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# Role of Al and Ti for ohmic contact formation in AlGaN/GaN heterostructures

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A mechanism for ohmic contact formation using Ti/Al based metals on AlGaN/GaN heterostructures has been investigated by measuring temperature dependence of sheet electron density ($n_s$) and mobility ($\mu$). It was found that both $n_s$ and $\mu$ at room temperature for Ti/Al deposited sample were increased by annealing in vacuum, while not for Al/Ti deposited one. The results, especially increase in $\mu$, cannot be understood by the conventional ohmic formation model, including Ti-N (nitrogen) complex formation or N vacancy formation. As the most probable mechanism for the increase in $n_s$ and $\mu$, we have proposed a model, in which tensile strain is induced by the reaction of Ti/Al and AlGaN after annealing. 
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An AlGaN/GaN high-electron-mobility transistor (HEMT) is a promising device applicable to power switching electronics due to its high breakdown voltage,[1,2] high drain current capability,[3,4] and high operable temperature.[5,6] In order to improve HEMTs' performance, it is inevitable to obtain a low resistive ohmic contact. So far, Ti/Al based metals, such as Ti/Al/Ni/Au and Ti/Al/Mo/Au, have been commonly used for ohmic contact to AlGaN/GaN materials. There have been three models proposed as a mechanism for ohmic contact formation using Ti/Al on AlGaN/GaN heterostructures:[7,8] (i) Ti reacts with N and forms Ti-N complex and/or N vacancies in AlGaN, acting as high density donor layer to form low resistive ohmic contact,[7,9–11] (ii) barrier height at Ti and AlGaN interface is lowered by formation of Ti-N,[12,13] and (iii) alloyed Ti/Al layer makes a spike, which penetrates into AlGaN barrier layer and touches two dimensional electron gas (2DEG) at AlGaN/GaN interface.[7,8,14,15]

However, there are several exceptions, for example, a low resistive ohmic contact is obtained by V (vanadium) instead of Ti[16] and a spike is not always observed in the ohmic contact.[10,17,18] Recently, Zhang *et al.*[19] proposed a model for ohmic contact formation that AlGaN surface was changed from N-rich to Al-rich and reduced the barrier height by formation of Al-Ti bonds, resulting in low contact resistance. In any case, the mechanism of ohmic contact formation is still under debate.

In this letter, a model for ohmic contact formation by the reaction between Ti/Al and AlGaN/GaN is proposed. In our previous report,[20] we have shown by Hall effect measurements that the reaction between Ti/Al and AlGaN has increased not only $n_s$ but also $\mu$ of 2DEG in the AlGaN/GaN heterostructure. The mobility increase observed is not explained by the previously reported ohmic contact formation models. This is because the high density of electrons, whatever the origin is, should lead to decrease in $\mu$ due to scatterings. We propose a model that a tensile strain is induced in an AlGaN barrier layer by annealing Ti/Al metals on AlGaN/GaN, which leads to the increase in $n_s$ and $\mu$ and thus to the formation of low resistive ohmic contact.

The samples used in this work were grown by metal organic chemical vapor deposition (MOCVD) on c-plane 3-inch sapphire substrates. The epitaxial layer consists of a 3 $\mu$m un-doped GaN channel layer and a 25 nm un-doped $Al_{0.25}Ga_{0.75}N$ barrier layer. Figures 1(a) and 1(b) show the cross-sectional and top view of the fabricated sample, respectively. Sample preparation was initiated by reactive ion etching (RIE) device

