Light-assisted magnetotunneling through a semiconductor double-barrier structure

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We have analyzed theoretically the effect of a laser on the tunneling current through a double barrier in the presence of a parallel magnetic field. The magnetotunneling current is modified by light due to the photon emission and absorption processes that assist the tunneling of electrons through the structure. We observe that the effect of light can be controlled by tuning the ratio between the cyclotron and the photon frequencies. It turns out that when this ratio is 1 the effect of the light is drastically reduced. The change of the accumulated charge in the well due to light and therefore the modification of the number of Landau levels contributing to the current is discussed.

I. INTRODUCTION

The analysis of resonant tunneling through semiconductor heterostructures has a lot of interest from a fundamental point of view as well as for its applications as microelectronic devices.[1] From the analysis of the tunneling current as a function of an external dc bias many properties of the electronic band structure and of the excitations in the system can be deduced. The application of an external field increases the parameters which can be externally controlled and gives additional information of the heterostructure and therefore increases the applications of these systems as devices. The analysis of the magnetotunneling current for both configurations, corresponding to a magnetic field applied parallel and perpendicular to the growth direction of the heterostructure, has been the subject of many papers[2–4] and gives information on the density of states in the well corresponding to the Landau level ladder in the first case, and on the edge states in the second configuration. Also the application of a radiation field modifies the transport properties of these resonant devices.

The work of Sollner *et al.*[5] 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 resonant tunneling current. Recently Chitta *et al.*[6] have studied the far infrared response of double barrier resonant tunneling structures. Tien and Gordon[7] studied the effect that microwave radiation has on superconducting tunneling devices. Several authors[8–12] have investigated the effect that external time-dependent potentials have in different problems. In a recent work[13,14] we have developed a model to analyze the coherent and sequential tunneling current in the presence of a photon field through a double barrier structure (DBS).

In this paper we have analyzed the effect of a photon field on both coherent and sequential magnetotunneling current through a DBS for a static magnetic field applied in the direction of the current. We have developed a quantum mechanical formalism to find the expression for the electronic state dressed by photons and we propose a model to obtain the sequential magnetotunneling current under the influence of an external electromagnetic field for linearly polarized light. By means of this model we obtain the charge in the well and its modifications due to the external electromagnetic field.

In our model for sequential magnetotunneling, before switching on the light, we consider that electrons tunnel coherently through the first barrier, then they lose memory within the well and in a third step they cross coherently the second barrier. In the presence of a magnetic field, coherent tunneling implies Landau level index conservation, however, for sequential tunneling, due to the scattering processes which take place in the well structure, the Landau level index corresponding to the states which contribute to the current is not conserved from the emitter to the collector. If a laser is switched on, it changes the charge occupation in the well and consequently the number of Landau levels (LL's) which contribute to the current density. We have analyzed this effect for different photon frequencies and field intensities as well as the change of the magnetotunneling current for different ratios between cyclotron and photon frequencies. We have compared also the two contributions to the magnetotunneling current: coherent versus sequential.

This paper is organized as follows: In Sec II we discuss and develop the theoretical formalism for the coherent and sequential magnetotunneling in the presence of a photon field. In Sec III we applied the discussed formalism to analyze both contributions to the current: sequential and coherent for different ratios between the cyclotron and the photon frequencies. Also the accumulated charge in the well for different magnetic and electromagnetic fields is analyzed for sequential magnetotunneling and therefore how the light changes the number of Landau levels which contribute to the sequential tunneling. We summarize our conclusions in Sec IV.

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II. MAGNETOTUNNELING CURRENT THROUGH A DOUBLE BARRIER STRUCTURE IN THE PRESENCE OF AN ELECTROMAGNETIC FIELD

A. Coherent magnetotunneling

We have analyzed the coherent magnetotunneling current density through a double barrier when a magnetic field is applied parallel to the current in the presence of light. We have considered light linearly polarized in the far infrared regime, and polarized in the same direction as the static magnetic field applied. For that configuration, the electronic motion is modified by the light only in the current direction and the electronic lateral state becomes unaffected by light.[13,14] With no magnetic field present in the sample the parallel component for the electronic wave vector is conserved during the coherent tunneling process. Now as the magnetic field is switched on the Landau level index is what is conserved: the current characteristic curve presents a peak as a function of the external bias when a Landau level in the emitter aligns with the corresponding Landau level in the well. As the magnetic field increases, less Landau levels contribute to the current, but the degeneration of each LL increases, giving in the current less, but more intense, peaks.

The effect of a magnetic field $\vec{B}$, parallel to the current direction, i.e., the z direction, is to change the parallel part of the density of states and due to that instead of a continuum of states we have now a Landau levels ladder. If a laser is applied to the sample, 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 describe in second quantization as

$$H_{\text{tot}} = H_e^0 + H_{\text{ph}}^0 + W_D(t) + W_{OD}(t) \tag{1}$$

where

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

$$H_{\text{ph}}^0 = \hbar w a^\dagger a , \tag{3}$$

$$W_D(t) = \sum_k [(e/m^*) \langle k|P_z|k\rangle c_k^\dagger c_k (\hbar/2\epsilon V w)^{1/2} \times (a e^{-iwt} + a^\dagger e^{iwt})] \tag{4}$$

$$W_{OD}(t) = \sum_k \sum_{k' \neq k} [(e/m^*) \langle k'|P_z|k\rangle c_{k'}^\dagger c_k (\hbar/2\epsilon V w)^{1/2} \times (a e^{-iwt} + a^\dagger e^{iwt})] , \tag{5}$$

