Coherent and sequential photoassisted tunneling through a semiconductor double-barrier structure

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We have studied the problem of coherent and sequential tunneling through a double-barrier structure, assisted by light considered to be present all over the structure, i.e., emitter, well, and collector as in the experimental evidence. By means of a canonical transformation and in the framework of the time-dependent perturbation theory, we have calculated the transmission coefficient and the electronic resonant current. Our calculations have been compared with experimental results and turn out to be in good agreement. Also, the effect on the coherent tunneling of a magnetic field parallel to the current in the presence of light has been considered.

I. INTRODUCTION

Resonant tunneling[1] through double-barrier structures (DBS's) has been one of the most active fields in research in solid-state physics, both from theoretical and experimental standpoints. The main reason is that resonant tunneling has been considered to have a great potential applicability in electronic devices. In the same way, the interaction of an external time-dependent potential with resonant structures is considered to have very interesting applications, for instance, the use of DBS's as detectors and generators of microwave radiation. In this paper we are going to study the effect of a photon field on both coherent and sequential tunneling current through a DBS.

The work of Sollner *et al.*,[2] is the experimental starting point for studies on the effect of time-dependent potentials in resonant tunneling through semiconductor microstructures: they studied the influence of electromagnetic radiation on the resonant tunneling current. Recently Chitta *et al.*[3] have studied the far infrared response of double-barrier resonant tunneling structures. Theoretical work on tunneling devices under the influence of a time-dependent potential has a long history. Tien and Gordon[4] studied the effect that microwave radiation has on superconducting tunneling devices. Several authors[5–10] have investigated the effect that external ac potentials have in different problems. Jonson,[11] Apell and Penn,[12] and Johansson and Wendin[13] have studied the sequential contribution to the tunneling through a DBS under an applied electromagnetic field, using models based on the transfer Hamiltonian formalism.[14] In all those models above, the coupling between electrons and the electromagnetic field is considered to take place in just a part of the structure; in most of them in the well, and in the case of Apell and Penn[12] in the emitter and collector, but in none of them affecting the whole structure.

In this paper we have calculated how the transmission coefficient and the current for electrons in a DBS are changed due to the presence of light in the whole structure. In order to do that we have developed a quantum mechanical formalism to find an expression for the electronic state dressed by photons and we have calculated the resonant tunneling current under the influence of an external electromagnetic field. This quantum mechanical formalism based on a canonical transformation and in the time-dependent perturbation theory has been applied to coherent and sequential tunneling processes, and the results we have obtained are in good agreement with the available experiments.[3] The case of coherent resonant tunneling assisted by light in the presence of a magnetic field parallel to the current has also been studied.

This paper is organized as follows. In Sec. II, we discuss and develop the theoretical formalism. In Secs. III A and III B, we apply that formalism to coherent and sequential tunneling, respectively. In Sec. IV, our results for both types of tunneling for different frequencies, external electromagnetic fields, and magnetic fields are presented and compared with experimental[3] results. We summarize our conclusions in Sec. V.

II. ELECTRONIC STRUCTURE OF THE SYSTEM WITH LIGHT

The quantum mechanical Hamiltonian for an electron in the presence of an electromagnetic field represented by a plane electromagnetic wave of wave vector $\vec{k}$, parallel to the x direction and polarized in the z direction $\vec{E} = (0,0,F)$ (see Fig. 1), can be written as

$$H_{\rm tot} = (1/2m^*)[\vec{P} + e\vec{A}(\vec{R},t)]^2 + V(\vec{R}) + \hbar w a^\dagger a. \quad (1)$$

In our problem we apply an external bias, such that the

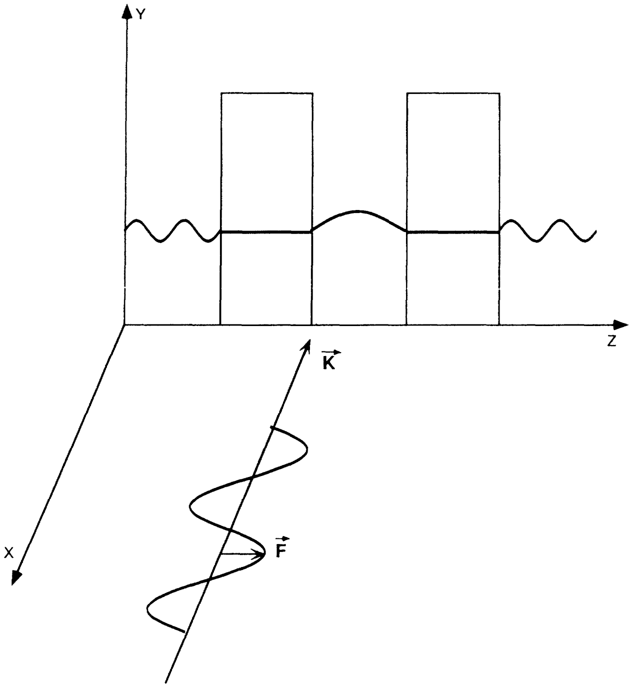

FIG. 1. Particle represented by a plane wave moving along the z direction crossing a DBS in the presence of an electromagnetic field polarized in the z direction.

electrostatic and barrier potential depends only on the z direction, so we take the potential $V(\vec{R})$ as $V(z)$. In the Coulomb gauge $\vec{\nabla}\cdot\vec{A}=0$ and (1) becomes

$$H_{\rm tot} = P^2/2m^* + (e/m^*)\vec{P}\cdot\vec{A}(\vec{R},t) + (e^2/2m^*)A^2(\vec{R},t) + V(z) + \hbar w a^\dagger a. \qquad (2)$$

