All-Optical Fiber Hanbury Brown & Twiss Interferometer to study 1300 nm single photon emission of a metamorphic InAs Quantum Dot

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New optical fiber based spectroscopic tools open the possibility to develop more robust and efficient characterization experiments. Spectral filtering and light reflection have been used to produce compact and versatile fiber based optical cavities and sensors. Moreover, these technologies would be also suitable to study N-photon correlations, where high collection efficiency and frequency tunability is desirable. We demonstrated single photon emission of a single quantum dot emitting at 1300 nm, using a Fiber Bragg Grating for wavelength filtering and InGaAs Avalanche Photodiodes operated in Geiger mode for single photon detection. As we do not observe any significant fine structure splitting for the neutral exciton transition within our spectral resolution (46 μeV), metamorphic QD single photon emission studied with our all-fiber Hanbury Brown & Twiss interferometer could lead to a more efficient analysis of entangled photon sources at telecom wavelength. This all-optical fiber scheme opens the door to new first and second order interferometers to study photon indistinguishability, entangled photon and photon cross correlation in the more interesting telecom wavelengths.

New emerging quantum optics technologies are mostly influenced by the possibility to design realistic proposals to implement and control quantum correlations between photons1. Single photon and entangled photon emission has been demonstrated by different techniques and systems2, as for example by non-linear processes (parametric down conversion or four wave mixing) or by two level systems (atoms, molecules, Quantum Dots, single impurities or Nitrogen Vacancies in Diamond). However, an entangled photon source must fulfill several requirements for its use in quantum applications3: deterministic generation of entangled photons, high fidelity to the Bell state, high photon indistinguishability, and high efficiency. Although non-linear processes generate entangled photons at room temperature, two-level systems offer the opportunity to build a deterministic device, i.e., a system where entangled photons are emitted on demand by an external control (laser pulse or electrical signal). Furthermore, it is interesting to generate entangled photon emission compatible with optical fiber technologies, thus it is necessary to tune the optical emission to the second and third optical telecommunication windows (1300 and 1550 nm).

In this regard, single self-assembled Quantum Dots (SAQDs) are well known solid-state semiconductor nanostructures that offer key advantages as single or entangled photon emitters fabricated on a GaAs substrate. SAQDs show confinement in all dimensions, leading to a 0-dimensional density of states similar to single atoms. The optical emission in the biexciton to neutral exciton cascade has been proposed as a deterministic polarization entangled photon source4. Along the last decade, single SAQDs have been used to develop single5 and entangled photon emitting diodes as sources of high fidelity Bell states6. Single charge states have been controlled in order to manipulate hole spins with very large decoherence times7, which is a desirable property in the development of future quantum computing devices. High values of photon indistinguishability have also been obtained in two photon...
excitation schemes, related to large coherence times\textsuperscript{8}. However, most of these milestones were demonstrated mainly by using SAQDs whose optical emission lies on the first telecommunication window (850–980 nm).

Among the possibilities offered by SAQDs engineering, the QD confinement potential can be controlled by the design parameters and the growth conditions, leading to a direct control of electronic states and optical properties, as for example to redshift the photon emission towards longer wavelengths (1300 or 1550 nm). However, in some cases the change in the design of the QD based structure and the growth techniques necessary to achieve such a wavelength tuning can deteriorate the optical quality: reduction of coherence times, increase of the homogeneous linewidth and spectral diffusion effects by the presence of fluctuating charges in the QD surroundings. These factors will invariably induce a reduction of fidelity and photon indistinguishability. At the same time, Fine Structure Splitting (FSS) from electron and hole exchange interaction usually increases with the QD size\textsuperscript{9}, hence reducing the possibility to generate entangled photons.

