

## Absence of exciton quenching in the presence of strong fields at high frequencies

A. H. Chin\*

*Information Science and Technology Division, Lawrence Livermore National Laboratory, P.O. Box 808, Mail Stop L-174, Livermore, California 94551*

J. Kono†

*Department of Electrical and Computer Engineering, Rice University, Houston, Texas 77005*

G. S. Solomon

*Solid State Laboratories, Stanford University, Stanford, California 94305*

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We have studied the response of excitons in a multiple quantum-well structure under the presence of intense midinfrared fields. Peak fields ( $\sim 10^6$  V/cm, in the plane of quantum wells) that would cause exciton quenching at low frequencies (up to  $\sim$ GHz) are observed to have no significant quenching effect on the exciton resonance when applied at  $\sim 100$  THz. We attribute this lack of quenching to the short period of the strong, high-frequency field compared to the exciton response time.

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The nonlinear optical response of excitons in quantum wells has been and continues to be a subject of intense research, due to the potential applications. One of these potential applications is ultrafast optical modulation via ultrafast electroabsorption in excitons.<sup>1</sup> The response of excitons to strong field transients,<sup>1,2</sup> to strong, low-frequency fields (photon energy less than the binding energy),<sup>3</sup> and to strong terahertz fields (photon energy comparable to the binding energy) (Refs. 4–7) have been studied previously.

Here we are considering an applied field whose strength is sufficient to cause field ionization at a frequency where the photon energy of the applied field is larger than the ionization energy. This regime has not previously been examined in atomic or semiconductor systems. At first glance, either field ionization or photoionization should lead to quenching of the exciton resonance. However, we observe that under such conditions the exciton resonance remains relatively unaffected. We attribute this resistance to quenching to the mismatch between the period of the applied field and the response time of the exciton.<sup>2</sup>

The sample used for these studies was an undoped  $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$  multiple quantum-well (MQW) structure grown on a semi-insulating GaAs substrate by a Varian Gen II molecular-beam epitaxy system using a cracked  $\text{As}_4$  ( $\text{As}_2$ ) source. The MQW contained 15 periods, where each period consisted of an 8 nm  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$  quantum well and 15 nm GaAs barrier. The growth temperature was 540 °C and the  $\text{In}_x\text{Ga}_{1-x}\text{As}$  composition was calibrated by x-ray diffraction on a separate sample. The experiments were performed with the sample at room temperature.

The experimental setup used to study the exciton response to strong, high-frequency fields is the same as the setup we used to study the dynamical Franz-Keldysh effect in bulk semiconductors.<sup>8</sup> The source of strong, high-frequency fields is an optical parametric amplifier (OPA) pumped by a Ti:Sapphire based regenerative amplifier. The system produced pulses at a 1 kHz repetition rate with  $\sim 1$  ps pulse

duration, and (with difference frequency mixing of the signal and idler) wavelengths from 3  $\mu\text{m}$  to 10  $\mu\text{m}$ . For these studies, we used 3.5  $\mu\text{m}$  midinfrared (MIR) pulses, where atmospheric absorption is small. We measured the transmission around the exciton resonance near the band edge of the GaAs substrate using broadband light as a probe. The broadband near-infrared (NIR) light was produced by continuum generation in a sapphire plate, using the residual pump pulse (800 nm) after the OPA. The broadband probe was temporally overlapped with the MIR pump (or driving field) by changing the time delay (via the optical path length) of the MIR pump relative to the probe. The NIR probe and the MIR pump were focused onto the sample using an off-axis paraboloid, with the beams crossing at  $\sim 10^\circ$ . After passing through the sample, the spectrum of the broadband probe was dispersed using a grating monochromator and detected using a Si charge-coupled device camera (response between 1.1 eV and  $\sim 3$  eV). Spectra were obtained with and without the driving field, and were subsequently normalized to the probe spectrum without the sample to obtain the absolute transmission (accurate to  $\pm 5\%$ ).

