# Structure design of Nitride double-step intersubband photodetectors for efficient carrier extraction

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***Abstract*—The structure parameters of III-nitride double-step intersubband photodetectors are theoretically analyzed to ensure efficient extraction of photo-excited electrons. The results indicate that the polarization field in barrier layer behaves sensitive to the thickness of well and step barrier layers. In addition, reducing the Al mole composition of step barrier or properly increasing its thickness will be helpful to enhance the photo-excited electrons tunneling. This knowledge is beneficial to the design of III-nitride terahertz intersubband photodetectors with high efficiency.**

***Keywords—intersubband, polarization field, double-step***

## I. Introduction

III-nitride intersubband (ISB) transition has attracted much attention because of its great potential to fabricate ultrafast optoelectronic devices with broad spectrum. Very recently, III-nitride ISB devices have been identified as promising candidates to operate with specific terahertz (THz) ranges (5-12 THz) even at room temperature [1]. The main challenge to achieve high performance III-nitride ISB THz devices, especially for our concerned photodetectors originates from the strong polarization effect inheriting in traditional c-plane materials. The discontinuity of polarization at the heterostructure interface will give rise to a strong but reversed electric field between the adjacent layers, which not only lower the ISB transition efficiency, but also hinder the extraction of photo-excited electrons due to the tilt of the band structure.

Many efforts have been made to overcome the above bottlenecks. A straight-forward approach is to grow semi-polar or nonpolar structures, nevertheless, material quality is still the main factor limiting the device performance [2]. From a design perspective, another method is to insert two step layers of different (Al)GaN compositions both in the wells and barriers to adjust the distribution of polarization-induced field [1]. This approach relies on the precise design of the band structure, and proves to be effective.

However, reports on designing the structure parameters of step-based ISB photodetectors to enable efficient extraction of photo-excited electrons are rare. In this paper, we investigate the influence of structure parameters on electric field distribution in barrier layer, trying to construct a virtually flat energy band profile to ensure the efficient transportation of photo-excited electrons. Furthermore, the tunneling effect of photo-excited electrons within this specific structure is also discussed.

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## II. Device Structure and Theoretical Basis

The basic structure under investigation is a double-step quantum well constituted by GaN (well, $l_w$)/$Al_{x_{sw}}Ga_{1-x_{sw}}N$ (step well, $l_{sw}$)/$Al_{x_{sbr}}Ga_{1-x_{sbr}}N$ (step barrier, $l_{sbr}$)/$Al_{x_{br}}Ga_{1-x_{br}}N$ (barrier, $l_{br}$) multilayers, where symbols $l$ and $x$ denote the thickness, Al mole composition of the designated layer, respectively. For a more intuitive demonstration, Fig. 1 shows the calculated conduction band profile and wave-functions distribution of a step-based THz ISB photodetector, with structure parameters taken from Ref. 1. Each period consists of a 1.6-nm-thick GaN well, a 7-nm-thick $Al_{0.08}Ga_{0.92}N$ step well, a 1.5-nm-thick $Al_{0.16}Ga_{0.84}N$ step barrier and a 12-nm-thick $Al_{0.08}Ga_{0.92}N$ barrier.

The structure parameters are carefully chosen to create an energy band profile where the electric fields in barrier layers are almost eliminated, in which case the photo-excited electrons could transport on continuum states without blocking except some small energy spikes formed by step barrier layers. The arrows in bold in Fig. 1 indicate the transport process of photo-excited electrons, and we can see that the tunneling effect plays an important role when carriers transport through the step barrier. As a result, how to design structure parameters to completely eliminate the internal field in barrier layers and enable the tunneling probabilities as high as possible are the key factors that we should concerned to obtain efficient extraction of photo-excited electrons.

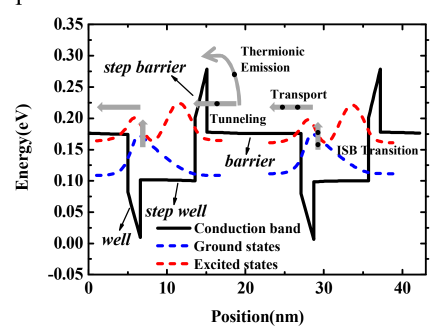


Fig. 1 Conduction band profile and squared envelop functions of a double-step ISB photodetector. The carrier dynamics is also shown.

The calculation of band structure and wave-functions are performed by self-consistently solving the Schrödinger-Poisson equations that takes account into both the spontaneous and piezoelectric polarization fields. The magnitude of electric field can be obtained by taking the derivative of energy band profile. In addition, tunneling probabilities are calculated by

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using the contact block reduction method since it can be regarded as quantum mechanical ballistic transmission [3].

