Preparation and characterization of multilayer AlGaAs/GaAs structures for photovoltaic application

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Abstract. In this paper, we present the preparation of multilayer AlGaAs/GaAs heterostructures for photovoltaic application. The structures developed consist of several layers grown on a highly conducting GaAs substrate: n-GaAs base, p-GaAs emitter embedded between two AlGaAs layers, and heavily doped p +GaAs capping contact layer. The second 0.03 µm thick “window” AlGaAs layer has band gap energy of 2.1 eV and ensures penetration of the higher-energy photons in the active region of the p-n junction. The electrical and optical parameters of the multilayer heterostructure as well as the layers thickness are designed by numerical simulation using computer modeling. The optimized heterostructure has a back-surface-field AlGaAs layer of several microns and an ultra thin (20-40 nm) window layer providing the best conversion efficiency and a maximum spectral response in the range 300-900 nm.

1. Introduction

High-efficiency GaAs solar cells are being developed on the basis of high-quality AlGaAs/GaAs heterostructures. Conversion efficiencies of approximately 25 % at one sun illumination and 27-28 % under concentrated light have been reached by leading laboratories for GaAs solar cells for terrestrial application [1-3]. These devices typically possess a very thin (30 nm) high aluminium arsenide fraction AlxGa1-xAs (x=0.8-0.9) window layer for surface passivation and a heavily doped GaAs capping layer, which serves the dual purpose of providing stable low-resistance contacts and protecting the window during most of the processing.

Among the growth methods for high-quality AlGaAs/GaAs heterostructures, liquid phase epitaxy (LPE) is the most simple and safe one. Both theoretical and experimental data on the thickness of the layers prepared by the low-temperature (LT) variant of the LPE show that it is possible to fabricate AlGaAs/GaAs heterostructures with layers as thin as 2-20 nm, as well as several microns thick, with a smooth surface and flat interfaces [4-6].

In this paper we discuss the preparation and characterization of multilayer AlGaAs/GaAs structures for photovoltaic application. By using a numerical analysis, we obtain the exact layers structure, which is then confirmed by scanning electron microscopy (SEM) and EDAX measurements.
2. Experimental
The schematic structure of our p-on-n (p-type emitter on n-type substrate) double heteroface (DH) AlGaAs/GaAs structure for photovoltaic application is shown in figure 1. It consists of GaAs p-n junction between two AlGaAs layers - a thick Al$_{0.3}$Ga$_{0.7}$As layer as a back surface field below the n GaAs base region and a thin Al$_{0.8}$Ga$_{0.2}$As window layer. The heavily doped p+ GaAs capping layer 0.2 - 0.3 μm were grown on the surface of the structure. In such a structure, the conversion efficiency of the cells could be improved due to the photon recycling process. Photon recycling is a strong effect in DH structures used for PL decay measurements [7] and it is also operative in DH solar cells. It increases the upper limit of effective minority carrier lifetimes for high-quality base materials.

The device simulator PC1D is used to investigate the dependence of the solar cells performance on the thickness and doping concentration of the layers. The optimized values obtained are shown in figure 1.

| Layer | Thickness | Doping Concentration |
|-------|-----------|----------------------|
| p+GaAs | 1.10^19 cm^-3 | Capping layer | 0.2 - 0.3 μm |
| p Al$_{0.3}$Ga$_{0.7}$As | ≤1.10^18 cm^-3 | Window | 0.02-0.05 |
| p GaAs | 1 - 2.10^17 cm^-3 | Emitter | 0.5 - 1 μm |
| n GaAs | 1.5 - 2.10^17 cm^-3 | Base | 3.0 - 3.5 μm |
| n+ Al$_{0.3}$Ga$_{0.7}$As | 1.10^18 cm^-3 | BSF layer | 2-3.0 μm |
| n+ GaAs | | Substrate |

