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Physical properties of highly uniform InGaAs pyramidal quantum dots with GaAs barriers: Fine structure splitting in pre-patterned substrates

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ABSTRACT

InGaAs Quantum Dots embedded in GaAs barriers, grown in inverted tetrahedral recesses of ∼7 μm edge, have showed interesting characteristics in terms of uniformity and spectral narrowness of the emission. In this paper we present a study on the fine structure splitting (FSS). The investigation of about 40 single quantum dots revealed two main points: (1) the values of this parameter are very similar from dot to dot, proving again the uniformity of Pyramidal QD properties, (2) there is a little chance, in the sample investigated, to find a dot with natural zero splitting, but the values found (the mean being ∼13 μeV) should always guarantee the capability of restoring the degeneracy with some corrective technique (e.g. application of a small magnetic field).

1. Introduction

Semiconductor Quantum Dots (QDs) are instruments of paramount importance for investigating the properties of the low-dimensional solid state. The proven capability of QDs to emit single and entangled photons [1,2] has renewed the interest for these nanostructures, especially since scientists started to look for a way to realize an appropriate photon source suitable for the nascent fields of quantum information, quantum computing and quantum key distribution. If the realization of such a "good" single photon source is a challenge on its own, an entangled photon emitter is even more delicate. Its realization with QDs is hindered by the very nature of the crystalline environment: structural asymmetries, defects, piezoelectric fields, alloy disorder [3–5] etc.; each of these factors

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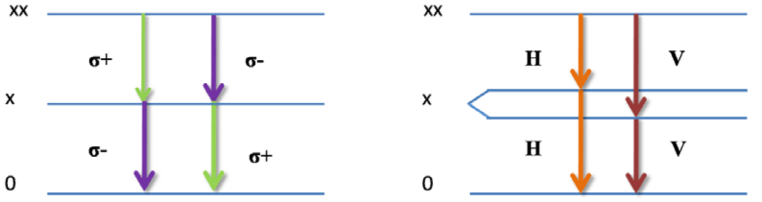

Fig. 1. (Colour online) Decay paths for the exciton (X) and biexciton (XX) in the case of degenerate levels (left) and split levels (right). In the first case the photons emitted are circular, in the second the mixing of states produced by asymmetries gives rise to linearly polarized photons.

can potentially lift the degeneracy between the cascaded photon pairs, giving origin to the so-called fine structure splitting (FSS) and destroying entanglement.

Recent studies on site-controlled InGaAs QDs embedded in GaAs barriers grown in inverted tetrahedral recesses have showed that this system has interesting characteristics in terms of uniformity and spectral purity: the standard deviation over a broad ensemble of pyramids of the neutral exciton emission energy was found to be only 1.19 meV, while the narrowest linewidth measured (18 μeV), obtained in conditions of low excitation, set the state of the art for site-controlled systems in terms of spectral purity [6].

Given these results, it is quite natural to further investigate this kind of dots in order to understand their eligibility as high quality sources of entangled photons, especially as a system, similarly based on InGaAs Dots embedded in GaAs barriers (but with a much smaller patterning pitch, i.e. with different growth and physical properties), has very recently proven to be suitable for the scope with carefully selected dots [7]. Indeed no geometrically induced level splitting is expected *a priori* since the C_{3v} symmetry of the tetrahedral recess (Fig. 4-inset) as a result of the (111) crystallographic symmetry does not exhibit any preferential axis. This has lead a number of authors [8–10] to suggest QDs grown on (111) surfaces as ideal for the production of entangled photons sources.

We present here the results of the study on about 40 QDs in one of our, spectrally speaking, best samples [6] in order to estimate the range of values of the fine structure splitting (FSS) characterizing the system. The main feature emerging from the study is a high uniformity and a small value of this parameter especially if compared to Stranski–Krastanow QDs: the average value of the splitting was found to be 12.9 μeV. Further work will be needed to elucidate the origin of such splitting in order to improve our control and to reproducibly obtain nearly zero FSS.

2. Results and discussion

The epitaxial growth of the layers occurs by metalorganic vapour phase epitaxy (MOVPE) on GaAs (111)B ± 0.1° substrate pre-patterned with a regular matrix of 7.5 μm pitch inverted tetrahedral recesses. As result of the selective etching process, the pyramids expose sharp lateral facets with crystallographic orientation (111)A [11]. The temperature during the growth of the inner barriers and the QD itself is kept around 730 °C (thermocouple reading), the V/III ratio in the range 600–800. The QD layer is composed by $In_{0.25}Ga_{0.75}As$ nominally 0.5 nm thick, the barriers by pure GaAs.

The measurements of the fine structure splitting were taken at 10 K in a low vibrations He closed cycle cryostat by high resolution (5 μeV) polarization resolving spectroscopy (basically by rotation of a half waveplate preceding a fixed polarizer in the signal path). The sample was illuminated by a continuous red diode laser at 656 nm; light was collected with a 100 × microscope objective and sent to 1 m long monochromator equipped with a 2048 pixels CCD array. The measurements were taken "as grown" after just a quick surface cleaning, but no substrate removal procedures [6]. Therefore relatively high pump powers were to be used during the measurements with the consequent line broadening due to excess carrier generation. In these conditions the average linewidth of the exciton line was around 100 μeV as explained in Ref. [6].

In Fig. 1 is shown a schematic representation of the effects of FSS [2]: in the presence of splitting the otherwise circularly polarized and indistinguishable photons generated by the recombination