Effect of bus-bar material and configuration on the efficiency of GaInP/GaAs/Ge solar cells

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Abstract. The effect of bus-bar material and configuration was investigated for multi-junction solar cells (SC) based on GaInP/GaAs/Ge structure. Different configurations of contact bus-bars were obtained by the electro-chemical deposition of Ag and Au materials. The resistivity of contact bus-bars of gold and silver were measured. It is established that the bus-bars configuration in a form of truncated pyramids of 3-10 µm wide and of 4-8 µm thick located with a spacing less than 100 µm allows to reduce optical and ohmic losses and to increase the efficiency of SCs.

1. Introduction

The efficiency increase in conversion of the sunlight into electric power is the main task for developing solar power engineering, which motivates the interest to multijunction SCs. The key ways to raise the multi-junction SC efficiency is the increase in the number of photoactive *p-n* junctions, the reduction of the contact ohmic resistance, the increase in bus-bars conductivity, the decrease in the coefficient of sunlight reflection from a photosensitive SC surface, the reduction of leakage currents on the chip rear surface. In the present work, investigations and developments in the field of reducing ohmic and optical losses in converting the sunlight for multijunction GaInP/GaAs/Ge SCs have been carried out. Studies of the effect of contact materials and different configurations of contact bus-bars on SC parameters were conducted.

The increase in the efficiency of multijunction SCs based on the GaInP/GaAs/Ge nanoheterostructure is achieved by using sunlight concentrators [1]. Application of sunlight concentrators allows reducing sizes of SCs down to 2 mm², which results in a substantial saving of the materials being consumed. However, essential difficulties in carrying out post-growth technological operations for creating SC chips arise. The contact bus-bar width is 3-6 µm with a spacing of 50-100 µm. Minimization of the bus-bar width and the increase in the spacing between bus-bars allow reducing losses caused by shadowing of the photosensitive SC surface. It should be noted that multijunction SCs are intended for operation at ratios of the sunlight concentration greater than 500. The photocurrent density in this case exceeds 10 A/cm², which leads to raising ohmic losses and decreasing SC efficiency.

A known procedure for reducing ohmic losses at high operating currents is decreasing the spacing between contact bus-bars. However, this technical solution results in raising optical losses due to increasing shadowing of a photosensitive SC surface by contact bus-bars, which, in turn, leads to the SC efficiency decrease.

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A known way for lowering down the mentioned above optical losses is decreasing the contact bus-bar width. But this technical solution results in the rise of the contact resistance, which, in turn, also decreases the SC efficiency.

In consequence of these reasons, the SC efficiency in the known designs drops at sunlight concentration ratios greater than 500. The main purpose of our research is the study of contact bus-bar resistance, the comparison of contact configurations and materials and their influence on the efficiency of SCs.

2. Experimental

The research was carried out on the GaInP/GaAs/Ge structure. The schema of SC based on this structure is presented in figure 1. It consists of Ge, GaAs and GaInP subcells, frontal and back contacts and an antireflection layer.

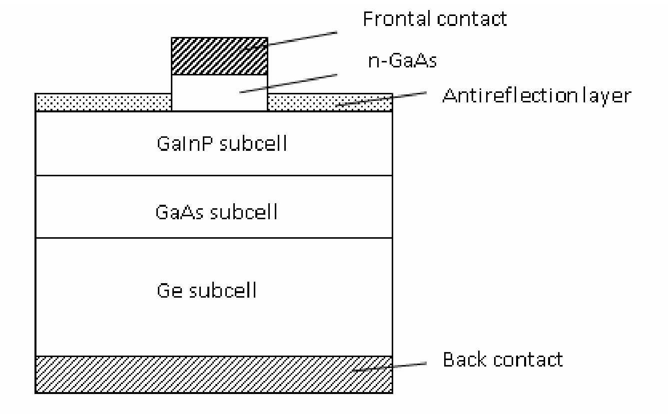


Figure 1. Schema of multi-junction solar cell based on GaInP/GaAs/Ge structure.

In fabricating the concentrator SCs with a frontal n-GaAs layer and a side part of p-Ge substrate, the use of multilayer contact systems is feasible [2]. In making a frontal ohmic contact, the successive deposition of layers is performed: the Au:Ge one based on an electric alloy (with the weight ratio of 88:12), the layers of Ni and Au. The layer thicknesses of the face contact to n-GaAs are: 30 - 150 nm for Au-Ge; 0-100 nm for Ni; 100-200 nm for Au.