In our case the vector potential operator $\vec{A}(\vec{R},t) = A_z(x,t)$. In general, $A^2(R,t)$ is negligible compared to the $(e/m^*)\vec{P}\cdot\vec{A}(\vec{R},t)$ term; therefore we can write in second quantization for the total Hamiltonian

$$H_{\rm tot} = H_e^0 + H_{\rm ph}^0 + W_D(t) + W_{\rm OD}(t), \qquad (3)$$

where

$$H_e^0 = \sum_k \epsilon_k c_k^\dagger c_k, \qquad (4)$$

$$H_{\rm ph}^0 = \hbar w a^\dagger a, \qquad (5)$$

$$W_D(t) = \sum_k [(e/m^*)\langle k|P_z|k\rangle c_k^\dagger c_k (\hbar/2\epsilon V w)^{1/2} \times (a e^{-iwt} + a^\dagger e^{iwt})], \qquad (6)$$

$$W_{\rm OD}(t) = \sum_k \sum_{k'\neq k} [(e/m^*)\langle k'|P_z|k\rangle c_{k'}^\dagger c_k \times (\hbar/2\epsilon V w)^{1/2} (a e^{-iwt} + a^\dagger e^{iwt})]. \qquad (7)$$

Here $A_z(x,t) = (\hbar/2\epsilon V w)^{1/2}\vec{\epsilon_z}(a e^{-iwt} + a^\dagger e^{iwt})$, w being the photon frequency, the wave vector of the electromagnetic field has been neglected, and the term e^{-iEt} is already included in the state vector $|k\rangle$. H_e^0 is the independent, electronic Hamiltonian and includes the double-barrier potential and the external applied bias; therefore the eigenstates of H_e^0, $\Psi_0(k)$, are the tunneling states for bare electrons. $H_{\rm ph}^0$ is the photon field Hamiltonian whithout coupling with electrons and W_D and $W_{\rm OD}$ describe the coupling between electrons and photons in the total Hamiltonian. We separate the coupling term into the "diagonal" (6) and the "off-diagonal" (7) contributions because we are going to be interested in problems where a quasilocalized state is connected by the electromagnetic field with a continuum of extended states. Therefore $W_{\rm OD}$ can be treated in first-order time-dependent perturbation theory. For problems in which two or more quasilocalized states should be connected by the light, the method could not be applied in the same way, requiring some generalization. Therefore the total Hamiltonian can be written as

$$H_{\rm tot} = H_D(t) + W_{\rm OD}(t), \qquad (8)$$

where $H_D(t) = H_e^0 + H_{\rm ph}^0 + W_D(t)$.

The Hamiltonian H_D can be solved exactly by considering a canonical transformation.[11,15] It allows one to obtain the exact electronic wave function dressed by photons: $\Psi_D(k) = U^\dagger\Psi_0(k)$, where $\Psi_0(k)$ is the electronic double-barrier eigenstate with no photon field present in the sample. Once we have obtained the eigenstates for H_D, we apply time-dependent perturbation theory in order to treat the $W_{\rm OD}$ term. The operator U for the canonical transformation is given by $U = e^s$, and s can be written as

$$s = \frac{e}{m^*\hbar w}\left(\frac{\hbar}{2\epsilon V w}\right)^{1/2} \langle P_z\rangle c_k^\dagger c_k (a^\dagger e^{iwt} - a e^{-iwt}) = \frac{M}{\hbar w} c_k^\dagger c_k (a^\dagger e^{iwt} - a e^{-iwt}). \qquad (9)$$

The Hamiltonian under this transformation becomes

$$\tilde{H}_D = \tilde{c}_k^\dagger \tilde{c}_k \left(\epsilon_k - \frac{M^2}{\hbar w}\right) + \hbar w \tilde{a}^\dagger \tilde{a}, \qquad (10)$$

where $\tilde{a}^\dagger = a^\dagger - \frac{M}{\hbar w} c_k^\dagger c_k$ and $\tilde{a} = a - \frac{M}{\hbar w} c_k^\dagger c_k$.[15] In the transformed Hamiltonian $\tilde{H}_D$ the electrons and photons are not coupled any more and the electronic eigenvalues are shifted by $\Delta = \frac{M^2}{\hbar w}$ which is negligible with respect to the free-electron eigenvalues. Finally we can write the exact eigenstate for H_D in terms of the electric field intensity F:[16]

$$\Psi_D(k) = \exp\left[\frac{-ieF}{m^*\hbar w^2}\langle P_z\rangle \sin(wt)\right]\Psi_0(k) = \Psi_0(k)\sum_{n=-\infty}^{\infty} J_n(\beta_k) e^{-inwt}, \qquad (11)$$

where $\beta_k = \frac{eF\langle P_z\rangle}{m^*\hbar w^2}$.

At this point, and in order to obtain the total wave function where nondiagonal terms ($k' \neq k$) are included, we consider time-dependent perturbation theory up to first order. For that purpose we calculate the total wave function time-dependent coefficients, which are given by

$$C_f^{(1)}(t) = \lim_{\alpha\to 0}\int_{-\infty}^{t}(1/i\hbar)\langle\Psi_D(k')|W(k)|\Psi_D(k)\rangle e^{\alpha t}dt, \quad (12)$$

where

$$W(k) = (eF/m^*w)\sum_{k'}\langle k'|P_z|k\rangle c^\dagger_{k'}c_k\cos(wt). \quad (13)$$

Since we consider first-order time-dependent perturbation theory, we keep only the J_0 Bessel function terms because if we took the J_1 terms or terms of higher order in the Bessel functions, that would mean considering second- or higher-order processes giving a very small contribution to the total wave function. Due to that we will see below that only one-photon absorption and emission processes are considered in our formalism. From (11), (12), and (13) we have

$$C_f^{(1)}(t) = \frac{-eFL}{4\pi\hbar^2 w}\int_{0,k'\neq k}^{\infty} J_0(\beta_{k'})J_0(\beta_k)\langle k'|P_z|k\rangle/k' \times\left[e^{i(w_{k'k}+w)t}\left(\mathrm{PP}\frac{1}{w_{k'k}+w}+i\pi\delta(w_{k'k}+w)\right)+e^{i(w_{k'k}-w)t}\left(\mathrm{PP}\frac{1}{w_{k'k}-w}+i\pi\delta(w_{k'k}-w)\right)\right]dw_{k'}. \quad (14)$$

In the calculation of this integral the principal part term results to be negligible compared to the δ term. If we carry out that integral taking the above into account we can obtain for the coefficients

$$C^{(1)}_{1,(-1)} = (-ieFL/4\hbar^2 w)J_0(\beta_{k_{1,(-1)}})J_0(\beta_{k_0}) \times\langle k_{1,(-1)}|P_z|k_0\rangle/k_{1,(-1)}. \quad (15)$$