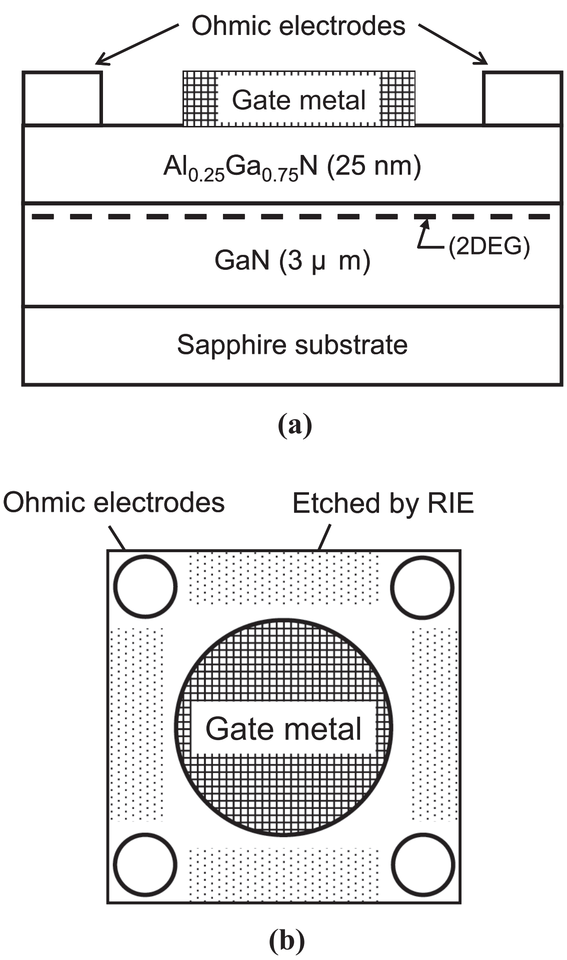


FIG. 1. Cross sectional (a) and top view (b) of the fabricated sample. The dotted and meshed regions show mesa etched and gate metal regions, respectively. The sample size is $7 \times 7$ mm$^2$ and the diameter of center circle is 5 mm.

 

isolation with a mesa depth of 100 nm. The etched region is shown as the dotted region in Fig. 1(b). Ohmic metals consisting of Ti/Al/Mo/Au (15/60/35/50 nm) were evaporated in the four corners to obtain van der Pauw configuration. Then, the sample was alloyed at 850 °C for 30 s in $N_2$ flow to ensure good ohmic contacts. After ohmic contact formation, an additional metal (hereafter referred to as "gate metal") was evaporated in the center of the sample, as shown as the meshed region in Fig. 1(b). We prepared several gate metals, such as Ti/Al/Mo/Au, Ti, Al, Ti/Al, and Al/Ti. The sample size was $7 \times 7$ mm$^2$ and the diameter of the gate metal was 5 mm. Prepared samples and obtained results are summarized in Table I.

The sample was set to the Hall measurement system (Toyo technica ResiTest 8310), and the temperature dependence of $n_s$ and $\mu$ was measured with increasing and decreasing the sample temperature ranging from 300 K (room temperature) to 820 or 1020 K. All the measurements were carried out in vacuum (around $1 \times 10^{-3}$ Torr) with an applied magnetic field of 0.55 Tesla.

In the first, $n_s$ and $\mu$ were measured at 300 K for the sample with a gate metal of Ti/Al/Mo/Au (15/60/35/50 nm). The measurements were made for as-deposited and annealed by rapid thermal annealing (RTA) at 850 °C for 30 s in $N_2$ flow samples. The metal thickness and annealing condition were the optimized ones in our laboratory so as to give the contact resistance below 0.3 Ω mm which was confirmed by transmission line model (TLM) method. The measured $n_s$ and $\mu$ were $0.96 \times 10^{13}$ cm$^{-2}$ and 1470 cm$^2$/Vs for the as-deposited sample and $2.7 \times 10^{14}$ cm$^{-2}$ and 1770 cm$^2$/Vs for the annealed sample, respectively. Note that an order of magnitude increase (28 times) in $n_s$ and 1.2 times in $\mu$ was observed for the annealed sample. The results indicate that the formed ohmic contact causes the increase not only in $n_s$ but also in $\mu$. It is to be noted that measured $n_s$ and $\mu$ in this Hall measurement correspond to those of 2DEG at AlGaN/GaN interface beneath the gate metal, and not those of alloyed Ti/Al/Mo/Au metal or AlGaN layer.[20] This is because current flowing with $\mu$ of around 1500 cm$^2$/Vs is only probable for electrons flowing at AlGaN/GaN interface as 2DEG.

