Dynamical localization and absolute negative conductance in an ac-driven double quantum well

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We analyze the *I-V* characteristic of a double quantum well integrated into an antenna and driven by THz radiation. We propose a microscopic model to calculate self-consistently the sequential current including the Coulomb interaction in a mean-field approximation. Additional features in the *I-V* characteristics appear that depend not only on the frequency and the intensity of the ac field but also on the charge in the wells. We observe dynamical localization and absolute negative conductance in the linear response regime. We compare our calculations with recent experiments in ac-driven double wells. [S0163-1829(97)07720-5]

The effect of an ac field on the transport properties of nanostructures has been a subject of increasing interest in the past few years. Recently transport experiments have been performed in semiconductor nanostructures in different ac fields. Photoassisted current through a double barrier (DB) irradiated with FIR light shows[1] additional features which can be explained in terms of the coupling of different electronic states induced by the electromagnetic field.[2] The effect of an ac potential on the conductance and current in quantum dots[3,4] in superlattices (SL's),[5] and in double quantum wells (DQW's) (Ref. 6) has been measured and new physical features, such as dynamical localization (DL) and absolute negative conductance (ANC), have been observed.[5] Also Rabi transitions between discrete states and electron pumping in double quantum dots (DQD's) have been analyzed within the Keldysh formalism.[7]

In this work we propose a model for analyzing the time-average current in a triple barrier (TB) integrated into an antenna and driven by THz radiation. In this configuration, the irradiated antenna produces an oscillatory signal between the left and right lead, i.e., a time-dependent bias drops between the emitter and collector. In order to account for scattering due to roughness at the interfaces, phonons, or impurities, we analyze sequential tunnel: we calculate the current from the emitter to the left well $J_{e,1}$, from the left well to the right well $J_{1,2}$, and from the right well to the collector $J_{2,c}$. Current conservation determinates the Fermi energies in the wells and the sequential current. The effect of electron-electron interaction in these quasi-3D structures can be treated as a perturbation to the noninteracting system within a mean field approximation.[8,9] The charge accumulated in the wells produces an additional electrostatic potential which modifies their electronic structure, transmission coefficient, and current. We solve self-consistently the Schrödinger equation including the ac field and the Poisson equation. The induced electrostatic potential does not drop linearly through the sample, and accumulation and depletion layers in the emitter and collector are built up. Details of the electrostatic model are given elsewhere.[9]

The Hamiltonian for the DQW driven by an ac potential is

$$H(t)=\sum_{k_i\epsilon L,R} E_{k_i}(t)\mathbf{c}^{\dagger}_{\mathbf{k_i}}\mathbf{c}_{\mathbf{k_i}}+\sum_{k_j\epsilon 1,2} E_{k_j}(t)\mathbf{d}^{\dagger}_{\mathbf{k_j}}\mathbf{d}_{\mathbf{k_j}} + \sum_{k_ik_j\left\{\substack{i=L,\ j=1\\ i=R,\ j=2.}\right.} (T_{k_ik_j}\mathbf{c}^{\dagger}_{\mathbf{k_i}}\mathbf{d}_{\mathbf{k_j}}+\text{H.c.}) + \sum_{k_1k_2}(T_{k_1k_2}\mathbf{d}^{\dagger}_{\mathbf{k_1}}\mathbf{d}_{\mathbf{k_2}}+\text{H.c.}). \tag{1}$$

