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ELECTRON-HOLE AND ELECTRON-IMPURITY BAND TUNNELING IN GaAs LUMINESCENT JUNCTIONS

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The possibility of photon-assisted tunneling in *pn* junctions has been considered by Aigrain,[1] Sommers,[2] and more recently by Pankove.[3]

We wish to report a group of measurements performed on electroluminescent GaAs diodes and to propose two tunneling mechanisms which are in quantitative agreement with these data.

Figure 1 includes a plot of the integrated light intensity I at 77°K vs the applied voltage V_x. The diode was prepared by diffusing Zn from a surface concentration of $p = 5\times10^{18}$ cm^{-3} into a GaAs crystal doped with $n = 2.5\times10^{18}$ cm^{-3} Te atoms. In region A, 1.23 V $< V_x <$ 1.37 V, the intensity is given by $\mathcal{I} = \mathcal{I}_0 \exp[S_A V_x]$, where $S_A = 42$ V^{-1}. In region B, $V_x > 1.37$ V, the slope changes to $S_B = 100$ V^{-1}. The values of S_A and S_B remain constant down to 4.2°K.

The main support for a tunneling model comes from the observation of the temperature independence of S_A and S_B. If the current were due to diffusion, S should be proportional to T^{-1}. The increase in the magnitude of the slope which occurs in moving from region A to B suggests the existence of two distinct tunneling mechanisms.

The model proposed to explain the diode behavior in region A is shown in Fig. 2. An electron on the n side of the junction and a hole from the p side tunnel into the junction region and recombine emitting a photon of energy $h\nu$. The matrix element describing this transition is

$$\mathcal{H}_{cv}' = \int \psi_c(r) \exp[i\vec{k}_c(r)\cdot\vec{r}\,]P\psi_v^*(r) \times \exp[-i\vec{k}_v(r)\cdot\vec{r}\,]d\tau, \quad (1)$$

where ψ_c and ψ_v are the wave functions for the conduction band and the valence band, respectively, at $k = 0$. P is the momentum operator.

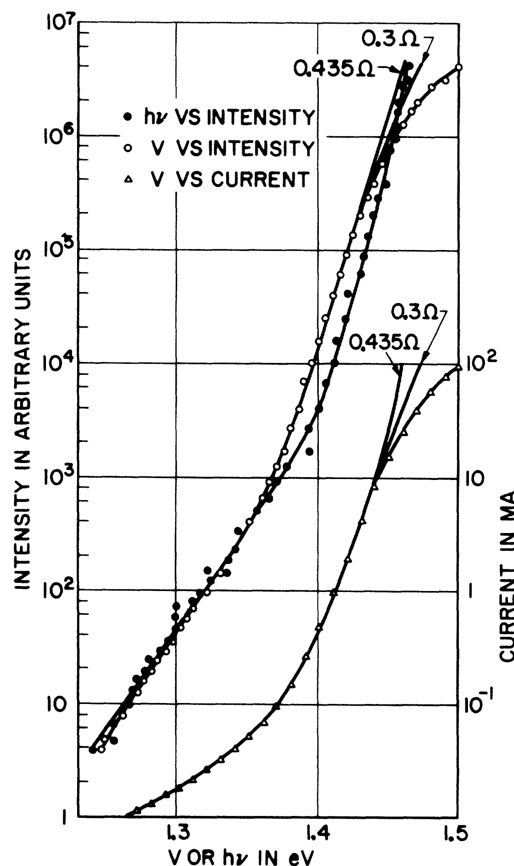

FIG. 1. A plot of the integrated radiation intensity vs the total applied voltage and the photon energy at maximum light output. To correct for series resistance, the voltage drops across $R = 0.435$ Ω and $R = 0.3$ Ω are subtracted. These corrections become important at $V_x > 1.43$ V. The lowest curve is that of the diode current. The quantum efficiency approaches a constant value (~1) at $V_x > 1.38$ V. The temperature is 77°K.

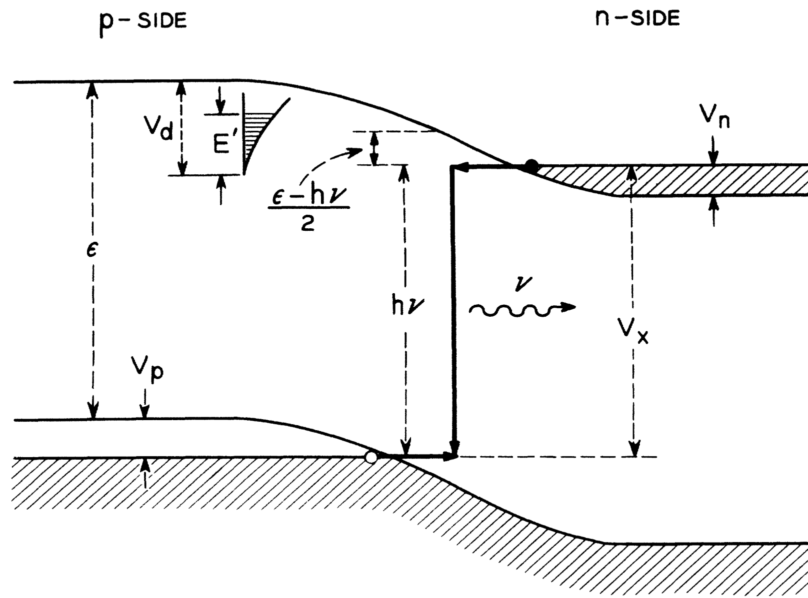

FIG. 2. A model for the electron-hole photon-assisted tunneling and the impurity-band tunneling in a GaAs *pn* junction. The second tunneling mechanism becomes operative as the applied voltage V_x is increased, above its value in this figure, so that V_n lies opposite the impurity band.

