Characteristics of double-cascade photodiodes based on p-i-n AlGaAs/GaAs diodes connected by n++-GaAs/i-GaAs/i-AlGaAs/p++-AlGaAs tunnel diodes

E V Kontrosh, V S Kalinovskii, G V Klimko, N V Vaulin and B Ya Ber
Ioffe Physical Technical Institute, Russian Academy of Sciences, St. Petersburg, 194021, Russia
E-mail: kontrosh@mail.ioffe.ru

Abstract. Characteristics of double-cascade nonmonolithic p-i-n AlGaAs/GaAs photovoltaic converters of high-power laser radiation, electrically combined with n++-GaAs/i-GaAs/i-AlGaAs/p++-AlGaAs tunnel diodes, have been studied. The AlGaAs/GaAs p-i-n structures of the photovoltaic converters and n++-GaAs/i-GaAs/i-AlGaAs/p++-AlGaAs tunnel diodes were grown by molecular-beam epitaxy. The photoelectric characteristics of the double-cascade AlGaAs/GaAs photovoltaic converters were examined in the temperature range from 103 to 298 K under excitation with a laser light wavelength of 809 nm and a power density ≤92 W/cm². The double-cascade p-i-n AlGaAs/GaAs nonmonolithic photovoltaic converters of planar design had a fill factor of 0.88 and efficiency of 58.2% at a temperature of 103 K. It was shown experimentally that the current-voltage characteristics of the connecting n++-GaAs/i-GaAs/i-AlGaAs/p++-AlGaAs tunnel diodes affect the photoelectric parameters of the double-cascade photovoltaic converters of high-power laser light.

1. Introduction
In contrast to concentrator multijunction solar cells with photoactive p-n junctions formed by semiconductors with different energy gaps [1, 2], the cascaded photovoltaic converters (PVCs) for high-power laser light consist of series-connected photoactive p-n junctions formed by a semiconductor with the same energy gap, but different layer thicknesses and doping profiles, which ensures equality of generated photocurrent densities. In cascaded PVCs for laser light, the joining tunnel diodes (TDs) connected opposite to the photoactive p-n junctions should provide high peak current values and minimal optical loss.

In the present study, we examined the dark and light I–V characteristics of single-cascade p-i-n GaAs/AlGaAs PVCs, n++-GaAs/i-GaAs/i-AlGaAs/p++-AlGaAs tunnel diodes, and double-cascade PVCs based on them in the temperature range from 103 to 298 K. The influence of the I–V characteristics of the connecting n++-GaAs/i-GaAs/i-AlGaAs/p++-AlGaAs tunnel diodes on the photoelectric parameters of double-cascade PVCs is experimentally shown.
2. Experiment

Double-cascade PVCs were formed with the use of a planar electrical switching of two single-junction AlGaAs/GaAs p-i-n PVCs with n++-GaAs/i-GaAs/i-AlGaAs/p++-AlGaAs TDs in between. The structures of the constituent elements of a double-cascade PVC were grown by molecular-beam epitaxy (MBE) on a STE3525 SemiTEq installation with elementary solid-state evaporating sources of Ga and Al and a valve source with As$_4$, Si (n) and Be (p) served as doping impurities.

Two types of n++-GaAs/i-GaAs/i-AlGaAs/p++-AlGaAs structures A and B of the connecting TDs were grown (figure 1a)[3]. Structure A was grown at a temperature of 500°C, and structure B, at 450°C. The undoped i-regions were formed both between the degenerate layers and in the p++ degenerate region, taking into account the diffusion of the Be impurity during the temperature treatment of the structure in the course of epitaxy. The post-growth technology without passivation of the lateral surface was used to form arrays of mesas with a diameter of 300 µm and AuGe-Ni-Au and AgMn-Ni-Au ohmic contacts to respectively n and p GaAs surfaces. The contacts were alloyed in the atmosphere of hydrogen at a temperature of 500°C. According to the calculated band diagram of the structure shown in figure 1b, p++-AlGaAs/i-AlGaAs/i-GaAs/p+-GaAs layers form a heterobarrier and a quantum well in the p-type conductivity region.