Here, $T_{k_ik_j}$ and $T_{k_1k_2}$ are the tunneling matrix elements (leads-well and well-well, respectively).[10] The ac field induces a time-dependent bias between the emitter and collector producing a dipole around the central region. The electronic energies become time dependent $E_{k_i}(t) =E^0_{k_i}+eFz_i\cos\omega_0 t$, where z_i is assumed constant (its mean position) in each spatial region. This implies that the mixing of electronic states within each spatial region due to the position operator $\hat{\mathbf{Z}}$ is neglected. This approximation, which was assumed in the model of Tien and Gordon,[11] is reasonable for this configuration where the time-dependent potential drops just between the leads and for nonresonant conditions (for $\omega_0\neq\Delta/\hbar,\Delta$ being the subband spacing). The operators acquire phase factors of the form $\mathbf{c_{ki}}(t)=e^{-(i/\hbar)E_{ki}t}e^{-ieFz_i/\hbar\omega_0\sin\omega_0 t}\mathbf{c_{ki}} =e^{-(i/\hbar)E_{ki}t}\sum_{n=-\infty}^{\infty}J_n(eFz_i/\hbar\omega_0)e^{-in\omega_0 t}\mathbf{c_{ki}}$.

Each term in the sum corresponds to the n sideband which develops the spectral density. In the case of sequential tunneling, first order in perturbation theory gives a good description of the tunneling (coherent tunneling considering infinite order in the tunneling perturbation has been solved in Ref. 10). We obtain the following transition probabilities:

$$P_1(E_e,E_1)=\frac{2\pi}{\hbar}\sum_{n=-\infty}^{\infty}J_n^2(\beta_{e1})\left(\frac{2\hbar^4}{m^{*2}}\right)\frac{k_e}{L}\left[\frac{k_ek_1^2(\alpha_1+\alpha_1')^2e^{-2\alpha_1 d_1}}{\left(d_2+\frac{1}{\alpha_1'}+\frac{1}{\alpha_2}\right)(k_e^2+\alpha_1^2)(k_1^2+\alpha_1'^2)}\right]\frac{2\pi^2}{S^2}\delta\vec{k}_{\parallel}\delta(E_e-E_1+n\hbar\omega_0),$$

$$P_2(E_1,E_2)=\frac{2\pi}{\hbar}\sum_{m=-\infty}^{\infty}J_m^2(\beta_{12})\left(\frac{\hbar^4}{m^{*2}}\right)\left[\frac{k_1^2k_2^2(\alpha_2+\alpha_2')^2e^{-2\alpha_2d_3}}{\left(d_2+\frac{1}{\alpha_1'}+\frac{1}{\alpha_2}\right)\left(d_4+\frac{1}{\alpha_2'}+\frac{1}{\alpha_3}\right)(k_1^2+\alpha_2^2)(k_2^2+\alpha_2'^2)}\right]\frac{2\pi^2}{S^2}\delta\vec{k}_\parallel\delta(E_1-E_2+m\hbar\omega_0),$$

$$P_3(E_2,E_c)=\frac{2\pi}{\hbar}\sum_{p=-\infty}^{\infty}J_n^2(\beta_{2c})\left(\frac{2\hbar^4}{m^{*2}}\right)\frac{k_c}{L}\left[\frac{k_2^2k_c(\alpha_3+\alpha_3')^2e^{-2\alpha_3d_5}}{\left(d_4+\frac{1}{\alpha_2'}+\frac{1}{\alpha_3}\right)(k_2^2+\alpha_3^2)(k_c^2+\alpha_3'^2)}\right]\frac{2\pi^2}{S^2}\delta\vec{k}_\parallel\delta(E_2-E_c+p\hbar\omega_0), \tag{2}$$

