Inhibition of spontaneous emission from quantum-well magnetoexcitons

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We propose a method for tailoring the radiative properties of two-dimensional magnetoexcitons. First, we show that the magnetoexciton-photon coupling is purely bilinear in the strong-magnetic-field limit, implying that optical nonlinearities appear through the breakdown of bosonic commutation relations at high densities. The dispersion curve of magnetoexcitons may be modified or *engineered* using external electric or optical fields. We show that the application of an in-plane electric field will render the ground-state magnetoexcitons stable against radiative recombination, as a result of the momentum conservation. Based on this effect, we propose a particular geometry which should allow for the investigation of condensation effects and superfluidity in direct-band-gap semiconductors. [S0163-1829(96)51344-5]

The condensation phenomenon is strongly influenced by the dispersion relation of the participating bosonic particles.[1] In particular for semiconductor excitons, the effective mass and radiative lifetime are fundamental parameters that determine whether a quantum degenerate gas of excitons and superfluid motion can be observed at a given temperature and density.[2,3]

In this paper, we propose a method to control and modify the dispersion relation of excitons using static electric and magnetic fields. The basic system that we envision is a semiconductor quantum well (QW) with a strong magnetic field $\mathbf{B}$ applied along the growth direction $\mathbf{a}_z$.[4–6] For simplicity, we assume that the semiconductor is direct band gap with symmetric (and parabolic) conduction and valence bands. We show that (i) in the strong magnetic field limit under consideration, the magnetoexciton photon coupling is purely bilinear; and (ii) a static electric field $\mathbf{E}$ applied perpendicular to the magnetic field will shift the minimum of the dispersion curve to a nonzero magnetoexciton wave vector along the direction $\mathbf{B}\times\mathbf{E}$, with the possibility of making ground-state excitons stable against radiative recombination, due to momentum conservation. Reversible coupling of magnetoexcitons to an optical cavity mode may be combined with the transverse electric fields to modify the effective mass of the magnetoexcitons. Finally, we propose a new cylindrical device geometry that should allow for the investigation of superfluid motion of condensed magnetoexcitons or polaritons with *tunable* mass and adjustable superfluid velocity.

Two dimensional electron-hole pairs in strong magnetic fields have been studied extensively over the past decade.[4–7] In particular it has been theoretically demonstrated that in the limit where the magnetic length $a_0=\sqrt{\hbar/eB}$ is much smaller than the bare exciton Bohr radius a_B, the ground-state excitons are ideal (noninteracting) bosons. In addition, it was shown that transverse electric fields result in exciton motion along $\mathbf{B}\times\mathbf{E}$ as indicated earlier.[5] To the best of our knowledge, however, radiative properties of magnetoexcitons in transverse electric fields have not been previously explored.

We follow Paquet *et al.*[5] and represent the electron and hole wave functions using Landau orbitals and choose the Landau gauge $\mathbf{A}=xB\mathbf{a}_y$. When the spin degree of freedom is suppressed, the field operators for the lowest Landau level in the lowest-energy subbands are given by

$$\hat{\psi}(\mathbf{r})=\sum_{i,k}\varphi_{i,k}(r)\hat{e}_{i,k}, \tag{1}$$

where $\hat{e}_{i,k}$ denotes the annihilation operator for the kth electron mode in the conduction $(i=1)$ or valence $(i=2)$ bands. $\varphi_{i,k}(r)=L^{-1/2}\exp[iky]\phi(x+ka_0^2)u_{i,k}(r)$ is the single-particle wave function: Here, L denotes the lateral dimension of the sample, $u_{i,k}(r)$ is the periodic part of the Bloch function, and $\phi(x)=(a_0\sqrt{\pi})^{-1/2}\exp[-x^2/(2a_0^2)]$ is the harmonic oscillator wave function. Identifying the electron and hole annihilation operators as $\hat{e}_k=\hat{e}_{1,k}$ and $\hat{h}_k=\hat{e}^{\dagger}_{2,-k}$ respectively, we can diagonalize the single electron-hole pair Hamiltonian using the *magnetoexciton operator*

$$\hat{d}^{\dagger}_K=\frac{a_0\sqrt{2\pi}}{L}\sum_q e^{-iK_xqa_0^2}\hat{e}^{\dagger}_{K_y/2+q}\hat{h}^{\dagger}_{K_y/2-q}. \tag{2}$$

One of the amazing results obtained by Lerner and Lozovik[4] and Paquet *et al.*[5] is the fact that ground-state $(K=0)$ magnetoexcitons are noninteracting particles to the extent that virtual interactions with higher-energy Landau levels can be neglected. This is justified in the strong-magnetic-field limit $a_0\ll a_B$. As noted in Ref. 5 however, magnetoexcitons with nonzero wave vector K interact with each other since they have a nonzero electric dipole moment.

