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Coherent Transfer and Electron Teleportation in Semiconductor Double Quantum Well

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When three or more levels are simultaneously coupled by light in a charge transfer double quantum well (QW), it is possible to transfer electrons coherently between the QWs. Using two light pulses of different wavelengths, the transient occupation of the space between the two QWs can be made arbitrarily small: electron teleportation. We discuss this phenomenon within a single electron model, estimate the effect of decoherence, and compare our results with experiments.

With the rapid development of quantum computing and the need for fast and small devices, the investigation of quantum coherency and the manipulation of quantum states has become increasingly important. Further, coherent processes are reversible and dissipate little energy. Indeed, experiments on coherent manipulation of excitons in semiconductors have shown that excitons can be created and destroyed, at will, with ultrafast optical pulses [1].

Coherent intersubband transitions have been much less studied than their interband counterpart, due to their shorter dephasing times and the relative scarcity of ultrafast mid-infrared sources in the 2 μm or longer wavelength range. Contrary to excitonic excitation that changes electron–hole population, intersubband excitations do not create new carriers, but modify the wavefunction, i.e. the spatial distribution of the carriers [2,3]. By using wavefunctions with different spatial extension, it is actually possible to move electrons in a coherent way.

In the following, we study systems where more than two levels are simultaneously coupled by the radiation field. In this case, we will show that it is possible to transfer electrons between states that have no spatial overlap whatsoever – electron teleportation. There will follow a discussion of the difficulties that are met in practical demonstration of this phenomenon, and a comparison between calculation and experiment.

In a two-level intersubband system with a single electron in the ground state, it is possible to transfer the electron coherently to the excited level by exciting the system with a resonant light pulse that has the right duration. Such a pulse is called a π-pulse.

π-Pulses can also be found in three-level systems coupled with a bichromatic light pulse (see, e.g., [4]). We consider a charge transfer double quantum well (CTDQW) structure (see Fig. 1), with a ground state ϕ_R in the right quantum well (QW), a second state ϕ_L, uncoupled to ϕ_R, in the left QW, and a third excited common state ϕ_C, that

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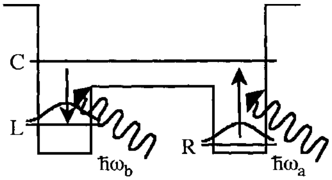

Fig. 1. Conduction band structure of a Charge Transfer Double Quantum Well (CTDQW) structure

spatially overlaps both ϕ_R and ϕ_L [5,6]. If our system is asymmetric, ϕ_R and ϕ_L will have different energies and the transitions R–C and L–C can be excited independently with light pulses of different photon energies. The general wavefunction of the system is written as a superposition of the three levels $\Phi = u_R(t) \exp(i\omega_a t)\, \Phi_R(x) + u_L(t) \exp(i\omega_b t)\, \Phi_L(x) + u_C(t)\, \Phi_C(x)$, where u_R, u_L and u_C are the amplitude of occupation of the three states. We excite the system with a bichromatic light pulse, of wavelengths ω_a and ω_b and electric field envelopes E_a and E_b satisfying $E_b(t) = (\mu_{RC}/\mu_{LC})\, E_a(t)$ where μ_{RC}, respectively μ_{LC}, are the dipole moments between levels R and C, resp. L and C. Using rotating wave approximation, we can show that the electron is coherently transferred between levels R and L when the electric field fulfills the condition

$$\int_{-\infty}^{\infty} E_a(t)\, dt = \frac{\sqrt{2}\,\pi\hbar}{\mu_{RC}}\,. \tag{1}$$

Such a light pulse is then a bichromatic π-pulse for a three-level system. The occupation probability $|u_C|^2$ of level C will reach a maximum of 1/2 at the middle of the π-pulse: the electron transfers from the right to the left QW without ever fully occupying the common level C.

It is possible to decrease arbitrarily the intermediate occupation probability of the common level C, if we shift pulse E_a forward in time compared to pulse E_b. The light intensity needed for the transfer is however inversely proportional to the square of the occupation probability of the common level. Figure 2a shows how electrons are transferred between R and L with two Gaussian pulses displaced in time. The transient occupation of level C is greatly reduced compared to the case of simultaneous E_a and E_b field. The evolution of the wavefunction displayed in Fig. 2b illustrates the negligibly small occupation of the space between the two QWs that is achieved during the transfer.

The small occupation of the excited level has a practical consequence. Though we did not include any effect of dephasing, in real systems scattering between common and ground levels occurs, destroying the phase information of the system and decreasing the transfer efficiency. The small occupation of the excited level during the transfer process should afford a much longer coherence, since the wavefunction is formed for the greater part of a superposition of the initial R and final L levels, which are stable levels.

