Electromagnetically induced transparency due to intervalence band coherence in a GaAs quantum well

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We demonstrate electromagnetically induced transparency in the transient optical response in a GaAs quantum well by using the nonradiative coherence between the heavy-hole and the light-hole valence bands. © 2003 Optical Society of America

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Nonradiative coherence between states that are not directly dipole coupled has been explored extensively in atomic systems, leading to discoveries of phenomena such as electromagnetically induced transparency (EIT), population trapped states, lasing without inversion, adiabatic population transfer, and slow light.[1–4] There is great interest in extending these studies to semiconductors, both for the understanding of the nature of quantum coherences in semiconductors and for the possible implementation of optical devices based on these coherent phenomena. A model system for the exploration of nonradiative coherence in semiconductors such as a GaAs quantum well involves heavy-hole (hh) and light-hole (lh) excitonic transitions. Coherent oscillation in transient four-wave mixing and differential transmission arising from impulsive excitations of both transitions has been extensively investigated.[5,6] Recent observations of the coherently coupled optical Stark shifts associated with these transitions have been interpreted as strong evidence of coherence between the hh and the lh valence bands.[7] Earlier theoretical studies also suggested the possibility of creating a population trapped state by use of the hh–lh intervalence band coherence.[8]

The band structure of a GaAs quantum well near the band edge consists of a doubly degenerate conduction band with $s_z = \pm 1/2$ and of two doubly degenerate valence bands, a hh band with $J_z = \pm 3/2$ and a lh band with $J_z = \pm 1/2$. As is shown in the band diagram in Fig. 1a, a hh transition with σ^+ circularly polarized light and a lh transition with σ^- circularly polarized light share a common conduction band state. One can in principle induce nonradiative coherence between the two valence bands by means of this three-level system. In this Letter we report the experimental observation of EIT signatures in the transient pump–probe response that arises from this intervalence band coherence.

There are a number of difficulties in using the intervalence band coherence to achieve EIT. The hh and lh transitions do not form a Λ-type three-level system because both valence bands are initially occupied. These transitions should be viewed as a V-type three-level system, as shown schematically by the exciton energy diagram in Fig. 1b. In this case, strong resonant excitation of either a hh or a lh transition can lead to excessive decoherence for both the dipole coherence and the nonradiative coherence as a result of incoherent exciton–exciton scattering. To attain the large Rabi frequencies necessary for overcoming the inhomogeneous broadening that is inherent in typical semiconductor heterostructures without inducing excessive decoherence, pulsed instead of continuous-wave excitations are desirable. However, the use of pump pulses with extremely short durations (for example, of the order of 100 fs) also effectively shortens the coherent interaction time for the EIT process.

A key feature of our experimental approach is the use of pump pulses with durations long compared with the relevant decoherence time. Temporally long pump pulses allow for a longer time scale over which to induce and interact with nonradiative coherence, which is essential for the observation of EIT. The spectrally narrow pump also prevents the excitation of other transitions, especially the excitation of free carriers. In addition, the use of a temporally long pump pulse prevents complications caused by coherent spectral oscillations.[9]

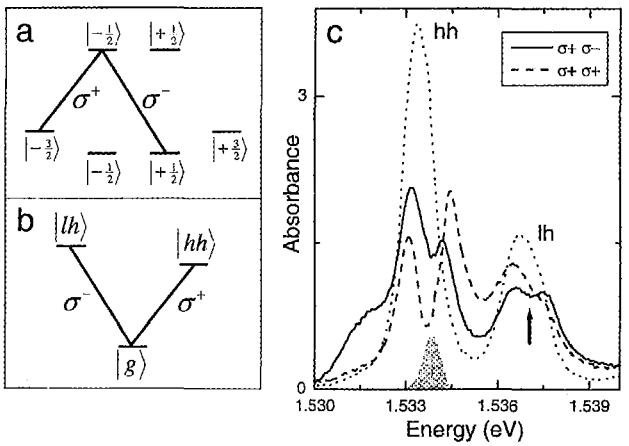

Fig. 1. a, Coupling of valence band states in GaAs. b, Corresponding V-type level diagram, showing the hh exciton, the lh exciton, and ground (g) states. c, Absorption spectrum of a σ^- polarized probe in the presence of a pump resonant with the hh exciton and with σ^+ (solid curve) and σ^- (dashed curve) polarization. The linear absorption spectrum is also shown (dotted curve). The pump spectrum is shown by the shaded area, and the probe arrives 1 ps before the peak of the pump. The arrow indicates the dip in the lh absorption.

