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Considerations on equilibration of two-dimensional excitons in coupled quantum well structures

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Abstract

In this paper we discuss the issues of the equilibration dynamics of spatially indirect two-dimensional excitons in a coupled quantum well structure, in particular those trapped by an in-plane harmonic potential trap. We discuss the relative timescales for several processes. In the experiments with an in-plane trap, we can use the size of the exciton cloud as a measure of the temperature of particles. At low lattice temperatures the exciton temperature is higher than that of the lattice, even long after equilibrium has obviously been reached. We discuss the effects that can be responsible for this.

(Some figures in this article are in colour only in the electronic version)

The ensemble of spatially indirect excitons in double quantum wells has been predicted to be a viable candidate for Bose–Einstein condensation[4]. The underlying reason for this expectation is that due to the separation of the electron and hole, these excitons have long lifetime (in excess of 20 μs [2]), which is pivotal for successful thermalization of the particles, while the repulsive interaction between the particles stabilizes the gas against the collapse of the condensate [3].

While the concept of making bosonic particles condense is simple (in principle, one only has to cool them to a low enough temperature), there are specific and nontrivial milestones to pass, especially in the case of quasiparticles like excitons in quantum wells. First of all, it must be demonstrated that the particles can move freely and are not localized. At very low temperatures, it may be the case that the excitons all become localized in potential minima created by disorder and do not behave as a gas at all. Second, the particle lifetime must be long compared to the equilibration time. As mentioned above, the lifetime of the excitons in our traps is 20 μs or greater, but it must be shown that the equilibration time is shorter than this.

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[4] For a recent review of theory and experiments on Bose condensation of excitons, see [1].

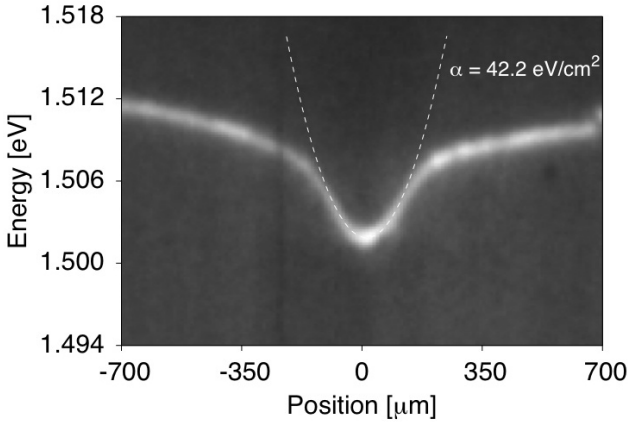

Figure 1. The potential profile, obtained by illuminating the entire area with a defocused, very low intensity laser. The light emitted by the excitons gives the energy of the excitons at each point. Dashed line: best fit of the function $U = \frac{1}{2}\alpha r^2$ to the intensity maximum of the luminescence at each point.

Third, a suitable macroscopic trapping potential must be created. In 2D, this step is crucial, because a condensate cannot exist in a translationally invariant 2D system. Fourth, it must be shown that the particles can sample this potential during their lifetime, in other words, they can reach equilibrium not only locally, but globally through drift and diffusion to a spatial equilibrium. If all these criteria are met, then at low enough temperatures the Bose–Einstein condensation phase transition can be expected.

Recent work [2, 4] has shown that many of these criteria appear to be met. The spatially indirect excitons created in a GaAs/AlGaAs double quantum well structure live for tens of μs and diffuse hundreds of microns. An in-plane harmonic potential can be produced by inhomogeneous external stress [4], as shown in figure 1. In those experiments, the excitons equilibrated in the trap to a constant cloud size, indicative of a constant temperature. Questions remain, however, whether the exciton temperature can be reduced low enough for the gas to condense.

