GaInNAs/GaAs QW Based Structures to Compensate Parasitic Effect of Quantum-Confined Stark Effect in Photodetector Applications

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Abstract. *The inhomogeneities of multicomponent semiconductor alloys, as well as phase segregation, can be utilized for enhancement of photodetector absorption properties and thus its efficiency. In this paper, the influence of external electric field on the probability of light absorption in the GaInNAs quantum well is discussed. Both phenomenon: indium and nitrogen composition gradient as well as step-like quantum well are applied to design the QW with compensation of the Quantum-Confined Stark Effect (QCSE) Parasitic effect of QCSE results from decrease of the wave functions overlapping in the QWs placed in reverse biased junction, which finally decrease the efficiency of the photodetector.*

Keywords

Dilute nitrides, multicomponent semiconductor, photodetectors, Quantum-Confined Stark Effect.

1. Introduction

Efficiency of the semiconductor photodetectors depends on the absorption characteristics of active region of the devices. Despite the benefits of using quantum wells, effective thickness of such active region is small what decreases the radiation absorption. Thus, it is a challenge to provide high device's efficiency containing quantum structures. There is strong built-in electric field in the active area of the semiconductor photodiodes operating under reverse bias. Such field is a result of the p-n (p-i-n) or Schottky junction built-in potential and the external bias. That electric field has strong impact on the electronic structure of the quantum wells and influences the transition selection rules tuning the probability of light absorption, described by quantum-confined Stark effect [1]. This paper describes our proposal for increasing the absorption efficiency of quantum wells placed in the reverse biased p-n (p-i-n) or Schottky junction by compensation of electric field impact on the wells absorption properties.

The main motivation of present work is to extend the knowledge of properties of low dimensional multicomponent semiconductor structures, especially dilute nitrides and its potential application in photodetectors constructions. The MOVPE grown GaInNAs/GaAs quantum well was chosen to describe the issue of tuning of the QW absorption efficiency. The growth and characterization of GaInNAs layers, especially QWs, is quite challenging. The problem of alloy immiscibility limits the range of possible compositions and contributes to the inhomogeneous distribution of elements in the direction of growth. Phase segregation is a common phenomenon in multicomponent materials [2] and [3]. Clusters of some atoms are formed during epitaxy, introducing lattice disorder. The increase of nitrogen concentration in dilute nitride materials leads to deterioration of structural and optoelectronic properties. Moreover, it promotes the formation of defects and disturbs growth kinetics. As a result of such growth disturbance, indium accumulates close to the top surface of the grown layers [3]. Additionally, presence of nitrogen in the GaInNAs QW enhances indium segregation regardless of the technique of epitaxial growth [4] and [5].

2. Experimental Methods

Investigated heterostructure was grown using Atmospheric Pressure Metal Organic Vapour Phase Epitaxy (AP-MOVPE) system with AIX200 R&D AIXTRON horizontal reactor on (100)-oriented undoped GaAs substrate. As sources of chemical elements: Trimethylgallium (TMGa), Trimethylindium (TMIn), Tertiarybutylhydrazine (TBHy) and 10 % mixture of AsH_3 in H_2 were used. All investigated structures contain three GaInNAs/GaAs quantum wells. As the main structural characterization methods were used High Resolution X-Ray Diffraction (HRXRD) and Secondary Ion Mass Spectrometry (SIMS). The HRXRD measurement was performed with X'pert PRO PANalytical diffractometer with Cu tube as an X-ray source. Collected data were analysed using X'Pert Epitaxy software. Simulation of diffraction curves was carried out based on dynamical theory of the diffraction. Chemical depth profiling measurements were performed using time of flight based SIMS instrument (Ion-TOF, SIMS IV) in dual beam mode.

3. Results and Discussion

3.1. Characterization Results of Epitaxial Structure

Determining the composition of a quaternary alloy is not a simple task and always requires a simultaneous analysis of the results obtained by various measurement methods. Problems with determining the composition of low-dimensional GaInNAs layers are described in our previous paper [6]. In this paper, we combine the information obtained from SIMS and HRXRD measurements. The SIMS profile of indium and nitrogen distribution versus sputtering time, across the 3×QWs GaInNAs/GaAs structure, is depicted in the Fig. 1. The maxima of indium and nitrogen signals are shifted by 38 s, which suggests inhomogeneous distribution of this elements in GaInAsN layer.

