Linear and Non-Linear Optical Responses of Exciton Fano Resonance in Semiconductor Heterostructure

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Quantum interference between continua and a discrete level embedded in the former gives rise to a pronounced asymmetric spectral profile having a peak-and-dip structure, known as Fano resonance (FR). It is well known that this phenomenon plays significant roles in nuclear, atomic and molecular physics for the studies of energy-structures of highly-excited states and the related relaxation dynamics due to interparticle correlation. Recently, the FR of exciton states has been intensively investigated in quantum wells (QW's), quantum wires, and superlattices with and without external electric and/or magnetic fields. These FR states arise from interactions of subbands ascribable to quantum confinement of these semiconductor heterostructures. Here a subband is also termed a channel. The interchannel interactions are classified into Coulomb coupling and valence-band mixing, where in-plane angular momenta of concerned channels remain unaltered in the former and the change of them is accompanied by the latter. Usually, the former coupling is considered dominant to the latter one.

The present talk is mainly focused on spectral modulation and further coherent control of FR of the low-dimensional exciton states with respect to material parameters and irradiated-laser parameters. The coherent control of quantum states is one of the current hot topics, extending over wide interdisciplinary fields of atom, molecule and semiconductor physics, non-linear optics, quantum electronics, laser science, and so on [1]. Aside from academic interests in the novelty, especially, these studies allow to open new possibilities of optoelectronic device engineering and laser technology.

First, linear absorption spectra of QW-exciton FR states are presented, where the FR profiles vary conspicuously with increasing well thickness d. This is due to the valence-band mixing effect that enlarges overlap with adjacent FR states with d larger [2]. In Fig. 1, FR spectra of the $B:[2,2]^h$-exciton are given for several GaAs/Al$_{0.3}$Ga$_{0.7}$As-QW's of $d=10-50$ nm. A heavy-hole exciton state, above all, $B1$, usually manifests itself as dominant resonance. These spectra are calculated by solving multichannel scattering problems pertinent to the present FR system by use of the R-matrix propagation technique [3]. This method provides calculations with high accuracy comparable to the recent high-resolution measurements of various exciton FR states [4]. The similar overlap resonance is also observed in excitons in biased superlattices when an applied dc-electric field F_0 normal to the layer plane is changed. For large (small) F_0, carriers are spatially localized (delocalized) in the crystal growth direction. This type of superlattices is termed the Wannier-Stark ladder (WSL).

Second, four-wave mixing (FWM) spectra of the WSL-exciton FR are considered in both temporal and frequency domains [5]. FWM with two (pump and probe) pulse-lasers arranged is one of the most powerful technique for examining non-linear optical response and transient relaxation dynamics. Strength of coupling between the irradiated pump laser field and exciton states can be optionally tuned so as to be comparable to or larger than that of the Coulomb coupling leading to the FR. Furthermore, many-body effects of exchange interactions between excitons become significant here, since interband transitions induced by this relatively strong pump laser generate a great number of electron-hole pairs. The many-body effects, giving rise to increase of self-energies of excitons and vertex-corrections associated with the generalized Rabi frequency, are characteristic of laser-material interactions in semiconductor systems, differing a lot from those in atom and molecule systems [6]. It is shown that these two couplings, namely, pump laser-exciton and exciton-exciton interactions, play notable roles for strong modulation and coherent control of FR states transiently formed for the duration of irradiation of the two fs-laser pulses. This behavior is reflected in the time-resolved FWM spectra and the relevant power spectra. Figure 2 shows that the many-body effect contributes to prominent modulation of the power spectra in 3.4nm-GaAs/1.7nm-$Al_{0.3}Ga_{0.7}As$-superlattices with $F_0 = 25$ kV/m. The numerical results are provided by solving the semiconductor Bloch equations with using exciton FR states as an expansion basis set [3].

