# Optimal design of superlattice periods and well doping for III-nitride intersubband photodetectors

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***Abstract***

**The influence of superlattice periods and well doping on the band structure and distribution of electrons for III-nitride intersubband photodetectors are theoretically studied. It is found that there are more wells populated with electrons with the increase of superlattice periods and doping concentration. This knowledge is beneficial to improve the intersubband absorption efficiency, providing theoretical supports for the optimal design of III-nitride intersubband photodetectors.**

## I. INTRODUCTION

III-nitride intersubband (ISB) photodetectors have been experiencing a rapid-development due to their great application potential in ultrafast optical communications. Since there exists a large conduction band offset (2 eV) between GaN and AlN, the ISB transition within GaN/AlN heterostructures could cover interesting wavelength region around 1.3/1.55 μm[1]. Furthermore, an ultrafast ISB relaxation time (150-400 fs) is observed benefitting from the strong electron-LO phonon interaction in III-nitride materials, and enables the devices to be operated with high speed[2].

There are mainly two types of III-nitride ISB photodetectors reported, namely, photoconductive quantum well infrared photodetectors (QWIPs) and photovoltaic QWIPs[3]. Photoconductive QWIPs are operated based on the transportation of photo-generated carriers, while photovoltaic QWIPs rely on the formation of electrical dipole moment in asymmetry quantum wells, with photocurrent and photovoltage output, respectively. The ISB absorption efficiency has a great influence on the performance of those photodetectors. However, suffering from the strong spontaneous and piezoelectric polarization inheriting in III-nitride materials, an unexpected internal electric field applied on the active region may lead to the depletion of doped carries, which directly shortens the effective absorption distance, and finally lowers the ISB absorption efficiency. The ideal situation for ISB photodetectors is that the active region under flat-band condition and the ground states are all populated with electrons.

In this paper, we theoretically studied the influences of superlattice periods and doping concentration on the band structure and electron distribution based on Photovoltaic QWIPs. Generally, the influence of superlattice periods was ignored, while we found that with a greater number of superlattice periods and a higher doping concentration, a larger number of quantum wells will be populated with electrons.

## II. THEORETICAL BASIS AND DEVICE STRUCTURE

Since the polarization-induced internal field causes the tilt of band structure and the redistribution of carrier in active region, the spontaneous and piezoelectric polarization effects must be considered in the simulation of III-nitride ISB photodetectors. Self-consistent solve of Eight-band k·p Schrödinger-Poisson equations is employed to calculate the GaN/AlN superlattices in this paper, with parameters taken from reference of[4].

Figure 1(a) shows the band structure (upper pane) and electron distribution (lower pane) under the ideal situation for III-nitride ISB photodetectors, the quantum wells of which are almost populated with electrons. In this structure, the active region consists of ten periods of GaN (1.5 nm)/AlN (1.5 nm) superlattice, which is sandwiched between $Al_{0.5}Ga_{0.5}N$ bottom and cap layers. Moreover, both the wells and cladding layers (including bottom layer and cap layer) are N-doped of $1\times10^{19}$ $cm^{-3}$. The thicknesses of wells and barriers are chosen for corresponding to absorption wavelength around 1.55 μm. The Al content in cladding layers is intentionally chosen to match with the average Al content of the superlattice to inhibit the polarization-induced field.

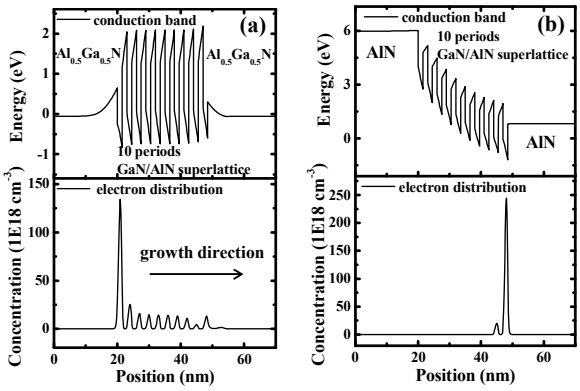


Fig. 1 Conduction band profile and electron distribution for a ten periods GaN/AlN superlattice sandwiched between $Al_{0.5}Ga_{0.5}N$ and AlN claddings.

However, the Al content in cladding layers is difficult to control accurately during the growth process. Because of the lack of suitable lattice-matched substrates, the $Al_{0.5}Ga_{0.5}N$ cladding layers have to be compressively strained grown on AlN buffer layers. Therefore, without considering of carrier transportation, most photovoltaic QWIPs are tend to choose AlN as bottom and cap layers as it can be pseudomorphic

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grown on AlN buffer layer, whose material quality can be improved for free from strain. Fig. 1(b) shows the corresponding band structure and electron distribution, with GaN wells N-doped of $1\times10^{19}$ $cm^{-3}$. As we can see, there exists a strong polarization field across the active region, resulting in the extremely low ISB absorption efficiency due to the depletion of electrons in most of the wells.

