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On-demand single-photons from electrically-injected site-controlled Pyramidal Quantum Dots

On-demand single-photons from electrically-injected site-controlled Pyramidal Quantum Dots

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Abstract
We report on the performance of electrically-injected Pyramidal Quantum Dots in terms of single-photon emission. We previously presented the generation of entangled photon pairs from similarly structured devices. Here we show that it is also possible to obtain single-photons upon continuous wave excitation as well as pulsed excitation, obtaining a low $g^2(0)$ of 0.088±0.059, by discarding re-excitation events within a single excitation pulse by applying time-gating techniques.

1. Introduction

Integration, scalability, reproducibility and high quantum state fidelities: these are some of the main technological challenges to be tackled in order to achieve a realistic source of photons to be employed in quantum computation [1][2]. Semiconductor quantum dot (QD)-based light sources have recently been gaining great relevance in this perspective, as they can be employed for the generation of quantum light while allowing for processing by means of standard semiconductor-based fabrication and integration techniques. Semiconductor QDs have been demonstrated as sources of single photons [3][4][5], highly indistinguishable photons[6][7], entangled photon pairs with high fidelity[8][9][10], time-bin entangled photons [11] and more, thanks to their versatility and tunability. In addition to this, among the requirements for a QD-based technology for quantum computation, efficient electrical injection would allow an extremely simplified excitation scheme and therefore easier QD integration.

Electroluminescence from semiconductor QDs has been reportedly achieved in the past[12], together with electrically driven single photon emission[13][14] and entangled photon emission[9][15], but only a few reported cases claimed to be site controlled as well[16][17]. Although, in most of these cases, it was generally about the possibility to statistically control the self-assembled QDs position, while the only instance of true deterministic site control of the electrically driven QDs was based on Pyramidal Quantum Dots (PQDs)[18][19], but without proof of single photon emission. Note also that references [18][19] discuss two different pyramidal site controlled material systems, each showing different challenges of their own, one based on AlGaAs barriers [20], the other on GaAs barriers.

Here we report for the first time on the possibility of generating single photons by embedding PQDs into a PIN-junction device, a structure largely similar to previous designs for entangled photon emission reported in [19], and therefore proving single photon electrically driven emission from a true site-controlled QD system. Besides the statistic regarding directly single-photon emission quality, we find that our analysis also provides interesting insight on the ability of filtering photon detection events to improve the performance of our devices. Our findings suggest, after a comparison with previous work on entangled-photon emission through electrical injection, that a good entangled photon emitter from QDs is not necessarily also a good single photon emitter (and, obviously, vice versa). We address this point more in detail further in our contribution.

