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Terahertz Probes of Transient Conducting and Insulating Phases in Quasi-2D Electron-Hole Gases

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Abstract

We employ ultrafast terahertz (THz) pulses to study the dynamical interplay of optically-induced excitons and unbound electron-hole pairs in GaAs/AlGaAs quantum wells. A distinct low-energy oscillator appears upon resonant excitation of heavy-hole excitons, linked to transitions between their internal degrees of freedom. Time-resolving changes in the THz conductivity, we can observe dynamical transitions between conducting and insulating phases as excitons form or ionize on ultrashort timescales.

Introduction

Understanding charge correlations in many-body systems forms a central theme in condensed matter physics. Confinement of carriers in semiconductor nanostructures, in particular, entails enhanced Coulomb correlations and unique low-energy excitations, and offers a well-defined model system to investigate complex interactions between large numbers of quasiparticles. Electrons and holes can form excitons, which exhibit internal transitions between their levels. Small reduced effective masses μ and large dielectric constants ε in semiconductors renormalize the Rydberg energy by a factor $\mu/(m_0\varepsilon^2) \ll 1$ and yield exciton binding energies of only a few meV. Whereas generation and annihilation of excitons was extensively explored with near-visible photons, studies of internal exciton transitions - at THz frequencies orders of magnitude below the optical bandgap - remained scarce. Microscopic theory further supports the notion that THz absorption of electron-hole gases provides important information about charge correlations, excitons and their dynamics [1]. Pulsed THz radiation offers a unique tool to measure such transient low-energy excitations. Here, we discuss optical-pump THz-probe experiments that explore dynamical processes of electron-hole gases on a picosecond timescale [2].

Optical-Pump Terahertz-Probe Experiments

Ultrashort near-infrared pump pulses are used to excite either excitons or unbound electron-hole pairs in GaAs quantum wells. Selective excitation of either species is achieved through spectral shaping of the amplified near-infrared pulses which are derived from a 250-kHz Ti:sapphire regenerative amplifier system. Probe pulses of ≈500 fs duration spanning the range from 0.5 – 3 THz are generated and detected in thin ZnTe crystals using optical rectification and electro-optic sampling. The sample investigated here was grown by molecular beam epitaxy and consists of ten 14-nm wide GaAs quantum wells separated by 10-nm wide $Al_{0.3}Ga_{0.7}As$ barriers [3].

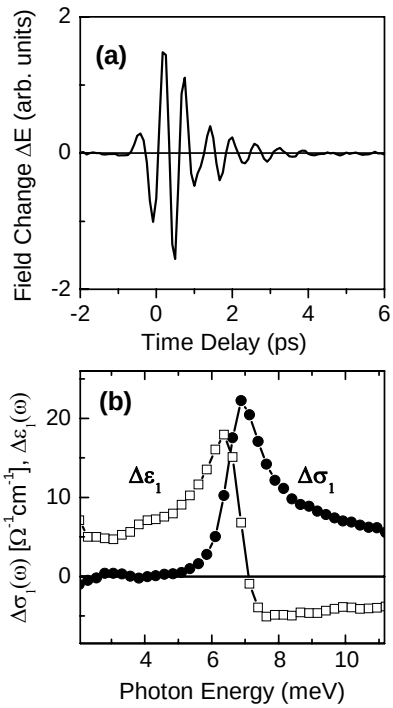

Fig. 1: **(a)** Induced change $\Delta E(t)$ of the THz field transmitted through photoexcited GaAs/AlGaAs quantum wells, and **(b)** corresponding change in the THz conductivity $\Delta\sigma_1$ (dots) and dielectric function $\Delta\varepsilon_1$ (open squares) at time delay $\Delta t = 5$ ps after resonant excitation of $n \approx 10^{10}$ cm^{-2} heavy-hole excitons. The data are for lattice temperature $T_L = 6$ K.

At each pump-probe delay Δt, we detect the THz field $E(t)$ transmitted through the sample in equilibrium and the pump-induced field change $\Delta E(t)$ shown in Fig 1a. Straightforward electrodynamical relations then yield the transient change of both real and imaginary parts of the complex THz conductivity $\sigma(\omega) = \sigma_1(\omega) + i\cdot\sigma_2(\omega)$. We take into account the phase shifts in the multilayer structure. In what follows, the response is analyzed in terms of (*i*) the real part $\sigma_1(\omega)$ which yields a measure of absorptive processes and (*ii*) the dispersive imaginary part, conveniently expressed via the real dielectric function: $\sigma_2(\omega) = \omega/4\pi\,[1-\varepsilon_1(\omega)]$. Availability of both parts is central to understanding the transient physical states.

