TUNNEL TRANSITIONS IN SEMICONDUCTORS IN STRONG CROSSED ELECTRIC AND MAGNETIC FIELDS

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We investigate the current-voltage characteristics of tunnel diodes in a constant transverse magnetic field up to 160 kOe. In regular-production alloyed tunnel diodes of Ge and GaAs, the influence of the magnetic field on the tunnel current is small. In GaSb tunnel diodes made by the diffusion method, an appreciable decrease of the tunnel current is observed; this decrease is satisfactorily described by the existing theory[5] for direct tunnel transitions in crossed electric and magnetic fields. It is observed that the excess current also decreases in a magnetic field, and an explanation of this phenomenon is proposed.

It is known that the tunnel current in semiconductors decreases with increasing intensity of the transverse magnetic field[1,2]. The theory developed by Aronov and Pikus[3], which is valid for tunnel transitions between parabolic bands with quasimomentum conservation, yields the following expression for the relative decrease of the tunnel current in a p-n junction in a transverse magnetic field:

$$\gamma(H) \equiv \frac{I(H)}{I(0)} = \left(1 - \frac{s^2H^2}{c^2E^2}\right) \exp\left\{\frac{B}{E}\left[1 - \left(1 - \frac{s^2H^2}{c^2E^2}\right)^{-1/2}\right]\right\}, \quad (1)$$

where $2ms^2 = \epsilon$, ϵ is the width of the forbidden band of the semiconductor, m the average of the effective masses of the electron and hole ($2m = m_n + m_p$), $B = \pi m^2 s^3/\epsilon\hbar$, E—electric field in the p-n junction, e—electron charge, ħ—Planck's constant and c—velocity of light. It follows from (1) that the $\gamma(H)$ dependence is determined both by the characteristics of the semiconductor (m, ϵ) and by the field E in the junction. Therefore a verification of the validity of the theoretical conclusions[3] is quite important, for by investigating the $\gamma(H)$ dependence we can determine, if formula (1) is valid, either the electric field in the p-n junction or the effective mass for the tunnel transitions. It should be noted that formula (1) is valid, strictly speaking, when $m_n = m_p$ (when $m_n \neq m_p$ an additional numerical factor enters into the exponential). If, however, the ratio m_n/m_p is not much different from unity (for most III-V compounds, where the tunnel transitions occur mainly between the conduction band and the light-hole band, we have $m_n/m_p \sim 0.8$–1.3), then formula (1) remains valid without introduction of correction factors.

One of the materials suitable for verifying experimentally the theoretical relation (1) is apparently gallium antimonide. First, the interband tunnel transitions in GaSb are direct. Second, the effective masses of the electron and of the light hole in GaSb are approximately equal and sufficiently small ($\sim 0.05\ m_e$), so that the influence of the magnetic field on the tunnel current should be relatively large. Third, in view of the sufficiently large width of the forbidden band, the tunnel effect in GaSb can be observed in a wide range of temperatures. Therefore the greater part of the experiments was performed with diodes made of GaSb.

It was also of interest to estimate, for comparison, the influence of a strong magnetic field on the current-voltage characteristics of tunnel diodes made of materials with both direct (GaS) and indirect (Ge) tunnel transitions.

EXPERIMENTAL PROCEDURE

The tunnel and inverted diodes of GaSb, used to verify the theory experimentally, were made by diffusion of zinc in n-type material. The technology of preparation of such diodes and their electric properties are discussed in detail in[4]. We note here only that the use of such diodes offers the following advantages:

1. The magnitude of the electric field in a diffusion p-n junction is smaller, owing to its larger width, than in an alloyed junction. This leads, as follows from (1), to an intensification of the action of the magnetic field on the tunnel current.

2. Diffusion p-n junctions can be readily made quite flat, making it possible, if the diode is accurately oriented in the magnetic field, to eliminate the current component parallel to the magnetic field, on which the latter acts much less than on the current component normal to **H**. In alloyed tunnel junctions it is difficult to avoid bending of the p-n junction, so they usually have a longitudinal component of the current, thus lowering the magnitude of the effect and hindering the comparison of experiment with theory.

