Heterointerfaces in the bottom tunnel part of GaInP/GaAs/Ge solar cells

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Abstract. The tunnel (intergenerator) part between the middle (GaAs) and bottom (Ge) subcell of a GaInP/GaAs/Ge triple-junction solar cell was investigated. It is shown that the previously observed features of the multi-junction solar cells IV-curves, namely the inflection of the characteristics, arises from heterointerfaces in the region between the GaAs p-n junction and the bottom tunnel p⁺⁺-n⁺⁺ junction. A theoretical study was carried out, and various ways of optimizing such heterointerfaces are proposed.

1. Introduction
At present time, triple-junction solar cells (TJ SCs) are actively analyzed, developed and improved. It is worth emphasizing that this activity is greatly hampered by the many-link topological structure of such SCs. This structure is based on three basic parts: GaInP, GaAs and Ge photovoltaic homo p-n junctions. In addition to the basic parts, the TJ SC structure also has a set of so-called connecting elements [1]. This set includes: resistive contacts, substrate, intergenerator layers and others. This work continues previous ones [2, 3] aimed in studying similar parts of the solar cells structure. First, it is a part located between GaInP and GaAs p-n junctions (photovoltaic generators); it includes: a tunnel GaAs homo p⁺⁺-n⁺⁺ junction, framed by two separation barriers - front and back ones. Such a part was called a top tunnel part [2, 3], otherwise the top intergenerator part. Secondly, it is a similar section located between the GaAs and Ge p-n junctions. It includes the tunnel hetero p⁺⁺(Al₀.₄Ga₀.₆As)-n⁺⁺(GaAs) junction, framed by several barriers including the front and back ones. Such part is called bottom intergenerator part or bottom tunnel part.
As previously established [2, 3], the properties of the intergenerator parts affect the characteristics and parameters of a multi-junction (MJ) SC, both positively [4, 5] and negatively [1-3,6]. In particular, it was established that the top tunnel part under certain conditions can counteract the basic photovoltaic GaInP, GaAs, and Ge p-n junctions. This is due to the presence of an opposite-connected tunnel junction.
In the paper, the IV-curves of the bottom tunnel part of the GaInP/GaAs/Ge SC has been obtained and analyzed. It was determined experimentally that this part does not generate counteracting photo-emf. Also it contains heterobariers responsible for inflection appearance on the SC IV-curve. Such effect was previously observed in a GaInP/GaAs/Ge SC [1,7], but location of heterobarier was not determined.
2. Object of study and energy diagram of the bottom tunnel (intergenerator) part
To study the bottom tunnel part, a double-junction GaAs/Ge SC has been used. The sample has been grown by metal-organic vapor phase epitaxy. The intergenerator part had a similar structure as in triple-junction SC used in [1] and included layers listed in Fig. 1.

![Energy diagram of GaInP/GaAs/Ge SC](image)

**Figure 1.** Bottom tunnel (intergenerator) part band diagram of a GaInP/GaAs/Ge SC.

Fig. 1 shows the bottom intergenerator part energy diagram. The emphasized attention in Figure 1 is paid to isotype heterointerfaces creating energy barriers. According to our interpretation, they are responsible for the inflection appearance on the light IV-characteristic (Fig. 2b). A similar inflection was already observed earlier for the GaInP/GaAs/Ge SC [1]. In that work, an IV-curve of the heterointerfaces responsible for the inflection was obtained, but the heterointerface location was not established.

3. Light IV-curves of the bottom tunnel (intergenerator) part
Figure 2a shows the experimental \( V_{oc-j_{sc}} \) dependence for the sample under study. As is known, such a dependence after a voltage shift by a certain value \( V_{a,oc} \) [8, 9] coincides with the resistiveless dark IV-curve. In its turn, a resistiveless light IV-curve is produced from the dark one by current shift to the photogenerated current value \( J_g \) and by using \( V_a \) correction [8, 9]. As shown in [8], this correction depends on the imbalance of the photogenerated currents (at full balance it becomes zero) and usually does not exceed 0.05 \( V \). The obtained tunnel part IV-curves was determined in the voltage range from 0.1 to 0.5 \( V \). The magnitude of these voltages is significantly exceeds \( V_{ao} \), therefore, to simplify the calculations, it was not taken into account. As can be seen (Fig. 2a), the \( V_{oc-j_{sc}} \) dependence, and, consequently the dark IV-curve, is well described by a two-exponential model:

\[
J_{sc} = J_0 \left( \frac{V_{oc}}{2kT} - 1 \right) + J_0 \left( \frac{V_{oc}}{3kT} - 1 \right)
\]

(1)

where \( k \) – Boltzmann constant, \( T \) – absolute temperature. Approximation by formula (1) of the \( V_{oc-j_{sc}} \) dependence allows to determining the parameters \( J_0 = 5.5 \times 10^{-13} A/cm^2 \) \( J_{ao} = 5.5 \times 10^{-9} A/cm^2 \). These parameters have been used to obtain a resistiveless light IV-curves (dashed lines in Fig 2b).
As can be seen (Fig. 2b), the obtained IV-curves do not coincide with the experimental ones. The voltaic subtraction of the restiveless IV-curves from the experimental ones results in a set of IV-characteristics of the intergenerator (tunnel) part for different $J_g$ (Fig. 2b on the left). One can see that the tunnel part IV-curve does not depend on $J_g$, what implies that the bottom tunnel part is not photoactive in contrast to the top one [2]. From the shape of the obtained IV-curves (Fig. 3b on the left), it is seen that they contain the inflection of the curve observed earlier for the GaInP/GaAs/Ge SC [1]. Such an inflection is associated with the presence of a heterointerface in the inter-generator part. The heterointerfaces IV-curve has been extracted from the tunnel part IV-curve and compared with the previously observed characteristic.

