Thermal stability of Schottky contacts on strained AlGaN/GaN heterostructures

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The thermal stability of Ni Schottky contacts on strained $Al_{0.3}Ga_{0.7}N$/GaN heterostructures and on *n*-type bulk GaN was investigated after various thermal stressings using capacitance–voltage and current–voltage characterization techniques. The reverse leakage current decreases after thermal treatment at up to 800 and 600 °C for Schottky contacts on the strained $Al_{0.3}Ga_{0.7}N$/GaN heterostructures and bulk *n*-GaN, respectively. Ni Schottky contacts on the heterostructure with 30-min thermal stressing at 700 °C exhibit lower reverse leakage current by more than three orders of magnitude lower than the control sample. However, decrease in two-dimensional electron gas sheet carrier concentration at the $Al_{0.3}Ga_{0.7}N$ and GaN interface possibly due to interactions between Ni and AlGaN surface was observed with increase of stressing temperature and time. Ni Schottky contacts on bulk *n*-GaN layers degrade at lower annealing temperature and their rectifying property practically disappears after 700 °C annealing, while $Al_{0.3}Ga_{0.7}N$/GaN heterostructures still exhibit nice Schottky behavior after 800 °C annealing. The better thermal stability of Ni Schottky contacts on the heterostructures than those on bulk *n*-GaN can be attributed to the presence of piezoelectric polarization. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1650875]

The properties of AlGaN/GaN heterostructure field-effect transistors (HFETs) have been intensively investigated owing to the potentials for high power and high temperature applications.[1,2] The thermal stability of Schottky gate contacts (SCs) on AlGaN/GaN heterojunctions has significant impact on device performance of GaN-based HFETs at high temperatures. Therefore, investigations of the thermal stability of SCs are of importance for implementation of such devices for high-temperature applications. Previous work has been focused on Pd, Pt, Ti, Ni, Au, Re, PtSi, and NiSi SCs on *n*-type bulk GaN and *n*-type bulk $Al_xGa_{1-x}N$.[3–11] Specifically, Ni SCs on *n*-type bulk GaN and *n*-type bulk $Al_xGa_{1-x}N$ have been studied intensively. The results showed that the rectifying behavior and the barrier height of Ni SCs on *n*-type bulk GaN deteriorate after annealing at 600 °C.[12] However, little research on SCs on AlGaN/GaN heterostructures has been conducted so far. The main reason is that one assumes SCs on AlGaN/GaN heterostructures behave the same way as on bulk AlGaN. Although Jeon *et al.* reported the thermal stability of Ir SCs on AlGaN/GaN heterostructures,[13] the role of oxygen during annealing rather than annealing effects was mainly dealt with to explain the increase of Schottky barrier heights (SBHs).

It is also important to point out here that SCs on strained AlGaN/GaN heterostructures exhibit electrical characteristics unlike those on bulk GaN because of the existence of piezoelectric polarization in the heterostructures. The polarization in the AlGaN/GaN heterostructures affects polarization-induced charges in AlGaN layer and two-dimensional electron gas (2DEG), all of which determine the barrier height of a Schottky contact on strained AlGaN/GaN heterostructures.[14,15] Apart from the polarization effect, surface donor states on the AlGaN layer, which are widely accepted as the origin of 2DEG carriers in undoped AlGaN/GaN structures,[16] should be considered as another factor to affect 2DEG and SBHs after annealing. Thus, it would be valuable to study the thermal stability of SCs on AlGaN/GaN heterostructures in comparison with that of SCs on bulk GaN. In this letter, we present electrical properties of Ni SCs on strained $Al_{0.3}Ga_{0.7}N$/GaN heterostructures and on *n*-type bulk GaN materials after various thermal stressings by $C-V$ and $I-V$ measurements. Qualitative explanations are suggested about the annealing effects on Ni SCs on both AlGaN/GaN structures and bulk GaN layers.