Our stress trapping method has the advantage that it does not modify the lifetime of the particles. By contrast, in electrostatic traps [5–7], the lifetime varies from place to place in the trap. Because the lifetime of the excitons is constant in our traps, we can take the luminescence intensity profile as directly proportional to the exciton density profile. The inset of figure 2 shows a typical spatial profile of the luminescence from the excitons in a trap, and the width of the spatial profile as a function of time following creation of the excitons at the centre of the trap with a laser pulse, when the exciton density is very low ($\sim 10^9$ cm^{-2}). If the exciton density is low enough, such that interactions between the excitons can be ignored and particle statistics are in the classical limit, the spatial density profile of the excitons in equilibrium is given by the Boltzmann occupation factor,

$$n(r) \propto \exp\left(-\frac{1}{2}\frac{\alpha r^2}{k_{\mathrm{B}} T_{\mathrm{eff}}}\right) \equiv \exp\left(-\frac{r^2}{2\sigma^2}\right), \tag{1}$$

where α is the spring constant of the trapping potential, k_{B} is the Boltzmann constant, and T_{eff} is the effective temperature of the excitons. In other words, the spatial profile of the cloud is a Gaussian with a variance σ proportional to the square root of the temperature. Therefore the cloud size becomes a direct measure of the temperature when the excitons have reached

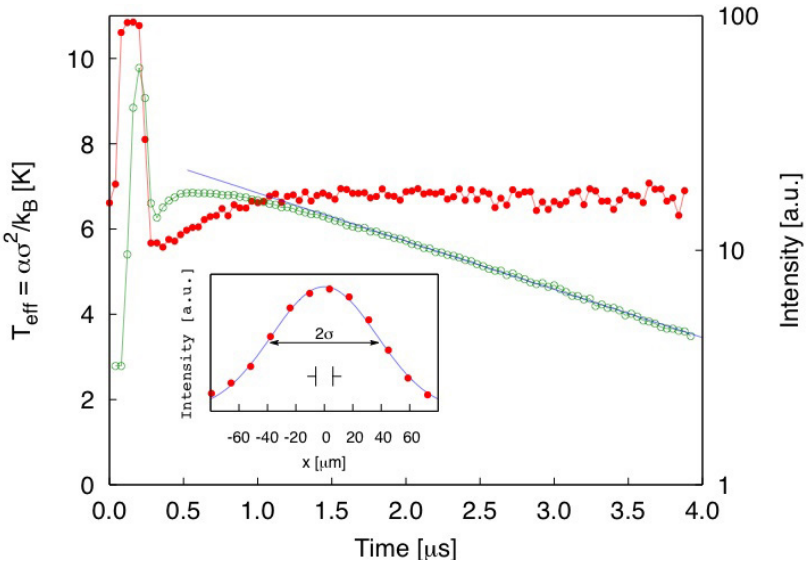

Figure 2. Closed circles: size of the exciton cloud in the trap as a function of time, from Gaussian fits to the spatial profile at all times, given as an effective temperature. Open circles: total luminescence intensity for the same data, integrated spatially and spectrally (right axis). Solid line: a straight-line fit to the late time–intensity data. The temperature of the lattice was 1.6 K, while the excitation power was ≈15 μW. Inset: a typical intensity profile at late time, with a Gaussian fit. Also given is the instrumental resolution.

equilibrium. The size of the cloud is plotted in terms of this effective temperature in figure 2. As seen in this plot, at late times both the cloud size and the lifetime of the excitons reach a constant, indicating that the temperature of the excitons is not changing.

The quantum well samples in these experiments were immersed in a liquid helium bath. When the bath temperature was 5 K or higher, and the density was very low, the exciton spatial profile in the trap implied an effective exciton temperature equal to the bath temperature. When the bath temperature was below 5 K, however, the excitons had a constant spatial profile of the same shape, but with an effective temperature that remained around 5 K, as shown in figure 3. Many readers familiar with the literature on hot carrier cooling in semiconductors will not be surprised by an effective carrier temperature which is different from that of the lattice. In this case, however, it is surprising. In typical semiconductor carrier equilibration experiments, the lifetime of the carriers is picoseconds to nanoseconds. In these experiments, the lifetime of the excitons is much longer than the natural timescales for cooling, as we will show below.

We emphasize that this experiment is one of the first to *directly* measure the exciton temperature. Several recent papers which have attempted trapping of excitons in 2D structures [8, 9] have made the assumption that the excitons reach the lattice temperature, but have no direct measure of the temperature of the excitons.