![Figure 1](image)

**Figure 1.** (a) Structure (A and B) design of n++-GaAs/i-GaAs/i-AlGaAs/p++-AlGaAs TDs; (b) band diagram of a TD (structure A) calculated at a forward bias voltage of 0.05V

The structure of single-junction photovoltaic converters with technological parameters is given in [4]. The structure included the following: n-Al$_{0.2}$Ga$_{0.8}$As as a backside potential barrier, an n-GaAs/i-GaAs/p-GaAs active region, a wide bandgap p-Al$_{0.12}$Ga$_{0.88}$As window, and a p+-GaAs contact layer. Using a post-growth technology, PVC chips with a frontal photosensitive surface with a netlike frontal contact grid 300 µm in diameter were formed on epitaxial wafers. The spectral sensitivity range of the single-cascade PVC at room temperature was 780–860 nm.

Planar double-cascade PVCs were created from AlGaAs/GaAs p-i-n PVCs and connecting n++-GaAs/i-GaAs/i-AlGaAs/p++-AlGaAs TDs (structures A and B), which were grown and preselected according to the method described in [4]. One type of double-cascade PVCs contained a counter-connected TD of structure A, and the other, a connecting TD of structure B. In this case, each type of TD connected two identical AlGaAs/GaAs p-i-n PVCs.
3. Results and discussion

On the epitaxial plate of structure A, a TD was selected with a nonlinear section of the I–V characteristic in the voltage range from 0 V to the peak voltage ($U_{\text{peak}}$) (figure 2 a, b; curve 1), while the I–V characteristic of the TD structure B (figure 2 a, b; curve 2) had a linear working section with a resistivity of $0.8 \text{ m\Omega cm}^2$. The nonlinearity of the tunneling component of the I–V characteristic of TD structure A can be associated with the presence of the i-GaAs/i-AlGaAs heterointerface between the degenerate TD layers, as well as with a potential barrier in the p-type conductivity region [5].

The experimental light I–V characteristics of single-cascade PVCs (figure 2a, b; curve 3) and double-cascade PVCs (figure 2a, b; curves 4, 5) are presented in figure 2. The parameters of single-cascade AlGaAs/GaAs p-i-n PVCs were used to calculate the light I–V characteristic of double-cascade PVCs (A), neglecting the influence of the TDs (figure 2a, b; curve 6). Measurements were performed in the temperature range from 103 to 298 K in the excitation mode by laser radiation with a wavelength of $\lambda = 809$ nm. The light I–V characteristics were measured for the cascaded PVCs (A and B) to evaluate the working efficiency of the TDs at tunneling current densities close to the peak values for TDs in structures A and B, which corresponded to an incident optical power density of $\sim 40 \text{ W/cm}^2$ for PVC A (figure 2a, b; curves 3, 4, 6) and $\sim 92 \text{ W/cm}^2$ for PVC B (figure 2a, b; curve 5). The non-uniformity of the incident light power over the area of double-cascade PVCs was $\sim 5\%$.

![Figure 2](image-url)

**Figure 2.** I–V characteristics at $T = 298$ K (a) and at $T = 103$ K (b): tunnel diodes of structures (A) (curve 1 - a, b) and (B) (curve 2 - a, b); single-cascade PVC (curve 3 - a, b); double-cascade PVC (A) (curve 4 - a, b); PVC (B) (curve 5 - a, b); I–V characteristic of PVC, neglecting the influence of the TD - (curve 6 - a, b).