The heterostructure layer employed in this study was epitaxially grown by metalorganic chemical vapor deposition (MOCVD) on a (0001) sapphire substrate. It consists of a 40 nm AlN nucleation layer, followed by a 3 μm undoped GaN and a 21.5-nm-thick undoped $Al_{0.3}Ga_{0.7}N$. Hall measurement indicated a sheet carrier density of around 1.36×10^{13} cm^{-2} and an electron mobility of 1200 $cm^2/V\,s$ at room temperature. The layer for *n*-type bulk GaN was epitaxially grown by MOCVD on a (0001) sapphire substrate. It consists of a 40 nm AlN nucleation layer, followed by a 2 μm doped *n*-GaN. For device processing, ohmic contacts of Ti/Al/Mo/Au were performed by e-beam evaporation and lift-off. These contacts were annealed at 850 °C for 30 s in a rapid thermal annealing system. Ni/Au (60 nm/200 nm) circular SCs with a diameter of 120 μm were then deposited by e-beam evaporation. The separation between the ohmic contact and circular SC was 20 μm. To examine the thermal stability of these contacts, samples were thermally treated in a furnace with N_2 ambient. $C-V$ measurements were performed using an Aglient 4284A LCR meter at a frequency of 10 kHz. $I-V$ measurements were performed using an Agilent 4156 semiconductor parameter analyzer.

Figure 1(a) shows the post-stressing $I-V$ characteristics

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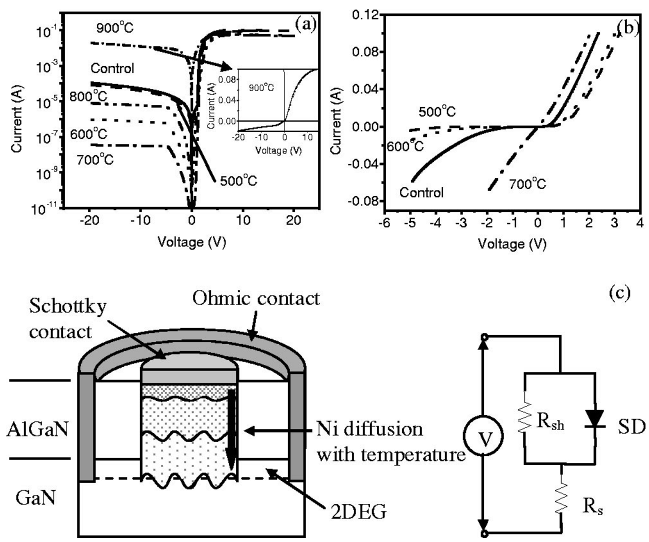

FIG. 1. Post-stressing $I-V$ characteristics of Ni SCs with 30 min. thermal stressing at different temperatures (a) on strained $Al_{0.3}Ga_{0.7}N$/GaN heterostructure and (b) on n-type bulk GaN. [The inset shows a linearly scaled $I-V$ curve of a 900 °C-annealed sample.] (c) A simple schematic of Ni diffusion with temperature (left), where lateral diffusion is not shown because the lateral dimension is much larger than vertical dimension; and an equivalent circuit (right), corresponding to the whole device including Ni Schottky diodes on the heterostructure and n-type bulk GaN, where SD, R_{Sh}, and R_s are a Schottky diode, shunt resistance parallel to the Schottky junction, and parasitic series resistance within the whole structure, respectively.

of Ni SCs on strained $Al_{0.3}Ga_{0.7}N$/GaN heterostructures with different temperatures. The thermal stressing time was 30 min. Decreases in reverse leakage current after thermal stressing up to 800 °C were observed in comparison with the control sample without thermal stressing. After 30 min thermal stressing at 700 °C, the reverse saturation current is more than three orders of magnitude lower than that of control sample. This can be explained by the increase of SBHs after annealing due to interactions between Ni and AlGaN, which has been experimentally confirmed by internal photoemission spectroscopy.[17] One possible reason might be the removal of donor-like defects or creation of acceptor-like defects[13] from interactions between Ni and AlGaN, pulling Fermi energy level down. In the case of Ni SCs on bulk n-GaN [Fig. 1(b)], decreases in reverse leakage current were observed after annealing up to 600 °C in comparison with the control sample. This improvement can be attributed to the reduction of density of interfacial defects.[18] However, as the annealing temperatures increased further, the $I-V$ characteristics of SCs deteriorated in both cases. The degradation is attributed to the creation of shunt paths[11] due to the deep diffusion of Ni atoms into GaN layer, as illustrated in Fig. 1(c); that is, smaller shunt resistances due to further diffusion of Ni at higher annealing temperatures become a dominant factor for the leakage current increase.

