POWERFUL HIGH EFFICIENCY GaSb TPV AND PV CELLS

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ABSTRACT: GaSb based structures were developed and fabricated by the Zn-diffusion technique for solar and thermophotovoltaic applications. The effect of Zn diffused emitter etching by means of anodic oxidation on the behaviour of characteristics of cells fabricated from GaSb (100) wafers was investigated. An optimum Zn diffused profile and penetration depth of a *p-n* junction have been found, which allowed obtaining the maximum efficiency of GaSb cells at a high generated photocurrent density up to 10 A/cm^2.
Keywords: Diffusion, GaSb, photovoltaic.

1 INTRODUCTION

In contrast to the traditional PV systems in thermophotovoltaic (TPV) generators, the distance between the "artificial sun" (i.e., the high-temperature emitter made of ceramics or refractory metals) and a cell is very small (several cm). The emitter can be heated by means of concentrating solar radiation by mirrors and Fresnel lenses in solar TPV systems [1, 2], or by burning the gas in fuel-fired TPV generators [3, 4]. In this case, TPV cells working efficiently at high photocurrent density (up to 10 A/cm^2) are needed. However, it has remained complicated to develop high-current photocells that can operate efficiently in PV and TPV systems at high sun concentration ratios or in the TPV generators with burning the gas at a high emitter temperature [5-7]. The major difficulty is the necessity to collect high absolute currents from the entire device area under illumination with minimum Ohmic losses.

The further improvement of the TPV generator efficiency requires the optimization of PV cells. Nevertheless, the photocell optimization for a given system operation condition can result in not only the gain of the total generator efficiency but also in the increase of both the life duration and stability of the generator under the operation conditions.

In this study, we have optimized the structure of the photocells that can be used in TPV or concentrator solar PV systems at a high illumination density produced by Zn diffusion from the gas phase into a GaSb substrate. Whereas the contact grid configuration has been kept invariable, the *p-n* junction depth has been precisely varied in the range from 1 to 0.2 μm, and the basic photocell parameters have been measured.

The effect of the shape and depth of the *p-n* junction on characteristics of the GaSb TPV cells has been studied. High efficient cells based on GaSb with reduced internal losses have been developed by means of the Zn diffusion technique. The optimum Zn diffused profile resulted in the rise of the fill factor, photocurrent density and GaSb cell efficiency.

2 INFLUENCE OF THE DOPING PROFILE ON THE GaSb CELL CHARACTERISTICS

The improvement of characteristics of the PV and TPV systems comes, first of all, from the improvement of the PV cell manufacture technology and cell parameters. For this reason, investigation of the effect of the *p-n* junction penetration depth and Zn diffusion profile in a *p*-GaSb emitter on basic parameters of GaSb cells is very important.

General investigation of "non-epitaxial" GaSb cells with varied thickness of the emitter was carried out for two ingots fabricated by the modified Chochralskii technique. The single crystal *n*-GaSb ingot №96 ($n = 1.8\cdot10^{17}$ cm^{-3}, $\mu \approx 3660$ cm^2/V·sec, T = 300 K) and the ingot №267 ($n = 1.1\cdot10^{17}$ cm^{-3}, $\mu \approx 2800$ cm^2/V·sec, T = 300 K) were received from the "Giredmet" Institute (Moscow). Cutting the ingot №96 and polishing the plates were carried out in the Ioffe Institute. Cutting the ingot №267 and preparation of wafers were carried out by the firm "Girmet" (Moscow).

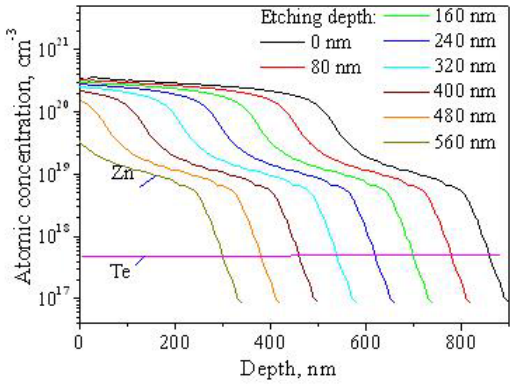

Figure 1: SIMS diffusion profiles of Zn doping in the GaSb cell structure (ingot №96).

