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Observation of Negative Differential Resistance in a GaN/AlGaN/GaN: Possible Tunneling Junction Using Polarization

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We report an anomalous current–voltage behavior in an n-type GaN/undoped InGaN/undoped GaN/undoped AlGaN/n-type GaN diode grown by metalorganic chemical vapor deposition. The tunneling-junction-like band profile of the undoped GaN/undoped AlGaN/n-type GaN (GAG) structure is formed by a spontaneous and piezo polarization effect. We observe negative-differential resistance (NDR) behavior in the diode with the GAG structure. The NDR behavior suggests a possible tunneling junction consisting in the GAG structure.

1. Introduction

Group-III nitrides are attractive semiconductors for making solar cells with high conversion efficiency. This is because the band gap of a ternary or quaternary compound can be set anywhere between 0.7 and 6.2 eV simply by changing the composition.[1–3] This band-gap range covers most of the solar spectrum. This means that the desired band gaps for subcells in a multi-junction tandem solar cell can be easily obtained and the current-matching condition can be easily realized. In fact, the very high conversion efficiency of over 50% has been predicted using a multijunction (over six junctions) tandem solar cell consisting of InGaN subcells.[4] For achieving a multijunction solar cell, it is necessary to connect the subcells to each other with a tunneling junction to avoid current loss at the interface of each subcell. To fabricate the tunneling junction, thin p- and n-type layers with very low resistivity are necessary. However, p-type GaN has very low carrier density and it is very difficult to achieve tunneling junction with a p^+–n^+ structure. Recently, some groups have proposed a new type tunneling junction using polarization-induced carriers.[5–10] Grundmann et al. fabricated a light-emitting diode with a GaN/AlN/GaN structure that connected two InGaN/GaN multiple-quantum well active regions with different emitting wavelengths and demonstrated multi-color electro-luminescence spectra.[5] Simon et al. proposed a GaN/AlN/GaN p–n tunneling junction and demonstrated backward diode characteristics.[6] Additionally, Krishnamoorthy et al. proposed another type of tunneling junction using InGaN and achieved very high forward tunneling peak current of 17.7 A/cm^2.[10] These results are very attractive for the application to multijunction tandem solar cells. However, InGaN is a little difficult to grow because of its low optimum growth temperature compared with other compounds. The small band gap of InGaN is another disadvantage for application to multi-junction tandem solar cells because the small band gap energy causes the optical loss at the tunneling junction. In this investigation, we examine the possibility of a tunneling junction with a simple structure that is easy to grow by metalorganic chemical vapor deposition (MOCVD) and that has larger band gap energy than the absorption layer in solar cells. We fabricate an n–i–n diode with a GaN/AlGaN/GaN structure and successfully demonstrate a negative-differential resistance (NDR) behavior, which suggests that the GaN/AlGaN/GaN structure acts as a tunneling junction.

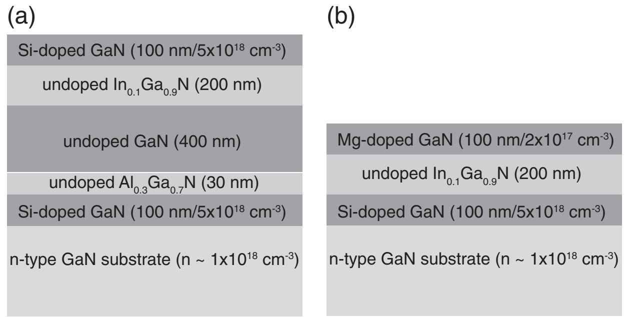

Fig. 1. Epitaxial layer structures of (a) an n–i–n diode with the GAG structure and (b) a p–i–n diode.

2. Experimental Procedure

Samples were grown on two-inch-diameter n-type GaN free-standing substrates by MOCVD. The group-III sources were trimethylgallium for GaN growth, and triethylgallium and trimethylindium for InGaN growth. The nitrogen source was ammonia. Silane was used for n-type doping and Cp_2Mg was used for p-type doping. The epitaxial layer structures are shown in Fig. 1, where (a) is the undoped GaN/undoped AlGaN/n-GaN structure. In this work, we call this the "GAG" structure. For comparison, a p–i–n diode structure without the GAG [shown in Fig. 1(b)] was also grown on a GaN substrate.

Diodes with a size of 0.1×0.1 mm^2 were fabricated on the whole 2-in. wafers. The current–voltage (I–V) characteristics were measured in the dark at room temperature. For the measurement of the I–V curve of the diode with the GAG, the top metal was used as a ground, while the backside metal was the ground for the p–i–n diode without the GAG.