Interestingly, degradation of $I-V$ characteristics in bulk n-GaN layers started at lower annealing temperature (about 500 °C) unlike in AlGaN/GaN heterostructures (about 700 °C). The rectifying property of Ni SCs on n-type bulk GaN practically disappeared after 700 °C annealing, while the Schottky behavior in AlGaN/GaN heterostructures was good after 800 °C annealing. Even after annealing at 900 °C, the device still exhibited Schottky-like behavior, as shown in

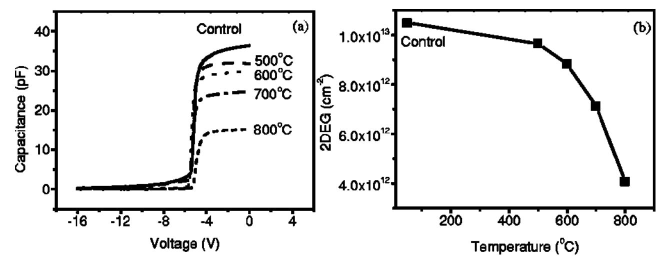

FIG. 2. (a) Post-stressing $C-V$ characteristics of Ni Schottky contacts with 30 min. thermal stressing as a function of stressing temperature. (b) The calculated 2DEG sheet carrier concentrations at the $Al_{0.3}Ga_{0.7}N$/GaN interface based on the measured $C-V$ characteristics.

the inset of Fig. 1(a). The higher reverse current is caused by the small shunt resistance because of the diffusion of Ni atoms into GaN. At higher annealing temperatures, the diffusion is more dominant, which results the decrease of strain energy in AlGaN and hence a decrease of SBHs. These results indicate clearly that the Schottky contacts on strained AlGaN/GaN heterostructures can sustain higher thermal stressing temperatures than on n-type bulk GaN.

Figure 2(a) shows the post-stressing $C-V$ curves of Ni SCs on the strained AlGaN/GaN heterostructures with 30 min thermal stressing at different temperatures. The 2DEG charge quantity in the channel can be estimated by[15]

$$n_s = \int_{V_g'}^{0} C_d dV_g,$$

where n_s is the sheet carrier concentration, V_g' is a voltage that should be lower than the pinch-off voltage, C_d is the capacitance, and V_g is the bias for SCs. The calculated 2DEG sheet carrier concentrations with 30 min of thermal stressing are shown in Fig. 2(b) as a function of stressing temperature. As one can see, the 2DEG concentration decreases as the thermal stressing temperature increases. There are primarily two reasons for the decrease of 2DEG concentration. First, more strain reduction at higher temperature can result in decrease in polarization field across AlGaN barrier and subsequent reduction in polarization charge density of the $Al_{0.3}Ga_{0.7}N$ layer, reducing the 2DEG sheet carrier concentration.[16] Second, more-wave function overlapping between the electrons of Ni atoms and the surface states results in a stronger influence on the density and energy levels of surface states of the $Al_{0.3}Ga_{0.7}N$ layer.[15]

Figure 3 shows the dependence of $I-V$ characteristics on thermal-stressing time in 600 °C stressing of Ni SCs on $Al_{0.3}Ga_{0.7}N$/GaN heterostructures and n-type bulk GaN. In the heterostructures [Fig. 3(a)], as expected, the leakage current increases with increasing stressing time. However, they are still lower than that of SCs without thermal stressing. On the other hand, the reverse saturation current of Ni SCs on n-type bulk GaN deteriorated after thermal stressing [Fig. 3(b)], indicating that SCs on strained AlGaN/GaN heterostructures have better thermal stability.

Figure 4 shows the calculated 2DEG sheet carrier concentrations based on the measured post-stressing $C-V$ characteristics of Ni Schottky contacts on the strained $Al_{0.3}Ga_{0.7}N$/GaN heterostructures with different thermal stressing time at 600 °C. As shown in Fig. 4, the 2DEG concentration decreases dramatically from 1.03×10^{13} to about

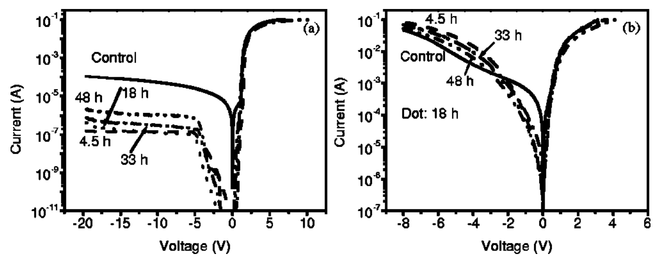

FIG. 3. Post-stressing $I-V$ characteristics of Ni SCs as a function of thermal stressing time (a) on strained $Al_{0.3}Ga_{0.7}N$/GaN heterostructure and (b) on *n*-type bulk GaN. The stressing temperature was 600 °C.