The developed GaSb cells were fabricated by the two-step Zn diffusion technique. The diffusion was carried out into *n*-GaSb substrates (100) doped with tellurium in a pseudo-closed graphite boat under the hydrogen flow. The first diffusion process, at which the photosensitive *p-n* junction was formed from vapor phase, was carried out during four hours at 460 ^{0}C. The depth of the initial *p-n* junction was of about 850 nm.

The second diffusion process deepens the *p-n* junction under the contact grid. Then, the frontal Cr-Au contact and the rear Au(Ge)-Ni-Au contact were formed by the thermal depositions and photolithographic processes. The contact grid spacing was 200 μm. Si_3N_4

antireflection coating was deposited on the samples, as well.

The anodic oxidation was used as post-diffusion processing of structures for thinning the photoactive *p*-GaSb. Then the selective etching of the sample oxide layer in HCl was performed. The specific rate of the GaSb layer thickness reduction was around 2.0 nm/V [8]. The thickness of removed surface layers was varied from 80 to 680 nm. The anodic oxidation of GaSb was made in the electrolyte with the similar basic components as in the procedure developed for GaAs [9].

Study was carried out on 3.5×3.5 mm^2 GaSb cells. Fig. 1 shows the diffused zinc profiles of GaSb after 4-hour diffusion without etching (original SIMS profile) and with etching (redrawn SIMS profiles) of the initial *p-n* junction. GaSb cells corresponding to such profiles have been fabricated.

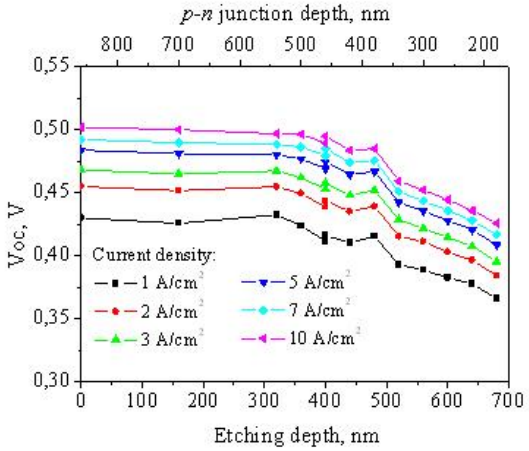

Figure 2: Dependencies of the open circuit voltage on the etching depth of a *p*-emitter for GaSb cells (ingot №96).

As is seen from Fig. 2 and 3, the open circuit voltage and the fill factor of fabricated cells drop after etching deeper than by 320 nm. The maximum value of FF takes place at photocurrent densities in the range of 3-5 A/cm^2 and has a second rise at the etching depth of about 600 nm.

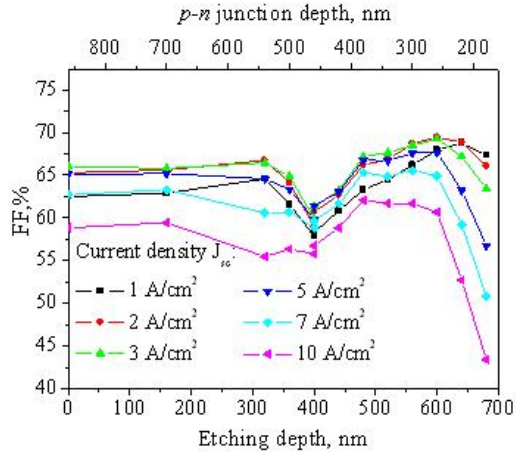

Figure 3: Dependence of the fill factor on the etching depth of a *p*-emitter for a GaSb cell (ingot №96).

As one can see from Fig. 4, the maximum gain of the generated photocurrent density in case of internal quantum yield about 20 mA/cm^2 (from 21.2 mA/cm^2 without etching up to 40.7 mA/cm^2 with optimum etching) takes place owing to the removal of heavily doped layer up to 320 nm and, hence, to reduction of the surface carrier recombination rate.

