

Condensation of Excitons in a Trap

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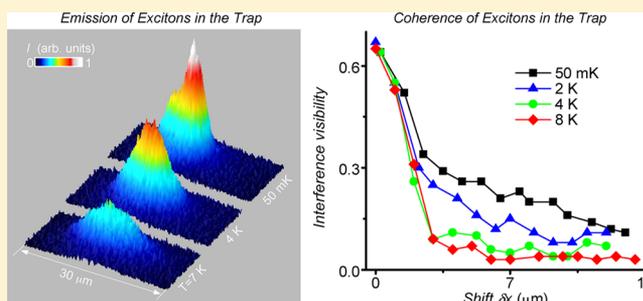
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S Supporting Information

ABSTRACT: Condensation is observed in a gas of indirect excitons confined in an electrostatic trap. Imaging and interferometric measurements detect that excitons condense at the trap bottom and exciton spontaneous coherence emerges with lowering temperature. Below a temperature of about 1 K, the direct signature of Bose–Einstein condensation, the extension of coherence over the entire cloud, is observed.

KEYWORDS: Excitons, traps, coherence, condensation



The confinement of atomic vapors in traps has led to the realization of Bose–Einstein condensation of atoms.^{1–3} Condensation is equivalent to the emergence of spontaneous coherence of matter waves.⁴ The detection of spontaneous coherence is a direct experimental measurement of condensation. Here, we report on the observation of condensation and spontaneous coherence in a gas of indirect excitons confined in an electrostatic trap. An exciton is a bound pair of an electron and a hole in a semiconductor. The bosonic nature of excitons allows for their condensation at low temperatures.⁵

Because of recombination excitons have a finite lifetime that is too short to allow cooling to low temperatures in regular semiconductors.^{6,7} In order to create a cold exciton gas, the exciton lifetime should be large compared to the exciton cooling time so excitons can cool down to the temperature of the crystal lattice. Furthermore, the realization of a cold and dense exciton gas requires an excitonic state to be the ground state.⁸

These requirements can be fulfilled in a gas of indirect excitons. An indirect exciton is a bound state of an electron and a hole in separate layers (Figure 1a). The spatial separation allows one to control the overlap of electron and hole wave functions and engineer structures with lifetimes of indirect excitons orders of magnitude longer than those of regular excitons.^{9,10} In our experiments, indirect excitons are created in a GaAs/AlGaAs coupled quantum well structure (CQW). Long lifetimes of the indirect excitons allow them to cool to low temperatures within about 0.1 K of the lattice temperature, which can be lowered to about 50 mK in an optical dilution refrigerator.¹¹ This allows the realization of a cold exciton gas with temperature well below the temperature of quantum degeneracy $T_{dB} = 2\pi\hbar^2 n/m$ (for the studied CQW with the exciton mass $m = 0.22m_0$, $T_{dB} \approx 3$ K for the density per spin state $n = 10^{10} \text{ cm}^{-2}$).

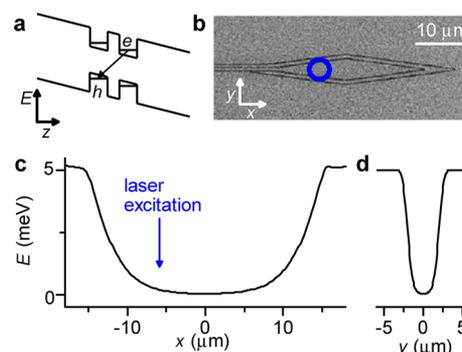


Figure 1. (a) Energy-band diagram of the CQW structure. e, electron; h, hole. (b) SEM image of electrodes forming the diamond trap: a diamond-shaped electrode is surrounded by a thin wire electrode followed by an outer plane electrode. (c,d) Simulation of exciton energy profile through the trap center along x (c) and y (d) for $V_{\text{diamond}} = -2.5$ V, $V_{\text{wire}} = -2$ V, and $V_{\text{plane}} = -2$ V. The position of the laser excitation spot is indicated by the circle in (b) and by the arrow in (c).

