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Analysis of Carrier Transport through GaN/AlN Periodically Stacked Structure Photodiode

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***Abstract*—Carrier transport through GaN/AlN periodically stacked structure photodiode (PSSPD) is investigated considering the polarization field in the structure. The movement of electrons out of quantum well is found as Fowler-Nordheim tunneling process helped by the polarization field in AlN barrier. The transport of electrons through PSSPD is found influenced by the reverse polarization field in GaN layer but could be suppressed by the external electric field. Different rates of current increase are also predicted from the analysis of polarized band structure, which is consistent with the PSSPD experimental results.**

Keywords—carrier transport, polarization, photodiode, periodically stacked structure

I. Introduction

Polarization is an important property of wurtzite III-nitride materials. It is well recognized that polarization should be discussed when dealing with heterointerfaces in GaN-based systems [1]. Recently, GaN/AlN periodically stacked structure photodiode (PSSPD) has been demonstrated of photomultiplier-like photocurrent characteristics [2-5]. However, polarization property was ignored in previous theoretical analyses when explaining the high external quantum efficiency (EQE) of PSSPD [2-5]. It has been theoretically demonstrated that polarization fields has large contribution to the electron ionization rate in the III-nitride multi-quantum-well structure [6]. Moreover, the directions of polarization fields in AlN and GaN heterolayer are contrary to each other [1]. Therefore the electrons transport through the PSSPD are expected influenced by the reverse polarization field in AlN and GaN layer. Thus the carrier transport and EQE of GaN/AlN PSSPD could not be well modeled if the polarization field in GaN/AlN periodically stacked structure is not considered.

In this work, carrier transport through GaN/AlN PSSPD is investigated considering the polarization field in the structure. At first, the GaN/AlN PSSPD is theoretically investigated to get the polarization-field-modified energy band profile. Then the influence of polarization field on carrier transport is presented based on the band profile at different external voltage. The current increase rate of PSSPD at low and high voltage bias is also analyzed.

II. Band Structure Considering Polarization Field

The structure of GaN/AlN PSSPD is illustrated in Fig. 1 and could be simply depicted as 20 AlN (10 nm)/GaN (10 nm) periodic layers inserted into the impact ionization region of p-i-p-i-n structure. The role of polarization field on conduction band structure of PSSPD is presented in Fig. 2. The calculation of band structure is based on self-consistent solution of Schrödinger-Poisson equations. The polarization field strength in AlN (10 nm)/GaN (10 nm) heterolayer is obtained as 3.2 MV/cm and -3.2 MV/cm respectively, based on the software package of Crosslight APSYS with Coulomb screening ratio set as 0.5. For the PSSPD intentionally ignoring the polarization field, the energy band diagram is shown as tilted profile dropped down by the built-in electric field and external electric field. In contrast, for the PSSPD considering the polarization field, uplifted energy band profile is found for the PSSPD structure, with nearly-flat energy band profile in the light-absorption layer. This nearly-flat band profile of the absorption layer is not considered in previously analyses of PSSPD [2-5] and is explained as follows. The polarization field in GaN layer is found in reverse direction contrary to the external electric field of PSSPD. Calculation shows that the field strength is changed from positive to negative for the spatial distribution of the electric field in the absorption layer. Hence the trend of energy band dropped-down by the external electric field is restored by the very high reverse polarization field inside the absorption layer.

III. Carrier Transport in the Polarized Structure

As previously demonstrated, the polarization field in the structure is beneficial to the electron ionization in PSSPD [6]. Here we show that the polarization field is also helpful to the movement of electrons out of quantum well. As shown in Fig. 3, electron trapping at GaN/AlN interface is expected due to the nearly-flat band profile of absorption layer and the tilted-up band profile of quantum well layer. Thermionic emission has been proposed in previous paper to explain the injection of photo carrier from absorption layer into the multi-quantum-well (MQW) region [5]. With the polarization modified band structure in Fig. 3, it is shown unlikely that the thermionic emission could explain the large EQE of PSSPD in [2]. The probability of thermionic emission process is extremely low considering the large AlN/GaN conduction band edge discontinuity around 2.0 eV. Moreover, the band profile of light absorption layer remains nearly-flat profile even at large voltage bias. Hence the photo carriers inside absorption layer could not be over heated to make thermionic emission process. In contrast, considering that the band profile of AlN layer is greatly dropped down by the polarization field, the electrons are more likely to transport through the AlN barrier in Fowler-Nordheim (FN) tunneling process. The FN tunneling current is proportional to $\varepsilon^2 \exp(-A/\varepsilon)$, where ε is electric field on tunneling barrier [7]. In consideration of the 3.2 MV/cm polarization field in AlN barrier, the FN tunneling probability is greatly enhanced in the PSSPD structure. Therefore, the reported large EQE of PSSPD is well explained with photoelectrons FN tunneling through the MQW region.

