I. INTRODUCTION

Single and entangled photon emitters are fundamental building blocks for emerging technologies such as quantum communication protocols and quantum networks. Entangled light can be generated through solid state quantum emitters with naturally low fine structure splitting, such as highly symmetric InAs quantum dots (QDs) grown on (111)-oriented surfaces. Incorporating this kind of QDs into optical cavities is critical to achieve sufficient signal intensities for applications, but has so far shown major complications. In this work we present droplet epitaxy of telecom-wavelength InAs QDs within an optical cavity on a vicinal (2° miscut) GaAs(111)A substrate. We show a remarkable enhancement of the photon extraction efficiency compared to previous reports together with a reduction of the density that facilitates the isolation of single spectral lines. Moreover, we characterise the exciton fine structure splitting and employ numerical simulations under the framework of the empirical pseudopotential and configuration interaction methods to study the impact of the miscut on the optical properties of the QDs. We demonstrate that the presence of miscut steps influences the polarisation of the excitonic states and introduces a preferential orientation in the C3v symmetry of the surface.

which relies on the formation of group-III metal droplets followed by crystallization in a group-V atmosphere. DE offers better control over the QD self-assembly dynamics and guarantees fine tuning of the shape, size and density of the nanostructures. The formation of telecom-wavelength InAs QDs with FSS as low as 16 µeV on GaAs(111)A has been recently demonstrated. Nevertheless, previous works on (100) substrates suggest that incorporating those emitters in a one-dimensional microcavity could improve the photon extraction efficiency and generate sufficient signal intensity for applications. Unfortunately, the deposition of distributed Bragg reflectors (DBRs) on singular, i.e. on-axis, (111) substrates has proven challenging because very low growth rates below 0.03 nm/s are required to obtain flat epilayers. Here, we demonstrate self-assembly of InAs DE QDs emitting in the telecom O-band within a DBR microcavity grown on a vicinal (2° miscut) GaAs(111)A substrate. Thanks to the presence of the miscut, the growth rate can be up to one order of magnitude higher (≈ 0.14 – 0.28 nm/s) and therefore similar to the ones used on standard GaAs(100) layers. Moreover the propensity of twin defects in the AlGaAs layers, which often limit the quality of structures grown on singular (111) substrates, is strongly reduced.

Combining the DE technique with the growth of a DBR microcavity enabled us to meet the high-brightness and low-density criteria necessary for the spectroscopic investigation of single QDs.
II. EPITAXY

The sample was grown on an undoped vicinal GaAs(111)A substrate with 2° miscut along the [\(\bar{1}12\)] direction in a solid source MBE system. After a GaAs buffer layer, a bottom DBR with 25 repeats of \(\lambda/4\) Al\(_{0.5}\)Ga\(_{0.5}\)As/GaAs layers was grown at 600°C using deposition rates of 0.28 nm/s and 0.14 nm/s respectively. Such a DBR provides high reflectivity for a wavelength range centred around 1310 nm. Next, DE InAs QDs with an approximate density of \(1 \times 10^8\) cm\(^{-2}\) were formed in the middle of a \(\lambda/2\) cavity consisting of 201.6 nm of In\(_{0.6}\)Al\(_{0.4}\)As (grown at 470°C with a deposition rate of 0.14 nm/s) by supplying 1 ML (monolayer) of In at 370°C with a deposition rate of 0.003 nm/s and then crystallizing for 8 minutes in As\(_4\) atmosphere at 300°C. During the In deposition the residual As\(_4\) beam equivalent pressure (BEP) was kept below \(3 \times 10^{-9}\) Torr. The As\(_4\) valve was then opened for crystallization, resulting in a BEP of \(3 \times 10^{-5}\) Torr. These parameters are similar to those previously developed for growth on singular GaAs(111) substrates [18].

Finally, three \(\lambda/4\) layers (GaAs/Al\(_{0.5}\)Ga\(_{0.5}\)As/GaAs) were deposited with the same conditions used for the bottom DBR. The asymmetric cavity was designed to limit the photon leakage into the substrate and direct the emission towards the collection optics.

III. OPTICAL CHARACTERIZATION

For optical characterization, the sample was mounted inside a closed-cycle cryostat at a temperature of 5 K and the QDs were excited by a CW laser at 785 nm. The emitted photons were collected using a fiber-coupled confocal microscope and sent to a spectrometer equipped with an InGaAs photodiode array for analysis.

Figure 1a shows a wide-range reflectivity measurement taken on the sample. The dip in the spectrum confirms the presence of a cavity mode at the desired wavelength, which is fitted with a Gaussian curve centered at 1307 nm. The extracted FWHM = 39 nm is similar to the value predicted by our simulations.

In Figure 1b, we report a typical O-band photoluminescence (PL) spectrum from the QDs. The inset shows an example of PL emission measured in equivalent conditions on a different sample [24] with the same InAs QDs but no DBR mirrors. (c) Gaussian fit of two transitions from the spectrum reported in (b). (d) Linewidth statistics obtained by fitting 30 spectral lines.
threading dislocations in the InAlAs barrier layers. We also notice an improvement in the signal/background ratio and an important reduction in the density of spectral lines, which makes it possible to isolate the emission pattern of single QDs.