Indirect excitons have a built-in dipole moment ed , where d is close to the distance between the QW centers. This allows control of the exciton energy by applied gate voltage; an electric field F_z perpendicular to the QW plane results in the exciton energy shift $E = edF_z$ giving an opportunity to create in-plane potential landscapes for excitons $E(x,y) = edF_z(x,y)$. Advantages of electrostatically created potential landscapes include the opportunity to realize a desired potential profile and control it in situ on a time scale shorter than the exciton lifetime. Excitons

Received: March 10, 2012

Revised: April 9, 2012

Published: April 17, 2012

were studied in various electrostatically created potential landscapes including ramps,^{12,13} lattices,^{14,15} circuit devices,¹⁶ and traps.^{17–23}

Along with electrostatic traps excitons were studied in a variety of traps including strain-induced traps,^{24–27} traps created by laser-induced interdiffusion,²⁸ magnetic traps,²⁹ and laser-induced traps.^{30,31} However, despite intensive studies, no emergence of spontaneous coherence of excitons in a trap was observed until present. Spontaneous coherence of excitons was probed in a ring-shaped trap,²⁰ however, no enhancement of the interference contrast, and, in turn, the degree of first-order coherence with lowering temperature was shown. Spontaneous coherence of excitons was also probed in a different system, an exciton ring.^{32,33} The ring forms on the interface between the electron-rich and hole-rich regions and lacks the crucial advantage of traps which is the opportunity to control the condensates.

Here, we realize an electrostatic trap for indirect excitons using a diamond-shaped electrode (Figure 1b). Because a thinner electrode produces a smaller F_z due to field divergence near the electrode edges, the diamond trap creates a confining potential with the exciton energy gradually reducing toward the trap center (Figure 1c,d).²² Details are presented in Supporting Information.

The excitons are photoexcited by a 633 nm HeNe laser. The excitation beam is focused to a spot about $5\ \mu\text{m}$ in diameter on a side of the trap (Figure 1b,c). This excitation scheme allows further cooling of the photoexcited excitons when they travel toward the trap center, thus facilitating the realization of a cold exciton gas in the trap (cooling of excitons away from the laser excitation spot also leads to the realization of a cold exciton gas in the inner ring in exciton emission pattern and in laser-induced traps³⁰).

The first-order coherence function $g_1(\delta x)$ is measured by shift-interferometry: the emission images produced by arm 1 and 2 of the Mach–Zehnder interferometer (Figure 2a) are

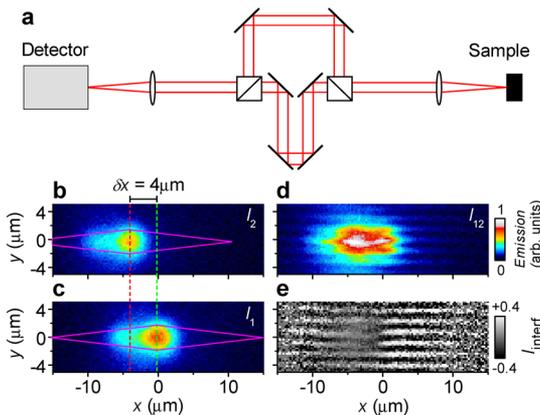


Figure 2. (a) Schematic of the interferometric setup. (b–d) Emission image of indirect excitons measured with arm 2 open (b), arm 1 open (c), and both arms open (d). $T_{\text{bath}} = 0.1\ \text{K}$, $P_{\text{ex}} = 1.9\ \mu\text{W}$. (e) I_{interf} obtained from (b–d).

shifted with respect to each other to measure the interference between the emission of indirect excitons spatially separated by δx . We measure emission intensity I_1 for arm 1 open, I_2 for arm 2 open, and I_{12} for both arms open, and calculate $I_{\text{interf}} = [I_{12} - I_1 - I_2] / [2(I_1 I_2)^{1/2}]$ (Figure 2b–e). $g_1(\delta x)$ is given by the

amplitude of the interference fringes in I_{interf} see Supporting Information for details.

