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Solar cells conversion efficiency enhancement techniques

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In order to enhance the conversion efficiency of GaAs *p-i-n* solar cells GaAs/$Al_xGa_{1-x}As$ QW within intrinsic region or gradation of Al fraction of $Al_xGa_{1-x}As$ emitter and base region were applied. The influence of AlAs Bragg reflectors on the performance of MQWSC was studied theoretically by using SimWindows software.

Keywords: quantum well solar cells, graded solar cells, Bragg reflectors, conversion efficiency, SimWindows.

1. Introduction

The main emphasis in the design of solar cells, dedicated to various applications, is placed on the enhancement of their conversion efficiency. For this purpose, antireflection coatings and back reflectors or/and texturing of solar cell surface are applied. Our investigation was focused on the improvement of conversion efficiency by application of quantum wells or band-gap gradation of the emitter and/or base region. Additional benefits can be obtained by application of Bragg reflectors.

GaAs quantum wells with $Al_xGa_{1-x}As$ barriers were placed within intrinsic region of GaAs *p-i-n* solar cell. Wells number and depth, the doping concentration and thicknesses of emitter and base regions, and the material composition of window layer were optimized by SimWindows simulations. The influence of light concentration and ambient temperature on conversion efficiency were determined. The results obtained were compared with similar *p-i-n* solar cells with *i*-region fabricated from both undoped GaAs or $Al_{0.1}Ga_{0.9}As$ material.

Optimization process was carried out because the change in thicknesses and composition of layers performed in order to increase the photocurrent could lead to the decrease of the open-circuit voltage. The absorption edge of the solar cell is determined by the width and depth of quantum wells. The higher photocurrent could be generated if wells are deeper. This allowes the absorption of longer wavelengths. The open-circuit voltage is determined by the barrier material band gap. Application of deeper wells enlarges the photocurrent but decreases the open-circuit voltage. Wider wells decrease the absorption edge because more energy levels at the QW are allowed. Larger quantity of wells within the intrinsic region decrease the absorption edge and increase the photocurrent [1–3]. The effect of quantum well number on photocurrent causes an opposite effect on open-circuit voltage [4].

One of the uncommon conversion efficiency enhancement techniques is gradation of band-gap by application of material composition gradation within particular layers of device. Our research was focused on $Al_xGa_{1-x}As$/GaAs materials system. GaAs is one of the most promising candidates for fabrication of solar cells but this material has great velocity of surface recombination in the range of $S = 10^6$–10^7 cm/s^2. This causes difficulties in obtaining high conversion efficiency. There are two methods which allow surface recombination reduction. The first one consists in the introduction of a wide-band gap material in emitter layer ("window effect" of heterojunction). The other method is based on application of built-in electric field in the surface layer which accelerates excess minority carriers toward the *p-n* junction, which reduces the time required for their collection and in consequence increases the collection of photogenerated minority carriers. The electric field occurrence could be obtained by variation of doping concentration or change of the energy band-gap at the surface [5–7].

Radiative recombination and Auger recombination are unavoidable loss mechanisms in solar cells. The Auger recombination could be restrained by reducting the thickness of the solar cell but this causes higher surface recombination losses and incomplete absorption. Proper gradation of material band-gap could decrease the Auger recombination losses and reduce the carrier concentration at the surface [8, 9]. Application of graded layers within solar cells device improves their radiation hardness [10]. It was observed that by the appropriate gradation of emitter and base band-gap the Auger recombination rate could be decreased and also short-circuit current, open-circuit voltage, maximum power and conversion efficiency could be enhanced. More details are given in [11].

Bragg reflectors could be applied in order to obtain reflection of unabsorbed photons from the bottom of the device. In studied solar cells AlAs/GaAs Bragg reflectors were placed within the base layer. Conversion efficiency enhancement was achieved by optimizing of the thickness of the mirrors at the maximum of the spectral characteristic of the solar cell.

Thicknesses d_{Bragg} of Bragg reflectors layers were chosen in accordance with the following equation:

$$d_{\mathrm{Bragg}} = \frac{\lambda}{4n_{\mathrm{Bragg}}(\lambda)}$$

where: λ – wavelength at maximum of spectral characteristic which was given in [4], n_{Bragg} – refractive index for Bragg reflector material.

2. Device description

The basic *p-i*(MQW)-*n* structure with quantum wells is shown in Fig. 1**a**. The *n*+ GaAs Si doped at 1×10^{18} cm^{-3} substrate (1) and buffer layer (2) with thicknesses of 400 μm and 0.5 μm, respectively, were applied. The *n*-type emitter (3) and *p*-type base (10) were composed of GaAs. Additionally separating layers (4, 9) made from intrinsic layer material were used in order to prevent diffusion of dopants into the region of the wells. GaAs quantum wells (5, 7) and $Al_xGa_{1-x}As$ barriers (6, 8) were placed within intrinsic layer. $Al_xGa_{1-x}As$ window layer (11) placed on the top of the structure was followed by the GaAs cap layer (12). Two reference *p-i-n* structures *p-i*(GaAs)-*n* and *p-i*($Al_{0.1}Ga_{0.9}As$) were also taken into consideration.