From a technological point of view, conventional Si detection technology is not useful for telecom wavelengths, as the detector efficiency drops dramatically beyond 1000 nm and InGaAs photodetectors are routinely used in photonic devices instead those based on Si, despite their higher noise characteristics. The use of those infrared detectors introduces a strong limitation in the experimental determination of single photon emission, particularly when the Signal to Noise Ratio (SNR) decreases towards unity, even if the detection scheme is enhanced by use of either gated InGaAs Avalanche Photodiodes (APDs) or changing InGaAs by superconductor based photodetectors\textsuperscript{2,10}. Single photon emission at 1300–1500 nm under both pulsed\textsuperscript{11} and continuous wave\textsuperscript{12,13} excitations, and entangled photon emission at 1300 nm\textsuperscript{14}, have been demonstrated on SAQDs by using the aforementioned photodetectors and the appropriate experimental set-ups, or by detection strategies based on frequency upconversion\textsuperscript{15}.

In this letter, we propose a new all-optical fiber Hanbury Brown & Twiss (HBT) interferometer containing a tunable Fiber Bragg Grating (FBG) optical filtering stage coupled to Geiger mode InGaAs Avalanche Photodiodes (APDs) for single photon detection (Fig. 1). The use of the FBG reduces the complexity and cost of the experimental set-up, avoiding the use of monochromators, free-space optics filters, lenses and collimators, and hence increasing the collection efficiency by more than one order of magnitude\textsuperscript{16}. The increase in photon collection efficiency translates into an increment of the SNR when light is detected by means of InGaAs APDs, and thus it will allow the identification of single-photon emission with APDs operated in the conventional Geiger mode. Our all-optical fiber HBT interferometer scheme does not require neither liquid helium operational temperatures, as for the case of superconductor photodetectors, nor synchronization, as in gated InGaAs APDs, and thus offers a compact detection set-up design using the same optical fiber that collects photons from SAQDs. Such a detection scheme would be the basis for a direct way to connect single photons into more complex telecom architectures.

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**Figure 1.** All-optical fiber Hanbury Brown & Twiss interferometry set-up for measuring photon coincidence experiment. From left to right: the laser (pulsed or continuous) is coupled to a single mode fiber. The fiber arrives to the excitation arm of a fiber based confocal microscope, and excite an isolated Quantum Dot at 4 K. Micro-Photoluminescence emission is directed to the collection arm of the microscope and coupled to another single mode fiber. A circulator operating for 1300 nm redistribute the light to the Fiber Bragg Grating installed on a metal strip to change curvature, and hence produce tunable wavelength filtering. The reflected light from the Fiber Bragg Grating arrives to the circulator and is distributed to the entrance of a 50/50 fiber coupler. Each coupler out-put port is attached to InGaAs Geiger mode Avalanche Photodiodes (ID230 at Start and ID220 at Stop channels). Both detector electronic outputs are plugged to a correlator, where stop channel includes a larger path (delay represented as black cable with single loop). Finally, photon coincidence plot is represented in the computer screen. In the same figure is represented the metamorphic QD sample, with brown representing GaAs layers and with blue In\textsubscript{0.15}Ga\textsubscript{0.85}As layers. InAs Wetting Layer and QDs are represented by gray and white colors.
and/or photonics chips. With the proposed all-optical fiber HBT interferometer we have identified single photon emission after noise subtraction from neutral exciton recombination in metamorphic InAs SAQDs emitting at the second telecommunication window (1300 nm), under cw and pulsed excitation conditions. We have labelled excitonic complexes in our InAs SAQDs by means of micro-Photoluminescence (µ-PL), polarization-selective µ-PL and time resolved µ-PL (µ-TRPL) experiments. Our excitonic assignation corresponds to a large SAQD with an excess of holes in its initial configuration. We identified all fine structure from all excitonic transitions of the QD, where neutral exciton transition does not show any significant FSS within our spectral resolution (46 μeV).

Our spectroscopic data is in agreement with the structural information of the SAQD epitaxial growth, and hence our metamorphic SAQD should represent an alternative source for polarization entangled photon emission.

