Peculiarities of tunneling in a system based on GaAs at high pressures

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We investigate the effect of pressure up to 3 GPa on the tunnel characteristics of diodes based on GaAs. The differential conductivity at pressures 1.5–2.8 GPa is found to be not single-valued, i.e., "switching" takes place. This effect has "memory." The results are qualitatively interpreted within the concept of trap levels with allowance for the pressure-induced change of the GaAs band structure.

Application of pressure usually leads to a change of the initial slope of the current-voltage characteristics (CVC), of the peak current, and of the voltage of semiconductor tunnel diodes.[1] These parameters are connected with the band structure of the superconductor and are used in particular to study its variation with pressure.

When studying the influence of pressure up to ~ 3 GPa on the tunnel characteristics of *p–n* junctions, we have observed an anomalous behavior of the CVC of tunnel diodes based on GaAs, viz., the differential conductivity (the initial slope of the characteristic) is not single-valued in a certain pressure and temperature interval, i.e., a "switching" effect takes place.

The investigated tunnel junctions were made by fusing Sn or Sn + 1% Ge in a GaAs(Zn) substrate with initial density $\sim 1.5 \times 10^{19}$ cm^{-3}. The pressure-production procedure is described in Ref. 2.

1. RESULTS OF EXPERIMENT

1) The action of pressure on a tunnel junction manifests itself, first, in a decrease of the peak current by approximately three orders, owing to the change of the GaAs band structure, and second in the appearance of the so-called "humped" component of the tunnel current, which is usually associated with the presence of impurity states.[1]

In our case the humped component was absent at $P = 0$ and appeared at room temperature at a pressure ~ 1.5 GPa and at a bias ~ 1.3 V. As the temperature was lowered its amplitude first increased (to ~ 200 K) and then gradually decreased and shifted toward lower bias. At the same time, a second weaker humped component appeared at bias values ~ 550 mV.

2) We regard as the most interesting the anomalous behavior of tunnel junctions investigated by us in two temperature intervals:

a) $T = 4.2$ K.

In the pressure range $1.5 < P < 2.8$ GPa there can correspond to the sample one of two CVC, *a* or *b*, which differ in their initial slope (Fig. 1). Let, for the sake of argument, the system be at low bias in a state with CVC *a*. To change now to the state with CVC *b*, it is necessary to apply to the sample a bias $V > V_{cr1}$ ($= 40$ mV). This switching takes place within a time $\tau_1 \sim 1$–5 sec, and fastest at $a \sim 550$ mV bias.

The state that set in after the CVC *b* has steadied will be preserved if the bias is varied in the range $0 \leqslant V < 800$ mV.

To restore the state with CVC *a* a bias higher than $V_{cr2} = 800$ mV must be applied. We note that this switching takes place much more rapidly and is completed within several milliseconds (τ_2).

The state *a* can be preserved also in the bias range $V_{cr1} < V < V_{cr2}$, by passing through this interval in a time shorter than τ_1.

Thus, at a bias up to V_{cr1} the slope of the CVC can take on two values corresponding to two states, *a* and *b*, each of which can be preserved for an arbitrarily long time (in an experiment time on the order of several hours), i.e., the tunnel junction is a bistable element with "memory".

It must be noted that V_{cr} varies little with pressure. Plots of the ratios of the initial slopes and of the peak currents vs pressure are shown in Fig. 2.

At $P > 2.8$ GPa no switching takes place in the rising branch of the CVC and there is only one CVC, but the switching manifests itself in a change of the slope of the descending branch of the CVC.

b) $T = 20$–40 K.

At pressures $0.6 < p < 2.15$ GPa the sample can be transferred from state *a* to state *b* by applying a voltage $V_{cr1} < V < V_{cr2}$, but it is impossible to fix the state *b* after removing the bias, inasmuch as after ~ 1 sec the state *a* is restored, i.e., there is no memory effect. In the range

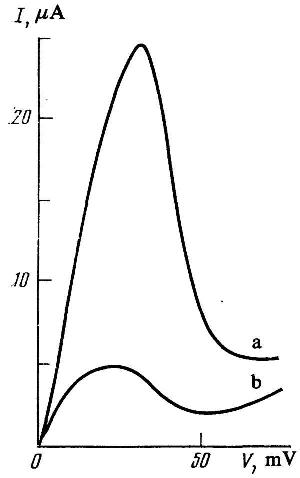

FIG. 1. Initial segment of current-voltage characteristics: $P = 2.0$ GPa, $T = 4.2$ K.