where $E_k=\hbar^2k_\parallel^2/2m^*+\epsilon_{k_z}$, $\beta_{e1}=eF(z_1-z_e)/\hbar\omega_0$, $\beta_{12}=eF(z_2-z_1)/\hbar\omega_0$, and $\beta_{2c}=eF(z_c-z_2)/\hbar\omega_0$ are related with the ac potential drops between the different regions [z_i is the position at the center of the i well and $z_{e,c}$ is the position at the emitter (collector)], α_i (α_i') are the complex wave vectors at the i barrier for the initial (final) energy, k_i is the wave vector of the ground state at the i well, and the terms in brackets are the inelastic transmissions $T_1(\epsilon_e,\epsilon_1)$, $T_2(\epsilon_1,\epsilon_2)$, and $T_3(\epsilon_2,\epsilon_c)$ through each barrier. The time describing the relaxation between the states due to coupling with phonons is $\sim 10^{-13}$ s.[12] The density of states (DOS) in the growth direction is then described as Lorentzians of 1 meV half-width. Irreversibility is assumed in formula (2). In this case the Fermi golden rule is valid.[13] This is clearly the case for P_1 and P_3, where there is a continuum of states involved. In the case of the transmission probability from the left to right well, we assume irreversibility due to the broadening of the DOS induced by scattering, as well as to the 2D continuous in-plane DOS. On top of that, if the tunneling time associated to the outer barrier is shorter than the one corresponding to the barrier separating the two wells, the process of tunnel becomes irreversible. However, in the case of an isolated DQD, disconnected with a continuous DOS at the leads and in the ideal case where no scattering occurs, the tunnel is a reversible process and a description in terms of Rabi transitions should be considered.[7,13] The expression for the currents is

$$J_{e1}=\frac{2ek_BT}{\pi^2\hbar}\sum_{n=-\infty}^{\infty}J_n^2(\beta_{e1})\int\frac{\gamma}{[(\epsilon_e+n\hbar\omega_0-\epsilon_{r1})^2+\gamma^2]}\times T_1(\epsilon_e,\epsilon_e+n\hbar\omega_0)\ln\left[\frac{1+e^{\frac{(\epsilon_F-\epsilon_e)}{k_BT}}}{1+e^{\frac{(\epsilon_{\omega_1}-\epsilon_e-n\hbar\omega_0)}{k_BT}}}\right]d\epsilon_e,$$

$$J_{12}=\frac{2e\hbar k_BT}{\pi^2m^*}\sum_{m=-\infty}^{\infty}J_m^2(\beta_{12})\int\frac{\gamma}{[(\epsilon_1-\epsilon_{r1})^2+\gamma^2]}\times\frac{\gamma}{[(\epsilon_1-\epsilon_{r2}+m\hbar\omega_0)^2+\gamma^2]}T_2(\epsilon_1,\epsilon_1+m\hbar\omega_0)\times\ln\left[\frac{1+e^{\frac{(\epsilon_{\omega_1}-\epsilon_1)}{k_BT}}}{1+e^{\frac{(\epsilon_{\omega_2}-\epsilon_1-m\hbar\omega_0)}{k_BT}}}\right]d\epsilon_1, \tag{3}$$

$$J_{2c}=\frac{2ek_BT}{\pi^2\hbar}\sum_{p=-\infty}^{\infty}J_p^2(\beta_{2c})\int\frac{\gamma}{[(\epsilon_2-\epsilon_{r2})^2+\gamma^2]}\times T_3(\epsilon_2,\epsilon_2+p\hbar\omega_0)\ln\left[\frac{1+e^{\frac{(\epsilon_{\omega_2}-\epsilon_2)}{k_BT}}}{1+e^{\frac{(\epsilon_F-eV-\epsilon_2-p\hbar\omega_0)}{k_BT}}}\right]d\epsilon_2,$$