Results

Excitonic Labelling of single Quantum Dot Transitions. Typical µ-PL spectra of our large size SAQDs are composed by a relatively high number of optical transitions, which originate from the multiple carrier configurations through the different QD levels. The number of available confined states increases as the QD becomes wider and hence charge carriers can recombine through multiple state configurations. In order to identify and label all these transitions, we performed power excitation, time resolved and polarization resolved µ-PL experiments. Figure 2a shows the µ-PL evolution as a function of the excitation power with the laser resonantly tuned to our Heavy Hole (HH)-WL transition (1.31 eV = 940 nm), exciting the sample in CW mode. This excitation wavelength is selected in order to significantly reduce the spectral diffusion (SD) effect related to random perturbations of the SAQD by a fluctuating charged environment, so that photogenerated carriers are practically independent of the extrinsic carrier dynamics in the GaAs barriers (see more details in the supplementary information). This strategy reduces the extrinsic broadening of the QD optical transitions, enabling their separation and classification. We have indicated in Fig. 2 the most probable labeling for the observed excitonic species, including exchange singlet, doublet and triplet states in positive quartons, hot positive trion and single positive charged biexciton, based on the analysis presented below.

The integrated intensity versus power excitation (Inset in Fig. 2a) provides information about the excitonic or biexcitonic nature of the observed optical transitions, as it is needed an average of one/two adsorbed photons to generate the excitonic/biexcitonic quasiparticle. Table 1 lists all slopes for the power dependence of every transition. The low power excitation spectrum is dominated by the neutral exciton (X⁰; one electron and one hole in conduction and valence band S-levels, repectively, i.e. [1Se1Sh]), with a slope of 0.98. At an emission energy higher than X⁰, i.e. with negative binding energy, we identify a positive Trion (X⁺¹; [1S₂2S₁P₁]), a doubly positive charged exciton, a positive Quarton (X⁺²; one electron and two holes in conduction and valence band S-levels, repectively, and one extra hole in the valence band P-level, i.e. [1S₂2S₁P₁]). X⁺² recombination is composed by single unpolarized transition (XUn⁺²) at a slight lower energy than X⁺¹, and two doublets at lower energy...
(X_D1)±2 and X_D2±2), as it has usually found in literature17,18. The slopes of X±1 and X±2 transitions are larger than the one of X0 (Table 1), as extra carriers are involved in their recombination paths19. The second doublet of the X±1 transition (X±1)2 appears at ~3.3 meV with respect to the unpolarized recombination20. On the opposite energy side relative to X±1, and hence with positive binding energy, we identified the neutral biexciton emission (XX±1, [2S1,2S0]), with slope ≈1.68, and a single positive charged biexciton (XX±1+, [2S1,2S0,1P±1]), with slope ≈1.9. XX±1 recombination is produced between electrons and holes in S-levels (S±S±) populating the hot positive trion state (X±1+; [1S±1,1S±1,1P±1]). As recently demonstrated in refs 21 and 22, the X±1+ transition is composed by singlet and triplet states, whose degeneracy is broken by the hole-hole exchange interaction, whereas the triplet degeneracy is broken by electron and hole exchange interaction. The complete description of the X±1+ state diagram, containing all exchange effects is presented in the supplementary information. In Fig. 2a we found that the X±1+ triplet state emission is characterized by a slope ≈1.5 for the power dependence of the µ-PL integrated intensity that is smaller than that of XX±1, but slightly larger than the one of X±1. Finally, we observe a biexcitonic transition with a slope = 1.9, matching the low energy sideband of the X0 transition. We were not able to extract enough information to propose a clear excitonic assignment, although here we tentatively assign to the singlet state transition of the hot positive trion X±1+.

On the basis of our previous experience in the study of selectively charged quantum dots23,19, the above described SAQD would represent a dynamical situation with an excess of holes in its initial configuration22. We attribute such an excess of holes to either the SAQD size or to the excitation conditions. Big-sized SAQDs are expected to be more exposed to the effect of surface charges in the QD interface, as it has been found for GaAs droplet epitaxy QDs24. At the same time, these big-sized QDs show a large number of very close hole states as compared to small QDs, and hence it is reasonable to assume that the probability to feed positively charged excitons can be enhanced under specific excitation conditions. In a previous work we have shown that positive excitonic complexes may be promoted when the laser excitation is resonant to the HH-WL state, observed for smaller InAs SAQDs samples23. Furthermore, we recorded power dependent µ-PL evolution with excitation above GaAs barrier (780 nm) (see supplementary information). Using this excitation wavelength, neutral and negative transitions dominates the µ-PL spectrum, as GaAs barrier absorption produces extra single and correlated carrier diffusion and injection feeding channels25,26. In conclusion, our hypothesis of a positively charged QDs seems reasonable as structural information, excitation conditions, and µ-PL in different excitation conditions support it.

