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A method to increase sheet electron density and mobility by vacuum annealing for Ti/Al deposited AlGaN/GaN heterostructures

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Temperature dependence of sheet electron density (n_s) and mobility (μ) for Ti/Al deposited AlGaN/GaN heterostructures annealed in vacuum has been investigated using Hall effect measurements. The vacuum annealing at 1020 K caused the increase in both n_s and μ at room temperature, with the amount of one order of magnitude and 65%, respectively, as compared to without annealed sample. The amount of increase was much less for only Ti or Al deposited or totally thin Ti/Al deposited sample. The origin of the increase is attributed to tensile strain induced by vacuum annealing. The method is useful for reducing the ohmic contact resistivity and/or the access resistance between source and gate in AlGaN/GaN HEMTs. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4748169]

AlGaN/GaN high electron mobility transistors (HEMTs) are attractive device for high output power and high temperature operations. This is enabled by high sheet electron density induced at AlGaN/GaN interface and GaN's high breakdown electric field. In order to extract high performance from HEMTs, sheet electron density (n_s) and mobility (μ) are key parameters. Higher n_s and μ are desirable for obtaining better performance. However, n_s is mainly determined by structural parameters of AlGaN layer, that is, Al composition, thickness, and surface barrier height (Φ_B).[1,2] Although n_s is increased by making Al composition high and/or AlGaN layer thick, μ tends to decrease due to the strong alloy and interface roughness scatterings.[3–6]

Another way to increase n_s is to introduce strain in AlGaN barrier layer by depositing, for example, SiN layer on AlGaN surface.[7–10] Azize and Palacios showed that n_s and μ were increased by controlling the biaxial strain with etching Si substrate from the backside.[11] However, the amount of increase so far is limited to 20%–30% and higher increase is preferable.

In this letter, a method to increase both n_s and μ (hereafter referred to as n_s/μ) is described. The method is based on annealing AlGaN/GaN heterostructures deposited by Ti/Al in vacuum. The increase of n_s/μ was confirmed by temperature dependent Hall effect measurements (van der Pauw technique) at temperatures from 300 K to 1020 K. One order of magnitude higher in n_s and 65% higher in μ were observed.

Epitaxial layers used in this study were grown by metal organic chemical vapor deposition (MOCVD) on a c-plane three inch sapphire substrate. After the growth of nucleation buffer layer, undoped GaN channel and undoped $Al_{0.25}Ga_{0.75}N$ barrier layers with thickness of 3 μm and 25 nm, respectively, were successively grown. Before starting the device process, surface was cleaned by organic solvents (acetone and ethanol), buffered HF, and rinsed by de-ionized water. Device processing was initiated by reactive ion etching (RIE) for remaining the active region with 100 nm depth isolation mesa using Cl_2 and BCl_3 gases. 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. The wafer was alloyed at 850 °C for 30 s in N_2 flow to ensure good ohmic contacts. Ti/Au (10/100 nm) evaporation was followed for pad metal. After ohmic contact formation, Ti/Al was evaporated in the center of sample with varying Ti and Al thickness. Only Ti or Al evaporated sample was also prepared for comparison. Cross sectional and top views of the fabricated sample are shown in Figs. 1(a) and 1(b), respectively. The sample size was 7×7 mm^2 and the diameter of center circle was 5 mm.

The processed sample was set to Hall measurement system (Toyo technica ResiTest 8310) and n_s/μ were measured with increasing and decreasing temperatures ranging from 300 K (room temperature) to 1020 K. The measurements were carried out in vacuum (around 1×10^{-3} Torr) with the applied magnetic field of 0.55 Tesla. The f values were 0.95–1.0 for all the measurements indicating that the fabricated samples were isotropic and uniform.

Figures 2(a) and 2(b) show temperature dependences of n_s and μ, respectively, for Ti/Al thickness of 100/100 nm. In the figures, open and closed circles correspond to the results for increasing and decreasing temperatures, respectively. The initial values of n_s and μ measured at 300 K were 0.98×10^{13} cm^{-2} and 1330 cm^2/Vs, respectively. With increasing temperature, n_s showed sudden increase at 520 K and had a peak of 2.8×10^{14} cm^{-2} at 820 K. As the temperature decreased from 1020 K, n_s was slightly increased, showed a peak at 620 K, and then monotonously decreased to 1.1×10^{14} cm^{-2} at room temperature. Surprisingly, n_s at 300 K was eleven times higher than the initial one. Furthermore, μ was also increased as shown in Fig. 2(b). It showed a hump at 520 K with the increase of temperature, which probably corresponded to the sudden increase observed in n_s, and monotonously decreased. With the temperature decrease from 1020 K, μ was increased monotonously without showing the hump. After vacuum annealing, μ at room temperature was 2190 cm^2/Vs, which was 65% higher than the initial value. Similar measurements were performed for samples having different Ti/Al thickness. The results are summarized in Table I. All the samples showed similar temperature dependences as shown in Fig. 2, that is, sudden