Figure 3 presents the temperature dependence of exciton emission and interference patterns. At high temperatures, the exciton cloud spreads over the trap resulting in a broad spatial profile of the exciton emission. With lowering temperature, excitons collect at the trap center (Figure 3a,b,c,e). Studies of atoms in traps also show the collection of atoms at the trap center with lowering temperature due to the reduction of the thermal spreading of atoms over the trap and, eventually, condensation of atoms.^{1–3}

To determine if condensation of excitons is realized in the trap, we performed shift-interferometry measurements. We found that the exciton collection at the trap center with lowering temperature is accompanied by a strong enhancement of the amplitude of the interference fringes A_{interf} for the interference between the emission of indirect excitons spatially separated by δx (Figure 3d,e). Quantitative characteristics of spontaneous coherence and condensation can be obtained from the measurements of A_{interf} as a function of δx .⁴ Such measurements are presented below.

Figure 4a presents $A_{\text{interf}}(\delta x)$ for different densities. The exciton temperature is higher in the excitation spot.³⁰ This is consistent with low values of A_{interf} at negative δx , which correspond to the interference between the emission of a hot exciton gas in the excitation spot and exciton gas in the trap center. We consider positive δx , which correspond to the interference between the emission of an exciton gas in the trap center and exciton gas at positive x further away from the hot excitation spot.

Figure 4c presents the density dependence of the width of the exciton emission pattern along x . At high temperature $T_{\text{bath}} = 4.5\ \text{K}$, the width of the emission pattern of the exciton cloud monotonically increases with density. This is consistent with screening of the potential landscape in the trap by indirect excitons due to the repulsive exciton–exciton interaction.²² However, a drastically different behavior is observed at low temperature $T_{\text{bath}} = 50\ \text{mK}$: the increase of density leads to the reduction of the cloud width, indicating the exciton collection at the trap center. Only at the highest densities, the high-temperature behavior is recovered.

Figure 4b presents the density dependence of A_{interf} . At high temperature $T_{\text{bath}} = 4.5\ \text{K}$, the coherence degree is low for all densities. However, at low temperature $T_{\text{bath}} = 50\ \text{mK}$, the increase of density leads to a strong enhancement of A_{interf} followed by its reduction. As in the case of varying temperature (Figure 3e), with varying density, the exciton collection at the trap center is accompanied by the enhancement of the coherence degree of excitons (Figure 4b,c).

The density at which the coherence degree of excitons is close to maximum (Figure 4b) has been chosen to study the temperature dependence due to the strongest coherence enhancement with reducing temperature. Figure 5a presents the amplitude of the interference fringes $A_{\text{interf}}(\delta x)$ for different temperatures. The spatial extension of $A_{\text{interf}}(\delta x)$ can be characterized by a coherence length ξ at which the interference visibility drops e times. A strong enhancement of the exciton coherence length is observed at low temperatures (Figure 5c). While at high temperatures ξ is considerably smaller than the exciton cloud width, at low temperatures the entire exciton cloud becomes coherent (Figures 3e, 5).

The data are discussed below. In the reported experiments, the laser excitation energy exceeds the exciton energy by about