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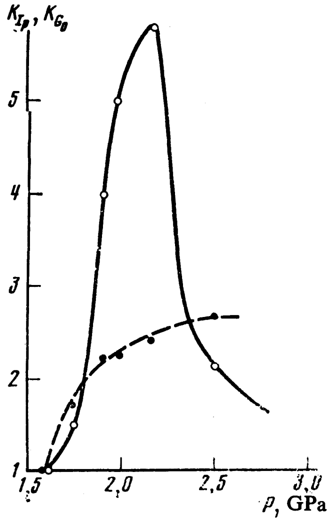

FIG. 2. Dependences of the ratios of the peak currents (K_{I_p}—○, and the initial conductances (K_{G_0}—●) in states a and b on pressure at $T = 4.2$ K.

$2.15 < P < 2.8$ GPa the sample can be transferred to the state with CVC b by applying a bias $V > 550$ mV, and this state will be preserved up to ~ 1.5 V (our maximum voltage). The CVC a can be restored in this case only by cooling the sample to 4.2 K and applying a bias $V > V_{cr2}$ (as in item a) or by heating to above 40 K.

The foregoing behavior of tunnel junction is consistently reproducible upon applying and removing pressure, and was observed repeatedly in different samples.

2. DISCUSSION OF RESULTS

Since the observed CVC are consistently reproducible after various repeated loadings and coolings, for one and the same sample and for different samples, an attempt might be made to explain the observed phenomenon as being due to changes in the GaAs band structure under pressure.

The pressure interval in which the described CVC switching is observed practically coincides with the pressure interval in which, according to our estimate, the electrons of GaAs with donor density $\sim 10^{19}$ cm^{-3} "spill over" from subband Γ to X. An estimate shows also that partial filling of the subband L, followed by depletion, takes place at pressures 0.6–1.5 GPa.

It might thus be suggested that the described phenomenon is due to participation, in the tunneling, of two carrier species with greatly differing effective masses. As a result of this strong mass difference the tunneling probabilities for the electrons of the two subbands differ greatly, and this might lead to a change of the space charge in the region of the p–n junction.

But then one would expect a CVC behavior similar to that described above to take place also in tunnel junctions based on GaSb, whose band structure and its pressure dependence up to ~ 1.2 GPa are similar to those of GaAs. We have carried out the corresponding investigations of GaSb tunnel junctions up to 1.5 GPa. We found that there is no switching in this case, so that the effect cannot be attributed solely to a change of the band structure of GaAs.

To explain our results we can invoke the concept of the conversion of deep levels of GaAs into traps under definite conditions.

The density of such traps can be estimated by assuming that the change of the characteristics is due to a change in the width of the space-charge region in the junction as a result of a change in the effective carrier density as the traps become filled and depleted. This approach was verified in Ref. 3, where the space-charge-layer width and its dependence on the number of traps were determined by measuring the volt-farad characteristics of p–n junctions based on $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$. It was shown, in particular, that the square of the capacitance is proportional to the space charge density and that the capacitance can take on two values, depending on the degree of filling of the trap levels. The fact that in this case the filled traps can be in a metastable state for a long time was attributed to the absence of thermal excitations at low temperatures.

From the expression for the tunnel-current density[4] we obtain for the conductance at low biases

$$G_0=\frac{m^*e^2}{4\pi\hbar^3}\exp\left(-\frac{E_g}{\bar{E}}\right)\bar{E}\left[1-\exp\left(-\frac{2E_s}{\bar{E}}\right)\right], \qquad (1)$$

where m^* is the effective tunnel mass of the electron, E_g is the semiconductor band gap, E_s is the lower of the two degrees of degeneracy on the two sides of the p–n junction, $\bar{E} = \sqrt{2}e\hbar\mathscr{E}/\pi(m^*E_g)^{1/2}$ is the average energy of the tunneling electrons, and $\mathscr{E}$ is the effective field in the p–n junction.

It is easy to verify that the dependence of G_0 on the space-charge density N^* is approximately described by the relation

$$\partial \ln G_0/dN^* \sim (N^*)^{-3/2},$$

then

$$\ln(G_a/G_b) \approx \frac{E_g(m^*\varepsilon)^{1/2}}{2e\hbar}(N_a^*-N_b^*), \qquad (2)$$

where G_a, N^*_a and G_b, N^*_b are the conductances and the effective space charge densities in the states a and b respectively, and ε is the dielectric constant of the semiconductor. The quantity $(N^*a - N^*b)$ determines the effective density of the traps.

A numerical estimate of $(N^*a - N^*b)$ from relation (2) yields a value on the order of $\sim 10^{19}$ cm^{-3}. This estimate seems reasonable and agrees in order of magnitude with the data of Ref. 3.

Thus, the existence of the two states is most readily due to the presence of traps, and the correlation between the anomalous behavior of the current-voltage characteristics and the change of the semiconductor electron structure can be related to selective mobility-governed trapping of carriers belonging to different subbands.

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[1] Tunnel'nye yavleniya v tverdykh telakh (Tunnel Phenomena in Solids), Russ. transl., V. I. Perel', ed., Mir, 1973, p. 191.

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