Resonant tunneling of charge carriers in InGaN/GaN superlattice

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Abstract. The result of studies of resonant tunnelling of charge carriers in InGaN/GaN unipolar structure is presented. Authors show that at temperatures below 150 K the multiple negative-differential resistance regions are observed on a reverse current-voltage characteristic which is typical for inhomogeneous distribution field for sample with 6 nm barrier thickness. At GaN barrier thickness 3 and 12 nm resonant tunneling were not observed.

1. Introduction

The InGaN/GaN superlattices (SLs) and multiple quantum wells (MQWs) are widely used as active regions or buffer layers in laser diodes, light-emitting diodes, receivers of visible and ultraviolet ranges, etc. As a rule, the electrical characteristics of these devices are investigated in details. However, the characteristics of InGaN/GaN SLs and MQWs are not studied intensively. The author’s different works showed that low-temperature transport of electrons cannot be explained by conventional quasi-equilibrium drift-diffusion model [1].

Studies of current-voltage (I-V) characteristics of structures with InGaN/GaN multiple quantum wells used for analysis of transport mechanism of charge carriers. It is well known that resonant tunneling of charge carriers in superlattice can be detected by using I-V measurements. In this case the regions of negative-differential resistance (NDR) at I-V curves are observed in the experiment [2]. Previously, such NDR regions were measured for different material systems (AlGaAs/GaAs [3], AlGaN/GaN [4, 5, 6] etc.) This paper presents the results of experimental study of resonant tunneling in InGaN/GaN superlattice.

2. Experimental details

Experiments were carried out for unipolar structures grown by a MOCVD method on the [0001] patterned sapphire substrate. As precursors of III-group elements the following metal organic compounds were used: trimethylindium In(CH$_3$)$_3$, trimethylgallium Ga(CH$_3$)$_3$, triethylgallium Ga(C$_2$H$_5$)$_3$. As nitrogen precursor an ammonia (NH$_3$) was used. For donor dopant (silicon) siliconmethane was used. The structure consisted of a 4-µm-thick GaN nucleation layer, a 2-µm-thick Si-doped $n$-type GaN, doped $n$-type layer with In$_{0.15}$Ga$_{0.85}$N/GaN MQWs, and 17-nm-thick Si-doped $n$-type GaN. The MQW layers comprised ten periods of an In$_{0.15}$Ga$_{0.85}$N well (2 nm) and a GaN barrier (6 nm). Additionally we investigated structures with GaN barrier thickness 3 and 12 nm. As a top contact we used Ni Schottky barrier. As an ohmic contact for buffer $n$-GaN layer we used fusing In contact of large area. Schematically investigated structure is shown in figure 1.
In the experiment we measured the current-voltage characteristics in the temperature range $T = 10$ – 300 K using a Janis cryostat and Keithley 2636A Source Meter. The measurements were carried out in a static and pulse mode to avoid overheating structures.

![Schematic view of experimental samples for investigated InGaN/GaN unipolar structures.](image)

**Figure 1.** Schematic view of experimental samples for investigated InGaN/GaN unipolar structures.

### 3. Experimental results

Initially we studied dependence of barrier height on temperature using $n$-GaN/Ni structure:

$$\Phi_k = kT \cdot \ln \left( \frac{A^* T^2}{j_s} \right),$$

(1)

where $k$ – Boltzmann constant, $T$ – temperature, $A^*$ – Richardson constant, $j_s$ – saturation current. In figure 2 the dependence of Schottky barrier height on temperature is shown. Drop height of the barrier is observed at temperatures below 200 K.