To quantify the FSS, we employed the well-established half-wave plate (HWP) method [3, 31] by sending the PL signal through a rotating HWP and a fixed linear polarizer (LP) mounted in the collection arm and measuring the resulting shift in energy at the spectrometer. An example of FSS measurement is shown in Figure 2a, where the energy shift as a function of the wave-plate angle fits well with the expected sinusoidal behavior.

A statistical distribution was obtained by repeating the measurement on 35 lines of unidentified species in the telecom O-band: as reported in Figure 2b, approximately 50% of them show a FSS < 50 µeV, while larger values between 70 µeV and 300 µeV are recorded in the other cases. In general, these values are similar to the ones reported in literature for DE QDs grown on GaAs(100) substrates [3].

The presence of emitters with large FSS may originate from unexpected anisotropy in some of the QDs examined. To gain more insight into this phenomenon, we carried out an additional investigation focusing on the orientation of the neutral excitons. First, we adjusted the position of the sample in the cryostat such that it was possible to identify clearly a XX-X pair and in blue when FSS and Δφ were extracted from one line only. (d) Corresponding histogram with Gaussian fit of the statistical distribution. The vertical dashed line shows the direction of the miscut steps.

In Figure 2d, we report a histogram of the dipole orientations: the Gaussian fit shows that the statistical distribution is centred around Δφ = 3.1°(± 2.2°), indicating that the component of the excitonic doublets higher in energy tends to be polarized along [112]. In fact, the small discrepancy of ≈ 3° can easily be attributed to limited accuracy while mounting the sample. Interestingly, a small group QDs exhibits perpendicular polarization aligned with [110]. As it was not possible for most emitters to
clearly identify a XX-X pair and the FSS was extracted from one spectral line only, it may be possible that these values originate from a XX transition and consequently have the highest energy component oriented at 90° with respect to the exciton due to conservation of energy and spin.

In summary, these results suggest that the presence of a 2° miscut introduces a privileged direction in the natural C3v symmetry of the system.

**IV. INFLUENCE OF THE MISCAST ON THE OPTICAL PROPERTIES OF THE QDS**

Following the experimental observations presented above, we carried out numerical simulations to better understand the impact of the miscut on the optical properties of the QDs. Since the full structure of the sample including the InAlAs barrier layers and the DBR mirrors could not be reproduced because of computational limitations, we considered 3 simplified material systems. First we studied GaAs/AlAs(111) QDs, which is a simple case with no strain or alloy. Then we examined GaAs/Al0.15Ga0.85As(111) QDs to isolate the effects of alloying and finally InAs/GaAs(111) QDs, which is an idealised version of the sample and reveals the impact of strain.

The dots were modelled as hexagonally based truncated pyramids with 70 nm diameter, 4 nm height and a variable miscut angle ranging from 0° to 3° along [112].They were placed at the centre of a cubic simulation box filled with the barrier material and the structure was allowed to relax in order to minimise the strain energy using a generalised valence force field (GVFF) model [32, 33].

The single-particle Schrödinger equation was then solved (both for the conduction and valence states) under the framework of the empirical pseudopotential method (EPM) [34] using a strained linear combination of bulk Bloch bands (SLCBB) [35] as a basis to expand the wave functions. Then, the many-body problem was addressed through a configuration interaction (CI) scheme [36], in which the correlated exciton wave functions are described as a linear combination of singly excited Slater determinants while the Hamiltonian is constructed from the electron-hole Coulomb and exchange integrals. The latter were calculated from the SLCBB wave functions and screened according to the Resta model [37].

In Figure 3 we show the polarisation of the two decay paths from the exciton state, with polar diagrams of the squared optical transition dipole matrix element calculated for the 3 cases described above as a function of the miscut angle α. For GaAs/AlAs(111) QDs...
FIG. 4. Spatial profile of the electron \( (e_0) \) and hole \( (h_0) \) wave functions calculated for GaAs/AlAs QDs (top panel) and InAs/GaAs QDs (bottom panel) with miscut angle \( \alpha \) ranging from 0° to 3°. The quantisation axis, i.e. [111], is pointing towards the reader.

characterized by the exact \( C_{3v} \) symmetry, the two decay paths from the exciton state are indistinguishable at \( \alpha = 0° \) and therefore can be represented by circularly polarised emission.

When a miscut is introduced, the decay paths become distinguishable and the polarisation of the emitted photons reconfigures such that the lowest lying bright exciton state (\( X_{\text{LOW}} \)) is polarised along the [110] crystal axis whereas the polarisation of second bright exciton (\( X_{\text{HIGH}} \)), higher in energy, is oriented perpendicularly along [112]. The net total polarisation aligns with [110] and the degree of linear polarisation (DLP) increases slightly with the miscut.