We first consider the interactions of magnetoexcitons with the radiation field reservoir. We start from the second-quantized interaction Hamiltonian for two-dimensional electron-hole gas in the electric-dipole form

$$\hat{H}_{\text{int-rad}}=\int d^2r\,\hat{\psi}^{\dagger}(\mathbf{r})e\mathbf{r}\cdot\hat{\mathbf{E}}\hat{\psi}(\mathbf{r}), \tag{3}$$

where $\hat{\mathbf{E}}$ denotes the electric field operator, with corresponding annihilation operators $\hat{a}_K$. If we assume that the quantum well is embedded inside a microcavity structure, we only need to consider coupling to a single optical (axial) cavity mode.[8] Provided that the lattice constant $a_{\rm latt}$ is much smaller than a_0, we obtain

$$\hat{H}_{\rm int-rad}=i\hbar\sum_{\mathbf{K}=K_\perp} g_K(\hat{d}_K^\dagger\hat{a}_K-\hat{a}_K^\dagger\hat{d}_K), \tag{4}$$

where

$$g_K=\left(\frac{\omega}{2\epsilon\hbar V_{\rm cav}}\right)^{1/2}\frac{\mu_{\rm cv}}{\sqrt{2\pi}}\frac{L}{a_0}e^{-K^2a_0^2/4}. \tag{5}$$

Here, ω, ϵ, and $V_{\rm cav}$ denote the frequency, dielectric constant, and effective volume of the optical cavity mode. $\mu_{\rm cv}$ denotes the valence-to-conduction–band dipole matrix element. Extension of this result to a three-dimensional (free) radiation field reservoir is straightforward; in this case, the magnetoexcitons couple to a continuum of modes with arbitrary momentum $K_\parallel$ along the z direction [modified version of Eq. (4) that corresponds to this case is included in Eq. (8) below]. Since the magnetoexcitons are two-dimensional, only the transverse momentum is conserved in the interaction.

The exact result of Eq. (4) indicates that the magnetoexciton-photon interaction Hamiltonian retains a bilinear form irrespective of the magnetoexciton density. This implies that all nonlinearities such as phase-space filling (PSF) effects, appear via the breakdown of the bosonic commutation relations. Physically, this can be traced back to the fact that the magnetoexciton annihilation (or creation) operator has an equal contribution from all electron-hole operators with the same total momentum [Eq. (2)]. Therefore, PSF for $K=0$ excitons is determined by the total density. In contrast, bare-exciton wave functions are *localized* in the momentum space of free electron-hole pairs, leading to an enhanced PSF contribution from $K\simeq 0$ states.

We now turn to magnetoexcitons interacting simultaneously with an optical and an in-plane (dc) electric field. As shown in Ref. 5, the application of an electric field of magnitude $\mathcal{E}_x$ along the x direction, leads to a new interaction Hamiltonian which can be reduced to

$$\hat{H}_{\rm int-e}=-ea_0^2\mathcal{E}_x\sum_{\mathbf{K}} K_y\hat{d}_K^\dagger\hat{d}_K. \tag{6}$$

As noted by Paquet *et al.*,[5] this new term in the Hamiltonian corresponds to the energy of the electric-dipole carried by the magnetoexciton and may be regarded as *magnetoelectric Stark effect*. It is straightforward to show that in the presence of the in-plane electric field, the single magnetoexciton dispersion curve becomes

$$E_{\rm exc}(K)=-\frac{e^2}{4\pi\epsilon a_0}\sqrt{\frac{\pi}{2}}\exp\left(-\frac{K^2a_0^2}{4}\right)I_0\left(\frac{K^2a_0^2}{4}\right)-ea_0^2\mathcal{E}_xK_y. \tag{7}$$