## III. Result and Discussion

Based on the above structure parameters, first of all, the barrier layer polarization fields as a function of Al mole composition of barrier ($x_{br}$) are plotted in Fig. 2, positive and negative values represent the fields with opposite direction. The Al mole composition of step barrier layer is fixed to be twice of step well in order to achieve the minimum ISB transition energy [4]. The zero polarization field in barrier layer is obtained under the condition that Al mole composition of barrier slightly deviates from half of that of the step barrier, and the absolute offset is enlarging with the increase of the step barrier Al mole composition. Namely, if the ratio between $x_{sbr}$ and $x_{br}$, and the ratio between $x_{sbr}$ and $x_{sw}$ are strictly fixed to be 2, the band profile of barrier layer is not perfectly flat.

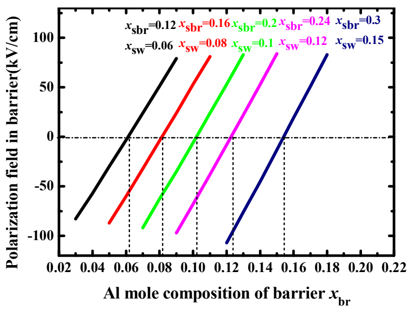


Fig. 2 Barrier layer polarization fields as a function of Al mole composition of barrier ($x_{br}$).

Furthermore, ensuring the condition that polarization field in barrier layer is kept at zero, the influence of each layer thickness on the change of Al mole composition of barrier is investigated, as shown in Fig. 3. As we can see, even if the thickness of step well and barrier changes, the internal field in barrier layer will stay the same without adjusting the Al mole composition of barrier. While for the change of well thickness or step barrier thickness, Al mole composition of barrier should be carefully adjusted to eliminate the emerging internal field. The above phenomena could be attributed to the differential

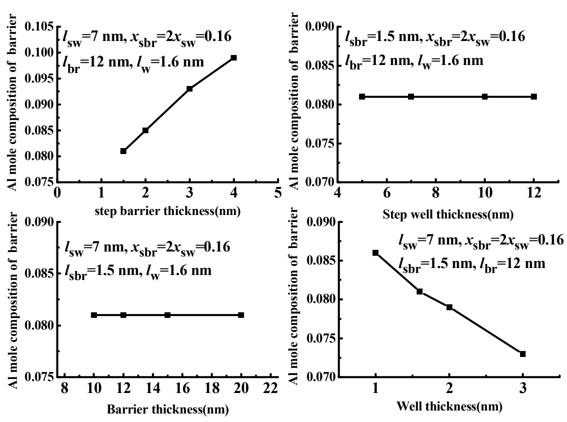


Fig. 3 The influence of each layer thickness on the change of Al mole composition of barrier under the condition that the polarization field in barrier layer is kept at zero.

distribution of the internal field, since there exit relatively strong internal fields in well and step barrier, the altering of the thickness will bring about a significant change of the overall potential.

Pay attention to the process of photo-excited electrons tunneling through the step barrier, the influence of the step barrier Al mole composition and thickness on transmission coefficient are shown in Fig. 4(a) and Fig. 4(b), respectively. The Al mole composition of the step well and barrier in Fig. 4(b) are deliberately chosen to ensure the internal field in barrier is kept at zero with the change of step barrier thickness. The calculation results indicate that carriers equipped with lower energy could achieve complete transmission with the decrease of the step barrier Al mole composition or with the increase of its thickness, which shows beneficial to the extraction of photo-excited electrons. Actually, the step barrier with thicker width will bring about a more tilt of triangle band profile, which results in a narrower width of effective tunneling structure than the nominal design values.

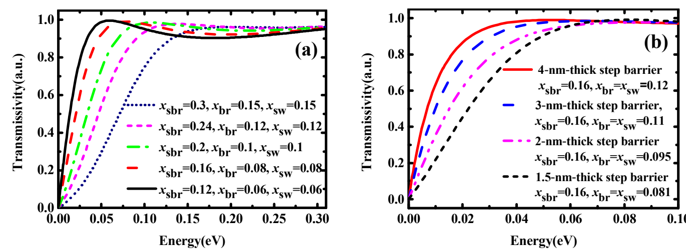


Fig. 4 Transmission coefficient as a function of energy. (a)With different Al mole composition of step barrier; (b)with different thickness of step barrier.

## IV. Conclusion

In this paper, we focused on the optimal design of structure parameters to achieve efficient extraction of photo-excited electrons for III-nitride double-step ISB photodetectors. The results showed that some specific parameters such as the thickness of well layer or step barrier layer had significant effects on the barrier layer polarization field. In addition, the step barrier should be carefully designed to ensure the photo-excited electrons had high transmission probabilities.

## Acknowledgment

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