Collective quantum states realized with semiconductor excitons have attracted a very large attention since seminal theoretical predictions were made in the 1960’s \[1\]-\[3\]. To demonstrate such phenomena numerous systems were probed, from bulk materials to low dimensional heterostructures \[4\], and promising realizations of excitons were then identified. These include notably para-excitons in cuprous oxide \[5–7\] but also spatially indirect excitons confined in bilayer heterostructures \[8–12\].

Spatially indirect excitons are created by imposing a spatial separation between the electrons and holes constituting excitons. This is achieved for instance by applying an electric field perpendicular to a single or a double quantum well. Thus, electrons and holes form two distant layers and have wave-functions which experience a small overlap. Indirect excitons thereby benefit from a lifetime that is long compared to the rapid thermalization to the lattice (bath) temperature in this two-dimensional geometry \[13\]. In addition, they exhibit a large and well-oriented electric dipole such that repulsive dipole interactions between excitons prevent the collapse into a plasma at large densities \[14\].

The unique physical properties of indirect excitons have allowed latest experiments to cool dense ensembles \((\sim 10^{10} \text{ cm}^{-2})\) to sub-Kelvin bath temperatures \[10\], \[12\], \[16\]. In this regime, theoretical studies indicate that the excitons quantum statistics shall be revealed \[15\] and for instance lead to the appearance of macroscopic spatial coherence \[17\]. Remarkably, such a spontaneous buildup of macroscopic coherence has been reported very recently by Butov and co-workers \[8\], \[10\], \[18\] who optically injected indirect excitons in a double quantum well heterostructure.

In this letter, we show that macroscopically coherent indirect excitons can also form in a wide single quantum well. Precisely, we report experiments where electron-hole pairs were optically injected and subsequently diffused to form indirect excitons spontaneously arranged along a ring-shaped pattern. Lowering the semiconductor bath temperature below a few Kelvin, we observed that the exciton ring contracted spatially and also underwent a fragmentation into microscopic beads. The emission spectrum indicates that the beads contain a large concentration of excitons at sub-Kelvin bath temperatures \((\sim 10^{10} \text{ cm}^{-2})\). Furthermore, interferometric measurements reveal that the fragmentation of the exciton ring coincides with a rapid increase of the emission’s spatial coherence. In the vicinity of the fragments, coherence extends over a micrometer at 350 mK.

In the following we report studies of a 1 \(\mu\)m thick field-effect device where a 250 \(\AA\) wide GaAs quantum well is embedded. The quantum well is surrounded by \(\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}\) barriers and placed 900 nm below a uniform semi-transparent gate electrode deposited on the surface of the sample. For our measurements this electrode was biased at a constant voltage \(V_g=-4.17\ \text{V}\) with respect to the conductive sample’s substrate that was grounded. Hence, minimum energy states for electrons and holes are displaced in opposite directions and the ground excitonic transition is then spatially indirect. We optically injected electronic carriers in this device using a 500 ns long laser excitation at 640 nm, i.e. at an energy slightly below the \(\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}\) bandgap \[19\]. Then we studied the photoluminescence reemitted by the electron-hole bilayer at low bath temperatures \((T_b \leq 7\ \text{K})\). Details of our experimental apparatus may be found in Ref. \[20\].

In Figure 1, we present the photoluminescence emission for \(T_b \leq 7\text{K}\). In this temperature range, above a threshold laser excitation we observed that a ring-shaped photoluminescence formed at about 30 \(\mu\)m from the illuminated region \((\approx 10 \mu m\) waist\) where electronic carriers were injected. As we lowered the bath temperature, we noted that the ring pattern contracted and was marked further (Fig.2.b). Most notably, it also underwent a spatial fragmentation into microscopic beads for \(T_b\) less than \(\approx 3\text{K}\) (see Fig. 1).

