On Current Injection Into Single Quantum Dots Through Oxide-Confined PN-Diodes

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***Abstract*—Current injection into single quantum dots embedded in vertical pn-diodes featuring oxide apertures is essential to the technological realization of single-photon sources. This requires efficient electrical pumping of sub-micron sized regions under pulsed excitation to achieve control of the carrier population of the desired quantum dots. We show experimental and theoretical evidence for a rapid lateral spreading of the carriers after passing the oxide aperture in the conventional p-i-n-design in the low-injection regime suitable for single-photon emitters. By an alternative design employing p-doping up to the oxide aperture the current spreading can be suppressed resulting in an enhanced current confinement and increased injection efficiencies.**

I. Introduction

For the field of quantum optics, quantum information processing and quantum cryptography [1], [2] the generation of single photons on-demand is an essential functionality. Electrically driven single-photon sources (SPS) have been successfully demonstrated using a layer of quantum dots (QDs) embedded in vertical p-i-n diodes with laterally oxidized apertures [3], [4], see Fig. 1. The OA acts as a buried stressor [5] and modifies the strain field in such a way that the QDs preferably nucleate in the center of the aperture during the Stranski-Krastanov (SK) growth, see [3], [4]. However, the nucleation of randomly occurring parasitic QDs in outlying regions can hardly be avoided as indicated in Fig. 1. Due to the insulating nature of the oxide a current confinement by the aperture can be expected and thus an efficient carrier injection into the site-controlled grown QDs in the center, see Fig. 1. Yet, our experimental and theoretical results obtained in [6] reveal an insufficient current confinement by the OA in the low-injection regime which is characteristic for the operation of SPSs. The electroluminescence map shown in Fig. 2 demonstrates that even QDs located about 7 μm away from the aperture can be excited. In [6] we analyzed this phenomenon by numerical simulation of the carrier transport based on drift-diffusion. Motivated by our findings on the mechanisms leading to the unintended current spreading in the conventional pin-device layout we proposed in [6] a revised pn-junction design which will be discussed in this paper. By a comparison of the conventional against the improved design on the response of the electron density along the QD layer to a pulsed excitation we show that the revised design can provide an efficient electrical pumping of sub-micron sized regions to achieve a control of the carrier populations in the central QDs.

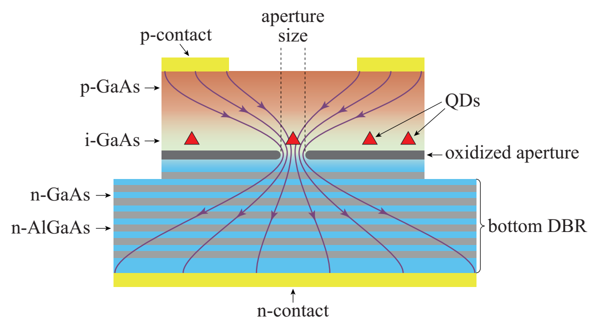

Fig. 1. Schematic of a design for a single-photon emitter based on QDs (indicated as triangles) featuring an oxidized aperture for current funneling and control of the QD nucleation, see [6]. The intuitive current flow paths are illustrated by purple lines.

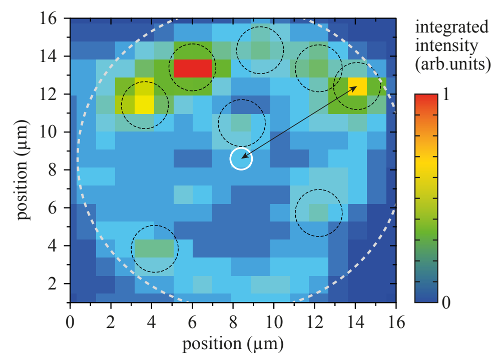

Fig. 2. Electroluminescence map of a mesa at 10 nA revealing several excited parasitic QDs (positions indicated by dashed black circles), see [6]. The white circle shows the OA. The arrow corresponds to a distance of about 7μm between the OA and the parasitic QD. The emission intensity from central QDs is about 30× weaker than from other parasitic QDs.