Next, we have prepared a sample with only Ti or Al with a thickness of 100 nm as the gate metal, and the temperature dependence of $n_s$ and $\mu$ was measured. The results are shown in Figs. 2(a) and 2(b). Here, the maximum measurement temperature was set to 820 K for Al to avoid melting. Although $n_s$ was increased and $\mu$ was decreased with increasing temperature for both Ti and Al, initial values (as-deposited condition) of them at 300 K were quite different. As shown in the figure, $n_s$ for Al ($n_s = 7.8 \times 10^{13}$ cm$^{-2}$) was much higher than that for Ti ($n_s = 0.92 \times 10^{13}$ cm$^{-2}$). Similarly, $\mu$ for Al exceeded 2000 cm$^2$/Vs, while it was 1490 cm$^2$/Vs for Ti. It should be noted that initial values of $n_s$ and $\mu$ for Ti are almost the same as those for Ti/Al/Mo/Au, suggesting that $n_s$ and $\mu$ of Ti/Al/Mo/Au are governed by Ti, and not affected by Al in the as-deposited condition. By annealing the sample in vacuum, $n_s$ at 300 K was slightly increased for Ti ($n_s = 1.5 \times 10^{13}$ cm$^{-2}$), while it was decreased for Al ($n_s = 4.6 \times 10^{13}$ cm$^{-2}$). Furthermore, a sharp increase in $n_s$ and a hump in $\mu$ were observed for Ti at around 520 K, indicating an occurrence of reaction between Ti and AlGaN. In contrast, Al showed monotonous increase with the increase of temperature. These results suggest that the interface at Ti/AlGaN and Al/AlGaN is quite different in the as-deposited condition, and the reaction at the interface with annealing is also different.

After the measurement for the sample with Ti or Al, the temperature dependence of $n_s$ and $\mu$ for the sample with Ti/Al (Ti bottom/Al top) or Al/Ti (Al bottom/Ti top) as a gate metal was investigated. Figures 3(a) and 3(b) show the results for $n_s$ and $\mu$, respectively. As shown in the figures, initial values of $n_s$ and $\mu$ at 300 K were small for Ti/Al

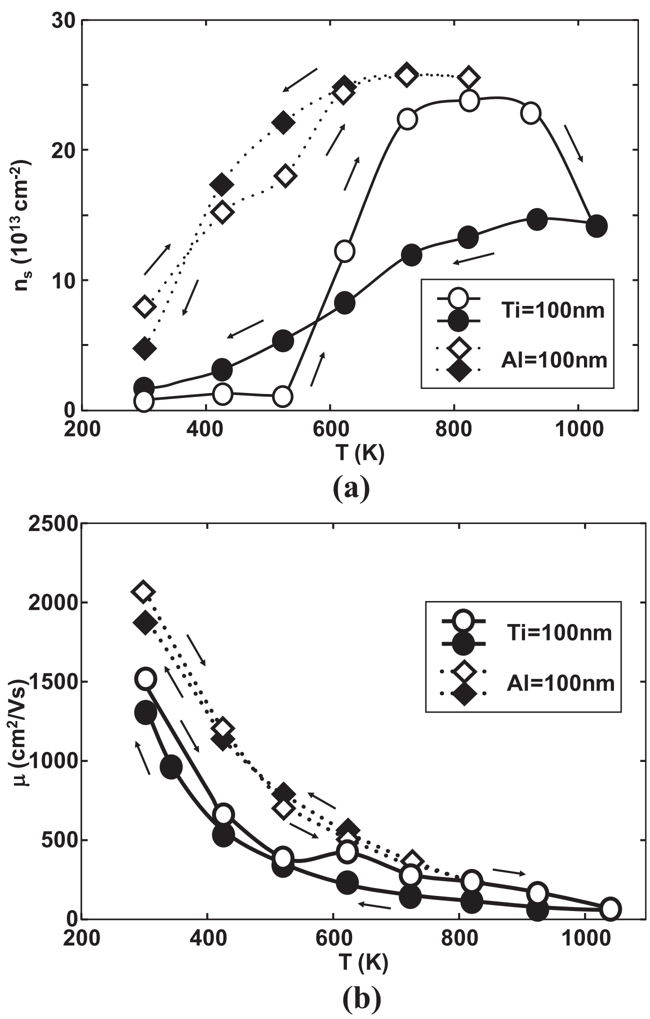


FIG. 2. Temperature dependence of sheet electron density (a) and mobility (b). Circles correspond to Ti and diamonds to Al. Open and closed symbols are for increasing and decreasing temperatures, respectively. The arrows show the temperature increase/decrease directions.

