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# Low resistance Ohmic contacts to *n*-GaN by Ar plasma and forming gas ambient treatments*

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In this article, a scheme for fabricating low resistance Ohmic contacts to *n*-GaN was developed. This approach takes advantage of Ar plasma treatment and thermal annealing in forming gas ambient. As a result, the adjustment of Ar flow rate was very effective in improving the contact resistance. After proper Ar plasma treatment, the contact resistance and specific contact resistance of as-deposited Ohmic contacts were reduced to 0.362 $\Omega$ mm and $3.9\times10^{-5}$ $\Omega$ cm$^2$, respectively. Low contact resistance (0.103 $\Omega$ mm) and specific contact resistance ($3.2\times10^{-6}$ $\Omega$ cm$^2$) were obtained after annealing in $N_2$ gas ambient. By performing thermal annealing in forming gas ambient, even lower contact resistance (0.093 $\Omega$ mm) and specific contact resistance ($2.6\times10^{-6}$ $\Omega$ cm$^2$) were successfully achieved, indicating that the electrical characteristics of Ohmic contacts would not be affected by the effect of hydrogen passivation of dopants in *n*-GaN. © *2003 American Vacuum Society.* [DOI: 10.1116/1.1596217]

## I. INTRODUCTION

Nitride-based electronic devices, such as heterostructure field effect transistors, and heterojunction bipolar transistors, are potentially very useful for high power and high temperature applications. To use these devices for such applications, good Ohmic contacts with low contact resistance are very important. In general, Ohmic contacts to *n*-GaN with low contact resistance are not easily obtainable because of its wide band gap. The improvement of contact resistance could be achieved by many approaches, such as the selection of the right contact metal,[1–7] surface treatments,[8,9] and plasma treatments.[10–16] In addition, thermal annealing is also very important. Thermal annealing in $N_2$ gas ambient was usually employed to obtain low resistance Ohmic contacts. The main reason for using nitrogen gas as the annealing ambient instead of hydrogen containing gas, as commonly used by most III–V compounds, is to avoid the effect of hydrogen passivation of dopants in GaN.[5,22] In this work, a scheme of combining Ar plasma treatment and annealing in forming gas ambient for fabricating low resistance Ohmic contacts to *n*-GaN was developed. We found that this approach could further improve the contact resistance. With appropriate Ar plasma treatment, the contact resistances of the as-deposited Ohmic contacts were improved substantially. Moreover, after subsequent annealing in the forming gas ambient, contacts treated with this scheme have even lower contact resistance than those annealed in $N_2$ gas ambient. This indicates that the electrical characteristics of Ohmic contacts would not be affected by the effect of hydrogen passivation of dopants in *n*-GaN.

## II. EXPERIMENT

The 2-$\mu$m-thick *n*-GaN films for this study were grown by metalorganic chemical vapor deposition on *c*-plane sapphire substrates. The electron concentration and the mobility obtained by Hall measurement were $3.3\times10^{18}$ cm$^{-3}$ and 248 cm$^2$/V s, respectively. After layer growth, mesa patterns for transmission line measurement (TLM) were defined by photolithography. Prior to contact metal deposition, the samples were treated by different Ar plasma conditions using inductive coupled plasma (ICP) system and then dipped in the solution of 1:1 HCl:$H_2O$ for 1 min. Contact metal, Ti/Al/Ti/Au (200/1500/450/550 Å), was then deposited and lifted off to form the contact pads. The dimension of contact pad was $110\times110$ $\mu$m$^2$. The samples were annealed at 750 °C for 30 s in $N_2$ or forming gas ambient. After annealing, the TLM measurement was performed for the determination of the contact resistance.

## III. RESULTS AND DISCUSSION

The conditions of the plasma treatment are shown in Table I. It should be noted that a very low bias power of 5 W was used in the plasma treatment to ensure a very slow etching rate for GaN. Only about 100–200 Å was etched during the plasma treatment. Figure 1 shows the current–voltage characteristics of the as-deposited Ohmic contacts under different Ar flow rate. With the increase of Ar flow, the current–voltage characteristics of these contacts became more linear.

