The effect of the photon recycling phenomena on the current gain characteristics of (GaAl)As-GaAs-GaAs heterojunction transistors

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Recibido el 18 de junio de 1997; aceptado el 2 de septiembre de 1997

The effect of the photon recycling phenomena on the current gain characteristic of (GaAl)As-GaAs heterojunction transistors is studied. We found that, in the presence of such phenomena, the transistor common-emitter current gain depends strongly on the minority carriers diffusion length in the collector region. Furthermore, the transistor current gain is determined by an *effective* base diffusion length which is not constant, but depends on the base width. The results show that in order to optimize the transistor performance, the collector diffusion length must be as large as possible.

Keywords: Transistor, photon recycling

Se estudia el efecto del reciclaje de fotones en las características de la ganancia de corriente de transistores de (GaAl)As-GaAs-GaAs. Se encuentra que, considerando tales fenómenos, la ganancia del emisor-común del transistor, depende fuertemente de la longitud de difusión en la región del colector. Más aún, la ganancia de corriente del transistor es determinada por una longitud de difusión *efectiva* de la base, la cual no es constante, sino que depende de la anchura de ésta. Los resultados muestran que con el fin de optimizar el desempeño del transistor, la longitud de difusión debe ser tan larga como sea posible.

Descriptores: transistor, reciclaje de fotones

PACS: 78.31.Fs; 85.30.Pq

1. Introduction

Heterojunction transistors have potential advantages over the conventional homojunction transistors, as was first recognized by Shockley [1], and later by Kroemer [2]. In fact, a heterojunction transistor, which consists of a wide-band-gap emitter and a narrow-band gap base should have a near unity minority carrier injection efficiency at the emitter-base junction. This is due to the large potential barrier for the injection of carriers towards the emitter, as compared with the potential barrier opposing the injection of carriers towards the base. In principle, there are many semiconductors pairs suitable for the fabrication of heterojunction transistors [3]. In practice, most of the recent developments on this field have been focused on GaAs based materials [4,5]. Nevertheless, successful devices of this type waited until the appearance of the (GaAl)As-GaAs heterojunction, which is relatively free of interface states [6–9]. From the technological point of view this kind of devices have many advantages as power and high speed applications [10].

In a previous paper [11], it has been pointed out that the photon recycling phenomena must play an important role in determining the current gain characteristics of transistors fabricated with materials having a high quantum efficiency of photon emission (η). On the other hand, due to the recent developments in growth techniques, such as molecular beam epitaxy (MBE) [12], metalorganic vapor phase epitaxy (MOVPE) [13] and LPE, GaAs and (GaAl)As [14,15] can yield values of η close to one. This high values of η indicate that the photon recycling should have an important role on the transistor performance. Thus, given this fact, it seems desirable to investigate quantitatively how the photon recycling phenomena affects the current gain characteristics (β) of (GaAl)As-GaAs transistors.

It is the purpose of this paper to contribute to shed light on this subject by determining the role of the photon recycling phenomena on the common-emitter current gain of (GaAl)As-GaAs heterojunction transistors. It is found that through this process β is not longer a function of the carrier transport parameters of the base region but also of those of the collector. The results are reported as a function of the parameters of the base region (minority carrier diffusion length and quantum efficiency of photon production) and the diffusion length of the collector region.

The rest of the paper is organized as follows. In Sect. 2 a brief account of the theoretical background is given. Results for β as a function of the relevant parameters are discussed in Sect. 3. Finally, Sect. 4 summarizes our conclusions.

2. Theory

We consider a (GaAl)As-GaAs heterojunction transistor with a (GaAl)As emitter and a GaAs base (Fig. 1). For simplicity, in order to derive an analytical expression for the common-emitter current gain including the effect of photon recycling, we assume that the minority carrier profile in the base is given by a straight line (Fig. 1). Notice that this is a very good approximation for high current gain devices [16]. Under these assumptions, the number of carriers effectively recombining per unit time in the base region (base current) is given by

$$I_b = \frac{qn_0 W}{2\tau_b}(1 - P\eta), \tag{1}$$

where n_0 refers to the electron concentration in the base region at the emitter-base junction, W to the transistor base width, τ_b to base minority carrier life time and η to the quantum efficiency of photon production in the base region.