Figure 2b shows µ-TRPL measurements under an intermediate excitation power (560 nW) and the excitation wavelength tuned to 780 nm. We were able to record the µ-PL transients for XX±1, XX0, X±1, X±0, X±0±2 and X±1 optical transitions, but not for the other transitions, as their µ-PL signal intensity under pulsed excitation was below the noise level. Table 1 lists the time constants obtained in the best fit (see supplementary information for fitting procedure). All transitions exhibit large rise times (~0.6 ns), which is attributed to the use of an intermediate excitation power under pulsed conditions. In a previous study we have shown that rise time increases as a function of the power excitation16 due to the multi-exciton cascade recombination27. Hence, single excitonic transitions must wait until this cascade is completed. Consistently with this observation, we have found a slightly larger rise time (~0.79 ns) for X0 transition, that coincides with the decay time for XX0 (0.73 ns), thus indicating that the recombination of X0 must wait for the radiative decay of XX0. These data reinforce our previous excitonic labeling. As we found in previous µ-TRPL measurements in a similar SAQD24, our best fit returns very similar decay times for the recombination of neutral exciton and biexciton states (Table 1), which was attributed to the weak confinement regime compatible with these big sized SAQDs28,29.

### Table 1. Experimental parameters of the excitonic complexes labelled in Fig. 2, obtained from the different experiments: the slope of power linearly dependent micro-Photoluminescence; decay and rise time constants from time resolved micro-Photoluminescence; and Fine Structure Splitting (FSS) from polarization-selective micro-Photoluminescence.

| Transition | X±1 | X±0±2 | X±0 | X±1 | X±0 | XX0 | XX±1 | XX±1±2 |
|------------|-----|-------|------|------|------|------|-------|---------|
| Slope      | 1.13| 1.14  | 1.21 | 0.98 | 1.95 | 1.13 | 1.15  | 1.63    |
| τ_r (ns)   | 0.64| 0.68  | —    | —    | 0.72 | —    | 0.73   | —       |
| τ_r (ms)   | 0.62| 0.65  | —    | —    | 0.79 | —    | 0.69   | —       |
| FSS (μeV)  | —   | —     | —    | —    | —    | —    | —     | —       |
|            | ≈160| ≈160  | —    | —    | —    | —    | —     | —       |

Polarization resolved spectra and Fine Structure Splitting. Figure 3 shows the contour plots of polarization-selective µ-PL spectra acquired for the most important optical transitions. In the majority of the optical transitions we observe that the µ-PL peak energy is independent of the collection polarization (Fig. 3a), except in the case of X±1+ and XX±1 transitions, which will be discussed below. Within our experimental spectral resolution (~46 μeV), we do not observe any significant FSS for X0 and XX0 optical transitions. The mean linewidth measured in our SAQD is about 100 μeV, which is slightly larger than those measured in standard SAQDs emitting at the first telecom window (~20–80 μeV23,30,31). Hence, if the FSS of X0 state is small enough, FSS would be blurred by a broadening that is mainly due to spectral diffusion.