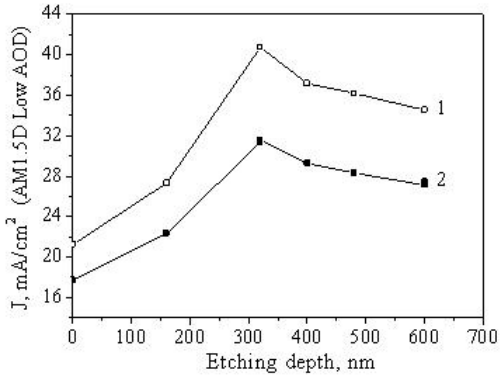

Figure 4: Dependencies of the GaSb cell short circuit current on the depth of the *p*-emitter etching (ingot №96). 1 – for internal quantum yield; 2 - for external quantum yield.

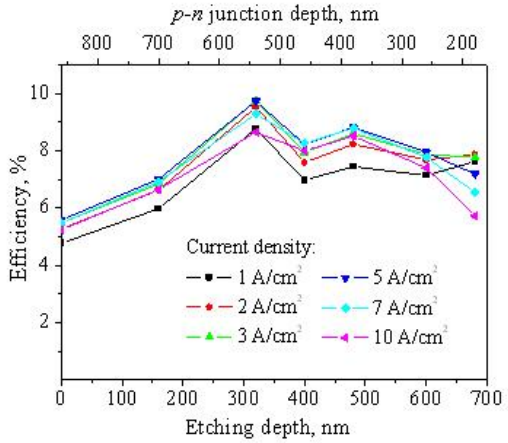

Figure 5: Dependencies of the efficiency (λ=500-1820 nm, AM1.5D, 1000 W/m^2) on the etching depth of the *p*-emitter for GaSb cells (ingot №96).

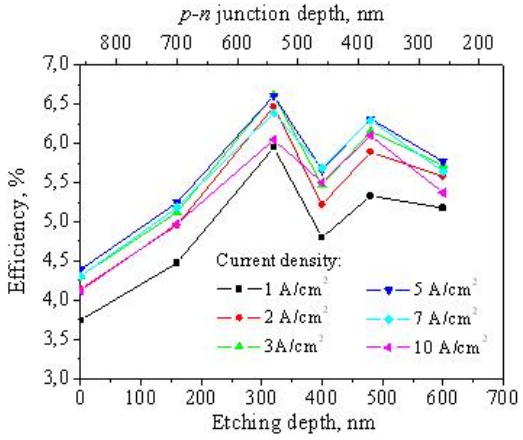

Figure 6: Dependencies of the efficiency (λ=900-1820 nm, AM1.5D, 1000 W/m^2) on the etching depth of the *p*-emitter for a GaSb cell (ingot №96).

Fig. 5, 6 and 7 present the dependencies of efficiency of photocells on the depth of the etched out p^+-layer for converting radiation of different parts of the solar spectrum. The maximum of efficiency is observed at the etching depth of 320 nm at the generated photocurrent density of 5 A/cm^2. It is about 10% for conversion of full spectrum solar radiation (Fig. 5). Efficiencies as high as 6.6% (Fig. 6) and 4.2% (Fig. 7) were estimated for the spectrum cutoff at $\lambda > 900$ nm (filtered by GaAs) and $\lambda > 1100$ nm (filtered by Si). So, developed cells can ensure such efficiencies in solar spectrum splitting modules.

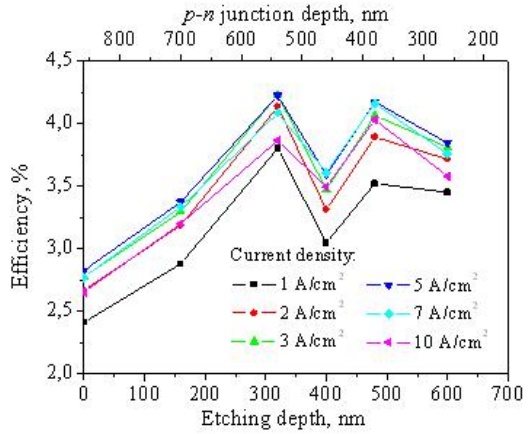

Figure 7: Dependencies of the efficiency (λ=1100-1820 nm, AM1.5D, 1000 W/m^2) on the etching depth of the *p*-emitter for a GaSb cell (ingot №96).

