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Optimization of structural and growth parameters of metamorphic InGaAs/GaAs photoconverters grown by MOCVD

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Abstract. Metamorphic $Ga_{0.76}In_{0.24}As$ heterostructures for PV converters of 1064 nm laser radiation have been grown by the MOCVD. Parameters of the GaInAs metamorphic buffer layer with a stepwise profile of In composition variation were calculated. Its epitaxial growth conditions have been optimized, which allowed improving collection of charge carriers from the n-GaInAs base region and obtaining the photo-response quantum yield of 83% at 1064 nm wavelength. It has been found that, due to discontinuity of valence bands at the $In_{0.24}Al_{0.76}As$-p/$Ga_{0.76}In_{0.24}As$-p heterointerface (window/emitter) a potential barrier for holes arises as a result of low carrier concentration in the wide-band-gap material. The use of InAlGaAs solid solution with Al concentration of < 40% has allowed raising the holes concentration in the wide-band-gap window, eliminating completely the potential barrier and reducing the device series resistance. Optimization of the PV converter metamorphic heterostructure has resulted in obtaining 1064 nm laser radiation conversion efficiency at the level of 38.5%.

1. Introduction

Development of photovoltaic (PV) converters of laser radiation (LR) with wavelength of the atmosphere transparency for wireless transmission of energy and information is an important task for elaborating cellular communication in remote and hard to reach places. In conditions, when construction of communication systems is difficult to perform or is not profitable, it is possible to apply unmanned aerial vehicles. They can play a role of base stations or Internet access points in communicating with terrestrial networks by means of a laser – PV converter optical pair [1, 2]. For such an application, a conventional Nd:YAG laser with a powerful emission mode at 1064nm is the best suited and also has a low absorption factor in the atmosphere. This leads to only 8% difference at 1064nm wavelength between space and terrestrial solar spectra. Currently, important is development of heterostructures for PV converters of the 1064nm LR energy and having high efficiency.

A record 1064 nm laser radiation conversion efficiency for silicon-based structures is close to 40% [3]. However, this result was achieved by using a very complicated procedure for the surface texturing. Furthermore, the maximum efficiency values were achieved at a LR concentration less than 1.5 W/cm^2, which is not enough for wireless power transmission networks, and the low carrier mobility makes Si unreasonable for the manufacture of high-frequency PV converters.

In the present work, PV converters of 1064 nm LR based on metamorphic $In_xGa_{1-x}As$ heterostructures grown by the MOCVD technique on cheap and conventional GaAs substrates have been developed.

2. Experimental details

Metamorphic PV structures were grown in a low pressure MOCVD reactor under 100 mbar on n−GaAs (100) substrates misoriented by 6° towards the [111] direction. Metal alkyls were used as sources of the III-group atoms: threemethylgallium, threemethylaluminum, threemethylindium. Arsine was used as a source of As atoms. Monosilane and diethylzinc were used to dope layers with n−type impurity p−type impurity respectively.

The PV structure represents a *p-n* diode with photoactive base (of n-type) and emitter (of p-type) regions, as well as functional layers: a back surface field (BSF) and wide-band-gap window layer (figure 1). Base and emitter thicknesses have been chosen 3.5 μm and 500 nm respectively from consideration of total absorption for GaAs PV converter. As a window layer ternary $Al_{1-x}In_xAs$ and quaternary $In_x(Al_{0.5}Ga_{0.5})_{1-x}As$ solid solutions were used. A metamorphic buffer (MB) was grown for the compensation of the lattice mismatch between $Ga_{1-x}In_xAs$ layer and GaAs substrate. Variation of In concentration *"x"* in $Ga_{1-x}In_xAs$ layers of the metamorphic buffer was performed in "steps" with a step of about 2.5%, each 120 nm thick, to create the sufficient amount of interfaces, at which dislocations can be bent.