The FSS for the X±2+ transition is composed of an unpolarized line and two fine-structure split doublets (Fig. 2a), each one composed of two fully polarized lines20. X±2+ spectral features are separated by an energy much smaller (3.5 meV in ref. 20 or 3.1 meV here, as observed in Fig. 2a) than the case of the X±1+ transition (10.1 meV in ref. 20). The FSS of the X±2±1 polarized doublets is expected to be in the order of the X±1 FSS and much smaller than that of X±2+. With our spectral resolution, we do not appreciate any FSS signature for X±1 transitions, as also happens for X0. It should be noticed that it has been previously shown that a reduction of strain in InAs QDs causes a decrease
of the FSS\textsuperscript{32,33}. As in these metamorphic InAs/InGaAs QDs the mismatch between QDs and confining layers is 6.34\%, below the 7.16\% value of pseudomorphic InAs/GaAs QDs\textsuperscript{34}, this strain effect could also explain the low FSS supposed here for both \(X^0\) and \(X^+2\) species. However, transitions labelled as \(X^+1^*\) and \(XX^+1\) exhibit opposite shifts with polarization-selective detection (zoom in Fig. 3b and profile in Fig. 3c), and a clear FSS ≈160\(\mu\text{eV}\) is measured. The recombination of hot trions (\(X^−1^*\) and \(X^+1^*\)) are expected to exhibit a FSS of the same nature as that observed for \(X^0\), but it is characterized by a larger magnitude (see supplementary information for a complete description of the positive hot trion state diagram and recombination\textsuperscript{21,22,35}). The origin of such large FSS for the \(X^+1^*\) state, is related to the P-type symmetry of the envelope wavefunction of the excited state hole shell that would enhance the anisotropy of the electron-hole exchange interaction\textsuperscript{35}. Following these arguments, we conclude that the FSS value of \(X^0\) and \(X^+2\) are well out of our spectral resolution or blurred by energy incertitude due to line broadening effects, whereas the measured FFS of \(X^+1^*\) is intrinsically large, ≈160\(\mu\text{eV}\).

**Single photon emission characterization.** Figure 4a shows the photon autocorrelation coincidence measurement for \(X^0\) recombination with CW excitation tuned to 940 nm. In order to extract information about the single photon emitter features we analyzed our results following the standard protocol\textsuperscript{36}. The HBT measurement returns a coincidence photon counting plot as a function of time delay (\(C(\tau)\)) that must be normalized following the relation:

\[
C_N(\tau) = \frac{C(\tau)}{H_iH_{\omega T}}
\]

where \(H_i = C_i + N_i\) is composed by the sum of the optical signal from QD emission (\(C_i\)) and dark counts (\(N_i\)) from detection channel \(i\) (Start/Stop), \(\omega\) is the time bin of the correlation board (190 ps) and \(T\) is the total integration time (11 hours). We fitted the normalized photon coincidence plot using the expression of the second order correlation function of a two level system, \(g^2(\tau)\), convolved by a Gaussian function representing the detector time resolution:

![Figure 3. Polarization resolved micro-photoluminescence spectra.](image-url)

(a) Polarization-selective \(\mu\)-PL contour plot of the same SAQD whose optical transitions were shown in Fig. 2 and (b) zoom centered at \(X^+1^*\) (Left) and \(XX^+1\) (Right) transitions; both contour plots show clear opposite shift that follows the FSS versus detection polarization. (c) \(\mu\)-PL spectra with orthogonal linear polarizations (\(\pi_x\); red, and \(\pi_y\); black) that yield a FSS ≈160\(\mu\text{eV}\) for transitions \(X^+1^*\) and \(XX^+1\).
where $\tau_c$ is the FWHM of the instrumental response (400 ps), $\tau_d$ is decay time of the transition and $n$ is the average number of photons in the photon stream. Following this procedure our fitting routine returns $g^2(0)=0.30\pm0.12$. When the photon correlation is measured with small SNR it must be considered the noise effect from dark count coincidences. In our experiment we found $H/N$ ratios of 1900/10 (start channel) and 1800/560 (stop channel) for id230 and id220 APDs, respectively. In order to take into account the unbalanced effect of noise, we used the following expression:

$$C_N(\tau) = \rho_1\rho_2 g^2(\tau) + (1 - \rho_1\rho_2)$$

(3)

where $\rho_1 = \frac{H_1}{H_2}$ and $\rho_2 = \frac{H_2}{H_1}$. From our signal and noise measurement $\rho_1 = 0.99$ and $\rho_2 = 0.69$. Under these detector conditions, an ideal single photon emission, $(g^2(0) = 0)$, would produce dark count correlations of $C_N(0) = 0.29\pm0.04$, which coincides with the experimental value extracted above by the fitting procedure. Therefore, we conclude that the $X^0$ transition of our SAQD is compatible with $g^2(0)=0.01\pm0.16$ after noise subtraction, which produces $n=1.01\pm0.16$ average photons.