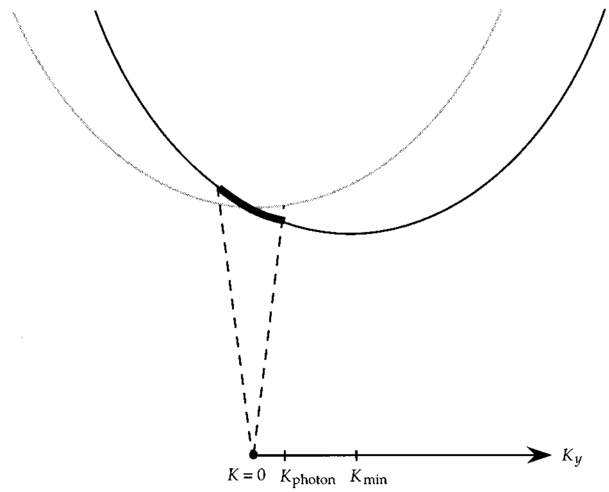

FIG. 1. The dispersion curve of magnetoexcitons with (black curve) and without (gray curve) an applied in-plane electric field. The dotted lines correspond to the dispersion curve of the free radiation field. Only those excitonic states that lie in between the dotted lines decay by radiative recombination.

As shown in Fig. 1, the effect of the in-plane electric field is to move the minimum of the magnetoexciton dispersion from $K=0$ to $K_y=K_{\rm min}=(8\sqrt{2\pi}\epsilon a_0/e)\mathcal{E}_x$. Equivalently, the ground-state magnetoexcitons have a nonzero momentum in a direction perpendicular to both the magnetic and electric fields. If the density is large enough to satisfy the onset of Bose condensation in the particular transverse confinement potential,[1] the excitons will preferentially populate the state with $(K_x,K_y)=(0,K_{\rm min})$. If we in addition assume an exciton gas with a low-filling factor such that the exciton-exciton interactions can be neglected, the total Hamiltonian can be written as

$$\hat{H}=\sum_{\mathbf{K}}\{[E_{\rm exc}(K)+E_{\rm gap}]\hat{d}_{K_\perp}^\dagger\hat{d}_{K_\perp}+\hbar\omega_{\rm ph}(K)\hat{a}_K^\dagger\hat{a}_K\}+\sum_{\mathbf{K}} i\hbar g_{K_\perp}(\hat{d}_{K_\perp}^\dagger\hat{a}_K-\hat{a}_K^\dagger\hat{d}_{K_\perp}), \tag{8}$$

where $E_{\rm gap}=\hbar\omega_{\rm cv}$ is the band-gap energy of the semiconductor and $\omega_{\rm ph}(K)$ denotes the photon mode frequency. For a free field $\omega_{\rm ph}(K)=cK$, whereas for a single axial cavity mode $\omega_{\rm ph}(K)=c\sqrt{K^2+\pi^2/L_{\rm cav}^2}$, with c and $L_{\rm cav}$ denoting the speed of light in the semiconductor and effective cavity length, respectively.

Radiative properties of magnetoexctions can be analyzed using a master equation approach starting from the Hamiltonian of Eq. (8).[9–11] If we set $K_{\rm min}>\omega_{\rm cv}/c$, it is straightforward to show that the coupling between the ground-state excitons to the radiation field modes will not be dissipative, due to the impossibility of conserving energy and in-plane momentum simultaneously. Equivalently, radiative self-energy of magnetoexcitons with $K_{\rm min}$ has no imaginary component. This is one of the principal results of our paper: by using an external static electric field we can generate a degenerate magnetoexciton gas at $K_{\min}$ with an *adjustable* and in principle arbitrarily long radiative lifetime. This result is valid for all exciton densities and is illustrated in Fig. 1; only excitonic states that lie between the dashed lines (*photon window*) are allowed to emit/absorb photons. We remark, however, that elastic momentum scattering induced by interface roughness will result in a finite radiative lifetime, unless $E_{\rm exc}(0) - E_{\rm exc}(K_{\min})$ is large enough that such a scattering process into optically allowed modes is energetically forbidden.

Despite several recent ingenious proposals,[12,13] the short radiative lifetime of ground-state excitons have so far limited the observation of condensation effects in direct-band-gap semiconductors, such as GaAs and ZnSe. We believe that the introduction of moderate strength electric fields ($\simeq 10^3$ V/cm) may solve this problem without increasing the Bohr radius, which is undesirable since it makes the system more prone to PSF. Condensation effects in the present system may be observed either by resonant or nonresonant optical pumping. In the former, one could adjust the $K_{\min}$ so that the optically generated $K=0$ magnetoexcitons can reach the ground magnetoexciton state by a single longitudinal acoustic (LA)-phonon emission event. Such a *matter laser* that generates coherent magnetoexcitons with $K_y = K_{\min}$ could have an extremely low *threshold density* due to reduced losses and efficient pumping.[14] For a GaAs quantum-well structure with $a_0 = 80$ Å ($B \simeq 10$ T), an electric field strength of 10^3 V/cm gives $K_{\min} \simeq K_{\rm photon}$.