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 destruction operators for the Landau states, and ϵ_z is the electronic energy perpendicular part and $A_z(x,t) = (\hbar/2\epsilon V w)^{1/2} \vec{\epsilon_z} (a e^{-iwt} + a^\dagger e^{iwt})$ being w the photon frequency (the wave vector of the electromagnetic field has been neglected). 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 in the presence of a magnetic field. H_{ph}^0 is the photon field Hamiltonian without coupling with electrons and W_D and W_{OD} describe the coupling between electrons and photons in the total Hamiltonian. In the following[13,14] we separate the coupling term in the "diagonal" and the "off-diagonal" contributions:

$$H_{\text{tot}} = H_D(t) + W_{OD}(t) , \tag{6}$$

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

The Hamiltonian H_D can be solved exactly by considering a canonical transformation[15] and the off-diagonal term is treated in time-dependent perturbation theory using the same procedure as in Refs. 13 and 14 for coherent resonant tunneling. The expression for the coherent magnetotunneling current can be written then as

$$J = (2/2\pi^2)(e/\hbar)^2 B \sum_{n=0}^{N} \int_{(n+1/2)\hbar w}^{E_F} \times dE [f(E) - f(E + V_f)] T(E, n) \tag{7}$$

n being the Landau level index, N, the maximum occupied Landau level index, and $T(E,n)$ the coherent transmission coefficient through a double barrier structure when the photon field is present in the sample.[13,14]

B. Sequential magnetotunneling

In order to describe the effect of light on the tunneling current and to compare with experiments, one should also analyze how the sequential contribution to the tunneling current is affected by light.

The electrons lose coherence when tunneling through the structure due to the different scattering processes which suffer with impurities, surface roughness, and phonons. Once the electrons cross the first barrier and if the scattering time is shorter than the tunneling time they relax in the well losing memory and in a next step they cross coherently the collector barrier.

In order to study the sequential tunneling current , before illuminating the sample, we have calculated in the framework of the transfer Hamiltonian formalism the current through the first and the second barriers separately, 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 into the well. In this model we adjust self-consistently the Fermi level in the well invoking current conservation through the whole heterostructure. The values calculated in this way for the current and the Fermi level in the well are indeed the actual current that is crossing the whole double barrier sequentially and the Fermi level corresponding to the actual amount of charge stored in the well. We improve a previous model for sequential tunneling[13] considering instead of a discrete level in the well a localized state with finite width due to its coupling with the continuum of states in the leads. This model takes into account macroscopically the possible scattering processes within the well.

The expression for the current through the emitter barrier J_1 to the resonant state in the well can be written including the finite width of the resonant well state as

$$J_1 = \frac{e}{2\pi^2\hbar}\int_0^{E_F} \frac{k_w T_1 L(E_z - E_{tn})}{w_2 + 1/\alpha_e + 1/\alpha_c}(E_F - E_z - E_w)dE_z \ , \tag{8}$$

where k_w is the electronic perpendicular wave vector in the well, T_1 is the single barrier transmission coefficient for the first barrier, w_2 is the well width, α_e and α_c are the perpendicular electronic wave vectors in the emitter and collector barriers, respectively, $L(E_z - E_{tn}) = \frac{\gamma}{\pi[(E_z-E_{tn})^2+\gamma^2]}$, γ is the half-width of the resonant state, E_{tn} is the resonant well state energy referred to the conduction band bottom, and E_w is the chemical potential in the well. The current through the collector barrier J_2 for electrons coming from the well can be evaluated in the same way:

$$J_2 = \frac{e}{2\pi^2\hbar}\int_0^{E_F} \frac{k_w T_2 L(E_z - E_{tn})}{w_2 + 1/\alpha_e + 1/\alpha_c}E_w dE_z \ , \tag{9}$$

where T_2 is the single barrier transmission coefficient for the the second barrier (collector barrier). Applying the initial condition of $J_1 = J_2$, we can obtain analytically an expression for the total current which is crossing sequentially the DB without light present:

$$J_T = \frac{e}{2\pi^2\hbar}\int_0^{E_F} \frac{k_w L(E_z - E_{tn})}{w_2 + 1/\alpha_e + 1/\alpha_c} \times (E_F - E_z)\frac{T_1 T_2}{T_1 + T_2}dE_z \ . \tag{10}$$

In the presence of light the sequential current can be evaluated within the framework of time-dependent perturbation theory as in the case of coherent tunneling for each barrier,[13,14] including the finite width of the resonant state. The expression obtained for the total sequential current through the DB invoking current conservation through the structure is:

$$J_T = \frac{e}{2\pi^2\hbar}\int_0^{E_F} \frac{k_w(E_F - E_z)T_{2t}}{w_2 + 1/\alpha_e + 1/\alpha_c} \times\left[L(E_z - E_{tn})\frac{T_d}{T_d + T_{2t}} + L(E_z + \hbar w - E_{tn}) \times\frac{T_a}{T_a + T_{2t}} + L(E_z - \hbar w - E_{tn})\frac{T_e}{T_e + T_{2t}}\right]dE_z \ , \tag{11}$$

where

$$T_d = \frac{T_1(E_z)}{1 + k_1/k_0|C_{1,0}^{(1)}|^2 + k_{-1}/k_0|C_{-1,0}^{(1)}|^2} \ , \tag{12}$$

$$T_a = \frac{T_1(E_z + \hbar w)|C_{1,0}^{(1)}|^2}{k_0/k_1 + |C_{1,-0}^{(1)}|^2 + k_{-1}/k_1|C_{-1,0}^{(1)}|^2} \ , \tag{13}$$

