Current–voltage characteristics of connecting tunnel diodes at temperature heating up to 80°C

E V Kontrosh, G V Klimko, V S Kalinovskii, V S Yuferev, 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. Investigations of the temperature stability of the peak tunneling current density of connecting tunneling diodes, which are necessary for the creation on their basis of multijunction photoconverters of powerful optical radiation, have been carried out. The structures of n++-GaAs/i-GaAs/i-AlGaAs/p++-AlGaAs of connecting TD with an intermediate undoped layer thickness of 7.5 nm and a growth temperature of 500 °C (structure "A") and with a thickness of 10 nm and a temperature of 450 °C (structure "B") were investigated. When heated to 80 °C, an increase in the peak tunneling current density of the TD structure "B" by 4% is observed. However, for structure "A", a decrease in the peak tunneling current density by 5% with heating is observed. The factors leading to the appearance of a negative or positive temperature coefficient of the peak tunneling current density are determined using mathematical modeling of tunneling diodes based on GaAs/AlGaAs materials. By reducing the epitaxial growth temperature of n++-GaAs/i-GaAs/i-AlGaAs/p++-AlGaAs tunnel diode structure to 450 °C and including an undoped i–layer 10 nm thick between the degenerate layers ensure the temperature stability of peak current density when heated to 80 °C.

1. Introduction
The operating temperature of monolithic multi–junction photoconverters (MJ PCs) upon excitation by powerful optical radiation can increase up to 80 °C [1, 2]. With an increase in the operating temperature of MJ PCs, the integrated tunnel diodes (TDs) should provide high values of the peak tunneling current density exceeding the photocurrent density [3]. Therefore, when developing MJ PCs of high-power optical radiation, researchers should take into account temperature coefficient of the peak tunneling current density (ΔJp) of connecting TDs. This temperature coefficient can be either positive or negative, depending on the doping level of the degenerate layers [2, 4, 5]. The presence of a negative temperature coefficient of connecting TDs reduces the maximum convertible power of optical radiation. In this work, we have investigated the current–voltage (J–V) characteristics of AlGaAs/GaAs connecting tunnel diodes designed to create MJ PCs on their basis in the temperature range from 25 °C to 80 °C.

2. Mathematical modeling of the temperature coefficient of the peak tunneling current density n+-+-GaAs/n+-+-GaAs/p+-+-AlGaAs tunnel diode structures
The calculation of the temperature coefficient of the change in the peak tunneling current density of the TD structure, presented in Table 1, has been carried out. The calculation was performed
using the Silvaco Atlas software package [6]. Two types of models were used in the calculations: that of nonlocal interband quantum tunneling (NIQT) and that of trap assisted tunneling (TAT). The mathematical expressions used in the models were reported in [6]. The probability of quantum tunneling in the NIQT and TAT models was calculated in the Wentzel–Kramers–Brillouin (WKB) approximation [7-9]. According to the NIQT model, the contribution to the tunneling current for electrons in the energy range \( E - \Delta E / 2 \) to \( E + \Delta E / 2 \) was described as follows:

\[
J(E)\Delta E = \frac{qkT\sqrt{m_em_h}}{2\pi^2h^3}\tau(E)D\Delta E
\]

where \( E \) is the carrier energy, \( \tau(E) \) is the probability of quantum tunneling, \( T \) is the temperature, \( k \) is the Boltzmann constant, \( q \) is the elementary charge, \( h \) is the reduced Planck’s constant, \( m_e \) and \( m_h \) are the effective masses of electrons and holes, respectively. The quantity \( D \) corresponds to the equation (2):

\[
D = \ln\left[\frac{(1 + \exp((E_{Fl} - E)/kT)) \cdot (1 + \exp((E_{Fr} - E - E_{max})/kT))}{(1 + \exp((E_{Fl} - E)/kT)) \cdot (1 + \exp((E_{Fr} - E - E_{max})/kT))}\right]
\]

where \( E_{Fl} \) and \( E_{Fr} \) are the Fermi level with the left- and right-hand sides of the tunnel junction. \( E_{max} \) is smaller of \( E - E_{lower} \) and \( E_{upper} - E \) where \( E_{lower} \) and \( E_{upper} \) are the lowest and the highest energy at which an electron can tunnel. The quantity \( D \) depends on the temperature and depth of penetration of the Fermi levels into the conduction and valence bands. The calculations were carried out taking into account the shape of the conduction and valence bands of the TDs structure. The Shockley–Read–Hall (SRH) nonradiative recombination, band-gap narrowing (BGN), and Fermi–Dirac statistics models were used in the transport equations [6].