*No proof corrections received from author prior to publication.
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TABLE I. Conditions of the plasma treatment.

| | | | | | | |
|---|---|---|---|---|---|---|
| ICP power (W) | ⋯ | 300 | 300 | 300 | 300 | 300 |
| Bias power (W) | ⋯ | 5 | 5 | 5 | 5 | 5 |
| Pressure (mTorr) | ⋯ | 15 | 15 | 15 | 15 | 15 |
| Ar flow (sccm) | ⋯ | 10 | 30 | 50 | 50 | 50 |
| Time (min) | ⋯ | 1 | 1 | 1 | 2 | 3 |

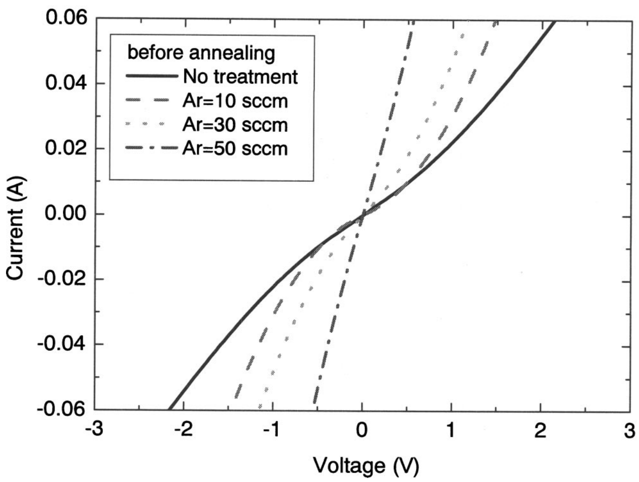


FIG. 1. Current–voltage characteristics of the as-deposited Ohmic contacts treated with Ar plasma at different Ar flow rates.

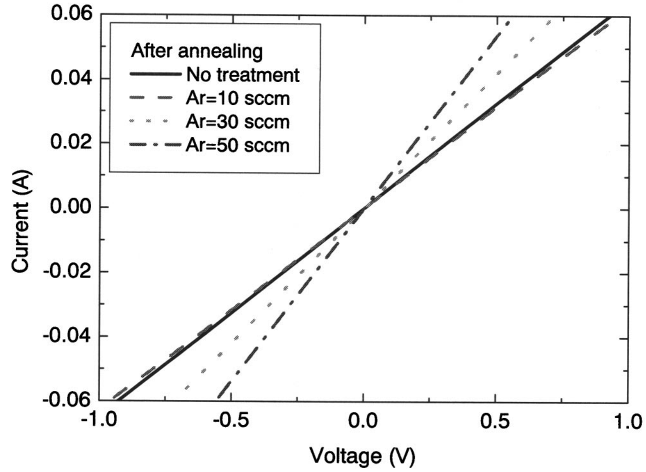


FIG. 3. Current–voltage characteristics of the alloyed Ohmic contacts under different Ar flow rates.

Figure 2 shows the dependence of the contact resistance and the specific contact resistance as functions on the Ar flow rate. Both the contact resistance and specific contact resistance decreased as the Ar flow rate was increased. For samples without Ar plasma treatment, the contact resistance and the specific contact resistance were too high to be extracted via TLM measurement. Samples treated with an Ar flow rate of 50 sccm showed the best result. Their contact resistance and specific contact resistance were 0.362 $\Omega$ mm and $3.9\times10^{-5}\ \Omega\,\mathrm{cm}^2$, respectively. After annealing, all samples showed linear current–voltage characteristics, as shown in Fig. 3. Similar dependences of the contact resistance and the specific contact resistance of the alloyed contacts on Ar flow rate were obtained as well, as shown in Fig. 4. All alloyed contacts have low contact resistances. Samples treated with 50 sccm of Ar flow rate still exhibited the best electrical characteristics. Their contact resistance and specific contact resistance were 0.103 $\Omega$ mm and $3.2\times10^{-6}\ \Omega\,\mathrm{cm}^2$, respectively.