$$T_e = \frac{T_1(E_z - \hbar w)|C_{-1,0}^{(1)}|^2}{k_0/k_{-1} + |C_{1,0}^{(1)}|^2 k_1/k_{-1} + |C_{-1,0}^{(1)}|^2} \ , \tag{14}$$

and $T_{1t} = T_d + T_a + T_e$ and T_{2t} are the transmission coefficients for the single barriers (emitter and collector, respectively) in the presence of the photon field:

$$T_{2t} = \frac{T_2(E_z)}{1 + k_1/k_0|C_{1,0}^{(1)}|^2 + k_{-1}/k_0|C_{-1,0}^{(1)}|^2} + \frac{T_2(E_z + \hbar w)|C_{1,0}^{(1)}|^2}{k_0/k_1 + |C_{1,-0}^{(1)}|^2 + k_{-1}/k_1|C_{-1,0}^{(1)}|^2} + \frac{T_2(E_z - \hbar w)|C_{-1,0}^{(1)}|^2}{k_0/k_{-1} + |C_{1,0}^{(1)}|^2 k_1/k_{-1} + |C_{-1,0}^{(1)}|^2} \ . \tag{15}$$

$C_{i,j}$ are the coefficients of the wave functions

$$\Psi_0(t) = \alpha[\Phi_D(k_0) + C_{1,0}\Phi_D(k_1)e^{-iwt} + C_{-1,0}\Phi_D(k_{-1})e^{iwt}]e^{-iw_0 t} \ , \tag{16}$$

$$\Psi_1(t) = \alpha'[\Phi_D(k_1)e^{-iwt} + C_{1,1}\Phi_D(k_2)e^{-2iwt} + C_{-1,1}\Phi_D(k_0)]e^{-iw_0 t} \ , \tag{17}$$

$$\Psi_{-1}(t) = \alpha''[\Phi_D(k_{-1})e^{iwt} + C_{1,-1}\Phi_D(k_0) + C_{-1,-1}\Phi_D(k_{-2})e^{2iwt}]e^{-iw_0 t} \ . \tag{18}$$

Here, α, α', and α'' are normalization constants, Ψ_0 corresponds to a state at one photon energy lower (higher) than Ψ_1 (Ψ_{-1}), and the coefficients $C_{i,j}$ are given in Ref. 13. For those coefficients, the first subscript is referred to the interaction with light processes, i.e., "1" ("−1") means absorption (emission) process, whereas the second subscript is referred to the state, i.e., the subscript "0" means the reference state energy and the subscripts "1" and "−1" mean one photon energy above and below that reference state, respectively.

We will consider now the sequential magnetotunneling current: before switching on the light the electrons tunnel sequentially through the first and second barrier suffering scattering events into the well as it was previously discussed. In this case, the LL index conservation takes place from the first barrier to the well and from there to the collector independently and not through the whole structure as in the case of coherent tunneling.

The expression for the current through the first barrier J_1 before illuminating the sample and in the presence of a magnetic field can be written as

$$J_1 = \frac{e^2 B}{2\pi^2 m^*}\int_0^{E_F - 1/2\hbar w_c} \frac{k_w T_1 L(E_z - E_{tn})}{(w_2 + 1/\alpha_e + 1/\alpha_c)} \times (N_t - \Delta)dE_z \ , \tag{19}$$

where Δ is the fraction of the total Landau levels which is occupied in the well, N_t the total number of Landau levels available to tunnel for an external applied bias (Δ runs between 0 and N_t), w_c is the cyclotron frequency, and w_2 the well thickness. For the second barrier, we apply exactly the same formalism and we obtain for the current through the second barrier J_2:

$$J_2 = \frac{e^2 B}{2\pi^2 m^*} \int_0^{E_F - 1/2\hbar\omega_c} \frac{k_w T_2 L(E_z - E_{tn})}{(w_2 + 1/\alpha_e + 1/\alpha_c)} \Delta dE_z \; . \tag{20}$$

The sequential magnetotunneling current is obtained when both currents J_1 and J_2 are equal and the current determines the Landau levels which are occupied within the well and therefore the Fermi energy in the well. By doing it this way we can obtain an analytical expression for the total magnetocurrent which crosses sequentially the DB before illuminating the sample:

$$J_T = \frac{e^2 B}{2\pi^2 m^*} \int_0^{E_F - 1/2\hbar\omega_c} \frac{k_w L(E_z - E_{tn})}{(w_2 + 1/\alpha_e + 1/\alpha_c)} \frac{T_1 T_2}{T_1 + T_2} \Delta dE_z \; . \tag{21}$$

Before switching on the light the electrons in the emitter have just one way to tunnel resonantly into the well: from an emitter state which is resonant with the well state. Once the external electromagnetic field is applied to the structure, there is a coupling between the photons and the electrons tunneling through the barrier structure. Now the electrons have three different ways to tunnel through the emitter barrier to the well. The first one is a direct way and corresponds to an emitter state which resonates with the well state, i.e., 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. After some algebra, we obtain the next expression for the sequential magnetotunneling current assisted by light:

$$\begin{aligned} J_T = \frac{e^2 B}{2\pi^2 m^*} \int_0^{E_F - 1/2\hbar\omega_c} & \frac{k_w T_{2t} \Delta}{w_2 + 1/\alpha_e + 1/\alpha_c} \\ & \times \Bigg[L(E_z - E_{tn}) \frac{T_d}{T_d + T_{2t}} \\ & + L(E_z + \hbar w - E_{tn}) \frac{T_a}{T_a + T_{2t}} \\ & + L(E_z - \hbar w - E_{tn}) \frac{T_e}{T_e + T_{2t}} \Bigg] dE_z \; . \end{aligned} \tag{22}$$

