Infrared Physics & Technology 89 (2018) 72–76

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Regular article

# Improved performance of $In_{0.83}Ga_{0.17}As/InP$ photodetectors through modifying the position of $In_{0.66}Ga_{0.34}As/InAs$ superlattice electron barrier

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## HIGHLIGHTS

- Position effects of electron barrier are analyzed and confirmed experimentally.
- Best position of SL electron barriers are at the edge of the depletion zone.
- Enhanced responsivity and lower dark current have been achieved.
- Performances of metamorphic $In_{0.83}Ga_{0.17}As/InP$ PD are improved dramatically.

## ARTICLE INFO

*Article history:*
Received 1 September 2017
Revised 12 December 2017
Accepted 24 December 2017
Available online 26 December 2017

*Keywords:*
Photodetector
Electron barrier
Superlattice
InGaAs
Metamorphic

## ABSTRACT

The performance of wavelength extended $In_{0.83}Ga_{0.17}As/InP$ photodetectors has been improved notably through modifying the position of electron barriers in absorption layer. In order to fully utilize the diffusion component of the photocurrent, the $In_{0.66}Ga_{0.34}As/InAs$ superlattice electron barrier is moved to the edge of the depletion region. Enhanced peak photo responsivity up to 0.84 A/W is realized, which raises 24% compared to that of a reference detector with the superlattice barrier in the middle of the absorber. The dark current slightly increases by 25% at room temperature while decreases by more than an order of magnitude at 150 K, resulting in about 10% or more than twofold improvements for the detectivity, respectively. The results suggest that optimized barrier position is a necessity for barrier-type photodetectors to achieve better performances.



## 1. Introduction

High-indium $In_xGa_{1-x}As$ ($x > 0.53$) photodetectors (PDs) are one prevailing detector choice in short-wave infrared (SWIR) band for a number of civil and military applications such as remote sensing, earth resource observation, night vision, and environmental monitoring [1–3]. The overall performance of such PDs has been evaluated in detail [4]. As for PDs in this wavelength range using different materials, HgCdTe (MCT) has worked successfully in SWIR band, but the weak Hg-Te bond remains a technological problem, The antimonide could be a lattice matched system in this band, but in practice the difficulties in the treatment of Sb containing materials in both epitaxy and chip processing aspects still exist [5]. Unlike the high response speed capabilities emphasized for PDs in optical communication applications, the dark- and photocurrents are more important indicators for detectors and focal plane arrays (FPAs) used in remote sensing applications. SWIR InGaAs detectors are typically operating at RT (or near RT), especially for lattice-matched materials $In_{0.53}Ga_{0.47}As$. While for metamorphic PDs of $In_{x>0.53}GaAs$ with narrower bandgap, which have relatively large dark current at room temperature, cooling down is often needed in practice. For this reason, the performance of the PDs at lower temperature is also our concern. In general, the major component of the dark current of $In_xGa_{1-x}As$ PIN PDs operated under zero or small biases at room temperature (RT) is the diffusion current, and the generation recombination (GR) current becomes assignable as temperature decreases, while at even lower temperatures, the trap-assisted tunneling (TAT) current becomes of major concern [3–7]. Due to the lack of a naturally lattice-

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https://doi.org/10.1016/j.infrared.2017.12.014
1350-4495/

matched substrate, high-indium $In_xGa_{1-x}As$ PDs are generally grown metamorphically on InP or GaAs substrates, and thus suffer from high dark current levels associated with high threading dislocation density [8]. A considerable amount of efforts have been devoted to improve the material quality to suppress the dark currents of these metamorphic PDs, for instance, optimizing the growth conditions and the buffer schemes [3–11].

Apart from efforts on improvement of material quality, another promising route towards further decrease of the dark current is from energy band engineering. The nBn or XBn detectors have been successfully demonstrated in which a unipolar electron barrier layer is introduced in the absorber to block the electron flow while allowing the flow of holes [12–17]. We have previously demonstrated a metamorphic $In_{0.83}Ga_{0.17}As$/InP PD with an $In_{0.66}Ga_{0.34}As$/InAs superlattice (SL) electron barrier, for which the dark current had been reduced by more than 2 orders of magnitude compared with a reference PD without barrier at 77 K [18]. However, influences of the SL barriers on the photo responsivity have not been extensively investigated thus far. Theoretically, photo-generated electrons in the n type $In_{0.83}Ga_{0.17}As$ absorbers could also be blocked by the SL barrier, leading to a reduced photocurrent. Given the fact that effective collection of carriers to give photocurrent is highly sensitive to the diffusion process within the active region of the PDs, this adverse effect is likely to be circumvented by optimizing the position of the SL barrier. Some simulation works on the performances of such detectors with different SL barrier periods and positions by using different software have been presented but resulting intricate results [19,20], while detailed mechanism analysis and experimental investigations are still lacking.

In this work, the effects of $In_{0.66}Ga_{0.34}As$/InAs SL electron barrier position on both dark and photo current have been analyzed, and confirmed experimentally. Compare to the reference detector in which the SL is in the middle of $In_{0.83}Ga_{0.17}As$ absorption layer (referred as PD-1 hereafter), the measured performance of the detector with SL at the edge of the depletion region (referred as PD-2 hereafter) is improved dramatically. The reasons and embedded mechanisms are investigated in detail.

