A Site-Controlled Quantum Dot Light-Emitting Diode of Polarization-Entangled Photons, Violating Bell's Inequality

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Abstract: The first site-controlled quantum dot light-emitting diode of non-classical light – single and polarization-entangled photons – violating Bell's inequality is presented in this work. The diode structure is based on highly symmetric, single, site-controlled pyramidal quantum dots.
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1. Introduction

Quantum Dots (QDs) are, ideally, sources of non-classical light – single and entangled photons. However, the requirements for practical applications, such as integrated quantum information processing circuits, are far more demanding than most of the current QD systems can deliver. Among the requirements are site-control, emission uniformity, spectral purity, and high QD symmetry. We have already shown that these properties are significantly improved by the Pyramidal QD system – site-controlled InGaAs QDs grown by Metalorganic Vapor Phase Epitaxy (MOVPE) in inverted pyramidal recesses etched in (111)B oriented GaAs substrates [1-3]. At the time, a high density of polarization-entangled photon emitters was shown from optically excited QDs. However, electrical injection is preferred in integrated devices. In this work, we show a further progress towards this by presenting our QDs as high performing, electrically driven sources of non-classical light.

2. Results

QD LEDs were fabricated from samples with single $In_{0.25}Ga_{0.75}As$ QDs grown in tetrahedron recesses (pitch of 7.5 or 10 µm) etched in (111)B oriented GaAs substrates. The non-planar geometry of the grown structure involves a specific set of processing steps to create metallic (Au) contacts in the region of the preferential QD injection as shown by our sketch of the final LED structure in Fig. 1(left). Our design of the final *pin* structure allows a flow of current only in the region close to the central axis of the pyramid, so to inject only the QD. Fig. 1(right) confirms that the device is a diode with a characteristic diode-like IV curve, end electroluminescence at 8K. The broad field electroluminescence at the voltages of 14.1 and 12.3 V shown in the images is not spectrally filtered and comes from an ensemble of self-formed InGaAs nanostructures, see for example [4].

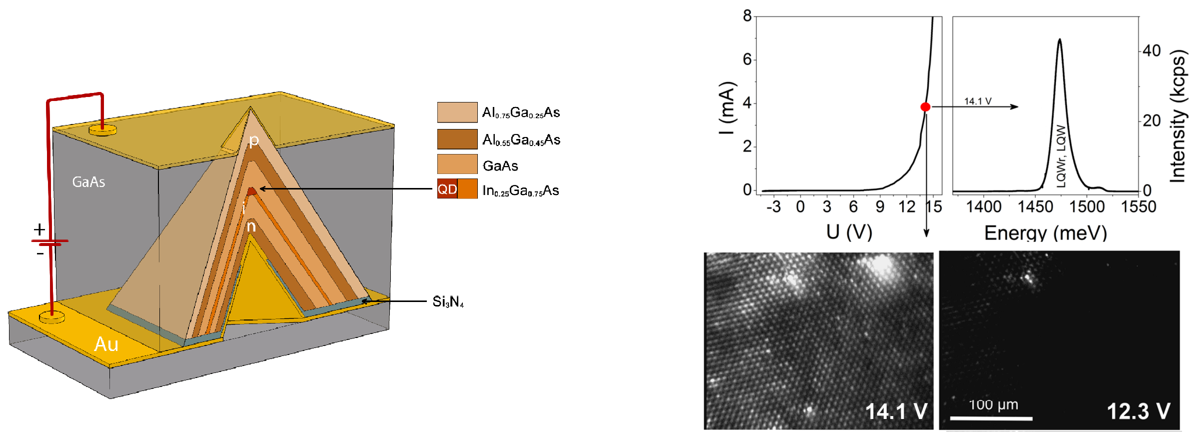

Fig. 1. (Left) The cross-section sketch of a single QD LED. (Right) Electroluminescence from a field of site-controlled LEDs with nearly each individual pyramids emitting: the IV curve, spectrum and CCD images at different voltage values.

