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Field and Hot Carrier Enhanced Leakage in InGaAsP/InP Heterojunctions

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Abstract—**A model calculation for the field and hot carrier enhanced electron leakage in InGaAsP/InP LED's and lasers is presented. The significant influence of the doping level in the P-InP confining layer on leakage current is confirmed.**

THE temperature sensitivity and power saturation of InGaAsP lasers and light emitting diodes (LED's) have triggered an extensive search for the responsible mechanisms. Prime candidates are nonradiative Auger recombination and carrier leakage over the heterobarrier. These are believed to be important factors affecting the performance of the family of quaternary optoelectronic devices emitting in the spectral range of 1.1-1.6 μm. A number of new structures have been designed to isolate and thus directly demonstrate the role played by carrier leakage in LED's [1], [2] and lasers [3].

An interesting experimental observation of Chen *et al.* [3] is the continued increase of leakage current with total current above lasing threshold. Leakage models based on diffusion of electrons [4]-[6] alone cannot explain the observed phenomenon, as clamping of carrier density leads to a constant leakage current above lasing threshold. However, the observed behavior can be explained by invoking the electric field dominated drift component of electron current in the cladding layer. Lee and Dentai had included the field term in their calculation of the carrier confinement factor in GaAs/GaAlAs LED's [7], but Anthony and Schumaker [8], [9] were the first to recognize the significance of this field. However, their theory predicted a linear dependence of leakage current on injection current above threshold, contrary to the experimental result of [3]. The observed result can be explained by a theory analogous to the minority carrier injection in a Schottky diode [10], when the band discontinuity at the heterojunction is taken into account. We will show that in the high injection regime where lasers normally operate, the electron leakage current J_e will be proportional to $J_p{}^{\alpha}$, the injected hole current where α is a positive number between 2 and 3. This would result in an "unclamped" leakage current which increases superlinearly with total injection current beyond lasing threshold. In this work, we present an electron leakage over the heterobarrier which incorporates the influence of both the electric field and carrier heating effect [11], [12].

Under high injection conditions in double heterostructure InGaAsP LED's and lasers, if the doping level in the P-InP cladding layer is low, it can easily be shown that there exists a substantial electric field across the InP layer. In such a case, the hole current can be written as

$$\vec{J}_p = e\mu_P N_A \vec{E} \tag{1}$$

where e is the electric charge, μ_P the hole mobility, N_A the doping level in the P-InP layer, and $\vec{E}$ the electric field strength. For simplicity, only the component transverse to the junction will be considered. The ratio of the drift and diffusion components of the electron leakage current across the p-InGaAsP-P-InP heterojunction is then given approximately by

$$\frac{J_{\text{drift}}}{J_{\text{diff}}} \approx \left(\frac{\mu_N}{\mu_P}\right) \frac{L}{eD_N N_A} J_p \tag{2}$$

where L is the thickness of the cladding layer, and is assumed to be small compared to the diffusion length of electrons in the P cladding layer, μ_N the electron mobility, and D_N the

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electron diffusion constant. Taking $\mu_N = 3000$ cm^2/V · s, $\mu_P = 150$ cm^2/V · s [13], $L = 1.5$ μm, $D_N = 77$ cm^2/s (at 300 K), and $N_A = 10^{17}$ cm^{-3}, it is easily verified that the drift current is larger than the diffusion current when J_p exceeds ~420 A/cm^2. Since normal lasers operate at much higher current densities, it is expected that the drift rather than diffusion current will dominate. Since the drift (leakage) current increases with the field $\vec{E}$, and $\vec{E}$ increases with J_p [see (1)], it follows that the leakage current continues to grow with current past threshold.

