inner metals and their compounds will diffuse outward quickly. Meanwhile, Au will diffuse inwardly and react with Al and form $AlAu_2$. These phenomena will lead to the deterioration of the surface morphology and the performance of the ohmic contacts[9, 12]. With the joint effect of these two behaviors, an annealing time of 30 s has become the most ap-

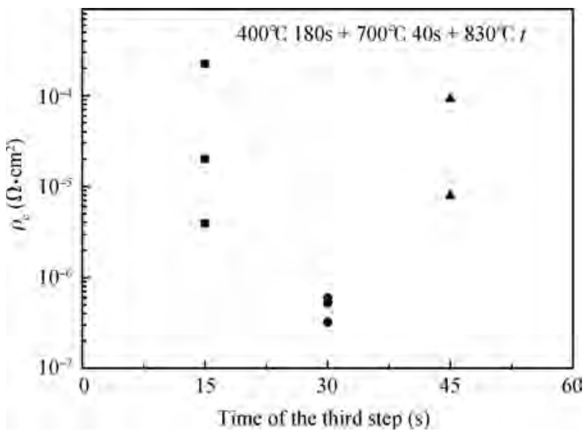

Fig. 6. Dependence of ρ_c on the annealing time of the third step.

propriate time for the third step. Figure 7 investigates the match of high temperature and annealing time. At an annealing temperature of 800 ℃, the reaction among Ti, Al and AlGaN is less intense, and an annealing time of 30 s is too short to reach the optimum reaction. As the annealing temperature rises to 860 ℃, the reaction is so intense during the 30 s time that the ohmic contacts will get worse.

Multi-step annealing process is conductive to the formation of a lower ohmic contact resistance, as described above. Only a high temperature (e.g. 830 ℃) of single-step annealing is not appropriate for the ohmic contacts. Under high temperature, a short annealing time must be taken to avoid the negative mechanism destroying the performance of the ohmic contacts. However, in such a short time the Ti, Al and AlGaN reaction cannot be fully accomplished. If the annealing temperature of

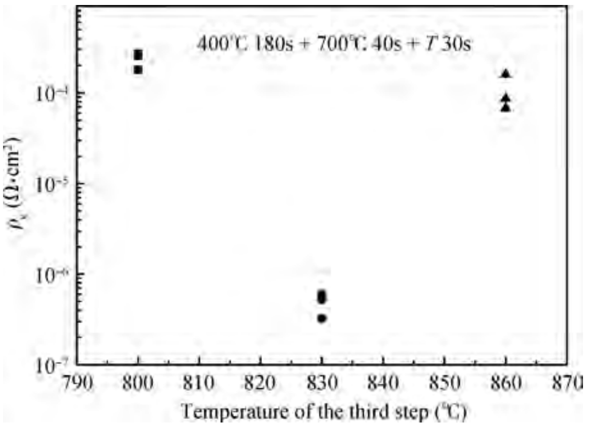

Fig. 7. Dependence of ρ_c on the annealing temperature of the third step.

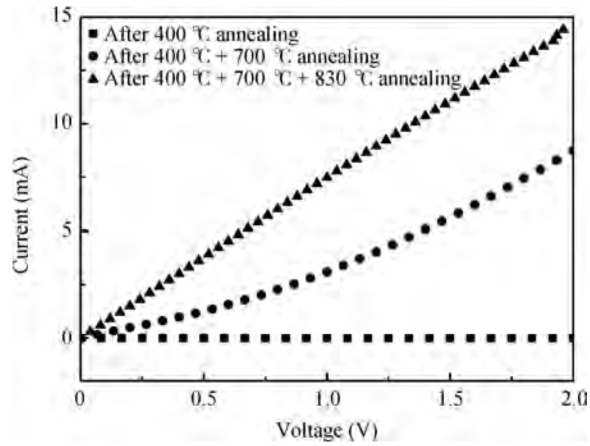

Fig. 8. The current–voltage characteristics of the ohmic contact after each step during multi-steps.

Table 1. Ohmic contact resistance of single-step and multi-step annealing.