Based on information of −In and −N phases misalignment distribution, the precise simulation of the diffraction curve (Fig. 2) was performed. Determined parameters of the GaInNAs layer are as follows: In 3–11 %, N 0.6–0 %, $d = 12$ nm, with indium and nitrogen gradient towards the surface.

Determined structural parameters of the QWs were applied for QW electronic structure calculation. The electron and hole wave functions were plotted in Fig. 3. Calculation were carried out using stationary Schrodinger equation and one-electron approximation with neglecting excitonic effect. Theoretical approach is described in detail in [7].

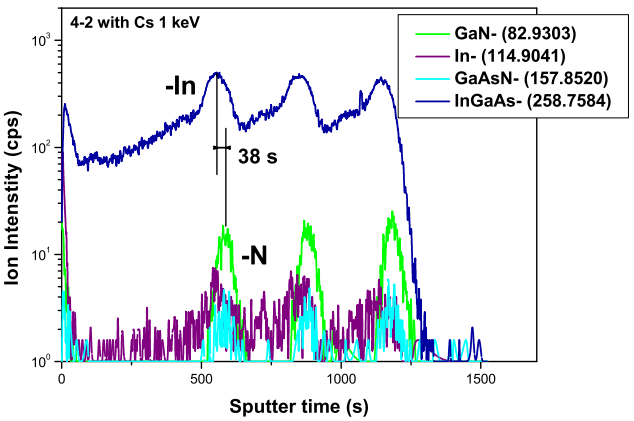


Fig. 1: SIMS profiles of the nitrogen and indium contents in the 3×QWs GaInNAs/GaAs structure with marked shift of maxima of indium and nitrogen s signals.

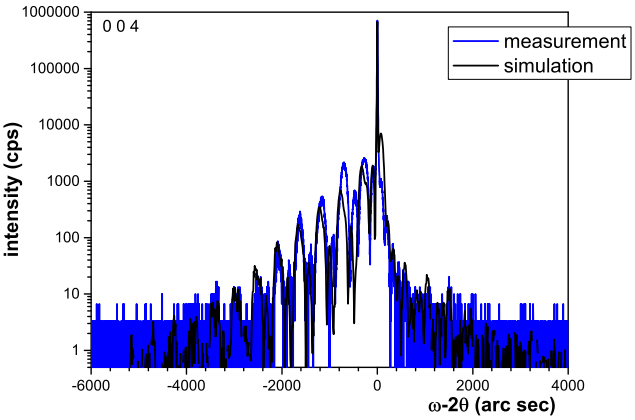


Fig. 2: HRXRD measurement and simulation curves 3×QWs GaInNAs/GaAs structure.

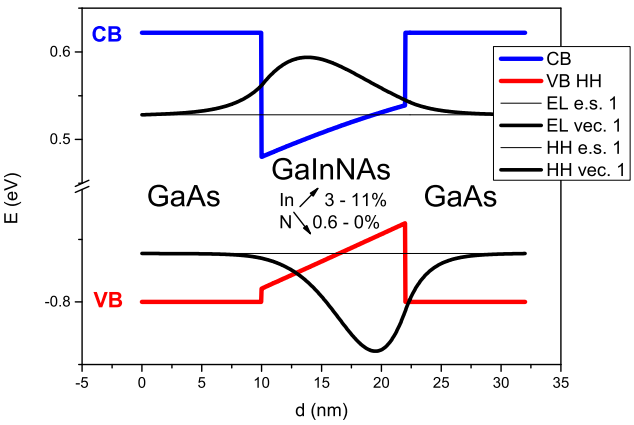


Fig. 3: Electronic structures of the QW GaInNAs/GaAs – composition of GaInNAs in accordance with HRXRD simulation.