Figure 4b shows the photon correlation experiment for the same $X^0$ transition under pulsed excitation at 780 nm. The process to obtain the information for $g^2(0)$ is similar to that developed above for CW excitation, except that under pulsed excitation the photon correlation counts are distributed periodically along the delay time axis and separated by the laser period. To normalize the coincidence counts now we use the expression:

$$C_N(m) = \frac{C(m)}{H_1H_2\theta T}$$

(4)

where $m$ is an integer value corresponding to the pulse number. $C(m)$ was obtained performing a multi Lorentzian peak fitting to calculate the integrated area of every m-peak, $H$ are defined as before, $\theta$ is the laser repetition period (13 ns) and $T$ is the integration time (8 hours). After this normalization we obtain $C_N(0) = 0.44\pm0.05$. This result compares well with the theoretical value $C_N(0) = 0.51\pm0.04$, which is deduced by considering the effect of the dark counts correlation assuming an ideal situation $(g^2(0) = 0)$. Again, the $g^2(0)$ value for the $X^0$ transition after noise subtraction is close to the ideal case.
Discussion

We have presented a complete optical study of a single metamorphic InAs SAQD by means of a novel all-optical fiber intensity interferometer containing a FBG-filtering stage coupled to Geiger mode InGaAs APDs. We analyzed and labeled the most relevant excitonic and biexcitonic transitions and identified a FSS $\approx 160\,\mu$eV associated to the single positive charged hot-trion state ($X^+_{1}$). Contrarily, we did not observe any measurable FSS related to neutral exciton ($X^0$) and positive quartons ($X^+_{2}$). Such a small FSS for $X^0$ is compatible with the nominal low lattice mismatch between these InAs/InGaAs SAQDs and the confining layers (6.34%), which has been proved to cause a decrease of the FSS. These results could also open the way towards the development of entangled photon sources at 1300–1550 nm telecom windows, as metamorphic QDs have been demonstrated to be able to emit beyond 1550 nm.

Single photon emission of the $X^0$ transition at the second telecom window ($\approx 1300$ nm) has been characterized, showing that the g’(0) value after noise subtraction analysis is close to the ideal case. This represents the first time where single photon emission at 1300 nm has been demonstrated by using InGaAs avalanche photodetectors under Geiger mode operation, which was possible by using a FBG filtering device integrated into the signal collecting optical fiber. The use of FBGs in conjunction with APDs in Geiger mode at 1300 nm is a novelty that offers a relatively simple and compact experimental architecture to study photon indistinguishability and coherence times. As an example of application, it has been recently found new and rich features in the simulation and measurement of frequency filtered N-photon correlation coincidences. The FBG-filtering stage included in our all-optical fiber photon correlator offers the possibility to measure these bunching and antibunching 2D patterns with an alternative set-up, as FBG filtering produce high collection efficiency, and can be tuned with high frequency/wavelength resolution and high stability. We have previously shown that FBG filtering is suitable to scan single QD transition. Here we used a broadband FBG in order to match the FBG FWHM with our QD transition linewidths and maximize the photon collection rate, although FBG FWHM can be reduced down to 0.4–3.5 $\mu$eV (1300 nm). At the same time, the tuning capabilities of the FBG transmission peaks can be as sensitive as $\approx 0.4\,\mu$eV. These FBG parameters are suitable to filter and scan any conventional QD linewidth, with typical FWHM between 20–100 $\mu$eV. Finally, the set-up illustrated in Fig. 1 may be adapted to study N-photon cross correlation architecture with the help of N-FBG filtering devices attached one after another, which represent an easy “plug and play” optical device, with reduced light losses.

In summary, our All-Optical Fiber proposal resembles the conventional procedure used in the analysis of SAQDs emitting below 1000 nm, where Si APDs photodetectors do not exhibit any SNR limitation and are used in the conventional Geiger mode. Our strategy represents a simpler, low cost and efficient tool to connect single/entangled photons into photonic architectures for telecommunications, as for example to develop new N-photon correlation experiments or more compact optical fiber based single and entangled photon devices. Single metamorphic QDs studied with our all-optical fiber based experiment shows single photon emission at 1300 nm with no evidence of neutral exciton Fine Structure Splitting, and hence represents a viable structure design to develop the more interesting deterministic entangled photon source at 1300–1550 nm telecommunication wavelengths.