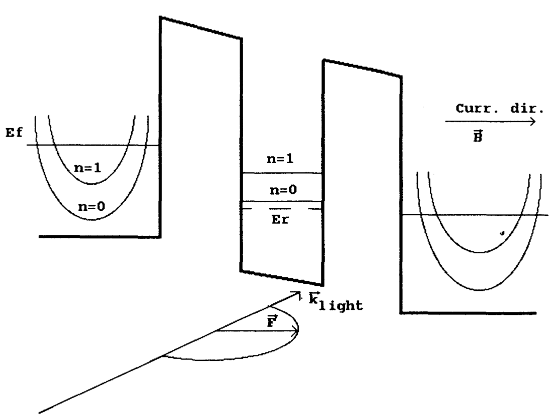

FIG. 1. Particle represented by a plane wave moving along the z direction crossing a DBS (well thickness lw=40 Å, barrier thickness lb=50 Å) in the presence of an electromagnetic field polarized in the z direction and a magnetic field parallel to z.

III. RESULTS

We have analyzed the effect of an external laser in the far infrared regime on the magnetotunneling current density through a semiconductor double barrier. The magnetic field and the electromagnetic field are applied in the configuration shown in Fig. 1. In Fig. 2(a) the coherent magnetocurrent density is represented as a function of the external bias for a magnetic field of 24 T and in the presence of an external electromagnetic field with a fre-

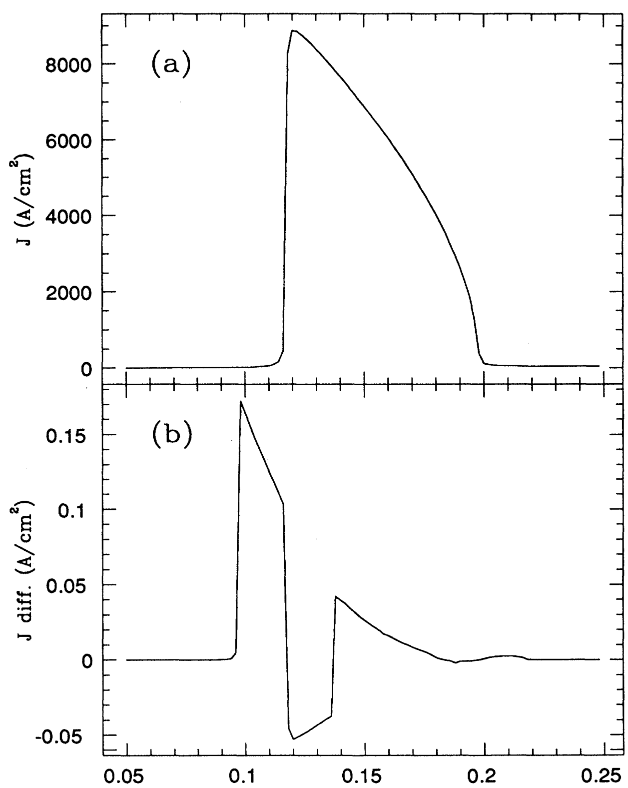

FIG. 2. (a) Coherent magnetotunneling current density assisted by light as a function of V. ($F = 5.10^4$ V/m, $\hbar w = 10.3$ meV, B=24 T). (b) Coherent magnetocurrent density difference as a function of V between photoassisted magnetocurrent and magnetocurrent without light present.