where ϵ_{r1} and ϵ_{r2} are the ground states of the left and right wells. For simplicity we restrict the previous equations to the tunneling between ground to ground state (the generalization to excited well states is straightforward). The Fermi energies ϵ_{w1} and ϵ_{w2} of the wells are obtained through the set of transcendental equations $J-J_{e1}=0;J-J_{12}=0;J-J_{2c}=0$. At this point we solve the Poisson and Schrödinger equation self-consistently to obtain the current. In order to compare with recent experiments,[6] we analyze a sample consisting of two GaAs quantum wells 180 Å and 100 Å wide separated by a barrier of $Ga_{0.7}Al_{0.3}As$ of 60 Å. The outer barriers are 35 Å thick (sample a). The emitter and collector are n^+ doped (5×10^{17} cm^{-3}). In Fig. 1(a) the J/V curve is shown with and without Coulomb interaction. We observe a main peak coming from the alignment of the two ground states of the two wells. Two additional peaks show up at both sides of the main peak symmetric in bias but asymmetric in intensity and which correspond to induced one-photon absorption and emission. The asymmetry takes place due to the increase in the transmission probability at higher bias and to the asymmetry of the charge accumulated in the wells [see Fig. 1(b)]. The behavior of J for different F and for fixed w_0 is shown in Fig. 2(a): as F increases, new satellites show up indicating that multiphoton processes increase in probability, the main peak is reduced, and the satellites become more intense. Also J is quenched for some frequencies and intensities of the field. This effect has been discussed[14,15] in terms of zeros of the J_0 Bessel functions: as the argument approaches the first zero (~ 2.4), dynamical localization of electrons takes place, independent of the transparence of the barriers. The experiments are very similar to our results. However, we did not observe the small shift that the peaks experience as F increases and which is interpretated as heating of the contact regions.[6] As the power increases, the effect of the ac field on the charge accumulated in the wells increases too. It would be expected[8] that for high intensities the ac field would affect the charge and the self-consistent current explaining also the shift of the peaks. We do not observe an appreciable shift for intensities of the order of 10^5 V/m but this is observed for intensities at least one order of magnitude higher.[8] There is also another effect that could explain this shift considering