Fig. 1 shows the band structure at the p-InGaAsP-P-InP heterointerface at thermal equilibrium. κ, the fraction of the diffusion potential (V_D) on the widegap side, is given by [14]

$$\kappa = \frac{1}{1 + (\epsilon_2 N_{A2}/\epsilon_1 N_{A1})} \tag{3}$$

where ϵ is the dielectric constant and the subscripts 1 and 2 denote the low and high gap materials, respectively. The hole current under a forward bias $V\,(= V_1 + V_2, V_2 = \kappa V, V_1 = (1-\kappa)V)$ is then given by

$$\begin{aligned} J_P &= \tilde{J}_{ps}(e^{eV_2/kT} - e^{-(eV_1/kT)}) \\ &= \tilde{J}_{ps} e^{-(eV_1/kT)} (e^{eV/kT} - 1) \\ &= J_{ps}(e^{eV/kT} - 1) \end{aligned} \tag{4}$$

with

$$\begin{aligned} J_{ps} = eN_{A2} \left(\frac{kT}{2m_{2h}\pi}\right)^{1/2} &\frac{1}{\left(1 + \dfrac{(kT/2m_{2h}\pi)^{1/2}}{V_{d2}}\right)} \\ &\cdot e^{-(eV_1/kT)} e^{-(\kappa eV_D/kT)} \end{aligned} \tag{5}$$

where

$$\begin{aligned} V_{d2}^{-1} = \frac{1}{\mu_{P2} kT} &e^{[(1-\kappa)eV_D]/kT} e^{-(\Delta E_v/kT)} \\ &\cdot \operatorname{erf}\left[\left(\frac{\kappa eV_D}{kT}\right)^{1/2}\right] \sqrt{\frac{\pi\epsilon_2 kT}{2N_{A2}}} \end{aligned} \tag{6}$$

which are exact analogues of the thermionic-diffusion model of a Schottky barrier [15]. In the previous equations, m_{2h} is the hole effective mass and ΔE_v is the discontinuity in the valence band. The electron concentration at x_2 (see Fig. 1) is given approximately by

$$\begin{aligned} N_2(x_2) = \left(\frac{m_{2e}}{m_{1e}}\right)^{3/2} &n_1 \exp\left[\sum_{i=1}^{4} A_i \left(\frac{n_1}{N_{c1}}\right)^i\right] \\ &\cdot \exp\left(-\frac{\Delta E_c}{kT}\right) \exp\left(\frac{eV_D}{kT}\right) \exp\left[\left(\frac{eV}{kT}\right) - 1\right] \end{aligned} \tag{7}$$

where n_1 is the electron density in material 1 (InGaAsP), A_i's are constants which account for the degeneracy [14], and N_{c1} and N_{c2} are the conduction band effective density of states.

In most cases, it can be verified that $v_d \gg (kT/2m_{2h}\pi)^{1/2}$, and the conduction mechanism is thermionic emission dominated [16]. Also, though (4) indicates a rectifying characteristic, the large J_{ps} value (which exceeds 1000 A/cm^2 in most cases) renders the junction more "ohmic" than rectifying in nature.

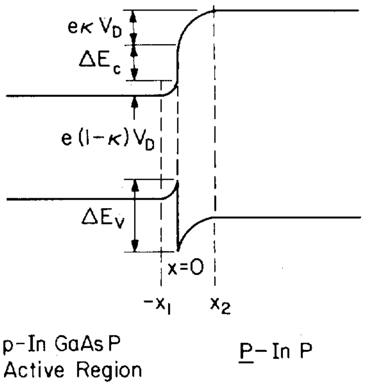

Fig. 1. Band structure at the p-InGaAsP-P-InP heterointerface at thermal equilibrium.

Solving the carrier transport and continuity equations for electrons, the electron leakage current is given by [10]

$$\begin{aligned} J_e(x) = \left(\frac{\mu_N}{\mu_P}\right) &\frac{J_p}{N_{A2}} N_2(x_2) - \frac{eD_N}{A} N_2(x_2) \\ &\cdot \left[\frac{1}{y_1} e^{L/y_2 - x/y_1} + \frac{1}{y_2} e^{-(L/y_1) + x/y_2}\right] \end{aligned} \tag{8}$$

where

$$A = e^{x_2/y_2 - L/y_1} - e^{-(x_2/y_1) + L/y_2}$$

$$y_{\frac{1}{2}} = \frac{\pm L_{ed}^2 + \sqrt{L_{ed}^4 + 4L_e^2}}{2}$$

$$L_{ed}^2 = \left(\frac{\mu_N}{\mu_P}\right) \frac{J_p \tau_{N2}}{eN_{A2}}, \quad \text{and} \quad L_e^2 = D_N \tau_{N2} \tag{9}$$

with τ_{N2} the electron lifetime in the InP cladding layer. In arriving at the above solution, we have assumed the boundary condition of $N_2(L) = 0$. However, when the leakage is drift dominated, the boundary condition $N_2(L)$ is not important, as is apparent from (8).