There are several timescales for the equilibration of the exciton gas. First, the absorbed laser light heats the sample, and the sample takes some time to cool down. A simple back-of-the-envelope calculation indicates that this timescale is around 10 ns. Knowing the heat capacity of GaAs, the laser light absorption length of approximately 1 μm, and the excitation area of (30 μm)^2, for 0.1 mW average laser power, one can easily estimate the maximum temperature as 9 K. Solution of the diffusion equation for the excess heat to diffuse away from the 1 μm region of absorption, given the thermal diffusion constant of the order of 1000 cm^2 s^{-1}

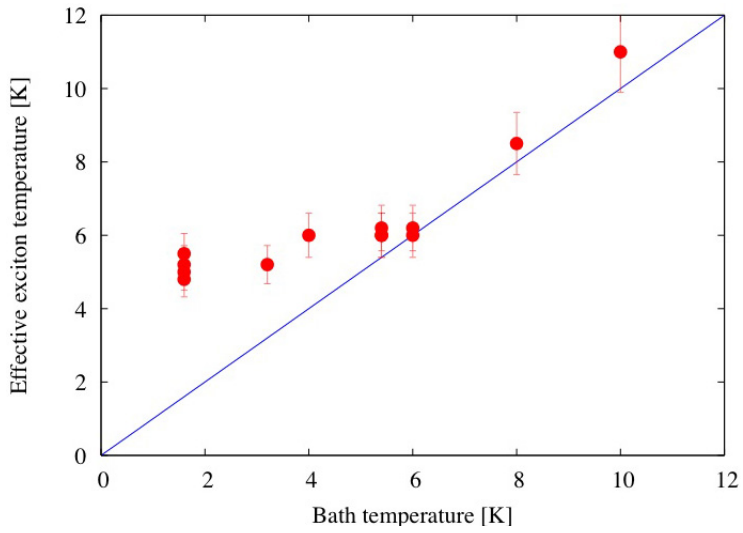

Figure 3. Measured effective temperature as a function of bath temperature. The solid straight line is the bath temperature. The errors are estimated from the uncertainty in determining the spring constant of the trapping potential. The instrumental resolution given in the inset of figure 2 was deconvolved assuming simple quadrature.

at these temperatures in GaAs [10], then gives the lattice cooling time of 10 ns. Even if we take into account that at the He–GaAs interface only longitudinal phonons can propagate into the liquid, this could not cause more than a threefold increase in the cool-down time.

Second, the excitons must cool down to the lattice temperature (which we can assume to be at the bath temperature after the first 10 ns). Figure 4 shows a simulation of the exciton temperature for a model of phonon emission similar to that of references [11] and [12]. As seen in this figure, the time to reach just a few per cent higher than the lattice temperature is just a few nanoseconds. To reach temperatures below 1 K can take much longer, hundreds of nanoseconds [12], but still less than our many-microsecond lifetimes. These simulations are in agreement with the experimental result, shown in figure 2, that the lifetime of the excitons does not change after the first 500 ns or so.

Third, the excitons must equilibrate spatially by drift and diffusion in the trap. The exciton diffusion constant has been measured [2] at low density for the same quantum well width and the same temperature. We can get an estimate of the equilibration time by solving the diffusion equation for a non-interacting gas with an initially Gaussian distribution placed under the constraint of a cylindrically symmetric harmonic potential. The drifted diffusion equation is

$$\frac{\partial n}{\partial t} = \nabla \cdot (D\vec{\nabla} n) + \frac{\tau_0}{m_x} \nabla \cdot (\alpha \vec{r} n), \tag{2}$$

where D is the diffusion constant, m_x is the exciton mass, and τ_0 is the average scattering time, in the relaxation time approximation. For the initial condition $n(r) = n_0 \exp(-r^2/2\sigma_i^2)$, this can be solved analytically, yielding a solution of the form

$$n(r) = n_0 \frac{\exp\left(-\frac{r^2}{2(\sigma_f^2 - (\sigma_f^2 - \sigma_i^2)\exp(-2t\alpha\tau_0/m_x))}\right)}{2\pi(\sigma_f^2 - (\sigma_f^2 - \sigma_i^2)\exp(-2t\alpha\tau_0/m_x))}, \tag{3}$$

where σ_f is the equilibrium variance of the cloud size. Hence, the characteristic time for the