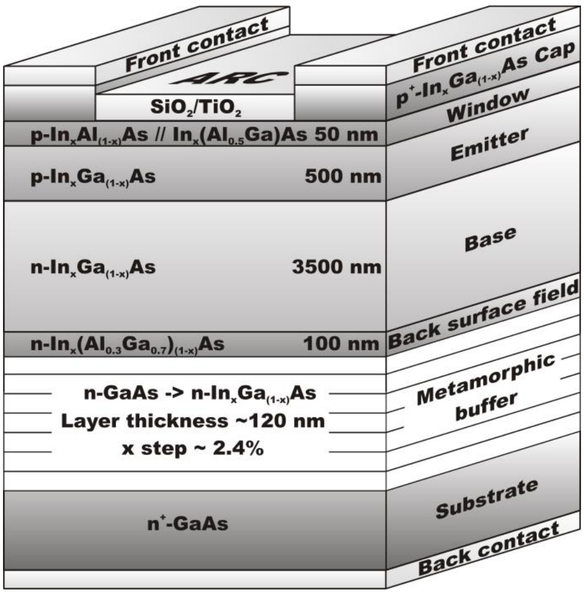


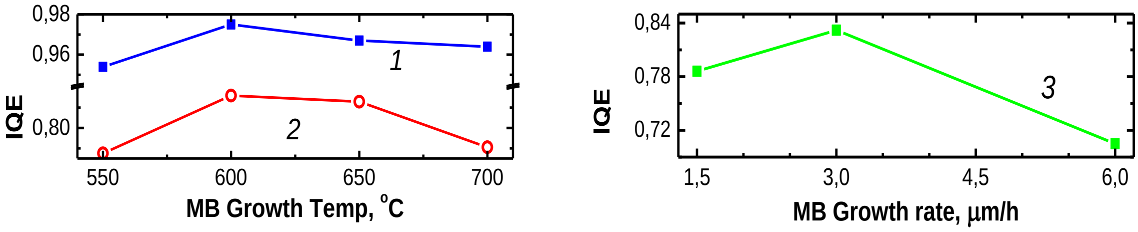
Figure1. Schematic of the metamorphic $In_xGa_{1-x}As$ PV converter cross-section.

Using the grown heterostructures, 3x3.4 mm PV converters were fabricated using photolithography, and then their spectral and photovoltaic characteristics were measured. Modeling of a band diagrams was carried out by means of the AFORS-HET software [4].

3. Results and discussion

Internal quantum efficiency (IQE) at 1064 nm wavelength for initial $Ga_{0.76}$ $In_{0.24}As$ PV converter was approximately 77%. Incomplete charge carrier collection from the n-GaInAs base region was due to small diffusion lengths of charge carriers [5], that is common for lattice mismatched heterostructures. One of the factors which might decrease diffusion lengths is a formation of threading dislocations in MB region.

Threading dislocation density in the base layer depends on parameters of MB – thickness and number of its sublayers with constant composition, as well as its growth temperature and growth rate. Thickness of each sublayer was approximately 120 nm, which is 1.5 times more than a critical thickness for $GaAs/Ga_{0.975}In_{0.025}As$ layer calculated by means of the Matthews-Blakeslee theory. In order to reduce threading dislocation density in the base layer and increase carrier's diffusion lengths, optimization of the growth parameters of MB was carried out: buffer layer growth temperature was varied within 550 – 700 ºC, and the growth rate – within 1.5 – 6 μm/h. Decrease of MB growth temperature to 550 ºC at a constant growth rate (3 μm/h) resulted in decreasing the IQE value (figure 2 (a)). At this temperature, adatom migration rate is dramatically reduced, therefore, at a constant delivery rate of precursors to the growth zone, the morphology of the structure becomes worse, leading to wave-like surface. Optimal growth parameters of forming MB have been found to be – 3 μm/h at 600 ºC.



(a) *(b)*

Figure2. *(a)* – Internal quantum efficiency (IQE) vs. MB growth temperature: 1 – maximal IQE, 2 – IQE at 1064 nm wavelength; *(b)* – IQE at 1064 nm wavelength (MB growth temp – 600 ºC) vs. MB growth rate.