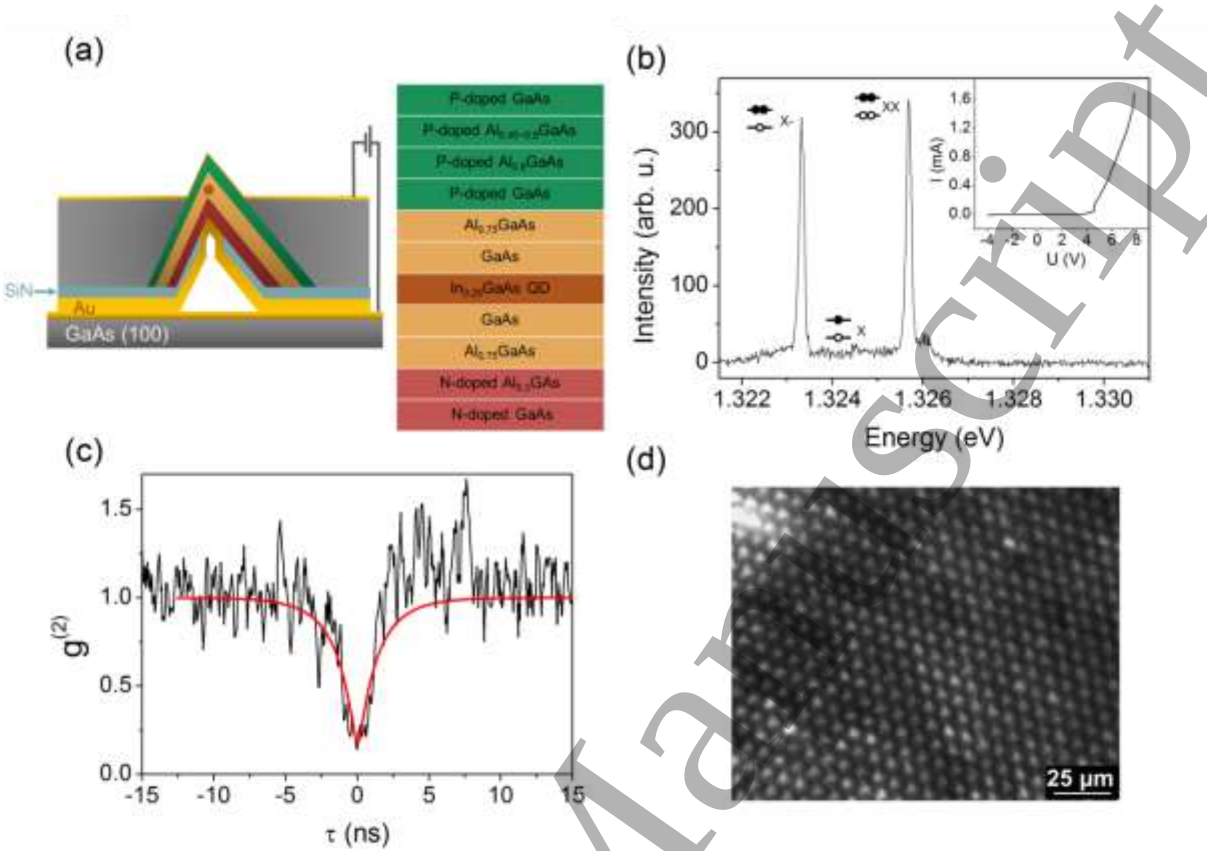

Fig.1: a) a sketch of a structure of a PQD-based LED; b) representative spectrum from an electrically injected PQD, showing a dominant X- behavior and an almost suppressed X and (inset) typical IV response of a PQD-based LED; c) autocorrelation for the X- transition from an electrically-driven PQD under DC bias excitation (black line) and fitting of the data using a $g^2(\tau)$ function convoluted with the response function for the measurement apparatus; d) CCD image of lit PQD-LEDs under DC bias excitation.

2. Fabrication and characterization methods

PQDs are fabricated starting from a (111)B GaAs wafer using a lithography based patterning technique to form an ordered array of inverted pyramidal recesses; Metalorganic Vapor Phase Epitaxy is then performed, allowing for the site control of the QDs, one for each recess. More recently we developed a more advanced type of device design for the realization of electrical injection. As detailed elsewhere [19], the QD is embedded into the intrinsic region of the PIN junction, whose detailed structure is reported in the supplementary material. The complex geometry and copiousness of nanostructure formation (e.g. lateral quantum wires formed along the edges of the pyramidal recess and lateral quantum wells formed along its sidewalls, see [21] and references therein) of the pyramidal system makes it necessary to perform a number of processing steps to achieve the proper electrical contacting of the devices: insulation of the corners of the pyramid, masking of the insulation through tilted Au evaporation, selective removal of the insulation, P-side contacting, back-etching [22], and N-side contacting. For simplicity of fabrication, the scheme relies on the simultaneous contacting of all the pyramidal QD devices, which share the same top and bottom contacts and therefore share the same applied electrical bias. Henceforth the electrical properties of the device we will refer to in this paper will be the total ensemble current vs. voltage characteristics. A typical I-V curve for one of our devices is shown in Fig.1b (inset), where it can be seen that the exponential rise in the current is obtained at about 6 V.

It is worth underling at this point the possible origin of the high turn-on voltage in our devices, compared to similar LED devices[23][9]. On one hand, the metal used for the metallization of the GaAs P-doped layer is not ideal and might be causing a Schottky barrier [24]. On the other hand, the carriers have to be channeled through a Ga-rich AlGaAs vertical quantum wire with a very small cross-section (<40 nm diameter through the centre of the pyramid)[19], which might cause a high resistance, although forcing the carrier through the centre of the structure, towards the QD. It is also relevant to note that different QDs could show different turn-on voltages: this is mainly due to the spread in etching depth of the original GaAs substrate on the top of each pyramid, resulting from the back-etching process. Each pyramidal structure presents a slightly different open area on the N-doped region for contacting, therefore leading to a distribution of surface resistances, from which the difference in turn-on voltages.

The QDs were analyzed by low-temperature (10K) micro-electroluminescence spectroscopy using a 100x magnification objective with a numerical aperture of 0.8, allowing for the spatial filtering of the light coming from different PQDs (which had a spacing of 10 μm) simply by scanning on the sample surface by means of piezoelectric actuators. Although the turn-on voltage was slightly different for each individual PQD diode, this was typically around 6 V; voltage at which it was possible to detect excitonic transitions.