In two-dimensional systems, the formation of large diameter ring-shaped photoluminescence patterns around a laser excitation has been the subject of intensive research since the seminal observations by Butov et al. \[21\] and Snoke et al. \[22\]. Studies have then concluded that the luminescence ring marks the charge separation between electron-rich and hole-rich regions \[23\], \[24\]: the hole-rich region results from the intense photo-excitation...
that leads to a high density of holes in the laser spot. Accordingly, photo-injected holes diffuse away from the illuminated region. On the other hand, single or double quantum wells embedded in a field-effect device confine a 2D electron gas which results from the structure’s modulation doping. These electrons then flow towards the laser spot, i.e. towards the hole-rich region, and a sharp boundary spontaneously forms between the domains of majority charges. The macroscopic ring forms at this interface and marks the recombination of indirect excitons made of well thermalized electrons and holes.

For our experiments, the above mechanism is qualitatively supported by the spectrum of the photoluminescence emission. As shown in Figure 2.a, at the position of the laser excitation (i) the photoluminescence is spectrally broad, with a full width at half maximum (FWHM) of 10 meV. This indicates that electronic carriers are mostly dissociated in this region and from the emission’s spectral width we estimate a carrier density of 5 x 10^{11} cm^{-2}. On the other hand, away from the illuminated region (ii) the photoluminescence exhibits an additional sharp peak on the low energy side. We attribute this spectral profile to the recombination of both indirect excitons and unbound electron-hole pairs, the excitonic emission lying at a lower energy. Finally, at the position of the ring (iii), but also in its vicinity (iv), we show in Figs.2.a that the photoluminescence spectrum reduces to the low energy emission line. This signals that these regions are dominantly populated by indirect excitons which emit a spectrally narrow fluorescence (≈ 2.5 meV FWHM at T_b= 340 mK).

The temperature dependence of the photoluminescence spectrum characterizes further the spontaneously formed indirect excitons. Indeed, we observed at the position of the ring, but also in its vicinity, that the emission spectrum developed an asymmetry initiated at T_b ≤ 4K. Precisely, the inset in Fig.2.a shows that the high energy side of the emission is narrowed while T_b is decreased whereas the low energy side is broadened. Such spectral asymmetry has been reported very recently in microscopic traps. Its establishment at very low temperatures was then interpreted as a manifestation for strong dipolar correlations between indirect excitons at densities of the order of 10^{10} cm^{-2}. For our experiments, the exciton density also lies in this range in the vicinity of the ring. Indeed, the energy of the photoluminescence is blue-shifted by 1 meV when T_b is lowered from 7 to 0.34 K (see Fig.2.b). We attribute this energy shift to the repulsive dipolar interactions distinctive to indirect excitons. Following latest theoretical works, we then estimate that the exciton concentration is increased by 10^{10} cm^{-2} at the position of the ring between T_b= 7 and 340 mK.

The measurements reported in Figure 1 also reveal a striking physical property of cold indirect excitons, namely that they form macroscopic rings that undergo a spatial fragmentation into microscopic beads for bath temperatures below a few Kelvin. To the best of our knowledge, this phenomenon has solely been reported by Butov and co-workers in a series of experiments performed on double quantum well heterostructures. Theoretical works have then addressed this puzzling transition: approaches relying on the Bose statistics of dipolar excitons have concluded that the fragmentation indicates the formation of a quantum degenerate gas. By contrast, other theoretical works have underlined that classical processes maybe sufficient to induce the fragmentation.

To further study the fragmentation of the exciton pattern, we performed spatially resolved interferometric measurements in order to deduce the excitons spatial co-
herence in the vicinity of the ring. For that, we magnified the emission and sent it towards a Mach-Zehnder interferometer aligned close to the optical contact. Therefore, our measurements were not affected by the temporal coherence of indirect excitons. The magnified photoluminescence emission was then split between the arms 1 and 2 of our interferometer, and, as in previous works [9, 10], we introduced a vertical tilt angle (α) between the output of the two arms. Hence, interference fringes are aligned horizontally and α was set such that the interference’s period was equal to ≈ 2.5 µm. Finally, we shifted horizontally the outputs produced by the two arms with respect to each other (by δx) and then measured the output intensity I1 and I2 of individual arms, and the interfering signal I12 when both arms are overlapped.