As a result, charge carrier collection from the n-GaInAs base region was improved, which allowed achieving the photo-response quantum efficiency at 1064 nm wavelength of 83% (figure 3).

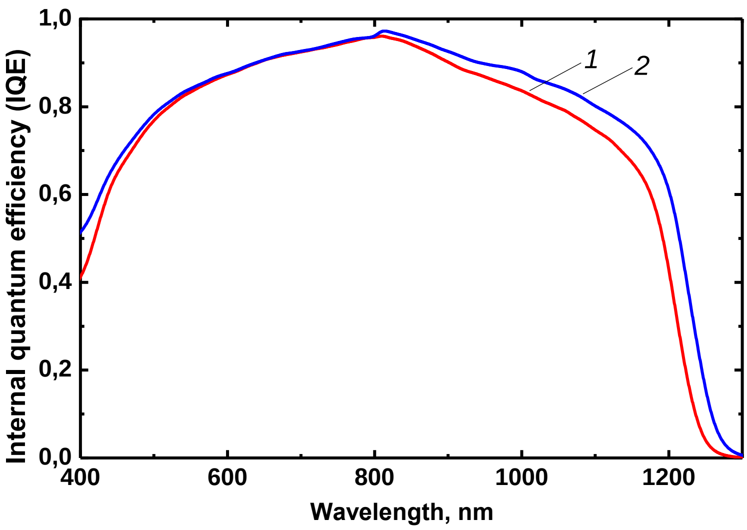


Figure 3. IQE spectral dependencies of $In_{0.24}Ga_{0.76}As$ PV converters with $In_{0.24}(Al_{0.5}Ga_{0.5})_{0.76}As$ window layer and: 1 – non-optimized MB, 2 – with optimized MB.

However, the light IV curves of such PV converters were characterized by a large series resistance and low fill factor (FF) (figure 4, blue curve). It may be caused by a potential barrier in PV structure for majority charge carriers.

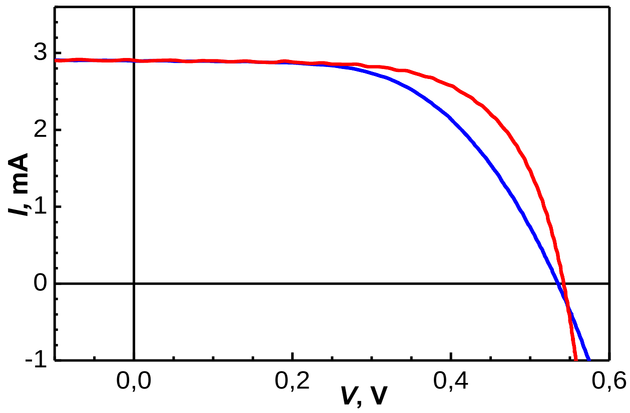


Figure4. Light IV curves of $Ga_{0.76}In_{0.24}As$ PV converter with window layer composition: 1 – $Al_{0.76}In_{0.24}As$, 2 – $In_{0.24}(Al_{0.5}Ga_{0.5})_{0.76}As$.

Simulation of the $Ga_{0.76}In_{0.24}As$ PV converter heterostructure band diagram was carried out by means of the AFORS-HET software. It has been found that a potential barrier for holes is present on the window/emitter heterointerface caused by discontinuity of the valence bands at the $In_{0.24}Al_{0.76}As$-p/$Ga_{0.76}In_{0.24}As$-p interface (figure 5). In case of $In_{0.24}Al_{0.76}As$ wide-band-gap window layer, the Fermi level departs substantially from the valence band. Such a shape of the band diagram is also associated with a low level of the wide-band-gap window carrier concentration compared with that of the emitter and contact layers. To eliminate the potential barrier introduction of Ga atoms into sublattice of the third group, at a concentration equal to Al, has been proposed. The use of the quaternary InAlGaAs solid solution (with Al concentration reduced down to 38%) as the wide-band-gap window has permitted to raise the holes concentration of up to about ~ 9×10^{18} cm^{-3}. Analysis of the band diagram has shown that application of the narrow-band $In_{0.24}(Al_{0.5}Ga_{0.5})_{0.76}As$-p material with a high acceptor concentration allows eliminating completely the observed potential barrier, which is supported experimentally by a significant reduction of the PV converter resistance (figure 5) and by fill factor increasing (figure 4, red curve).