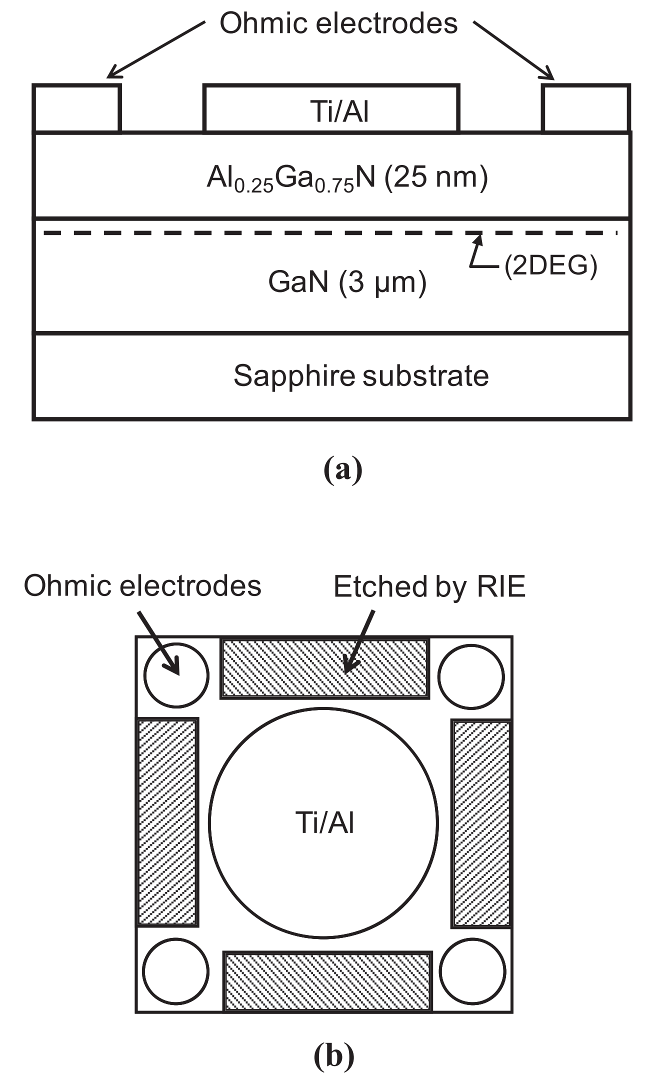

FIG. 1. Cross sectional (a) and top view (b) of the fabricated sample. The hatching is the mesa etched region. The sample size is 7×7 mm^2 and the diameter of center circle is 5 mm.

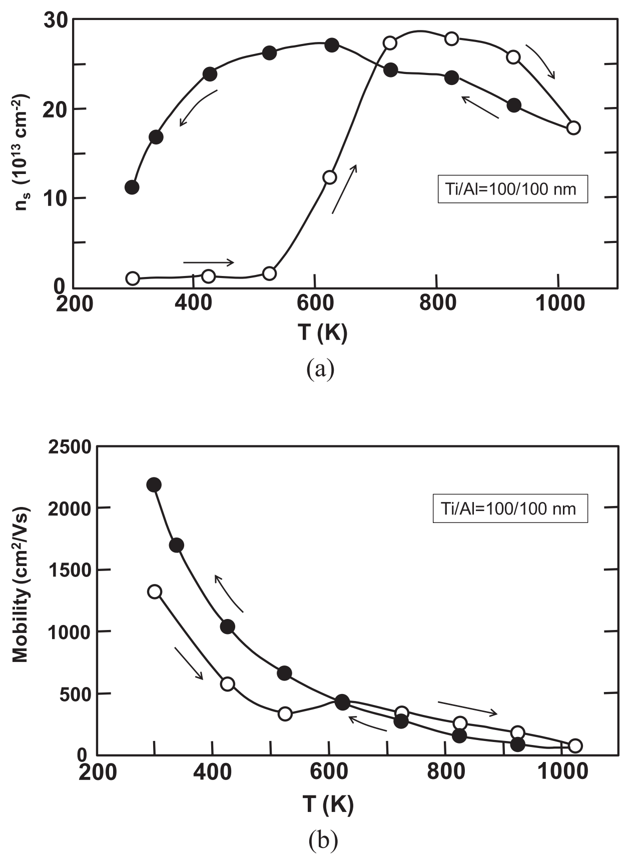

FIG. 2. Temperature dependence of sheet electron density (a) and mobility (b) for Ti/Al thickness of 100/100 nm. Open and closed circles correspond to increasing and decreasing temperatures, respectively. The arrows show the temperature increase/decrease directions.