Annealing condition	Ohmic contact resistance (Ω·mm)
RTA 830 ℃ 30 s	1.975/2.439/2.683/2.977
RTA 400 ℃ 180 s + 700 ℃ 40 s + 830 ℃ 30 s	0.129/0.140/0.178/0.458

single-step annealing is lower (e.g. 700 ℃), the Ti, Al and AlGaN reaction will be less intense and it will take more time to form the ohmic contacts. Meanwhile, the negative mechanism is still working. It is possible that the process has been dominated by the negative mechanism, even before the formation of ohmic contacts. This contradiction should be resolved when these two steps of 700 ℃ and 830 ℃ are combined. The samples are first annealed at 700 ℃ in an appropriate time. Al begins diffusing, while Ti, Al and AlGaN start reacting. During the third step, both the diffusion of Al and the protection of Ti will be more sufficient. The negative mechanism has not dominated the process either. The samples are then annealed at 830 ℃ in a short time. At this moment, Al has already diffused to the interface and the protection of Ti has already been done. During the third step, the positive mechanism is on-going and the negative one will be suppressed. From the above, it can be concluded that the multi-step annealing process is more effective than the single-step annealing process for metal stack Ti/Al/Ni/Au ohmic contacts. After experimental comparison, the optimal multi-step annealing process was achieved. The sample is first annealed at 400 ℃ for 3 min, the temperature then rises to 700 ℃ and is annealed for 40 s. Finally the temperature rises to 830 ℃ and is annealed for 30 s. The lowest ohmic contact resistance of the four measured data is 0.129 Ω·mm and the corresponding specific contact resistivity ρ_c is 5.98×10^{-7} Ω·cm^2. The lowest specific contact resistivity is 3.22×10^{-7} Ω·cm^2, while the corresponding ohmic contact resistance R_c is 0.140 Ω·mm. The average ohmic contact resistance value of these four data is 0.226 Ω·mm. The fluctuation in the measurement results may be due to material nonuniformity, although the test patterns are on the same wafer with the same processing methods. Table 1 summarizes the ohmic contact resistance of single-step annealing and multi-step annealing.

Figure 8 shows that the current–voltage characteristics of the ohmic contacts are improved for different annealing processes with one, two and three steps. The annealing temperature of 400 ℃ by a single step doesn't change the Schottky contact between the metal and semiconductor. The stack metal diffusion and the reaction with AlGaN begins after two-step annealing. There is a significant increase in current after two-step annealing, but it doesn't form ohmic contact characteristics until the annealing temperature rises to 830 ℃. This is also proof that it is hard to form ohmic contacts at 700 ℃ on un-doped AlGaN/GaN structures. Figure 9 shows the surface morphology of ohmic contacts after each step during a multi-step annealing process. The surface of the contact is smooth and free of visible defects at 400 ℃. Some nonmetallic matter appears at the surface of the contact at 700 ℃, which may be the nitrides of Al and Ti. At 830 ℃, the nonmetallic matter spreads over the whole surface. Annealing temperature and time are important parameters in optimizing the Ti/Al layer for lower resistance and the Ni/Au layer for smooth surface morphology. It is very important for good ohmic contacts to balance the rate of various reactions by adjusting the annealing temperature and time.

Lower ohmic contact resistance will reduce the parasitic resistance of the source and drain, thereby improving the performance of the devices. Figure 10 shows the I–V characteristics of the AlGaN/GaN HEMTs by applying the single-step and multi-step annealing processes, respectively. The R_{on} of the device is reduced from 9.0 to 1.7 Ω·mm. The device applying the multi-step annealing process exhibits $I_{max} > 1.4$ A/mm and $g_m = 445.4$ mS/mm. Further device details, DC and RF performance, and the submicron gates which have exhibited state of the art results will be reported elsewhere.

4. Conclusions

In summary, the mechanism of the multi-step annealing process was experimentally investigated. A series of comparative experiments were performed systematically by changing the annealing time at 400 ℃, 700 ℃ and 830 ℃. An optimized multi-step annealing process was proposed by experimental analysis of the ohmic contact formation mechanism. The minimum specific contact resistance obtained was 3.22×10^{-7} Ω·cm^2 on the un-doped AlGaN/GaN structure.