The experimental and calculated light I–V characteristics of double-cascade PVCs of each type were used to determine the open-circuit voltage ($U_{\text{oc}}$), short-circuit current ($I_{\text{sc}}$) and calculate the power at the optimal-load point ($P_{\text{opt}}$), the FF and efficiency as a function of temperature. The temperature dependences of the photoelectric parameters, found from the experimental and calculated I–V characteristics and those calculated for the PVCs under study, are presented in Table 1. According to the results obtained (Table 1), the short-circuit current grows with increasing temperature for all types of PVCs (A and B), which is due to the spectral characteristic of AlGaAs/GaAs p-i-n PVCs. The maximum quantum efficiency of a single PVCs at $T = 298$ K is $78\%$ at a laser wavelength of 809 nm. As the temperature is lowered, the...
Table 1. Photovoltaic parameters of PVCs

| No. | Type of PVC                  | $P_{\text{optic}}$, W/cm$^2$ | $T$, K | $U_{\text{oc}}$, V | $I_{\text{sc}}$, mA | FF, % | Eff, % |
|-----|------------------------------|-----------------------------|--------|-------------------|---------------------|-------|-------|
| 1   | Double-cascade PVC(A)        | 40                          | 103    | 2.5               | 13.6                | 71.2  | 42.4  |
|     |                              |                             | 213    | 2.4               | 13.6                | 68.0  | 39.0  |
|     |                              |                             | 253    | 2.3               | 14.1                | 67.0  | 38.0  |
|     |                              |                             | 298    | 2.2               | 14.4                | 63.0  | 35.2  |
| 2   | Calc. double-cascade PVC (A) | 40                          | 103    | 2.8               | 13.7                | 85.0  | 56.1  |
|     | without I-V of TD            |                             | 213    | 2.6               | 13.6                | 83.3  | 51.0  |
|     |                              |                             | 253    | 2.4               | 14.4                | 83.0  | 50.0  |
|     |                              |                             | 298    | 2.4               | 14.5                | 76.0  | 46.3  |
| 3   | Double-cascade PVC(B)        | 92                          | 103    | 2.8               | 31.1                | 88.0  | 58.2  |
|     |                              |                             | 213    | 2.6               | 31.1                | 85.3  | 53.4  |
|     |                              |                             | 253    | 2.5               | 32.9                | 83.0  | 53.0  |
|     |                              |                             | 298    | 2.4               | 33.1                | 81.4  | 50.0  |

absorption edge will shift to the shorter wavelength region, with the result that the quantum efficiency will decrease.

The variation of the photoelectric parameters $U_{\text{oc}}$, FF, and efficiency of the cascaded PVCs with temperature are attributed to the change in the domination of current-transport mechanisms in the space-charge region of p-n junctions and "saturation" currents corresponding to these mechanisms upon a change in the temperature of the cascaded PVCs [1, 2, 4].

According to a comparative analysis of the experimental and calculated photoelectric parameters of the PVC (A), the nonlinearity of the I–V characteristic of TD structure A in the tunneling section leads to a decrease in $U_{\text{oc}}$ by 10% and in FF by 18% in the temperature range under study, which in turn leads to a decrease in the efficiency by 24%.

At $T = 298$ K, the FF and efficiency were respectively 63.0% and 35.2% for PVC A, and 81.4% and 50.0% for PVC B, and at $T = 103$ K, the FF and efficiency were respectively 71.2% and 42.4% for PVC A, and 87.5% and 58.2% for PVC B.

4. Conclusion

It was experimentally shown that the light I–V characteristic of a double-cascade PVC is affected by the nonlinearity in the forward I–V characteristic of the n$^{++}$-GaAs/i-GaAs/i-AlGaAs/p$^{++}$-AlGaAs tunnel diode.

Analysis of the load I - V characteristics of double-cascade PVCs and TDs showed that the use of n$^{++}$-GaAs/i-GaAs/i-AlGaAs/p$^{++}$-AlGaAs connecting TDs obtained at a lower growth temperature in the structure of double-cascade PVCs provides a lower-resistance connection.

FF values of 0.88 and efficiency of up to 66% were achieved for a double-cascade AlGaAs/GaAs PVC when converting laser radiation with a power density of $\leq 92$ W/cm$^2$ at a wavelength of 809 nm and a temperature of 103 K.

References

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