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The experimental results presented in this Letter were obtained at 10 K by use of a (001) GaAs/AlGaAs QW with eight periods of 13-nm GaAs wells and 15-nm $Al_{0.3}Ga_{0.7}As$ barriers, grown by molecular beam epitaxy. Qualitatively similar results were also obtained with a sample with 17.5-nm well width. A mode-locked Ti:sapphire laser with an 82-MHz repetition rate supplied both the pump and the probe pulses. An external pulse shaper was used to reduce the spectral linewidth of the pump pulses and to tune the pump wavelength within the bandwidth of the laser output. The resultant pump pulses had a duration of 6 ps and were focused to a 3×10^{-5} cm^2 spot on the sample. The probe pulses, with a duration of 150 fs, had a spot size of 4×10^{-6} cm^2 and an energy flux less than 1% of the pump. We measured absorption spectra by spectrally resolving the probe pulse after its transmission through the sample.

To induce the nonradiative coherence between hh and lh valence bands we applied the pump with σ^+ polarization and with an energy flux per pulse of 160 nJ/cm^2 to the hh exciton transition. In a pump-and-probe configuration, the EIT signature should then appear as a dip in the lh exciton absorption resonance measured by the weak probe pulse with σ^- polarization. Figure 1c shows the absorption spectrum measured by the probe beam in the presence of the pump with the same (dashed curve) and with the opposite (solid curve) circular polarization. When the pump and the probe had the same circular polarization, Rabi splitting of the hh exciton transition was observed. The magnitude of the splitting is in agreement with the Rabi oscillation period observed in the separate transient measurements (not shown). When the pump and the probe had opposite circular polarization, an absorption dip (marked by an arrow in the figure) in the lh exciton resonance was observed. Note that a more pronounced absorption dip also appeared in the hh exciton resonance. The dip in the hh transition is due to EIT arising from the exciton spin coherence and has been discussed elsewhere.[10]

We carried out additional experimental studies to show that the absorption dip satisfies the two-photon resonance condition expected for intervalence band coherence. Figure 2 plots the spectral position of the absorption dip versus the spectral position of the pump. The dashed line in the figure indicates the two-photon resonance condition for nonradiative coherence in a V-type three-level system. The experimental data are in general agreement with the theoretical expectation.

One possible complication in the experiment described above is that inhomogeneous broadening of the excitonic transition can lead to spectral hole burning. In our experiment, the Rabi frequency of the pump (near the peak amplitude of the pump pulse), Ω_{pump}, exceeded the inhomogeneous linewidth, as shown by the Rabi splitting in Fig. 1c. Under these conditions, spectral hole burning is no longer possible.[11] Figure 3 shows absorption spectra measured by the probe as we varied the delay between the probe and the pump. The absorption dips in both the hh and the lh exciton resonances appeared when the probe–pump delay was near zero or when the probe arrived slightly ahead of the pump but completely vanished when the probe arrived 10 ps after the pump. The temporal dependence confirms that the observed absorption dip is not due to spectral hole burning.

Whereas the transient conditions used in our experiments prevent the formation of population trapped states, nonradiative coherence can still lead to destructive quantum interference and give rise to a dip in the probe absorption spectrum, as was shown in an earlier study.[10] In fact, in the absence of spectral hole burning, the observed dip in the probe absorption spectrum can arise only from the nonradiative coherence. To illustrate this, we performed numerical calculations of the transient optical response, using a homogeneously broadened V-type three-level system. The density matrix equations were solved to first order of the probe field and to all orders of the pump field. We plot in Fig. 4 the absorption spectra that we calculated as we varied nonradiative decoherence rates γ_{nonr} while keeping the other parameters unchanged. In this case, increasing γ_{nonr} to infinity is equivalent to artificially turning off the nonradiative

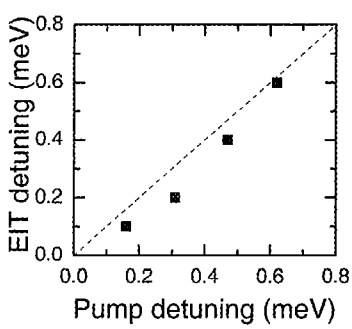

Fig. 2. Detuning of the absorption dip relative to the lh exciton versus detuning of the pump relative to the hh exciton. Filled squares, experimental data, taken from absorption spectra under the conditions described for Fig. 1. Dashed line, theoretical expectation for an ideal atomic model.