The graded solar cell is shown in Fig. 1**b**. Gradation of $Al_xGa_{1-x}As$ was applied in emitter/ base or within emitter and base simultaneously. Gradation in an intrinsic layer

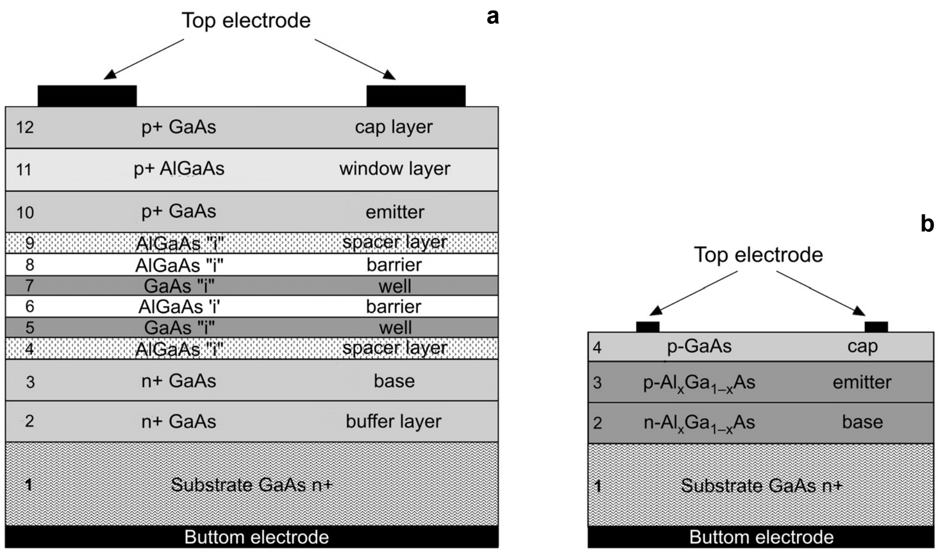

Fig. 1. Solar cell structure: *p-i*(MQW)-*n* (**a**), graded solar cell (**b**).

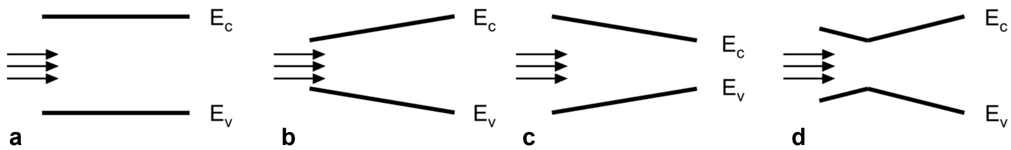

Fig. 2. Types of band-gap profiling: without profiling (**a**), normal (**b**), reverse (**c**), double (**d**) [11, 12].

was also employed for *p*-*i*-*n* solar cells. Layers without profiling were composed of GaAs.

There were investigated three types of material band-gap gradation: normal, reverse and double gradation – Fig. 2 [11, 12].

Bragg reflectors composed of AlAs/GaAs with appropriate thicknesses were placed within the base layer of optimized multi quantum well solar cell structure without graded layers.

3. Device optimization

Devices were simulated by using SimWindows version 1.5.0. A non-concentrated AM 1.5 spectrum with P_{in} equal to 1000 W/m^2 was applied. Optimization was carried out by simulation of devices with various geometrical and electrical parameters. The geometry of layers was changed by altering their thicknesses. The doping concentration and band-gap energy of particular layers materials were considered as the main electrical parameters. The appropriate steps of optimization were chosen, a detailed discussion of the procedure employed being described earlier [4]. For *p*-*i*(MQW)-*n* solar cell simulations parameters such as the widths of the wells and barriers, the depth of wells with a constant value of intrinsic region width, the number of wells in the intrinsic layer, doping concentration of emitter layer, width and doping concentration of the base layer, width of separation layers and Al fraction in the window layer were changed. In the next step, the width of separation layers and Al fraction in window material were modified. Devices which have achieved the highest value of conversion efficiency were classified to the next step of optimization.

For optimized MQW solar cell structure AlAs Bragg reflectors were applied within the base layer. The number of reflector layers, thickness and composition were optimized.

For graded solar cells the gradation profile of the composition of layer, emitter thickness and doping concentration were optimized. Normal, reverse and double gradations were used within the emitter, base and intrinsic regions (see Section 2). Various values and localization of minimum band-gap energy of material were applied in the case of double gradation.