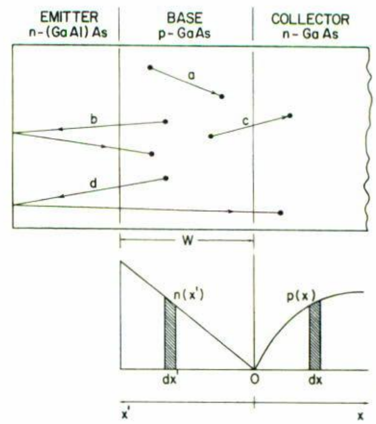

FIGURE 1. Schematic representation of the geometrical structure of the (GaAl)As-GaAs heterojunction transistor.

$P = P_1 + P_2$, where P_1 is the probability for a photon generated in the base region to be absorbed there (through processes a and b in Fig. 1). P_2 refers to the probability that a hole is generated in the base region (through processes c and d in Fig. 1) and is collected at the collector-base junction. Obviously, these collected holes contribute to decrease the base current. P_1, is obtained from

$$P_1 = 1 - \frac{1}{W^2}\int_0^W \int_0^{\pi/2} x' \sin\theta \exp\left[\frac{-\alpha_b(W + x')}{\cos\theta}\right] dx'\, d\theta - \frac{1}{W^2}\int_0^W \int_o^{\pi/2} x' \sin\theta \exp\left[\frac{-\alpha_b(W - x')}{\cos\theta}\right] dx'\, d\theta, \tag{2}$$

where α_b stands for the base optical absorption coefficient, and θ is the angle between propagating photon and the normal to the (GaAl)As-GaAs interface. Notice that we have taken into account photon absorption through both processes a and b in Fig. 1.

To calculate the probability P_2, we must solve the hole diffusion equation in the collector region,

$$D_c \frac{d^2 p}{dx^2} - \frac{p}{\tau_c} + G(x) = 0, \tag{3}$$

with the boundary conditions (see Fig. 1)

$$p(0) = 0, \qquad p(\infty) = 0.$$

Here, $p(x)$ refers to the hole concentration in the collector region and D_c to the collector minority carrier diffusion coefficient. The hole generation, $G(x)$ is given by

$$G(x) = \frac{1}{W^2}\int_o^W x' G(x, x')\, dx', \tag{4}$$

$$G(x, x') = F\alpha_c E_1[\alpha_b x' + \alpha_c x] + E_1[\alpha_b(2W - x') + \alpha_c x], \tag{5}$$

where F is the total number of photons generated per unit time in the base region, and α_c is the collector optical absorption coefficient. $E_1[x]$ refers to the exponential-integral function. Notice that the expression for $G(x)$ takes into account hole generation by both processes c and d in Fig. 1. Furthermore, we should note that, as justified in the Appendix, in writing Eq. (3) we have not explicitly taken into account photon recycling effects.

Solving Eq. (3) for $p(x)$ with the given boundary conditions, we obtain the derivative of $p(x)$ evaluated at $x = 0$:

$$p'(0) = \frac{F\alpha_c L_c}{D_c W^2}\int_0^W \left\{ x' E_1[\alpha_b x'] + E_1[\alpha_b(2W - x')] - E_1\left[x'\left(\alpha_b + \frac{\alpha_b}{\alpha_c L_c}\right)\right] \exp\left(\frac{\alpha_b x'}{\alpha_c L_c}\right) - E_1\left[(2W - x')\left(\alpha_b + \frac{\alpha_b}{\alpha_c L_c}\right)\right] \exp\left[\frac{\alpha_b(2W - x')}{\alpha_c L_c}\right]\right\} dx', \tag{6}$$

where we have made use of the integral formulas given in Ref. 17, and $L_c = \sqrt{D_c \tau_c}$ is the minority carrier diffusion length in the collector region.