AlGaAs/GaAs heterostructures were grown in a conventional LPE reactor using a multiple-bin “piston” boat designed for a 15×10 mm$^2$ substrate. The substrate surface in this boat is always covered by melt after the first wetting. This solves the most difficult problems of wetting of AlGaAs heterostructures grown in the range 500-600 °C. The crystallization was carried out on an n-type (100) oriented GaAs substrate from a very diluted (~500 μm) Ga solution. The source materials used for the growth solutions consisted of 99.9999-percent pure Ga, Al, and undoped polycrystalline GaAs. The elements used as dopants were Te for n-type GaAs and Ge, Mg for p-type GaAs and AlGaAs layers. The charged boat was heated at 800 °C for 1h in a purified H$_2$ gas flow in order to decrease the contaminations of the residual impurities in the melt. The initial epitaxy temperature was 670 °C and the p-n junction was formed at 520 °C. The thin AlGaAs window layer was deposited at 480 °C.

3. Results and discussion
The fabrication of AlGaAs/GaAs multi layer solar cells is strongly dependent on the knowledge and control of the electrical and physical parameters of each layer in the structure. It is necessary to know the thickness of the layers, as well as Al the content in the BSF and window layers. Furthermore, knowledge of the carrier concentration and mobility in the emitter and base region is especially important.

Figure 2 shows an optical microscope cross-section view of the heterostructure. It is seen that the layers are different due to the different band gap energy: the second and the fifth layers - of AlGaAs - are nearly equal in color, actually violet in the used color gamma. The photo was taken with a 5 MP camera at 80 μm area of the sample. One can see that the thickness of the layers are near the technologically predicted ones (figure1) and the interfaces are flat and of a good quality.

The molar fraction $x$ of AlAs in the AlGaAs is estimated by EDAX in the substrate, the back surface field (BSF) region and the base+emitter region. The results are shown in table 1. We note that the molar fractions needed of GaAs and AlAs are approximately equal to the doubled atomic fractions of Ga and Al given in the table 1.

The separate control layers of the heterostructures, grown on semi-insulating GaAs substrates, are characterized by Hall-effect measurements of the carrier concentration and mobility in the range of...
80-300 K. Temperature rate of $n_h$ and $\mu_h$ for the base layer are shown in figure 3(a) and figure 3(b). Reasonable values and behavior are obtained which correspond to good quality epitaxial layers.

Table 1. Composition of the layers.

| Layer             | Ga (At %) | As (At %) | Al (At %) |
|-------------------|-----------|-----------|-----------|
| GaAs substrate    | 51,52     | 48,48     |           |
| AlGaAs BSF        | 35, 53    | 41.42     | 23.04     |
| Base + Emitter    | 50,24     | 49.76     |           |

Figure 2. Cross-sectional view of the structure:
1 – Substrate,
2 - BSF layer – 4 μm,
3 - Base - 3.1 μm,
4 - Emitter - 1.5 μm,
5+6 - Window & Capping layer - 1.0 μm.

Figure 3. Temperature dependences of (a) Hall concentration and (b) Hall mobility for an n-GaAs base layer.

The I-V measurements are preformed on completely grown multilayer heterostructures with ohmic contact to the n+ GaAs substrate and to the front p+ side prepared by electroless plating of Sn/Ni layers with thicknesses 30 and 100 nm, respectively, followed by rapid thermal annealing at 500°C. Typical I-V characteristics of the grown p-n heteroface structures taken in the dark at 300 K are shown in figure 4.

As it is seen the structure exhibits very good rectifying properties with nearly exponential behavior of the forward current and built-in potential higher than 1.5 eV. The higher value of the ideality factor ($n > 2$) extracted from the slope of the curve log $I(V)$ for forward bias could be explained with the assumption that the externally measured ideality factor of the multilayer heterostructure is the sum of the ideality factors of the individual rectifying interfaces [8].
4. Conclusion
Multilayer AlGaAs/GaAs heterostructures for photovoltaic application was prepared by LPE. The results obtained from the characterization of the structure confirm that the key technological parameters of a single junction multilayer cell were achieved. These results will be applied in the fabrication of the AlGaAs/GaAs solar cells.

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