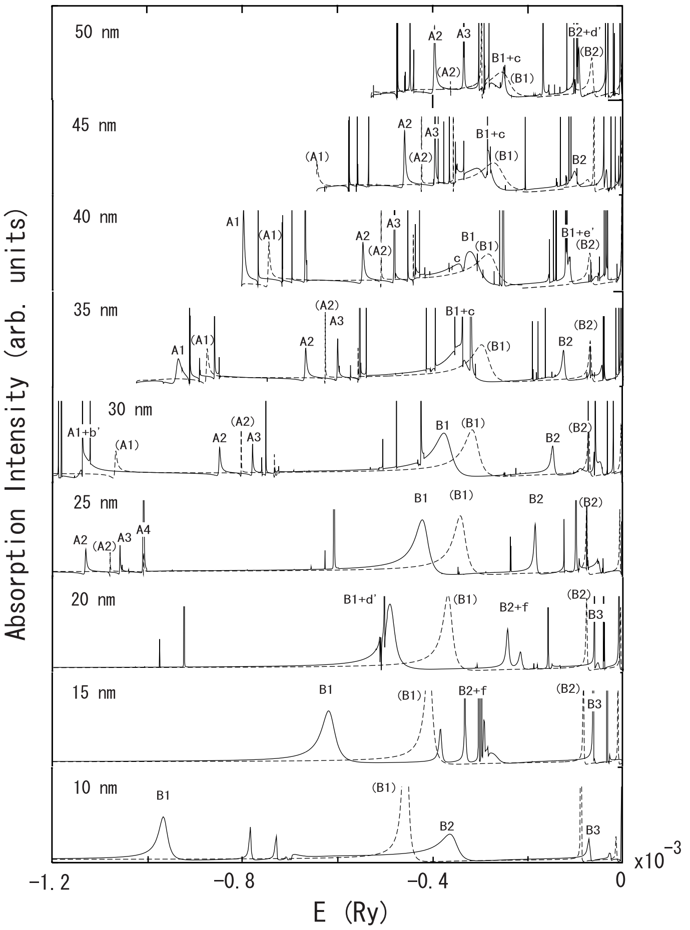

Figure 1: Absorption spectra of FR states pertaining to the channel B in GaAs/$Al_{0.3}Ga_{0.7}As$-QW's of 10-50 nm versus an energy E reckoned from the subband energy of this channel. Here, each subband for a heavy-hole (HH) (a light-hole (LH)) exciton is designated as $[n_e, n_h]^{h(l)}$, with n_e and n_h electron and hole quantum numbers of respective QW's. Channels of optically active even-parity HH-excitons are denoted as capital letters, $A : [1,3]^h$, $B : [2,2]^h$. Channels of LH-excitons are as small letters, $c : [1,2]^l, f : [2,1]^l$, and those of odd-parity HH-excitons are as primed small letters, $b' : [1,2]^h, d' : [2,1]^h, e' : [1,4]^h$. Solids lines with labels of FR states stand for results calculated with valence-band mixing. Dashed lines with parenthesized labels of FR states are for results calculated without it for comparison. $A1$, $B2$, etc. mean the $1s$-state of A, the $2s$-state of B, and so on.

Finally, the WSL driven by far infrared cw-laser and an associated excitonic effect are considered. Here this laser induces intraband transitions between WSL subband states. This is termed the dynamic WSL (DWSL). As for electronic states of a free carrier in the DWSL, these can be analyzed in terms of the Floquet theorem because of temporal periodicity of the system concerned. The electronic structure resulting from such optical non-linearity indicates quasi-energy band formation and band collapse, depending on strength of this applied laser field F, as is shown in Fig. 3(a) for 4.5nm-GaAs/4.5nm-$Al_{0.3}Ga_{0.7}As$-superlattices with $F_0 = 10$ kV/m. These phenomena akin to the Autler-Townes splitting are interpreted in terms of dynamic delocalization (DDL) and dynamic localization (DL) of the carrier, respectively [7]. Both DDL and DL are caused by photon-assisted tunneling between adjacent subband states coupled by the intraband transitions. Next the excitonic effect that is significant in a real system is introduced into the DWSL. An electron-hole pair concerned here manifests itself as a dressed exciton, and the associated quasi-energy structure is altered, as is seen in Fig. 3(b). Specifically, it is seen that the energy structure for DL is blurred to some extent due to the excitonic effects. Examining FR absorption spectra of exciton DWSL by irradiating another weak probe laser, it is found that the spectral intensity and profile vary drastically at F tuned to the position of DL from those corresponding to DDL. Moreover, binding energies of the dressed excitons are notably changed from those of WSL excitons with $F = 0$. More detailed investigations of the exciton DWSL are in progress, resorting to the semiconductor Bloch equations for FWM spectroscopy with arranging three laser pulses.

