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THz Electro-absorption Effect in Quantum Dots

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In a THz pump - optical probe experiment we demonstrate an instantaneous electro-absorption effect in InGaAs/GaAs quantum dots, induced by the electric field of a single-cycle THz pulse with 3 THz bandwidth and with free-space peak electric field reaching 220 kV/cm. The transient modulation of QD ground state optical absorption at 1040 nm coherently follows the evolution of the absolute value of THz electric field. The optical modulation signal was found to be as short as 460 fs at FWHM, and retained the 3 THz bandwidth of the THz pulse. Optical absorption modulation in QDs by the THz field is dominated by absorption quenching effect due to the electron- and hole wavefunction separation in THz field, rather than by the Stark shift away from the optical probe.

We have performed a THz pump - optical probe experiment on InGaAs/GaAs quantum dot (QD) sample [1]. The sample used in our experiments was a QD-based semiconductor saturable absorber mirror (SESAM), comprising of a broad-band GaAs/$Al_{0.9}Ga_{0.1}As$ distributed Bragg reflector (DBR), and a QD absorber layer featuring 80 layers of sub-monolayer – grown $In_{0.5}Ga_{0.5}As$/GaAs QDs, alternated by the GaAs barriers of 10-14 nm thickness. The QD ground state resonance was at 1040 nm, providing the strong dip in SESAM reflectivity at this wavelength (see Fig. 1). The sample was similar to the one studied in Ref. [2]. A

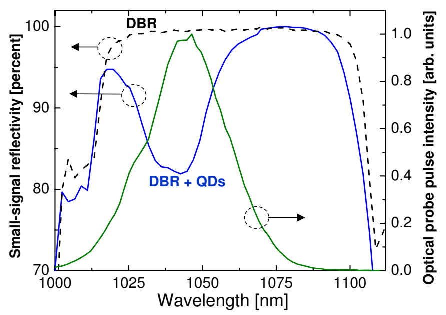

FIG. 1: Small-signal reflectivity spectrum of the whole QD sample (solid line), a bare DBR (dashed line), and the intensity spectrum of the probe laser pulse at QD ground state resonance at 1040 nm.

strong THz pump pulse with peak electric field in air of 220 kV/cm and a bandwidth of 3 THz (Fig. 2(a)) was produced by tilted pulse front optical rectification of an 800 nm, 80-fs Ti:Sa amplifier pulse in a lithium niobate crystal [3]. A weak probe pulse at 1040 nm, resonant with a ground state QD absorption in the absence of THz field, was produced by an OPA synchronized to the THz source. *Our main result* - the change in optical probe reflectivity $\Delta R/R$ of a QD SESAM sample, induced by the THz pulse, as a function of time is shown in Fig. 2(b) together with the absolute value of the electric field on the QDs. The latter was calculated taking into account the THz field transmission coefficient at the sample GaAs interface $t_{THz} = 0.435$. The values of $\Delta R/R$ are always positive, demonstrating that resonant optical absorption in QDs always *decreases* in the presence of a THz field.

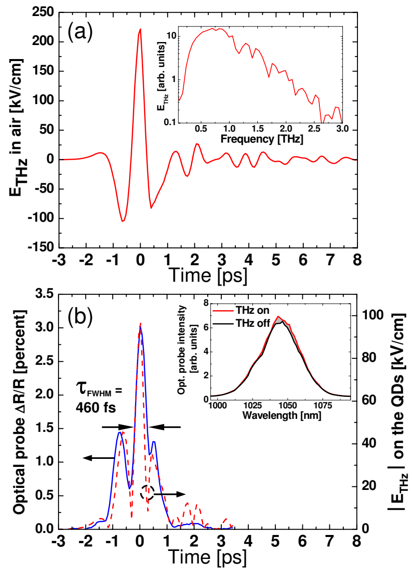

FIG. 2: (a) THz pulse with peak free-space electric field strength of 220 kV/cm. Inset: its amplitude frequency spectrum. (b) *Our main result:* Solid line - reflectivity modulation $\Delta R/R$ of the probe signal at 1040 nm in the QD sample, under influence of THz pulse from (a). Dashed line - absolute value of the electric field in the THz pulse from (a) experienced by QDs. Inset: spectrum of the optical probe signal with and without peak electric field of the THz signal from (a) on the QD sample.