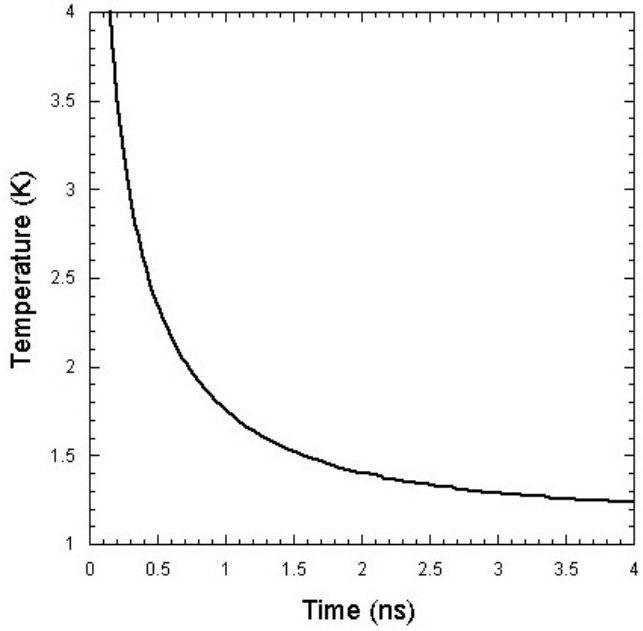

Figure 4. Temperature of an exciton gas in GaAs quantum wells as a function of time, for initial temperature $T = 10$ K and lattice temperature 1.2 K, as calculated using a Boltzmann equation model of phonon emission.

equilibration is

$$\tau = \frac{m_x}{2\alpha\tau_0} = \frac{k_B T}{2\alpha D}. \tag{4}$$

Substituting $\alpha = 40$ eV cm^{-2}, $D = 0.74$ cm^2 s^{-1} (from [2]), $m_x = 0.3m_e$, and $T = 1.6$ K yields $\tau \approx 1.5$ μs, consistent with figure 2.

The natural timescales of the system all indicate that the gas of excitons should be in equilibrium at the bath temperature. We therefore must consider the possibility of a heat source. There are two possible sources. First, we must consider the possibility that leakage light from the laser heats the exciton ensemble. Although the excitons are created by a pulsed laser, a continuous wave (cw) component, even if it is small, acts as a continuous source of excitons with excess energy ∼40 meV, since the laser creates direct, single-quantum-well, excitons which must convert down into spatially indirect excitons in the double quantum well structure. In order to ascertain whether this is the case, we sent the laser light through an acousto-optic modulator (AOM) and repeated the measurements with different duty cycles, to allow different amounts of the cw light between the laser pulses to pass through to the sample. If leakage light between the pulses were responsible for the heating, then the two duty cycles would give different time evolutions of the cloud size. As figure 5 shows, there is no discernible difference between the two cases.

Another possibility is that current through the sample heats the excitons. The current density through the sample was in the order of 1 μA cm^{-2}. While this value seems to be rather low, we have to keep in mind that an electron that tunnels into the quantum wells comes with an excess energy of about 300–400 meV, as illustrated in figure 6. If these hot electrons can spend enough time in the quantum wells, then we cannot rule out the possibility that this leads to elevated temperatures. If we imagine a small population of hot carriers $n_{\rm hot}$ added to a cold