3. Results and discussion

Fig.1b shows a representative spectrum from an electrically injected PQD under DC excitation. We identify each transition as exciton (X), biexciton (XX) and a negatively charged exciton (X-; based on previous results [25] where negatively charged excitons and positively charged excitons were systematically identified also by employing a second wavelength excitation for the release of extra holes in the surrounding of the QD), which is typically the predominant transition in terms of intensity. In some cases the exciton was completely suppressed by the excess of negative charges[25]. When operating in DC, it was possible to obtain single-photons from the X- transition, for example. We chose this transition to test for single photon emission mostly as it was the brightest transition of the excitonic ensemble, typically showing at least 3 times the exciton overall intensity, but also because the trion transition is ideally the more suited for single photon emission, not being subject to special selection rules [26]. Moreover, the X- transition is more suitable for the generation of indistinguishable photons, as it is not affected by a fine structure splitting and therefore more often studied for indistinguishability studies (see for example [27]).

A standard HBT setup was employed for autocorrelation measurement. One representative case is shown in Fig.1c. Upon the application of 6.8 V, the $g^2(0)$ autocorrelation function reaches 0.17, which has been fitted taking into account the detector response function (a Gaussian response with 400 ps FWHM).

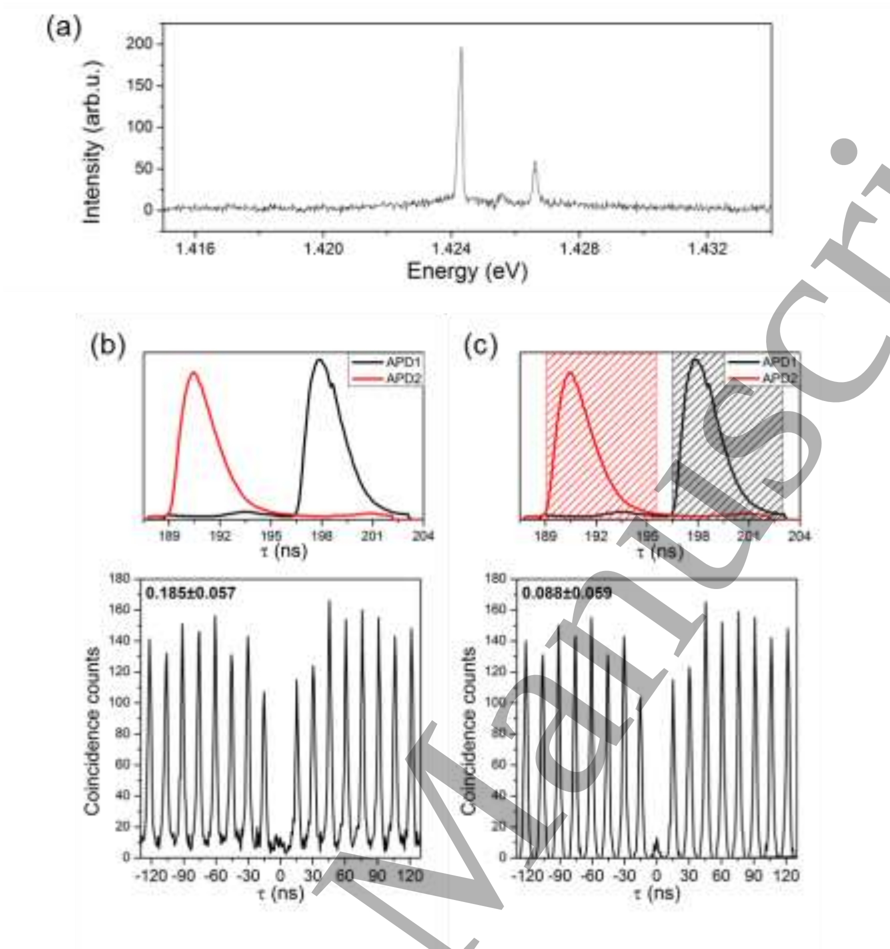

Fig.2: a) Emission dynamics of a PQD under pulsed electrical injection; b) to c) lifetime measurement for the two detectors employed (top) and autocorrelation measurement (bottom) in pulsed excitation selecting different time windows (highlighted in the top graph) within one excitation pulse period for the time gating filtering process: all detection events are selected in b), second-pulses events are discarded in c) by selecting a time window of 6.5 ns; the resulting $g^2(0)$ for each case is shown in the inset of the corresponding graph.