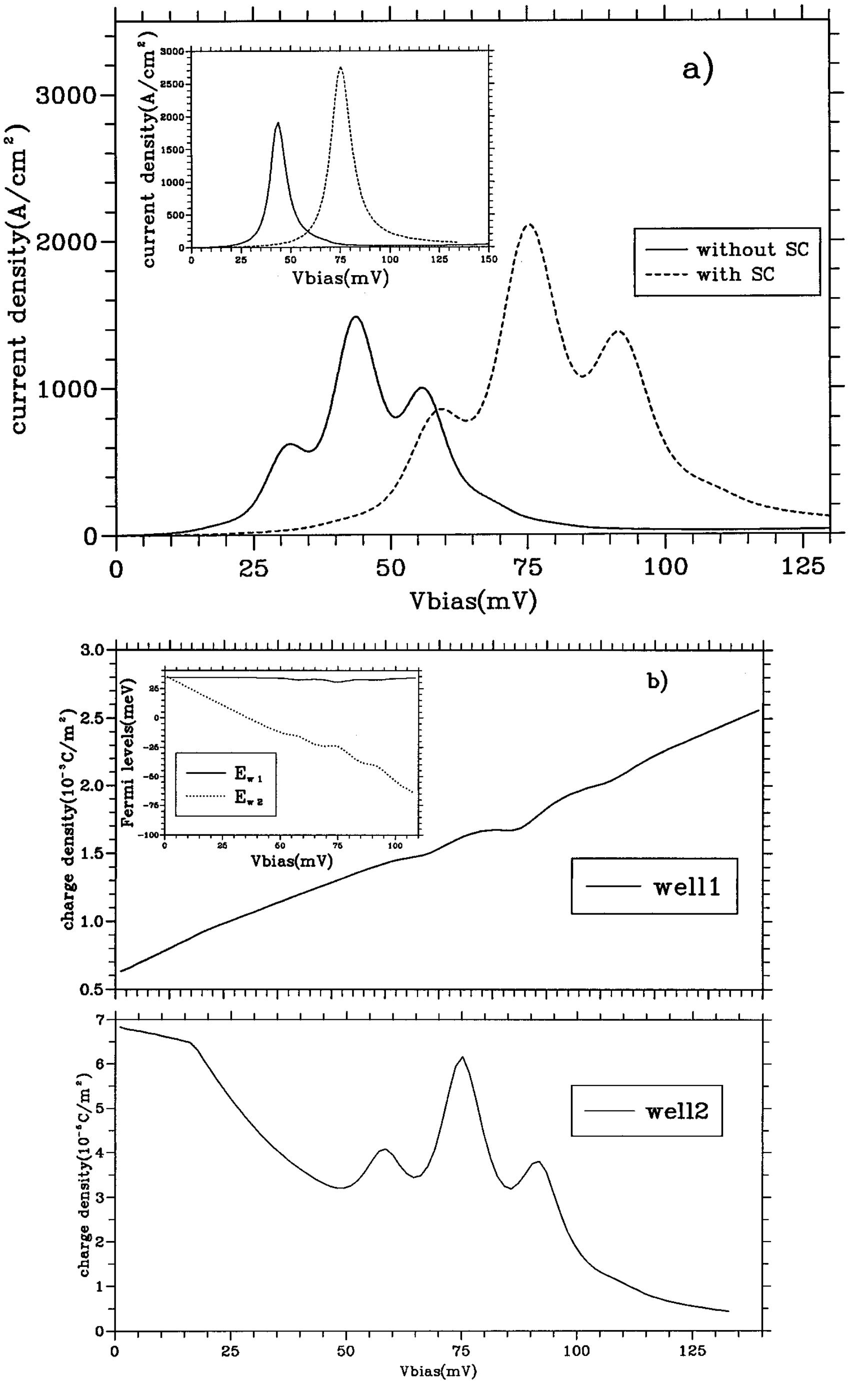

FIG. 1. (a) J/V for ac sequential tunneling through a TB (with and without self-consistency) (inset without ac); (b) 2D self-consistent charge in the left and right well as a function of V (the inset shows the Fermi levels of the two wells) for sample a ($F=1.5\times10^5$ V/m, $\omega_0=1.5$ THz, $T=100$ K).

the dipole term as a quantum operator.[4,16] The term $eF\hat{\mathbf{Z}}\cos(\omega_0 t)$ will produce a shift of the energies: $\delta=e^2F^2\langle k_i|\hat{\mathbf{Z}}|k_i\rangle^2/\hbar\omega_0$. However, the shift becomes negligible,[2] due to the smallness of the diagonal matrix elements of $\hat{\mathbf{Z}}$. J/V for different frequencies is shown in Fig. 2(b). As ω_0 increases, the satellite peaks move far apart linearly from the main one, which increases in intensity as the satellite peaks decrease. Finally, we observe ANC in a different sample: a $Ga_{0.7}Al_{0.3}As$ TB of 50 Å and a DQW of GaAs of 150 Å with an emitter Fermi energy of 18 meV (sample b). This effect, which has been discussed for different systems,[14,16,17] has been observed in SL's (Ref. 5) for low bias. The negative conductance induced by the ac field can be explained in terms of the Fermi distributions. Equation (3) shows that the supply function contains a superposition of effective dc voltages $\pm p\hbar\omega_0/e$, each one weighted nonlinearly by the Bessel functions. This effect is responsible for the negative conductance due to the fact that the Fermi factors can be expressed in terms of effective Fermi energies (for instance, $E_{F_{\rm eff}}=E_F-eV\pm p\hbar\omega_0$, in the collector). For some ranges of F and ω_0, the electrons are able to overcome the static bias ($eV\leqslant p_{\rm max}\hbar\omega_0$) and electronic pumping in the opposite direction occurs.[18] We study the dependence of the ANC with F. In some cases we observe that the differential conductance and the current change sign by tuning F (Fig. 3) and that the conductance becomes negative with increasing F and again positive as F increases further. The differential conductance at zero bias changes sign