The model structure contained an n\( ^+ - \)GaAs/n\( ^{++} - \)GaAs/p\( ^{++} - \)AlGaAs active region. The thickness and doping level of the degenerate n\( ^{++} - \)GaAs region varied from 9 to 20 nm and from 1.4 \( \times \) 10\( ^{19} \) cm\(^{-3} \) to 1.9 \( \times \) 10\( ^{19} \) cm\(^{-3} \), respectively. The parameters of the p\( ^{++} - \)AlGaAs layer remained unchanged, the doping level was 4 \( \times \) 10\( ^{19} \) cm\(^{-3} \) at a thickness of 10 nm.

Less doped isotype layers adjacent to the degenerate layers of connecting tunneling diodes can significantly affect the carrier concentration in the degenerate layers, thereby determining the position of the bottom of the conduction band [10,11]. To take this effect into account, an isotype n\( ^+ - \)GaAs layer with a doping level of \( \sim 5 \cdot 10^{18} \) cm\(^{-3} \) was adjacent to the n\( ^{++} - \)GaAs degenerate layer.

In this work, during the growth of the structure, an Si impurity was used as a donor type and a Be impurity as acceptor type. However, unlike Si impurities, concentration of the Be acceptor impurity to 1 \( \cdot \) 10\( ^{18} \) cm\(^{-3} \) and more entails the anomalous diffusion of Be atoms toward the less doped isotype layers adjacent to the degenerate layers and the p-n junction boundary. Therefore, the concentration of the acceptor impurity in the degenerate p\( ^{++} - \)AlGaAs layer and adjacent layers was taken to be the same. Thus, in the calculations the influence of the adjacent layers from the side of the degenerate p\( ^{++} - \)AlGaAs layer was not taken into account.

The temperature coefficient was calculated according to the following equation (3):

\[
\Delta J_p = \left(\frac{J_{pTJ} - J_{pRT}}{J_{pRT}}\right) \cdot 100\%
\]

where \( J_{pTJ} \) is the peak tunneling current at temperatures of 25, 50, 70, 80 °C, and \( J_{pRT} \) is the peak tunneling current at room temperature 25 °C.

Figure 1 shows the calculated dependences of the temperature coefficient of the peak tunnel current density at T=80 °C on the doping level (curve 1) and the thickness (curve 2) of the n\( ^{++} - \)GaAs layer of the TD with the structure parameters presented in Table 1. According to
Table 1. Parameters of the modeled structure of n$^+$–GaAs/n$^{++}$–GaAs/p$^{++}$–AlGaAs tunnel diode

| Layers          | Doping concentration, cm$^{-3}$ | Thickness, nm |
|-----------------|---------------------------------|---------------|
| n$^+$–GaAs      | $\sim 5 \cdot 10^{18}$         | 300           |
| n$^{++}$–GaAs   | (1.4–1.9)$\cdot 10^{19}$       | (9–20)        |
| p$^{++}$–AlGaAs | 4$\cdot 10^{19}$               | 10            |

the calculated curves for the model structure of the TD, the presence of a positive temperature coefficient can be ensured by increasing the thickness of the degenerate n$^{++}$–GaAs layer $\geq 10$ nm and the doping level $\geq 1.7\cdot 10^{19}$ cm$^{-3}$.

Figure 1. The calculated dependences of the temperature coefficient of the peak tunnel current density at $T=80^\circ$C on the doping level and the thickness of the n$^{++}$–GaAs layer for the TD with the structure parameters presented in Table 1, where curve 1 – the doping level of n$^{++}$–GaAs varied in the range (1.4–1.9)$\cdot 10^{19}$ cm$^{-3}$ at a layer thickness of 10nm, curve 2 – the thickness of the n$^{++}$–GaAs layer varied in the range (9-20) nm at a doping level of 1.7$\cdot 10^{19}$ cm$^{-3}$.

The presence of a positive or negative temperature coefficient of the peak tunnel current density of the TD can be caused by two factors. First, with increasing temperature, the GaAs band gap ($E_g$) decreases, which leads to a decrease in the height of the potential barrier and an increase in the probability of quantum tunneling – $\tau(E)$ (Eq. 1). Secondly, an increase in temperature leads to a redistribution of electrons along energy levels, and the number of electrons under the Fermi level ($E_f$) in the conduction band ($E_c$) of the n-region decreases, as some of the free electrons move to higher energy levels, and the Fermi level shifts down. As a result, the value of $D$ decreases (Eq. 1, 2). At high donor concentrations ($\geq 1.7\cdot 10^{19}$ cm$^{-3}$), the effect of
temperature on the factor $D$ is small, and the effect of a decrease in $E_g$ on the probability of tunneling – $\tau(E)$ is predominant. As a result, the density of the peak tunnel current increases with increasing temperature. At low doping level ($<1.7\cdot10^{19}$ cm$^{-3}$), the decrease in $D$ with increasing temperature prevails and the temperature coefficient is negative.