Application of the AuGe-Ni-Au contact system allows obtaining a low contact resistance of the order of $1 \cdot 10^{-6} - 5 \cdot 10^{-6}$ Ohm·cm^2 to the n-GaAs layer [3]. The Au:Ge eutectic alloy possesses good adhesion to the structure surface. The Ni layer performs the function of a barrier layer between the AuGe and Au ones, which is required for the following brazing the ohmic contact – Ni hinders Au diffusion into the structure. The top Au layer is deposited for the following operation of electrochemical deposition of a metallic contact and thickening up to 2 - 8 µm.

To create contact bus-bars of 2 - 8 µm thick, the electrochemical deposition of a material with low resistivity is conducted. The most widespread materials for performing electrochemical thickening of contacts are Au and Ag. The Au resistivity is 0.023 Ohm·mm^2/m. That of Ag is 0.015 - 0.016 Ohm·mm^2/m.

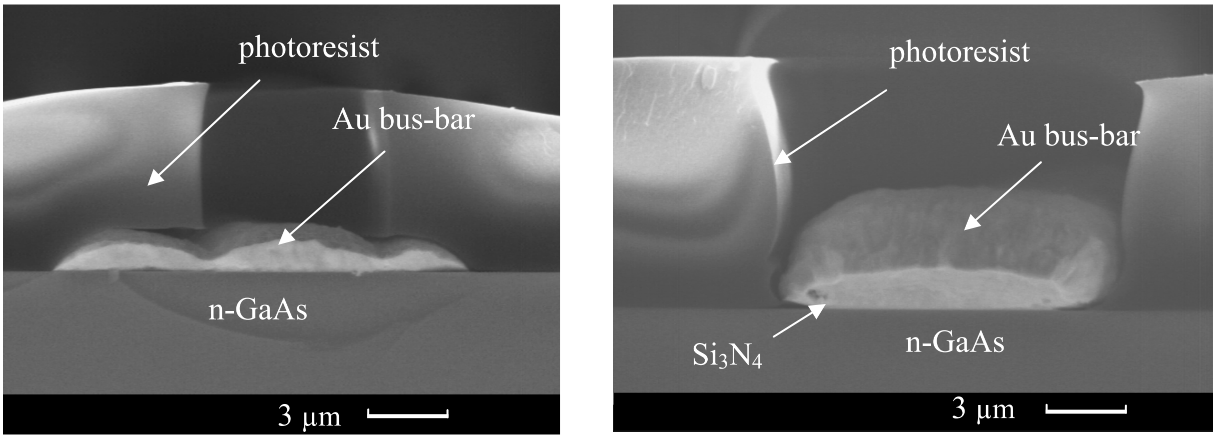
The cyanide electrolyte is widely used for Au electrochemical deposition [4]. Main merits of the given electrolyte are an elaborate technology for preparing electrolyte and for the deposition process and also long lifetime. These aspects define expediency of its application in indoor research and in production.

The gold electrochemical deposition is performed through a photoresist mask. It has been elucidated during experiment that, in carrying out deposition on the semiconductor plate surface, growth of a metal under the photoresist layer takes place due to the destruction of photoresist by cyanide ions on the interface of the photoresist and semiconductive surface (figure 2(a)).

Study of the gold electrochemical deposition through a photoresist mask in the pulse current mode has been carried out. The advantage of the pulsed technique of deposition compared to deposition at direct current is the increase in density of the material being deposited and improvement of its adhesion.

During developing electrochemical deposition of gold in the pulsed current mode, a result depicted in figure 2(a) has been obtained. In depositing gold on the semiconductor structure surface, we could not avoid its growth under the photoresist. The pulsed electrochemical deposition of a gold layer was performed at the current density of 0.02-0.2 mA/mm^2, the duty cycle of 0.25 and the frequency of 30 - 40 Hz.

An optimum way to decrease the rise of the Au layer is the additional passivation of the semiconductor structure from the frontal surface by the evaporation of the dielectric layer, for example Si_3N_4 after which the surface conduction decreases. Figure 2(b) presents SEM pictures of a deposited Au layer through the mask consisted of a Si_3N_4 layer and a photoresist layer.