In order to operate the device in pulsed excitation - and prove on demand generation of single photons - we applied a DC bias on the top of which we superimposed the AC pulses. From the I-V curve we can deduce the resistance of the device when the turn-on has been reached, which falls in the kΩ range. This high resistance causes a high impedance mismatch between the LEDs and the pulse generator (which has a standard 50 Ω output resistance). The mismatch could result in reflections of the signal at the device and re-excitation pulses. Since individual QDs had diverse turn-on voltages, different settings of the pulse generator (frequency, DC and AC voltages) resulted in different behaviors of the device in terms e.g. of intensity of the spectrum features and single-photon emission performance. For instance, an inefficient or insufficiently high excitation level leads to a low-intensity spectrum, while an excessive population of the QD would result in a quick re-excitation of the same transition. At different DC and AC voltage levels the whole apparatus and QD system had a different response also in terms of pulse reflections along the line, making it necessary to tune the excitation frequency as well. Therefore ad hoc settings had to be chosen for each individual QD. Nonetheless, in most of the cases it was possible to find a set of parameters for which the PQD could be operated in pulsed excitation in a good regime for single-photon emission.

Fig. 2 shows a representative case: in order to operate the device in pulsed excitation, we applied a DC bias of 0.85 V on the top of which we superimposed a pulse of 8.67 V and 1.425 ns pulse width with a frequency of 66 MHz. The autocorrelation from this type of excitation is presented in Fig.2b: $g^2(0)$ is 0.185±0.057. As it can be seen in the time-dependence in Fig.2, reflections along the line often caused a low intensity second pulse. A time-gating technique was then employed in order to discard such second pulsing event. In this case, the correlation curves were obtained by recording all photon detection events in a time tag mode, followed by a post-construction procedure of the correlation curve [28]. This method allowed testing correlations of photons from different time windows using the raw data obtained at exactly the same experimental conditions. Fig.2c shows the autocorrelation obtained by considering detection events falling only in a determined time window (*time gating*). With a 6.5 ns wide window, the $g^2(0)$ improves significantly to 0.088±0.059), which if corrected for noise levels and detectors time resolution, is effectively a very low value.

Finally, we would like to discuss briefly the different filtering approaches employed in this work and in our previous work on the electrical excitation of PQDs for entangled photon emission [19]. While in this paper we applied a standard time gating technique (as e.g. in [29]) which allows filtering the detection events based on the lifetimes to discard re-excitation events and "restore" the single photon quality, in our previous work [19] we applied a different approach. In [19] we selected a time-window from the correlation measurement itself rather than from the lifetimes, therefore filtering time events based on the direct time difference between the detection of biexciton and exciton related photons coming in sequence in the cascade. This other time-filtering technique allows selecting fast transitions between exciton and biexciton and, if a narrow enough time-window is selected, it discards biexciton re-excitation events, which is necessary but not sufficient to result in single-photon emission. Selecting photons based on the time separation of the biexciton and exciton means to discard background events coming from any type of source of contamination of the correlation and filter the photons which are part of an entangled pair even if they wouldn't be per se single photon events. We could think of this method as of a specific filter for the selection of biexciton-exciton detection events correlated through a direct cascade. To provide an intuitive example, rapid re-excitation of biexciton might occur, followed by a recombination cascade which actually results in entangled photon pair emission, properly selected by the method employed in [19], although the biexciton second photon would degrade the single photon statistics (a similar argument might be employed for exciton re-excitation) and would be discarded in standard time-gating techniques like the one employed in this paper, depending on the selected time-window.

Although it might seem trivial, this was previously unreported for this specific case (and could effectively be useful for practical purposes), while, to some extent, has similarities to what is called, in downconversion processes, photon heralding (see e.g. [30]). The successful application of this post-selection technique used in [19] means in principle that perfect single photon emission is not required to obtain high fidelity (>0.8) entangled photons. Our conclusion is that, although perfect entangled-photon emission is definitely limited by single photon pair quality, generally, high fidelity entanglement can be obtained from non-perfect single-photon emitting devices if the correct events are selected.

4. Conclusion

In conclusion, we showed the single photon emission performance of PQDs under both DC and pulsed electrical excitation, yielding respectively a $g^2(0)$ of 0.17 and 0.185. In pulsed excitation, the application of a simple time gating technique allowed to discard re-excitation events and obtain a $g^2(0)$ of 0.088, therefore proving that it is possible in principle to achieve a high quality single photon emission from our devices. Further improvements will be the subject of future research, and could be achieved either by employing even shorter pulses or improving the overall injection of the PQD, for example reducing the contact resistance or producing smaller pyramids.

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