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Single photon detectors based on quantum dot devices – from principle of operation to single photon counting.

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ABSTRACT

We show that by controlling the size of the InAs dots we can increase the signal to noise ratio of the single photon detection, leading to a very low dark count rate ($< 10^{-9}$ ns^{-1}). The maximum rate of photon detection is shown to be 3 MHz and is determined by the time of refilling of the dots after photo-hole capture.

1. INTRODUCTION

Photon counting is a technique that allows measurements of low intensity light with noise limited only by Poissonian statistics. As such it finds many applications in scientific experiments, medicine etc. It is a key component for many quantum cryptography and computation schemes, which rely on coding information on single photons. Most commonly used detectors for photon counting are photomultiplier tubes and avalanche photodiodes [1]. Detectors based on quantum dot semiconductor devices such as field effect transistors (FETs) [2] and resonant tunnelling diodes (RTDs) [3] rely on sensing the charge of a single photo-hole. They are low-power devices and have been demonstrated to operate at 77 K [2].

2. EFFECT OF QUANTUM DOTS ON RTD CHARACTERISTICS

A typical QDRTD detector consists of 10 nm thick GaAs well sandwiched between 5 monolayer thick AlAs barriers. Photons are absorbed in the 300 nm GaAs photon absorber on the collector side of the device. Photo-holes generated in the absorber are captured on InAs quantum dots, positioned 2 nm from the collector barrier of the RTD. The charge of the InAs dots introduces a dipole field in the RTD that locally modifies the tunnelling conditions compared with the device without dots. The high sensitivity of the RTD to the charge in the dots means that a single photo-hole captured on a dot results in measurable current change in devices with a few microns area. The collective effect of the dots results in a shift of the resonance in the device to a higher V_{CE}. This is shown in Figure 1a in - measured 4.5 K - *IV* characteristics of devices from three wafers, which differ only with deposition time of InAs, which was 0, 59s (onset of dot formation) and 79s. The shift of the *IV* characteristics of the two devices with dots as compared with the one without corresponds to a dipole field of uniformly distributed negative charge density of 0.9 and $4.2 \cdot 10^{14}$ m^{-2}, respectively.

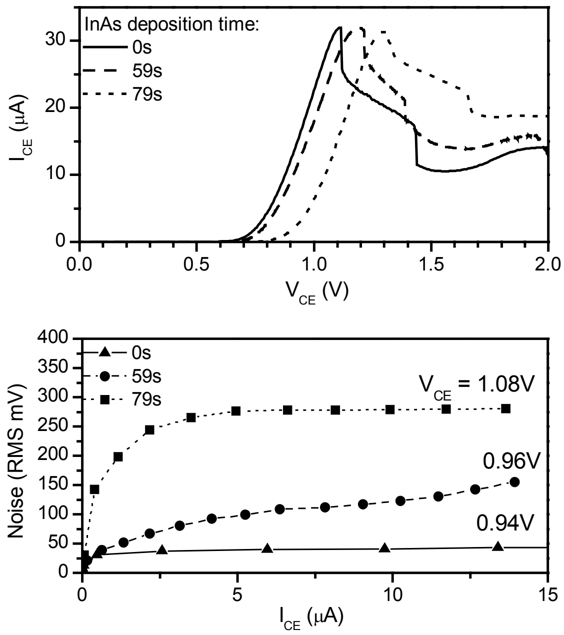

Figure 1a): Current – voltage characteristic of RTDs with different amount of InAs in the collector. b) Corresponding RMS voltage noise measured on the output of the transimpedance amplifier.