3. In diffusion diodes it is possible to measure the area of the p-n junction with high accuracy (one completely unattainable for alloyed diodes), making it possible to determine the value of E from other measurements and to compare it with the value obtained from the $\gamma(H)$ dependence.

Preliminary investigations made with such diodes in a superconducting solenoid at $H \leq 64$ kOe and $T = 4.2°K$[5] have shown that in this region of magnetic field intensities the theory agrees well with the experimental data. However, the decrease of the tunnel current in these experiments did not exceed 7–10%. It

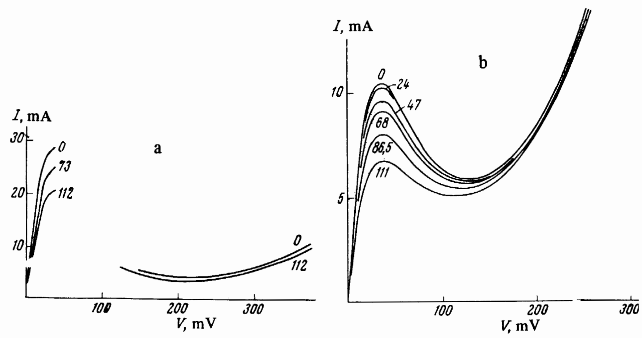

FIG. 1. Forward current-voltage characteristics of a diffusion tunnel diode of GaSb at 80 (a) and 300°K (b). The numbers on the curves designate the magnetic field intensity in kOe.

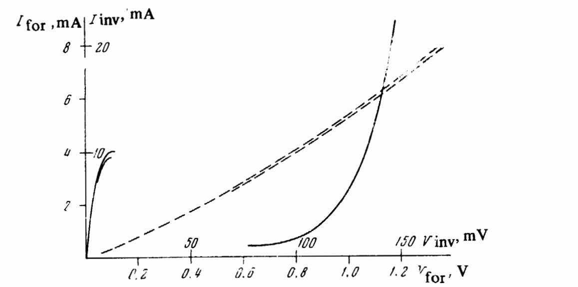

FIG. 3. Forward ($I_{for}(V_{for})$ – solid lines) and inverse ($I_{inv}(V_{inv})$ – dashed lines) current-voltage characteristics of an alloyed tunnel diode of gallium arsenide at 300°K. Upper curves – H = 0, lower curves – G = 160 kOe.

was therefore of interest to verify the agreement between the theoretical and experimental curves in the region of stronger magnetic fields and at higher temperatures.

Diodes made of Ge and GaAs, on which the measurements were made, were commercial alloyed tunnel diodes. The measurements were made with the "Solenoid" apparatus for obtaining superstrong magnetic fields, constructed at the P. N. Lebedev Physics Institute of the USSR Academy of Sciences, in constant magnetic fields up to 112 kOe at T = 80°K and up to 160 kOe at T = 300°K. The construction of the "Solenoid" setup and its operating procedure are described in[6]. The dc current-voltage characteristics of the diodes were plotted either point by point by a potentiometer method, or were recorded with an automatic x-y recorder with continuous variation of the diode bias.

EXPERIMENTAL RESULTS

Figures 1 and 2 show the current-voltage characteristics of GaSb diodes, plotted in a transverse magnetic field at 80 and 300°K. We see that at any diode voltage (including voltages corresponding to excess current), the tunnel current decreases with increasing magnetic field, but in the region of excess currents (as was also noted in[5]) the influence of the magnetic field is much smaller. The current-voltage characteristics shown in Fig. 2 pertain to a diode in which the thickness of the p-n junction was artifically increased by means of special heat treatment. The electric field in this p-n junction was noticeably weakened, and consequently the decrease of the direct tunnel current under reverse bias in a magnetic field was large enough to permit its use for the measurement of the intensity of strong magnetic fields[7].