P_2 is obtained from $P_2 = D_c p'(0)/F$. With the previously obtained expressions for P_1 and P_2, we finally get

$$\begin{aligned} P =& \left(\frac{1}{3\alpha_b W} - \frac{1}{3} - \frac{2}{3\alpha_b^2 W^2} + \frac{2\alpha_c^2 L_c^2}{\alpha_b^2 W^2} + \frac{\alpha_c L_c}{\alpha_b W} - \frac{\alpha_c L_c}{\alpha_b^2 W^2} \right) \exp(-\alpha_b W) \\ &+ \left(\frac{1}{6\alpha_b W} + \frac{1}{3\alpha_b^2 W^2} + \frac{\alpha_c L_c}{2\alpha_b^2 W^2} - \frac{1}{3} - \frac{\alpha_c L_c}{\alpha_b W} - \frac{\alpha_c^2 L_c^2}{\alpha_b^2 W^2} \right) \exp(-2\alpha_b W) \\ &+ \frac{\alpha_c^3 L_c^3}{\alpha_b^2 W^2} \ln\left(1 + \frac{1}{\alpha_c L_c}\right) + 1 + \frac{1}{3\alpha_b^2 W^2} - \frac{\alpha_c^2 L_c^2}{\alpha_b^2 W^2} + \frac{\alpha_c L_c}{2\alpha_b^2 W^2} - \frac{1}{2\alpha_b W} \\ &+ E_1[2\alpha_b W]\left(\frac{\alpha_c^3 L_c^3}{\alpha_b^2 W^2} + 2\frac{\alpha_c^2 L_c^2}{\alpha_b W} + 2\alpha_c L_c + \frac{2}{3}\alpha_b W \right) - E_1[\alpha_b W]\left(\alpha_c L_c + \frac{2\alpha_c^2 L_c^2}{\alpha_b W} + \frac{2\alpha_c^3 L_c^3}{\alpha_b^2 W^2} - \frac{\alpha_b W}{3} \right) \\ &+ \frac{2\alpha_c^3 L_c^3}{\alpha_b^2 W^2} E_1[W(\alpha_b + \alpha_b/\alpha_c L_c)] \exp(\alpha_b W/\alpha_c L_c) - \frac{\alpha_c^3 L_c^3}{\alpha_b^3 W^2} E_1[2W(\alpha_b + \alpha_b/\alpha_c L_c)] \exp(2\alpha_b W/\alpha_c L_c). \end{aligned} \tag{7}$$

Since the collector current I_c is given by $qD_b n_0/W$ (D_b refers to the base minority carrier diffusion length), the current gain $\beta = I_c/I_b$ can be written as

$$\beta = 2\left(\frac{L_0}{W}\right)^2 \frac{1}{(1 - P\eta)}, \tag{8}$$

where $L_0 = \sqrt{D_b \tau_b}$ refers to the diffusion length in the absence of photon recycling and P is obtained from Eq. (7). Notice that in writing Eq. (8) an unity emitter injection efficiency was assumed. If $P = 0$, Eq. (8) reduces to the classical expression for β [16]. Moreover, the factor $(1 - P\eta)^{-1}$ represents the modification in β due to the photon recycling processes. We can also say that, in the presence of these processes, there is an effective diffusion length in the base equal to $L_0/(1 - P\eta)^{1/2}$.

3. Results and discussion

In this section we present and discuss results for the probability P and the common-emitter gain β of (GaAl)As-GaAs heterojunction transistors as a function of base width W for several values of the collector diffusion length, L_c. For the calculations of P and β we have made the following assumptions: (1) a doping concentration of 1.2×10^{18} and 5×10^{16}/cm^3 for the base and collector regions respectively; (2) a semi-infinite epitaxial collector region. (3) a negligible absorption for photons crossing the (GaAl)As layer by paths b and d in Fig. 1; (4) a mirror-like 100% reflection for emitted photons incident on the (GaAl)As-air interface; (5) a zero optical mismatch at the (GaAl)As-GaAs interface. It should be also noted that Eq. (7) stands only for monochromatic light. As it is not the case for real systems and applications, P should be calculated by considering an average over the whole luminescence spectrum. In our calculations, this spectrum was obtained by using the van Roosbroeck-Shockley detailed balance approach[18], and published values of α_b and α_c [19].

In Fig. 2 we present the calculated values of P as a function of W for several values of L_c. Our results show a strong dependence of P on the considered values of L_c. As a consequence, L_c has also a large influence on the base effective diffusion length. For $L_c = 0$, P increases monotonically as a function of W. This is not the case for finite values of L_c. Notice that for small values of L_c ($L_c = 5\,\mu$m), P is almost constant for $0.05\,\mu\text{m} \leq W \leq 1.0\,\mu$m. For large values of L_c ($L_c = 25\,\mu$m), the P dependence on W shows an interesting behavior. First, notice that P decreases as W increases. This is due to the dependence of P_1 and P_2 on W and L_c [see Eqs. (2) and (6)]. First notice that P_1 increases as W increases. On the other hand P_2 decreases for increasing W. Therefore, the total probability P as a function of W is obtained as a competition between P_1 and P_2. For larger values of W ($W \geq 5\,\mu$m), however, we obtain that P is close to