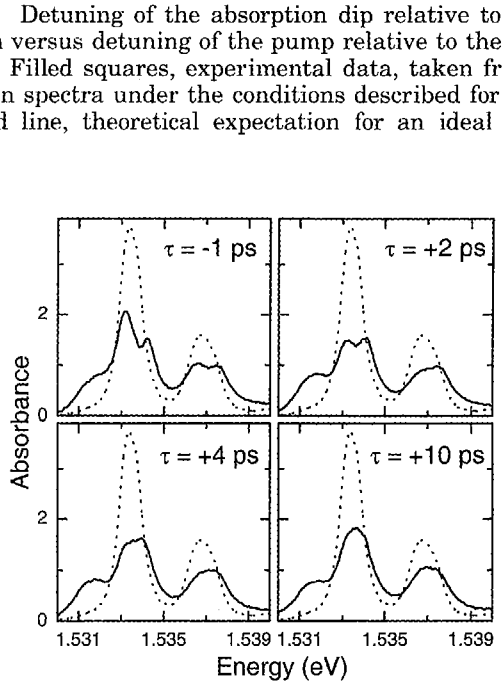

Fig. 3. Absorption of a σ^- probe in the presence of a σ^+ pump for several values of pump–probe delay τ. Negative values of τ indicate that the probe pulse arrives before the peak of the pump pulse. The pump spectrum is the same as in Fig. 1c.

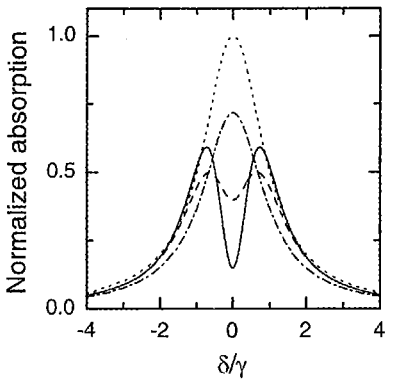

Fig. 4. Calculated absorption spectra of a σ^- probe pulse in the presence of a σ^+ pump pulse, where δ is the detuning relative to the lh exciton resonance and with $\Omega_{\text{pump}} = \gamma$, for $\gamma_{\text{nonr}} = 0.1\ \gamma$ (solid curve), $\gamma_{\text{nonr}} = 0.5\ \gamma$ (dashed curve), and $\gamma_{\text{nonr}} = 10\ \gamma$ (dotted–dashed curve), where γ is the decoherence rate for both dipole transitions. Dotted curve, probe absorption in the absence of the pump. The pump is resonant with the hh exciton and with a duration of $6/\gamma$. The probe duration is $0.1/\gamma$, and the pump–probe delay is $-1/\gamma$. The population relaxation rate is $0.01\ \gamma$.

coherence without affecting all other effects such as incoherent saturation. Whereas the incoherent saturation is present regardless of the presence of nonradiative coherence, the absorption dip appears only when γ_{nonr} is sufficiently small, and it vanishes when γ_{nonr} far exceeds Ω_{pump}. These calculations, although they do not provide a quantitative description of the experiments, confirm that the absorption dip observed in the lh exciton resonance arises from destructive interference associated with intervalence band coherence and can thus be viewed as a signature of EIT.

In summary, we have demonstrated signatures of electromagnetically induced transparency that arise from the coherence between heavy-hole and light-hole valence bands. The degree of transparency that can be achieved from the intervalence band coherence, however, is limited by decoherence induced by exciton–exciton scattering. In a V-type system such as this one, strong resonant excitation by the pump cannot be avoided. Systems analogous to a Λ-type or a cascaded three-level system, which avoid strong resonant excitations, are thus needed for achieving strong EIT in a semiconductor.

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