![Dependence of Schottky barrier height on different temperature.](image)

**Figure 2.** Dependence of Schottky barrier height on different temperature.

Then we measured I-V characteristics of unipolar samples (GaN barrier thickness at 3, 6, 12 nm). And we found that at the different thickness barriers GaN experimental results for I-V curves are very different. The measurements of I-V curves showed an increasing of current limitation with barrier thickness increasing (figures 3 - 6). This limitation trend is more expressed at reverse bias for Ni/GaN Schottky barrier.
In the figures 3 and 4 it is show that structures with thickness 3 and 12 nm don’t have NDR regions. This can be explained by the fact that the tunneling probability of the charge carriers is decreased with increasing GaN barrier thickness up to 12 nm. A split of discrete levels in InGaN/GaN QW in the miniband occurs with reducing GaN barrier thickness up to 3 nm where carriers are transported without tunneling.

**Figure 3.** I–V curves of InGaN/GaN with 3 nm barrier thickness at different temperatures.

**Figure 4.** I–V curves of InGaN/GaN with 12 nm barrier thickness at different temperatures.

In the figures 5 and 6 experimental I-V characteristics for sample with 6 nm are shown. In the range from 0.5 to 0.7 V one or two regions of the NDR are observed on forward I-V characteristics which disappear when the temperature increases (Figure 1). Such behavior of I-V characteristic is typical for the case of homogeneous electric field distribution in superlattice [2]. At temperatures below 150 K at above 0.7 V the multiple NDR regions are observed on a reverse I-V characteristic which is typical for inhomogeneous distribution field (Figure 2).

In both figures 5 and 6 it is shown that the numbers of NDR regions are decreased by growing up the temperature. However, at room temperature ($T = 300$ K) those NDR regions are not observed at all.

**Figure 5.** Forward I–V curves of InGaN/GaN with 6 nm barrier thickness at different temperatures.

**Figure 6.** Reverse I–V curves of InGaN/GaN with 6 nm barrier thickness at different temperatures.
4. Conclusion

Thus, according to the results of this study, NDR regions were observed in the forward and reverse I-V curves for the InGaN/GaN SL with GaN barriers thickness of 3 nm. Found areas are observed at temperatures below 150-200 K. And at the same temperature reduction in the potential $n$-GaN/Ni barrier height occur.

Therefore it is explained the fact that NDR regions occur due to the resonant tunneling of charge carriers through the GaN barriers. By increasing the thickness of GaN barrier NDR regions do not occur. It can be associated with decreasing of tunneling probability of the charge carriers. By reducing the thickness of barriers a split of discrete levels in the miniband occurs. The detailed analysis of experimental results considers miniband vertical transport and resonant tunneling under condition of homogeneous and inhomogeneous electric field distribution in SLs [2]

In this work we have shown the result which demands additional studies. Hopefully, in the next few years, we are going to have new data that will provide answers and guidance for our next steps in the investigation of transport change carries of InGaN/GaN SL.

References
[1] Browne D A, Mazumber B, Wu Y, Speck J S 2015 J. Appl. Phys. 117 185703
[2] Waker A 2002 Physics Reports 357 1
[3] Andronov A A, Dodin E P, Zinchenko D I, Nozdrin Yu N 2009 Semiconductors 43 240-247
[4] Haoran Chen, Lin’an Yang, Yue Hao 2014 Journal Of Applied Physics 116 074510
[5] Warde E, Sakr S, Tchernycheva M Julien H 2012 Journal of Electronic Materials 41 965-970
[6] Noriyuki Watanabe, Haruki Yokoyama, Naoteru Shigekawa 2013 Jpn. J. Appl. Phys. 52 08JN03
Corrigendum: Resonant tunneling of charge carriers in InGaN/GaN superlattice

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Description of corrigendum:

1. **Abstract.** "The result of studies of resonant tunnelling of charge carriers in InGaN/GaN unipolar structure is presented" change to "The results of study of resonant tunnelling of charge carriers in InGaN/GaN unipolar structures are presented";

2. "At GaN barrier thickness 3 and 12 nm resonant tunneling were not observed" change to "For structures with GaN barrier thickness of 3 and 12 nm resonant tunneling was not observed";