Figure 1 shows transmission data taken using  $\sim 1$  ps, 3.5  $\mu\text{m}$  MIR (86 THz) pulses with peak intensity of  $\sim 2 \times 10^{10}$  W/cm<sup>2</sup> ( $\sim 4 \times 10^6$  V/cm peak field) compared to data taken without the strong, high-frequency field. The MIR beam is at nearly normal incidence to the sample, so that the MIR electric field is primarily in the plane of the quantum wells and perpendicular to the growth direction. The reduction in transmission near 1000 nm is the 1 s exciton resonance associated with the transition between the highest hole subband (H1) and the lowest electron subband (E1) in the quantum wells, and the reduction in transmission around 890 nm is the band edge of the GaAs substrate. The primary feature of the data obtained in the presence of the strong MIR field is the overall reduction of transmission over the wavelength range shown. This is due to the dynamical Franz-Keldysh effect (DFKE) (Refs. 7–10) in the GaAs substrate,

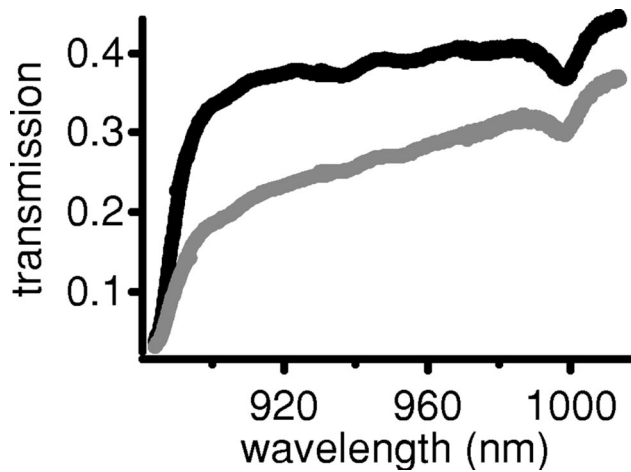


FIG. 1. Transmission below the GaAs band edge of a quantum-well sample on a GaAs substrate. The black curve represents data with no applied field. The gray curve represents data with a  $3.5 \mu\text{m}$  driving field with  $\sim 2 \times 10^{10} \text{ W/cm}^2$  peak intensity ( $\sim 4 \times 10^6 \text{ V/cm}$  peak field). The reduction in transmission is due to the dynamical Franz-Keldysh effect (see text). Note the continued exciton resonance at 1000 nm, even with the strong, high-frequency field.

and is discussed in detail elsewhere.<sup>8</sup> The fact that we observe this effect in the substrate indicates that we are also applying a strong field in the MQW sample that is of sufficient strength to ionize excitons, if the field was applied at a lower frequency. The other feature in the data is that the exciton resonance remains relatively unaffected with the strong MIR field. To better examine any effects on the exciton resonance, we removed the absorption change in the substrate by assuming a baseline on either side of the resonance and subtracting the baseline from the data. Figure 2 shows the result of such data processing. There is a small decrease in the peak amplitude of the exciton resonance in the presence of the MIR field, but there is little broadening apparent in the peak width, as is expected from field ionization.<sup>3</sup>

We attribute this lack of quenching of the exciton resonance by the strong MIR field to the mismatch between the period of the strong field and the exciton orbit time. The time scales relevant to exciton response are the exciton orbit time ( $\sim h/E_{\text{binding}}$ ), the electron tunneling time [ $\sim (mE_{\text{binding}})^{1/2}/(eF)$ , where  $F$  is the applied electric field], and the exciton lifetime. Among these relevant time scales, the intrinsic exciton lifetime (estimated to be several hundreds of picoseconds from the homogeneous linewidth) and the lifetime determined by the inhomogeneous linewidth ( $\sim 100 \text{ ps}$ ) are much longer than the period of the applied field, and thus should not play a role here. Under our conditions,  $eF \approx 4 \times 10^6 \text{ eV/cm}$ ,  $m \approx 0.07m_0$ , and  $E_{\text{binding}} \sim 10^{-2} \text{ eV}$ , the tunneling time is  $\sim 0.2 \text{ fs}$ . Since the period of the  $3.5 \mu\text{m}$  MIR field (12 fs) is longer than the tunneling time, the peak field is strong enough to cause field ionization of the exciton. However, the applied field has a photon energy that is larger than the exciton binding energy, i.e., the period of the applied field (12 fs) is significantly shorter than the exciton orbit time ( $h/E_{\text{binding}} \sim 360 \text{ fs}$ ). Thus, the exciton cannot respond to the high-frequency field, because the