Apparently, the Ar flow rate has a significant influence on contact resistance. With the increase of Ar flow rate, the con-

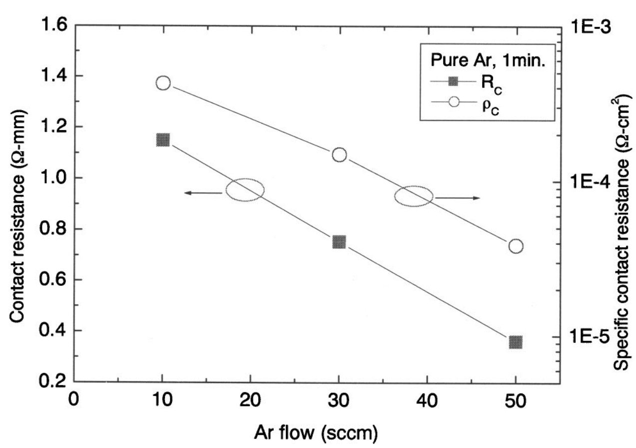


FIG. 2. Dependence of contact resistance and specific contact resistance of the as-deposited Ohmic contacts on Ar flow rate.

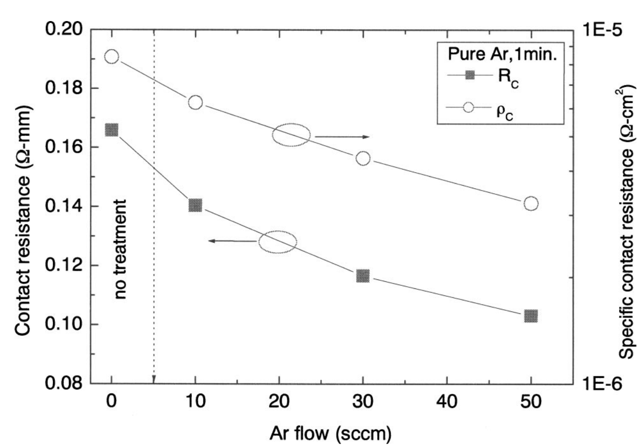


FIG. 4. Dependence of contact resistance and specific contact resistance of the alloyed Ohmic contacts on Ar flow rate.

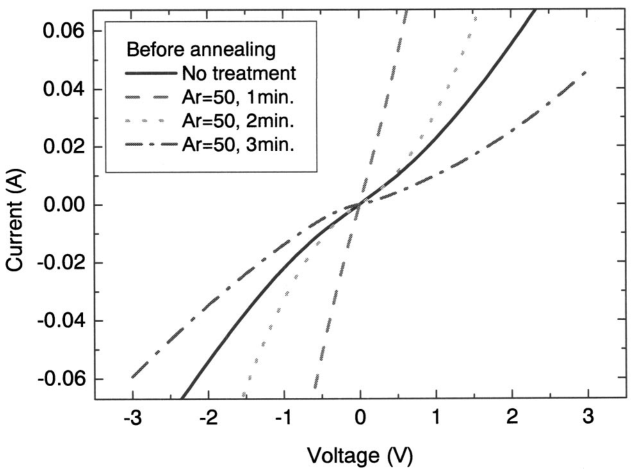


FIG. 5. Current–voltage characteristics of the as-deposited Ohmic contacts under different Ar treatment times.

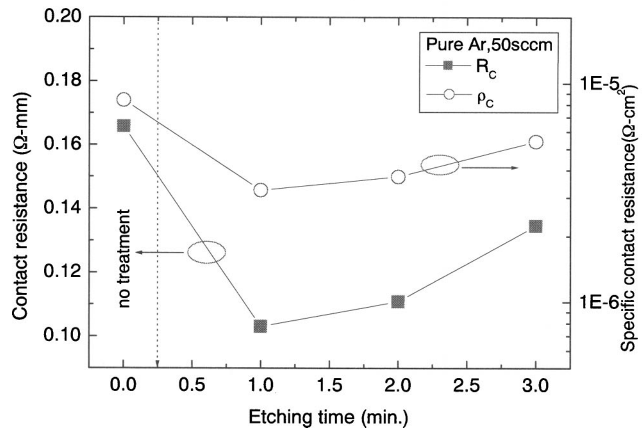


FIG. 7. Dependence of contact resistance and specific contact resistance of the alloyed Ohmic contacts on Ar treatment time.

