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Midwave infrared InAs/GaSb superlattice photodiode with a dopant-free p–n junction

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HIGHLIGHTS

- MWIR SL photodiode was made using the flexibility properties of InAs/GaSb superlattice.
- MWIR SL photodiode was made without intentional doping the pn junction.
- Electrical and electro-optical characterizations of MWIR pin SL photodiode made of dopant-free p–n junction have been reported.

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ABSTRACT

Midwave infrared (MWIR) InAs/GaSb superlattice (SL) photodiode with a dopant-free p–n junction was fabricated by molecular beam epitaxy on GaSb substrate. Depending on the thickness ratio between InAs and GaSb layers in the SL period, the residual background carriers of this adjustable material can be either n-type or p-type. Using this flexibility in residual doping of the SL material, the p–n junction of the device is made with different non-intentionally doped (nid) SL structures. The SL photodiode processed shows a cut-off wavelength at 4.65 μm at 77 K, residual carrier concentration equal to $1.75 \times 10^{15}\ \text{cm}^{-3}$, dark current density as low as $2.8 \times 10^{-8}\ \text{A/cm}^2$ at 50 mV reverse bias and R_0A product as high as $2 \times 10^6\ \Omega\ \text{cm}^2$. The results obtained demonstrate the possibility to fabricate a SL pin photodiode without intentional doping the pn junction.

1. Introduction

Twenty years ago, Yang and Bennet reported the first fabrication of Type-II InAs/GaSb superlattice (SL) pin photodiode operating in the midwave infrared (MWIR) [1]. Since then, many advances have been made, making the SL photodetector technology suitable for high performance infrared imaging [2]. In particular, important developments have been made to control the SL technology leading to a dual-color MWIR camera [3] and to raise the operating temperature of MWIR SL photodiode and focal plane arrays (FPAs) with demonstration of human body imaging up to 170 K [4].

Despite these impressive progresses, experimental results on SL detectors have not yet reached their theoretical performances that are strongly dependent to their residual background carrier concentration. Consequently, fundamental studies on MWIR SL material, such as minority carrier lifetime [5–7], in plane and vertical effective masses [8] and mobilities [9,10], residual background carrier concentration [11–13], have been investigated for a better understanding of the carrier transport in this minority carrier detector. Recently, influence of the SL period thickness and composition on the electrical and optical properties of MWIR SL photodetectors has been reported [14].

The non-intentionally doped (nid) active region of MWIR pin SL photodiode, fabricated by molecular beam epitaxy (MBE), usually exhibits a residual background carrier concentration between $5 \times 10^{14}\ \text{cm}^{-3}$ and $5 \times 10^{15}\ \text{cm}^{-3}$. These values, in many cases extracted from capacitance–voltage (*C–V*) measurements [14–18], are related to the thickness and composition of the InAs/GaSb SL

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period. The type of conductivity of the nid region is also linked to the InAs/GaSb SL period. Indeed, because the nid GaSb and InAs layers have p-type and n-type residual backgrounds, respectively, the background of the nid SL active region is likely to be either n-type or p-type. The InAs/GaSb SL tends to result in n-type material for thicker InAs layer (“InAs-rich” structure) whereas thicker GaSb layer (“GaSb-rich” structure) makes the material p-type [18]. Consequently, with this peculiar property of carrier-type flexibility of SL material, it is possible to avoid doping the detector and fabricate a p–n junction by using only nid SL structures. In addition, previous studies have shown good performances in term of low dark current for the “InAs-rich” SL structures [14,17] while p-type SL structures with electron minority carriers are relevant to obtain high quantum efficiency. Consequently, each type of structure displays particular electro-optical properties, motivating their association in the design of a pin photodiode.

In this paper, we report on electrical and electro-optical characterizations of SL MWIR pin photodiode made of dopant-free p–n junction.

2. Choice and fabrication of the SL pin structure

The InAs/GaSb SL presents a specific staggered type-II (or type-III) band alignment, in which the top of the conduction band is below the bottom of the valence band. Consequently, the band gap of the SL periodic structure, determined by the energy difference between the first heavy hole state V1 and the first electron miniband C1, depends only on the layer thicknesses, in symmetric (same thickness of InAs and GaSb layers) or asymmetric (one of the two layers thicker than the other) configurations. To quantify the symmetric or asymmetric period design, we define the quantity R as the InAs to GaSb thickness ratio in each InAs/GaSb SL period. $R > 1$ corresponds to “InAs-rich” structure while $R < 1$ stands for “GaSb-rich” structure.