$6.3-\sim 7.0\times 10^{12}\ cm^{-2}$ after 20 h thermal stressing and then reached a relatively stable value, indicating that initial reaction with Ni at AlGaN surface is more crucial than that in the AlGaN layer. Even after 72 h thermal stressing at 600 °C, these Ni Schottky diodes on AlGaN/GaN heterostructures still have nice rectifying behavior with low reverse leakage current, due mainly to the existence of piezoelectric polarization field across the AlGaN layer although strain can be reduced with thermal stressing time. Thus, the differences of physical mechanisms on AlGaN/GaN and bulk GaN can be attributed to (1) the difference of diffusivity in AlGaN and GaN; and more importantly, (2) the existence of piezoelectric field in the AlGaN. The latter plays a dominant role that gives better thermal stability to SCs on AlGaN/GaN heterostructures, even though the strain energy in AlGaN is somewhat less after annealing.

Currently, our efforts are being directed to investigate the diffusion and strain change in the AlGaN layer during thermal stressing. Nevertheless, these Schottky diodes on the heterostructures exhibit similar trends but better thermal stability compared to those Schottky diodes on bulk *n*-GaN. This discovery is significant and it will have great impact on AlGaN/GaN HFETs: (1) This will make it worth while to examine and revisit the thermal stability issues of all other Schottky contacts on AlGaN/GaN heterostructures as extensively investigated on bulk GaN or AlGaN materials; and (2) it will make self-aligned AlGaN/GaN HFETs possible, which will greatly enhance the device speed performance because of the significantly reduced source–access resistances.

In summary, the Schottky behaviors of Ni Schottky contacts on strained $Al_{0.3}Ga_{0.7}N$/GaN heterostructures and Ni SCs on *n*-type bulk GaN were investigated after various thermal stressing conditions by $C-V$ and $I-V$ measurements. Ni SCs on strained $Al_{0.3}Ga_{0.7}N$/GaN heterostructures showed better thermal stability due to piezoelectric effect than those on *n*-type bulk GaN. At suitable conditions of thermal stressing, the reverse leakage current characteristics of Ni SCs on strained $Al_{0.3}Ga_{0.7}N$/GaN heterostructures can be dramatically improved compared to that of the control sample without thermal stressing. Even the sample annealed at 800 °C for 30 min exhibited lower reverse leakage current than the control sample. After thermal stressing for 30 min at 700 °C, the reverse leakage current was more than three orders of magnitude lower than that of the control sample. However, after annealing, the sheet carrier concentration at the

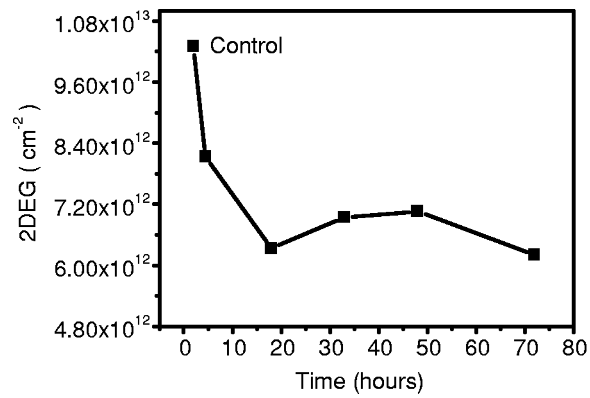

FIG. 4. The calculated 2DEG sheet carrier concentrations of Ni Schottky contacts on strained $Al_{0.3}Ga_{0.7}N$/GaN heterostructure based on the measured post-stressing $C-V$ characteristics in dependence of stressing time with a stressing temperature of 600 °C.

$Al_{0.3}Ga_{0.7}N$/GaN interface decreased. This can be attributed to the change in surface states of the AlGaN layer due to interaction with Ni and the piezoelectric polarization reduction due to the partial strain relaxation or reduced effective strained thickness of AlGaN layer. The good thermal stability of SCs on AlGaN/GaN heterostructures will have a great impact on GaN-based HFETs.

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