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Spectral responses in near-infrared of the mixed compounds III-V, ternary and quaternary, based on GaSb

B. Mbow, N. Rezzoug, C. Peremarti, A. Mezerreg and C. Llinares

Centre d'Electronique de Montpellier (C.E.M.), Université Montpellier II, 34095 Montpellier Cedex 05, France

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Résumé. — Les mesures de réponse spectrale dans la gamme [0,4 eV à 2 eV] ont été effectuées sur des homojonctions, $\text{Ga}_{0,6}\text{In}_{0,4}\text{Sb}_n/\text{Ga}_{0,6}\text{In}_{0,4}\text{Sb}_p$ déposées sur un substrat de GaSb et des hétérostructures ternaires $\text{Ga}_{0,75}\text{In}_{0,25}\text{Sb}_p/\text{GaSb}_n$ et quaternaires $\text{GaSb}_p/\text{Ga}_{0,74}\text{In}_{0,26}\text{As}_{0,23}\text{Sb}_{0,77p}/\text{GaSb}_n$. La couche de GaSb_p avec un gap plus grand que celui de $\text{Ga}_{0,74}\text{In}_{0,26}\text{As}_{0,23}\text{Sb}_{0,77p}$ joue le rôle d'effet fenêtre. En s'appuyant sur les résultats de la simulation et en accordant les spectres expérimentaux aux spectres théoriques, on détermine les valeurs des paramètres photoélectriques (longueurs de diffusion, les vitesses de recombinaison en surface...) intervenant dans le rendement quantique.

Abstract. — From the simulation of the spectral response of the different photodetector devices elaborated in our laboratory (C.E.M.), we determine the influence of geometrical and physical parameters in order to achieve the best photodetector operating at the wavelength 2.55 μm . In this paper we present: $\text{Ga}_{0,6}\text{In}_{0,4}\text{Sb}_n/\text{Ga}_{0,6}\text{In}_{0,4}\text{Sb}_p$ homojunctions matched on GaSb_p substrate, $\text{Ga}_{0,75}\text{In}_{0,25}\text{Sb}_p/\text{GaSb}_n$ ternary heterojunction and $\text{GaSb}_p/\text{Ga}_{0,74}\text{In}_{0,26}\text{As}_{0,23}\text{Sb}_{0,77p}/\text{GaSb}_n$ quaternary heterojunction. The GaSb_p layer with an energy band gap greater than $\text{Ga}_{0,74}\text{In}_{0,26}\text{As}_{0,23}\text{Sb}_{0,77p}$ optical gap will act as a window, reducing the effect of surface recombination. Results of the simulation are compared to experimental curves to determine the values of photoelectrical parameters (diffusion length, recombination velocity at the surface...).

Introduction.

$\text{Ga}_{1-x}\text{In}_x\text{Sb}$ ternary alloys grown onto GaSb substrate and $\text{Ga}_{1-x}\text{In}_x\text{As}_{1-y}\text{Sb}_y$ quaternary alloys lattice matched on GaSb substrate are potentially useful materials for detectors in the near-infrared wavelength range [2-4 μm] [1]. This wavelength range is interesting to achieve an extremity component in optical fiber communication systems using fluoride glasses. Such fibers are predicted to have minimum losses smaller than silica fiber at 2.55 μm . Ternary materials lattice onto GaSb substrates used have been grown mainly by metal-organic vapour phase epitaxy (M.O.V.P.E.) [2, 3] and quaternary layers grown by Liquid Phase Epitaxy [L.P.E.] [4]. Photoelectric devices are $\text{Ga}_{0,6}\text{In}_{0,4}\text{Sb}_n/\text{Ga}_{0,6}\text{In}_{0,4}\text{Sb}_p$ homojunction grown

onto GaSb_p substrate, $\text{Ga}_{0.75}\text{In}_{0.25}\text{Sb}_p/\text{GaSb}_n$ ternary heterojunction and $\text{GaSb}_p/\text{Ga}_{0.74}\text{In}_{0.26}\text{As}_{0.23}\text{Sb}_{0.77p}/\text{GaSb}_n$ quaternary heterojunction. We report the experimental results of spectral response of quantum efficiency (number of carriers per incident photon at each wavelength) and the theoretical values of photoelectrical parameters determined on simulation.