Therefore, denoting by k_0 the wave vector of the initial electron we can write for the total wave function

$$\Psi(t) = \alpha[\Psi_D(k_0) + C_1^{(1)}(t)\Psi_D(k_1) + C_{-1}^{(1)}(t)\Psi_D(k_{-1})]. \quad (16)$$

The normalization constant $\alpha = 1/[1 + |C_1^{(1)}(t)|^2 + |C_{-1}^{(1)}(t)|^2]^{1/2}$ in Eq. (16) guarantees current conservation; in other words, in the presence of a barrier the addition of transmision and reflection probabilities will give 1, as discussed below. $\Psi_D(k_0)$ is the "dressed" reference state, $\Psi_D(k_1)$ and $\Psi_D(k_{-1})$ are the two coupled "dressed" states due to one-photon absorption and emission processes, and $C^{(1)}_{1,(-1)}(t)$ are the corresponding coefficients for $\Psi(t)$ coming from the one-photon absorption (emission) processes ($w_{1,-1} = w_{k_0} \pm w$).

III. LIGHT-ASSISTED TUNNELING THROUGH A DBS

A. Coherent tunneling

Now we use the above electronic structure to analyze the problem of coherent resonant tunneling in a DBS assisted by light. Before turning on the light we are going to calculate, applying the transfer matrix technique, the transmission coefficient for a double barrier. First of all we write in this framework the wave function in the emitter and collector regions for an electron [$\Psi_{e0}(k_e)$ and $\Psi_{c0}(k_c)$, respectively] crossing the double barrier (see Fig. 1):

$$\Psi_{e0} = 1/\sqrt{L}(e^{ik_e z} + re^{-ik_e z})e^{ik_x x}e^{ik_y y}e^{-iw_0 t}, \quad (17)$$

$$\Psi_{c0} = t/\sqrt{L}e^{ik_c z}e^{ik_x x}e^{ik_y y}e^{-iw_0 t}, \quad (18)$$

where k_e and k_c are the electronic wave vector perpendicular components in the emitter and collector, respectively. The incident and transmitted currents are $J_i = \frac{\hbar k_e}{m^*\sqrt{L}}$ and $J_t = \frac{\hbar k_c}{m^*\sqrt{L}}|t|^2$, respectively, so that the transmission coefficient is $T_0 = \frac{k_c}{k_e}|t|^2$, where the factor $|t|^2$ is calculated by means of the transfer matrix formalism, i.e., imposing the boundary continuity of wave function and current at the barrier interfaces.[17]

If now we turn on the light, our state is transformed into the electron-photon wave function $\Psi(t)$ (16). From that we calculate the new incident and transmitted currents, and after some algebra the transmission coefficient in the presence of light becomes

$$T = T_0/(1 + k_1/k_0|C_1^{(1)}|^2 + k_{-1}/k_0|C_{-1}^{(1)}|^2) + T_1|C_1^{(1)}|^2/(k_0/k_1 + |C_1^{(1)}|^2 + k_{-1}/k_1|C_{-1}^{(1)}|^2) + T_{-1}|C_{-1}^{(1)}|^2/(k_0/k_{-1} + k_1/k_{-1}|C_1^{(1)}|^2 + |C_{-1}^{(1)}|^2). \quad (19)$$

A similar expression can be obtained for the reflection coefficient

$$R = R_0/(1 + k_1/k_0|C_1^{(1)}|^2 + k_{-1}/k_0|C_{-1}^{(1)}|^2) + R_1|C_1^{(1)}|^2/(k_0/k_1 + |C_1^{(1)}|^2 + k_{-1}/k_1|C_{-1}^{(1)}|^2) + R_{-1}|C_{-1}^{(1)}|^2/(k_0/k_{-1} + k_1/k_{-1}|C_1^{(1)}|^2 + |C_{-1}^{(1)}|^2), \quad (20)$$

where R_0, R_1, and R_{-1} (T_0, T_1, and T_{-1}) are the standard coherent double-barrier reflection (transmission) coefficients, evaluated at the reference energy, at one photon above and one photon below the reference energy, respectively. This expression for the reflection coefficient verifies the current conservation $|T|^2 + |R|^2 = 1$; it means that the probability for an electron to tunnel with no photon absorption or emission is smaller than the corresponding with no light present in the sample. This is due to the finite probability associated with emission and absorption processes; it is a consequence of the unitarity,[18] and comes directly from the normalization of the total electronic wave function where one-photon absorption and emission processes are considered. As the electromagnetic field intensity increases, the inelastic processes are more probable, and therefore the elastic or direct tunneling has a smaller probability than for low field intensities. In order to analyze the dc current, which is the only one observed in experiments,[3] we have made a time average so that no interference terms appear. Finally the total electronic current can be written as

$$J_{\rm tot} = \frac{em^*}{2\pi^2\hbar^3} \int [f(E) - f(E+V_f)] T dE_z \int dE_p, \quad (21)$$

f being the Fermi function, E_p the parallel part of the electronic energy, and V_f the external dc applied bias.

We can now consider the problem of adding a magnetic field $\vec{B}$ parallel to the current direction, i.e., the z direction. In the Landau gauge $\vec{A_B} = (-yB, 0, 0)$. The effect of this magnetic field is to change the parallel part of the density of states, and due to that instead of a continuum of states we now have a Landau level ladder. The Hamiltonian for an electron in the presence of an electromagnetic field in the configuration considered above and a magnetic field parallel to the current can be described in second quantization as

$$H_{\rm tot} = H_e^0 + H_{\rm ph}^0 + W_D(t) + W_{\rm OD}(t). \quad (22)$$

$H_{\rm ph}^0$, $W_D(t)$, and $W_{\rm OD}(t)$ are exactly the same as the ones described in the general formalism, but H_e^0 has been transformed due to the presence of the magnetic field and can be written now in second quantization as

$$H_e^0 = \sum_k \epsilon_z c_z^\dagger c_z + \hbar w_c (a_B^\dagger a_B + 1/2), \quad (23)$$