TABLE I. Prepared samples and obtained results by Hall measurements ($n_s$ and $\mu$ are the values measured at 300 K).

| Gate metal | Thickness (nm) | Initial (as-deposited) $n_s$ ($10^{13}$ cm$^{-2}$) | Initial (as-deposited) $\mu$ (cm$^2$/Vs) | After annealed $n_s$ ($10^{13}$ cm$^{-2}$) | After annealed $\mu$ (cm$^2$/Vs) |
|---|---|---|---|---|---|
| Ti/Al/Mo/Au | 15/60/35/50 | 0.96 | 1470 | 27.0 | 1770 |
| Ti | 100 | 0.92 | 1490 | 1.5 | 1350 |
| Al | 100 | 7.8 | 2080 | 4.6 | 1900 |
| Ti/Al | 15/100 | 1.2 | 1380 | 19.0 | 2090 |
| Al/Ti | 100/15 | 4.0 | 1790 | 5.6 | 1860 |

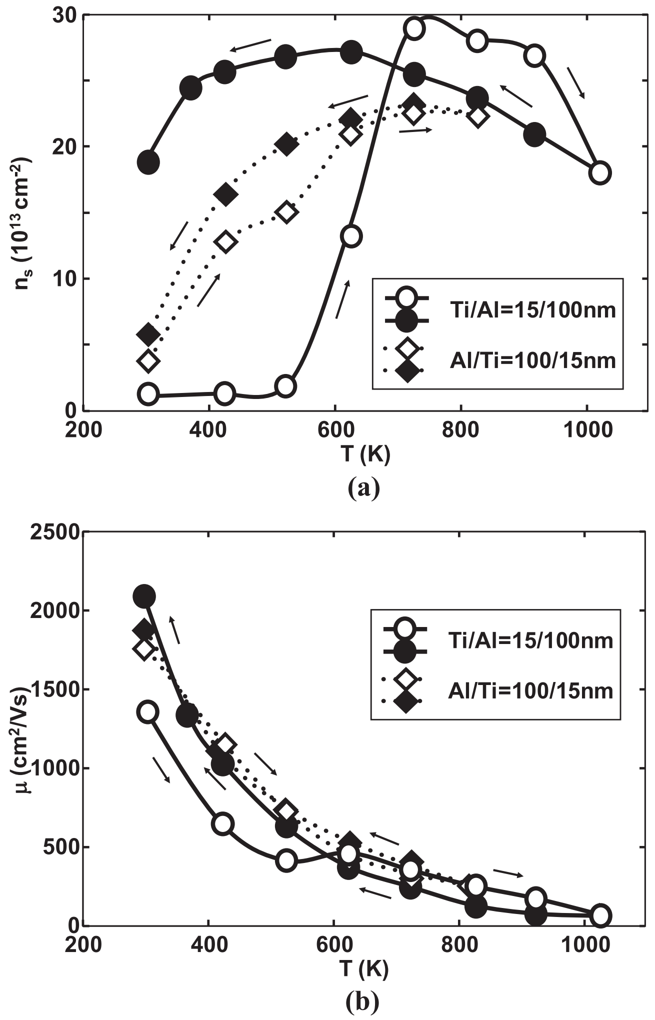


FIG. 3. Temperature dependence of sheet electron density (a) and mobility (b). Circles correspond to Ti/Al and diamonds to Al/Ti. Open and closed symbols are increasing and decreasing temperatures, respectively. The arrows show the temperature increase/decrease directions.