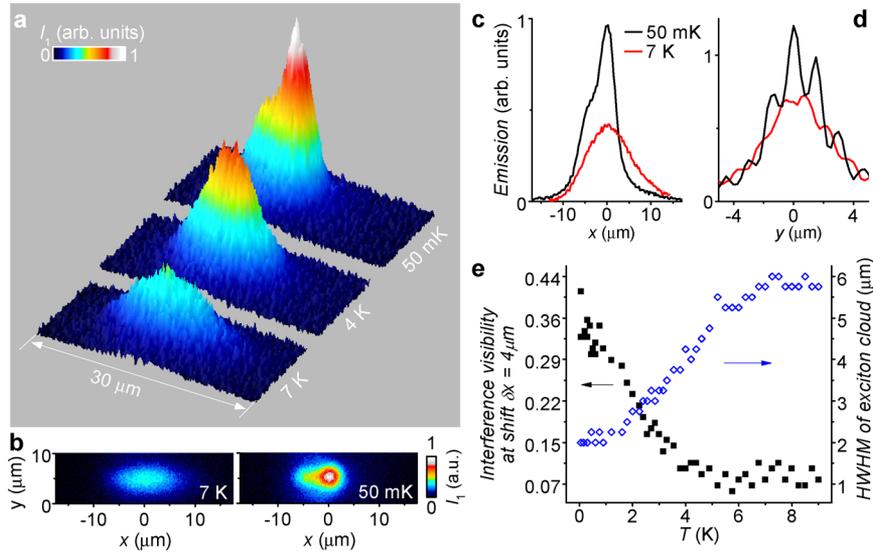


Figure 3. (a,b) Emission patterns I_1 for temperatures $T_{\text{bath}} = 7, 4,$ and 0.05 K. (c,d) Spatial profiles of the emission patterns (c) and interference patterns I_{12} at shift $\delta x = 4 \mu\text{m}$ (d) for $T_{\text{bath}} = 7$ K (red) and 0.05 K (black). (e) Amplitude of the interference fringes A_{interf} at shift $\delta x = 4 \mu\text{m}$ averaged over $0 < x < 1.5 \mu\text{m}$ (black squares) and half-width at half-maximum (hwhm) of the exciton emission pattern along x (blue diamonds) vs temperature. $P_{\text{ex}} = 1.9 \mu\text{W}$.

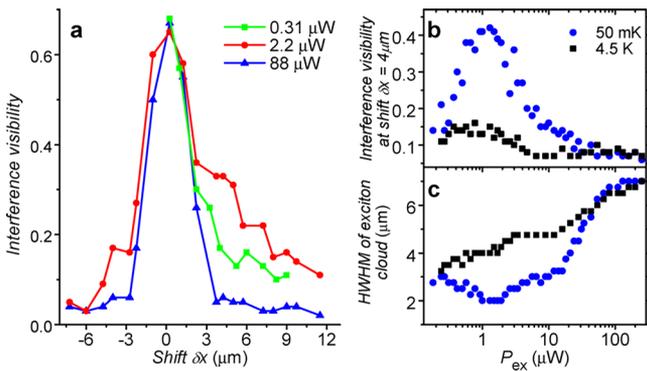


Figure 4. (a) Amplitude of the interference fringes $A_{\text{interf}}(\delta x)$ for excitons in the trap for excitation density $P_{\text{ex}} = 0.31 \mu\text{W}$ (green squares), $2.2 \mu\text{W}$ (red circles), and $88 \mu\text{W}$ (blue triangles) at $T_{\text{bath}} = 50$ mK. (b,c) A_{interf} at shift $\delta x = 4 \mu\text{m}$ averaged over $0 < x < 1.5 \mu\text{m}$ (b) and hwhm of the exciton emission pattern along x (c) vs P_{ex} for $T_{\text{bath}} = 50$ mK (blue circles) and 4.5 K (black squares).

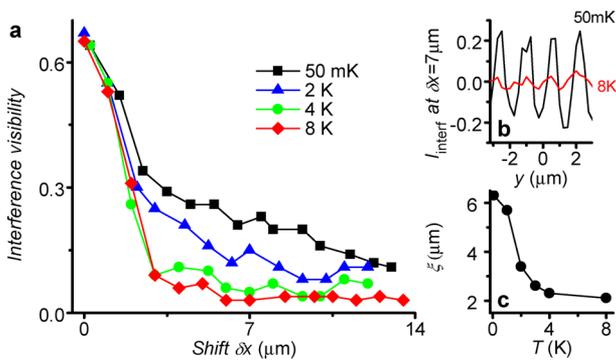


Figure 5. (a) $A_{\text{interf}}(\delta x)$ for excitons in the trap for $T_{\text{bath}} = 50$ mK (black squares), 2 K (blue triangles), 4 K (green circles), and 8 K (red diamonds). (b) I_{interf} for $T_{\text{bath}} = 50$ mK (black) and 8 K (red) at shift $\delta x = 7 \mu\text{m}$. (c) The exciton coherence length ξ as a function of temperature. $P_{\text{ex}} = 1.9 \mu\text{W}$.

