Quantum Stark confined strongly correlated indirect excitons in quantum wells

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In this contribution we consider small ensembles of optically excited indirect excitons in a single quantum well. Using Path Integral Monte Carlo we compute from first principle the spatial separation of electrons and holes and the lateral quantum Stark confinement of the excitons in the quantum well which is produced by an external electric field of a single tip electrode. By changing the field strength, the tip to sample distance, the excitation intensity (exciton number) and temperature, the exciton-exciton correlations can be varied in broad ranges. Discussing two different semiconductor quantum well heterostructures (GaAs/AlGaAs and ZnSe/ZnSSe) we propose a possible setup which should allow to observe in experiments interesting many-particle phenomena.

1 Introduction In the last three decades increasingly intense research efforts have been devoted to indirect excitons in quasi two-dimensional double quantum wells (QWs), since Lozovik and Yudson [1] proposed that the lifetime of photoexcited (metastable) excitons can be drastically increased if the electrons and holes are spatially separated in different wells. A long radiative lifetime is a prerequisite to enable the electrons and holes to form bound pairs and thermalize to a quasi-equilibrated (ground) state. These bipolar electron-hole pairs are permanent dipoles aligned parallel to a static electric field, which is perpendicular to the QW plane, separating the carriers. The accompanied repulsive mutual dipole-dipole interaction of the indirect excitions prevents formation of biexcitons and electron-hole droplets and masks at the same time the fermionic character of the excition constituents, so that the indirect excitons are approximately of bosonic nature [2].

For investigation of exciton correlation phenomena, i.e. to achieve strong coupling of a mesoscopic number of excitons an additional lateral confinement within the QW plane is needed to compensate the exciton-exciton repulsion. For this purpose, we consider optically excited indirect excitons in a single QW where the spatial separation of electrons and holes is produced by an *inhomogeneous* electrostatic field along the QW growth direction. The lateral confinement arises from the quantum confined Stark effect (QCSE) with a typical trap size being on the order of several micrometers. An electrostatic exciton trap based on the QCSE, which demonstrates voltage-controlled localization of quantum-well excitons, has been realized by Zimmermann et al. [3]. Resting upon field induced band-gap engineering, different circular symmetrical exciton traps have been suggested, e.g. [4, 5, 6]. In contrast, the trap considered here possesses two independent control parameters: the applied voltage and, additionally, the electrode to sample distance allowing for high flexibility regarding the depth and the steepness of the parabolic in-plane potential.

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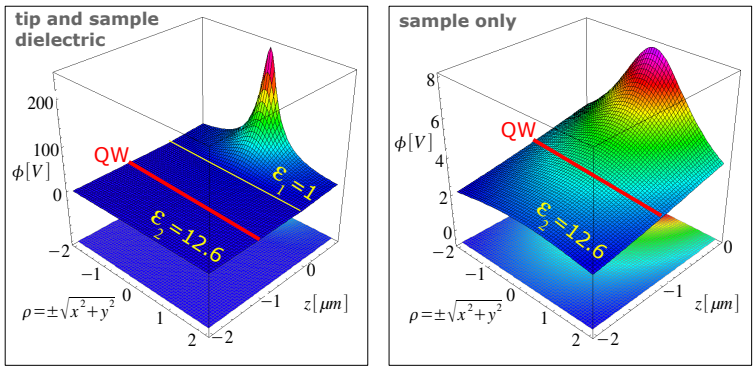

Fig. 1 (Color online) The electrostatic potential ϕ induced by a single tip electrode. Left: Due to screening the potential gradient, e.g. field strengths, in the tip dielectric region is much higher than in the QW, therefore high fields are needed. Right: Potential only in the sample region. Due to symmetry on the $\rho = 0$ axis the radial field component E_r vanishes.

2 Electrostatic trap potential We examined various electrode geometries to find one that complies with following requirements: (a) sufficient separation of the carriers, (b) creation of a *harmonic* lateral QW confinement due to the QCSE (analogous to the traps for atomic condensates), (c) minimization of the radial field component which destabilises the excitons and diminishes their lifetime. Two oppositely charged point-like electrodes, equidistant vertically placed from the sample top and bottom, respectively, could eliminate the radial field in a symmetric positioned QW plane and perfectly satisfy all aforementioned criteria. Unfortunately, this electrode geometry cannot be realized due to high experimental demands. Instead, a fine tip electrode placed above the sample creates a comparable field configuration with the restriction that the radial field, which is zero below the tip electrode, increases linearly with the in-plane distance form the trap center [7], see Fig. 2a. The trap center is below the tip; there the field component $|E_z|$ is maximal and the effective exciton energy is minimal. With increasing distance ρ from the center $|E_z|$ decreases giving rise to a force on the excitons directed towards the center (QCSE, Fig 2b). By changing the tip to sample distance the potential curvature, i.e. the trap frequency, is tuneable in the range of a few to several hundred GHz, Fig. 2a. This allows one to change the exciton density over several orders of magnitude.