($n_s = 1.2 \times 10^{13}$ cm$^{-2}$, $\mu = 1380$ cm$^2$/Vs) as compared with Al/Ti ($n_s = 4.0 \times 10^{13}$ cm$^{-2}$, $\mu = 1790$ cm$^2$/Vs). However, $n_s$ was drastically increased by as much as 15.4 times by annealing for Ti/Al ($n_s = 1.9 \times 10^{14}$ cm$^{-2}$, $\mu = 2090$ cm$^2$/Vs), while the amount of increase was only 1.4 times for Al/Ti ($n_s = 5.6 \times 10^{13}$ cm$^{-2}$, $\mu = 1860$ cm$^2$/Vs). The results in Fig. 3 together with Fig. 2 show that the initial values of $n_s$ and $\mu$ are high when Al contacted with AlGaN layer (corresponding to samples for Al and Al/Ti), and are lowered by annealing, which are in contrast to the Ti/Al case. In addition, the temperature dependence was also different between Ti/Al and Al/Ti. A sudden increase in $n_s$ was observed only for Ti/Al case. From these results, it is concluded that the metal stack of Ti/Al instead of Al/Ti is inevitable to obtain high $n_s$ and $\mu$ by annealing, resulting in low resistive ohmic contact formation.

In order to investigate the reaction between Ti/Al (or Al/Ti) and AlGaN, Auger electron spectroscopy (AES) measurements were performed. The results are shown in Fig. 4, where (a), (b), and (c) correspond to the as-deposited sample with Ti/Al (15 nm/50 nm), the annealed sample (1020 K in vacuum) with Ti/Al (15 nm/50 nm), and the annealed sample (1020 K in vacuum) with Al/Ti (50 nm/15 nm), respectively.