Methods

Sample. In Fig. 1 is shown the schematic of the metamorphic SAQD structure, grown by Molecular Beam Epitaxy. After a 100 nm GaAs buffer, a metamorphic In$_{0.15}$Ga$_{0.85}$As layer of 500 nm was deposited, followed by 5 nm of GaAs. Then a sub-critical coverage of 1.5 ML of InAs was deposited at 490 °C followed by 20 s annealing at the same temperature under As flux. SAQDs were finally capped by a 20 nm thick layer of In$_{0.15}$Ga$_{0.85}$As. Photon emission from these single SAQDs in the long wavelength range has been previously demonstrated. The use of a metamorphic InGaAs layer allows for the red-shift of the emission wavelength thanks to the reduction of strain of QDs and band discontinuities, whereas the deposition of a sub-critical coverage of InAs followed by thermal annealing allows to obtain very low densities of SAQDs ($1 \times 10^8$ cm$^{-2}$). In these samples with In$_{0.15}$Ga$_{0.85}$As metamorphic layers the diameter of the QDs ($d_{QD}$) has been estimated by AFM to be in the 30–45 nm range, which is larger than the diameters of metamorphic QDs grown with the SK method. Similarly, heights for QDs grown by the sub-critical method are in the 6–9 nm range, larger than those of SK QDs.

All Optical Fiber Photon Correlation Experiment. Figure 1 also shows a detailed scheme of the all-optical fiber HBT interferometer set up used here to measure single photon coincidences. The QD sample was held in a fiber-based confocal microscope at 4 K to record the single QD optical emission. Single SAQDs were excited by tunable Ti:Saphire laser (Mira 900D) working under either continuous wave (CW) or pulsed excitation (120 ps width). Wavelength selection was carried out by filtering the SAQD emission through a FBG device. The FBG was patterned by means of a CW Frequency-doubled Argon ion laser at 244 nm and a phase mask technique (120 ps width). Time resolved -PL (µ-TRPL) spectra were acquired with the same FBG wavelength filtering and correlating the InGaAs APD output with a laser triggering. The µ-PL spectra were recorded using a conventional detection scheme with 0.5-m focal length grating monochromator (with
an optimal resolution of 46 μeV at 1300 nm) and an Andor iDus InGaAs Charged Coupled Device (CCD) detector. For more details about μ-PL and μ-TRPL set-up arrangements see the supplementary information.

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Acknowledgements
G Muñoz-Matutano thanks the Spanish Juan de la Cierva program (JCI-2011-10686). We acknowledge the support of the Spanish MINECO through projects TEC2014-53727-C2-1-R & TEC2014-60378-C2-1-R, the Research Excellency Award Program GVA PROMETEO 2013/012 PROMETEOII/2014/059 and the Explora Ciencia Tecnología TEC2013-50552-EXP MULTIFUN project, and the Nanoscale Quantum Optics MPNS COST Action MP1403.

Author Contributions
G.M.M. assembled the all-fiber optics Hanbury - Brown & Twiss set-up, developed spectroscopy and photon correlation experiments and made the analysis of the data. D.B. build the Fiber Bragg Grating (FBG) operating at 1300 nm, fabricated a device for FBG wavelength tuning and optimized the FBG spectral characteristics. C.R.F.P conceived the central idea of the work and related experiments. R.C.J. contribute to experimental measurements. L.S., G.T. and P.F. grew the metamorphic quantum dot sample. S.S. and J.M.P. supervised the experimental work and contributed to discussion. Manuscript writing was done by G.M.M. and J.M.P. All author reviewed the manuscript.

Additional Information
Supplementary information accompanies this paper at http://www.nature.com/srep

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Muñoz-Matutano, G. et al. All-optical fiber Hanbury Brown & Twiss interferometer to study 1300 nm single photon emission of a metamorphic InAs Quantum Dot. Sci. Rep. 6, 27214; doi: 10.1038/srep27214 (2016).

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