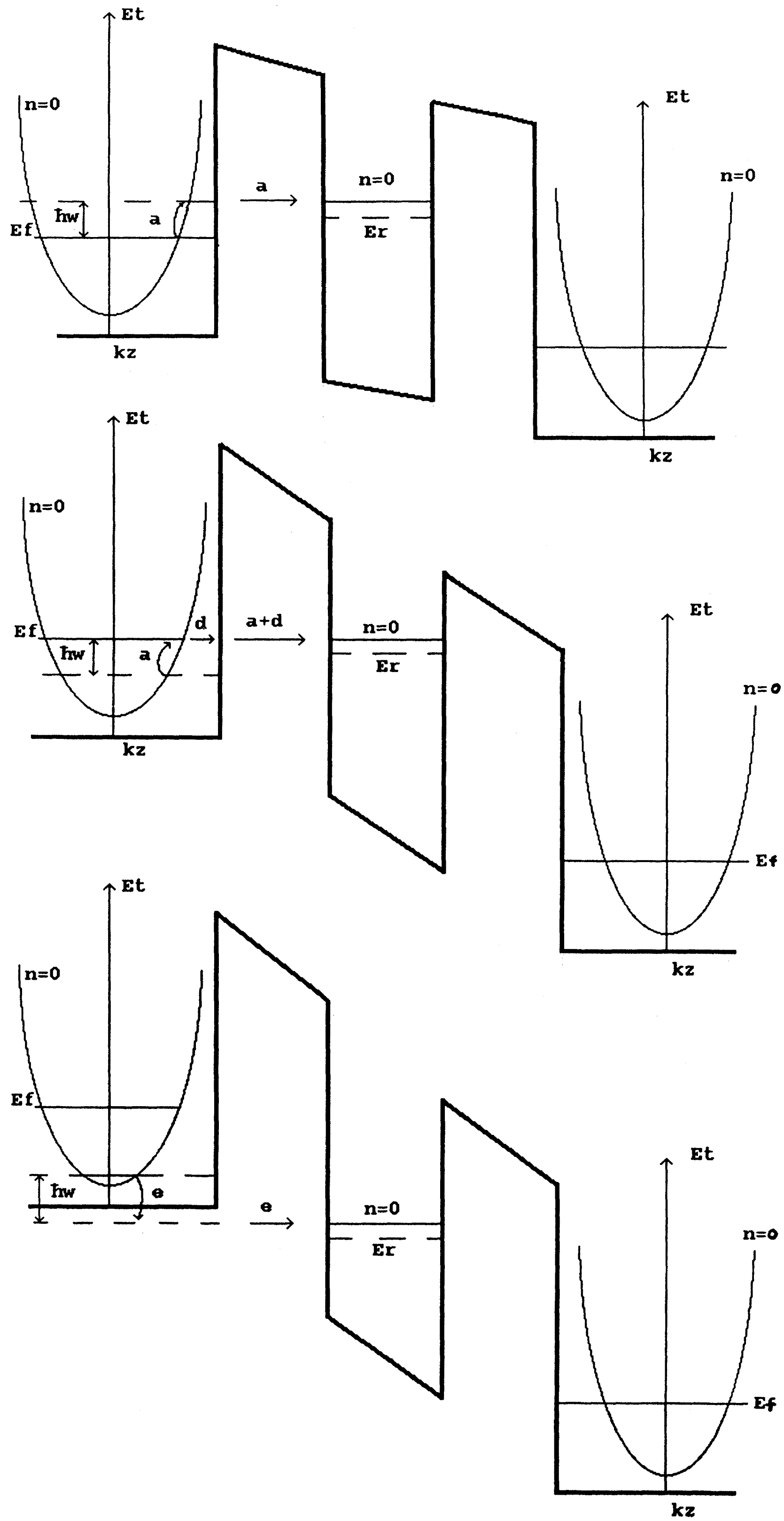

FIG. 3. Schematic drawn of photoassisted tunneling processes for increasing bias.

quency of 10.3 meV and an intensity 5 10^4 V/m. In this case, only one LL's contributes to the tunneling current and the analysis of the effect of the light on the current can be done in a simpler way than in the case where more LL's participate in the current. The current difference between the case where there is a laser present and where there is no light applied to the heterostructure is represented in Fig. 2(b). In this case we observe a main peak which appears for smaller bias than the threshold bias for the magnetotunneling current with no light present. As the bias increases the current difference decreases and becomes negative. There is also a small positive and a negative structure for higher bias and as the bias corresponding to the cutoff of the current is reached there is an additional positive contribution to the current difference. These features can be schematically explained in Fig. 3: for small bias the resonant state in the well with energy corresponding to the first LL is higher in energy than the Fermi energy in the emitter. As the bias increases there are electrons close to the Fermi energy which are able to absorb a photon and tunnel resonantly from the first Landau level in the emitter with Landau level index conservation, therefore the threshold bias for the current is smaller than the corresponding one for no light present and there is a positive peak in the current difference. For higher bias the first Landau level in the well crosses the Fermi energy in the emitter and the current difference becomes negative abruptly due to the fact that the electrons in the emitter have the possibility of absorbing a photon and this reduces the number of electrons efficient to tunnel resonantly. For higher bias there are absorption, emission, and direct tunneling processes whose combinations give the positive structure observed. As the bias increases and the energy of the resonant state in the well for the first LL lies one photon higher than the conduction band bottom of the emitter the electrons have a probability emitting a photon below the bottom of the conduction band and the resonant current is reduced (it corresponds to the small negative contribution of the current difference for high bias). Once the resonant state crosses the bottom of the conduction band there are electrons in the emitter which can emit a photon and tunnel resonantly, therefore there is a positive peak in the current difference and the current cutoff moves to higher

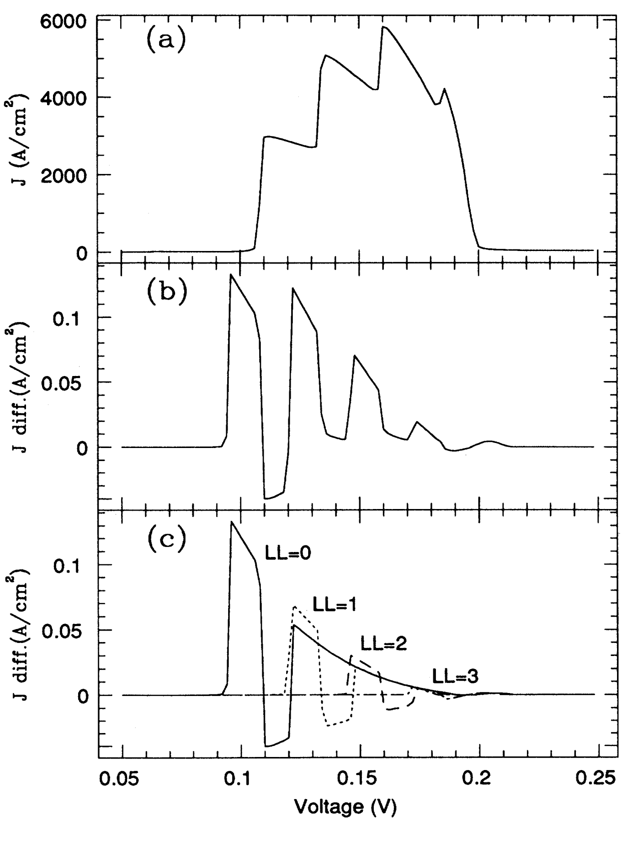

FIG. 4. (a) Same as 2(a) for $F = 5.10^4$ V/m, $\hbar w = 6.9$ meV, B= 8 T. (b) Same as 2(b) for $F = 5.10^4$ V/m, $\hbar w = 6.9$ meV, B= 8 T. (c) Coherent magnetocurrent density difference as a function of V for each Landau level separately.