Experiment and samples.

The experimental apparatus provides on the photodetector a constant radiation power or a constant photon density into the spectral range $0.7 \mu\text{m} < \lambda < 4 \mu\text{m}$. The use of a reflecting objective (magnification : $\times 36$) allows us to obtain spectral response measures on sample with size around $50 \mu\text{m}$ for the diameter. The spectral response of samples (external efficiency η_{exp}) is calibrated with a Ge photodiode tied up to an optical fiber at $1.3 \mu\text{m}$ (the external efficiency of the Ge photodiode at this wavelength is 85 %). The internal efficiency of samples η_{int} is determined by taking the reflection coefficient value R into account $\eta_{\text{int}} = (1 - R)^{-1} \eta_{\text{ext}}$. For GaSb material, the mean value R is approximately 0.34 in the wavelength range.

The samples used in this work are photodetectors devices in the $2\text{--}2.6 \mu\text{m}$ wavelength range : $\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_n/\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_p$ homojunctions on GaSb_p substrate, $\text{Ga}_{0.75}\text{In}_{0.25}\text{Sb}_p/\text{GaSb}_n$ ternary heterojunction achieved in our laboratory [3] by M.O.V.P.E. with a depth of junction of $1.6 \mu\text{m}$ and $\text{GaSb}_p/\text{Ga}_{0.74}\text{In}_{0.26}\text{As}_{0.23}\text{Sb}_{0.77p}/\text{GaSb}_n$ quaternary heterojunction grown by L.P.E. technique. N type samples are obtained by Te doping. The width of $\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_n/\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_p$ is $4.5 \mu\text{m}$ and the depth of junction is about $0.5 \mu\text{m}$. For the $\text{GaSb}_p/\text{Ga}_{0.74}\text{In}_{0.26}\text{As}_{0.23}\text{Sb}_{0.77p}/\text{GaSb}_n$ quaternary heterojunction, GaSb_p thin layer is approximately equal to $1 \mu\text{m}$ and the depth of the junction to $4 \mu\text{m}$. For all samples, the thickness of substrate is infinitely longer comparately to the other geometrical parameters.

Results and discussion.

For all samples, spectral responses are calculated [5], using theoretical models given by Hovel [6]. Photocurrents in each region are determined by solving diffusion equation with boundary conditions at the surface and the interface using usual parameters like surface recombination velocity S_n or S_p and diffusion length of minority carriers L_n or L_p .

$\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_n/\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_p/\text{GaSb}_p$ HOMOJUNCTION. — This homojunction presents a spectral response with energy band gap around 0.45 eV . We used theoretical models given by Hovel [6] for the first upper layer and depletion region. For efficiency in the second layer we took results calculated from the model of Luquet *et al.* [4] and Laugier [7]. The photocurrent (Fig. 1) of this device is given by the two front layers constituting the homojunction. The spectral response is those of a GaInSb homojunction with energy band gap around 0.45 eV . For this device, in which the ternary compound width is $4.5 \mu\text{m}$, most of carriers are generated within the two first regions. The carriers generated in the GaSb substrate (region 3) are less important and have no influence in the modeling. Figure 2 shows the contribution of the $\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_p$ layer, the front layer and the space charge region.

At low energies, photocurrent is given essentially by the intermediate region (GaInSb_p) and it is necessary to have a pure material (10^{16} cm^{-3} impurities in doping) with a minority diffusion length stronger in order to increase the quantum efficiency. The photocurrent in high energies is reduced by the low value of the diffusion length ($L_p = 0.14 \mu\text{m}$) and the high value of the surface recombination velocity ($S_p = 2 \times 10^7 \text{ cm/s}$) at the top layer (region 1).