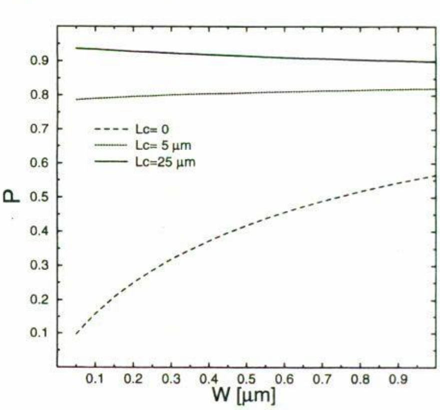

FIGURE 2. P as a function of the transistor base width W, for three different values of the minority carrier diffusion length in the collector region L_c.

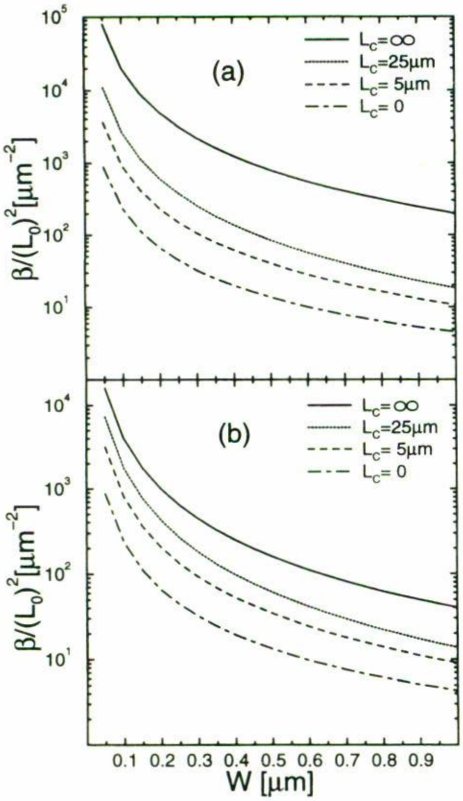

FIGURE 3. The current gain divided by the square of the diffusion length in the absence of photon recycling, β/L_0^2, as a function of the transistor base width W, for different values of the collector diffusion length L_c. (a) refers to results obtained using $\eta = 0.99$ and (b) refers to results obtained using $\eta = 0.95$.

unity as expected. Obviously these results should have a strong influence on the calculated values of β. For instance, if $L_c = \infty$ ($P = 1$, independently of W) β depends on W in the same way as in the classical expression [16]. On the other hand, if L_c has a finite value, P changes if the transistor base width is modified. In this case, β depends on W in a different way form that in the classical expression, since here the effective diffusion length in the base changes as a function of W.

In Figs. 3a ($\eta = 0.99$) and 3b ($\eta = 0.95$), we show the common-emitter current gain of the (GaAl)As-GaAs transistor as calculated from Eq. (8) by using the P values of Fig. 2. β is shown as a function of W, using L_c as a parameter. Because the above mentioned dependence of the base effective diffusion length on L_c, there is also a strong dependence of β on this parameter. The maximum dependence is found for large values of η. For instance, for $\eta = 0.99$, β changes about two orders of magnitude when we go from $L_c = 0$ to $L_c = \infty$, the change being larger the smaller the base width. It should be noted that this high value of η is not unreasonable as reported elsewhere [14,15].

Interestingly, the results of Fig. 3 show that β depends not only on the parameters of the transistor base, but also on the diffusion length of the collector region. This might have important consequences for technological purposes. For instance in designing a transistor, one should look for a collector diffusion length as large as possible. Furthermore, in order to optimize the transistor performance, we must fabricate the epitaxial collector width much larger than L_c, otherwise the current gain will be strongly reduced due to the small diffusion length of the GaAs substrate (see Fig. 3). It should be stressed that the results of Fig. 3 were obtained by assuming a semi-infinite collector. Therefore, for a collector width of the order or smaller than L_c should decrease the transistor $\beta's$ to values smaller than those reported in Fig. 3.