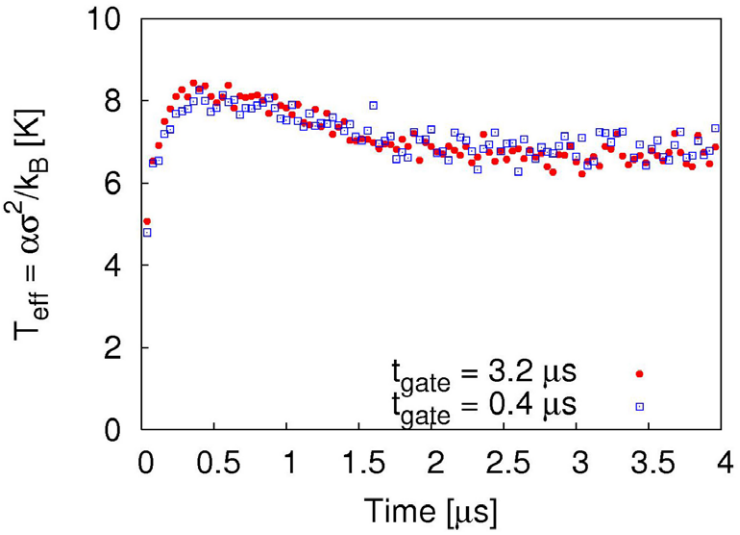

Figure 5. Time evolution of the cloud size expressed as the effective temperature for two different duty cycles of the AOM cell. Full (red) circles: 10%, open (blue) squares: 80%.

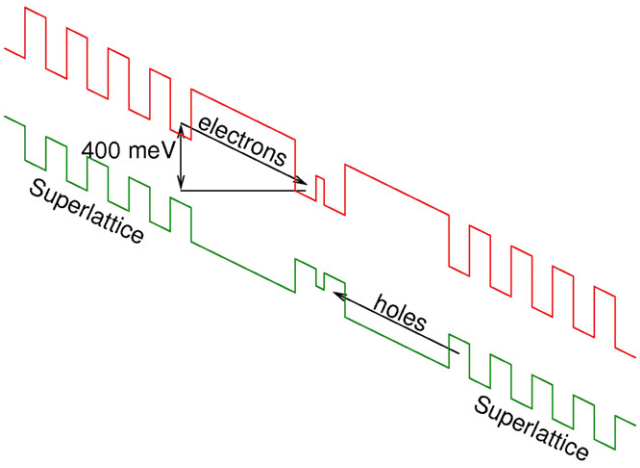

Figure 6. The band structure of the quantum well structure with superlattice barriers. An electron tunnelling through the 500 Å barrier separating the superlattices from the quantum wells can have energy up to 400 meV with respect to the ground state of a quantum well exciton.

population of thermalized excitons n_{cold}, the new effective temperature will be approximately $(T_{\mathrm{hot}}n_{\mathrm{hot}} + T_{\mathrm{cold}}n_{\mathrm{cold}})/(n_{\mathrm{hot}} + n_{\mathrm{cold}})$. In the low density case of figure 3, we estimate that the cold exciton densities are a few times 10^9 cm^{-2}. If the tunnelling current remains hot for 1 ns, then a current of 1 μA cm^{-2} corresponds to a density in the quantum wells of about 10^4 cm^{-2}. For 400 meV excess energy per carrier, this is marginally enough to raise the cold exciton temperature by a few tenths of a degree. This is a very approximate estimate, however, and therefore we cannot rule out that current plays a role in heating the exciton gas. We note that if current does play a role in heating the excitons, its effect will be much less at higher excitation densities, since the tunnelling current is roughly constant, and therefore the ratio of these hot

