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Overflow of a dipolar exciton trap at high magnetic fields

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ABSTRACT

We study laterally trapped dipolar exciton ensembles in coupled GaAs quantum wells at high magnetic fields in the Faraday configuration. In photoluminescence experiments, we identify three magnetic field regimes. At low fields, the exciton density is increased by a reduced charge carrier escape from the trap, and additionally, the excitons' emission energy is corrected by a positive diamagnetic shift. At intermediate fields, magnetic field dependent correction terms apply which follow the characteristics of a neutral magnetoexciton. Due to a combined effect of an increasing binding energy and lifetime, the exciton density is roughly doubled from zero to about 7 T. At the latter high field value, the charge carriers occupy only the lowest Landau level. In this situation, the exciton trap can overflow independently from the electrostatic depth of the trapping potential, and the energy shift of the excitons caused by the so-called quantum confined Stark effect is effectively compensated. Instead, the exciton energetics seem to be driven by the magnetic field dependent renormalization of the many-body interaction terms. In this regime, the impact of parasitic in-plane fields at the edge of trapping potential is eliminated.

The investigation of many-body effects and quantum phase transitions in dense ensembles of dipolar excitons has motivated different approaches to increase their density [1]. In particular, the exciton density can be increased by elongating the radiative lifetime of the excitons, which is typically achieved by reducing the spatial overlap of the electron and hole wave functions. This has been realized in tunnel-coupled quantum well structures (CQW), where photogenerated electron-hole (*e*-*h*) pairs are spatially separated by the application of a perpendicular electric field. Hereby, the photogenerated electrons tunnel to one quantum well and the holes to the other one, but they are still bound to each other by the Coulomb interaction. Such indirect or dipolar excitons (IX) have a permanent dipole moment and they feature long lifetimes up to several microseconds [2]. Huge efforts have been made over the last years to further increase the IX density as required for quantum phase transitions to achieve exciton fluids [1] and even a Bose-Einstein condensation (BEC) [1]. Promising approaches to

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increase the IX density include a lateral confinement of the IX ensembles, e.g. by strain in the hosting materials [3–6], by shaping the excitation laser light profile [7] and most commonly, by tailored electric field landscapes and gradients within the plane of the quantum well structures [8–16]. Hereby, electrostatic traps for the IXs can be formed, and it has been demonstrated that one can create dense ensembles therein with the temperature of the IXs close to the lattice temperature [17,18]. The functionality of such electrostatic traps is typically altered by unwanted parasitic effects [12]. These effects comprise in-plane electric fields, which can lead to the dissociation of the IXs, and consequently, charge carrier escape processes, which give rise to the excess of one sort of charge carriers within the traps, i.e. photogenerated electrons or holes [19]. The presence of such unbound excess carriers in the trap can weaken the Coulomb interaction between the bound *e*-*h* pairs by screening and scattering effects [20–23]. Moreover, charged excitons, so-called trions, can form with an emission energy lower than the one of the IXs [24,25]. Such trions obey Fermi-Dirac statistics rather than Bose-Einstein statistics and are therefore not suitable to observe a BEC [26]. An experimental way to reveal the presence and the density of excess charge carriers is given by the application of a magnetic field perpendicular to the quantum well plane [27]. The application of large magnetic fields can greatly suppress the formation of charged excitons. The underlying reasons are localization processes, which prevent the free charge carriers from escaping the electrostatic trap region [27]. As a direct consequence, the IX density can be enhanced by the localization of both electrons and holes within the trap.