4. Results

A multi quantum well solar cell optimized structure (sample A) is shown in Fig. 3, it contains two 15 nm wide GaAs wells and 10 nm wide $Al_{0.1}Ga_{0.9}As$ barriers. $Al_{0.1}Ga_{0.9}As$ spacer layers were 20 nm and 25 nm wide. Optimized thickness of $Al_{0.8}Ga_{0.2}As$ emitter layer was 100 nm and doping concentration 4×10^{18} cm^{-3}. Base layer was 1000 nm thick and doped on 2×10^{17} cm^{-3}. Reference structures were identical

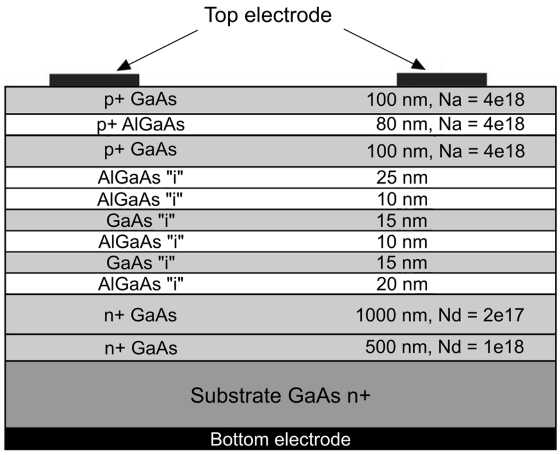

Fig. 3. Optimized structure of MQW solar cell.

as sample A but without quantum wells within intrinsic layer made of GaAs (sample refA1) and $Al_{0.1}Ga_{0.9}As$ (sample refA2). Promising results were obtained for two pairs of AlAs/GaAs reflectors of 63 nm in thickness (sample B).

The best parameters for graded solar cell were obtained for structures with emitter thickness equal to 0.3 (sample C) and 0.4 μm (sample D), doping concentration $N_a = 2\times10^{17}$ cm^{-3}, reverse gradation from $Al_{0.4}Ga_{0.6}As$ to $Al_{0.1}Ga_{0.9}As$, base thickness 2 μm, doping concentration $N_d = 2\times10^{18}$ cm^{-3}, gradation from GaAs in the metallurgical junction to $Al_{0.4}Ga_{0.6}As$. Simulations were also carried out for reference *p*-*n* solar cells without profiling any of the layers with thicknesses of the layers and doping concentration identical to those of the graded solar cell.

Parameters for quantum well solar cells with and without Bragg reflectors and graded solar cells are given in the Table.

Additionally, the influence of ambient temperature on conversion efficiency of multi quantum solar cell and reference devices was determined and shown in Fig. 4.

T a b l e. Parameters of optimized solar cell structures.

	I_{sc} [mA/cm^2]	U_{oc} [V]	*FF* [%]	η [%]
A	26	1.01	95	27.4
RefA1	–	–	–	26.6
RefA2	–	–	–	27.5
B	26.53	1.03	89	29.7
C	18.13	1.11	76	19.5
Ref.C	14.8	0.86	82	13.1
D	16.45	1.11	87	20
Ref D	13.66	1.06	39	7.1

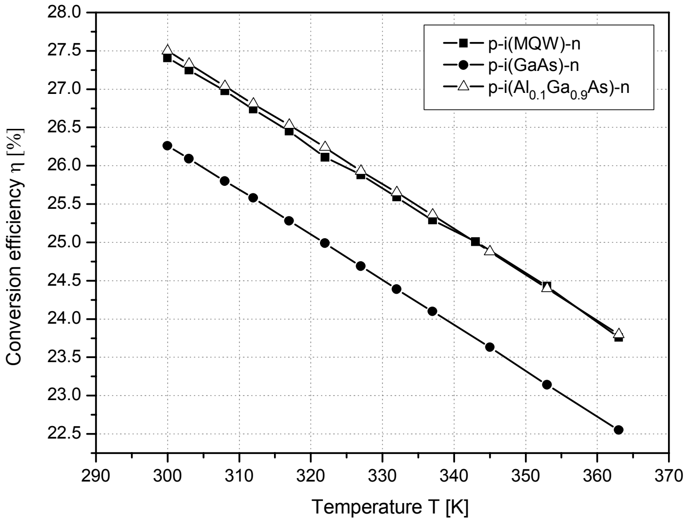

Fig. 4. Conversion efficiency of optimized MQW and reference solar cells *vs*. temperature.

It has been observed that with an increase in temperature conversion efficiency decreases linearly for all of the *p-i-n* solar cells. Identical temperature dependence was observed for the graded solar cell characteristics.

5. Conclusions

Simulations of solar cells with quantum wells, Bragg reflectors and graded layers were carried out. Optimization of the parameters of particular layers allowed us to achieve conversion efficiency enhancement. Very promising parameters were obtained for a multi quantum well structure with Bragg reflectors. Results obtained for the graded solar cells were sufficiently good according to the reference samples. A very important advantage of solar cell with gradation lies also in its simplicity of technology.

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