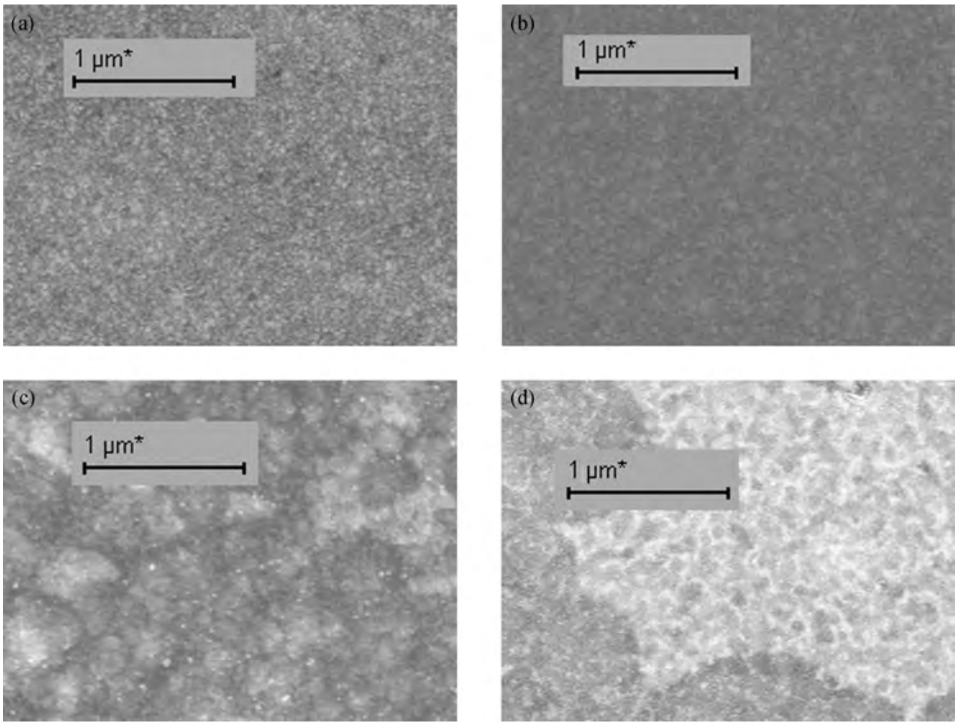

Fig. 9. The surface morphology of the ohmic contact after each step during multi-steps: (a) as-deposited, (b) after 400 ℃, (c) after 400 ℃ + 700 ℃, (d) after 400 ℃ + 700 ℃ + 830 ℃.

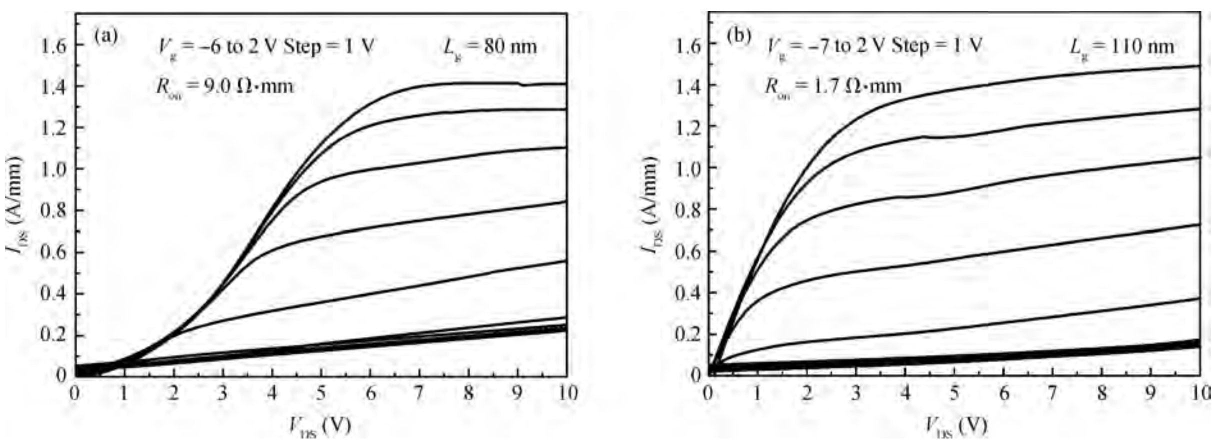

Fig. 10. $I-V$ characteristics of the AlGaN/GaN HEMT devices. (a) Annealed at 835 ℃ for 30 s. (b) Annealed at 400 ℃ 3 min + 700 ℃ 40 s + 830 ℃ 30 s.

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