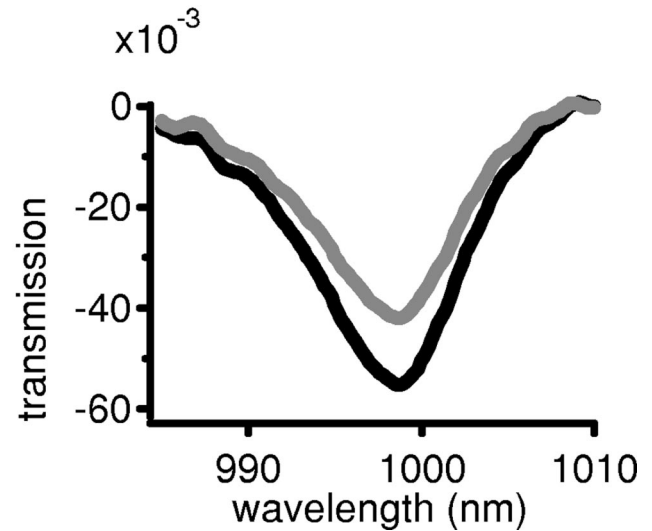


FIG. 2. Transmission around the exciton resonance of a quantum well sample on a GaAs substrate from the data shown in Fig. 1. The black curve represents data with no applied field. The gray curve represents data with a  $3.5 \mu\text{m}$  driving field with  $\sim 2 \times 10^{10} \text{ W/cm}^2$  peak intensity ( $\sim 4 \times 10^6 \text{ V/cm}$  peak field). The data are modified to subtract the transmission data around the exciton absorption peak in order to subtract the dynamical Franz-Keldysh effect in the substrate.

field is trying to drive the exciton at a frequency well above the resonance frequency. In the case of atoms, the analogous response (in the x-ray regime) is a very weak interaction of the valence electrons with the applied field, and therefore a refractive index close to unity and a scattering cross section approaching the free-electron value (i.e., no resonance enhancement).<sup>11</sup> In our case, with  $0.35 \text{ eV}$  MIR photons and  $E_{\text{binding}} \sim 10^{-2} \text{ eV}$ , we have a relative frequency of  $\omega/\omega_{\text{resonance}} \approx 30$  and a damping factor  $\gamma/\omega_{\text{resonance}} \approx 0.5$ , which is in a frequency region where no significant resonance enhancement occurs. Therefore, *the strong, high-frequency field views the exciton as a free electron and hole, not as a bound pair.*

Another ionization mechanism for these strong, high-frequency fields that could affect the exciton resonance is photoionization. Since the photon energy ( $0.35 \text{ eV}$ ) of the high-frequency field is much greater than the exciton binding energy ( $\sim 0.01 \text{ eV}$ ), photoionization of the exciton is allowed. However, assuming exciton photoionization behaves like atomic photoionization, which scales as  $(E_{\text{photon}} - E_{\text{binding}})^{-7/2}$  (where  $E_{\text{photon}}$  is the photon energy of the applied field), the photoionization probability decreases rapidly with increasing photon energy above the ionization threshold. This is related to the lack of resonant enhancement stated above, i.e., photoionization is greatest when the incident photon energy is resonant with the relevant binding energy. In our case, we should have a photoionization probability that is  $\sim 4 \times 10^{-6}$  times that of the photoionization probability near resonance. Nevertheless, we do observe evidence of a decrease (see Fig. 2) in the excitonic absorption in the presence of the strong, high-frequency field, which may be due to this photoionization process.

In conclusion, we have observed that a quantum-confined exciton does not respond strongly to a high-frequency field (i.e., well above the exciton resonant frequency) that would cause field ionization at a lower frequency. We attribute this lack of field ionization to the fact that the exciton response time is slow relative to the period of the strong field. These observations represent some of the possible strong-field phenomena that may be studied in excitons in semiconductors

that are very difficult to observe in atoms, due to the lack of intense ultraviolet sources.

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\*Present address: UltraPhotonics, 48611 Warm Springs Blvd., Fremont, California 94539. Electronic address: china@ultraphotonics.com

†To whom correspondence should be addressed; URL: <http://www.ece.rice.edu/~kono>; Electronic address: kono@rice.edu

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