The electric field of the THz pump pulse induces a quantum-confined Stark effect (QCSE) [4] on the QDs,

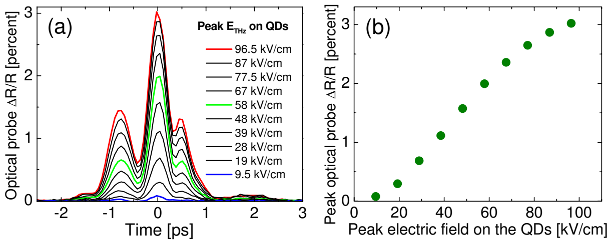

FIG. 3: (a) Reflectivity modulation $\Delta R/R$ of the optical probe in the QD sample, at various THz peak electric field strength. (b) Peak values of $\Delta R/R$ of the signals from (a), as a function of peak THz electric field on the QDs.

which manifests itself in two ways: *(i)* in decrease of optical transition energy (Stark shift) as a result of band structure tilt, moving the QD absorption out of the optical probe spectrum, and *(ii)* in a reduced wavefunctions overlap in the presence of electric field $M(E) = \langle\psi_e|\psi_h\rangle$. The value of $|M(E)|^2$ dictates the strength of optical absorption in QDs. The Stark shift and absorption quenching may be dominant in different spectral parts of the absorption peak [5]. In the inset of Fig. 2(b) the optical spectra of probe pulses are shown in the case when optical probe pulse was in temporal overlap with the peak of the THz pulse from Fig. 2(a), and when the THz pulse was blocked. The THz field - induced modulation of optical probe pulse is distributed more or less spectrally homogenously, which suggests that the absorption quenching is likely to be the dominating effect here.

Controllable attenuation of the THz electric field by a pair of wire-grid polarizers [6] allowed us to observe the nonlinear dependency of the electro-absorption modulation depth on the peak THz electric field, typical for QCSE mostly dominated by quenching contribution [4] - see Fig. 3. As expected from the 3D geometry of the QD, we found no dependency of the electro-absorption modulation strength on the polarization of THz signal. We observed a weak dependency on the polarization of the optical probe signal, which is most likely due to a well-known optical absorption anisotropy in the QDs [7].

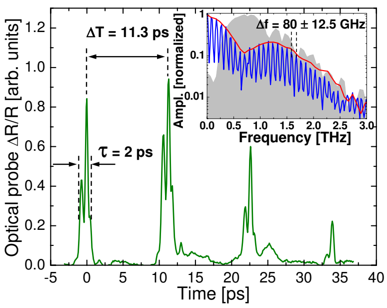

FIG. 4: $\Delta R/R$ of the optical probe, resulting from multiple reflections of a single THz pulse in the QD sample. Inset: Amplitude Fourier spectra of the isolated first $\Delta R/R$ pulse around 0 ps (red line), and of the full multi-pulse sequence (blue line). Amplitude Fourier spectrum of a single THz pulse is shown in the background.

We note that in Refs. [8, 9] an electro-absorption modulation was also observed at the exciton resonance in quantum wells (QWs) and carbon nanotubes (CNTs). In [8] the QWs were polarized in the plane by the strong THz pulse, and increase of THz field strength lead to exciton ionization. In [9] the CNTs were polarized along the long dimension, and the modulation speed limit of around 1 THz was assigned to exciton dephasing.

In Fig. 4 we demonstrate an optical modulation of QDs induced by a train of THz pulses, originating from the multiple reflection of a single THz pulse between the surface of the sample, and the metal mirror attached to the back side of its $450 \pm 25\mu$m - thick GaAs substrate. This experiment emulates the direct THz-to-optical encoding in a ultra-high-speed THz-frequency digital communication channel [10]. The inter-pulse interval of 11.3 ps, i.e. the repetition rate of 88 GHz, results in the data rate of 88 Gbit/s. The ratio of inter-pulse interval to the individual pulse duration 11.3 ps / 2 ps = 5.65 shows the achievable wireless data capacity of at least 88 Gbit/s $\times$ 5.65 = 0.5 Tbit/s using this modulation scheme.

In the inset of Fig. 4 the amplitude spectra of the isolated $\Delta R/R$ pulse, and of the whole multi-pulse sequence are shown, with the amplitude spectrum of the single THz pulse in the background. The full bandwidth of the THz pulse of 3 THz is encoded onto the optical probe signal, demonstrating the coherency of electro-absorption modulation in QDs with the driving THz field. This coherency will be most likely limited by the THz frequencies high enough to excite intra-band transitions in the QDs, such as approximately 10 THz or higher.

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