Electromagnetically induced transparency in low-doped *n*-GaAs

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Abstract. We report the observation of electromagnetically induced transparency (EIT) with an ensemble of donor-bound electrons in low-doped *n*-GaAs. We used pure GaAs layers with Si doping at very low concentration in a strong magnetic field. EIT was implemented with the two optical transitions that exist for the three-level system that is formed by the two electron spin states and a donor-bound trion state. Our results show that EIT with *n*-GaAs can serve as a platform for studies of nonlocal quantum entanglement with spins in semiconductors, as well as for controlling and probing dynamical nuclear polarization with coherent electron spins.

Keywords: Electromagnetically induced transparency, donor-bound electrons, donor-bound excitons, GaAs
PACS: 42.50.Gy, 78.47.jh, 71.55.Eq, 71.35.Pq

Electromagnetically Induced Transparency (EIT) is the phenomenon that an absorbing optical transition becomes transparent because destructive quantum interference with another driven optical transition prohibits populating the optically excited state. EIT can occur with three-level systems as in Fig. 1, for which it is essential that the two low-energy spin states can have a long-lived quantum coherence and that one can selectively address the two optical transitions. In Fig. 1 this is depicted for the Zeeman-split spin states $|\uparrow\rangle$ and $|\downarrow\rangle$ of a donor-bound electron (D^0) in GaAs and the state $|e\rangle$, which is the lowest energy level of a donor-bound trion system (with two electrons and a hole localized at the donor site, D^0X). An ensemble of these systems can become transparent for the probe field (labeled as ω_p) when this meets the condition for a two-photon Raman resonance with the applied control field (ω_c). Under these conditions the systems are trapped in a dark state which is in the ideal case $(\Omega_c\,|\uparrow\rangle - \Omega_p\,|\downarrow\rangle)/\sqrt{|\Omega_c|^2+|\Omega_p|^2}$, where Ω_c and Ω_p are the Rabi transition frequencies [1, 2]. Photoluminescence studies on GaAs showed that optical control can prepare D^0 systems in this dark state [3].

Till now, EIT was most extensively studied with ensembles of alkali atoms. A key result from this field was that it established that EIT gives access to very robust quantum optical techniques for controlling strong correlations between the quantum state of a collective spin excitation in an ensemble and the state of the probe field [4, 1]. Such experiments are technically less demanding than similar quantum optical experiments that use a single atom in a high-finesse optical cavity. In particular, this field realized studies of quantum entanglement between atomic ensembles with several meters spatial separation, with state preparation and readout via a quantum optical measurement scheme [5, 6]. Notably, this was realized only a few years after initial work on EIT applications demonstrated slow light [7] and storage of light [8]. Our result here are initial steps for a study of nonlocal quantum entanglement with spins in solid state [9].

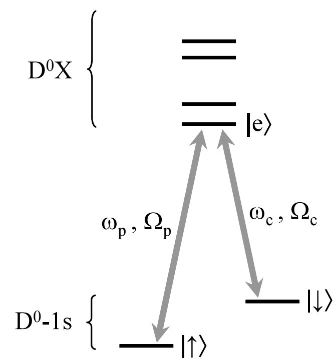

FIGURE 1. Energy levels of the D^0-D^0X system with the optical transitions that are addressed with the probe field (photon energy $\hbar\omega_p$, Rabi frequency Ω_p) and control field ($\hbar\omega_c$, Ω_c).

We report here the realization of EIT in epitaxially grown GaAs films of 10 μm thickness with Si doping at very low concentration $n_{\mathrm{Si}} = 3\times10^{13}$ cm^{-3}. We studied these at 4.2 K where the donors are not ionized. This yields an ensemble of donor-bound electrons in hydrogen-like 1*s* orbitals. These ensembles were addressed with the driving scheme as in Fig. 1, with the driving fields at normal incidence on the films and the magnetic field *B* parallel to the films. With a polariza-

Physics of Semiconductors
AIP Conf. Proc. 1399, 1039-1040 (2011); doi: 10.1063/1.3666734

tion maintaining fiber to a cryogenic confocal microscope we could identify the spin-selective excitations in this medium in transmission, and extend this to a direct demonstration of EIT.