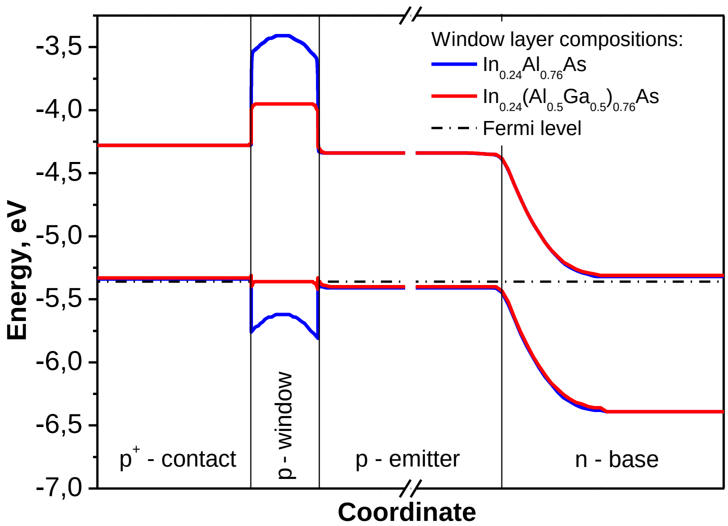


Figure5. Band diagram of the $Ga_{0.76}In_{0.24}As$ PV converter heterostructures: with $Al_{0.76}In_{0.24}As$ window (blue curve) and $In_{0.24}(Al_{0.5}Ga_{0.5})_{0.76}As$ window layer (red curve).

The photovoltaic converters fabricated on the base of metamorphic heterostructures with optimized wide-band window layers and metamorphic buffer layer have demonstrated the 1064 nm LR conversion efficiency of about 38.5% (figure 6, curve 2).

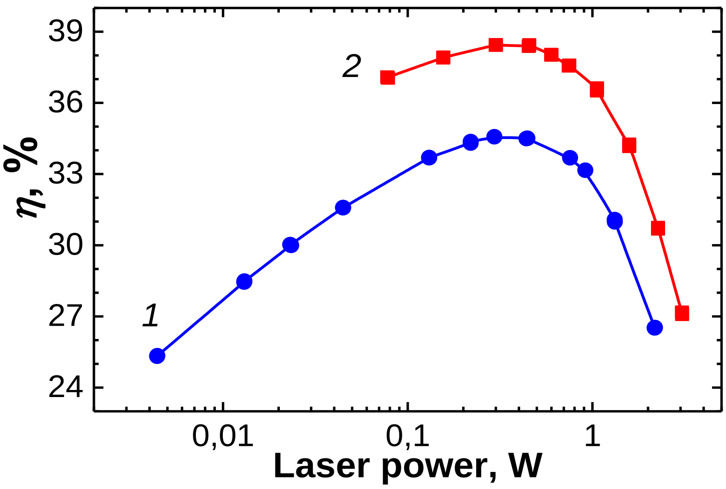


Figure6. Dependence of the 1064 nm LR conversion efficiency on laser power of $In_{0.24}Ga_{0.76}As$ PV converter with $In_{0.24}(Al_{0.5}Ga_{0.5})_{0.76}As$ window layer and: 1 – non-optimized MB, 2 – optimized MB.

4. Conclusion

Optimization of structural and growth parameters of the $In_{0.24}Ga_{0.76}As$ metamorphic PV converters consisted in analysis of the band diagram and development of growth parameters of stepwise MB has allowed reaching 1064 nm radiation conversion efficiency of 38.5% (at laser radiation power density ~ 5 W/cm^2).

Acknowledgments

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