400 meV and the laser excitation spot is spatially separated from the interfering excitons for positive δx . Therefore studied coherence in the exciton gas is spontaneous coherence; it is not induced by coherence of the laser excitation. (Note that for negative δx , the interfering excitons spatially overlap with the laser excitation spot and exciton coherence is suppressed (Figure 4a), confirming that exciton coherence is not induced by the laser excitation.)

The coherence of an exciton gas is imprinted on the coherence of emission, which is described by the first-order coherence function $g_1(\delta x)$. In turn, this function is given by the amplitude of the interference fringes $A_{\text{interf}}(\delta x)$ in “the ideal experiment” with perfect spatial resolution. In real experiments, the measured $A_{\text{interf}}(\delta x)$ is given by the convolution of $g_1(\delta x)$ with the point-spread function (PSF) of the optical system used in the experiment.³³ The PSF is determined by measuring the emission profile across a source of vanishing width, see Supporting Information. The PSF is a peak at $\delta x = 0$ of the width corresponding to the spatial resolution of the optical system. A peak in $A_{\text{interf}}(\delta x)$ at $\delta x = 0$ due to the PSF can be seen both at low and high temperatures.

Both for a classical gas and quantum gas $g_1(\delta x)$ is close to 1 at $\delta x = 0$ and drops with increasing δx within the coherence length ξ . The difference between the classical and quantum gas is in the value of ξ . For a classical gas, ξ_{cl} is close to the thermal de Broglie wavelength $\lambda_{\text{dB}} = (2\pi\hbar^2/mT)^{1/2}$, which is well below the PSF width in the studied temperature range ($\xi_{\text{cl}} < \xi_{\text{cl}@0.1\text{K}} \sim 0.5 \mu\text{m}$, the PSF width is $\sim 2 \mu\text{m}$). Therefore, for a classical gas at temperatures above 4 K, the measured ξ is given by the PSF width (Figure 5).

For a classical gas, the coherence length $\xi \propto T^{-1/2}$ gradually increases with reducing temperature and remains small $< 0.5 \mu\text{m}$ for $T > 0.1$ K, much smaller than the coherence length observed at the lowest temperatures (Figure 5). Therefore, an increase of the coherence length in a classical gas cannot lead to the increase in the contrast of the interference pattern at large δx observed in the experiment (Figure 5).

In contrast, for a condensate the coherence length becomes much larger than the thermal de Broglie wavelength and

reaches the size of the exciton cloud in the trap so the entire exciton cloud becomes coherent. This signature of Bose–Einstein condensation is observed at the lowest temperatures in the experiment (Figures 3e, 5). The measured transition temperature is ~ 2 K (Figure 5c). Estimates of the temperature of exciton BEC in the trap are close to 2 K, see Supporting Information.

Finally, Figure 5a also illustrates why $\delta x = 4 \mu\text{m}$ is selected for presenting coherence degree of excitons in Figures 3 and 4. The shift $\delta x = 4 \mu\text{m}$ exceeds both λ_{dB} and the PSF width. At such δx , only weak coherence given by the PSF value at $\delta x = 4 \mu\text{m}$ can be observed for a classical gas. Higher A_{interf} exceeding such background level reveal spontaneous coherence of excitons.

The realization of exciton condensate in a trap opens the opportunity to study the condensate properties. Traps allow precise control of condensates by in situ control of trap shape and depth that has been effectively used in studies of condensates of atoms. Similar control of condensates of excitons in condensed matter materials will allow studying condensates with parameters, such as mass, interaction, temperature, and characteristic times, orders of magnitude different from those in condensates of atoms. This will be the subject for future research.

■ ASSOCIATED CONTENT

■ Supporting Information

In Supporting Information we present the following: sample structure; details of shift-interferometry measurements and analysis; emission spectra and Fourier spectroscopy measurements; measurement of the point spread function; and estimates of the temperature of Bose–Einstein condensation of excitons in the trap. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank Michael Fogler for discussions. This work was supported by ARO Grant W911NF-08-1-0341 and NSF Grant 0907349. The development of spectroscopy in a dilution refrigerator was also supported by the DOE award DE-FG02-07ER46449.

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