Typical results are presented in Fig. 2(a). For these results we fixed the control laser near resonance with the $|\downarrow\rangle$-$|e\rangle$ transition, while the probe laser is scanned across the $|\uparrow\rangle$-$|e\rangle$ transition and we measure its transmission. When the control and probe field meet the condition for two-photon Raman resonance (the difference in photon energy exactly matches the D^0 spin splitting), a narrow peak with enhanced transmission appears inside the broader $|\uparrow\rangle$-$|e\rangle$ absorption dip. A fingerprint of EIT is that the spectral position of the EIT peak position depends on the detuning of the control field from exact resonance with the $|\downarrow\rangle$-$|e\rangle$ transition. The EIT peaks in Fig. 2(a) indeed follow the detuning of the control field. In Fig. 2 the EIT occurs for an absorption with optical density 0.3. We obtained similar results for optical density 1.0 using an epi-layer with $n_{\mathrm{Si}} = 1 \times 10^{14}$ cm^{-3}.

Figure 2(b) presents results of fitting EIT spectra with the established theory [1, 3]. This involves calculating the steady-state solution of a density-matrix equation for the three-level system, and accounts for coherent driving by the lasers and relaxation and dephasing rates between the levels. We obtain good fits and the main features in our results are consistent with EIT. The reduction of the EIT peak height with red detuning of the control field is not captured by the standard three-level EIT model. Our fits show that this is due to a reduction of Ω_c with red detuning. We analyzed that this probably results from a weak Fabry-Perot-like interference between the two surfaces of the GaAs film [10].

EIT relies on quantum coherence between the electron spin states, and in systems with a very long electron spin dephasing time T_2^* EIT can fully suppress absorption. The EIT peak then reaches up to ideal transmission. The EIT peaks in Fig. 2 are clearly lower. The fits yield $T_2^* \approx$ 2 ns for our system, and this compromises the EIT peak height. This T_2^* value is consistent with earlier work [3, 11] that showed that electron spin dephasing results from hyperfine coupling between each electron spin and $\sim 10^5$ fluctuating nuclear spins (the D^0 systems have a $\sim$ 10 nm Bohr radius). Our EIT studies showed weak signatures of dynamical nuclear polarization (DNP) which confirmed the role of nuclear spin fluctuations [10]. We anticipate that T_2^* can be enhanced with controlled DNP effects that suppress the nuclear spin fluctuations [12, 13], despite the fact that the DNP effects in our experiments were much weaker than in microwave-driven experiments on GaAs D^0 systems [14] and DNP effects in related optical experiments on quantum dots [12, 13].

In conclusion, we presented direct evidence that a D^0 ensemble in GaAs can be operated as a medium for EIT. The electron spin dephasing time limits the quality of the EIT, and is in the range $T_2^* \approx 2$ ns that results from hyperfine coupling to fluctuating nuclear spins. Our results provide a pathway to further quantum optical studies, and controlling and probing dynamical nuclear polarization with optically-controlled coherent electron spins.

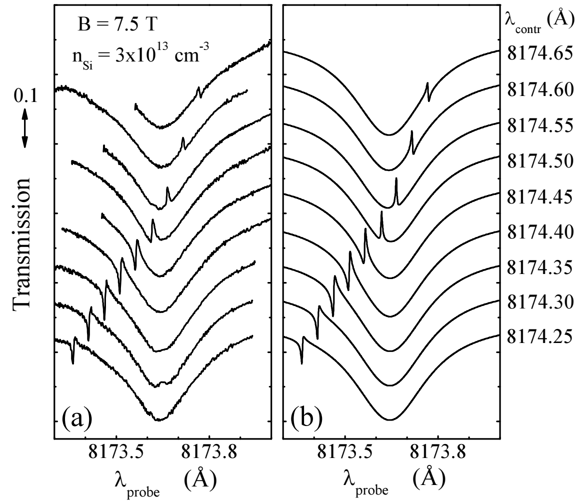

FIGURE 2. Experimental results (a) and numerical fits (b) of EIT spectra for various values of the control-field wavelength λ_{contr}. Traces are offset for clarity. The fits yield $T_2^* \approx 2$ ns. The other key parameters from the fits are $\Omega_p = 50$ MHz, $\Omega_c \approx 5$ GHz (see main text), and 6 GHz for the inhomogeneous broadening of the optical transitions [1, 10].

We thank B. Wolfs and J. Sloot for help, and the Dutch NWO and FOM, and the German programs DFG-SPP 1285, BMBF nanoQUIT and the Research school of Ruhr-Universität Bochum for financial support.

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