increase of n_s at around 520 K, having a peak with increasing temperature, and monotonous decrease with decreasing temperature. However, the ratio of initial n_s to vacuum annealed (VA) one, n_{s2}/n_{s1}, and that of initial μ to VA one, μ_2/μ_1, showed marked differences with Ti/Al thickness. It was found that: (i) the increase of n_s was not observed or much less and μ was decreased for only Ti or Al deposited sample (rows 1, 2, and 7 in Table I), (ii) the amount of n_s increase was small when the total Ti/Al thickness was thin (30 nm) (row 3 in Table I), and (iii) the amount of n_s/μ increase was independent of Ti/Al thickness in case of total thickness over 65 nm (rows 4–6 and 8–9 in Table I). The measured samples were kept for one week in the air, and n_s/μ were measured again at room temperature. The results were almost the same as after vacuum annealed ones within the experimental error of $\pm 3\%$, which indicated that n_s/μ values were not recovered to the initial ones. After successive experiments described above, annealed Ti/Al layers were removed by diluted HF. Figures 3(a) and 3(b) show temperature dependences of n_s and μ, respectively, for Ti/Al

TABLE I. Sheet electron density (n_s) and mobility (μ) with varying Ti/Al thickness. n_{s1} and μ_1 are the initial values and n_{s2} and μ_2 are after VA ones measured at room temperature. Vacuum annealing were performed at 1020 K except for Ti/Al = 0/100 nm (annealed at 820 K, below the melting point of Al).

Ti/Al (nm/nm)	n_{s1} initial (10^{13} cm^{-2})	n_{s2} after VA (10^{13} cm^{-2})	n_{s2}/n_{s1}	μ_1 initial (cm^2/V s)	μ_2 after VA (cm^2/Vs)	μ_2/μ_1
15/0	0.9	0.8	0.89	1460	1250	0.86
100/0	0.9	1.6	1.71	1490	1360	0.91
15/15	1.0	1.4	1.35	1370	1730	1.26
50/15	0.9	5.3	6.13	1470	1710	1.16
15/50	1.2	12.9	11.00	1430	1970	1.38
100/50	1.1	14.1	13.30	1050	2150	2.05
0/100[a]	7.8	4.6	0.59	2080	1900	0.91
15/100	1.2	19.0	15.50	1380	2090	1.51
100/100	1.1	11.4	11.60	1330	2190	1.65

[a]Vacuum annealed at 820 K.