The investigations have made it possible to reveal one more feature of GaSb tunnel diodes, namely the influence of the magnetic field on the direct tunnel current (connected with the direct transitions) is stronger at room temperature, whereas in the excess-current region the effect is more noticeable at 80°K.

In GaAs diodes (Fig. 3), the magnetic field has much less influence on the direct tunnel current than in GaSb, and has practically no influence on the excess current. At the same time, in Ge diodes (Fig. 4), the influence of the magnetic field on the direct and on the excess tunnel currents is approximately the same. The appreciable effect observed in the region of the diffusion current ($V > 0.4$ V) in germanium tunnel diodes is apparently due to the decrease of the diffusion length of the minority carriers in the magnetic field.[8]

A quantitative comparison of the theory of[3] with the results obtained for GaAs and Ge tunnel diodes was not made, in view of the smallness of the effect. For GaAs, the theory is not applicable (the tunnel transitions in it are direct), and the smallness of the effect

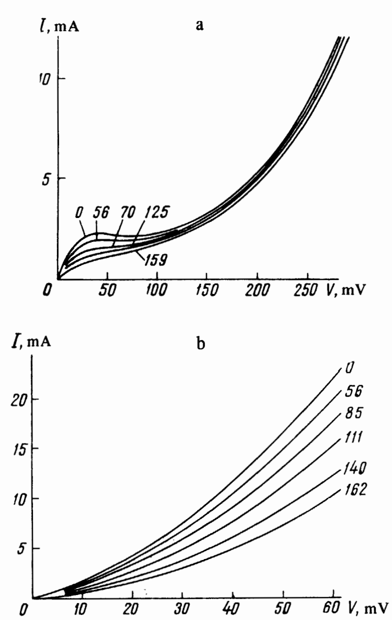

FIG. 2. Forward (a) and inverse (b) current-voltage characteristics of an inverted diffusion diode of GaSb at 300°K. The numbers at the curves designate the magnetic-field intensity in kOe.

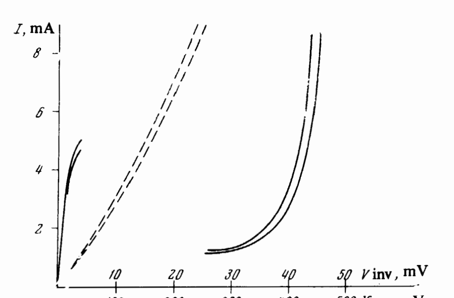

FIG. 4. The same as Fig. 3, but for an alloyed germanium tunnel diode at 300°K.

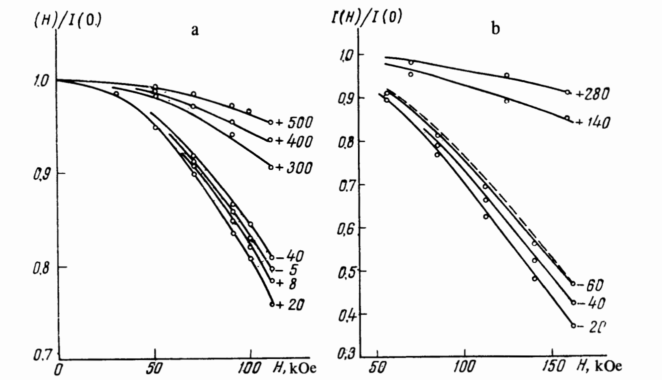

FIG. 5. Plot of γ (H) for GaSb diffusion diode of the tunnel type at 80°K (a) and inverted type at 300°K (b). Points – experimental data; solid curves – calculated from formula (1). The numbers in the curves correspond to the diode voltage in mV. The dashed curve (b) is a plot of formula (2).