Another case of interest is the quasi-symmetric system. In a perfectly symmetric system, the ground wavefunctions ϕ_R and ϕ_L are degenerate. In order to decouple them, we need to introduce a small asymmetry in the system. This asymmetry should be small enough that the energies ϵ_R and ϵ_L of levels R and L and the dipole moments μ_{RC} and μ_{LC} are nearly equal. Then, a single light pulse of photon energy simultaneously resonant to transitions R–C and C–L can be used to realize the transfer. The time evolution

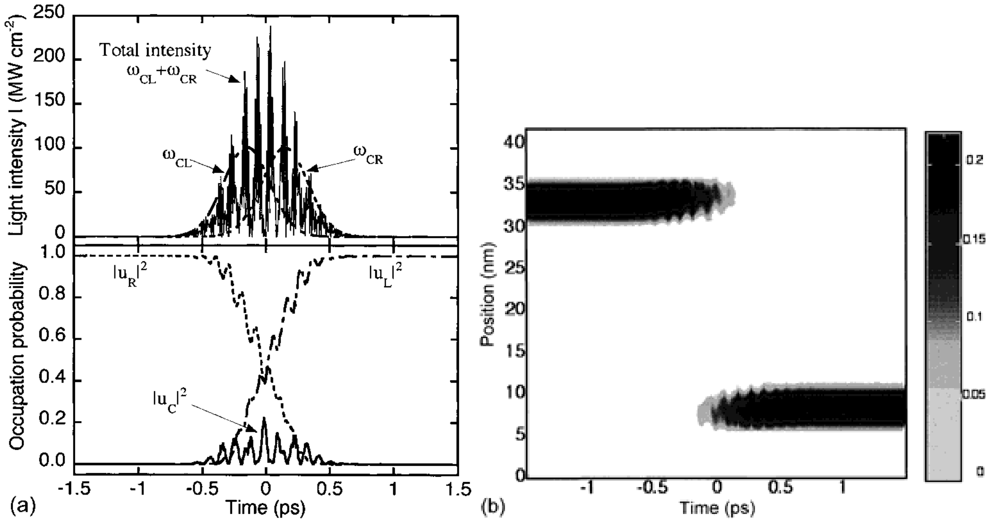

Fig. 2. Evolution of an asymmetric CTDQW excited with two light pulses shifted in time, in order to decrease the transient occupation of the common level. a) Top: envelope of the two light pulses, and total light intensity; bottom: occupation probabilities of three levels. b) Evolution of the wavefunction, that shows the transfer from one QW to the other. Presence probability of the electron between the two QW is negligible during the transfer

is similar to the asymmetric system with simultaneous light pulse treated above. In particular, we find that we can transfer electrons from ϕ_R to ϕ_L with a single monochromatic pulse satisfying

$$\int_{-\infty}^{\infty} E(t)\,\mathrm{d}t = \frac{\sqrt{2}\,\pi\hbar}{\mu}\,, \tag{2}$$

i.e. with two times more intensity than a π-pulse in a two-level system.

In real quantum well systems, higher levels play a role in the transfer. These other levels become particularly important when the bandwidth of the pulse is larger than the energy separation between the common level C and the additional levels. Also, in quasi-symmetric systems, the small asymmetry results in a difference in energy between levels L and R, and in a difference in the dipole moments μ_{RC} and μ_{LC}. In consequence, it is not possible to realize a perfect transfer with a single monochromatic pulse. The two-pulse scheme for asymmetric system offers more flexibility, but works only when the asymmetry is larger than the bandwidth of the pulse.

An illustration of the effect of additional levels is shown in Fig. 3. It plots the amplitude of teleportation, i.e. the probability for an electron to be transferred to the other well at the end of the light pulse as a function of light intensity and wavelength, for a single pulse excitation in a quasi-symmetric system. Figure 3a shows the case of a 1 ps pulse, and Fig. 3b shows the case of a 200 fs pulse. Two common levels separated by 15 meV were introduced in the calculations, as well as non-resonant contributions. We see that a good – though not perfect – transfer can be obtained with a 1 ps pulse, either when it is resonant with the transition to the first excited level, or resonant with the second excited level. However, the 200 fs pulse couples two both common levels