Generally speaking, the application of magnetic fields significantly modifies the exciton wave functions in the CQWs and turns the excitons into so-called magnetoexcitons. In particular, the exciton binding energy is enlarged in the presence of strong magnetic fields due to shrinkage of the exciton wave function [28]. The exciton oscillator strength is altered by the magnetic field, and the application of a field parallel to the CQWs affects the excitons' dispersion [29,30]. Magnetoexcitons have been investigated theoretically [31–35], and a variety of fascinating effects including quantum phase transitions to an exciton liquid or BEC have been suggested [32,35–39]. Indirect magnetoexcitons built from indirect, dipolar excitons feature an increased effective mass reducing the IX localization, particularly in the low-field region [29]. As a direct consequence, the lifetime of indirect magnetoexcitons is increased compared to IXs at zero magnetic field. In principle, the application of an external magnetic field normal to the QW plane results in an opposite Lorentz force experienced by the electron and hole. The corresponding relative displacement results in an additional dipolar moment [30]. The application of perpendicular electric fields pushes the electrons and holes away from each other [28]. The application of an electric field perpendicular to the plane of the CQWs induces a cross-over from a direct to an indirect exciton ground state. For extended exciton ensembles, this cross-over shifts to larger electric field values under the application of magnetic fields as was shown experimentally [40] and theoretically [28].

In this manuscript, we study the impact of large magnetic and electric fields on laterally confined dipolar excitons that are photogenerated in CQWs. We demonstrate that a trap of IXs can 'overflow' at high magnetic fields. The excitons are electrostatically trapped in micrometer scale lateral traps to realize dense ensembles of IXs at low temperatures. In magnetic field dependent photoluminescence experiments, two critical magnetic field values are found, which we baptize B^* and B^{**}. In the low field regime ($B < B^*$), the exciton ensembles occupy the trapped region in co-existence with free charge carriers [27], and the IX energy is dominated by dipole-dipole interactions. This low magnetic field regime has been investigated in great detail in an earlier publication [27]. For intermediate magnetic field values ($B^* < B < B^{**}$), the ground state energy of the IXs is dominated by Landau Level (LL) formation of the electron and hole bands. In principle, both are single particle energies. However, the exciton emission energy is shifted to higher values by density-dependent dipole-dipole interactions, independent of the minor increase in the IX binding energy. In this magnetic field regime, we demonstrate that the exciton density within the traps is continuously increased with an increasing magnetic field. We interpret this situation such that all excess carriers are localized within the trap and that the increasing binding energy allows for a larger exciton density [27]. At the second critical field value B^{**}, we observe that the IX emission energy can be independent from the electrostatic trapping potential. As a function of laser intensity, the traps can overflow. We attribute this unusual behavior to the situation that the trap is completely filled with neutral indirect magnetoexcitons and that the many-body interaction induced renormalization of the exciton energy compensates the electrostatic trapping potential. As a consequence, the excitons are no longer effectively confined by the trap potential. They are able to diffuse out of the excitation spot. This diffusion effectively lowers the exciton density and hence their many-body energy inside the trap. Moreover, we observe another impact of the trapping potential, namely that the electric field induced shift of the cross-over from direct to indirect exciton ground state remains unaffected by the external magnetic field. This finding is different to the observations by Butov et al. [40] and Morales *at al.* [28] for non-trapped exciton systems at high magnetic fields. We attribute the different behavior between laterally confined (trapped) and extended exciton systems also to density-dependent renormalization effects of the IX energies.

The exciton ensembles are photogenerated in GaAs-based CQWs with AlGaAs-barriers grown by molecular beam epitaxy (MBE) on semi-insulating (001) GaAs substrates. The heterostructure consists of two 8 nm-wide GaAs quantum wells separated by a 4 nm-thick $Al_{0.3}Ga_{0.7}As$ tunnel barrier. The valence and conduction band structure is tilted under the application of an electric field perpendicular to the QW plane [Fig. 1(a)]. The CQWs are embedded in a 370 nm-thick field-effect device with an MBE grown heavily n-doped GaAs back-gate electrode and 5 nm-thick semi-transparent top-gate electrodes made from titanium by e-beam evaporation. The application of an electric field shifts the energy of the IXs with respect to the energy of the direct excitons (DX) by the so-called linear quantum confined Stark (QCSE) effect by an amount of $-\vec{p}\cdot\vec{F}$, where $\vec{p}$ denotes the effective exciton dipole moment and $\vec{F}$ the electric field. The electric field can be approximated as $\vec{F} = -(V_G + V_{Schottky})/s$, with V_G the voltage between a top gate and the global bottom gate, and $V_{Schottky} = -0.7$ V the effective