The electroluminescence features of single QDs were studied in a standard micro-photoluminescence set-up. The QD intensity dependence on the applied voltage is shown in Fig. 2(left). In this representative case, the dominant transition is a negative trion, exceeding in intensity the other two – an exciton (X) and biexciton (XX). Correlation measurements of single photon detection events proved that the emitted light showed a sub-Poissonian distribution statistics – i.e. single photon emission (not shown here).

The X and XX transitions are of a particular interest, as these photons are emitted in the cascade (XX→X) and they are, potentially, polarization-entangled, provided the recombination process occurs coherently [5,6]. Here, we discuss the representative dot with the spectrum shown in Fig. 2(left) which also featured a small fine-structure splitting of 0.2±0.2 μeV- a necessary condition to ensure that a QD can be a bright source of entangled photons described by the Bell state $\left|\Phi^+\right\rangle = \frac{1}{\sqrt{2}}\left(\left|HH\right\rangle + \left|VV\right\rangle\right)$. A standard procedure [6] – polarization-resolved cross-correlation measurements between XX and X photons – was carried out to measure the fidelity to the expected maximally entangled state $\left|\Phi^+\right\rangle$. Measurements were taken in both, constant and pulsed current, injection modes. To note that, the pulsed mode is of bigger practical interest, as the photon emission can be considered as triggered/on demand. The clear, “characteristic”, polarization correlations in the pulsed second-order correlation curves shown in Fig. 2(right) confirm the non-classical behavior of the polarization states. The fidelity value obtained was 0.678±0.023. This set of measurements allowed a simplified estimate of the Bell parameter S_{CHSH}, which, within broad assumptions, can be mathematically expressed by three equivalent parameters S_{LD}, S_{LC} and S_{DC} as discussed in [7]. By using a gating technique and discarding photons outside a 1.8 ns window, all Bell’s parameters exceeded the limit of 2, violating Bell’s inequality, while maintaining 77% of the overall intensity (inset of Fig. 2(right))

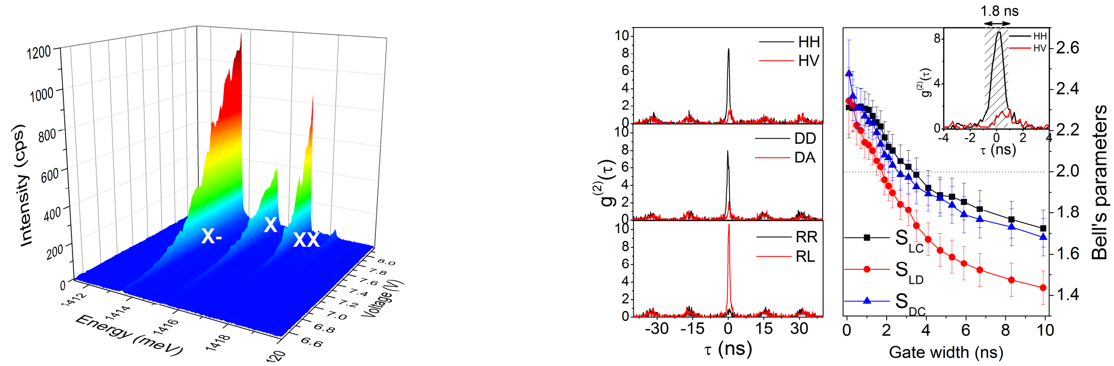

Fig. 2. (Left) The spectrum of a representative QD LED at different voltage values. (Right) Polarization-resolved second-order correlation curves (between biexciton and exciton photons) that show entanglement of the polarization states; Bell’s parameters gating dependence..

3. Summary

The first site-controlled LED of triggered single and polarization-entangled photons was presented in this work. Violation of Bell’s inequality shows a high quality of the source and its strong potential for application to integrated quantum information processing devices.

4. References

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