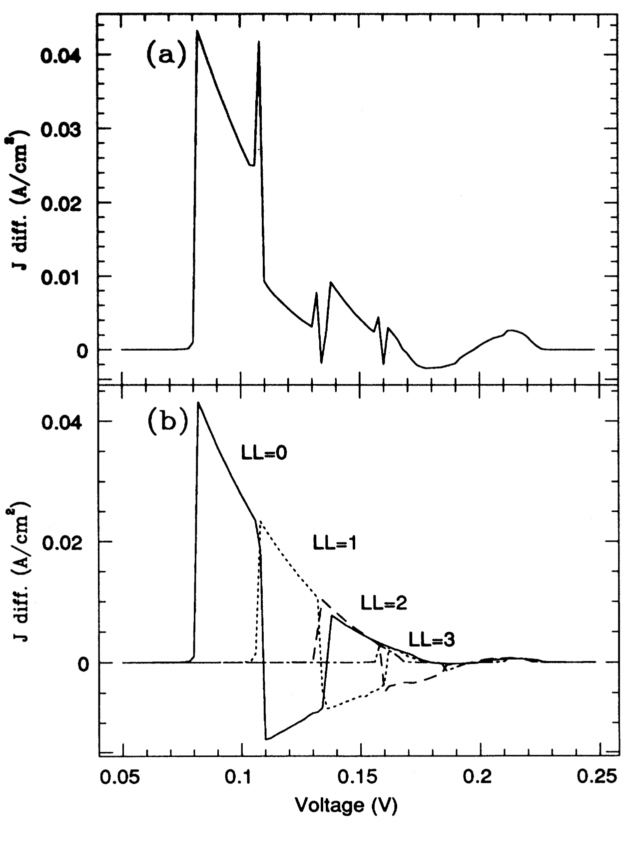

FIG. 5. (a) Coherent magnetocurrent difference for B= 8 T and $\hbar w = \hbar w_{\mathrm{cyclotron}}$. (b) Same as in (a) for each Landau level separately.

bias.

As the magnetic field decreases there are more Landau levels which contribute coherently to the current. In Fig. 4(a) the current as a function of the external bias is represented for a field of 8 T. We observe four LL's which contribute to the current. The photon frequency is 6.9 meV (one-half of the cyclotron frequency). The current difference is shown in Fig. 4(b). In this case the main peak in the current difference due to the effect of light appears at a different bias for the different Landau levels and the contribution at the cutoff is added up for the four levels. In Fig. 4(c) the current difference has been drawn separately for each Landau level, for the same case as in Fig. 4(b). If one now changes the photon frequency to the same value as the cyclotron one for the same magnetic field (8 T), the current difference changes dramatically and the main contribution comes from the peak at the threshold bias and an additional narrow structure in this region of bias [Fig. 5(a)]. For higher bias the additional features to the current difference are much smaller in intensity than in the previous case [Fig. 4(b)]. The reason for this difference between both cases is not only the change of the bias threshold and cutoff of the current due to the difference of photon frequencies (the threshold bias is lower for higher photon frequencies and the cutoff bias is larger for higher photon frequencies) but also is due to the fact that when the ratio of the cyclotron frequency to the photon frequency is 1, there are absorption and emission processes taking place for electrons coming from different Landau levels which compensate each other. This feature can be observed in Fig. 5(b), where the contribution to the current density coming from each LL is represented. Due to this compensation it is possible to control the the effect of light on the magnetocurrent by tuning the ratio between the cyclotron and the photon frequency.

As we have already discussed, in order to see the total effect of light on the magnetocurrent the sequential contribution to the current and the modifications it suffers due to light should be analyzed. We have evaluated the sequential magnetotunneling current for the same cases as the coherent one: In Figs. 6(a) and 6(b) the current density and the current density difference are represented for a magnetic field of 24 T and an electromagnetic field

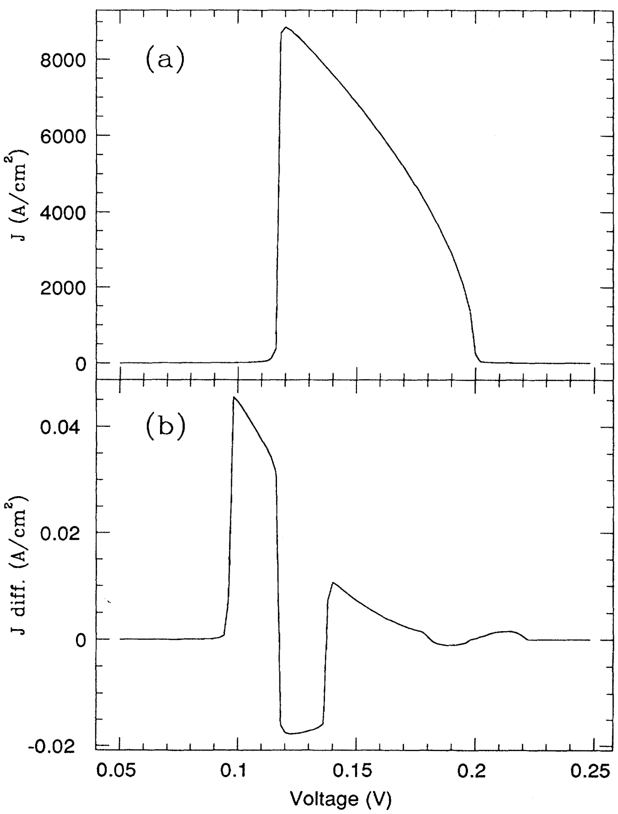

FIG. 6. (a) Sequential magnetotunneling current density as a function of voltage ($F = 5.10^4$ V/m, $\hbar w = 10.3$ meV, $B=$ 24 T). (b) Sequential magnetocurrent difference as a function of voltage between sequential light assisted tunneling and sequential tunneling without light present. Same configuration as in (a).