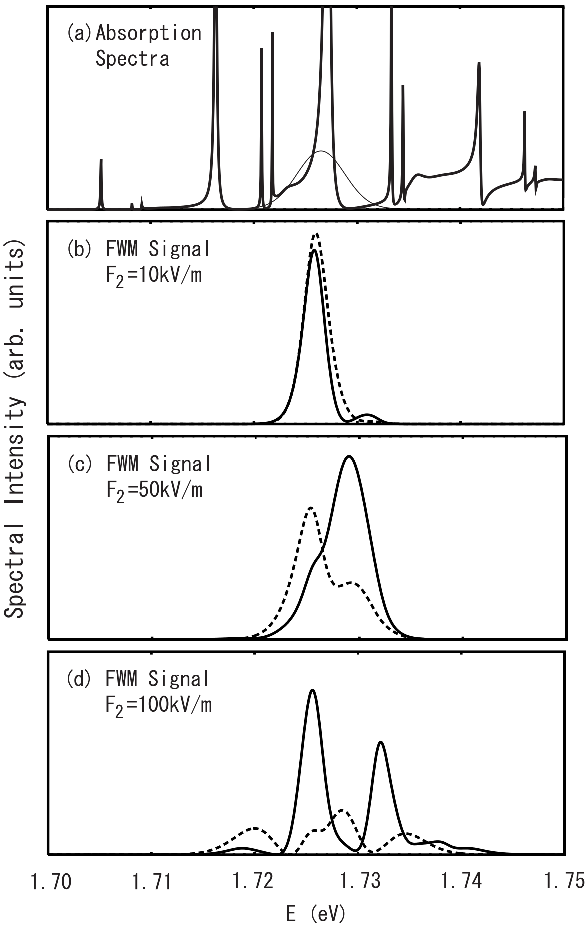

Figure 2: (a) Linear absorption spectra of exciton FR states in 3.4nm-GaAs/1.7nm-$Al_{0.3}Ga_{0.7}As$-superlattices with a biased dc-electric field F_0 =25 kV/m as a functions of photon energy E. (b) FWM spectra (power spectra of time-resolved FWM signals) for the WSL exciton FR versus E, where a peak amplitude of the probe pulse laser F_1 =1 kV/m, that of the pump laser pulse F_2 =10 kV/m, and F_0 =25 kV/m, respectively. Here temporal pulse widths of both lasers is set 500 fs, dephasing time and population relaxation time are given by 400 fs, and the time delay of the two-pulse irradiation is 0 fs. The solid line represents the FWM signal obtained by full calculations including the pump laser-exciton interaction and the many-body exciton-exciton exchange-interaction, while the dotted line means that without the latter. Spectral distribution of the pulses are depicted as a bell-shaped curve denoted by a thin line in (a), where the 1s state of the WSL index $\nu = 0$ is selectively excited. (c) Same as (b) but F_2 =50 kV/m. (d) Same as (b) but F_2 =100 kV/m.

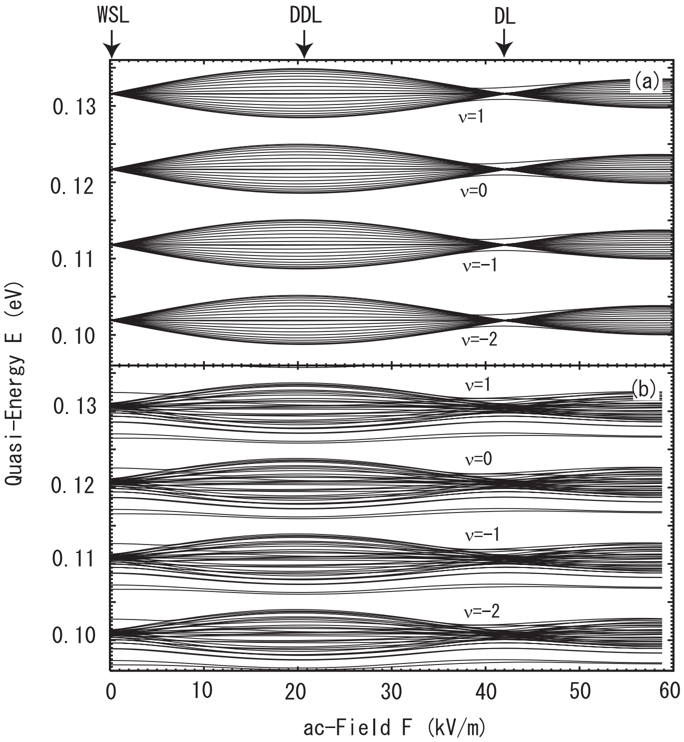

Figure 3: Quasi-energies E of DWSL as functions of applied cw-laser field F in 4.5nm-GaAs/4.5nm-$\mathrm{Al}_{0.3}\mathrm{Ga}_{0.7}$As-superlattices with a biased dc-electric field F_0 =12 kV/m. Frequency of the laser coincides with the Bloch frequency of the system. Here E is reckoned from the bottom of the conduction band of GaAs. The label of ν denotes the WSL index associated with an energy level at F=0, where $\nu = 0$ means the parent band and other indices represent photon side bands (replica). Positions of F relevant to WSL, DDL, and DL are indicated at the top of the figure. (a) DWSL without excitonic effects. (b) DWSL with excitonic effects.

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