Furthermore, our results show that the determination of the current gain of a given transistor by using base diffusion lengths measured with a structure different might lead to wrong conclusions. This is due to the fact that these values of the diffusion length may be different from those of the effective base diffusion length of the actual device. For instance, as pointed out elsewhere [11], it may be possible that the diffusion lengths deduced from the photo-response to a laser beam of a bevelled p-n junction [20] approximately correspond to $L_0/(1-\eta)^{1/2}$, that is to say to the condition $P = 1$. In a narrow base transistor, on the other hand, P may be significantly different from unity depending on the L_c and base width values as given in Eq. (7).

4. Summary

In this work, the influence of the photon recycling phenomena on the common emitter current gain of (GaAl)As-GaAs heterojunction transistors was investigated. Simple analytical expressions for the transistor effective diffusion length in the base region have also been derived. We have shown that β is largely dependent on the minority carrier diffusion length of the collector region. This dependence is more remarkable the closer η is to unity. Moreover, the transistor effective diffusion length in the base region, depends strongly, among other parameters, on the base width. Because of this, β depends on W in a different way from that in the case of the classical expression [16].

Several improvements would be desirable in order to achieve a more realistic description of the physical situations of direct experimental interest. In fact, in the actual heterojunction bipolar transistor (HTB) designs, the base has to be much more heavily doped than the collector. Otherwise, the base resistance is high, losing the advantage of the HBT. Namely, the effective gaps considerably differ between the two layers. The proposed collector design in this work does not match the high-speed HBT's. However, the main purpose of this work, was to demonstrate the gain enhancement due to photon recycling. From this point of view, the calculations presented in this paper should provide, in spite of the limitations of the structure design, a valuable first insight into the role of the photon recycling phenomena on the current gain characteristics of HBT's.

Acknowledgments

This work has been supported in part by CONACyT (México) through grant No. 485100-5-4977E and the Organization of the American States.

Appendix

In this Appendix, we justify the approximation made upon solving Eq. (3). The main approximation refers to the neglecting of photon recycling in the collector region. If we were to take explicitly into account this phenomena, we would have to add to $G(x)$ in Eq. (4) a term which considers the hole generation of the absorption of photons in the neighborhood of x (see Ref. 11). This complicates considerably the solution of the diffusion equation in the collector region. However, we can show that it is not really necessary to solve such a complicated equation, since the P values obtained by considering photon recycling in the collector region are not significantly different from those calculated by using the simpler Eq. (4). On the other hand, though not explicitly, we are *implicitly* considering photon recycling processes in Eq. (3), since the L_c values may be determined by them. The physical assumption made in writing Eq. (4) is that there are not emitted photons escaping from the collector towards the base. Therefore, there is not contribution of those emitted photons to the recycling process. In addition, L_c is given by the "bulk" value defined in Ref. 11.

In the following we estimate the ratio of the number of emitted photons leaving the collector towards the base (F_c) to the total number of holes collected at the base-collector junction (I_c/q). Since a rough estimation is enough, we expand the hole concentration $p(x)$ in a Taylor series around $x = 0$, retaining only the linear term. Then,

$$F_c = \frac{p'(0)}{2\tau_{rc}} \int_0^\infty \left[\int_0^{\pi/2} \int_0^\infty x \sin\theta \times \exp\left(\frac{-\alpha_c}{\cos\theta}\right) dx\, d\theta \right] \rho(h\nu)\, d\nu \tag{9}$$

where we have made use of the fact that the quantum efficiency of photon production in the collector region is given by τ_c/τ_{rc} (τ_{rc} refers to the collector minority carrier radiative life time). Evaluating the integrals inside the square bracket, and considering that $I_c/q = D_c p'(0)$, we get

$$\frac{F_c}{I_c/q} = \frac{1}{6} \int_0^\infty (\alpha_c L_{rc})^{-2} \rho(h\nu)\, d\nu. \tag{10}$$

Here, $L_{rc} = \sqrt{D_c \tau_{rc}}$. Notice that L_{rc} is not the same as L_c, since this last parameter includes the effects of non radiative recombination and photon recycling [11]. Due to the fact that $(\alpha_c L_{rc})^{-2}$ is much smaller than unity for most of the emitted photons, the ratio of the number of photons leaving the collector to the total number of holes collected is very small. This result justifies the use of Eq. (4) for the calculation of P_2, since the number of collected holes obtained in this way is overestimated at most by F_c.

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