Strong phase segregation influences such QW's properties like the shape of electric potential, wave functions distribution of electrons and holes, together with carrier confinement within the well. In fact it leads to reduction of the overlap integral of electrons-holes

wave functions and finally affects QW emission [8] and absorption [9] and [10] spectra. The inhomogeneous distributions of indium and nitrogen atoms along the growth direction of GaInNAs QWs are therefore the main factors having significant impact on the QWs absorption efficiency. However, as shown in the analysis presented in Subsec. 3.2. , the inhomogeneous distribution of elements may have a positive effect on the efficiency of absorption in the quantum well in a reverse biased p-n junction.

3.2. Numerical Analysis

To clarify the issue of electric field impact on distribution of QWs potential and carriers wave functions we investigated four types of GaInNAs/GaAs QWs. In the case of all considered GaInNAs/GaAs QW, the average content of nitrogen was equal 2 % whereas indium was equal 15 %. The QWs thicknesses were assumed 10 nm. The overestimated contents of In and N were chosen in order to magnify the QCSE. Electronic structures of all analysed types of GaInNAs QWs are illustrated in Tab. 1: type #1 – QW with uniform distribution of In (15 %) and N (2 %), type #2 – QW with convergent In (10–20 %) and N (1–3 %) linear graded distribution, type #3 – QW with opposed In (10–20 %) and N (3–1 %) linear graded distribution and type #4 – step-like $Ga_{0.8}In_{0.2}As/GaN_{0.02}As_{0.98}/GaAs$ QW. The electronic structures of each QW type are presented at three conditions: without electric field, under electric field and under electric field acting in opposite direction. Such conditions corresponds to the QWs located in the centre of p-i-n or n-i-p junction. At the standard working condition of semiconductor photodetectors, the junction built-in electric field is increased by reverse bias. For our consideration, the overall electric field acting the wells was assumed at a level of 80 kV·cm^{-1}.