Fig. 1. — Experimental and theoretical curves of quantum efficiency *versus* photon energy of $\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_n/\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_p/\text{GaSb}_p$ homojunction ($L_n = 6 \mu\text{m}$, $L_p = 0.14 \mu\text{m}$, $S_p = 2 \times 10^7 \text{ cm/s}$, $\tau_i = 0.5 \mu\text{s}$, $x_i = 4.5 \mu\text{m}$).

Fig. 2. — Quantum efficiency contributions of the different regions *versus* photon energy of $\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_n/\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_p/\text{GaSb}_p$ homojunction.

The major problem of these devices comes from the GaInSb/GaSb interface where the lattice mismatch prevents from most carriers created by illumination to pass through the barrier. The quality of the device is limited by the dislocations induced by the lattice mismatch between the GaSb substrate and the GaInSb active layer. It is the reason why between the GaSb substrate and the GaInSb absorbing layer, a compositionally graded $\text{Ga}_{1-x}\text{In}_x\text{Sb}$ alloy (a buffer layer) is grown in order to avoid most of the effect of high lattice mismatch. The composition of indium must not be higher than 40 % since very high dislocations are then generated into the GaInSb/GaSb interface. The best result for the internal efficiency η_{int} is about 64 % at $2.6 \mu\text{m}$.

$\text{Ga}_{0.75}\text{In}_{0.25}\text{Sb}_p/\text{GaSb}_n$ HETEROJUNCTION. — $\text{Ga}_{0.75}\text{In}_{0.25}\text{Sb}_p/\text{GaSb}_n$ is a heterojunction with indium composition $x = 25$ %. Theoretical models are given by Hovel [6]. The front layer is P type ternary material with a width of $1.6 \mu\text{m}$. Figure 3 shows two distinct levels. The first one, between 0.52 and 0.72 eV, corresponds to the absorption in the ternary material. Another one, corresponds to the supplementary absorption in the GaSb material which band gap is 0.72 eV. GaInSb upper layer is thin enough to allow absorption in GaSb substrate. The maximum efficiency value is less than 20 %.

Fig. 3. — Experimental and theoretical curves of quantum efficiency *versus* photon energy of $\text{Ga}_{0.75}\text{In}_{0.25}\text{Sb}_p/\text{GaSb}_n$ heterojunction ($L_n = 0.4 \mu\text{m}$, $L_p = 3 \mu\text{m}$, $S_p = 20 \text{ cm/s}$, $x_j = 1.6 \mu\text{m}$).

Comparing diffusion length ($L_n = 0.4 \mu\text{m}$) in front layer, where the impurity concentration is important ($p = 7 \times 10^{17} \text{ cm}^{-3}$), to the thickness of front layer ($e = 1.6 \mu\text{m}$), we note that most electrons created in this region have no possibility to diffuse towards the junction. To enhance signal level, it is necessary to increase diffusion length in order to collect more carriers. Another solution is to reduce the thickness of front layer and to achieve the junction near the surface.

The GaSb_n substrate contributes to photocurrent when radiations have an energy greater than 0.72 eV. Most of the photons are absorbed in this substrate and created holes contribute to photocurrent because the material is somewhat pure in this region (doping level of the substrate about 10^{16} cm^{-3}). Diffusion length is more important in the substrate and response level

increases. We neglected recombination carriers at the $\text{Ga}_{0.75}\text{In}_{0.25}\text{Sb}_p/\text{GaSb}_n$ interface and low quantum efficiency values are related to low diffusion length value $L_n = 0.4 \mu\text{m}$ in the top layer.

$\text{GaSb}_p/\text{Ga}_{0.74}\text{In}_{0.26}\text{As}_{0.23}\text{Sb}_{0.77p}/\text{GaSb}_n$. — To obtain a photodetector with high efficiency, GaSb_p thin layer ($1 \mu\text{m}$) is grown by Liquid-Phase Epitaxy on P type quaternary and represents a « window effect ». Theoretical models are given by Hovel and Woodal [8, 9]. Interfaces between these semiconductors present weak defects. The GaSb_p thin layer is transparent to most of the photons near the GaInSb gap and eliminates the surface recombination improving a front surface field that forces photocarriers to diffuse towards the interface junction. Figure 4 gives theoretical and experimental curves of internal quantum efficiency *versus* photon energies.

