Excitonic Autler-Townes splitting induced by an intense Terahertz field

S. G. Carter, V. Ciulin*, and M. S. Sherwin
Physics Department and iQUEST, Broida Hall Building 572,Room 3410, University of California, Santa Barbara, California 93106
scarter@physics.ucsb.edu

C. S. Wang and L. A. Coldren
Electrical and Computer Engineering Department, University of California, Santa Barbara, California 93106

A. V. Maslov
Center for Nanotechnology, NASA Ames Research Center, MS 229-1, Moffett Field, California 94035

Abstract: An InGaAs quantum well driven by a strong THz field has exhibited a splitting of the exciton line, due to strong coupling of hole states. This effect is closely-related to the Autler-Townes effect and electromagnetically-induced-transparency.

OCIS Codes: (190.5970) Semiconductor nonlinear optics including MQW; (270.1670) Coherent optical effects

The effect of a Terahertz (THz) electric field on quantum well (QW) interband absorption has been given a great deal of theoretical attention due to interest in THz-dressed states and in ultrafast optical modulation,[1,2] but few experimental results have been published.[3] We have measured the effect of a strong THz field from the UCSB Free Electron Laser on the linear interband absorption of InGaAs QWs at low-temperature. The results demonstrate a THz-induced splitting of the exciton absorption analogous to Autler-Townes splitting in atomic systems.[4]

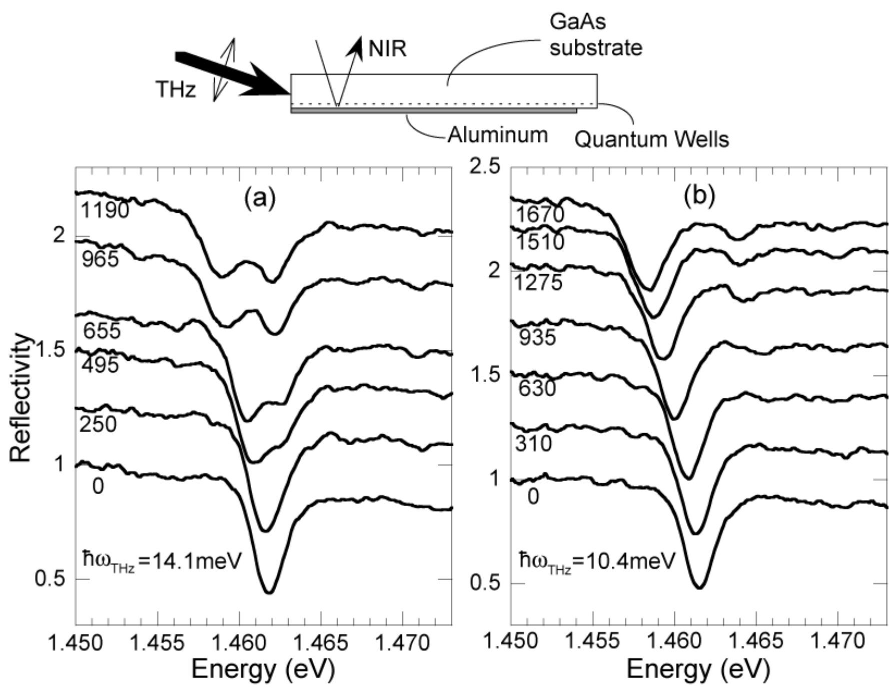

Fig. 1. Reflectivity spectra at 10 K for a series of THz powers at (a) $\hbar\omega_{THz}$ = 14.1 meV and (b) $\hbar\omega_{THz}$ = 10.4 meV. The spectra are offset and labelled according the the THz power (in Watts). A schematic of the sample and experimental geometry is displayed above.

The sample consists of 10 undoped 14.3 nm $In_{0.06}Ga_{0.94}As$ QWs separated by 30 nm $Al_{0.3}Ga_{0.7}As$ barriers. The experimental geometry is shown above Fig. 1. The interband probe beam, from a near-infrared (NIR) LED, passed through the GaAs substrate, through the QWs, and then reflected off of an Al layer evaporated on the surface. This Al layer gave a strong growth-direction THz field and prevented any in-plane fields, a significant improvement over previous THz-coupling methods.[5]

Figure 1 displays a series of NIR reflectivity spectra taken at increasing THz powers for (a) $\hbar\omega_{THz}$ = 14.1 meV and (b) 10.4 meV. Without the THz field (lowest spectra), the reflectivity shows absorption by the lowest exciton state, e1hh1X. The e1hh2X state is optically forbidden in these symmetric QWs and is expected to be ~13.5 meV above e1hh1X. Higher electron and heavy-hole states are expected to be sufficiently far away that they can be ignored. The lowest light hole exciton appears to be shifted out of the way due to strain.

In the presence of the THz field, the changes in absorption were quite striking. For $\hbar\omega_{THz}$ = 14.1 meV, which was near the e1hh1X-e1hh2X resonance, there was a clear splitting of the exciton line, which increased as a function of power. For $\hbar\omega_{THz}$ = 10.4 meV, which was below the resonance, the splitting was more asymmetric, with a weaker absorption line appearing above the undriven exciton line. This splitting has been predicted by several authors for QWs driven by a strong intersubband pump,[1,6] but has never before been observed. These results show for the first time clear evidence of Autler-Townes splitting of excitons in a THz-driven QW. Fig. 2(a) displays the exciton splitting schematically.