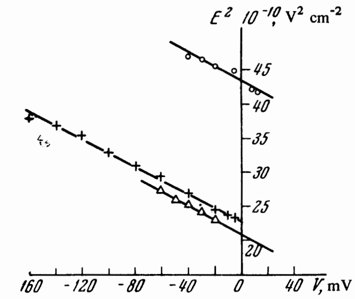

FIG. 6. Dependence of the square of the electric field intensity E in a p-n junction, determined from γ(H), on the diode voltage for three diffusion diodes of GaSb.

is due to the strong electric field ($\sim 2 \times 10^6$ V/cm) in the alloyed p-n junction, owing to the large width of the forbidden band of GaAs. The weak influence of the magnetic field on the tunnel current in germanium diodes can be attributed to the indirect character of the tunnel transitions.

DISCUSSION OF RESULTS

Direct Tunnel Transitions

The points of Fig. 5 show typical experimental $\gamma(H)$ relations corresponding to different values of the diode bias. The solid curves were calculated from formula (1), and the only selected parameter was the electric field E in the p-n junction. It was assumed in the calculations that $\epsilon = 0.787$ eV at 80°K and $\epsilon = 0.697$ eV at 300°K[9], $m_n = m_p = m = 0.05\ m_e$[10,11]. We see that the theoretical curves are in good agreement with experiment. The agreement is particularly good at 80°K. This is to be expected, inasmuch as formula (1) is valid in essence only at low temperatures. However, the character of the $\gamma(H)$ dependence predicted by the theory is retained up to room temperature.

From the form of the current-voltage characteristics (Figs. 1 and 2) we see that the contribution of the excess current to the total current is large in the investigated GaSb diodes even at small positive bias. The essential role that can be played by the excess currents at small positive bias was pointed out also by others[12,13]. Therefore, in a quantitative comparison of the experimental data with the theory, we used the region of negative bias. In this region it is possible to determine, from the $\gamma(H)$ dependences at different values of the bias, the dependence of the electric field intensity E, which enters in formula (1), on the bias. Examples of such dependences are shown in Fig. 6. Extrapolation of the E(V) plot to V = 0 yields the value of the electric field E_0 in the p-n junction in the absence of a bias. The value of E_0 can be determined from other measurements.

By the way of control methods of the measurement of E_0 we used the following:

1) Measurement of the conductivity of the diodes G_0 at zero bias; in this case[14] $G_0 = AE_0 \exp(-B/E_0)$, where $A = Qe^3/\pi h^2 s$ and Q is the area of the p-n junction.

2) Measurement of the diode capacitance (at 300°K).

3) Measurement of the shift of the maximum peak of diagonal tunneling in the electroluminescence spectrum of the diodes as a function of the diode bias[15] (at 80°K).

The results of the determination of E_0 by different methods are listed in the table. The agreement obtained allows us to assume that the theory of[3] describes correctly the influence of the transverse magnetic field on the current in the tunnel diode not only qualitatively but also quantitatively.

Values of electric field E_0 (in units of 10^5 V/cm), determined by various methods for three GaSb diodes

Diode number	T, °K	Method of determining E_0				
		$\gamma(H)$, Formula (1)	$\gamma(H)$, Formula (2)	Measurement of G_0	Measurement of capacitance	From the electroluminescence spectrum
1	80	6.55	6.20	6.6	—	6.7
2	300	4.55	4.37	4.6	4.9	—
3	300	4.75	4.44	4.7	5.0	—

In[16], an expression similar to (1) was obtained for the decrease of the tunnel current in a transverse magnetic field (in the quasiclassical approximation), but without the pre-exponential factor:

$$\gamma(H) = \exp\left\{\frac{B}{E}\left[1-\left(1-\frac{s^2H^2}{c^2E^2}\right)^{-1/2}\right]\right\}. \tag{2}$$

In weak magnetic fields ($s^2H^2/c^2E^2 \ll 1$) the absence of this factor does not influence the qualitative character of the $\gamma(H)$ dependence, but the parameter E, determined from formula (2), turns out to be 5–10% smaller. On the other hand, if $s^2H^2/c^2E^2 \gtrsim 0.1$, then the experimental $\gamma(H)$ plots, especially at room temperature, fit much better the theoretical plot of type (1) (Fig. 5b).