The electrostatic potential of the fine tip can be treated as the one of a point charge in front of a planar dielectric ε_2. This is true, if the radius of tip curvature R_{tip} is much smaller than the tip to sample distance z_{tip}. As the problem is symmetric around the tip axis z, i.e. $\phi(\rho, \varphi, z) = \phi(\rho, z)$, in cylindrical coordinates the potential solving Poisson's equation $\nabla^2\phi = -\varrho/\varepsilon_0$ for $z > 0$ and $\nabla^2\phi = 0$ for $z < 0$ can be written as

$$\phi = \begin{cases} \frac{q}{4\pi\varepsilon_0}\left(\frac{1}{r_1} + \frac{\varepsilon_1-\varepsilon_2}{\varepsilon_1+\varepsilon_2}\frac{1}{r_2}\right), & z > 0 \\ \frac{q}{4\pi\varepsilon_0}\frac{2}{\varepsilon_1+\varepsilon_2}\frac{1}{r_1}, & z < 0 \end{cases} \tag{1}$$

with the substitutions $r_1^2 = \rho^2 + (z - z_{tip})^2$ and $r_2^2 = \rho^2 + (z + z_{tip})^2$, where $\rho^2 = x^2 + y^2$ is the radial and z the vertical coordinate, see Fig. 1. The given potential satisfies the Dirichlet boundary condition $\phi(r \to \infty) = 0$ as well as the continuity condition at the boundary layer $z = 0$ for the electrical potential, $\phi_{z>0}(z = 0) \equiv \phi_{z<0}(z = 0)$, and the normal component of the electric displacement field

$$\left.\frac{\partial\phi_{z>0}}{\partial z}\right|_{z=0} \equiv \frac{\varepsilon_2}{\varepsilon_1}\left.\frac{\partial\phi_{z<0}}{\partial z}\right|_{z=0}. \tag{2}$$

The z-field discontinuity at the boundary layer given by eq. (2) implies, that an experimental realisation for z-fields in the QW plane stronger than approximately 2-3kV/cm has to be done under vacuum conditions due to dielectric breakdown in air at 30kV/cm field strength and a static dielectric constant ε_2 of the semiconducting sample with a typical value around 10. An advantage of this non-lithographically defined electrode design is a good experimental accessibility of the excitonic photoluminescence.

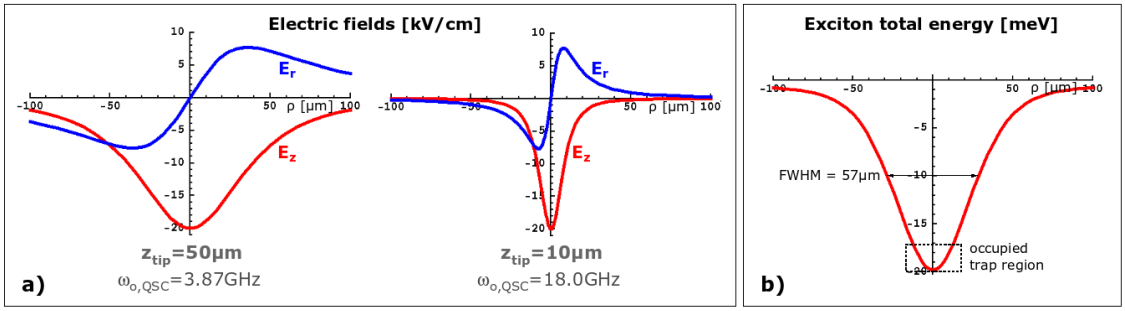

Fig. 2 a) Dependence of the z-field E_z and radial field E_r component on the tip to sample distance z_{tip}; the voltage is tuned to a constant field in the trap center $E_z(\rho = 0) = 20kV/cm$. Also given is the corresponding trap frequency $\omega_{0,QSC}$ of the quantum Stark confinement. b) The (parabolic) lateral exciton confinement in the QW is obtained from the exciton total energy change (Stark shift, see Fig. 3) with respect to the laterally varying z-component of the field ($L_{QW} = 30nm$, $z_{tip} = 50\mu m$). Changing z_{tip} the potential geometry and hence the trap size and exciton density become tuneable.

