Superfluorescence from magnetically formed quantum dots: mixing, temperature, and pulse-width dependence

Young-Dahl Jho*, David H. Reitze**, Junichiro Kono***
*Dep. of Info. & Comm., GIST, **Dep. of Physics, Univ. of Floria, ***ECE Dep., Rice Univ.
jho@gist.ac.kr

The spontaneous appearance of macroscopic coherence such as Bose-Einstein condensation and superconductivity is among the most dramatic cooperative phenomena in condensed matter physics, and search for ordered exciton states is the subject of intense current research.(1) In quantum electrodynamics, there exists a related self-organization process of the same fundamental importance, called superfluorescence (SF). In this process, a system of N inverted atomes is incoherently prepared, but macroscopic coherence builds up self-consistently starting from vacuum fluctuations. The resultant macroscopic dipole decays superradiantly, producing a burst of coherent radiation. The exotic SF pulses have been observed in atomic gases and rarefied impurities in crystals but only recently observed in semiconductor systems because of ultrafast decoherence.(2) As a new route to overcoming this obstacle, we use magnetic field in order to confine charged carriers within, so called, magnetic length (~ 25 nm/$B^{1/2}$, with magnetic field B in the unit of Tesla) in quantum wells (QWs). As such, we can simulate ideal nano-scale quantum optics in atomic-like environment without disturbance from alloy or size fluctuations.

Using a 150 fs, 775 nm Ti:sapphire regenerative amplifier, we have measured photoluminescence (PL) as a function of energy level mixing and temperature under magnetic fields. The temperature T was fixed at 10 K otherwise mentioned. The laser beam is delivered into a 31 Tesla (T) Bitter-type magnet through free space. The QW plane was perpendicular to B and to laser propagation direction. Two right-angle micro-prisms redirected the edge emission from the sample to collection fibers.

In Figure 1(a), a contour map of the field-dependent PL emission is presented. The spectra is dominated by amplified sharp features at fields > 10 T while spontaneous emission (with linewidth ~ 9 meV) was relatively strong below 10 T. Fig. 1(a) is normalized to the maximum intensity and scaled into rainbow colors. In addition to the H1(the lowest heavy-hole state) Landau levels(LLs) [labeled 0-0, 1-1, etc in the figure window], the higher heavy hole states $H2^{0-0}$ and $H2^{1-1}$ are observed. The dashed vertical lines identify the mixing energies and the oscillation peaks of intensity in Fig. 1(b): a clear correlation is seen for higher LLs between the mixing points of the H1-H2 levels and the peaks in the oscillations of the emission. 0-0 LL mostly doesn't show oscillatory behavior as the density of state is fully filled up to ~ 28 T. Gray (for 1-1) and red (for 0-0) vertical lines in Fig. 1 (b) indicate the threshold fields B_{TH} at 10 K.

Because the formation of SF inherently relies on the establishment of a macroscopic

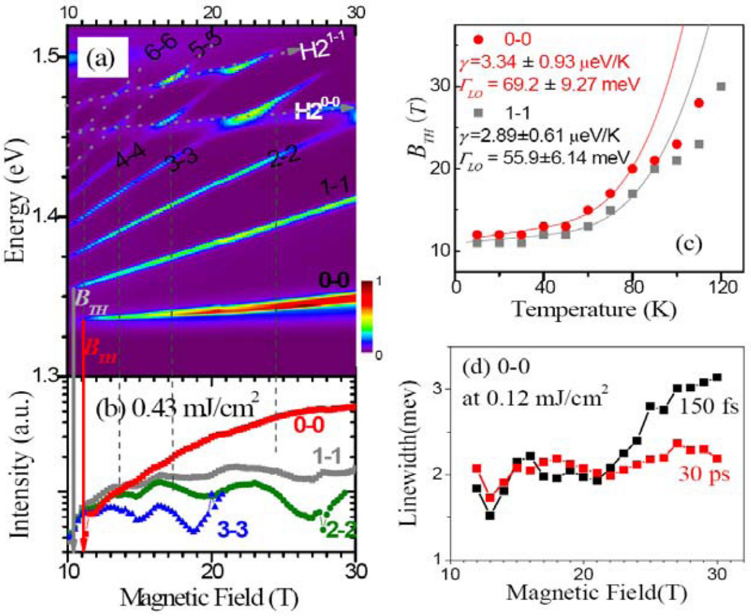

Fig. 1. (a) Counterplot of the emission strength versus field at a pump fluence of 0.43 mJ/cm2, (b) integrated emission intensity of amplified features. The dashed vertical lines in (a,b) show the mixing points between various LLs and higher sublevels. (c) Threshold fields $B_{TH}(T)$ for the 0-0 (red circles) and 1-1 LL (black squares). (d) Linewidths of amplified features excitedby pulsewidth of 150 fs (black) or 30 ps (red).

coherence among the photoexcited carrier density, we expect that the emission threshold and strength should depend sensitively on temperature. An increasing phonon number with temperature should increases the intercarrier dephasing rate T_2 and thus increase the critical magnetic field B_{SF} for SF generation can be formulated as a function of temperature T in a simplified picture, based on dephasing rate $2/T_2$ varied due to carrier scatterings with acoustic and optical phonon; $2/T_2 \propto \Gamma_0 + \gamma T + \Gamma_{LO}/[e^{(E/kT)} - 1]$, where Γ_0 is the width due to the inhomogeneous broadening and γ (Γ_{LO}) is fitting parameter which measures the interaction with acoustic phonon (polar LO phonons), respectively. Since the LO phonon energy E in our sample structure, which is expected to be similar to that of GaAs-based QW (~ 36 meV), is much larger than thermal energy (kT) in our temperature range up to 120 K, we tentatively identify the acoustic phonon contribution as a dominant temperature mechanism for varying B_{SF}. We trace $B_{TH}(T)$ for LLs presuming that $B_{TH}(T)$ will follow the same trend with $B_{SF}(T)$. The fitting results in Fig. 1(c) (solid lines) are shown in the figure window, where the γ (Γ_{LO}) is very similar to the zero-dimensional case.

To further investigate the emission characteristics in regard to ultrafast formation and decay of macroscopic coherence, we vary the excitation pulsewidth in Fig. 1(d) at 10 *K* at fixed pump fluence of 0.12 mJ/cm^2. We obtained linewidths for 150 fs (black) and for 30 ps (red), following the Lorentzian lineshape analysis. Fig. 1(d) displays the clear trend of linewidth increment at 150 fs in constrast to at 30 ps which is much broader than estimated coherence buildup time for SF in our system (~ 10 ps).

1. See e.g., H. Deng *et al.*, "Condensation of Semiconductor Microcavity Exciton Polaritons", Science 298, 199 (2002).
2. Y.D. Jho *et al.*, "Cooperative recombination from a quantized electron-hole plasma", Phys. Rev. Lett. **96**, 237401 (2006); "Superfluorescence from Dense Electron-Hole Plasmas under High Magnetic Fields", J. Mod. Opt. 53, 2325 (2006).