where B is the magnetic field intensity, w_c is the cyclotron frequency ($w_c = eB/m^*$), $a_B^\dagger$ and a_B are the creation and annihilation operators for the Landau states, and ϵ_z is the perpendicular part of the electronic energy. With no magnetic field present in the sample the parallel component for the electronic wave vector is conserved during the photoassisted tunneling process. Now, as the magnetic field is switched on, it is the Landau level index that is conserved. The alignment of the Landau levels in the emitter and in the well with the same index gives a jump in the electronic current, giving[19] eventually a sawtooth profile for the I-V characteristic depending on the magnetic field intensity. The expression for the current can then be written as

$$J = (2/2\pi^2)(e/\hbar)^2 B \times \sum_{n=0}^{N} \int_{(n+1/2)\hbar w}^{E_F} dE [f(E) - f(E+V_f)] T(E,n), \quad (24)$$

n being the Landau level index, N the maximum occupied Landau level index, and $T(E,n)$ the transmission coefficient when the photon field is present in the sample (19).

B. Sequential tunneling

In order to study the sequential tunneling, we have developed a model that calculates separately the current for the first and second barriers, J_1 and J_2. These currents are related to the Fermi level in the well E_w or, in other words, to the amount of electronic charge stored in the well. In this model we adjust the Fermi level self-consistently till the currents through the first and the second barriers become equal. The values calculated in this way for the current and the Fermi level in the well are indeed the actual current which crosses the whole double barrier sequentially and the Fermi level corresponding to the actual amount of charge stored in the well. This model takes into account macroscopically the possible scattering processes within the well.

In order to calculate J_1 and J_2 without light, we use the transfer Hamiltonian method.[14] We calculate for the first barrier the probability P_1 for the electron to cross from the emitter to the well,

$$P_1 = (2\pi/\hbar)(2\pi/L^2)^2 \left[\frac{\hbar^4 k_e k_w}{2m^{*2} L [w_2 + (1/\alpha_b) + (1/\alpha_d)]} \times T_s \delta(k_p^w - k_p^e) \delta(E_z - E_{tn}) \right], \quad (25)$$

where T_s is the transmission coefficient for a single barrier; k_e (k_p^e) and k_w (k_p^w) are the perpendicular (parallel) component for the electronic wave vector in the emitter and well, respectively; E_{tn} is the well state energy referred to the conduction band bottom [$E_{tn} = E_R - V_f(w_1 + w_2/2)/w_t$ (where E_R is the well state energy referred to the well bottom)]; $\alpha_b = \sqrt{\frac{2m^*(V_0 - E_R + V_f(w_1+w_2)/2w_t)}{\hbar^2}}$, $\alpha_d = \sqrt{\frac{2m^*(V_0 - E_R + V_f(w_2+w_3)/2w_t)}{\hbar^2}}$; w_1, w_2, and w_3 are the first barrier, well, and second barrier widths, and w_t is the total width for the whole structure. It is important to stress the presence of the $\delta(E_z - E_{tn})$ term in the P_1 expression. It implies that only for those emitter states which resonate with the well state will it be possible to cross the emitter barrier to the well and therefore contribute to the current. With this probability P_1, we can calculate the current J_1 that, after integrating in the energy, is given by

$$J_1 = (e/2\pi\hbar) \frac{k_w T_s}{w_2 + (1/\alpha_b) + (1/\alpha_d)} (E_F - E_{tn} - E_w), \quad (26)$$

where E_F and E_w are the Fermi level energies in the emitter and in the well, respectively. For the second barrier, we apply exactly the same formalism and we obtain for the probability of crossing from the well to the collector, P_2, and for the current through the second barrier J_2

$$P_2 = (2\pi/\hbar)(2\pi/L^2)^2 \left[\frac{\hbar^4 k_w k_c}{2m^{*2} L[w_2 + (1/\alpha_b) + (1/\alpha_d)]} \times T_s \delta(k_p^c - k_p^w)\delta(E_z - E_{tn}) \right], \qquad (27)$$

$$J_2 = (e/2\pi\hbar) \frac{k_w T_s}{w_2 + (1/\alpha_b) + (1/\alpha_d)} E_w, \qquad (28)$$

where k_w is the perpendicular component for the electronic wave vector in the well.

Repeating the arguments we have made to study the effect of the light on coherent tunneling, it is straightforward to extend that formalism to the sequential tunneling case. Before switching on the light the electrons have just one way to get into the well state from the emitter: from an emitter state which is resonant with the well state, i.e., having the $\delta(E_z - E_{tn})$ term in the integral. Now, when we switch on the light, the electrons have three different ways to tunnel through the emitter barrier to the well. The first one is a direct way and it corresponds to an emitter state which resonates with the well state; the transmission takes place without light absorption or emission. The second one is through an absorption process from an emitter state which is found at one photon energy below the resonant well state. And finally the third way is through an emission process from an emitter state which is found at one photon energy above the resonant well state. For those reasons above we will have in the J_1 expression the sum of three terms; in each one appears a different δ function. The direct term has in its expression a $\delta[E_z - E_{tn}]$, the absorption term a $\delta[E_z - (E_{tn} - \hbar w)]$, and finally the emission term a $\delta[E_z - (E_{tn} + \hbar w)]$. So the final expression we have for the current J_1 is

$$J_1 = (e/2\pi\hbar) \int_0^{E_F} dE_z \frac{k_w}{w_2 + (1/\alpha_b) + (1/\alpha_d)} \times \left[\delta[E_z - E_{tn}] \frac{T_{s,0}}{1 + k_1/k_0 |C_{1,0}^{(1)}|^2 + k_{-1}/k_0 |C_{-1,0}^{(1)}|^2} + \delta[E_z - (E_{tn} - \hbar w)] \frac{T_{s,1} |C_{1,0}^{(1)}|^2}{k_0/k_1 + |C_{1,0}^{(1)}|^2 + k_{-1}/k_1 |C_{-1,0}^{(1)}|^2} + \delta[E_z - (E_{tn} + \hbar w)] \frac{T_{s,-1} |C_{-1,0}^{(1)}|^2}{k_0/k_{-1} + k_1/k_{-1} |C_{1,0}^{(1)}|^2 + |C_{-1,0}^{(1)}|^2} \right] \int_{E_w}^{E_F - E_z} dE_p. \qquad (29)$$