tact resistance is improved greatly. The mechanism of Ar plasma etching is physical ion bombardment. Higher Ar flow rate generates higher Ar ion density in the plasma, which enhances the effect of ion bombardment on wafer surface. Thus, more lattice damage and crystalline defects are created on the wafer surface. The increase of nitrogen vacancies on the wafer surface after plasma treatment has been shown by many researchers[10,13,15] and they are generally believed to be native donors.[17,18] Therefore, after plasma treatment with Ar, the improvement of contact resistance is due to the increase of nitrogen vacancies on the wafer surface.

Figure 5 shows the current–voltage characteristics of the as-deposited Ohmic contacts (before annealing) with different Ar treatment time. We found that Ar treatment improves the Ohmic contact if the duration is less than 1 min. But, if it is too long, the Ohmic contact becomes worse. After a 3 min of Ar plasma treatment, the current–voltage characteristics are even poorer than those without treatment. After thermal annealing, all samples show good Ohmic behavior, as shown in Fig. 6. Substantial improvement can be obtained for the samples treated with shorter times ($t=1$, 2 min). Figure 7 shows the dependence of contact resistance and specific contact resistance of the alloyed contacts on the treatment time. As a whole, samples with different treatment times all have lower contact resistances and specific contact resistances than those without treatment. However, for the best result, the treatment time has to be kept no longer than 1 min. The samples with 1 min of Ar plasma treatment have the lowest contact resistance (0.103 Ω mm) and specific contact resistance ($3.2\times10^{-6}$ Ω cm$^2$).

Plasma treatment not only produces nitrogen vacancies on the surface, which is desirable for the improvement of contact resistance, but also causes crystalline defects, which can degrade the film quality and the contact resistance.[12] So, to use such a technique for contact improvement, one has to carefully choose the treatment time so that the damage it causes does not overwhelm the benefit it produces.

Figure 8 shows the current–voltage characteristics of the Ohmic contacts after annealing in forming gas (15% $H_2$). All samples showed good Ohmic behavior. In comparison with the samples without plasma treatment, substantial improve-

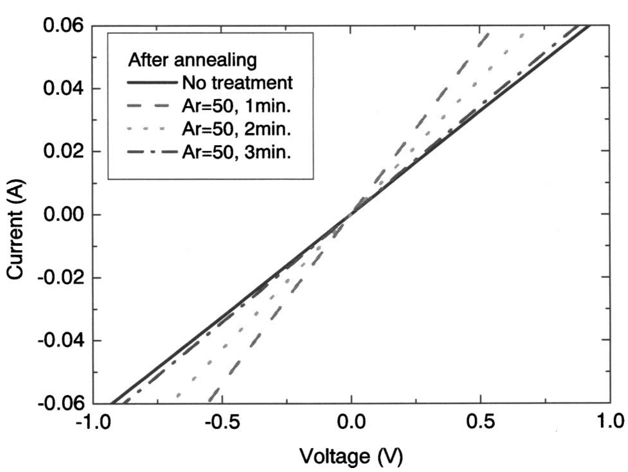


FIG. 6. Current–voltage characteristics of the alloyed Ohmic contacts under different Ar treatment times.

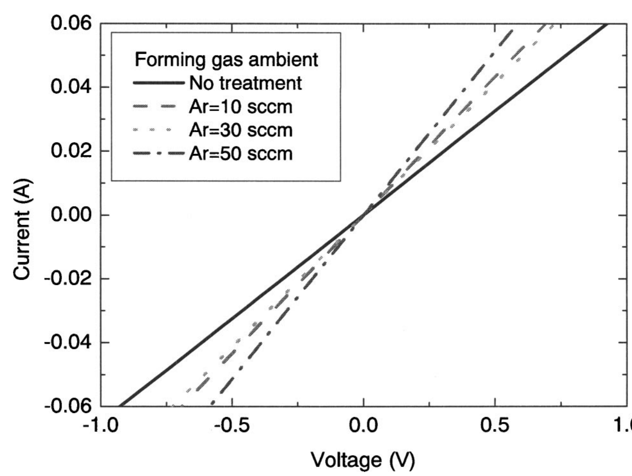


FIG. 8. Current–voltage characteristics of the Ohmic contacts annealed in forming gas ambient.