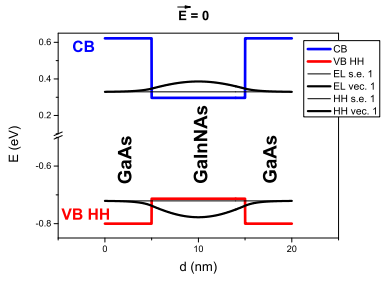
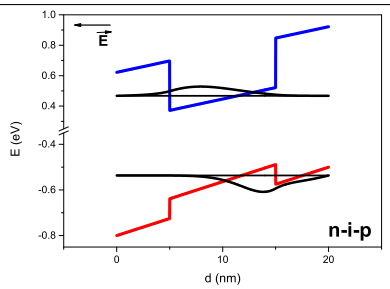
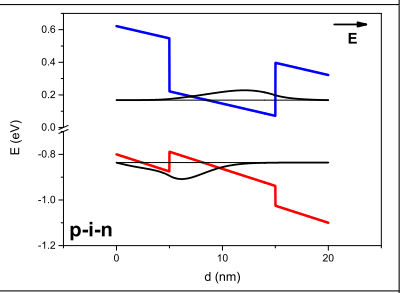
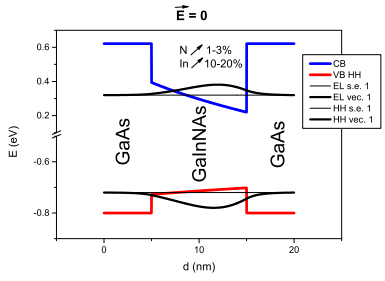
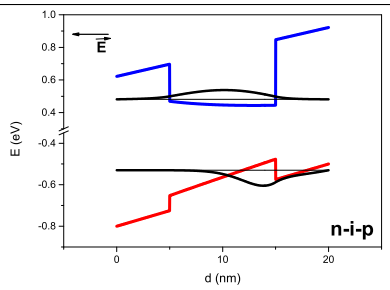
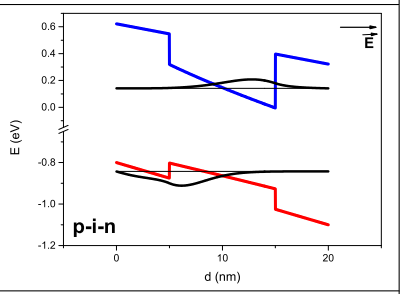
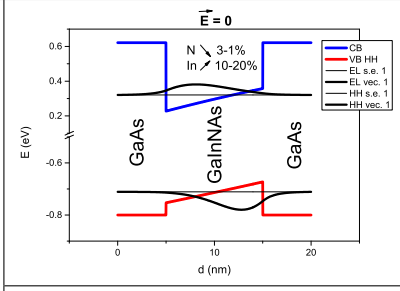
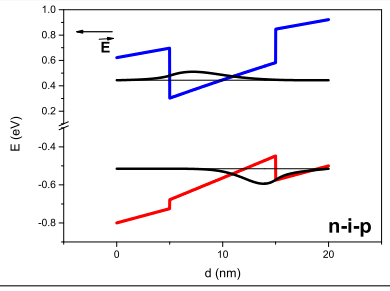
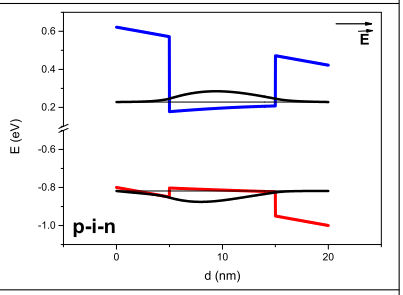
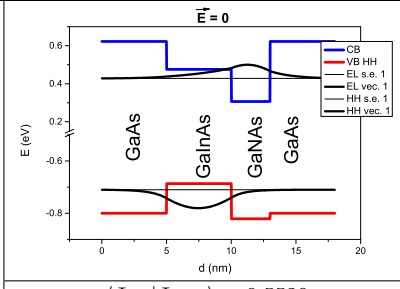
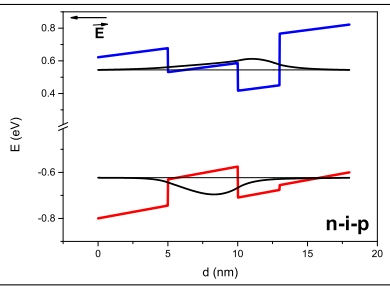
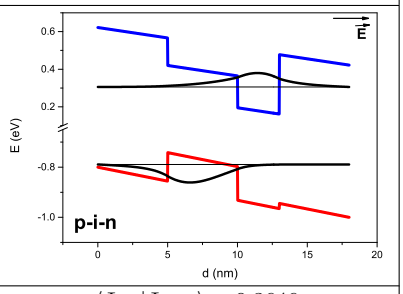
For each presented QWs type, the value of electron-hole wave functions overlap integrals $\langle\Psi_{1e}|\Psi_{1hh}\rangle$: is given below the electronic structure scheme. Only ground states transitions were considered in this work. The efficiency of the electron-hole transition according to Fermi's golden rule is directly proportional to the square of a value of electron-hole wave functions overlap integral $|\langle\Psi_{1e}|\Psi_{1hh}\rangle|^2$, which is also the reason why Tab. 1 includes this factor.

Uniform distribution of atoms along the QW is an ideal case (#1). Value of electron-hole wave functions overlap integrals is almost 1 in the case of the QW with no acting electric field. In the real structures, some imperfections can be always found due to atoms interdifusion what reduces wave functions overlap integral. In the case of GaInNAs, indium and nitrogen distributions are distinctly inhomogeneous. As it was mentioned, in structures #2, #3, and #4, the gradients of components are intensified to clearly indicate the analysed phenomena and to present the applicability of intentionally graded layer in photodetector structures. What must be highlighted is that under the electric field influence, the spatial distributions of electron and hole wave functions undergo modification. In the case of QW #1, spatial separation of the electrons and holes wave functions can be observed and results in decrease of $|\langle\Psi_{1e}|\Psi_{1hh}\rangle|^2$ to 27.89 % for both electric field directions. In the case of the structure type #2, presence of the electric field decreases the value of $|\langle\Psi_{1e}|\Psi_{1hh}\rangle|^2$. However, the drop of the $|\langle\Psi_{1e}|\Psi_{1hh}\rangle|^2$ value strongly depends on the direction of electric field. In case of structures #3 and #4, one can notice that with no electric field, the conduction band ground state wave function is shifted left – towards nitrogen rich side of the QW. The adequate valence band wave function is shifted right – towards indium rich QW side. That spatial separation can be enhanced when type #3 QW is placed in the electric field corresponding to the field of reverse biased n-i-p junction and type #4 QW is placed in the electric field corresponding to the reverse biased p-i-n junction. In the opposite cases, the spatial separation of the wave functions is reduced. Reduction of spatial separation of the electron and hole wave functions result in their higher overlapping and absorption efficiency increase. Electric field can therefore improve overlapping of the electrons and holes wave functions according to photodetector design (for type #3 QW in case of p-i-n structure and for type #4 QW in case of n-i-p design) that effects absorption properties of QWs-based photodetectors due to compensation of adverse impact of the QCSE on their absorption efficiency.