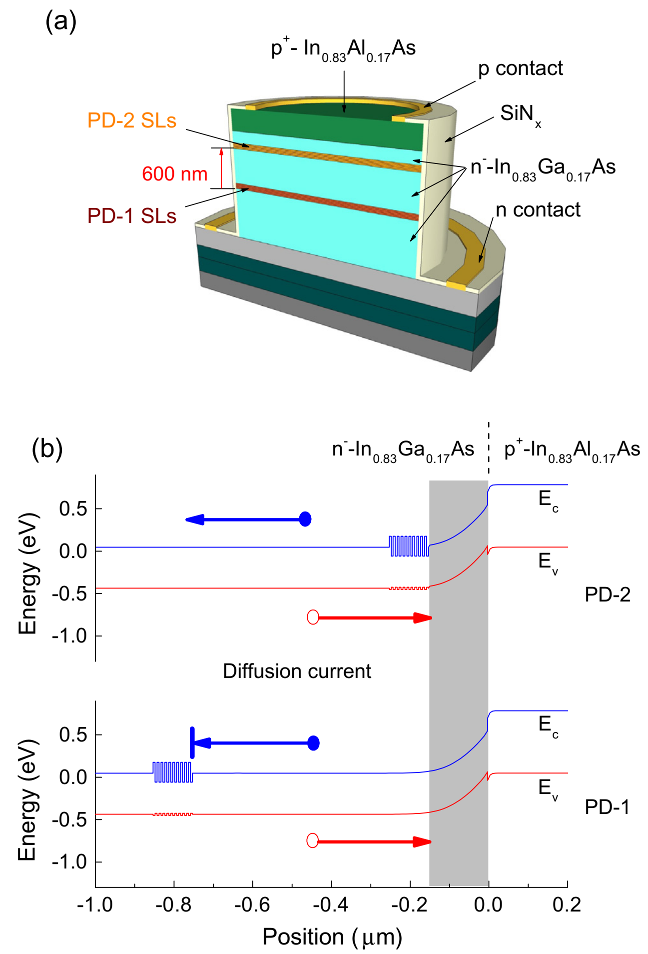


**Fig. 1.** (a) Schematic illustration of the detector structure for both PDs. (b) The calculated zero bias band edge line-up and the depletion regions (shade area) for both PDs. Different blocking effects for diffusion component of dark currents for both PDs are also indicated.

## 2. Experimental details

Both PD wafers were grown on semi-insulating InP substrates by using a VG Semicon V80H gas source molecular beam epitaxy (GSMBE) system. Device structures are identical for both PDs except for the positions of the SL barrier in the $In_{0.83}Ga_{0.17}As$ absorber. The growth started in turn from a 0.2-µm-thick InP, a 0.1-µm-thick $In_{0.52}Al_{0.48}As$, and a 1.9-µm-thick $In_yAl_{1-y}As$ (y increased from 0.52 to 0.83) continuously graded buffer layers, which were all doped with silicon to $3 \times 10^{18}\ cm^{-3}$. After that, a 1.5-µm-thick $n^-$ doped (silicon, $3 \times 10^{16}\ cm^{-3}$) $In_{0.83}Ga_{0.17}As$ absorption layer was grown. Finally, a 0.55-µm-thick $p^+$ $In_{0.83}Al_{0.17}As$ cladding layer heavily doped with beryllium to $5 \times 10^{18}\ cm^{-3}$ was grown to finish the whole structure. During growth of the $In_{0.83}Ga_{0.17}As$ absorbers, a 0.1-µm-thick $In_{0.66}Ga_{0.34}As$/InAs SL barrier structure was inserted exactly in the middle of the 1.5-µm-thick $In_{0.83}Ga_{0.17}As$ absorber for PD-1 [18]. For PD-2, this SL barrier structure was shifted upward towards the depletion region in the $In_{0.83}Ga_{0.17}As$ absorption layer by 600 nm with respect to that in PD-1. After crystal growth, the wafers were processed into 500-µm-diameter mesa type detectors and passivated with $SiN_x$, where x is close to 1.3, then alloyed and diced into chips. Fig. 1(a) illustrates the schematic PD structure and the different positions of SLs. The calculated zero bias band edge line-up and the depletion regions for both PDs along the growth direction are also shown in Fig. 1(b) [21]. In regards to the different SL barrier positions, because the SL positions of the two samples are all outside the depletion zone at zero bias, the blocking effects of the SL barrier remain almost unchanged for both the GR and the TAT currents in depletion layer, whereas for the diffusion current outside depletion layer the blocking effect is restrained by moving the SL barrier closer to the edge of the depletion layer (PD-2) as shown in Fig. 1(b), which could help to improve the collection of photocurrent [22].

## 3. Results and discussion

Fig. 2 shows the zero bias spectral responsivities of both PDs at RT and 150 K measured by Thermo Scientific Nicolet iS50 Fourier transform infrared (FTIR) spectrometer with a $CaF_2$ beam splitter and an Ever-Glo IR source. Both PDs exhibit the same peak and 50% cutoff wavelengths of 2.05 and 2.57 µm at RT, respectively. As temperature decreases to 150 K, a blueshift of the response spectra is presented. The absolute spectral responsivity values were scaled using the responsivity at 1.55 µm obtained from current-voltage (I-V) measurements using a 1550 nm semiconductor laser with accurately calibrated light power. The measured peak responsivity for PD-1 is 0.68 and 0.50 A/W at RT and 150 K, corresponding to external quantum efficiency of 41% and 30%, respectively. In contrast, the peak responsivities increase by 24% and 36% for PD-2 (0.84 and 0.68 A/W) at RT and 150 K, with enhanced quantum efficiency of 51% and 41%, respectively. These