The possibility of obtaining a radiatively stable exciton condensate with an adjustable group velocity is especially important if one is interested in studying superfluidity.[1,5] Figure 2(a) shows the device geometry we consider: We assume a cylindrical sample with a QW equidistant from the top and bottom electrical contacts, where an equal (positive) voltage is applied. When the cylindrical side gate contacting the QW is grounded, the electric field lines in the QW plane are in the radial direction $\mathbf{r}$ [dotted lines in Fig. 2(b)]. Since $\mathbf{B} \| \mathbf{a}_z$, the ground-state magnetoexcitons will have momentum in the direction $\mathbf{B} \times \mathbf{E}$. If in addition, the magnetoexcitons are (weakly) confined to a region with $\overline{r} > 0$ using applied stress or inhomogeneous magnetic fields, one obtains the exact analog of the ring structure discussed in the studies of rotational superfluidity in He II. In this geometry, it should also be possible to change $\mathcal{E}$ after the condensation has taken place and study the nonequilibrium phenomena by observing the weak fluorescence from the rotating magnetoexcitons. However, we remark that even though the modification of the magnetoexciton dispersion relation due to condensation has been studied previously,[5] the extension of these results to the spatially inhomogeneous system considered here have not been carried out. Among the interesting questions that can be studied using the system of Fig. 2 is the value of the critical superfluid velocity.

An alternative method for modifying the dispersion relation of excitons is by introducing strong reversible coupling to a single microcavity mode.[8,15,16] In this regime, one obtains microcavity exciton-polaritons as the relevant quasiparticles, with an effective mass predominantly determined by the cavity-photon dispersion. As seen from the Hamiltonian

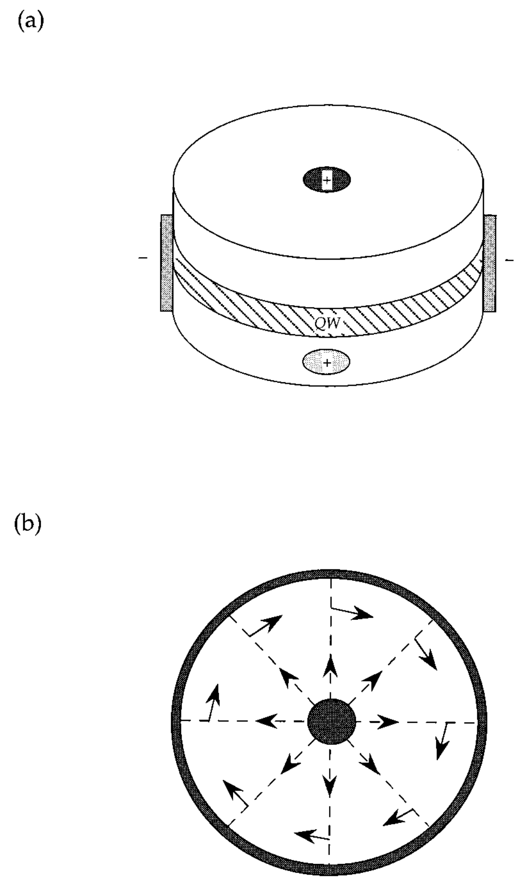

FIG. 2. The cylindrical geometry (a) for the observation of superfluid motion of magnetoexcitons. It is assumed that the device is symmetric, with equal voltages applied to the top and bottom contacts, and grounded side contacts extending over the whole device. The electric field lines in the quantum well are in the radial direction (b).

of Eq. (8), the evaluation of the dispersion curve of magnetopolaritons in transverse electric fields presents no difficulties. It is in principle possible to condense magnetopolaritons into a finite momentum state. Even though the change in the radiative recombination rate induced by the electric field is negligible, the orders of magnitude reduction in the effective mass may render such a system useful for the observation of condensation effects and superfluidity at high temperatures ($T \geqslant 3$ K).

In summary, we have investigated the radiative properties of two-dimensional magnetoexcitons in transverse electric fields. We showed that moderate electric field strengths can inhibit the spontaneous emission rate of ground-state magnetoexcitons and allow for the observation of condensation effects into finite momentum states. We also discussed a particular device geometry that could be used to study the rotational superfluid motion of condensed magnetoexcitons.

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