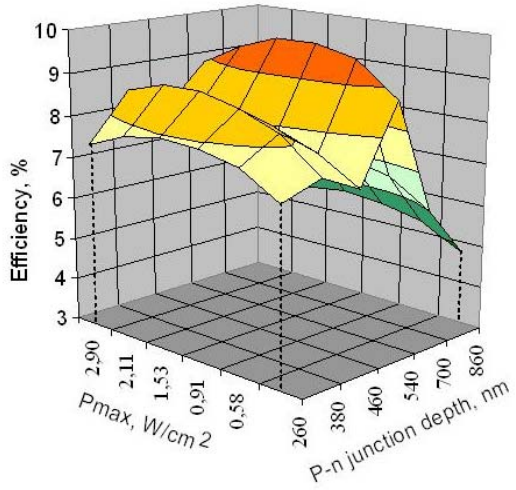

Figure 8: Dependencies of generated power density and efficiency on the emitter etching depth (ingot №96).

According to the plots of Fig. 1 the heavily doped layer is removed in etching out the near-surface layer to the 320 nm depth, however at the same time, the concentration gradient remains unchanged. In further etching out, the concentration gradient decreases, and, due to this, the build-in field is reduced, which may explain the decrease in the GaSb cell efficiency at the etching depths higher than 320 nm.

As it seen from Fig. 8 developed GaSb cells with maximum efficiency of 9-10% AM1.5D, 1000 W/m^2 (with rise of efficiency at 56 relative % compared with efficiency of cells without etching) at etching depth of 320 nm of the *p*-emitter are optimum for obtaining electric power at the range of 0.5-3 W/cm^2.

Fig. 9 (curve 1) shows the as-diffused zinc profile of GaSb cells fabricated from the ingot №267 after 4-hour diffusion without etching. The initial *p-n* junction was etched similar to the cells fabricated from ingot №96, and corresponding cells have been manufactured. Curve 2 (Fig. 8) corresponds to the optimum etching depth (320 nm as well) of the *p*-emitter.

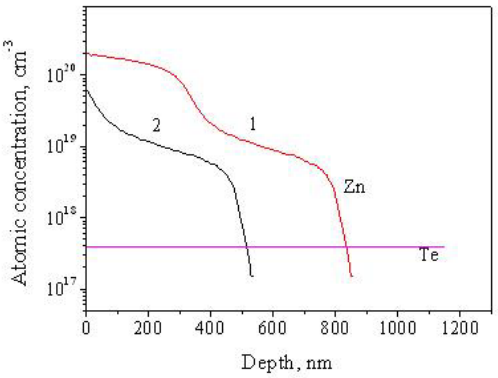

Figure 9: SIMS diffusion profiles of Zn doping in the GaSb cell structures (ingot №267).

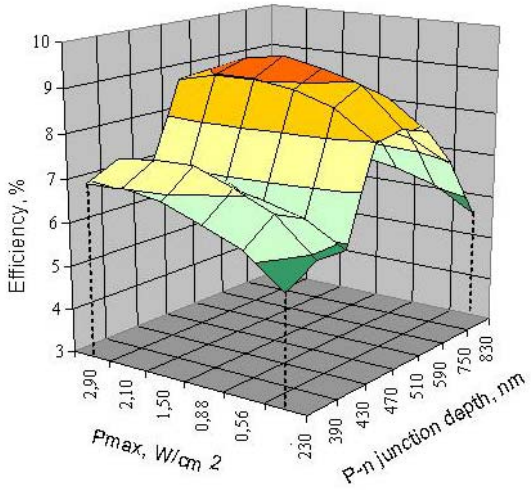

Figure 10: Dependencies of generated power density and efficiency on the emitter etching depth (ingot №267).

As is seen from Fig. 10, GaSb cells fabricated from another ingot (№267) have the maximum efficiency (AM1.5D, 1000 W/m^2) of 9-10% (with a rise of efficiency at 69 relative % compared with efficiency of cells without etching). Optimum etching depth for obtaining electric power in the range of 0.5-3 W/cm^2 is found to be 320 nm as well. Similar "etching" effect has been observed at epi-ready wafers received from Wafer Technology Ltd. Thus, these results evidence that the "etching" effect of the PV cells efficiency encrease is not connected with a substrate preparation technology.