4. IV-curve of heterointerfaces in the bottom tunnel (intergenerator) part

From the shape of the tunnel part IV-curves (Fig. 2a on the left), it is clear that they contain a voltaic sum of two characteristics: one - IV-curve of tunnel p$^+$$^+$-n$^-$ junction, the another one - heterointerface IV-curve. For heterointerface IV-curve extraction, it has been suggested that in the region below the tunnel diode peak current, the IV-curve is determined by the voltaic sum of the linear part of the tunnel diode, series resistance, and the heterointerface. It is seen that, in the current range from 0 to the peak current the IV-curve is linear. Consequently, the sum of the tunnel diode and the resistive component gives a linear IV-curve. Such a linear characteristic, as is well known, is described by the $I\cdot R$ function, where $R$ is the lumped linear equivalent of the series resistance. Thus, in order to obtain the heterointerface IV-curve, it is sufficient to determine the value of the lumped resistive equivalent R and subtract from the tunnel part IV-curve the linear function $I\cdot R$. As a result, the obtained IV-curve in the current region below the tunnel junction peak current will be determined only by the heterointerface.
Figure 3. Heterointerfaces IV-curves extracted from full IV-curves of double-junction GaAs/Ge (blue) and triple-junction GaInP/GaAs/Ge (green) solar cells. Symbols - extracted from experimental IV-curves, dashed lines – approximation by eq.(2). Approximation parameters are given in Table 1.

The above described procedure has been carried out. The lumped resistive equivalent $R$ has been determined by the method described in [8, 9], $R=0.4$ Ohm·cm$^2$. The extraction result is shown in Fig. 3. The figure also contains the IV-curve of the heterointerface extracted from the full IV-curve of a triple-junction GaInP/GaAs/Ge SC[1]. Note that both IV-curves are well approximated by formula (2) proposed in [1] to describe the heterointerfaces characteristics.

$$J = J_0 \left( \exp \left( - \frac{V}{E_1} \right) - \exp \left( \frac{-V}{E_2} \right) \right)$$

(2)

The result of the approximation is shown in Fig. 3 (dashed lines). The obtained parameters are given in Table 1.

| Solar cell          | $E_1, V$ | $E_2, V$ | $J_0, A/cm^2$ |
|---------------------|----------|----------|---------------|
| GaInP/GaAs/Ge       | 0.1      | 0.44     | 2.75          |
| GaAs/Ge             | 0.035    | 0.19     | 0.19          |

Investigation of the triple-junction structures has shown that samples, which do not contain a p-GaAs/p-GaInP, and p-AlGaInP/p$^{++}$-AlGaAs heterointerfaces (Fig 1 circled in red) in the bottom tunnel part do not have an inflection on its IV-curves. Thus, such heterointerfaces are responsible for forming an inflection on the full IV-curves of MJ SCs. From the energy diagram (Fig. 1), it can be seen that these heterointerfaces can be optimized either by reducing the thickness or by increasing the doping level of a p-GaInP and p-AlGaInP layers or by replacing them with other materials. Under
these conditions, the IV-curves of MJ SCs do not contain an inflection. For example, in [9, 10], instead of the p-GaInP and p-AlGaInP layers, the AlGaAs barrier was used, and the presented IV curves did not contain a region with an inflection.

Conclusions
The connecting parts of multi-junction solar cells sometimes significantly affect the performance of such devices. Therefore, the definition of the main properties of these parts is important for the purpose of further increasing the number of sub-cells. The bottom intergenerator tunnel part (between GaAs and Ge photovoltaic p-n junctions) has been experimentally analyzed. For this, the method of extracting the IV-curve of the tunnel part previously developed for top tunnel part (between GaInP and GaAs p-n junctions) IV-curve extraction, has been used. It has been found that, in contrast to the top, the bottom tunnel part has no counteracting photovoltaic effect.

A correlation was also established between the presence of an inflection on the IV-curve and the presence of heterobarriers on the bottom part energy band diagram. A comparison of IV-curves having a similar inflection in double-junction (GaAs/Ge) and triple-junction (GaInP/GaAs/Ge) solar cells has been performed. The shape of the heterointerfaces IV-curve significantly affects the shape of the full IV-characteristic and is approximated by a two-exponential function. Optimizing such heterointerfaces (increasing the doping level, reducing the thickness of the layers or replacing them with other materials) make it possible to eliminate the nonlinearity of the IV-curves. The obtained properties of the tunnel inergenerator part should be taken into account in the development of multi-junction solar cells.

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