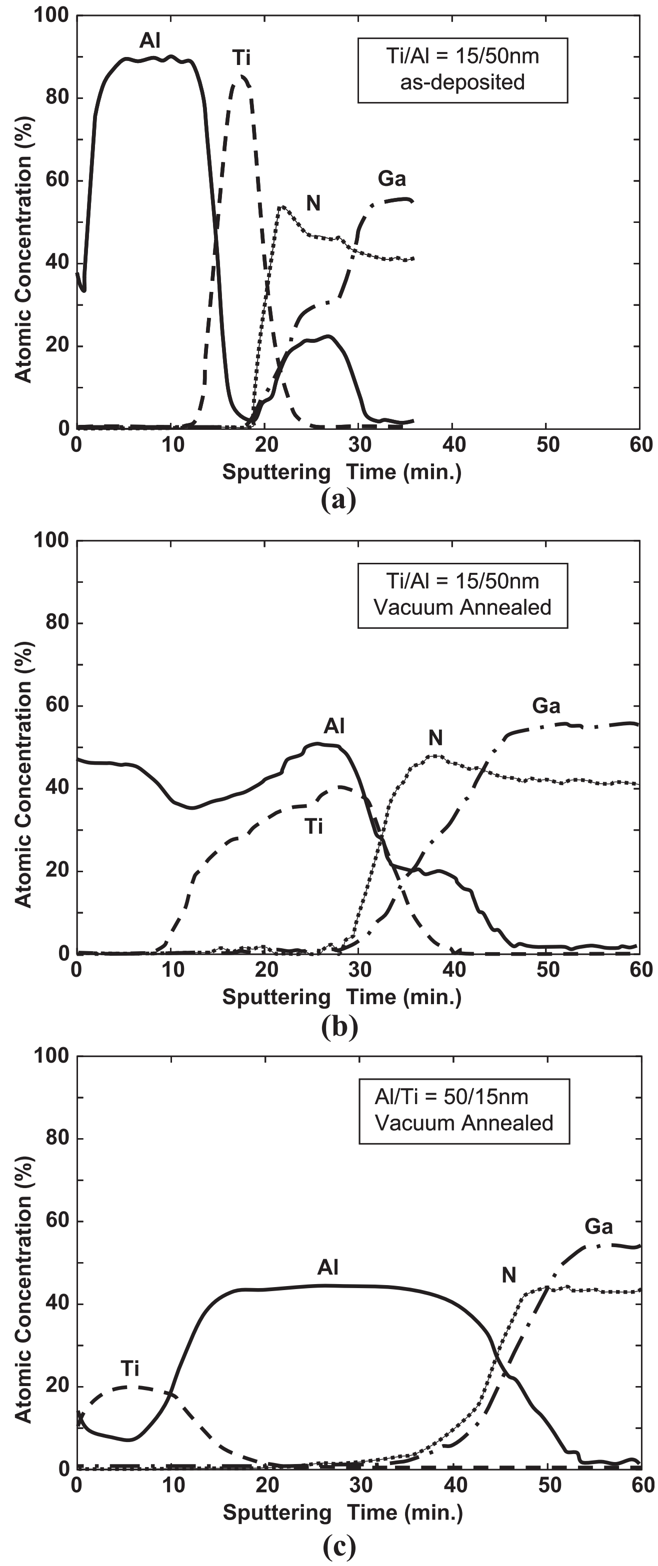


FIG. 4. Depth profile of atomic concentration measured by AES, where (a) is as-deposited Ti/Al (15/50 nm), (b) vacuum annealed for Ti/Al (15/50 nm), and (c) vacuum annealed for Al/Ti (50/15 nm).

The interface at Ti/AlGaN is sharp in the as-deposited sample (Fig. 4(a)). However, Al diffuses toward AlGaN in the annealed sample (Figs. 4(b) and 4(c)). Note that the metal layer became thick due to the volume expansion. In fact, the metal thickness for the annealed sample with Ti/Al and Al/Ti, measured by the step-height meter, was thickened to

100 nm and 120 nm, respectively. As shown in Fig. 4, Al diffused into Ti layer by annealing for Ti/Al sample, while Ti didn't diffuse into Al for Al/Ti. Noticeable deficiency in N, reported in Ref. 19, was not observed in the present work, suggesting that N-vacancy and/or Ti-N complex formation was not essential for the increase in $n_s$ and $\mu$.

From these results mentioned above, the most probable mechanism for ohmic contact formation by using Ti/Al based metals on AlGaN/GaN is as follows. With the increase of temperature, Ti/Al starts to react with AlGaN at 520 K (see Fig. 3) and $n_s$ is increased. The reaction occurs between Ti and AlGaN accompanied by Al diffusion into the AlGaN layer. Since the atomic radius of Al is larger than that of N, the tensile strain is induced in the AlGaN layer, which brings about the increase of polarization charge at the AlGaN/GaN interface, resulting in $n_s$ increase. The amount of induced strain by Al diffusion is estimated to be around 20 times higher as compared with $Al_{0.25}Ga_{0.75}N$/GaN structure. The mobility increase seems to be brought from the reduction of electron effective mass with the induced strain[21] or screening of scatterings by high density of 2DEG.[22] In the case of Al/Ti, on the contrary, $n_s$ and $\mu$ are high in the as-deposited condition due to the tensile strain induced by Al on AlGaN. With the temperature increase, the induced strain is relaxed, resulting in $n_s$ decrease. Ti seems to play a role of enhancing and suppressing strain relaxation for Al/Ti and Ti/Al, respectively. Since the tensile strain is governed by Al, Al plays a key role for increasing $n_s$ and $\mu$.

In conclusion, a mechanism for ohmic contact formation using Ti/Al based metals on AlGaN/GaN heterostructures has been investigated by measuring the temperature dependence of $n_s$ and $\mu$. It was found that both $n_s$ and $\mu$ at room temperature were increased by annealing, however, the amount of increase was much higher for the sample with Ti/Al than that with Al/Ti. The increase in $\mu$, observed in this work, was not explained by the conventional models, i.e., Ti-N complex formation or N vacancy related model. A model was proposed as the most probable mechanism for the increase in $n_s$ and $\mu$, in which the tensile strain is induced by annealing with the reaction between Ti/Al and AlGaN. The results herein will contribute to obtain deeper understandings of the mechanism for ohmic contact formation.

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