Effect of collisions and relaxation on coherent resonant tunneling: Hole tunneling in $GaAs/Al_xGa_{1-x}As$ double-quantum-well structures

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Direct measurements of resonant and nonresonant hole tunneling times in a $GaAs/Al_xGa_{1-x}As$ double-quantum-well structure show that tunneling time at resonance is considerably longer than expected for coherent tunneling or intersubband relaxation. We demonstrate that coherent tunneling and relaxation cannot be treated independently since the coherence is destroyed by collisions and relaxation. This leads to a large increase in the tunneling times observed at resonance. We show furthermore that resonant tunneling due to mixing between heavy- and light-hole states is less important than tunneling between heavy-hole states.

Tunneling, as one of the fundamental quantum-mechanical processes, has gained renewed interest in recent years.[1] Transport measurements in double-barrier structures (DBS) and multiple-quantum-well structures (MQWS) (Ref. 2) have given much insight into the physics of tunneling in such structures and have shown promising applications. However, they have also raised a number of questions concerning the basic properties of the tunneling process itself. One unresolved topic, the *time* that a particle needs to traverse a potential barrier,[3] is still the subject of numerous theoretical studies (e.g., Ref. 4). One case in which the definition of a tunneling time is obvious and unambiguous is that of a double-quantum-well structure (DQWS), in which two electronic levels are brought in resonance.[5] In the ideal case of no collisions and no relaxation, a wave packet created in one well oscillates between the two wells with a well-defined frequency (the Rabi frequency) and the tunneling time can be defined as half the period of this coherent oscillation.

The *influence of scattering and relaxation* on coherent tunneling processes is an interesting topic that has received very little attention. It was shown[6] that scattering processes broaden the transmission peak, but keep the total transmission constant. Accordingly, it was found for DBS and small scattering rates that the static current is identical for coherent and noncoherent or sequential tunneling.[7] Luryi has shown[8] that weak-scattering processes lead to a damping of coherent oscillations in DQWS. However, the influence of strong scattering and relaxation on coherent oscillations has not been considered before.

Recently, electron escape rates from DBS,[9] resonant electron tunneling[10] rates in DQWS,[11] as well as transport across MQWS (Ref. 12) have been measured with picosecond time resolution using ultrafast optical techniques. Although static investigations of hole tunneling have been reported,[13,14] *dynamics of hole tunneling,* which is of fundamental interest and also relevant to devices based on perpendicular transport of carriers in MQWS, has not been investigated.

In this paper we present results that provide new insight into both of these unexplored and unresolved questions. We report the first measurement of hole tunneling times in a semiconductor DQWS for both nonresonant and resonant conditions. The tunneling time decreases abruptly at a resonance between two heavy-hole states but is much longer than expected for a coherent process or for intersubband relaxation. We show that surprisingly long tunneling times result from *phase-breaking collisions and relaxation processes* which are much faster than the coherent oscillation frequency. A theoretical model that properly takes into account the influence of strong collisions and relaxation on coherent tunneling is developed. The model shows that coherent tunneling and relaxation and/or collisions cannot be treated independently; i.e., the tunneling time is not simply the longer of the coherent tunneling time and the relaxation time. In fact, for relaxation and collision times much shorter than the coherent tunneling time, the measured tunneling time *increases* as the relaxation time *decreases.* The model gives a quantitative understanding of the experimentally observed hole tunneling times. Finally, our experiments show that tunneling due to mixing between heavy- and light-hole valence bands is not very effective.

The samples used in these studies were grown by molecular-beam epitaxy on (100) *n*-type GaAs substrate. Results presented in this paper were obtained on a sample in which the basic structure is an asymmetric double quantum well with a 63-Å narrow well (NW) and a 90-Å wide well (WW), separated by a 50-Å $Al_{0.30}Ga_{0.70}As$ barrier. Eight periods of this basic structure were grown, separated by 150-Å $Al_{0.30}Ga_{0.70}As$ barriers. All thicknesses are determined by transmission electron microscopy (TEM) and are consistent with optical studies. This structure is in the *i* region of a *p-i-n* diode; the electric field is varied by applying a voltage to square mesas of 200 μm size. The field is calibrated by measuring the luminescence shift due to the quantum confined Stark effect. The sample is mounted in a cryostat ($T = 10$ K) and excited with a synchronously mode-locked dye (LDS-750) laser. The excitation photon energy used for collecting the data shown is 1.69 eV, i.e., carriers are created in WW and in the ground state of the NW. Experiments with lower excitation energy for which only the WW is excited give identical results. The excitation density estimated from the measured spot diameter and laser power is $\leq 2\times 10^{10}$ cm^{-2}. The luminescence is detected by the up-conversion technique[15] with an overall time resolution of about 2 ps.