3. Experiment

Table 2 shows the design of the investigated $n^+-GaAs/n^{++}-GaAs/i-(GaAs/AlGaAs)/p^{++}-AlGaAs$ TD structures - “A” and “B”, obtained in accordance with the methods described in the works [10-12] by molecular beam epitaxy (MBE). As a donor-type dopant we used Si and acceptor – Be. Structure “A” was grown at an epitaxy temperature ($T_{growth}$) of 500 °C, and structure “B” at 450 °C. Structures “A” and “B” differed in thickness of the lightly doped region of i–GaAs located between the degenerate TD layers, 7.5 nm – “A”, 10 nm – “B”. Mesas 225 µm in diameter with ohmic contacts were formed on the structures by photolithography.

**Table 2. Parameters of the grown A and B n$^+-GaAs/n^{++}-GaAs/i-(GaAs/AlGaAs)/p^{++}-AlGaAs$ structures of tunnel diodes**

| Layers       | Doping concentration, cm$^{-3}$ | Thickness, nm |
|--------------|--------------------------------|---------------|
| $n^+-GaAs$:Si | 4$\cdot$10$^{18}$              | 300           |
| $n^{++}-GaAs$:Si | 1.7$\cdot$10$^{19}$            | 10            |
| i–GaAs       | 5$\cdot$10$^{16}$              | 2.5(A); 5 (B) |
| i–AlGaAs     | 5$\cdot$10$^{16}$              | 5             |
| p$^{++}-AlGaAs$:δBe | 4$\cdot$10$^{19}$          | 10            |
| i–AlGaAs     | 5$\cdot$10$^{16}$              | 2.5           |
| i–GaAs       | 5$\cdot$10$^{16}$              | 2.5           |
| p$^+-AlGaAs$:Be | 2$\cdot$10$^{19}$            | 250           |
| p$^+-AlGaAs$:Be | 1$\cdot$10$^{19}$            | 350000        |

**Figure 2.** Atomic concentration dependences for structures A (a) and B (b), measured using SIMS method, where the curves are: 1–Ga, 2–Si, 3–Al, 4–Be

Using dynamic secondary ion mass spectrometry (SIMS), it was found that structure “A” has a significant overlap of the distribution of dopants of Si donors and Be acceptors (figure...
2a), in contrast to structure “B” (figure 2b). Diffusion of the Be impurity in structure “A” led to a decrease in the thickness of the n\textsuperscript{++}–GaAs layer and a decrease in the degree of doping with Si impurity due to overcompensation with a Be impurity. As a result, the thickness of the region of the n\textsuperscript{++}–GaAs layer in structure ”A” uncompensated by the Be impurity has become less than 10nm. According to figure 2b in structure B, the thickness of the n\textsuperscript{++}–GaAs region uncompensated by the Be impurity was approximately 20 nm.

Figure 3. (a) J–V characteristics of TD structure A and B at 25 and 80 °C and (b) the temperature coefficient of variation of the peak tunneling current density of structure A and structure B.

The J–V characteristics of several tunnel diodes diced from the grown epitaxial wafers of structures A and B plate were measured at a positive bias of up to 0.6 V in the temperature range from 25 °C to 80 °C. An example of the measured J-V characteristics at temperatures of 25 °C and 80 °C for two tunnel diodes of structure A and B is shown in figure 3a. The measured J-V characteristics were used to calculate the values of the temperature coefficient of the peak tunneling current density averaged over the epitaxial plates of structures A and B (figure 3b). As the temperature rises from 25 to 80 °C for structure “A”, a negative temperature coefficient of the peak tunneling current density is observed over the entire temperature range. The drop in the peak tunneling current density was 5%. For structure “B”, a positive temperature coefficient of the peak tunneling current density is observed, with \( J_{\text{peak}} \) increasing by 4%. This, in turn, in accordance with the calculations and measured SIMS distributions, is associated with a decrease in the degree of doping and the thickness of the n\textsuperscript{++}–GaAs layer due to the temperature diffusion of the Be impurity.

4. Conclusion

It was found that in n\textsuperscript{+}–GaAs/n\textsuperscript{++}–GaAs/i–(GaAs/AlGaAs)/p\textsuperscript{++}–AlGaAs connecting tunnel diodes with an intermediate i-layer thickness of 10 nm, grown at a temperature of 450 °C with an increase operating temperature up to 80 °C, an increase in the peak tunneling current density by 4% is observed. At the same time, for the structure of tunnel diodes with a thickness of the intermediate i-layer of 7.5 nm and an epitaxial growth temperature of 500 °C, a decrease in the peak tunneling current density by 5% is observed with an increase in the operating temperature. According to the performed mathematical modeling and SIMS studies, the drop in the peak current density with heating for tunnel diodes with a smaller i-layer thickness and
a higher growth temperature is due to the temperature diffusion of the acceptor impurity Be towards the p-n junction boundary. The diffusion of the Be impurity promoted a decrease in the doping level of the degenerate n++–GaAs layer and its thickness.

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