4. Summary

From the analysis of structural and electronic properties of MOVPE grown 3xQWs GaInNAs/GaAs structures and from the theoretical research of inhomogeneous GaInNAs QWs, it can be concluded that electron and hole wave functions distributions along the GaInNAs/GaAs QWs can be strongly modified by naturally occurring or intentional intensified composition gradients of the GaInNAs QW layers. Moreover, the proper design of step-like quantum wells can compensate the adverse impact of the QCSE. Such structures could be used to design novel class of high efficiency junction based QWs photodetector based on multicomponent alloys.

Tab. 1: Electronic structures of the QWs with no electric field acting the bands and under the influence of electric fields with two the opposite sense.

	no electric field	**negative electric field n-i-p structure**	**positive electric field p-i-n structure**
#1			
	$\langle\Psi_{1e}\vert\Psi_{1hh}\rangle = 0.9994$	$\langle\Psi_{1e}\vert\Psi_{1hh}\rangle = 0.5280$	$\langle\Psi_{1e}\vert\Psi_{1hh}\rangle = 0.5280$
	$\vert\langle\Psi_{1e}\vert\Psi_{1hh}\rangle\vert^2 = 0.9988$	$\vert\langle\Psi_{1e}\vert\Psi_{1hh}\rangle\vert^2 = 0.2789$	$\vert\langle\Psi_{1e}\vert\Psi_{1hh}\rangle\vert^2 = 0.2789$
#2			
	$\langle\Psi_{1e}\vert\Psi_{1hh}\rangle = 0.9964$	$\langle\Psi_{1e}\vert\Psi_{1hh}\rangle = 0.7472$	$\langle\Psi_{1e}\vert\Psi_{1hh}\rangle = 0.3840$
	$\vert\langle\Psi_{1e}\vert\Psi_{1hh}\rangle\vert^2 = 0.9928$	$\vert\langle\Psi_{1e}\vert\Psi_{1hh}\rangle\vert^2 = 0.5583$	$\vert\langle\Psi_{1e}\vert\Psi_{1hh}\rangle\vert^2 = 0.1475$
#3			
	$\langle\Psi_{1e}\vert\Psi_{1hh}\rangle = 0.6306$	$\langle\Psi_{1e}\vert\Psi_{1hh}\rangle = 0.2929$	$\langle\Psi_{1e}\vert\Psi_{1hh}\rangle = 0.8024$
	$\vert\langle\Psi_{1e}\vert\Psi_{1hh}\rangle\vert^2 = 0.3976$	$\vert\langle\Psi_{1e}\vert\Psi_{1hh}\rangle\vert^2 = 0.0858$	$\vert\langle\Psi_{1e}\vert\Psi_{1hh}\rangle\vert^2 = 0.6438$
#4			
	$\langle\Psi_{1e}\vert\Psi_{1hh}\rangle = 0.5520$	$\langle\Psi_{1e}\vert\Psi_{1hh}\rangle = 0.7593$	$\langle\Psi_{1e}\vert\Psi_{1hh}\rangle = 0.3646$
	$\vert\langle\Psi_{1e}\vert\Psi_{1hh}\rangle\vert^2 = 0.3047$	$\vert\langle\Psi_{1e}\vert\Psi_{1hh}\rangle\vert^2 = 0.5765$	$\vert\langle\Psi_{1e}\vert\Psi_{1hh}\rangle\vert^2 = 0.1329$

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