We used the output of our shift-interferometer, I12, to quantify the spatial coherence of optically active exciton states. Indeed, the interference signal can be modelled as $I_{12}(r) = |\langle \psi_g(r) \rangle|^2 = |\langle \psi_0(r) + e^{i\alpha \delta x} \psi_0(r + \delta x) \rangle|^2$ where $\psi_0(r)$ is the wave-function of bright excitons, $\langle \cdot \rangle$ denotes a time averaging, $r=(x,y)$ is the coordinate in the plane of the quantum well while $q_0=2\pi \sin(\alpha)/\lambda$ with λ equal to the emission wavelength. The normalized interference pattern $I_{int}(r)=(I_{12}-I_1-I_2)/2\sqrt{I_1I_2}$ then reveals the first order coherence function of indirect excitons, $g^{(1)}(\delta x)=\langle \psi_g^*(r) \psi_g(r+\delta x) \rangle/\sqrt{(\langle \psi_g(r) \rangle^2)(\langle |\psi_0(r+\delta x)|^2 \rangle}$, since $I_{int}(r)=\cos(q_0\delta y + \phi_r)|g^{(1)}(\delta x)|$ where $\phi_r=\arg(g^{(1)}(\delta x))$. Hence, the interference’s visibility is controlled by the degree of spatial coherence of bright excitons, while the position of the interference fringes reveals the phase of the $g^{(1)}$-function, i.e. the phase difference between the interfering excitonic wave-functions.

In Figure 3 we present the results of our interferometric measurements. At the lowest bath temperature ($T_b=340$ mK) and for a lateral shift $\delta x=1.4$ µm (Fig. 3b), $I_{int}$ displays clear interference fringes in the region outside of the fragmented ring while at the position of the ring itself and in the inner part the signal is more blurred. Interestingly, we note that the interference pattern bends at the position of the ring while it is horizontally aligned on the left and right hand-side, as imposed by the vertical tilt in the interferometer. This signals that the bright excitons’ wave-function experiences a phase shift across the fragmented ring, by approximately $\pi$ in these measurements. Increasing the lateral shift to $\delta x=2.5$ µm (Fig. 3c) almost annihilates this structure while fringes persist in the outer region of the ring. By contrast, we observed that the interference pattern does not exhibit such a rich structure at $T_b=7$K, i.e. when the exciton ring is no longer fragmented (see the right column in Fig. 3). In general, the interference visibility is reduced compared to the low temperature regime, the interference pattern vanishing for a lateral shift $\delta x=2.5$ µm.

In Figure 4.a we show the variation of the interference visibility at the position of the exciton ring but also at a distance of 10 µm outside the latter. At $T_b=340$ mK, these data confirm quantitatively that the interference contrast drops more rapidly at the position of the ring than in its outer region. There, spatial coherence extends beyond our instrumental resolution (of ≈ 1.5 µm) with $|g^{(1)}| \approx 15\%$ for $\delta x=2$ µm. To estimate the degree of spatial coherence, we modeled phenomenologically the variation of $|g^{(1)}|$ by the convolution between a Gaussian profile with a 1.5 µm full-width at half-maximum and an exponential with a decay constant $\xi$, the excitons coherence length. The former function accounts for our instrumental resolution while the latter function provides the theoretical variation of the $g^{(1)}$-function $|g^{(1)}(\delta x)| \propto e^{-\delta x/\xi}$. Hence, for the best fit to our experimental data we estimate that $\xi \approx 1.3$ µm at a distance of 10 µm outside of the ring. By contrast, at the position of the ring we deduce a coherence length that is limited by our spatial resolution and we estimate that $\xi \leq 200$ nm (see solid and dash lines in Fig. 4.a). On the other hand, at $T_b=7$K, the interference visibility decays rapidly at the position of the exciton ring but also in the outer re-
FIG. 4. (Color Online): (a): Interference visibility \( |g^{(1)}| \) as a function of the lateral shift \( \delta x \) of the Mach-Zehnder interferometer. Measurements were realized at \( T_b=340 \text{ mK} \) and at the position of the ring (filled circles) and \( 10 \mu m \) outside (open circles). The inset displays the same measurements at \( T_b=7K \), filled and open squares respectively. Solid and dash lines show the best fit of our theoretical model to the experimental data. (b): Variation of \( |g^{(1)}| \) measured \( 10 \mu m \) outside the ring as a function of \( T_b \) for \( \delta x=1.8 \mu m \).