(a) (b)

Figure 2. Scanning electron microscope (SEM) pictures of an electrochemically deposited Au bus-bar on the semiconductor structure surface through the mask of photoresist (a) and through the mask of Si_3N_4 and photoresist (b).

In fabricating a concentrator multijunction SCs, an important task is to reduce the semiconductor structure series resistance. With increasing solar radiation density, the losses on the device internal resistance rise, the essential part of which is the contact resistance. Reduction of the contact resistance is necessary for raising the current collecting from the devices and decreasing the heating associated with flow of a large density current.

A version of using silver for electrochemical thickening of the contact has been considered. The use of silver is determined by a high plasticity of the given material, which allows depositing thicker layers without contact growth up. At electrochemical growth of silver through a photoresist mask with a preset rear wall profile, silver repeats exactly the photoresist mask profile according to its high plasticity. Thus, the rear walls of contact bus-bars have smooth specular surface.

The electrochemical deposition of silver is performed at 18 - 25 ^{0}C from electrolyte with a mass content of silver of 20 - 30 g/l and pH of 7.5 - 8.5 [5]. Figure 3 presents SEM pictures of the silver layer after electrochemical deposition, which repeats exactly the profile of the photoresist mask side wall. In creating photoresist masks with different side profiles, one can obtain contact bus-bars of different configurations [6]. To protect the silver contacts from the effect of the environment, a gold layer of 0.1 - 0.2 μm thick is deposited electrochemically.

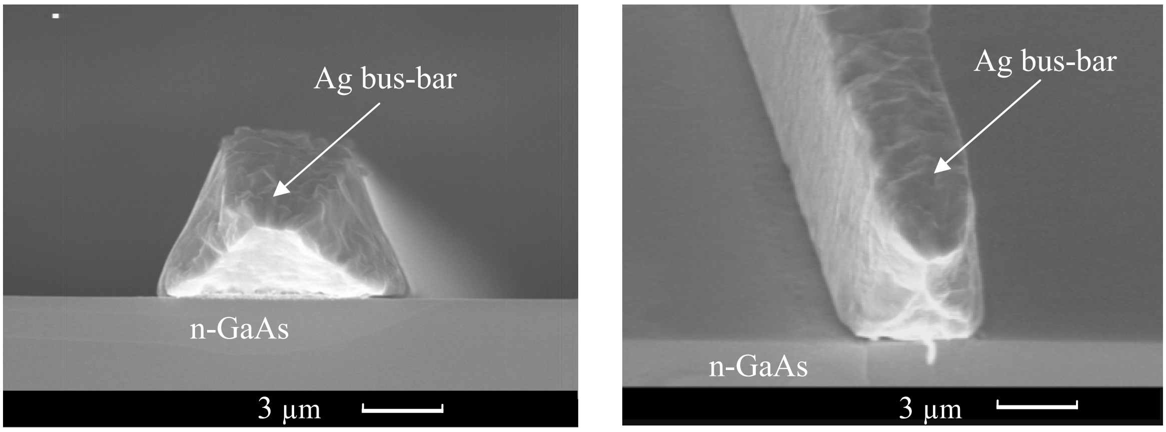


Figure 3. SEM pictures of a Ag bus-bar deposited electrochemically in a form of a truncated pyramid with the wide low base when using different photoresist mask configurations.

Results and discussion

The investigation of the contact material effect on SC parameters has been carried out. The aim of the experiment was to create contact bus-bars on a nonconducting silicon substrate by electrochemical deposition of gold and silver and to measure the resistance for bus-bars of different configurations by the 4-probe method. For the calculations, the measured values of bus-bar length, width and cross section area were used. The contact bus-bar resistance was measured on a laboratory multimeter.

The resistivity was calculated by the following expression:

$$\rho = \frac{RS}{L} \quad (1)$$

where ρ is resistivity, R is the measured resistance, S is the bus-bar cross section area, L is the bus-bar length.

The theoretical values of Ag and Au resistivity are the following: ρ(Ag)=0.015÷0.016 Ohm·mm^2/m; ρ(Au)=0.023 Ohm·mm^2/m. Deposition of silver and gold was conducted in the DC and AC modes. Data of measurements and calculations are presented in Table 1.