If the AlAs barrier is replaced with \( \text{Al}_{0.15}\text{Ga}_{0.85}\text{As} \) the degeneracy of the exciton states for \( \alpha = 0° \) is broken, presumably because of the inhomogeneous composition. Furthermore, the rotation of the polarisation as a function of the miscut progresses smoothly such that perfect alignment with the crystallographic axes is only achieved for higher values of \( \alpha \). Finally, InAs/GaAs(111) QDs shows the same behaviour already described for GaAs/AlAs(111), but with a steeper increase of the DLP.

These simulations explain the experimental results reported in Figure 2, indicating that the 5 data points in Figure 2 with polarization oriented along [110] are most likely biexciton transitions. To clarify the physical origin of this behaviour, Figure 4 presents the charge densities of the electrons \( (e_0) \) and holes \( (h_0) \) in the conduction and valence ground states for GaAs/AlAs(111) and InAs/GaAs(111) QDs. In strain-free QDs both the hole and electron wave functions have a circular s-like symmetry for \( \alpha = 0° \). The introduction of the miscut steps makes the side of the QD towards [112] thicker than the one towards [112]. As a result, the wave functions localise at the thicker edge of the dot and their spatial distribution becomes strongly elongated in the [110] direction. The same situation is observed in the alloyed case, except for the distortion in the otherwise circular wave function that it causes.

The picture becomes more complicated in InAs/GaAs(111) QDs: in fact, the electron wave functions can spread more than in the strain-free case (Figure 4) and they are also found to be more elongated in the [110] direction. At the same time, the holes are more confined (Figure 4m) so that their progression towards the edge of the QD is slower and their charge densities are less elongated than in GaAs/AlAs(111) QDs. The elongation of the electron wave function increases with the miscut and is responsible for the growth of the intensity of polarisation along [110] \( (I_{[110]}) \) in agreement with previous studies on elongated QDs [38]. Nevertheless, because of the different progression of the wave functions towards the edge of the dot, there may be a second motivation behind the optical anisotropy which
derives directly from the definition of the dipole moment and is not only function of the elongation but also of the spatial separation between opposite carriers \((d_{eh})\). In fact, such a distance remains nearly constant and close to zero in the [110] direction but keeps diminishing along [11\(\bar{2}\)] as \(\alpha\) increases, which ultimately provokes a lowering of the intensity of polarisation along [11\(\bar{2}\)] \((\vec{I}^{[11\bar{2}]}))

The combination of the two phenomena discussed above lies behind the optical anisotropy in QDs grown on (111) vicinal substrates and the resulting preferential orientation for the polarisation of the neutral excitons observed in our measurements. It is now clear that in GaAs/AlGaAs QDs the anisotropy originates from the elongation of the electron and hole wave functions which are localised within the same effective volume of interaction. On the other hand, in InAs/GaAs QDs, the two effects discussed above come into play so that \((\vec{I}^{[11\bar{2}]}))\) is modulated by the magnitude of \(d_{eh}\). As a result, when a 2° miscut is introduced the polarisation aligns with the direction of the steps in both cases, but with a different DLP.

Finally, the analysis presented here is intended to provide an intuitive explanation connecting the shape of the envelope functions to the optical properties of the QDs. A more rigorous treatment would require taking into account the heavy-hole light-hole mixing and the Bloch functions, which are directly affecting the polarisation anisotropy [49].

V. CONCLUSIONS

Previous reports have demonstrated the growth on GaAs(111)A vicinal substrates of DE InAs/InAlAs QDs with low FSS that can be used to generate entangled photons at telecom wavelength. Nevertheless, for their practical use in quantum communication applications it is highly desirable to improve the photon extraction efficiency.

In this work we showed that incorporating the QDs in an optical microcavity based on GaAs/AlGaAs distributed Bragg reflectors produces an enhancement of the brightness by a factor > 5 in the telecom O-band, together with a remarkable reduction in the density of spectral lines and background. The optical characterization of the sample also revealed that the fraction of emitters with less than 50 \(\mu\)eV splitting is approximately 50%. Because of the wide applicability of the DE growth scheme, those results can be easily transferred to different wavelengths or material systems.

Further improvements in the extraction efficiency can be achieved by etching nanostructures such as mesas or micropillars. Also, linewidths and FSS can be reduced by changing the composition of the barrier layer from InAlAs to InGaAs [24] and employing a smaller miscut angle, respectively.

Finally, we reported that the QDs tend to have dipoles aligned along a specific direction, despite the symmetry of the (111)-oriented substrate. In fact, numerical simulations based on the EPM and CI methods have confirmed that presence the miscut modifies the spatial distribution of the electron and hole wave functions, leading to their elongation in the [110] direction. This phenomenon influences the polarization of the excitonic states introducing a clear preferential orientation in the natural \(C_{3v}\) symmetry of the surface, while the addition of strain due to lattice mismatch modulates and enhances this effect.

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