3 GaSb TPV CELLS

Fig. 11 and 12 show the dependencies of the fill factor, open circuit voltage and generated photocurrent

density of GaSb cells (ingot №96) as TPV photoconvertors without etching (Fig. 11) and with optimum etching of 320 nm (Fig. 12) of p+-layer.

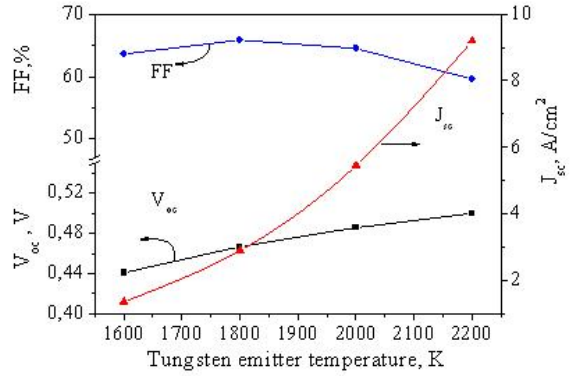

Figure 11: Fill factor, open circuit voltage and photocurrent density of GaSb TPV cells without etching of p^+-layer in dependence on the tungsten emitter temperature.

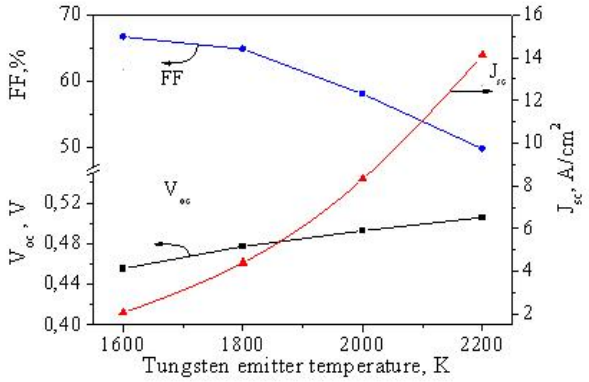

Figure 12: Fill factor, open circuit voltage and photocurrent density of GaSb TPV cells with optimum etching of p^+-layer in dependence on the emitter temperature.

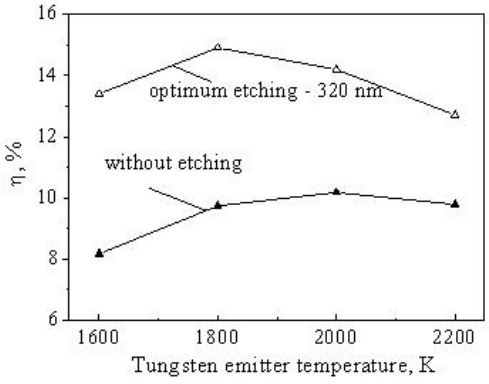

Figure 13: Dependence of GaSb TPV cell efficiency on the tungsten emitter temperature with optimum etching (top curve) and without (bottom curve) etching of the GaSb p^+-layer.

Fig. 13 presents the dependencies of efficiency of photocells at different tungsten emitter temperatures without etching and with optimum etching of the diffused layer. The improvement of general characteristics of GaSb TPV cells (Fig. 11 and Fig. 12) in the case of the etched p^+-layer gives the gain of TPV cell efficiency from 9.5% up to 15% (i.e., 63 relative %) at tungsten emitter temperature of 1800K.

4 SUMMARY

The effect of influence of Zn diffusion profiles in a *p*-GaSb emitter on the characteristics of GaSb PV cells was observed. The fill factor, the spectral response and the open circuit voltage were investigated at different densities of cell illumination. The optimum depth of the *p-n* junction has been found allowing increase the efficiency (AM1.5D, 1000 W/m^2) of cells for the cell photocurrent densities up to 10 A/cm^2. Developed high-power photoconvertors are promising for using in solar TPV systems at high sun concentration ratios or in the fuel-fired TPV generators at high emitter temperature. These cells are perspective for concentrator multijunction mechanically stacked solar cells with the top, for example, GaInP/GaAs IR transparent tandem cells. The developed GaSb cells have perspectives also for using in the high concentrator PV systems based on light splitting technologies, which allows to split the solar spectrum on the several spectral bands.

5 ACKNOLEDGMENTS

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