Calculations of miniband energies of SL structures have been performed using a modified envelope function approximation (EFA) model, sufficient to predict the band structure of MWIR SLs [19]. Fig. 1 reports the evolution of the calculated fundamental interminiband V1C1 energy transitions at 77 K as a function of the SL period thickness, for different thickness ratio R. This figure highlights the possibilities of the SL structure to assign the 3–5 μm MWIR spectral range. For a given band gap around 250 meV ($\lambda_c = 5$ μm) at 77 K, we can choose different SL structures. One can be a symmetric InAs/GaSb SL structure ($R = 1$) where the SL's period is composed by equal number of 10 InAs and GaSb monolayers (MLs). The others can be a n-type “InAs-rich” structure with $R = 1.75$, made of 7 MLs InAs/4 MLs GaSb per SL period or a p-type “GaSb-rich” structure ($R = 0.5$) with a SL period composed of 10 MLs InAs/19 MLs GaSb.

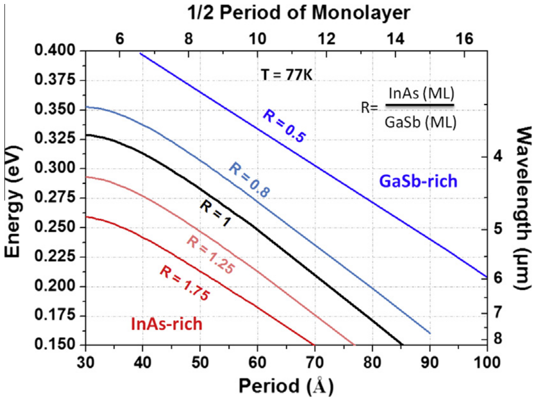

Fig. 1. Calculated interminiband SL bandgap at 77 K versus SL period thickness (1ML = 3 Å) for different thickness ration R = InAs/GaSb.

Selected symmetrical, “InAs-rich” and “GaSb-rich” structures were preliminary fabricated by MBE on GaSb substrate. Next, specific process with removing of the conductive GaSb substrate has been made [12] to perform Hall measurement as a function of temperature using magnetic field up to 1 T. Temperature dependence of the effective carrier concentration n_H are presented in Fig. 2a and b. In the case of the symmetric SL structure (Fig. 2a), an apparent change in type of conductivity in the nid InAs/GaSb SL is observed around 120 K. Because the MBE grown InAs layers are residual n-type while GaSb layers are residual p-type, the residual doping in symmetrical InAS/GaSb SL is therefore induced by the compensation, as a function of temperature, of donors in the InAs and acceptors in the GaSb layers. At low temperature, the sample is p-type with carrier density $p_H = 2.8 \times 10^{15}$ cm^{-3} at 77 K. Such a change in type of conductivity is not observed in the case of nid “InAs-rich” and “GaSb-rich” SL samples (Fig. 2b) that are, respectively, n-type and p-type in the whole range of temperature. At low temperature, the samples show carrier concentration equal to 8×10^{14} cm^{-3} for the n-type “InAs-rich” SL structure and 5×10^{15} cm^{-3} for the p-type “GaSb-rich” SL sample. These values are consistent with C–V measurements performed on diodes with similar SL designs [14].

Combining “InAs-rich” and “GaSb-rich” structures, the SL structure was grown by MBE on p-type GaSb (100) substrate. Because the quantum efficiency of the “GaSb-rich” structure is better at low bias voltage than the “InAs-rich” one [20], p-type “GaSb-rich” structure was used as absorbing layer. Fig. 3 shows the schematic view of the SL pin structure. The p-type absorbing layer was made

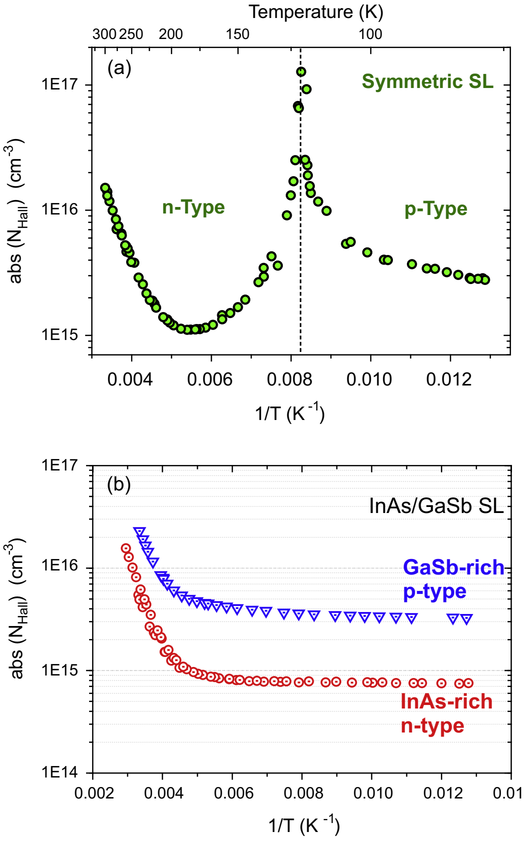

Fig. 2. Measured apparent Hall carrier concentration N_H as a function of $1/T$ for the InAs/GaSb symmetrical SL structure (a) and for the “InAs-rich” and “GaSb-rich” SL structures (b).