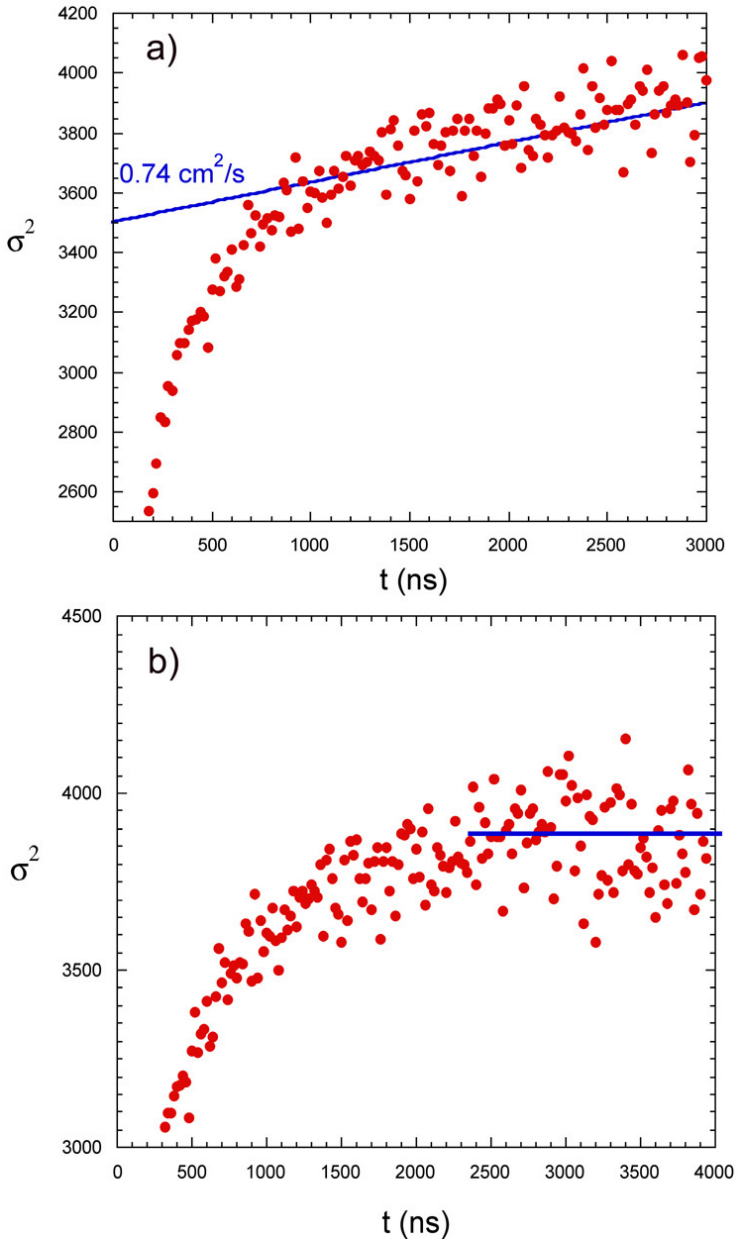

Figure 7. (a) Variance of the spatial distribution of the exciton cloud as a function of time in the case when there is no trap, for $T = 1.8$ K. The straight line is a fit to the prediction of the diffusion equation, $\sigma^2 \propto D$. (b) The same data at late times. After 3 μs there is evidence that the diffusion constant drops. The solid line is has zero slope.

carriers to the total population will decrease and become negligible when the generated exciton density is higher, in the range 10^{10} cm^{-2}.

Finally, one other possibility is that the diffusion constant drops at low density. In the above discussion, we assumed that the excitons diffuse with $D = 0.74$ cm$^2/2$ at low densities and

late times. This is based on measurements of the exciton diffusion constant [2] under identical conditions but without a trap, as shown in figure 7(a). The exciton motion has an initial fast expansion due to exciton–exciton repulsion, and then remains diffusive up to 3 μs after the laser pulse. At very late times, however, the diffusion of the excitons appears to slow. It is possible that excitons at very low density become trapped in local minima and cannot diffuse. In this case, when the excitons are in the trap, the cloud of excitons may fail to contract in size because the excitons simply have too low density to move. As with the possibility of a small tunnelling current, discussed above, this effect will become less important at higher exciton density.

These results give a consistent picture of a well-thermalized exciton gas in the trap with a well-defined density. The exciton temperature as deduced from the cloud size does not always reach the helium bath temperature, which is surprising, since the timescales for equilibration are all shorter than the lifetime of the excitons, and the heating sources in the experiment are very small. No fundamental barriers to Bose–Einstein condensation of excitons in these traps have appeared, but the indications are that going to very low exciton density and very low temperature is not a good direction to search, since the excitons may become localized at low density and also may be heated by the tiny tunnelling current. Going to higher exciton density remains promising, but requires more understanding of the renormalization of the exciton states at high density, which leads to blue shift and broadening of the exciton luminescence.

Acknowledgments

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