Intra-Exciton Terahertz Response

A distinct asymmetric peak appears in the THz conductivity $\Delta\sigma_1$ around 7 meV photon energy, as shown in Fig 1b, after resonant excitation at the 1s heavy-hole exciton line at low lattice temperature (T = 6 K). The dispersive feature seen in $\Delta\varepsilon_1$ corroborates the appearance of this far-infrared oscillator. Calculations explain the peak which arises from transitions between the exciton bound states, most notably from the 1s $\rightarrow$ 2p transition. Due to the correlated motion of electrons and holes, charge-neutral excitons are electrically insulating up to a frequency that matches the separation between their lowest internal states. This is reflected directly in the THz conductivity. In contrast, above-bandgap excitation at elevated temperatures (not shown) generates unbound *e-h* pairs which represent a conducting ionized gas with a Drude-like response.

Dynamics of Conducting and Insulating Phases

The distinct responses of these extreme phases allows us to follow in time a transition between conducting and insulating phases which occurs upon formation of excitons out of a gas of unbound *e-h* pairs. Non-resonant excitation above the bandgap is employed to generate unbound e-h pairs at

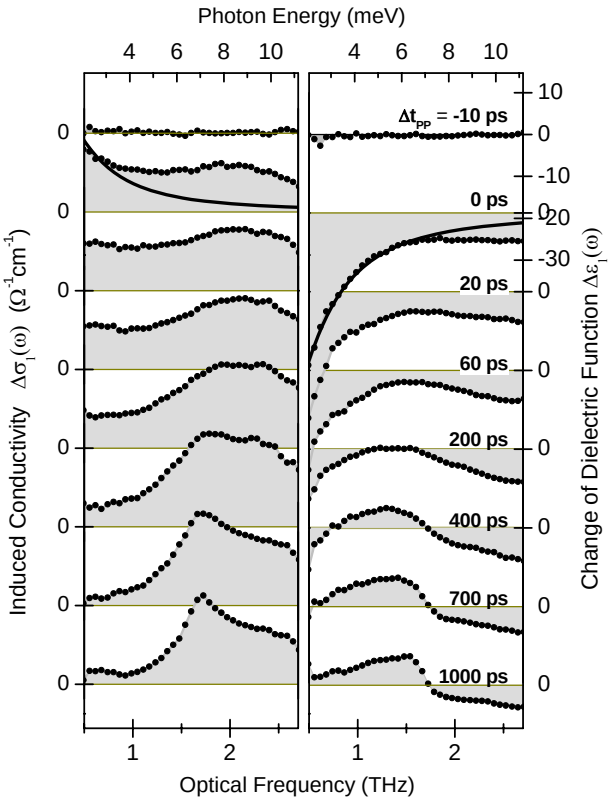

Fig. 2: Transient spectra at T_L = 6 K after excitation into the continuum of unbound e-h pairs. The excitation pulse is tuned 21 meV above the HH 1s exciton line. The thick solid line at Δt = 0 ps is a Drude model calculation, and all panels are equally scaled.

T=6 K. Fig 2 shows that directly after excitation (0 ps) we indeed observe a broadband THz response that indicates a predominantly conducting gas of ionized e-h pairs. Low-frequency conductivity is acquired in $\Delta\sigma_1(\omega)$ and the dielectric profile in $\Delta\varepsilon_1(\omega)$ changes into the all-negative response expected from a Drude oscillator. However, even at the earliest times, it is important to note that the conductivity is not fully described by the Drude model (thick line) but rather around ≈ 8 meV photon energy shows a strong excitonic enhancement. With increasing delay time in Fig 2, the spectra exhibit complete reshaping as they evolve into a characteristic exciton response. Binding of pairs into excitons on a timescale of several 100 ps eventually gives rise to an insulating quantum state with fundamental excitation gap equal to the exciton binding energy. The decay of conducting properties is a direct indicator of the increasingly correlated motion of oppositely charged quasi-particles. Two distinct timescales appear in exciton formation, one associated with the quasi-instantaneous appearance of a strong excitonic enhancement, and another much slower transformation from the photoexcited conducting e-h gas to a fully charge-neutral excitonic phase.

Conclusions and Outlook

In summary, we study fundamental processes of exciton physics by probing internal exciton transitions at THz frequencies. Resonant generation of excitons results in a low-energy response closely described by transitions between an exciton's internal degrees of freedom. Changes in the THz response are sensitive indicators for the transient state of an *e-h* gas. We anticipate that the distinctively different nature of THz conductivity compared to interband probes will enable new studies of many-body effects and correlated phases of *e-h* pairs.

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