The total injected current density J_{tot} is simply

$$J_{\text{tot}} = J_p + J_e = J_{\text{rec}} + J_{\text{leak}}. \tag{10}$$

Since J_e is just the leakage current J_{leak}, it follows that the recombination current $J_{\text{rec}} = J_p$. Up to lasing threshold, J_p can be expressed as

$$\begin{aligned} \frac{J_{\text{rec}}}{ed} = Bn_1(n_1 + N_{A1}) &+ C_{\text{chcc}} n_1^{2.09} (n_1 + N_{A1}) \\ &+ C_{\text{chsh}} n_1 (n_1 + N_{A1})^{2.14} \end{aligned} \tag{11}$$

where d is the active layer thickness, B the radiative recombination constant, C_{chcc} and C_{chsh} are the Auger coefficients for the CHCC and CHSH processes [17]. B is estimated from spontaneous lifetime data and C_{chcc} and C_{chsh} are calculated as described in [17].

As can be seen from (4)-(7), the discontinuities in the conduction (ΔE_c) and valence band (ΔE_v) play an important role in determining the magnitude of the leakage current. Unfor-

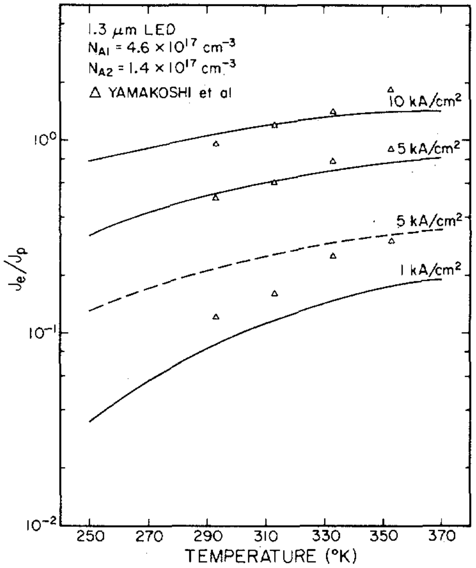

Fig. 2. Calculated J_e/J_p under different injection conditions. Experimental data are from [2]. The dashed line denotes the result when hot carrier effect is neglected.

tunately, the discontinuity in the quaternary system is not accurately known. However, there are experimental [18], [19], and theoretical [20] indications that a substantial fracion of the discontinuity lies in the valance band. We have used $\Delta E_c = \frac{1}{3}\Delta E_g$ as measured in [18] and [19]. If the interface is graded, then the potential "spike" which is resistive to hole injection would decrease, resulting in less leakage. In this work, an abrupt interface is assumed. However, the ratio $\Delta E_c/\Delta E_v$ as well as the doping level N_{A2} are varied to provide a quantitative trend and estimate of the leakage current and its effects.

It was found that for 1.3 μm LED's, if effects of carrier heating and/or Auger enhanced leakage [21] were excluded, the predicted leakage using reasonable parameters would be much smaller than the observed values. Much better agreement could be obtained by incorporating carrier heating effect or employing a boundary condition $n_2(x_2) \sim \exp\left[-\frac{3}{4}(\hbar\omega_o/E)\cdot(d^2/L_P^2)\right]$ (when $\hbar\omega_o$ is the optical phonon energy, E is the maximum energy an Auger electron can lose and still be able to surmount the heterobarrier, and L_P is the electron mean free path). Due to the uncertainty in L_P and the availability of experimental data on carrier heating effect, the former is chosen. The results of T_e at 300 K from [12] have been used and the electron temperatures at various lattice temperatures (T_L) are estimated from the expression

$$T_e(T_L) = T_e(300)\frac{C_{\text{chcc}}(T_L)}{C_{\text{chcc}}(300)}. \tag{12}$$

Thus, it is implicitly assumed that the hot carriers are generated by the Auger process.