The transition is thus described by a single matrix element and does not involve virtual states.[3] The main contribution to (1) is from the "tunneling" region where the components of $\vec{k}_c(r)$ and $\vec{k}_v(r)$ in the direction normal to the junction plane are imaginary.

To test our model, we calculate the simultaneous tunneling proability to midjunction[4] of a hole near the Fermi level on the p side and of an electron on the n side as shown in Fig. 2. The tunneling probability for each one of these events is given by Keldysh[5] as

$$P_x = \exp[-\alpha \epsilon_x^{3/2}/E], \tag{2}$$

where $\alpha = \pi(m)^{1/2}/2eh$, m is the tunneling mass, E is the electric field in the junction, and ϵ_x is the energy barrier through which the electron and hole tunnel. From Fig. 2 we have

$$\epsilon_x = \tfrac{1}{2}(\epsilon - h\nu) = \tfrac{1}{2}e(V_i - V_x), \tag{3}$$

for $V_n + V_p \ll \epsilon/e - V_x$. ϵ is the energy gap and eV_i is the built-in potential $eV_i = \epsilon + e(V_p + V_n)$.

A plot of the measured diode capacitance vs voltage showed that the impurity profile is of the linear-gradient type, and the junction width W is given by

$$W = W_1(V_i - V_x)^{1/3}, \tag{4}$$

with $W_1 = 1300$ Å-V$^{-1/3}$. The electric field E is taken as the maximum field

$$E_m = 1.5(V_i - V_x)/W. \tag{5}$$

Combining (2), (3), (4), and (5), we get

$$I \propto P_x^{\,2} = \exp[(-\alpha W_1 e^{3/2}/1.5\sqrt{2})(V_i - V_x)^{5/6}], \tag{6}$$

where we assume that most of the emitted radiation is due to electron-hole midjunction tunneling.

A plot of $\log I$ vs V_x should thus possess a slope S given by[6]

$$S = (5/6)(\alpha W_1 e^{3/2}/1.5\sqrt{2})(V_i - V_x)^{-1/6}. \tag{7}$$

The factor $(V_i - V_x)^{-1/6}$ varies between 0.76 and 0.85 over the range of V_x plotted in Fig. 1. This small deviation from a constant slope behavior could not be resolved in a logarithmic plot such as that of Fig. 1 and none, indeed, was observed.

To calculate S we use $W_1 = 1300$ Å-V$^{-1/3}$, $m^{-1} = m_h^{-1} + m_e^{-1} = (0.04\,m_0)^{-1}$, and replace the function $(V_i - V_x)^{-1/6}$ by its average value over the range $1.25 < V_x < 1.37$ which is ~0.8. The result is

$$S_{\text{calc}} = 47\ \text{V}^{-1},$$

which is to be compared with the measured value $S = 42$ V^{-1}.

The following added observations are consist-

ent with the tunneling model proposed above: (a) The emitted frequency at peak output is, as shown in Fig. 1, equal to eV_x/h, (b) the measured slope S in diodes with a different doping profile remains proportional to W_1, and (c) spectra in region A show multiple peaks resulting from the interference of primary beams from the recombination region and secondary beams reflected from the surface of the diode. This interference implies a narrow recombination region. We deduce an upper limit of about 500 Å. This region, as has been suggested by Kane,[8] would correspond to the part of the junction where the overlap of $\psi_v(r)$ and $\psi_e(r)$ is a maximum. No interference peaks are observed in region B.

The different value of S_B for $V_x > 1.37$ can be explained if we assume that the radiation is due to electrons tunneling into an impurity band as shown in Fig. 2 (a distance V_d below the conduction band edge). The existence of such a band with a density of states

$$\rho(E') = \mathrm{const} \times \exp[aE'] \tag{8}$$

has been suggested by Nelson et al.[8] If the current cycle is completed by a radiative recombination with a characteristic lifetime τ which is independent of E', we can write

$$\mathcal{I} \propto \exp[aE']. \tag{9}$$

Since only electrons near the top of the Fermi level find themselves opposite empty states in the band, we have from Fig. 2,

$$E' = e(V_d - V_i + V_n + V_x),$$

which when substituted in (9) yields

$$S_B = ea. \tag{10}$$

As an independent check we plotted $\log \mathcal{I}$ vs $h\nu$. The band-filling model requires that at peak output $h\nu = eV_x + eV_0$, where V_0 is some constant voltage. As a consequence, a plot of $\log \mathcal{I}$ vs $h\nu$ should possess the same slope as $\log \mathcal{I}$ vs eV_x. This, as shown in Fig. 1, is the case. The two values of S_B thus measured are both 100 V^{-1}.

If we assume that in region B the recombination takes place from the impurity band to the valence band, we should have, at $T = 0°K$, $eV_x = h\nu + eV_0$, where $V_0 \sim S^{-1}$. This is the case at 4.2° and 20°K where S^{-1} is 10 mV while the measured V_0 is 15 mV. At 77°K we find (see Fig. 1) $V_0 = -14$ mV. Although a decrease in V_0 with increasing temperature is expected, we could not account quantitatively for the observed decrease.

By comparing the radiation intensity and the total current data of Fig. 1, it becomes clear that the recombination quantum efficiency in region A is very small. As a matter of fact, a relationship $\mathcal{I} \propto I^{3.3}$ is found to hold over a 10:1 range of current. In region B the radiation intensity becomes approximately proportional to the total current I which indicates a constant quantum efficiency.

The mechanism of excess current flow in region A must involve tunneling since its characteristics are, too, temperature independent. An investigation into its nature is now in progress.

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