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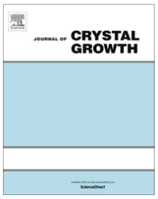

Ultra-low charge and spin noise in self-assembled quantum dots

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ABSTRACT

Self-assembled $In_xGa_{1-x}As$ quantum dots (QDs) are promising hosts for spin qubits with excellent coupling to photons. Nuclear spin and charge fluctuations lead to dephasing and limit the applicability of QDs as qubits. We show that charge noise can be minimized by high quality MBE growth of well-designed heterostructures yielding natural optical linewidths down to 1.15 μeV. To minimize the nuclear spin noise, one direction would be to reduce the wave function overlap with the nuclei. We show that this is indeed the case for a single hole spin in a QD that we embedded in the intrinsic region of an n-i-p-diode. For random nuclei, the heavy-hole limit is achieved down to neV energies, equivalent to dephasing times of microseconds.

1. Introduction

Huge efforts are underway to develop semiconductor nanostructures as sources of identical single photons and low noise hosts for qubits. Nuclear spin and charge fluctuations lead to dephasing and limit their applicability for this purpose. We present routes applied to overcome these issues in our semiconductor QDs by high-quality MBE growth, appropriate heterostructure designs and the use of holes as a qubit.

2. MBE growth

The sample growth is performed on a III-V-Riber-Epineat MBE. The setup is equipped with effusion cells and an electron-beam carbon source from Createc Fischer & Co. GmbH and a Veeco valved cracker. Ultra-high-vacuum is pumped and maintained by two 600 L/s ion getter pumps, a titanium sublimation pump and a liquid nitrogen filled cryo-shroud. Sample loading is done through a loadlock chamber with a 150 °C degas step and a transfer chamber. After careful baceout and several moths of growth, the main chamber base pressure is 10^{-10} Torr when the H_2O partial pressure drops below 10^{-12} Torr. An important point seems to be the gallium material quality, reflecting itself in good electron mobility. Here, we used extra refined Geo gallium (MBE grade+) with a residual resistivity ratio of >75,000. With this state of the setup, an electron mobility of nearly 5×10^6 cm^2/Vs at $T = 4.2$ K is achieved in a two dimensional electron gas, 90 nm deep single heterojunction high electron mobility transistor structure after illumination with a near infrared ($\lambda \approx 950$ nm) LED.

The structures under investigation are grown on semi-insulating (001) oriented surface side polished 625 μm thick 3″ GaAs wafers from Wafer Technology Ltd., grown in vertical gradient freeze mode. An As_4 partial pressure flux of 9.6×10^{-6} Torr and a substrate temperature of $T = 600$ °C, measured with a pyrometer are used throughout the whole growth process, except for the QDs. For the growth of the QDs, the substrate temperature is lowered to 525 °C and the arsenic flux is reduced to 6.8×10^{-6} Torr. After temperature stabilization, nominally 1.6 monolayers of InAs are deposited without wafer rotation to obtain a material gradient on the wafer and QDs are formed by the Stranski-Krastanow

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process [1]. The QDs are then partially capped by 2.6 nm GaAs at 500 °C and flushed for 1 min. to 600 °C at the initial arsenic flux, after which the growth is continued with a GaAs QD cap layer [2]. In the Schottky diode structures (sample A, B and C), this cap consists of 30 nm GaAs for sample A and 150 nm for samples B and C, followed by a short-period superlattice and a GaAs cap layer. In the n-i-p-structure, sample D, the QD cap acts as a tunnel barrier. Doping is performed by a silicon effusion cell for all n-type layers (samples A, B, and D) with a doping density of $N_D = 2 \times 10^{18}\ \mathrm{cm}^{-3}$ and a carbon electron beam cell for p-type doping (samples C and D) with $N_A = 2 \times 10^{18}\ \mathrm{cm}^{-3}$. One specialty in the n-i-p-sample is a 15 nm p^{++} doped contact layer with an acceptor density of $N_A = 1 \times 10^{19}\ \mathrm{cm}^{-3}$ on top of the heterostructure. Sample processing for the n-contacts is done by standard indium solder at the corners. For samples A, B, and C, 8 nm gold is deposited and lithographically defined by lift-off as semi-transparent Schottky-gates. Sample D (n-i-p) is mesa etched and 200 nm thick gold bond pads are deposited to contacts the p-type back contact, while the photon extraction region is left as grown. Note that the "back" contact in this sample is grown on top, see Fig. 1. All samples are equipped with cubic zirconia lenses to enhance the photon collection efficiency. Resonance fluorescence measurements are performed at 4.2 K in a liquid helium cryostat [3].

3. Charge noise

The charge state of the dots can be controlled by the gate voltage, while the DC quantum confined Stark effect additionally shifts the emission line by several meV [4]. The same effect leads to spectral wandering of the emission line from a random electric field induced by fluctuating charges in the crystal host material. Even in high quality material, fluctuating minority carriers at the GaAs/blocking barrier interface result in unwanted charge noise, as demonstrated by Houel et al. [5].