region (see inset in Fig. 4.a): \( |g^{(1)}| \) exhibits a similar decay at these positions and we estimate that \( \xi \) does not exceed \( 200 \text{ nm} \) at \( T_b=7K \).

Theoretical calculations are not available yet to model the coherence length of indirect excitons. We then compare our estimations of \( \xi \) to the case of an ideal exciton gas for which the thermal de Broglie wavelength reads \( \Lambda = h/\sqrt{2\pi m k_B T} \), \( m=0.2m_0 \) being the excitons mass \( (m_0 \text{ is the electron’s mass}) \). For bath temperatures ranging from 0.34 to 7K, \( \Lambda \) then varies from 160 to 40 nm. At 340 mK and \( 10 \mu m \) outside the fragmented ring \( \xi \gg \Lambda \) unambiguously signals the appearance of spatial coherence beyond the textbook situation of non-interacting particles. On the other hand, at the ring’s position, but also in the higher temperature regime (7K), we observed that \( \xi \sim \Lambda_{DB} \) with our experimental resolution which does not allow us to draw clear conclusions.

In a last experiment, we studied the establishment of extended coherence outside the ring while the bath temperature is lowered. Precisely, we measured the interference visibility as a function of \( T_b \) for a fixed lateral shift \( \delta x=1.8 \mu m \) and \( 10 \mu m \) outside the macroscopic ring. As shown in Fig.4.b, we then observed two regimes at low and high temperatures respectively. In the latter one \( (T_b \geq 4 \text{ K}) \) the interference contrast remains constant \( (|g^{(1)}|=12 \%) \) while at lower temperatures \( (T_b \leq 4 \text{ K}) \) it abruptly increases to \( \approx 22 \% \). This behavior reveals that extended coherence is solely established in the regime where the ring of indirect excitons is fragmented, i.e. below a few Kelvin. At higher temperatures, we attribute the non-vanishing interference visibility to our experimental resolution \( [37] \), however we can not exclude that long-range correlations persist in this regime.

To summarize, we have shown that spatially indirect excitons can realize a macroscopically coherent state in the regime where they form a ring shaped pattern fragmented in microscopic beads. Particularly, our experiments agree with latest studies by Butov et al. \([9]\) and signal that extended coherence is established in the vicinity of the ring fragments. Interestingly, the photoluminescence intensity in this region is weak compared to that of microscopic beads. This behavior may relate to the striking physical properties of indirect excitons at very low temperatures, as underlined in recent theoretical works \([34, 35]\).

This work was supported financially by the EU-ITN INDEX, by the Spanish MEC (TOQATA), by the Spanish MINECO (Grant TEC2011-29120-C05-04), CAM (Grant S2009ESP-1503) and by the ERC AdG QUAGATUA. F.D. also acknowledges the Ramon y Cajal program. Furthermore M.A. and F.D. are grateful to M. Lewenstein for his continuous support.

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these contrasts are $\approx 5\%$ greater than for the measurements shown in Fig.3 which we attribute to a better alignment of our interferometer.