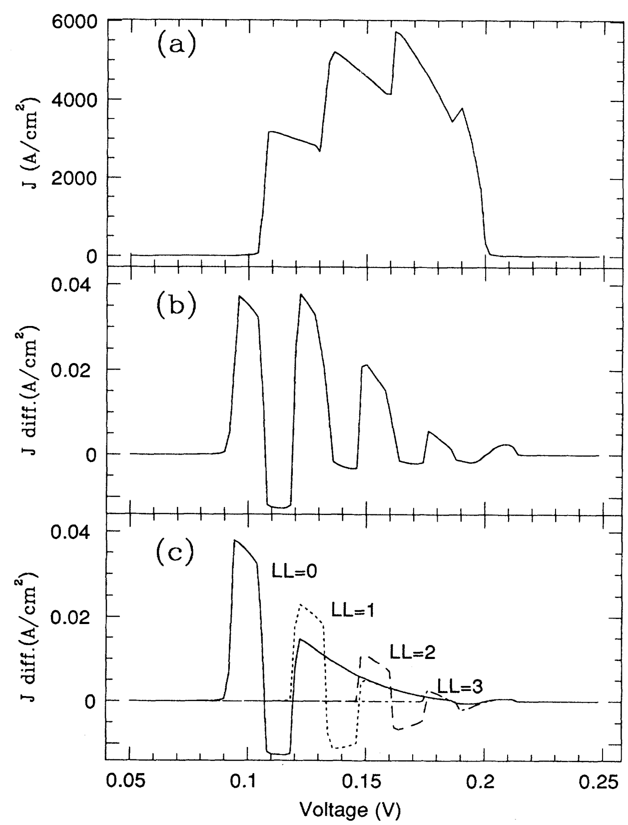

FIG. 7. (a) The same as 6 (a) for $B=$ 8 T, $\hbar w = 6.9$ meV. (b) Same as 6(b) for $B=$ 8 T, $\hbar w = 6.9$ meV. (c) Same as in (b) for each Landau level separately.

of energy 10.3 meV (one-fourth of the cyclotron energy). The structure observed in the current difference can be understood in the same footing as in the coherent case.

As the magnetic field is decreased to 8 T the four peaks in the sequential magnetocurrent indicates the participation of four Landau levels [Fig. 7(a)]. The current difference for a laser field of 6.9 meV (one-half of the cyclotron frequency) is represented [Figs. 7(b) and 7(c)] and similar features as in the coherent case are observed, but when comparing with the coherent case [Fig. 4(b)] we obtain that the effect of light is smaller for the sequential current than for the coherent one in spite of the fact that the current density due to both contributions are of the same order. When the frequency of the applied laser is the same as the cyclotron frequency (the photon energy is 13.8 meV) there are again compensations in the current difference coming from different Landau levels [Figs. 8(a) and 8(b)] and light affects mainly the current density at the threshold and the cutoff bias.

In summary, the observed feature coming from our calculations is that the coherent contribution to the magnetotunneling current is more affected by light than the sequential one and that the effect of a laser on both contributions to the current can be controlled and modified by tuning the ratio between the cyclotron and the photon frequency. A drastic modification is observed when this ratio becomes 1.

There is an additional effect which occurs when the electrons tunnel sequentially and which can also be externally modified by an external electromagnetic field. It is the fact that when sequential tunneling takes place, the electrons which have tunneled coherently through the first barrier conserving the Landau level index in the process relax in the well and tunnel coherently in a subse-

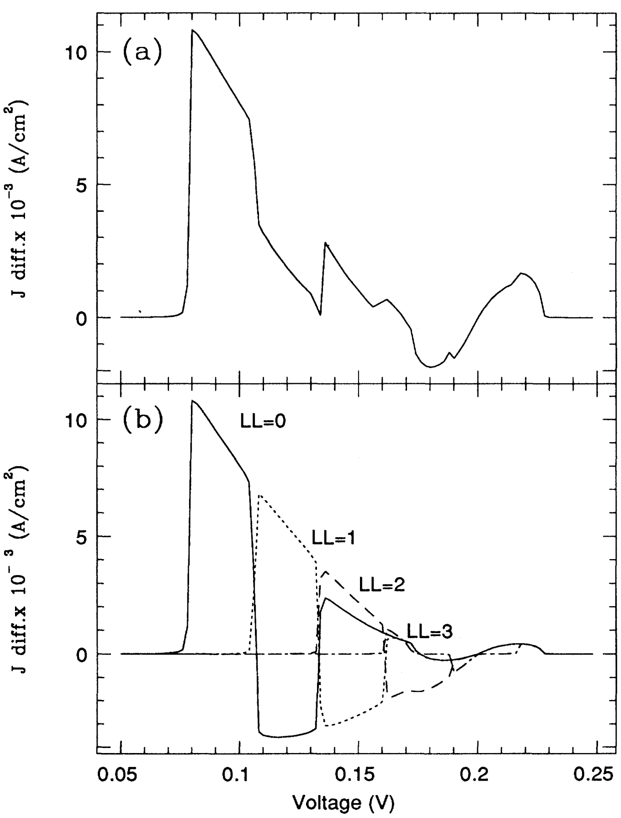

FIG. 8. (a) Sequential magnetocurrent difference (with and without light) for B= 8 T and $\hbar w = \hbar w_{\mathrm{cyclotron}}$. (b) Same as (a) for each Landau level separately.