If we perform this integral, we can finally obtain for J_1

$$J_1 = (e/2\pi\hbar) \left[\frac{k_{w,0} T_{s,0} (E_F - E_{tn} - E_w)}{w_2 + (1/\alpha_{b,0}) + (1/\alpha_{d,0})} \frac{1}{1 + k_1/k_0 |C_{1,0}^{(1)}|^2 + k_{-1}/k_0 |C_{-1,0}^{(1)}|^2} + \frac{k_{w,-1} T_{s,0} [E_F - (E_{tn} - \hbar w) - E_w]}{w_2 + (1/\alpha_{b,-1}) + (1/\alpha_{d,-1})} \frac{|C_{1,-1}^{(1)}|^2}{k_{-1}/k_0 + |C_{1,-1}^{(1)}|^2 + k_{-2}/k_0 |C_{-1,-1}^{(1)}|^2} + \frac{k_{w,1} T_{s,0} [E_F - (E_{tn} + \hbar w) - E_w]}{w_2 + (1/\alpha_{b,1}) + (1/\alpha_{d,1})} \frac{|C_{-1,1}^{(1)}|^2}{k_1/k_0 + |C_{1,1}^{(1)}|^2 k_2/k_0 + |C_{-1,1}^{(1)}|^2} \right], \qquad (30)$$

where, as above, the subscript 0 means the reference state energy that in our case is the resonant well state energy. The subscripts 1 and −1 mean one photon energy above and below, respectively, etc.

For the second barrier we do not have the constraint of crossing to a specific discrete state, but what we have now is a continuum of states in the collector. The expression we have for the current through the second barrier in the presence of light is formally equal to the J_1 expression, i.e., it is formed for the sum of three contributions, each one at different energy. At this point we apply the same procedure as in the case where there is no light present, i.e., we calculate the Fermi level in the well self-consistently till both currents for the first and second barriers become equal. The values obtained in this way are the actual photoassisted sequential current and Fermi level in the well.

IV. RESULTS

We have performed a calculation for a GaAs-$Ga_xAl_{1-x}As$ DBS with well and barrier thicknesses of 50 Å, in order to analyze the experimental information.[3] The electromagnetic field is polarized along the sample growth direction (Fig. 1), and the carrier density $n = 10^{18}$ cm^{-3}. First of all we have calculated the total transmission coefficient for coherent tunneling for a field intensity $F = 4 \times 10^5$ V/m and energy $\hbar w = 13.6$ meV and for different external bias [V_f = 0.0, 0.1, and 0.14

V, Figs. 2(a), 2(b), and 2(c)]. The main features observed in the transmission coefficient as a function of the total energy are two satellite peaks coming from the one-photon absorption and emission processes (higher-order processes are neglected in our model as has been discussed above). As the bias increases, due to the asymmetry in the sample, the satellites become asymmetric too, and for high bias only the satellite coming from the one-photon emission process shows up. In Fig. 3(a) we have plotted the coherent resonant tunneling current density as a function of the external bias in the presence of the electromagnetic field. The effect of the light on the current density can be observed in Fig. 3(b), where the calculated current difference between the case where there is light present in the sample and the case where there is not light present is drawn. One observes a main structure in the region corresponding to the current density threshold, the appearence of a shoulder for bias roughly at the center of the current peak, and a smaller structure associated with the current cutoff.

The change in the tunneling current as a function of the external bias comes mainly from the change in the transmission coefficient where two satellites appear corresponding to the one-photon absorption and one-photon emission processes. The current is then obtained by integrating to all the available states with energies up to

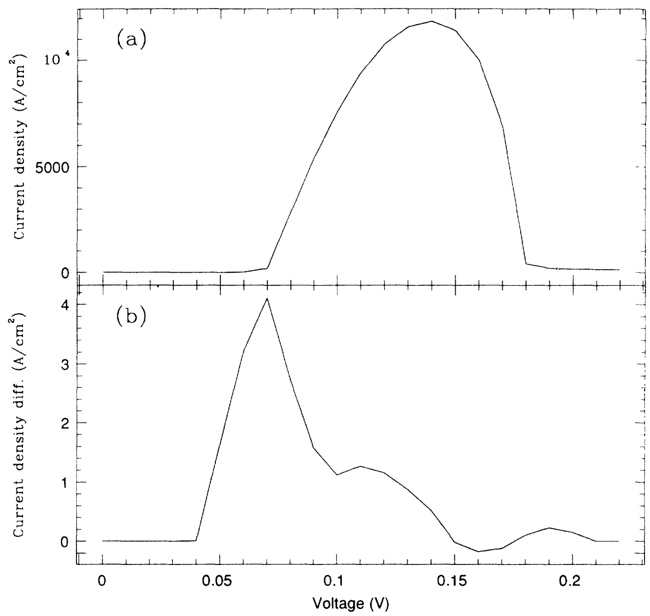

FIG. 3. (a) Coherent tunneling current density as a function of voltage for light-assisted tunneling ($F = 4 \times 10^5$ V/m, $\hbar w = 13.6$ meV). (b) Current difference as a function of voltage between coherent light-assisted tunneling and coherent tunneling without light present ($F = 4 \times 10^5$ V/m, $\hbar w = 13.6$ meV).