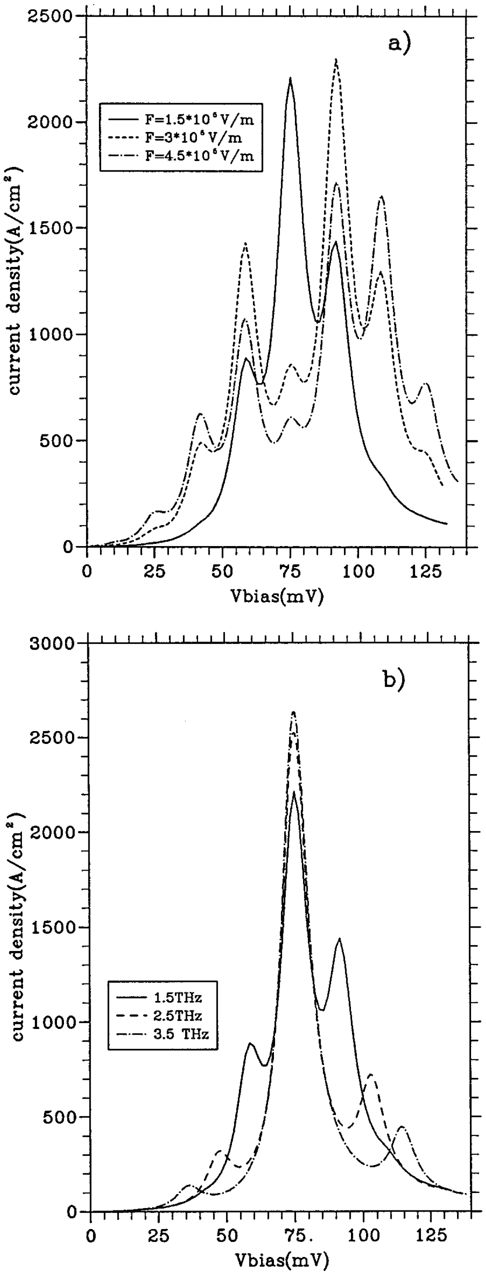

FIG. 2. (a) Self-consistent J/V for $\omega_0 = 1.5$ THz and different F; (b) at $F = 1.5 \times 10^5$ V/m and different ac frequencies (sample a, $T = 100$ K).

at field intensities of the order of 710^5 V/m as in experiment.[5] The reason for this is that at this frequency and intensity of the field the direct tunneling channel J_0 is quenched (dynamical localization) and the one-photon processes are the available ones for tunneling. However, for low bias the emission from the left to the right well is blocked due to the occupation of the ground state in the right well. Then the absorption channel is enhanced and the current flows in an opposite direction to the dc bias. As the bias increases, the emission channel is opened and the current becomes positive again.

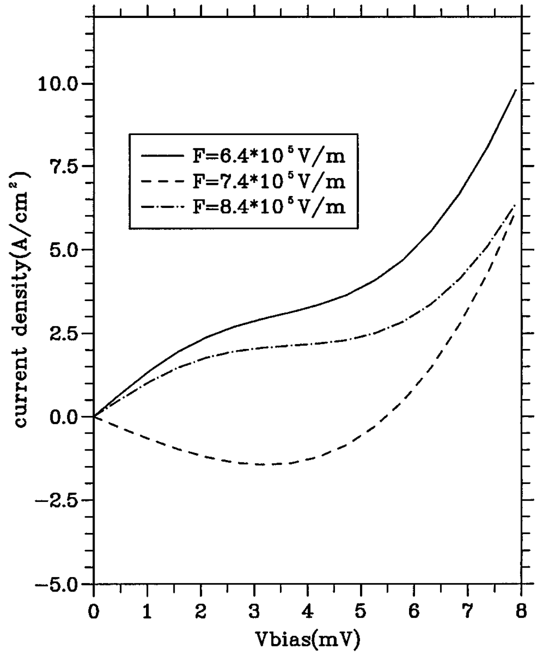

FIG. 3. J/V for $\omega_0 = 1.5$ THz and different F in the low bias regime (sample b, $T = 10$ K).

In conclusion, the ac sequential current through a triple barrier is evaluated including the Coulomb interaction, scattering effects, and temperature. By means of our model, we can explain the behavior of J/V as a function of the ω_0 and intensity in good agreement with the experimental information. We analyze different samples and we observe interesting features in the current, such as DL and ANC. Both effects can be controlled by tailoring the sample and the harmonic potential configuration.

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