Results of the calculation are presented in Figs. 2–4. Fig. 2 shows the calculated ratio of J_e/J_p in an LED with $d = 0.15$ μm, $L = 0.3$ μm at various temperatures under three different injection conditions. The triangles are experimental data from [2]. For $\Delta E_c = \frac{1}{3}\Delta E_g$, reasonable agreement can be obtained by taking $N_{A1} = 4.6 \times 10^{17}$ cm^{-3} and $N_{A2} = 1.4 \times 10^{17}$ cm^{-3}.

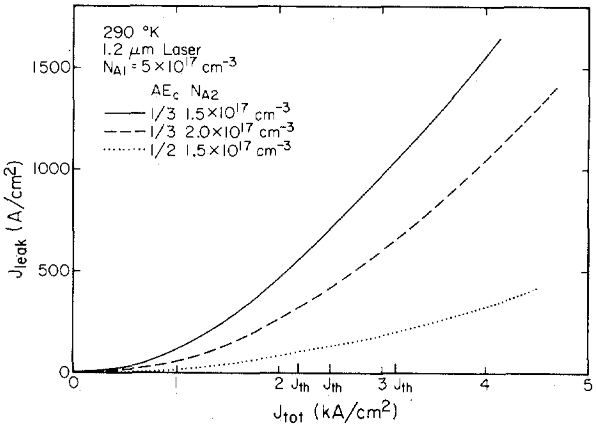

Fig. 3. Calculated electron leakage current versus total injected current for different P-InP doping levels and different discontinuities (ΔE_c) in the conduction band.

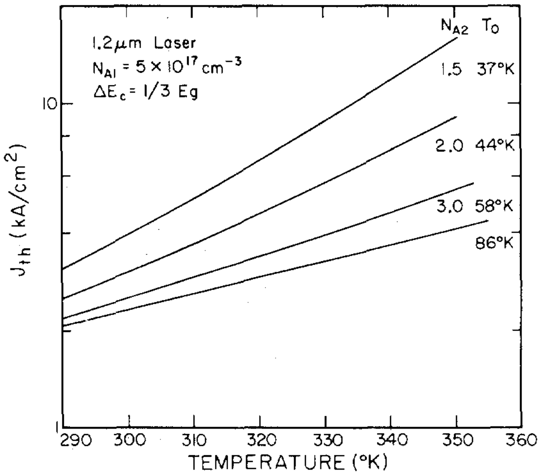

Fig. 4. Calculated T_o for different P-InP doping levels. The $T_o = 86$ K is calculated without electron leakage.

The dashed line denotes the ratio of J_e/J_p when carrier heating effects have been neglected. Note that the temperature dependence of J_e/J_p remains the same when (12) is used. Fig. 3 shows the calculated effect of doping and discontinuity on the magnitude of leakage current in a 1.2 μm laser with $d = 0.2$ μm and $L = 1.5$ μm. It is apparent that in order to minimize leakage, the cladding layer could be heavily doped or a graded junction be grown to smear the "spike" at the interface. There is a slight discontinuity in slope at J_{th}. However, for larger leakage currents, the change in slope is very small and insignificant. Fig. 4 depicts the effect of leakage current on the T_o of the laser. The influence of the P-doping is again conspicuous. The general trend is in agreement with the experimental results of Ng *et al.* [6] and Mito *et al.* [22].

In lasers, as a comparison, for $\Delta E_c = \frac{1}{3}\Delta E_g, N_{A1} = 5 \times 10^{17}$ cm^{-3}, and $N_{A2} = 2 \times 10^{17}$ cm^{-3}; the ratios of J_e/J_{tot} at an ambient temperature of 290 K for 1.2, 1.3, and 1.5 μm devices are estimated to be 22, 11, and 4 percent, respectively, when carrier heating effects [12] are taken into account. The corresponding figures are 11, 3, and 0.4 percent when hot carriers are absent. Thus, it can be seen that carrier heating effects play an important role in device performance, especially for wavelengths beyond 1.3 μm.

In conclusion, a model calculation for the field and hot carrier enhanced electron leakage over the heterobarrier in InGaAsP/InP LED's and lasers has been presented. Results reveal the importance of the doping level in the P-InP confining layer in determining the magnitude of the leakage current.

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