We demonstrate that this charge noise can be suppressed for an n-type Schottky-diode sample by highest quality material growth and by an enlarged capping layer thickness which increases the separation between quantum dots and the fluctuating charges (Fig. 2). An alternative is to make the capping layer thickness very small, pushing the minority charge states well above the quantum dot levels such that the states are unlikely to be occupied at low temperature. For a hole experiment (sample D) [6], we choose such a small capping layer thickness, 10 nm, to suppress these space charge effects and also to prevent optically-excited electrons from tunneling out of the device. Usually, in p-type devices, it is more difficult to achieve high material quality. The reason is threefold: First, growing a p^+ - layer involves heating the carbon cell to very high temperatures: this results in a degradation of the vacuum and a loss of quality of all material grown on top of the p^+ - layer. Second, intrinsic GaAs grown on top of p^+ - GaAs has much poorer optical quality than i-GaAs grown on top of n^+ - GaAs. This is probably related to the lattice defects in the p^+ - layer leading to a broadband of states in the energy gap. Third, even weakly C-doped GaAs is problematic as the carbon atoms represent relatively deep trapping centers. By growing the p^+ - layer last, these problems are avoided: high quality is locked into the intrinsic

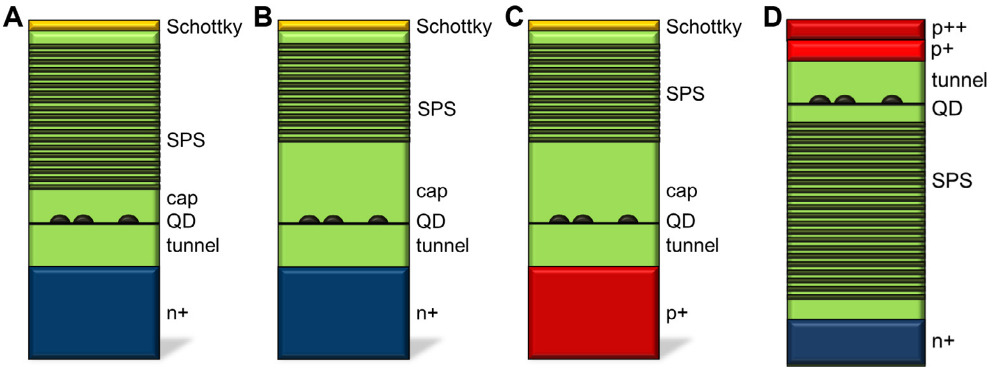

Fig. 1. Sketches of sample structures A–D. The short-period superlattice (SPS) is composed of multiple repetitions of 3 nm AlAs and 1 nm GaAs each. (D) Sketch of the low noise n-i-p heterostructure used in this study. The epitaxial gate is superior to a Schottky gate in various respects: it is lattice-matched and thus strain-free, monolithic, and highly transparent for optics; it has a well-defined potential step; it is grown in situ in the MBE without prior exposure to air and moisture; it withstands higher reverse bias voltages; and it is thermally more stable than a Schottky gate.

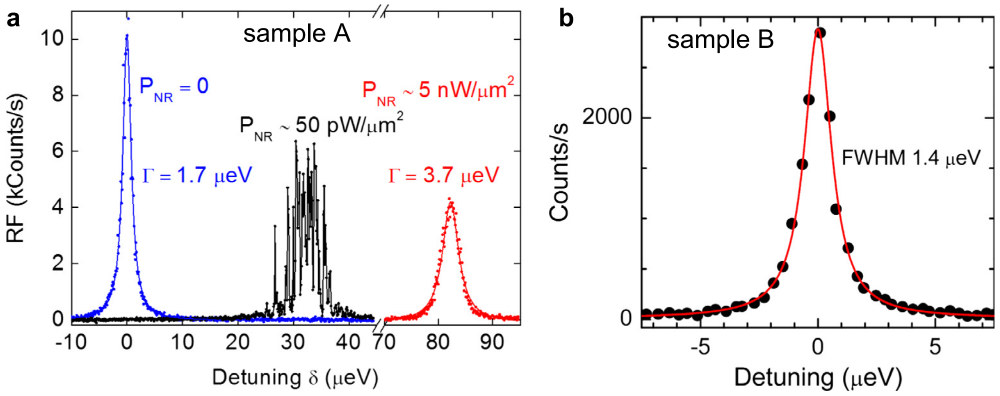

Fig. 2. Resonance fluorescence measurements. (a) Emission line of a QD in sample A. Non-resonant laser light induces strong fluctuations. (b) In sample B, the SPS interface is moved 150 nm above the QD. The linewidth is much narrower due to less charge noise [5].

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