We note that the accuracy with which the field intensity E in the p-n junction is determined from the $\gamma(H)$ plot is much higher (not worse than ~3%) than from other known measurements. Therefore, by determining the value of the electric field in the p-n junction from the decrease of the tunnel-diode current in the magnetic field, it is possible to increase appreciably the accuracy of other experiments with these diodes, inasmuch as the calculation formulas for many effects in strongly doped p-n junctions contain the quantity E, which is usually determined with a large degree of error.

Strictly speaking, the theory of[3] is valid only for the case of simple bands with a quadratic dispersion law, whereas the valence band in semiconductors of the III-V type, and also in Ge and Si, is degenerate. It can be assumed, however, that in the case when the tunneling probability is determined in practice only by light holes, the presence of degeneracy should not noticeably influence the investigated effect[1)]. The influence of the (111) subband of the conduction band on the probability of the tunnel transitions should also be small (the ratio of the effective masses of the electrons in the lower and the upper minima in GaSb is of the order of 0.1). Furthermore, the transitions from the (111) subband are not direct.

Excess Current

As seen from Figs. 1 and 2, the magnetic field also decreases the excess current, and this effect is also described by a relation of the type (1) (see Fig. 3, the curves corresponding to large intensities). This result is not unexpected, since the excess current is due to the tunneling of the electrons and holes inside the potential barrier in the p-n junction and to the subsequent recombination (radiative, impurity, or impact). The major differences between this process and the direct interband tunneling are as follows. First, the excess current is due to indirect tunnel transitions and participation of a third particle is essential (photon, impurity atom, or one more carrier). Second, the height of the potential barrier for the electrons located near the Fermi level is much lower in the case of the excess current than in direct tunneling, and equals $\epsilon - eV$, i.e., it decreases with increasing diode voltage.

Apparently, the first difference should not greatly affect the character of the dependence of the tunnel current on the magnetic field, if it is assumed that the decisive influence is exerted by the magnetic field on the probability of penetration into (or passage through) the potential barrier. Under such an assumption, the decrease of the influence of the magnetic field in the region of the excess current can be attributed to the decrease of the characteristic energy of the electron-hole pair production $2ms_1^2 = \epsilon - eV$. This makes it possible to explain qualitatively both the weakening of the influence of the magnetic field on the excess current with increasing diode voltage (connected with the decrease of s_1 with increasing V), and the observed decrease of the influence of the magnetic field on the excess current with increasing temperature (connected with the decrease of s_1 as a result of the thermal decrease of the width of the forbidden band[2)]).

[1)]Indeed, as was kindly reported by L. V. Keldysh during a discussion of the present paper, according to his calculations, the presence of a degenerate valence band can be neglected in the analysis of interband tunneling if the mass of light holes is much smaller than the mass of the heavy ones (in GaSb, the ratio of these masses is of the order of 0.2).

[2)]The relative change of s_1 with changing temperature is much larger than the change of s, and therefore it is precisely s_1 which determines the temperature dependence of γ (H) in the region of excess currents.

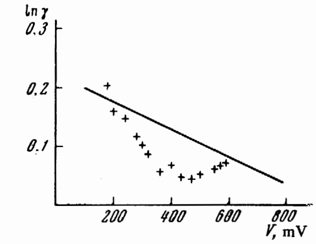

FIG. 7. Dependence of ln γ_1 on the diode voltage in the excess-current region for a GaSb tunnel diode at 80°K; H = 112 kOe. The solid line is calculated from (5).

Let us attempt, using such an assumption, to estimate qualitatively the influence of the magnetic field on the excess current, assuming that formula (1) in which s is replaced by s_1 is valid.