## III. Result And Discussion

Ten periods of superlattice is commonly adopted in simulation of III-nitride ISB photodetectors in most reported papers[5], however, the superlattice periods of the actual grown device is in the range of 30-50. Assuming that the polarization field is codetermined by cladding layers and well doping, the average polarization field applied on active region may follow the change of superlattice periods provided that the above influential factors keep constant. And on this basis, twenty periods and even fifty periods of superlattices are simulated based on the basic structure of Fig. 1(b), the corresponding band structure and distribution of electrons are presented in Fig. 2. The dashed lines indicate the boundary between depleted wells and un-depleted ones, and the extremely high electron concentration next to the cap layer is due to the formation of 2-D electron gas. The results show that with the increase of superlattice periods, the number of depleted wells has not been changed, which means more wells are under flat-band condition. This calculation results are consistent with our estimation for that the average polarization field is decreasing with the increase of superlattice periods. Therefore, the simulation periods should match the actual grown structure in future studies.

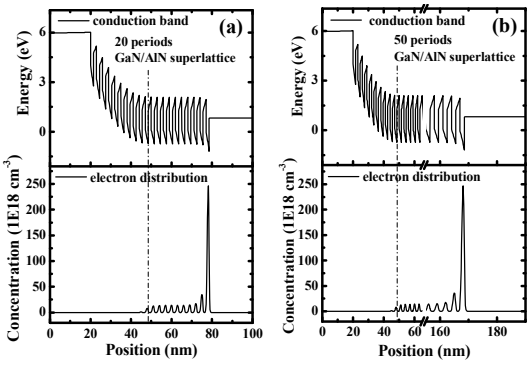


Fig. 2 Conduction band profile and electron distribution for a twenty periods and a fifty periods GaN/AlN superlattices.

Moreover, the influence of the well doping is also studied based on a fifty periods GaN/AlN superlattice structure, as is shown in Fig. 3. The doping concentration is in the range of $5\times10^{18}$ $cm^{-3}$ to $5\times10^{19}$ $cm^{-3}$. From the calculation results, we can see that the average polarization field intensity shows a gradual increase with the decrease of doping concentration, which behaved as more wells toward bottom layer are depleted. The amount of the accumulated electrons within 2-D electron gas appeared to a downward trend with the decrease of doping concentration. The above phenomena can be interpreted with the opinion of charge compensation. Since more free electrons are able to compensate with interfacial charge under the condition of a heavier doping concentration, the screening effect against polarization field strengthens with increasing doping concentration. The simulation results show that there has a great influence of well doping on the active region conduction band profile and electron distribution.

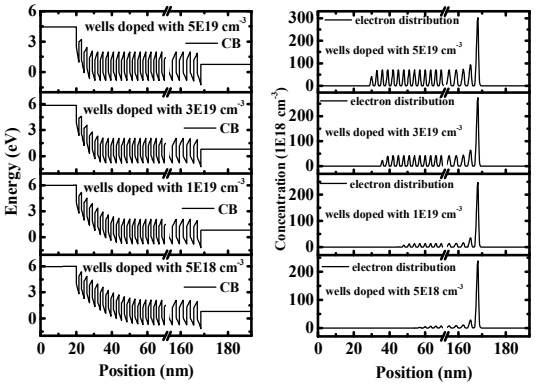


Fig. 3 Conduction band profile and electron distribution with different doping concentrations in wells.

## IV. Conclusion

In this paper, the influences of superlattice periods and well doping on the band structure and distribution of electrons were theoretically studied based on III-nitride photovoltaic QWIPs. We found that with the increase of superlattice periods and doping concentration, a weaker average polarization field is observed, and as a result a higher ISB absorption efficiency will be achieved.

## Acknowledgment

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## References

[1] M. Eva, “Nitride-based devices at telecom wavelengths,” *Optical Fiber Communication Conference*. Optical Society of America, pp. M3F-5, Mar. 2017.

[2] J. Hamazaki, S. Matsui, H. Kunugita, K. Ema, H. Kanazawa, T. Tachibana, A. Kikuchi, and K. Kishino, “Ultrafast intersubband relaxation and nonlinear susceptibility at 1.55 μ m in GaN/AlN multiple-quantum wells,” *Appl. Phys. Lett*., vol. 84, no. 7, pp. 1102-1104, Feb. 2004.

[3] E. Baumann, F. R. Giorgetta, D. Hofstetter, H. Lu, X. Chen, W. J. Schaff, L. F. Eastman, S. Golka, W. Schrenk, and G. Strasser, “Intersubband photoconductivity at 1.6 μm using a strain-compensated AlN/GaN superlattice,” *Appl. Phys. Lett*., vol. 87, no. 19, pp. 191102, Oct. 2004.

[4] I. Vurgaftman, J. R. Meyer, “Band parameters for nitrogen-containing semiconductors,” *J. Appl. Phys*., vol. 94, no. 6, pp. 3675-3696, Jun. 2003.

[5] H. Machhadani, P. Kandaswamy, S. Sakr, A. Vardi, A. Wirtmüller, L. Nevou, F. Guillot, G. Pozzovivo, M. Tchernycheva, A. Lupu, L. Vivien, P. Crozat, E. Warde, C. Bougerol, S. Schacham, G. Strasser, G. Bahir, E. Monroy and F. H. Julien, “GaN/AlGaN intersubband optoelectronic devices,” *New J Phys*., vol. 11, no. 12, pp. 125023, Dec. 2009.