Table 1. Contact parameters

Sample No	Bus-bar material	Deposition mode	Bus-bar No	L, mm	S, mm²	R, Ohm	ρ, Ohm·mm²/m
1	Ag	DC	1	19.7	4.0×10^{-5}	12.1	0.025
			2	19.2		12.2	0.026
			3	19.2		12.1	0.025
2	Au	DC	1	15.1	4.0×10^{-5}	8.5	0.028
			2	15.1		8.9	0.024
			3	15.1		9.1	0.024
3	Au	AC	1	20.8	3.6×10^{-5}	13.2	0.023
			2	19.2		13.2	0.025
			3	18.7		11.5	0.024

It has been determined according to the carried out experiment that the resistivity of contact bus-bars of gold and silver are close by values. The golden bus-bar resistivity corresponds to the theoretical one. That of silver bus-bar is greater than the theoretical one, which is due to the structure of obtained bus-bars. In our experiment the cross section areas of compared bus-bars are close by values. However, the advantages of using silver for contact bus-bars fabrication are as follows: the cross section areas of bus-bars can be increased due to the termination of contact growth up on the conducting surface. Moreover, a form of a truncated pyramid of silver bus-bar allows increasing the contact thickness. Contact bus-bars of 3-6 µm wide can be fabricated of 5 - 8 µm thick, the similar contact bus-bars of gold can be only 2 - 3 µm thick. So, the cross section area of silver bus-bars will be 2 - 3 times greater than that of gold bas-burs. Thus, if we use silver as a contact material, the electric resistance, according to the expression (1), can be decreased by 2 - 3 times with increasing contact thickness.

The comparison of the efficiencies of GaInP/GaAs/Ge SCs fabricated with the use of silver and gold as a contact material is presented in figure 4. It is necessary to mention that the experiments were carried out on the same structure. The maximum efficiency of SCs with silver bus-bars is 35.3% at sunlight concentration (Kc) of 1000 suns, and not less than 35.0% in the range of 500 – 1500 suns. The maximum efficiency of SCs with gold bus-bars is 33.7% at sunlight concentration of 1000 suns.

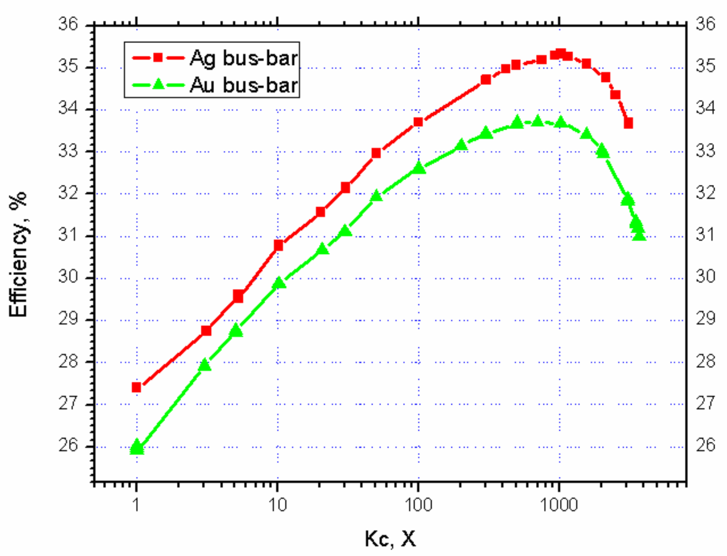


Figure 4. Efficiency of GaInP/GaAs/Ge SCs with contact bus-bars made of silver and gold.

4. Conclusion

The main advantage of gold material for contact creation is its high chemical tolerance to the environment. The advantage of using silver for creating contact bus-bars is a feasibility to make them of different configurations, which allows reducing losses at shadowing the SC photosensitive region.

Creation of silver contact bus-bars in a form of truncated pyramids of 3 - 10 µm wide and of 4 - 8 µm thick located with a spacing less than 100 µm allows reducing losses at shadowing the SC photosensitive surface, increasing absorption of the sunlight due to sunlight reflection from the side walls of contact bus-bars and decreasing ohmic losses due to increasing thickness of the current collecting bus-bar. As a result of carried out experiment, the efficiency of SCs was increased by 1.5% at the sunlight concentration of 1000 suns and the range of sunlight concentration was increased up to 1500 suns without a considerable reduction of SC efficiency.

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