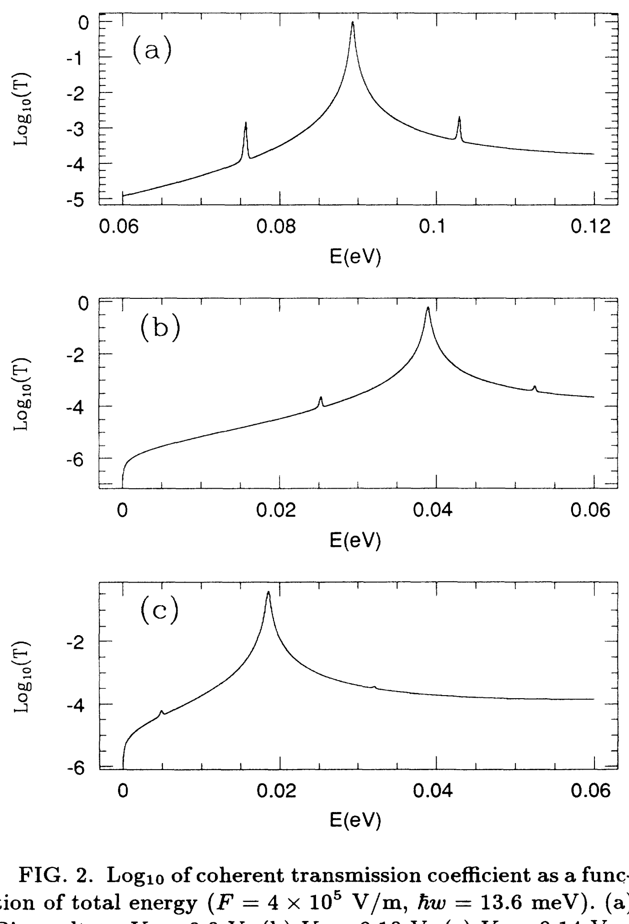

FIG. 2. $\mathrm{Log_{10}}$ of coherent transmission coefficient as a function of total energy ($F = 4 \times 10^5$ V/m, $\hbar w = 13.6$ meV). (a) Bias voltage $V_f = 0.0$ V. (b) $V_f = 0.10$ V. (c) $V_f = 0.14$ V.

the Fermi level. In Fig. 3(b) a main peak shows up at an external bias smaller than the current threshold bias for the case where no light is present in the sample. Physically this comes from the fact that electrons in the emitter close to the Fermi energy have a probability to absorb a photon and to tunnel through the resonant state. Therefore the current increases in the presence of light and the threshold bias for the current is smaller than that corresponding to the case where the sample is not illuminated, and a positive peak appears in the current difference. For higher voltages, as the resonant level crosses the Fermi energy, there is also an additional contribution to the current coming from electrons absorbing a photon and tunneling nonresonantly through the double barrier. Finally, the physical reason for the structure appearing at the current cutoff bias (around 0.18 mV) comes from the emission processes once the resonant state in the well crosses the bottom of the conduction band of the emitter. These features are in good agreement with the experimental curve.[3]

In order to compare with the experimental evidence we have to analyze the sequential contribution to the tunneling current and compare it with the coherent one. Therefore we have calculated the sequential tunneling current density in the presence of light as well as the current difference with and without the photon field [Figs. 4(a) and 4(b), respectively]. One observes that the sequential current decreases at the bias corresponding to the current cutoff more abruptly than the coherent one, and that the current intensity is of the same order as the coherent one. More interesting is the fact that the current

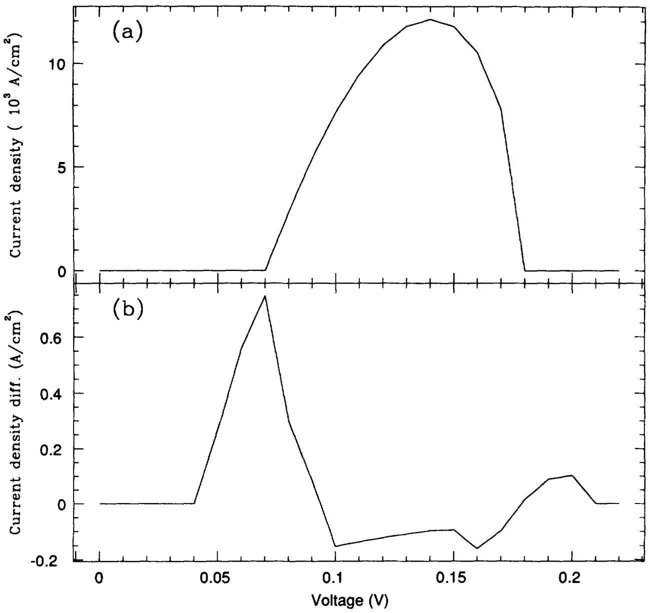

FIG. 4. (a) Sequential tunneling current density as a function of voltage for light-assisted tunneling ($F = 4 \times 10^5$ V/m, $\hbar w = 13.6$ meV). (b) Current difference as a function of voltage between sequential light-assisted tunneling and sequential tunneling without light present ($F = 4 \times 10^5$ V/m, $\hbar w = 13.6$ meV).

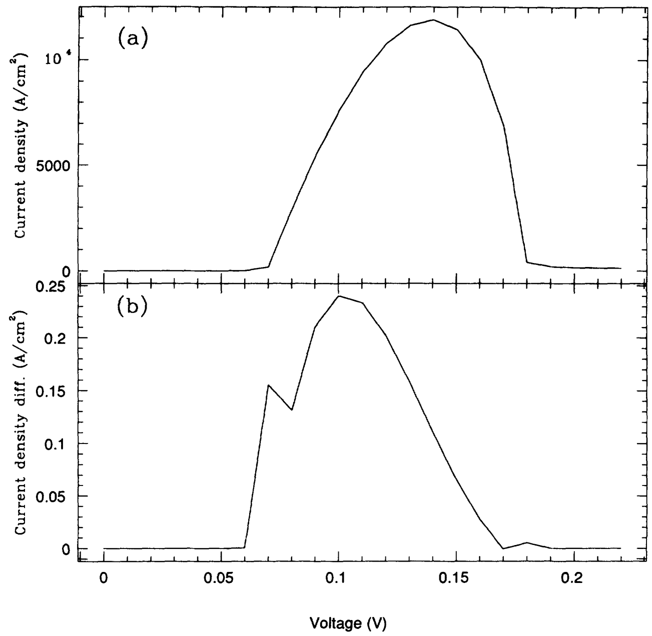

FIG. 5. (a) Coherent tunneling current density as a function of voltage for light-assisted tunneling ($F = 4 \times 10^4$ V/m, $\hbar w = 4.2$ meV). (b) Current difference as a function of voltage between coherent light-assisted tunneling and coherent tunneling without light present ($F = 4 \times 10^4$ V/m and $\hbar w = 4.2$ meV).