3. Results and Discussion

Figure 2 shows the simulated[11] band diagrams of the samples shown in Fig. 1. Note that the band diagram of n-GaN/undoped InGaN/undoped GaN structure in the diode with the GAG is almost the same as that of the p–i–n type

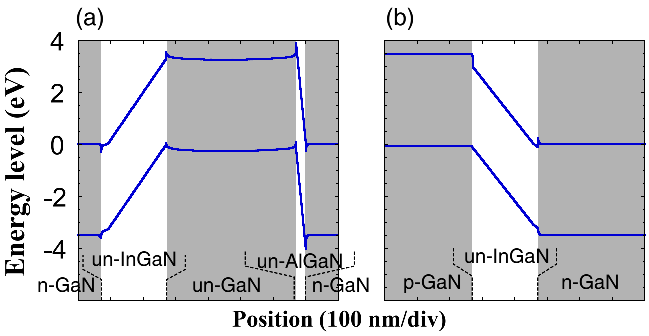

Fig. 2. (Color online) Band diagrams of (a) the n–i–n diode with the GAG structure and (b) the p–i–n diode.

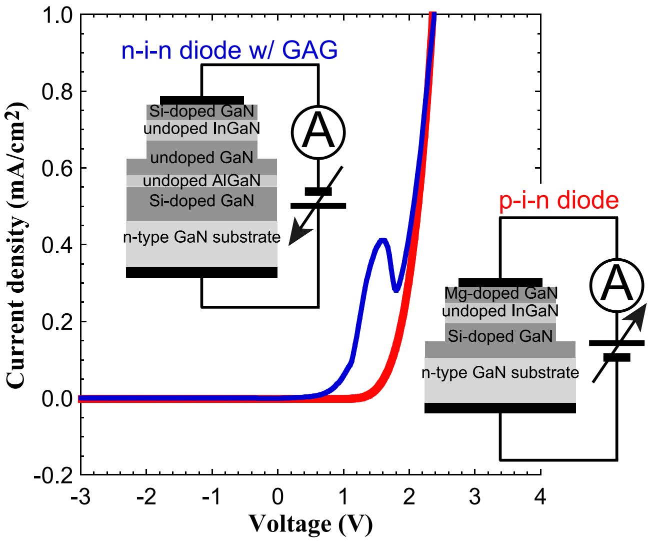

Fig. 3. (Color online) *J*–*V* curves of the n–i–n diode with the GAG structure (blue line) and the p–i–n diode (red line). Insets are schematics of the setups for *J*–*V* characteristics measurement.

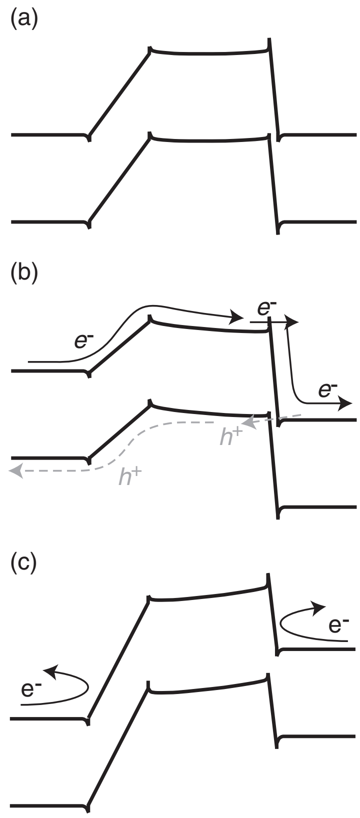

Fig. 4. Schematic band diagrams of the n–i–n diode with the GAT under several bias conditions: (a) zero bias, (b) forward bias, and (c) reverse bias.

diode. The band diagram around the AlGaN layer in the GAG structure is quite similar to a tunneling junction except for the thickness of the AlGaN (30 nm, which is too thick for the usual tunneling).

Figure 3 show the voltage (V) dependence of current density (J) of the fabricated diode. For the p–i–n diode, the J–V curve indicates the usual rectifying behavior: the current is near zero in the reverse bias region while it increases rapidly in the forward bias region. On the contrary, the n–i–n diode with the GAG structure shows an anomalous behavior. The J–V curve of the diode with the GAG structure exhibits roughly rectifying characteristics. However, note the pronounced peak at a voltage of around 1.5 V. Additionally, a clear NDR behavior can be seen. This suggests that some tunneling process is involved in producing the J–V characteristics of the n–i–n diode with the GAG structure.

As mentioned above, the band diagram of the n-GaN/undoped InGaN/undoped GaN region is p–i–n-like shaped. Therefore, a forward bias raises the conduction band of the n-GaN, the top layer of the diode, as shown in Fig. 4(b), which causes electrons to move from the n-GaN through the undoped InGaN and undoped GaN. Electrons injected to the undoped GaN diffuse to the interface between the undoped GaN and undoped AlGaN, then go through the energy barrier to n-GaN. Thus, the electron current in the diode increases as the forward bias increases. On the other hand, a reverse bias pushes the conduction band of the n-GaN top layer downward, preventing electrons from moving as shown in Fig. 4(c). In this situation, the electron current is very small. Additionally, if the GAG acts as a complete tunneling junction, holes can go through the undoped AlGaN from the n-GaN bottom layer when the bias is applied in a forward direction, resulting in increasing the diode hole current. At least, the diode with the GAG should exhibit rectifying behavior whether the hole current exists or not, resulting in a J–V curve similar to that of the p–i–n diode.

