Electrical switching of photoluminescence of single site-controlled InAs quantum dots

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Voltage-controlled photoluminescence (PL) switching is demonstrated for single site-controlled InAs quantum dots (QDs) embedded in Schottky-i-n diodes grown by molecular beam epitaxy on nanoimprint lithography patterned GaAs templates. The PL emission was quenched by applying a voltage over the diode structure due to the increased tunnelling rate of charge carriers out of the QDs.

Introduction: In recent years, quantum dots (QD) have found application in novel displays [1], solar cell concentrators [2] and advanced light sources [3]. Furthermore, in all-optical computing, which requires nanosized light sources, QDs are ideal because of their small size, robustness and quantum efficiency. For the development of single QD-based applications, it is crucial to control the location and control the optical properties of the individual QD. With epitaxially grown QDs, lateral positioning can be achieved by patterning the substrates before QD deposition [4]. Control of the emission, for example, switching on and off, can be realised by embedding the QDs in diode structures and using electric fields [5]. In addition, arrays of QDs at controlled distances are a potential building block for QD cellular automata (QCA), in which logical operations are affected by internal reorganisation of charges within the cells of QDs and which enable computation after photoexcitation could be a new path to addressing, clocking and reading of QCAs.

In this Letter, we demonstrate voltage-controlled switching of the photoluminescence (PL) of single, site-controlled InAs QDs despite a considerable amount of defects from the regrowth interface close to the QDs. The electric field is applied parallel to the growth axis. Though the PL emission of site-controlled QDs (SCQDs) can be controlled by the electric field, regrowth interfaces in the junction must also be considered.

Experiments: The site-controlled InAs QDs were grown on a patterned n-GaAs(001) wafer by molecular beam epitaxy (MBE). First, an n-GaAs (N_D = 10^{19} cm^{-3} where N_D is the density of donor atoms) buffer and an undoped GaAs layer of 200 and 100 nm thicknesses, respectively, were grown. Afterwards, a soft ultraviolet nanoimprint lithography process was applied in order to pattern the GaAs surface. Dry etching was used to form pits for QD nucleation as well as alignment marks in the same patterning step. The pits were aligned in a square array with a period of 2.5 μm and diameters of 80, 100 and 120 nm, with a depth of 15–20 nm. In the next step, the samples were chemically cleaned, and the native oxide was removed. Subsequently, the samples were loaded into the MBE chamber. These processes are described in [7]. After patterning, a 30 nm undoped GaAs buffer layer and 1.8 monolayers of InAs were deposited at 470 and 540°C, respectively. For surface characterisation, the sample was unloaded from the MBE chamber after the QD deposition. For micro-PL (μ-PL) studies, the QDs were capped by 100 nm undoped GaAs grown at 540°C. The full layer structure is sketched in Fig. 1a. Atomic force microscopy and SEM were used to characterise the surface samples.

To characterise optically SCQDs, the QDs were embedded under a GaAs cap, the sample was loaded into a low-vibration closed-cycle helium cryostat and the μ-PL was measured at 5 K temperature. QDs were optically exited with a laser diode at 640 nm. An approximately 1 μm spot diameter was achieved with a 50X high numerical aperture objective, which was also used to collect the PL signal. A 0.75 m spectrometer with a 1800 lines/mm grating and a cooled Si CCD camera was used to analyse the spectrum.

For electrical measurements, a 7 nm thick semi-transparent titanium Schottky contact on top and an ohmic Ni/Au/Ge/Au contact on bottom were prepared. A microscope image of the processed sample is shown in Fig. 1b. The marker structure and the titanium contact are clearly visible. The array markers surrounding the SCQDs (Fig. 1d) are depicted in Fig. 1c. Each of these areas contains an array of 5 × 5 QDs with a period of 2.5 μm.

Results and discussion: To study the QD PL emission as a function of electric field, first we measured the excitation-power dependent μ-PL of a suitable InAs QD, as shown in Fig. 2. The exciton (X) and bie exciton (XX) emission lines are identified according to their PL intensities when excited with different laser powers. The X and XX have slopes of 0.75 and 1.4, respectively, in the log-log depiction of PL intensity against excitation power, which is common for typical InAs QDs [8].

Fig. 2 Excitation-power dependent μ-PL of InAs QD. Exciton (X) and bie exciton (XX) emission lines are identified

Fig. 3 μ-PL measurements of single SCQDs against applied voltage. Inset shows wavelength shift of X emission

Fig. 3 presents μ-PL measurements of the same single QD against the applied voltage across the Schottky junction. PL quenching is clearly observed when the voltage is made more negative. By −2 V the PL emissions of the X and XX have disappeared. Furthermore, we observe a slight shift of the X PL wavelength against the reverse voltage, as shown in the inset of Fig. 3. The decreasing PL signal is explained by an increased tunnelling rate of charge carriers, mainly electrons due to their lower effective mass, out of the QDs. At a certain
point, below −0.8 V in this case, the electrons tunnel faster than they can recombine radiatively. Thus, the exciton peaks are quenched in the PL spectrum. The wavelength shift is attributed to the quantum confined Stark effect, in which the applied electric field modifies the band structure of the QDs resulting in the wavelength shift of the exciton lines. The PL intensities of the exciton and the biexciton against the voltage are shown in Fig. 4. The quenching of the PL signal of the X and XX appears at different voltages (X: −2 V, XX: −1.6 V). This is related to the different saturation levels of the exciton and the biexciton. Steps in the PL intensities against voltages are observed for both the exciton and the biexciton. These can be associated to the non-homogeneous electric field distribution in the junction due to the regrowth interface.

Fig. 4 Exciton and biexciton PL intensities of single, site-controlled InAs QD against applied voltage.

Conclusion: We have demonstrated voltage-controlled PL emission of single, site-controlled InAs QDs embedded in Schottky–i–n diodes. Despite the considerable amount of defects in the regrowth interface as a result of the patterning process, the emission of excitons and biexcitons can be quenched by the applied electric field. This enables the use of voltage control to influence the charge states of QDs after optical excitation. In the future, voltage control of the PL will enable QDs to be used as optical switches and as means to manipulate single-photon sources. In addition, control of the charge states in QD arrays can be a promising path towards QCAs controlled by a combination of electric field and light.

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