difference [Fig. 4(b)] for sequential tunneling is one order of magnitude smaller than that corresponding to the coherent process [Fig. 3(b)]; therefore we conclude that the experimental difference of currents corresponds to the coherent tunneling process, which dominates the sequential one. We have also evaluated the coherent and sequential current densities for the same sample but considering photons with lower energy $\hbar w = 4.2$ meV (Figs. 5 and 6) in order to compare with the experimental results.[3] In this case the same behavior is observed as in the previous case when the coherent contribution is compared with the sequential one: the coherent tunneling current density is comparable in intensity with the sequential one and the current difference (with and without light present in the sample) is one order of magnitude larger in the coherent process than in the sequential one; therefore the latter is hidden by the coherent contribution and it is this one which should be compared with the experiment. The agreement for this case (lower frequency) is not as good as for the previous one: the current difference for the coherent case [Fig. 5(b)] presents a peak for a bias smaller than that corresponding to the threshold current density without light. As in the previous case, this structure comes from electrons close to the Fermi level which absorb one photon. This peak, which is less intense than in the previous case (fewer electrons with energies below E_F than in the case with higher photon energy) and narrower, is not observed experimentally; however, the main features are well reproduced. In order to see how the relative intensity between coherent and sequential tunneling current densities changes as a function of the barrier

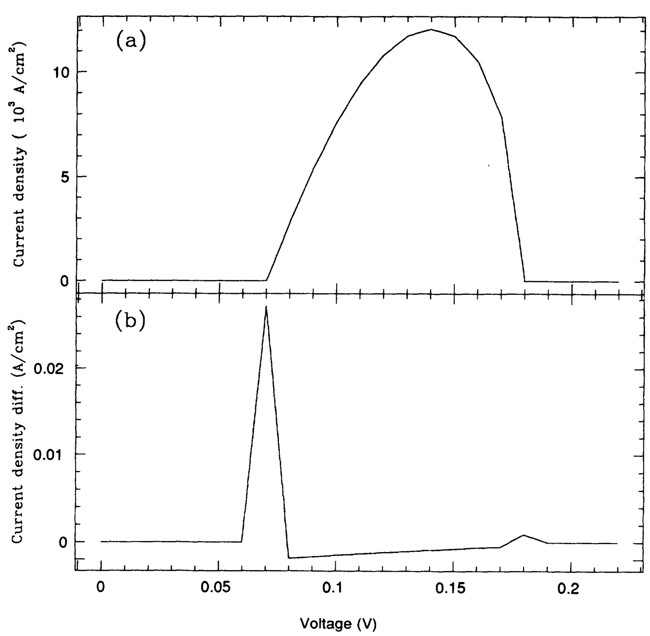

FIG. 6. (a) Sequential tunneling current density as a function of voltage for light-assisted tunneling ($F = 4 \times 10^4$ V/m, $\hbar w = 4.2$ meV). (b) Current difference as a function of voltage between sequential light-assisted tunneling and sequential tunneling without light present ($F = 4 \times 10^4$ V/m and $\hbar w = 4.2$ meV).

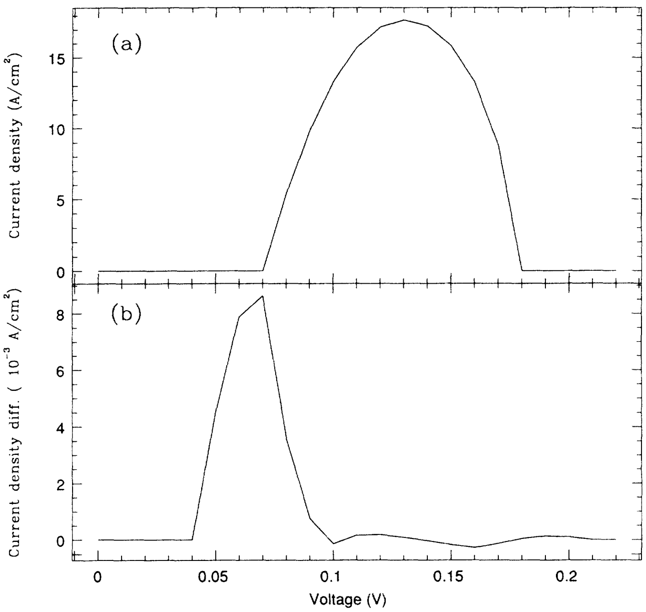

FIG. 7. (a) The same as Fig. 3(a) but for a barrier thickness of 100 Å. (b) The same as Fig. 3(b) but for a barrier thickness of 100 Å.

thickness, we have performed the same calculations as explained above for thicker samples. For barrier thicknesses of 100 Å and a well thickness of 50 Å the same behavior as before is observed, i.e., the coherent tunneling dominates the current density difference with and without light (Figs. 7 and 8). We have not considered the case for thinner barriers because our model, developed to describe the sequential tunneling, cannot be applied properly to such cases, and due to that we cannot make

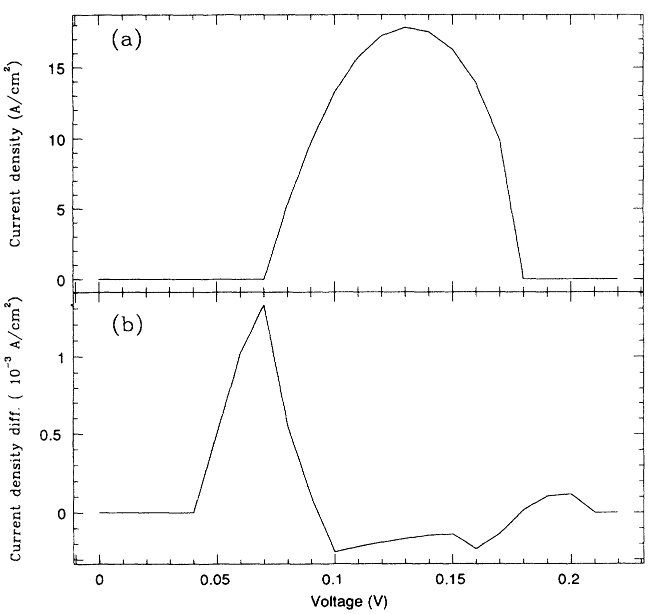

FIG. 8. (a) The same as Fig. 4(a) but for a barrier thickness of 100 Å. (b) The same as Fig. 4(b) but for a barrier thickness of 100 Å.

a correct comparison with the coherent tunneling case. The reason is that we neglect in our model for sequential tunneling the finite width of the resonant state in the well, which increases as the barrier thickness decreases.