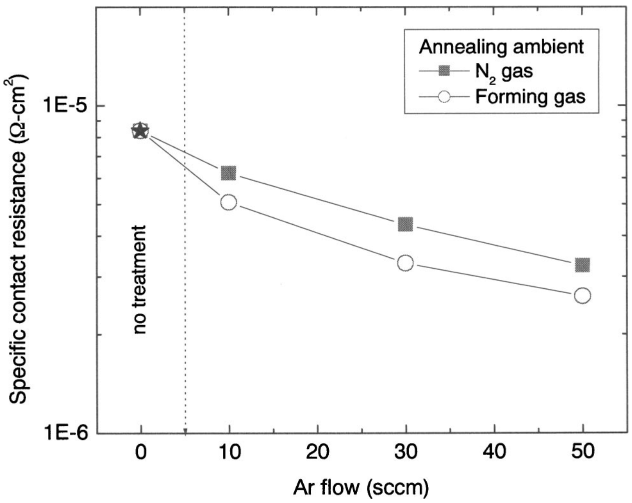


FIG. 9. Comparison of specific contact resistance of the Ohmic contacts annealed in $N_2$ gas and in forming gas ambient.

ment in electrical characteristics was obtained as well. Figure 9 shows the comparison of specific contact resistance of the Ohmic contacts annealed in $N_2$ and in forming gas ambient. Similar to the results of those annealed in $N_2$ gas, the specific contact resistance of the samples annealed in forming gas decreases with the Ar flow rate. It is apparent that the forming gas treated contacts have lower specific contact resistance than those annealed in $N_2$ gas ambient. The lowest contact resistance and specific contact resistance obtained here are 0.093 Ω mm and $2.6\times10^{-6}$ Ω cm$^2$, respectively.

Obviously, from the results presented above, annealing in forming gas is better than annealing in $N_2$. The possible reason is the reduction capability of the forming gas because of the $H_2$ content. It may reduce the oxidation reaction of metal at high temperatures and, therefore, help reduce the contact resistance. Similar results were also observed in the Al/*n*-GaN Ohmic contacts annealed in Ar/4% $H_2$ forming gas.[19] The $H_2$ content, however, may cause concerns in doping reduction because of hydrogen passivation. It is known that hydrogen passivation of *p*-type dopants in *p*-GaN would result in a large decrease of hole concentration.[20,21] Whether annealing in forming gas ambient would lead to a similar reduction in electron concentration and increase of contact resistance of *n*-GaN needs to be answered. During the annealing process, $H_2$ could diffuse into the bulk *n*-GaN to form neutral complexes with dopants at annealing temperature higher than 500 °C. On the other hand, the high temperature annealing process would also result in the dissociation of neutral dopant-H complexes.[22] Although the effect of hydrogen passivation of *n*-type dopants in *n*-GaN during the annealing and subsequent cooling process is not completely known, the results obtained here indicate that annealing in forming gas ambient would not lead to electrical degradation of Ohmic contacts.

## IV. CONCLUSION

Ar flow rate can have a significant effect on contact resistance for Ohmic contacts to *n*-GaN. With the increase of Ar flow rate, the contact resistance of plasma-treated Ohmic contacts to *n*-GaN was greatly improved. Longer plasma treatment time does not necessarily improve the contact resistance of contacts. Therefore, proper control over plasma damage is required for the greatest improvement of contact resistance. Lower contact resistance and specific contact resistance were obtained for contacts annealed in forming gas ambient than those annealed in $N_2$ ambient. This indicates that the electrical characteristics of Ohmic contacts would not be influenced by the effect of hydrogen passivation of dopants in *n*-GaN. With such a combination of appropriate Ar plasma treatment and annealing in forming gas ambient, low resistance Ohmic contacts to *n*-GaN were obtained.

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