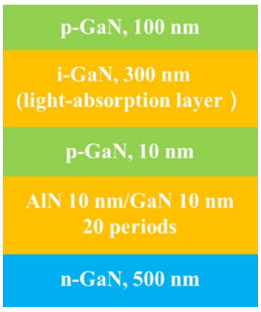

Fig. 1. Structure of the AlN/GaN periodically stacked structure photodiode.

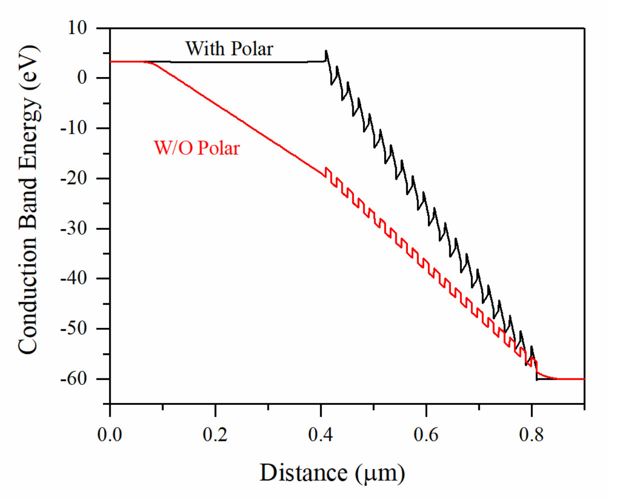

Fig. 2. Conduction band profile of GaN/AlN PSSPD at 60 V voltage with or without considering the polarization field.

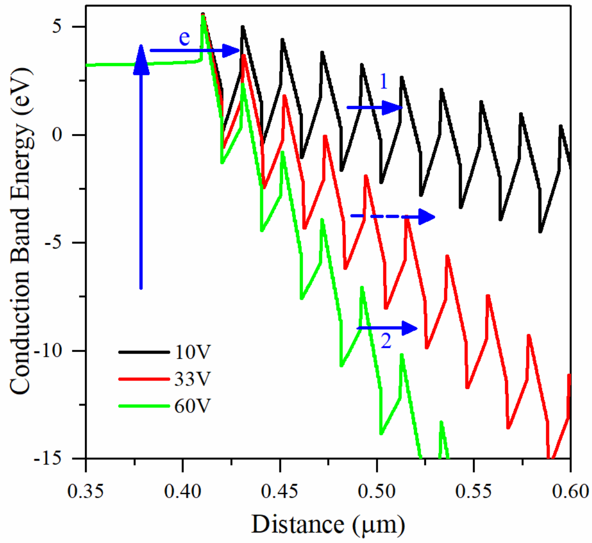

Fig. 3. Calculated conduction band profile for the GaN/AlN PSSPD in 10 V, 33 V, and 60 V voltage bias. The arrows indicate the electron stream through the multi-quantum-wel structure.

The photoelectrons in each GaN well layer is step by step transported through the following GaN/AlN interfaces. As shown in Fig. 3, the transport of photoelectrons is influenced by the reverse polarization field in GaN layer. There are two kinds of electrons inside each quantum well layer: local electrons created by impact ionization at current quantum well and drifting electrons from previous quantum well to current quantum well. As indicated by arrow 1 at low voltage bias, the local photoelectrons are greatly trapped and scattered by the reverse polarization field in quantum well layer while the drifting electrons are scattered at previous and current AlN barriers. At high voltages bias, not only the reverse polarization field in GaN well layer is partly offset by the external field, but also the FN tunneling through AlN barrier is enhanced. Furthermore, as indicated by arrow 2, the drifting electrons are heated over next AlN barrier by the external electric field at high voltage, thereby minimizing the influence of MQW structure on the carrier transport. Accordingly, it is expected that the quantum efficiency of PSSPD is greatly decreased at low voltage bias and then quickly increase at high voltage bias. As indicated by the dash arrow in Fig. 3, the AlN barrier is dropped just below the previous quantum well at 33 V, which sets the transition voltage for arrows 1, 2 indicated electron stream. Therefore the current characteristic of GaN/AlN PSSPD could be predicted with quick increase above 33 V, thanks to the greatly reduced carrier trapping and interface scattering inside the MQW structure. The predicted current increase above 33 V is confirmed by the reported photocurrent-voltage curve of PSSPD [8].

IV. Conclusion

In summary, the carrier transport of GaN/AlN PSSPD has been theoretically investigated based on the polarized band structure. The electrons drifting through the PSSPD structure is found helped by the polarization field in AlN layer but obstructed by the reverse polarization field in GaN layer. The absorption layer in PSSPD is found with near-flat band profile even in high voltage bias. Accordingly, the GaN/AlN PSSPD is expected of weak Franz-keldysh effect over typical homo-junction avalanche photodiode. The responsivity spectral cut-off is thus improved for the GaN/AlN PSSPD.

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