Figure 5 shows an enlargement of the band diagram around the GAG structure. At the interface between the undoped AlGaN and n-GaN, spontaneous and piezo polarization produce a dense two-dimensional electron gas (2DEG). There is also a two-dimensional hole gas (2DHG) at the interface between the undoped AlGaN and undoped GaN. In the tunneling process, the electrons at the quasi-Fermi level of the undoped GaN should go through the undoped AlGaN layer to the n-GaN layer. When there is a forward bias, which produces a reverse bias in the GAG, the energy level of the 2DEG and the quasi-Fermi level of n-GaN are pushed downward. In this situation, the electrons at the quasi-Fermi level might pass through the AlGaN layer and go to the n-GaN if the AlGaN thickness is small enough for interband tunneling. However, in our sample, the AlGaN layer is 30 nm thick, which is too thick for the usual

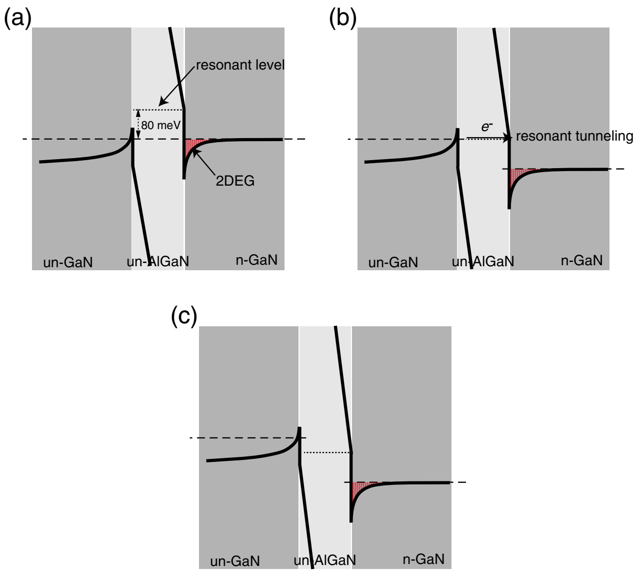

Fig. 5. (Color online) Enlarged band diagrams around the GAG structure of the n–i–n diode under the condition of (a) zero bias, (b) resonant tunneling of an electron under forward bias forward bias, and (c) off-resonant state under forward bias.

interband tunneling. Moreover, interband tunneling itself could not cause the NDR behavior. The NDR behavior requires some resonant tunneling process. That is, some resonant level should exist in the AlGaN layer and the energy level of the resonant level and the quasi-Fermi level in the valence band should match when the forward bias of about 1.5 V is applied.

From the epilayer structure shown in Fig. 2, the voltage applied to the AlGaN layer in the GAG is estimated to be about 5% of the total bias voltage. Therefore, the difference in the energy level between the quasi-Fermi level of the undoped GaN and n-GaN is considered to be about 75 meV. This means that, if the NDR behavior was caused by some resonant tunneling process, the resonant level in the AlGaN layer should be located 75 meV above the quasi-Fermi level of the n-GaN. From the band diagram simulation, the band discontinuity between the Fermi level in the n-GaN and the conduction band of the undoped AlGaN is estimated to be about 80 meV, which is almost the same as the evaluated resonant level in the AlGaN. Therefore, it is speculated that the resonant level might be located at the conduction band edge of the interface between the undoped AlGaN and the n-GaN. While the origin of the resonant level is not clear yet, imperfections in the material, such as dislocations, point defects, and impurities, might be involved in the resonant tunneling process that causes the NDR behavior.

Anyway, our results indicate the possibility of achieving a tunneling junction using an AlGaN layer, and suggest that the higher density of imperfections in the material could make the tunneling current larger. As described above, the forward bias on the n–i–n diode produces reverse bias in the GAG. That is, our results were obtained under a reverse bias situation for the GAG. On the contrary, tunneling junctions in a multijunction tandem solar cell are under forward bias when the solar cell is operated. Therefore, for application of the GAG to multijunction tandem solar cells, introducing some resonant level below the Fermi level (i.e., deep traps) would be effective. Additionally, a thinner AlGaN layer and higher carrier concentration would make the tunneling probability larger, resulting in larger tunneling current. For example, higher Al content in the AlGaN layer could reduce the thickness of the AlGaN layer and increase the 2DHG density at the interface between the undoped AlGaN and undoped GaN. The polarization-induced hole doping reported in Ref. 12 might be another way to obtain high hole concentration. After these further investigations, we believe we can achieve a tunneling junction using the GAG structure that meets the requirements of a multijunction tandem solar cell.

4. Summary

In summary, we fabricated n–i–n type diodes of a group-III nitride with a GaN/AlGaN/GaN structure on a GaN substrate by MOCVD. We obtained anomalous current–voltage characteristics, that is, the NDR behavior. This behavior suggests that resonant tunneling through the AlGaN layer might be involved. However, the AlGaN is too thick for the normal tunneling process. We speculate that imperfections in the material might be involved in producing the NDR. For application of the GaN/AlGaN/GaN structure to a multijunction tandem solar cell, we need further investigation to understand the anomalous characteristics.

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