Finally, we have analyzed the effect of an external magnetic field applied in the current direction on this sample in the presence of the photon field in the same configuration as in Fig. 1. We pay attention just to the coherent current which was dominant in the absence of magnetic field. We have analyzed two different cases: in the first one the magnetic field intensity is 15.72 T and the photon energy $\hbar w = 13.6$ meV, therefore the cyclotron frequency is twice the photon frequency. The second case corresponds to the same magnetic field intensity but a photon energy of $\hbar w = 27.2$ meV. For this magnetic field there are two Landau levels which contribute to the current [Fig. 9(a)]. As the electromagnetic field is switched on,

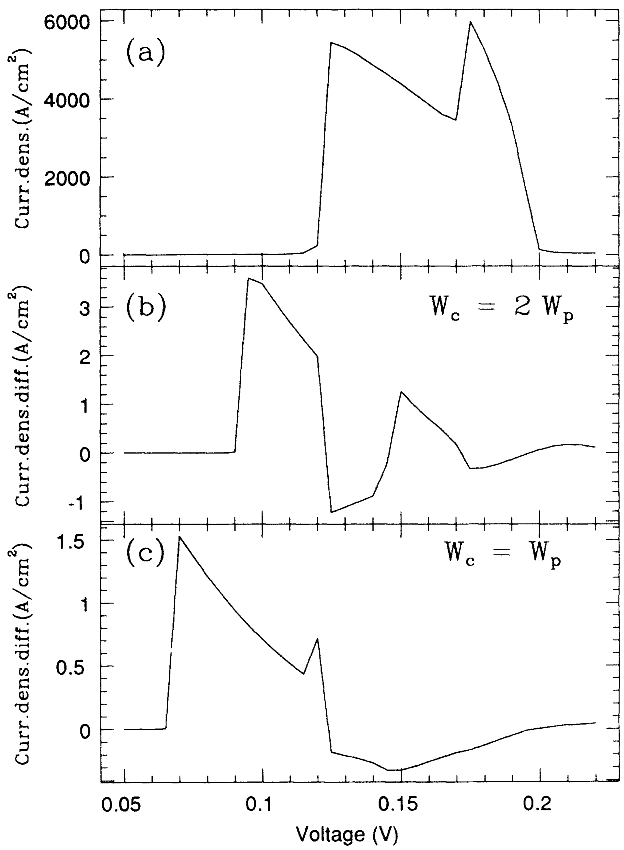

FIG. 9. (a) Coherent tunneling current density as a function of voltage for light-assisted tunneling, in the presence of a magnetic field parallel to the current ($B = 15.72$ T, $\hbar w_c = 27.2$ meV, $F = 4 \times 10^5$ V/m, $\hbar w = 13.6$ meV). (b) Current difference as a function of voltage between coherent light-assisted tunneling and coherent tunneling without light present, for both cases, in the presence of a parallel magnetic field ($B = 15.72$ T, $\hbar w_c = 27.2$ meV, $F = 4 \times 10^5$ V/m, $\hbar w = 13.6$ meV). (c) Current difference as a function of voltage between coherent light-assisted tunneling and coherent tunneling without light present, for both cases, in the presence of a parallel magnetic field ($B = 15.72$ T, $\hbar w_c = 27.2$ meV, $F = 4 \times 10^5$ V/m, $\hbar w = 27.2$ meV).

the current density is modified independently for each Landau level. This can be observed in Figs. 9(b) and 9(c). In the case that the cyclotron frequency is twice the photon frequency [Fig. 9(b)], the way the light affects each Landau level separately is well resolved. In the second case, where the cyclotron frequency is the same as the photon frequency [Fig. 9(c)] the current difference structures associated with each Landau level overlap but remain decoupled from each other. This result does not give any additional information to the photoassisted tunneling without magnetic field, because in this configuration the magnetic field only affects the planes parallel to the interfaces, while the light affects the tunneling in the current direction. Therefore the effects of the two fields on the tunneling current are completely decoupled. More interesting would be to consider an electromagnetic field with a component of the electric field in the interface planes. In this case the effect on the current due to the magnetic field and the light will not be independent of each other anymore and different physical effects could be expected. That is the task of a forthcoming paper.

V. CONCLUSIONS

We have studied the problem of coherent and sequential tunneling through a double-barrier structure assisted by light, which is considered to be present all over the structure, i.e., in the emitter, well, and collector, which is a realistic description of the experiments. By means of a canonical transformation and time-dependent perturbation theory up to first order, we have calculated the coherent transmission coefficient and the electrical current through the system for this specific problem, with the result that the electromagnetic field couples states of different energies due to one-photon absorption and emission processes. The higher-order contributions to the current (multiphoton absorption and emission processes) are much weaker and their contribution can be neglected in first approximation. As a result of that, two satellite peaks appear in the transmission coefficient at both sides of the main resonant peak. Therefore, the total transmission coefficient and the coherent tunneling current are affected by the photon field and resultant features in the current density are observed. In order to obtain the total density current we have developed a model to analyze the sequential tunneling current through a double barrier in the presence of light. We have calculated the electronic tunneling current through the first barrier, i.e., from the emitter to the resonant state in the well in the presence of light, and the current through the collector barrier coming from the electrons in the well. Current conservation is reached when both currents are equal and it determines the Fermi level in the well, i.e., the charge stored in the well. The sequential contribution to the current coming out is of the same order as the coherent one. For the current difference with and without electromagnetic field the coherent part is one order of magnitude larger than the sequential one for the samples considered in our calculation. Therefore it is the coherent current which should be compared with the experiments,[3] and both theory and experiment turn out to be in good agreement. We have also considered an external magnetic field applied in the growth direction on the double-barrier structure and in the presence of light. The analysis of the coherent tunneling current has been done for different ratios between the cyclotron and the photon frequencies.

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