Reflectivity measurements were performed for many THz frequencies at a series of powers. The spectra taken at a THz power near 550 W were fitted to two Lorentzians, and the results are plotted in Fig. 2(b). The absorption strength is represented on a greyscale for each marker. The existence of the two absorption lines is due to the two dressed (Floquet) states created by the THz field. On resonance, the oscillator strength is shared equally between the two dressed states and thus, the two absorption peaks are equal in magnitude. Off-resonance, the oscillator strength is strongest for the absorption line nearest the undriven exciton line. Using a Rabi splitting model, the energies of these dressed states are $E_{\pm} = E_0 - (1/2)(\Delta \mp \sqrt{\Delta^2 + (2\mu E_{THz})^2})$, where E_0 is the undriven exciton energy, Δ is the detuning from resonance, μ is the intersubband dipole moment, and E_{THz} is the THz field. The measured absorption energies fit very well to this simple formula. A much more sophisticated model using the semiconductor Bloch equations has also been applied to this system, giving similar results.

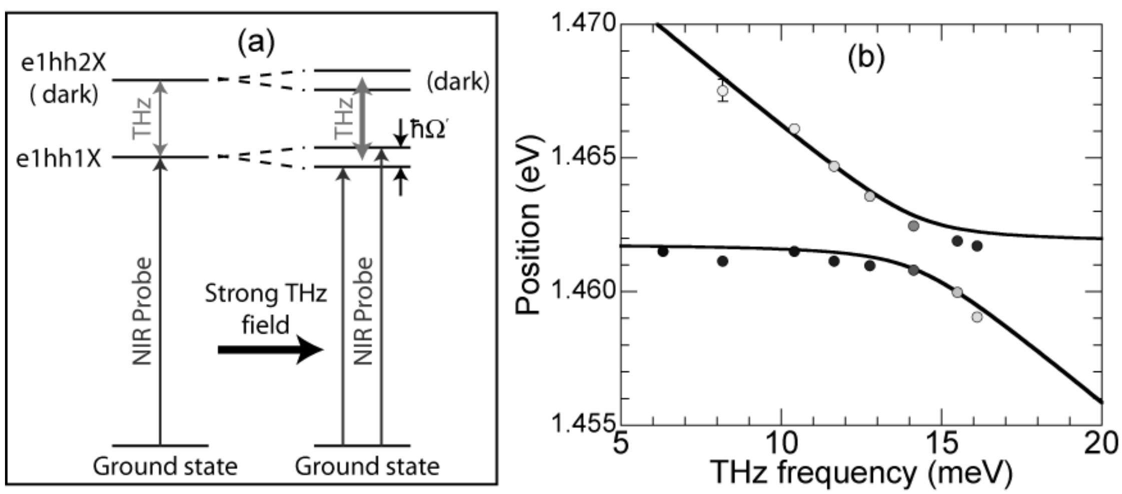

Fig. 2. (a) Schematic exciton energy level diagram showing the splitting that occurs in the presence of a resonant THz field. (b) Absorption line positions vs. THz frequency, showing the anticrossing behavior. The absorption strength for each point is represented on a greyscale. A completely black dot indicates the absorption strength was the same as the undriven absorption strength, while a white dot indicates very small absorption. The lines are plots of $E_{\pm}$ from the Rabi model with μE_{THz} = 2 meV.

The observation of THz-dressed excitons in this system is particularly interesting since the dressed states can be observed for detunings that are a significant fraction of the level spacing. This comes from the fact that the Rabi frequency can be comparable to the THz frequency, making a number of nonperturbative strong-field effects potentially observable.[7] This system is also technologically interesting as it is essentially a QW modulator driven at THz frequencies. The presence of quantum coherence in a QW modulator may enable fascinating new functionalities. This work was supported by the NSF and SUN Microsystems.

* Present address: V. Birkedal née Ciulin, Department of Chemistry, University of Aarhus, Langelandsgade 140, DK-8000 Aarhus C, Denmark.

[1] A. V. Maslov and D. S. Citrin, "Optical absorption and sideband generation in quantum wells driven by a terahertz electric field," Phys. Rev. B **62**, 16686-91 (2000).
[2] K. Johnsen and A.-P. Jauho, "Quasienergy Spectroscopy of Excitons," Phys. Rev. Lett. **83**, 1207-10 (1999).
[3] K. B. Nordstrom, K. Johnsen, S. J. Allen, A. –P. Jauho, B. Birnir, J. Kono, T. Noda, H. Akiyama, and H. Sakaki, "Excitonic dynamical Franz-Keldysh effect," Phys. Rev. Lett. **81**, 457-60 (1998).
[4] S. H. Autler and C. H. Townes, "Stark effect in rapidly varying fields," Phys. Rev. **100**, 703-22 (1955).
[5] V. Ciulin, S. G. Carter, M. S. Sherwin, A. Huntington, and L. A. Coldren, "Terahertz optical mixing in biased GaAs single quantum wells," Phys. Rev. B **70**, 115312 (2004).
[6] A. Liu and C. Z. Ning, "Exciton absorption in semiconductor quantum wells driven by a strong intersubband pump field," J. Opt. Soc. Am. B **17**, 433-9 (2000).
[7] A. V. Maslov and D. S. Citrin, "Mutual transparency of coherent laser beams through a terahertz-field-driven quantum well," J. Opt. Soc. Am B 1**9**, 1905-9 (2002).