3 Exciton properties in the confinement field In the following we will discuss the indirect exciton properties for two different QW heterostructure materials GaAs/AlGaAs and ZnSe/ZnSSe.[8] Using Path Integral Monte Carlo we compute from first principles the electron-hole separation as well as the excition total energy as a function of the applied field strength, Fig. 3. The used simulation technique is described in Ref. [9]. The fundamental Hamiltonian reads

$$\hat{H} = \hat{H}_e + \hat{H}_h + \sum_{i=1}^{N}\sum_{j=i+1}^{N} \frac{e_i e_j}{\varepsilon|\mathbf{r}_i - \mathbf{r}_j|}, \quad \hat{H}_{e(h)} = \sum_{i=1}^{N_{e(h)}} \left(-\frac{\hbar^2}{2m^*_{e(h)}} \nabla^2_{\mathbf{r}_i} + V^{ext}_{e(h)}(z_i) \right) \tag{3}$$

where $N = N_e + N_h$ is the number of electrons and holes and $V^{ext}(z)$ is the external potential which combines the effect of the quantum confinement of the quantum well (presented as a square well) and the applied electric z-field

$$V^{ext}_i(z) = \begin{cases} e_i E_z z, & |z| \le L/2 \\ V^0_i + e_i E_z z, & |z| > L/2 \end{cases} \tag{4}$$

Using the Hamiltonian (3) we calculated the electron and hole density distribution at different field strengths.

Due to the higher electron and hole masses in ZnSe [10], the electron and also the hole localization in ZnSe is stronger than in the GaAs-based QW. Hence in ZnSe the electron-hole as well as the electron-electron wave function overlap is significantly reduced. While the former leads to a reduced spontaneous recombination (enhanced exciton life time) and the latter reduces particle exchange. At the same time the exciton binding energy in ZnSe ($E_B = 27meV$) is much higher than in GaAs ($E_B = 5.7meV$) allowing for a larger electron-hole separation, at a given temperature. This permits us to consider a wide ZnSe/ZnSSe *single* quantum well, where the electron hole separation is tuned by the electric field strength. The reduced number of QW boundaries, compared to a double QW, reduces the effect of unfavorable quantum well thickness fluctuations.

As shown in Fig. 3b) tuning the field strength in the QW, which is proportional to the tip voltage, the dipole moment (and thus the strength of exciton-exciton repulsion and also the exciton lifetime, which is inversely proportional to the electron hole wave function overlap), can be tuned. As the figure shows, due to the strong binding energy in ZnSe, a field of approximately 10kV/cm is needed to separate the charge carriers. Furthermore, a wide quantum well and a large dipole moment $\mu(\rho) = e_0 z^{eff}(\rho)$, which itself depends on the exciton trap position, is advantageous as the gradient of the band gap, i.e. the confinement

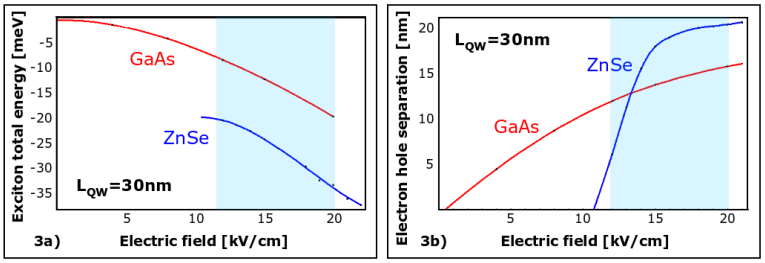

Fig. 3 a) Quadratic and linear Stark effect: exciton total energy decreases with increase of the electric field strength $|E_z|$. b) Effective electron hole separation z^{eff} depending on E_z. Dipole moment and Stark shift are controllable by changing the field strength.

strength is, at high fields, proportional to the dipole moment: $\Delta E = E_z(\rho)\mu(\rho)$ (linear Stark effect). Due to the higher localization of electrons and holes, in ZnSe the dipole moment reaches higher values than in GaAs and saturates at lower field strength, see Fig. 3b). Further increase of the z-field strength has to be avoided since it will cause tunnel ionization out of the QW plane.

Performing thermodynamic Monte Carlo simulations of several tens to thousands of indirect excitons in a GaAs-based QW, we have shown [9] that in a very shallow parabolic lateral confinement ($\omega_{0,QSC} = 3.8$ GHz) corresponding to low densities ($r_s \gg 1$), in the case of a large particle number and low temperature, strong exciton-exciton coupling ($\Gamma \equiv U_{xx}/k_BT \approx 100$) can be reached. The present trap configuration together with the use of ZnSe instead of GaAs, should allow for a further improved localization of the exciton wave functions and make exciton crystallization experimentally accessible.

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[7] A further reduction of the in-plane field component can be attained with a conducting layer close to the QW as discussed in [5, 6].
[8] Due to the smaller dielectric constant, $\varepsilon_{2,ZnSe} = 8.7 < \varepsilon_{2,GaAs} = 12.6$, in the case of ZnSe a smaller external field is sufficient.
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[10] We use $m_{e,ZnSe} = 0.15m_0$, $m_{e,GaAs} = 0.067m_0$, $m^z_{hh,ZnSe} = 0.86m_0$, $m^{xy}_{hh,ZnSe} = 0.37m_0$, $m_{h,GaAs} = 0.34m_0$, where m_0 is the free electron mass.