3. "The author’s different works showed that low-temperature transport of electrons cannot be explained by conventional quasi-equilibrium drift-diffusion model" change to "There is few works showed that low-temperature transport of electrons cannot be explained by conventional quasiequilibrium drift-diffusion model";

4. "Studies of current-voltage (I-V) characteristics of structures with InGaN/GaN multiple quantum wells used for analysis of transport mechanism of charge carriers" change to "The measurements of current-voltage (I-V) characteristics of structures with InGaN/GaN multiple quantum wells were used for study of transport mechanism of charge carriers";

5. "As a top contact we used Ni Schottky barrier" change to "As a top contact we used Ni Schottky barrier contact";

6. "The measurements were carried out in a static and pulse mode to avoid overheating structures." change to "The measurements were carried out in a static and pulse modes to avoid overheating of the structures";

7. "Drop height of the barrier is observed at temperatures below 200 K." change to "Barrier height drop is observed at temperatures below 200 K.";
8. "And we found that at the different thickness barriers GaN experimental results for I-V curves are very different." change to "We found that at the different GaN barrier thickness the experimental results for I-V curves are different."

9. "The measurements of I-V curves showed an increasing of current limitation with barrier thickness increasing (figures 3 - 6). This limitation trend is more expressed at reverse bias for Ni/GaN Schottky barrier." change to "The measurements of I-V curves showed an increase of current limitation with barrier thickness increasing (figures 3 - 6). This limitation trend is more pronounced at reverse bias for Ni/GaN Schottky barrier."

10. "A split of discrete levels in InGaN/GaN QW in the miniband occurs with reducing GaN barrier thickness up to 3 nm where carriers are transported without tunneling." change to "A split of discrete levels in InGaN/GaN QW in the miniband occurs with reducing of GaN barrier thickness up to 3 nm."

11. "In both figures 5 and 6 it is shown that the numbers of NDR regions are decreased by growing up the temperature. However, at room temperature (T = 300 K) those NDR regions are not observed at all." change to "It is shown from figures 5 and 6 that the numbers of the NDR regions decreases with by growing of the temperature. At room temperature (T = 300 K) the NDR regions are not observed."

12. "Thus, according to the results of this study, NDR regions were observed in the forward and reverse I-V curves for the InGaN/GaN SL with GaN barriers thickness of 3 nm" change to "Thus, according to the results of this study, the NDR regions were observed in the forward and reverse I-V curves for the InGaN/GaN SL with GaN barriers thickness of 6 nm."

13. "Found areas are observed at temperatures below 150-200 K. And at the same temperature reduction in the potential n-GaN/Ni barrier height occur." change to "The NDR regions are observed at temperatures below 150-200 K."

14. "Therefore it is explained the fact that NDR regions occur due to the resonant tunneling of charge carriers through the GaN barriers. By increasing the thickness of GaN barrier NDR regions do not occur. It can be associated with decreasing of tunneling probability of the charge carriers. By reducing the thickness of barriers a split of discrete levels in the miniband occurs. The detailed analysis of experimental results considers miniband vertical transport and resonant tunneling under condition of homogeneous and inhomogeneous electric field distribution in SLs [2] In this work we have shown the result which demands additional studies. Hopefully, in the next few years, we are going to have new data that will provide answers and guidance for our next steps in the investigation of transport change carries of InGaN/GaN SL. " change to "NDR regions appears due to the resonant tunneling of charge carriers through the GaN barriers. With increasing of thickness of GaN barrier the NDR regions disappears. It can be associated with decreasing of tunneling probability of the charge carriers. With reducing of thickness of barriers a split of quantum levels in the miniband occurs. The detailed analysis of experimental results considers"
miniband vertical transport and resonant tunneling under condition of homogeneous and inhomogeneous electric field distribution in SLs [2].

15. to add: Acknowledgements This study was supported by the Ministry of Education and Science of the Russian Federation project no. 3.1206.2014/K.