Fig. 4. — Experimental and theoretical curves of quantum efficiency *versus* photon energy of $\text{GaSb}_p/\text{Ga}_{0.74}\text{In}_{0.26}\text{As}_{0.23}\text{Sb}_{0.77p}/\text{GaSb}_n$ heterojunction ($L_n = 7 \mu\text{m}$, $S_{n2} < 2 \times 10^4 \text{cm/s}$, $S_{n1} = 2 \times 10^7 \text{cm/s}$, $v_i = 4 \mu\text{m}$).

The radiation energies lowest than GaSb energy band gap but greater than $\text{Ga}_{0.74}\text{In}_{0.26}\text{As}_{0.23}\text{Sb}_{0.77p}$ quaternary energy band gap pass through the front layer to be absorbed into the intermediate region. The $\text{Ga}_{0.74}\text{In}_{0.26}\text{As}_{0.23}\text{Sb}_{0.77p}$ layer is matched on GaSb substrate because of the As presence, so the recombination velocity at the $\text{GaSb}_p/\text{Ga}_{0.74}\text{In}_{0.26}\text{As}_{0.23}\text{Sb}_{0.77p}$ interface is low and collection becomes very important. Relatively weak (10^{16}cm^{-3}) doping of intermediate region induces a significant enhancement of the efficiency. The minority carrier diffusion length is increased ($L_n = 7 \mu\text{m}$).

When photon energy reaches GaSb energy band gap, efficiency decreases drastically. Most of photons are absorbed in the window. The lowest signal due to absorption in the window layer is related to the low carrier diffusion length (evaluated to $0.2 \mu\text{m}$). These carriers are created too far from the junction. An important part of these carriers are recombined at the surface ($S_{n1} = 2 \times 10^7 \text{cm/s}$) while the interface recombination is low ($S_{n2} < 2 \times 10^4 \text{cm/s}$).

An improvement could be to decrease the thickness of the window layer for increasing the number of photons reaching the intermediate region in order to enhance signal at high energies.

Conclusion.

Theoretical and experimental spectral responses of infrared photodetectors based on GaSb have been studied. Simulations allowed the study of spectral responses by the variation of physical (L_n , S_n , L_p , S_p , ...) and geometrical parameters (x_l , x_r , W). We evaluated these parameters in order to optimize performances of the device. Comparisons between calculated and experimental results allows us to determine the optimum conditions for realizing the best detectors based on antimonide compounds in this wavelength range.

We have presented $\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_n/\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_p$ homojunction grown on GaSb_p substrate, $\text{Ga}_{0.75}\text{In}_{0.25}\text{Sb}_p/\text{GaSb}_n$ ternary heterojunction and $\text{GaSb}_p/\text{Ga}_{0.74}\text{In}_{0.26}\text{As}_{0.23}\text{Sb}_{0.77p}/\text{GaSb}_n$ quaternary heterojunction. Our best efficiency results on ternary materials have been obtained on $\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_n/\text{Ga}_{0.6}\text{In}_{0.4}\text{Sb}_p$ homojunctions on GaSb_p substrate with internal efficiency η_{int} of 64 % in the wavelength range 2-2.6 μm . For the $\text{Ga}_{0.75}\text{In}_{0.25}\text{Sb}_p/\text{GaSb}_n$ heterojunction, defects at the interface prevent most carriers from passing through the barrier. A thin film of the GaSb grown onto quaternary decreases the effect of surface recombination velocity and internal efficiency becomes excellent $\eta_{\text{int}} > 80$ % for the wavelength range 1.8 to 2.3 μm with a maximum $\eta_{\text{int}} = 90$ % at 2 μm .

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