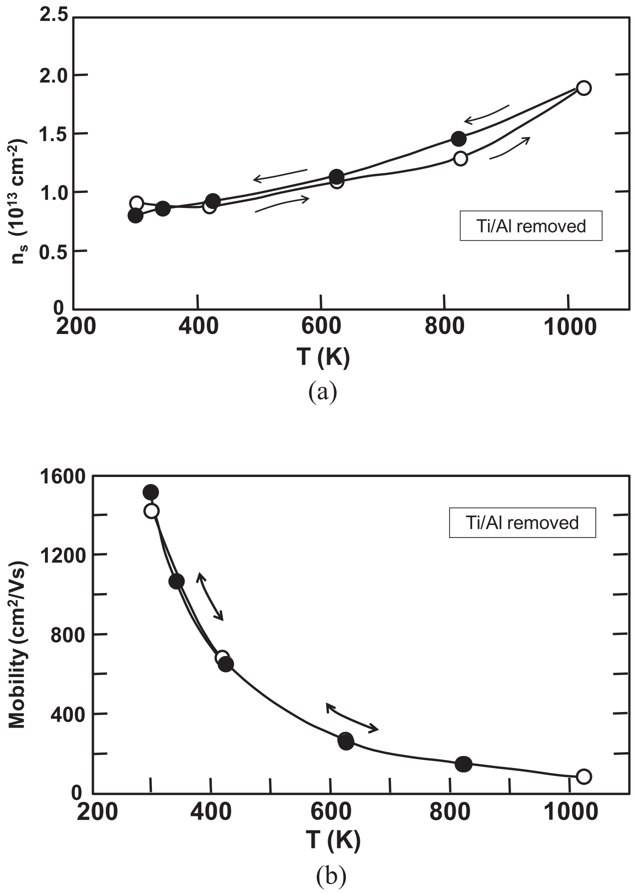

FIG. 3. Temperature dependence of sheet electron density (a) and mobility (b) for Ti/Al removed sample. Open and closed circles correspond to increasing and decreasing temperatures, respectively. The arrows show the temperature increase/decrease directions.

removed sample. As is clearly seen, no increase in n_s/μ was observed, and the values were almost recovered to the initial ones (before annealing). The result implies that the increase in n_s/μ is brought from vacuum annealed Ti/Al layer, not from AlGaN/GaN heterostructures.

In order to investigate the origin of increase in n_s/μ, several possibilities are considered. One of them is that the measured n_s/μ values may correspond to those of the annealed Ti/Al metallic layer, and not of electrons at AlGaN/GaN interface. However, such a concern is excluded because μ never exceeds 2000 cm^2/Vs if electrons flow in the metallic layer. For elaborate measurement, Ti/Al (15/50 nm) was deposited on the whole surface of the epitaxial layer and n_s/μ were measured. The results were 1.2×10^{18} cm^{-2} and 3.4 cm^2/Vs for n_s and μ, respectively, which were quite different by four orders in n_s, and three orders of magnitude in μ from those of Ti/Al circular patterns. Therefore, it is concluded that the measured n_s/μ values correspond to electrons flowing at AlGaN/GaN interface.

The n_s at AlGaN/GaN interface is determined by the following parameters: surface barrier height (Φ_B), band discontinuity between AlGaN and GaN (ΔE_c), thickness of AlGaN layer (d_{AlGaN}), and polarized charge (σ_p, including spontaneous and piezoelectric), where Φ_B, σ_p, and ΔE_c depend on the Al composition of AlGaN layer. Among them, the most probable origin for n_s increase seems to be the change of σ_p. As shown in Fig. 2, Ti/Al starts to react with AlGaN at around 520 K. Since atomic radii of Al and Ti are larger than that of N, the reacted Al and Ti atoms, which are introduced interstitially or substituting N atoms, tend to expand the lattice in AlGaN layer, resulting in the increase of tensile strain. Such enhanced strain remains unchanged even after the temperature decreased to 300 K.

The strain induced by vacuum annealing produces polarized charge. The charge is added to the originally existing polarized charge leading to the net increase of n_s. The validity of above mentioned model is supported by the experimental results that n_s increase was not observed for totally thin Ti/Al layer and for Ti/Al removed sample. Within the experiments in this study, it was confirmed that over 65 nm total thickness of Ti/Al was needed for obtaining high n_s/μ, and Ti or Al solely did not cause n_s/μ increase. It is to be noted that only Al deposited sample showed extremely high n_s/μ in the initial values, although they were decreased by vacuum annealing (see row 7 in Table I). This result suggests that Al plays a key role for increasing n_s/μ. The tensile strain is increased by the intrusion of Al into AlGaN layer, however, it tends to be relaxed by high temperature annealing. Ti acts to suppress the lattice relaxation by reacting with Al.

The net incremental induced σ_p responsible for n_s increase was calculated by using analytical equation and parameters found in Ref. 12. The estimated values were 1.7×10^{-5}, 1.9×10^{-5}, and 2.2×10^{-5} C/cm^2, for Ti/Al thickness of 100/100, 15/50, and 100/50 nm, respectively. The reason of the increase in μ is not clear at present. The induced high sheet density of electrons may screen the polar optical phonon and other dominant scatterings at room temperature,[4,13–15] or the induced strain may reduce the effective mass of electrons,[11] though more experimental evidences are needed to confirm it.

In conclusion, a method to increase n_s and μ for AlGaN/GaN heterostructures is described. It is to anneal Ti/Al deposited layer on AlGaN/GaN heterostructures at around 1000 K in vacuum. One order of magnitude higher in n_s and 65% higher in μ were observed as compared with the initial values. A model to explain the origin of increase is proposed, which tensile strain is increased with annealing in vacuum. The method described, herein, will be useful for reducing the ohmic contact resistivity and/or the access resistance between source and gate in AlGaN/GaN HEMTs.

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