We determine the tunneling time of holes in such a structure (Fig. 1) by measuring the time decay of luminescence from the *wide well.* Electrons and holes created by photoexcitation in the WW well behave very differently: electrons are confined by the very thick barrier to the next period and cannot leave the WW, except at high fields. The holes, however, can tunnel out through the thin and low barrier to the NW at low or moderate fields. In the NW, they can relax to the ground state, from which the probability of tunneling back is negligible. By monitoring the decay of the WW luminescence, we can directly determine the hole tunneling time, i.e., the average time a hole needs to tunnel from the WW to the NW through the barrier separating the two wells.[16] A variation of the electrical field allows one to obtain resonance between different hole levels.

The inset of Fig. 1 shows a time-resolved luminescence spectrum taken at 10 K and built-in field (27 kV/cm). The WW and NW transitions are clearly visible. The time-resolved data in Fig. 1. show the decay of the WW luminescence for various electric fields. At zero field, we observe a decay time of about 800 ps, as expected for the carrier lifetime in such a structure. Increasing the field leads to a change in the decay times, as shown in the lower part of Fig. 2. From zero field to about 40 kV/cm, the decay time stays approximately constant. Above 40 kV/cm, however, the decay time drops sharply to ≈ 500 ps. For further increases in the field, the luminescence

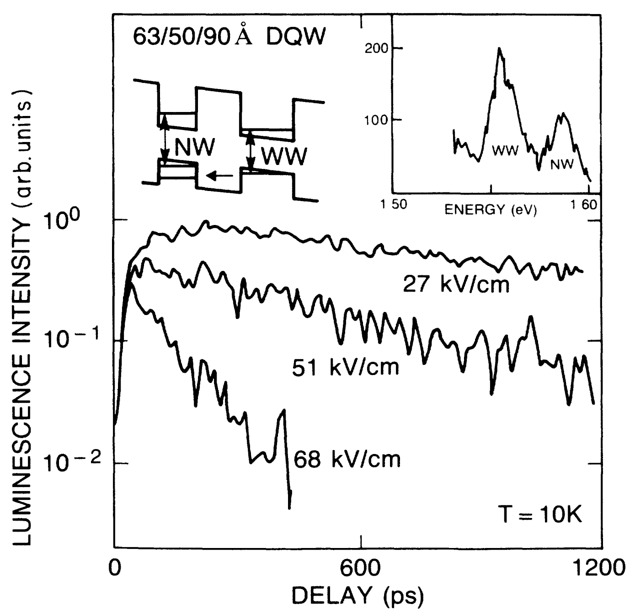

FIG. 1. Luminescence decay of the wide well (right arrow in the schematic drawing of the structure) for different electric fields. The inset shows a time-resolved luminescence spectrum at a delay time of 30 ps, showing the WW and NW transitions.

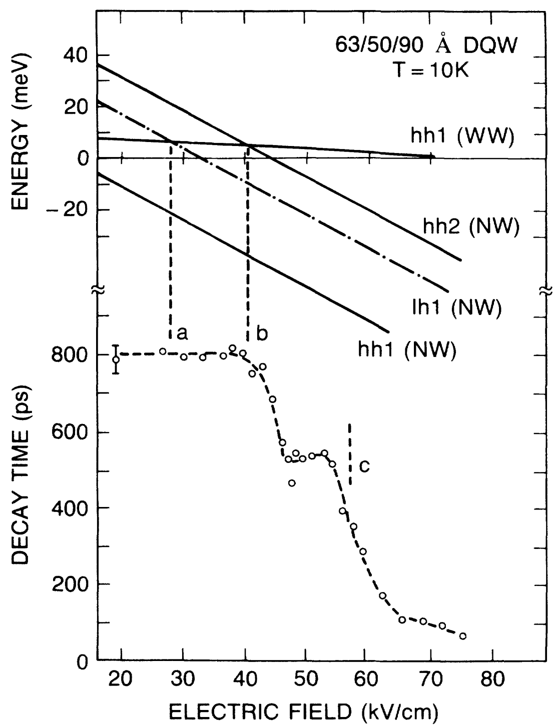

FIG. 2. The lower part shows the decay time of the WW as a function of the electric field. The upper part shows calculated hole energy levels as a function of the field. Zero energy is set to the center of the WW. Resonances between levels as discussed in the text are indicated by vertical dashed lines.

decay time increases slightly, drops abruptly to ≈ 100 ps, and then decreases continuously.