II. Modeling approach and device designs

In order to understand counterintuitive excitation of the QDs across the whole mesa region fully three-dimensional simulations of the carrier transport using a drift-diffusion model have been carried out using WIAS-TeSCA. The QDs have been neglected in the current calculations to reduce the computational effort. Control calculations additionally taking

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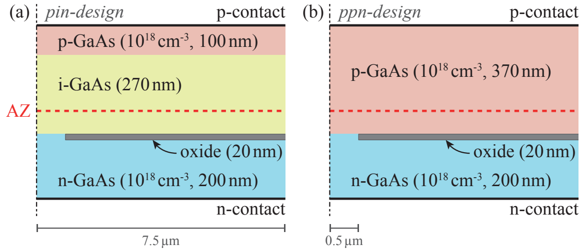

Fig. 3. Cross sections of the device geometries of the two axisymmetric device structures used in the simulation study, see [6]: (a) pin-design containing a 270 nm thick intrinsic layer between the n- and p-doped regions. (b) ppn-design, in which this layer is also p-doped. The materials are GaAs except the current-blocking oxide on top of the n-layer with a thickness of 20 nm forming an aperture with diameter 1 μm for the current. The dashed red line labeled AZ indicates the position of the QD-layer. The QDs are disregarded in the carrier transport simulations.

into account the capture processes into the QDs showed only a weak influence on the carrier flow on large scales justifying this approach, see [6]. This can be explained by the tiny current of about 0.1 nA caused by the recombination of one electron-hole pair captured in a single QD (lifetime $\tau_{\text{rad}} \approx 1\,\text{ns}$) relative to the orders of magnitude larger total current through the device.

We consider two axial symmetric mesa designs differing only in their doping profile (p-i-n and p-p-n), see Fig. 3. The position of the embedded QD-layer called the active zone (AZ) is indicated by a red dashed line. The layer thickness and doping concentration for the pin-design have been chosen close to the experimental structure. To study the carrier flow between the aperture and the AZ the experimental structure has been simplified by modeling the highly conducting cap layer as well as the complete bottom DBR by Ohmic contacts. The cryogenic device temperature of $T = 30K$ assumed for the simulations is challenging for the numerics. For further details and parameters used in the simulation see [6].

III. Simulation Results

In [6] first the carrier flow in the pin-structure has been analyzed under continuous wave excitation showing that the current confinement by a small OA can fail in the low injection regime. The current spreading is explained by unhindered lateral diffusion of electrons above the aperture caused by a huge difference in the effective electron and hole carrier lifetimes. The electron lifetime becomes extremely long due to the orders of magnitude smaller hole density within the intrinsic layer above the oxide. The current spreading can also be observed in the dynamic case of pulsed operation. The temporal evolution of the radial electron distribution along the active zone is depicted in Fig. 4a for the pin-design showing a homogenous rise until a value of about 10^{15} cm^{-3} is reached.

In order to suppress the lifetime-induced current spreading above the oxide a ppn-design has been suggested in [6], in which the intrinsic layer is also p-doped, see Fig. 3. The simulation results under continuous wave excitation confirmed this expectation by showing that electron lifetime indeed

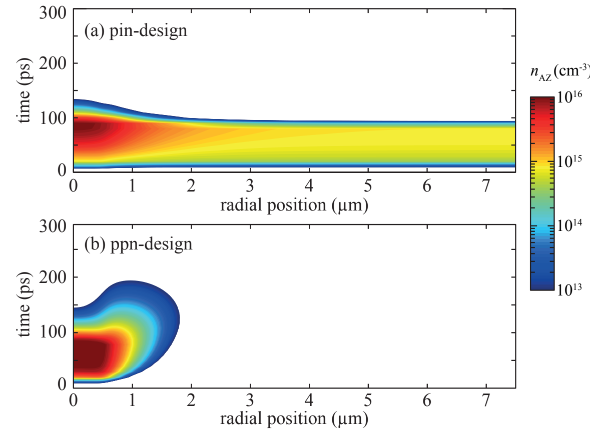

Fig. 4. Response of the electron density in the AZ to a periodically pulsed contact voltage (100 long bias pules with repetition rate of 1 GHz on top of a constant bias voltage U_0 with 20 ps rise and fall time), see [6]. (a) pin-design ($U_0 = 1.43\,\text{V}$, $\Delta U = 70\,\text{mV}$), (b) ppn-design ($U_0 = 1.48\,\text{V}$, $\Delta U = 30\,\text{mV}$).Time is measured relative to the onset of the respective bias pulse. White areas indicate very small electron densities lower than $10^{13}\,\text{cm}^{-3}$ corresponding to capture probability of a QD below 1%.

becomes small and current spreading is drastically reduced. The same effect can be observed in the pulse-response of the ppn-design as illustrated in Fig. 4b where the carrier injection is entirely restricted to the central part. The tradeoff for the excellent current funneling is an increase of total current needed to compensate the larger total recombination. A further consequence of p-doping the active zone is that the emission of positively charged complexes namely trions will become more likely while decreasing the emission from the neutral exciton and bi-exciton.

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