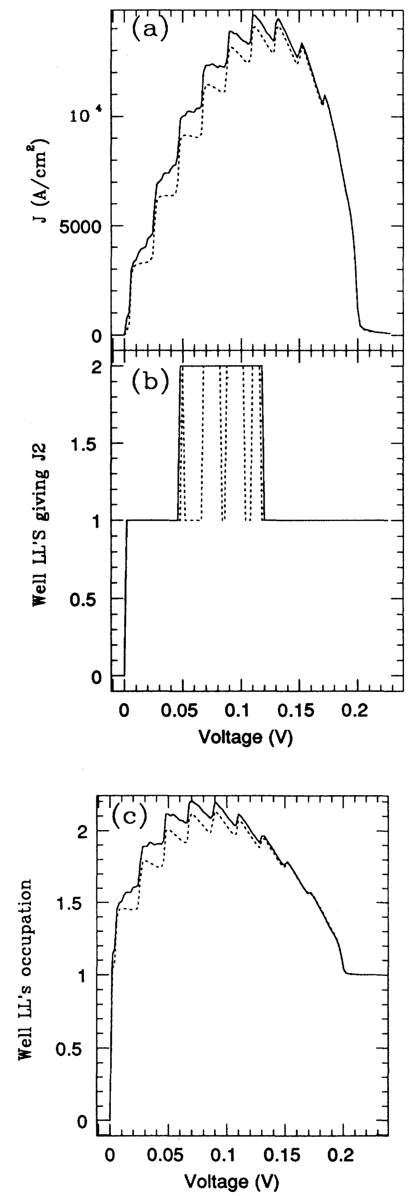

FIG. 9. (a) Sequential magnetocurrent density as a function of V. B= 6 T, $\hbar w$ = 7 meV, F = 5.10^6 V/m. Continuous line, light present; dotted line, no light present. (b) Total number of Landau levels into the well contributing to the current as a function of V with (continuous line) and without (dotted line) light. (c) Landau levels occupation into the well as a function of V. Continuous line, light present; dotted line, no light present.

quent process through the second barrier. Therefore, the number of the Landau levels at the emitter contributing to the current can be different than the number corresponding to the Landau levels in the well participating in the tunneling current through the second barrier, and those numbers can be modified by applying an external laser. This can be seen in Fig. 9(a), where at low field (6 T) there are many Landau levels giving current. The dotted line represents the magnetocurrent when no light is present into the sample and the continuous line corresponds to the case where a laser with a frequency of 7 meV and intensity of 5 10^6 V/m is applied to the sample. We observed that the current with no light presents a sawtooth profile coming from the participation of additional Landau levels as the bias increases. When the light is switched on, the current threshold moves to lower bias and there is a three steplike structure between each jump. For high electromagnetic field intensities the effect of light can be seen clearly in the current density curve as in Fig. 9(a). In Fig. 9(b) we represent the total number of Landau levels partially occupied in the well as a function of the bias for both cases: with (continuous line) and with no light (dotted line). We observe clearly, for instance, that around 0.04 V the second Landau level begins to be occupied in the case where light is present in the sample. As the bias slightly increases the second Landau level begins also to contribute to the current through the second barrier even with no applied light. As the bias increases, the well is discharged and the second Landau level becomes empty for the case in which there is no light present (dotted line). Finally, for high bias, the second Landau level becomes discharged for smaller bias in the case where there is no light present (dotted line) than in the presence of a laser (continuous line). From the above discussion we conclude that for a fixed bias the number of Landau levels participating in the sequential magnetocurrent through the second barrier (which is determined from the Landau level occupation in the well) can be modified illuminating the sample.

IV. CONCLUSIONS

In this paper we have extended the formalism proposed for photoassisted tunneling[13,14] to analyze both coherent and sequential magnetotunneling through a double barrier structure. We have considered a magnetic field applied parallel to the current and a laser with the electric field in the same direction as the current. We have observed that the modification of the current (for both sequential and coherent processes) due to the photon field can be controlled by tuning the ratio between the cyclotron and the photon frequency; turns out that when this ratio becomes 1, there is a compensation in the current difference coming from different Landau levels and this magnitude changes drastically and most of the structure observed in the cases where the cyclotron and the photon frequency are different is quenched.

Another interesting effect is that the light changes the Landau level occupation and modifies for a fixed bias, the number of Landau levels which participate in the current through the emitter (J_1) and also through the collector barrier (J_2). It means that for a given sample and an external magnetic field, by changing the photon frequency and intensity of the external applied laser, it is possible to get information on the Landau level density of states in the well.

In conclusion, the effect of light on the magnetotunneling current has been analyzed for both coherent and sequential tunneling processes; it turns out that it is the former that is most affected by light. This effect can be controlled by tuning the ratio between the two characteristic frequencies: the cyclotron and photon frequencies and it can be drastically modified when this ratio becomes 1. Very interesting effects are also expected for smaller systems where the electron-electron interaction is important and where the occupation of the resonant structure is crucial for the electron transport. This is the aim of a future work.

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