The sharp drops in the decay times result from the increase in the tunneling rates at these fields. In the upper part of Fig. 2, the calculated energies of various hole levels are plotted as a function of the electric field, with the band edge at the center of the WW taken as the zero. We note that (i) at about 30 kV/cm, the first hh level of the WW and the first light-hole level in the NW come into resonance (denoted *a* in Fig. 2). Experimentally, no effect is observed, so that $\tau_{\rm tun} > 8$ ns. Measurements at elevated temperature (T=80 K) and carrier density ($n = 4\times 10^{11}$ cm^{-3}) also showed no resonance. We conclude that tunneling due to hh-lh mixing is not important in our case. This result seems to disagree with a recent calculation[17] predicting large tunneling rates due to hh-lh mixing. (ii) At about 40 kV/cm, the first hh level of the WW and the second hh level of the NW come into resonance (denoted *b* in Fig. 2); correspondingly, we see a sharp drop in the luminescence decay time. We have ruled out other possible causes[18] and conclude that the increase in the tunneling rate near 40 kV/cm is due to *resonant tunneling of holes.*

For fields above 55 kV/cm, one has to consider several different tunneling processes. The estimated tunneling times for the escape of holes out of the DQWS, and for phonon-assisted tunneling between hh1 in WW and lh1 in NW are ≈ 100 ns in this field range. However, at 55 kV/cm, the lowest electron level in WW comes in resonance with the second electron level in the NW of the next period (through the thick 150 Å barrier). Our calculations[19] show that this resonance (c in Fig. 2) facilitates tunneling of electrons out of the WW into the continuum and gives tunneling times of $\lesssim 60$ ps at 60 kV/cm. We therefore attribute the second increase in the tunneling rate of 55 kV/cm in the data in Fig. 2 to electron tunneling, which will not be discussed further in this paper.

The magnitude of the hole tunneling time at resonance is determined by taking the difference in the inverse of the decay times at 0 and 48 kV/cm. We determine that the hole tunneling time at the hh1-to-hh2 resonance is 1300 ps, a surprisingly large value. Photoexcitation with a short pulse creates a carrier wave packet in the WW consisting of a linear superposition of the eigenstates of the coupled system in resonance (see below). For the parameters of our sample, this wave packet will oscillate to the NW (see, e.g., Ref. 5) with a half period (coherent tunneling time) of 28 ps, much smaller than the value observed experimentally. Since the experimentally measured splitting between the hh2 and the hh1 states in NW is 39 meV, larger than both the TO- and the LO-phonon energies, we expect intersubband hole relaxation to be fast. Therefore, we must conclude that one *cannot* simply take the longer of the coherent tunneling time and the relaxation time to explain the tunneling times at resonance. In the following, we show by developing a quantitative theory that relaxation in the final well and collisions break the coherence of the tunneling process and lead to tunneling times which are considerably *longer* than expected for coherent tunneling. This provides a quantitative understanding of the experimental results.

The necessary theory is particularly simple in the absence of scattering processes. Then the wave vector parallel to the quantum wells, $k_{\parallel}$, is a good constant, and transitions occur only between states of the same $k_{\parallel}$. Let $|\Psi_1\rangle$, with energy E_1, represent the uncoupled hole state of the WW, computed as though the NW well were absent. Similarly, let $|\Psi_2\rangle$, with energy E_2, represent the uncoupled excited state of the NW. The energies E_1 and E_2 are brought into resonance by adjusting the applied electric field. The matrix element for resonant tunneling between these two states is given by

$$V_{12} \cong -V\int_{\mathrm{WW}} \Psi_1 \Psi_2 \, dx \cong -V\int_{\mathrm{NW}} \Psi_1^* \Psi_2 \, dx \ , \qquad (1)$$

where V is the well depth, and the integral goes over the extent of either well. The wave packet oscillates between the two wells with the resonance Rabi frequency given by $\Omega_R = (2/\hbar)|V_{12}|$.