Recognizing that in this case $1 - \gamma \ll 1$, i.e., $s_1^2H^2/c^2E^2 \ll 1$, we insert the pre-exponential factor in the exponential, obtaining for the relative decrease of the excess current I_{exc} in the magnetic field

$$\gamma_1 \equiv \frac{I_{\text{exc}}(H)}{I_{\text{exc}}(0)} = \exp\left[-\left(\frac{B_1}{2E}+1\right)\frac{s_1{}^2H^2}{c^2E^2}\right], \tag{3}$$

where $B_1 = \pi m^2 s_1^3/e\hbar$.

We assume further that the field E, in the region of bias values corresponding to excess currents, can be obtained by extrapolating the relation

$$E = E_0(1 - eV/\varepsilon)^{1/2}, \tag{4}$$

where E_0 is the initial field in the p-n junction and is determined from the experimentally obtained E (V) dependence at $V < 0$. We can then readily find that

$$\ln\gamma_1 = -CH^2(\varepsilon + D - eV), \tag{5}$$

where C and D are constants that depend only on the known quantities m, ϵ, and E_0.

Figure 7 shows experimental points representing a plot of $\ln\gamma_1$ on V for one of the diodes in a magnetic field H = 112 kOe at 80°K, and the theoretical line calculated from (5). We see that the simple considerations advanced above allow us to predict the correct magnitude of the influence of the transverse magnetic field on the excess current. For a more correct theoretical analysis of the influence of the magnetic field on the excess current in a large range of bias voltages V it is necessary to take into account the following considerations.

1. As can be seen from Fig. 6, when the experimental E(V) plot is extrapolated to the region $V > 0$, the lines $E^2(V)$ cross the abscissa axis at values V_i that are much lower than the contact potential V_c (for these diodes $V_c \geq 0.8$ V, and it follows from Fig. 6 that V_i = 290—550 mV). We can therefore conclude that the real character of the E(V) dependence at $V > 0$ should differ noticeably from the assumed simple dependence (4). In particular, in a large region of bias values the value of E should decrease with increasing V more slowly than predicted by formula (4)[3)]. This leads to a decrease of the influence of the magnetic field compared with that expected from (5), as is indeed observed (see Fig. 7). Therefore, for a correct theoretical description of the γ(H) dependence at $V > 0$ it is necessary to have more information on the E(V) dependence in this region of bias values.

[3)]This is also indicated by the results of [17], where a more accurate calculation was made of the dependence of the p-n junction capacitance on the bias.

2. In the region of large positive bias values (especially at high temperatures), the characteristic energy $2ms_1^2$ decreases additionally, owing to the thermal energy of the carriers, and this leads to further weakening of the influence of the magnetic field on the excess current. Indeed, the experimental values of $|\ln \gamma_1|$ for the excess currents at room temperature are smaller by a factor 3–5 than those calculated from formula (5).

CONCLUSION

The performed experiments have confirmed that the tunnel current connected with the direct interband transitions in semiconductors decreases in a strong transverse magnetic field, in agreement with the predictions of the theory. Owing to the use of diffusion tunnel and inverted GaSb diodes, characterized by a relatively weak electric field in the p-n junction and small effective mass, appreciable changes of the tunnel current were obtained (a decrease by 50–65% in magnetic fields up to 160 kOe). This has made it possible to compare quantitatively the theory[3,16] with the experimental data in a wide range of changes of H, $\gamma(H)$, and V at 80 and 300°K.

The results indicate that the theory of Aronov and Pikus[3] provides a good quantitative description of the change of the tunnel current under the influence of the transverse magnetic field. The values of the electric field in the p-n junction, calculated from (1), agree well with the results obtained by independent methods.

We observed and investigated the influence of the magnetic field on the excess tunnel current. The much smaller magnitude of the effect compared with the region of direct interband transitions is qualitatively explained on the basis of the concepts developed in[3]. Assuming that the simple relation between the electric field in the p-n junction and the bias (4) is valid, satisfactory agreement can be obtained between the theoretical and experimental values of $\gamma(H)$ in the region of excess currents at low temperatures.

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