The presence of dots in the collector has a strong effect on the noise of the diode, as shown in Figure 1b The noise was measured on the output of the ac transimpedance amplifier with a peak gain of 95mV/nA and a bandpass of 0.6- 4.6 MHz. Since the device in the circuit is biased with 27kΩ resistor in series, we plot the noise in the figure as a function of I_{CE}, on the rising edge of the tunnelling peak. There is no change in the noise measured with quantum dots in the emitter. The excess noise of RTDs with dots on the collector side is caused by charge fluctuations in the dots due to electron tunnelling in and out of the dots and as such is a measure of dark counts in the devices. More InAs results in larger dots, with more states which can contribute to noise. The excess noise in the diode with the lowest deposition time of InAs is small and we found that photon counting using this device can be performed with very low dark count rate.

3. SINGLE PHOTON COUNTING

Photon counting was performed with the device biased at I_{CE} = 4.9μA, with single photon induced current peaks amplified using an ac transimpedance amplifier. The device was illuminated with a 684 nm wavelength pulsed laser with 100 kHz repetition rate. The mean number of photons per pulse was varied between 10^{-2} and 100. Light was focused on the detector area of 0.7 x 3 μm^2 using an objective lens.

Photon counting was performed in gated mode with 260 ns time gate to simultaneously measure photon induced and dark counts, as shown in Figure 2. Photon induced counts are measured with the gate synchronised in time with the laser pulse; the dark counts were measured in between the two laser pulses (5 μs after arrival of the laser pulse).

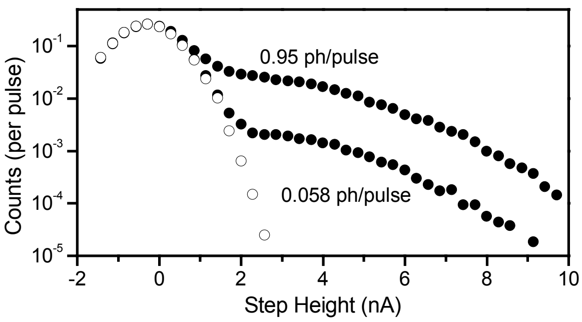

Figure 2: Number of single photon (full circles) and dark counts (open circles) as a function of discriminator level at two different illumination levels. The discriminator level is expressed in units of the RTD current change.

The single photon efficiency for this device is 3% at a 2.3 nA discriminator level, while the dark count rate is 5.8 10^{-7} ns^{-1}. Increasing the discriminator level to 2.8 nA reduces efficiency to 2.5% but the dark count rate is then less than 10^{-9} ns.

Figure 3 shows the frequency dependence of the number of photon induced counts normalised to its maximum value. While the laser clock frequency was varied the mean number of photons in a pulse was constant and equal to 4.7. As the frequency increases the detection efficiency stays constant until it becomes comparable with the rate of refilling of the dots with electrons after capturing of the photo-hole. From fitting the data in Figure 3 the refilling time is determined to be 300ns.

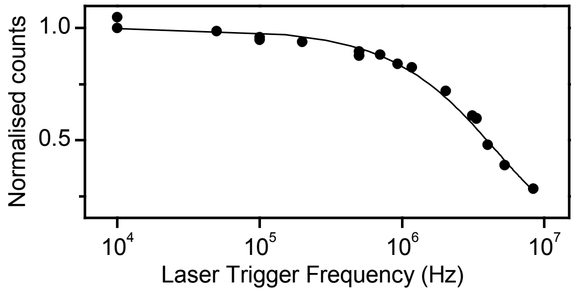

Figure 2: Laser repetition frequency dependence on number of single photon induced counts with constant filling factor of 0.47 photons/pulse.

4. SUMMARY

We have shown that very low dark count single photon counting is achieved in quantum dot resonant tunnelling diodes by keeping the size of the dots, and therefore the number of electronic states low. We showed that when using illumination from 684 nm laser it is possible to count photons with an efficiency of 2.5 % with a dark count rate of less than 10^{-9} ns^{-1}. The detection is possible with a rate of 3MHz. Futher improvement of the dark count rate and the detection rate should be possible by reducing the capacitances in the device and circuit as well as by increasing the current density of the diode.

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