If we now include the energy relaxation processes for the two states, then the equations of motion for the state amplitudes a_1 and a_2 in $|\Psi\rangle = a_1|\Psi_1\rangle + a_2|\Psi_2\rangle$ for resonant excitation in the WW are the same as for a pair of coupled damped harmonic oscillators, namely

$$da_1/dt + (\Gamma_1/2 + i\omega_1)a_1 = -i(V_{12}/\hbar)a_2 \ , \qquad (2)$$

$$da_2/dt + (\Gamma_2/2 + i\omega_2)a_2 = -i(V_{21}/\hbar)a_1 \ , \qquad (3)$$

where Γ_i is the decay rate (reciprocal lifetime) of the ith state, and $\omega_i = E_i/\hbar$, ($i=1,2$). Note that $|\Psi\rangle$ is not normalized; it need not be, as this is only a partial description of the hole system. For the case under consideration, where Γ_2 is much larger than Γ_1 and Ω_R, the solution of these equations yields a modified decay rate for holes in state 1 given by

$$\Gamma_1' \cong \Gamma_1 + \frac{\Omega_R^2 \Gamma_2}{\Gamma_2^2 + 4(\omega_2-\omega_1)^2} \ . \qquad (4)$$

Therefore the effect of relaxation is to broaden the resonance by Γ_2. The tunneling rate at resonance *decreases* as Γ_2 (intersubband relaxation rate) *increases*, because the rapid damping prevents the buildup of state amplitude a_2. This result, which is counterintuitive in a sequential picture of the tunneling and relaxation processes, is a consequence of the loss of coherence due to relaxation.

In a real physical system, there are additional scattering processes (e.g., carrier-carrier-scattering, relaxation in the WW) destroying the phase coherence between the state amplitudes a_1 and a_2. A density matrix formalism required in this case gives an increase in the width of the tunneling resonance, with Γ_2 in Eq. (4) replaced by $\Gamma_2 + 2\Gamma_\Phi$, where Γ_Φ is the additional decay rate of the phase coherence due to this elastic scattering. It is noteworthy that the integral of the tunneling decay rate with respect to the frequency detuning (i.e., the area under the resonance curve) $\omega_2-\omega_1$ is $\pi\Omega_R^2/2$, independent of the width (Γ_2 or $\Gamma_2+2\Gamma_\Phi$) of the resonance.

We check the agreement with our experimental result for resonant hole tunneling with these theoretical results in two ways. (i) We estimate that the full width at half maximum of the observed resonance ($\hbar\Gamma$) near the 48 kV/cm is 6 meV and the tunneling rate at the peak is 1/1330 ps. Therefore the area under the resonance tunneling curve is about a factor of 2.5 smaller than the theoretically expected value $\pi\Omega_R^2/2$ based on $\Omega_R = 1.1\times10^{11}$ rad/s (corresponding to an energy splitting of 0.074 meV). (ii) By inserting the width of the resonance and Ω_R into Eq. (4), we calculate the expected tunneling time at resonance to be 770 ps, a factor of 1.7 shorter than the experimentally observed time of 1330 ps. A deviation from the barrier thickness assumed for the calculation of Ω_R or inhomogeneous broadening of the quantum well states might be responsible for these differences. However, the result of both comparisons can be regarded as reasonable agreement considering the *large factor* (≈ 40) between the experimentally determined tunneling time and the prediction for a coherent process, and the uncertainty in the determination of the area and width of the resonance.

In conclusion, our experimental results and theoretical considerations show that the idea of treating resonant tunneling in a double-well structure as an ideal coherent process breaks down in a real system due to collisions and relaxation. Tunneling time is not simply the longer of the coherent oscillation time and relaxation time. The destruction of the coherence of tunneling by collisions and relaxation can increase tunneling time by orders of magnitude, if scattering and relaxation are *faster* than the idealized coherent tunneling process. Hole tunneling due to mixing of heavy-hole with light-hole states is not very effective compared with heavy-hole tunneling.

Note added in proof. After completion of this manuscript, results about resonantly enchanced hole transport in superlattices [H. Schneider *et al.*, Phys. Rev. B **40**, 10 040 (1989)] and nonresonant hole tunneling in a DQW [M. Nido *et al.*, Appl. Phys. Lett. **56**, 355 (1990)] were reported. Furthermore, we became aware of a recent theoretical study (C. Y. Chao and S. L. Chuang, unpublished) about the influence of valence-band mixing on hole tunneling, which indicates that resonances between hh and lh states are less important if the detailed valence-band structure is taken into account.

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[19]Calculated is the inverse width of the resonance transmission peak, in a similar way as described in Livescu *et al.*, Ref. 12.