Observation and manipulation of dipole-forbidden exciton transitions in semiconductors

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Abstract: We discuss recent experimental and theoretical results that report on the observation of dipole-forbidden intra-exciton transitions in semiconductors via terahertz excitation. Additional manipulation capabilities are gained through the application of a magnetic field.

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Excitation with terahertz (THz) light has become a convenient tool to characterize fundamental properties of solids and semiconductors. In particular, THz excitation has been applied to monitor rotational resonances of molecules and phonons in solids. In semiconductors, THz spectroscopy has led to a new field that allows for a direct detection of many-body states [1, 2] because the spectral range of a THz field matches with typical transition energies [in milli-electron volt (meV) range] between many-body states. Here, we study excitons that are Coulomb-bound electron–hole pairs similar to a hydrogen atom. In general, the THz excitation is sensitive to particle correlations and thus couples directly to the many-body state of a semiconductor. Hence, THz excitation has become a versatile method that allows us to detect and manipulate many-body interactions.

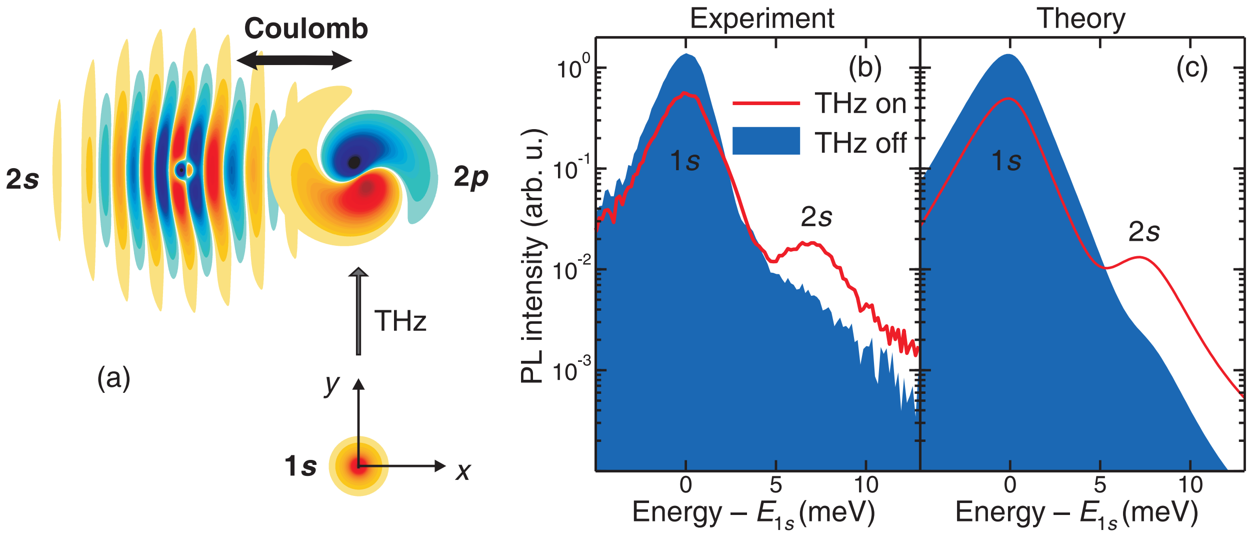

Fig. 1: (a) Schematic diagram of THz and Coulomb coupling among exciton wave functions which are shown in real space. (b) Measured PL intensity 50 ps after the THz-pulse center. (c) Computed PL intensity 50 ps after the THz-pulse center. In (b)-(c), the $1s$ and $2s$ exciton peaks are labeled. PL spectra with (solid) and without (shaded) THz field are shown.

To demonstrate how new interactions among excitons can occur, we present in Fig. 1 recent experimental and theoretical observations which were performed with the help of a THz field [3]. A laser field pre-excites an (InGa)As multiple quantum-well sample and initiates $1s$-excitonic polarization which eventually is transformed into $1s$-exciton population. A free-electron laser is then used to produce a THz field which is resonant with the $1s$-to-$2p$ transition [4], as indicated by the vertical arrow in Fig. 1(a) which also shows the exciton wave functions of $1s$, $2p$, and $2s$ states in real space. Since only the s-like states are nonvanishing at the origin, i.e., a nonzero probability to find an electron and hole at the same position, only these states can radiatively recombine and are thus visible in photoluminescence (PL) spectra. Hence, non-interacting excitons would suggest emission only at the $1s$-exciton energy for this experiment because the direct $1s$-to-$2s$ transition is dipole-forbidden for the THz field such that no $2s$-exciton population can be directly addressed. However, measured PL spectra [Fig. 1(b)] shortly (50 ps) after the THz-pulse center show clear emission at the $2s$-exciton energy when a THz field is present (solid line). This observation has been explained with our theoretical model [5, 3] and we have obtained a very good agreement between experiment and theory, see Fig. 1(c). The observed excess $2s$ PL could be explained via the Coulomb interaction that mixes the $2p$ and $2s$ exciton states, as indicated by the horizontal arrow in Fig. 1(a), allowing an efficient $1s$-to-$2s$ transition that is unique to interacting many-body semiconductor states and no analog exists for atoms.

It is a fascinating endeavor to study further how one can manipulate the new $1s$-to-$2s$ channel. We have achieved this by using an external magnetic field [6] that changes the exciton wave functions and energies. For instance, the p-like states encounter a splitting into p_- and p_+ states according to different magnetic quantum numbers, similar to the Zeeman effect. Furthermore, these changes imply strong modifications of Coulomb-scattering strengths, THz-dipole strengths for intra-exciton transitions, excitation-induced dephasing, and oscillator strengths. These combined effects lead to intriguing control possibilities of exciton interactions simply by choosing certain combinations of THz frequency and magnetic-field strength [6]. We present the details of these findings and the resulting implications for other applications.

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