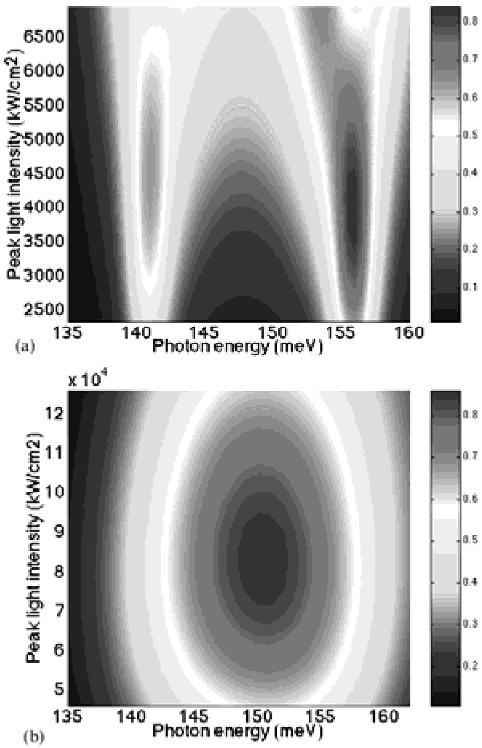

Fig. 3. Transfer probability between to QWs in a quasi-symmetric system, as a function of wavelength and pulse amplitude. Pulse duration: a) 1 ps, b) 200 fs

simultaneously and achieves the largest transfer efficiency at a wavelength intermediate between the two transition energies.

Experimentally, coherent transfer can be investigated by monitoring the near-infrared luminescence. We first optically fill the right QW with electrons, and the left QW with holes. Electrons transferred from the right QW to the left one recombine with holes, generating luminescence [6]. Decoherence effects can be investigated by two-pulse experiments. The first pulse partially transfers electrons, which are then transferred back to the initial state by the second pulse if it has the opposite phase. Inversely, when the second pulse is in phase with the first one, transfer of the electrons will be enhanced. In the interval between the two pulses the phase information is solely carried by the electron wavefunction. A comparison of the transfer amplitude obtained by in-phase and opposite-phase pulses will give us a direct information of the dephasing time of the system.

This experiment was performed on a biased GaAs CTDQW under monochromatic ultrafast pulse excitation [7]. The system presents levels R and L very close in energy, but a large asymmetry of the common level that favors strongly R–C transitions. Due to this asymmetry, the coherent transfer between R and L is small, and the transfer to level L is expected to be dominated by LO phonon scattering of electrons coherently transferred from level R to level C.

Figure 4 shows the experimental interferogram compared with theory. The sample was excited with two identical pulses shifted in time. The luminescence intensity induced by the transfer was monitored as a function of the time delay between the pulses. In the calculations, dephasing times of 0.2 ps were arbitrarily chosen between excited and ground levels. The relaxation times were obtained from calculations of LO phonon scattering rates. We took a detuning of 10 meV in the calculation between photon energy and R–C transition.

The agreement between calculated and experimental interferogram is excellent. In particular, both present oscillations beyond the duration of the pulses, which were of 200 fs. This feature indicates that the phase information is maintained by the electron wavefunction during the interval between the two pulses. The fast decrease of ampli-

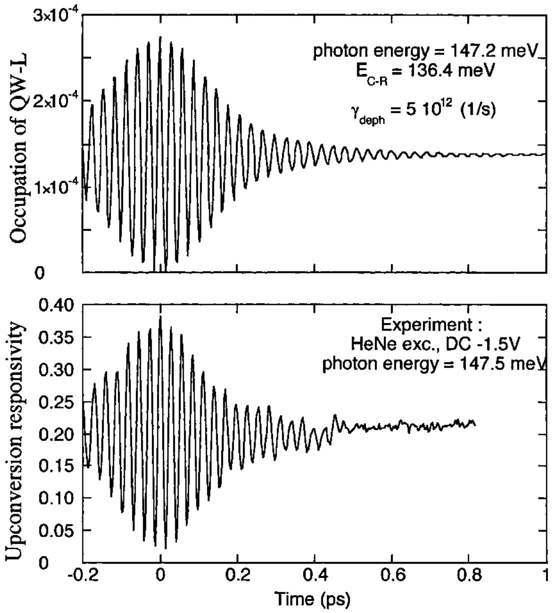

Fig. 4. Interferogram of the transfer probability. The horizontal axis shows the time delay between two identical pulses. Vertical axis is the transfer probability. a) Theory, with detuning of 10 meV and dephasing time of 200 fs. b) Experiment

tude of the interferogram at a delay time coinciding with the end of the first pulse is a consequence of the detuning of the light.

In conclusion, we discussed optical coherent transfer between two and more subbands in double quantum well structures within a single electron model. We showed theoretically that a coherent transfer – or teleportation – can be obtained between spatially uncoupled levels when a third common level is used. By using two pulses separated in time, we saw that the occupation of the excited level can be made negligibly small during the transfer. Our calculation could satisfactorily explain the main features of a coherent transfer experiment in a charge transfer double quantum well.

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