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E-2-1 (Invited)

A Light Emitting Diode for Single Photons

A.J.Shields,[1] Z.Yuan,[1] M.B.Ward,[1] R.M.Stevenson,[1] B.E.Kardynal,[1] P.See,[1] C.Lobo,[2] P.Atkinson[2] and D.A.Ritchie[2]

[1] Toshiba Research Europe Ltd., Cambridge Research Laboratory
260 Cambridge Science Park, Milton Road, Cambridge CB40WE. UK
[2] Cavendish Laboratory., University of Cambridge, Cambridge CB30HE. UK.
Phone: +44-1223-436930 E-mail : andrew.shields@crl.toshiba.co.uk

1. Introduction

Optical implementations of quantum information technology require novel light sources that generate single photons at well regulated times. Such characteristics cannot be obtained using even very faint laser pulses, for which the number of photons per pulse obeys Poissonian statistics. The multi-photon pulses produced in quantum cryptography systems using weak lasers, allow an eavesdropper to perform the optimal photon number splitting attack and thereby greatly restricts the maximum fibre length and bit rate of the system.[1] Single photon sources are thus important for unconditionally secure quantum cryptography, as well as for photonic implementations of quantum computing.[2,3]

A natural approach to generate single photons is to adapt conventional semiconductor light emission technology. A quantum photon source can be fabricated by integrating a single quantum dot into a conventional light emitting diode (LED). [4] Single photon emission has been observed from optically pumped quantum dots by several groups including ourselves. [5-11] The advantage of an electrically driven device is that it eliminates the need for a pump laser and its cumbersome alignment with the quantum dot, which would be difficult in real applications. Electrically driven sources are thus more compact and rugged.

2. Device Structure

The device, shown schematically in Fig.1, consists of a GaAs p-i-n junction with a layer of InAs quantum dots grown inside the intrinsic region. The quantum dot growth was controlled to produce a relatively low density of quantum dots (~3×10^{8} cm^{-2}) and for emission around 900nm. Electroluminescence from a single quantum dot is isolated by a combination of restricting the emitting area using an aperture in the opaque top contact and spectral filtering.

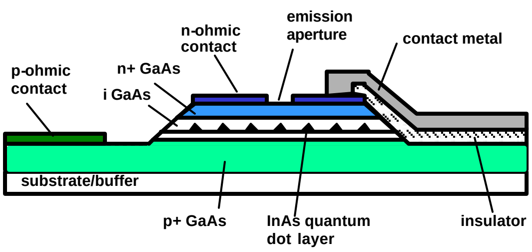

Figure 1: Schematic of single photon LED device structure.

3. Single Dot Electroluminescence

Electro-luminescence spectra recorded on the diode at 5K at low injection currents show a single sharp line is observed near 1.3942 eV. Since the intensity of this line increases approximately linearly with current (I), it is ascribed to recombination of the single exciton (X). At higher injection currents, a second strong line (marked X_2) appears to higher energy. This line, which strengthens with current as $I^{2.0}$, is ascribed to the biexciton transition of the dot. Time resolved photo-luminescence measurements on the same dot determined the exciton and biexciton lifetimes to be 1.02 and 0.47 ns, respectively.[1] We also observe the X decay to be delayed relative to X_2 at high laser power, as expected, since the biexciton photon must be emitted before the exciton.[9]

4. Second Order Correlation Function

The emission statistics from the device were studied using a set-up shown schematically in Fig.2 to measure the second order correlation function, $g^{(2)}(\tau)$. Here the emission is split with a 50/50 beamsplitter and detected using two photon counting avalanche photodiodes. We record the time intervals between counts in the two detectors. A histogram of the frequency of different time intervals is proportional to $g^{(2)}(\tau)$ at low-moderate count rates. A single photon source is characterized by a suppression in the rate of coincidence counts in the two detectors.

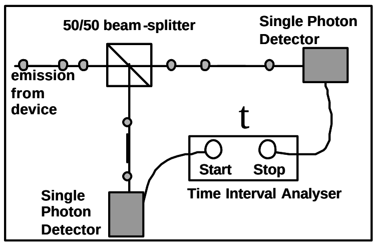

Figure 2: Set up to record emission statistics of the diode.

The diode was biased by applying a dc component of 1.50V superimposed on voltage pulses with a height of 0.15 V, a width of 400 ps and a repetition rate of 80 MHz. The dc component was chosen to be just under the turn-on voltage, so as to generate little electroluminescence.

Figure 3 compares $g^{(2)}(\tau)$ recorded for the exciton transition of the quantum dot, with that of the wetting layer. Notice that both traces consist of a series of peaks separated by the repetition period of the electrical injection pulses. The peaks in the correlation of the wetting layer emission are of roughly equal height. This can be interpreted to mean that two photons are just as likely to be emitted in the

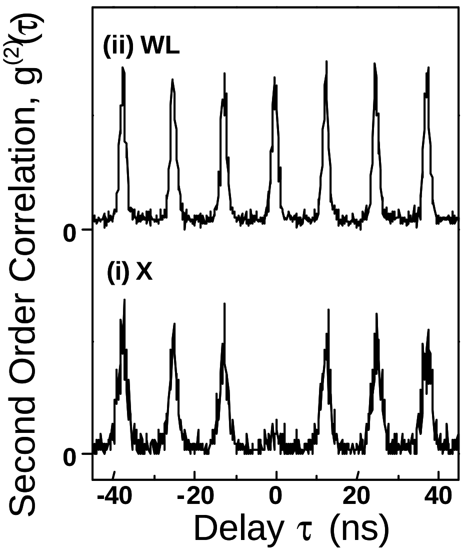

Figure 3 : Second order correlation function recorded for the electroluminescence of the quantum dot and wetting layer. Notice the strong suppression of co-incidence counts, ie $g^{(2)}$ (τ=0), for the quantum dot emission.

same excitation period, as they are to be separated by any finite number of periods. This is the behaviour expected for a LED with random emission times.

For the quantum dot emission, in contrast, the peak at τ=0 is much weaker than those at finite delays, proving that there is a suppression of multi-photon emission from the dot. In fact the strength of the weak τ=0 peak suggests there is an order of magnitude suppression in the multi-photon emission for the single photon LED compared to an ordinary LED of the same average intensity.

5. Single Photon Emission at Fibre Optic Wavelengths

In the experiments described above the quantum dots were designed to emit around 900nm, so as to facilitate detection with a Si CCD or Si avalanche photodiode. We now discuss progress towards creating a single photon source at the wavelengths used for fibre optic communications, namely 1.3 and 1.55 µm. Such development of the device is important for the future utilisation of the single photon LED in fibre based quantum cryptography.

Figure 4 plots 4K electroluminescence spectra recorded for a p-i-n with a low density of dots designed to emit near 1.3 µm. The spectra were recorded using a liquid N cooled InGaAs photodiode array. Discrete sharp lines deriving from individual dots can be clearly observed. The line structure is considerably more complicated than for 900nm dots, consistent with the larger number of electrons and holes that can be confined in these larger dots.

5. Conclusions

These experiments suggest that a semiconductor technology for generating single photons, as well as photon pairs, may be within reach. The electrically driven diode structure would be a particularly attractive source, as it

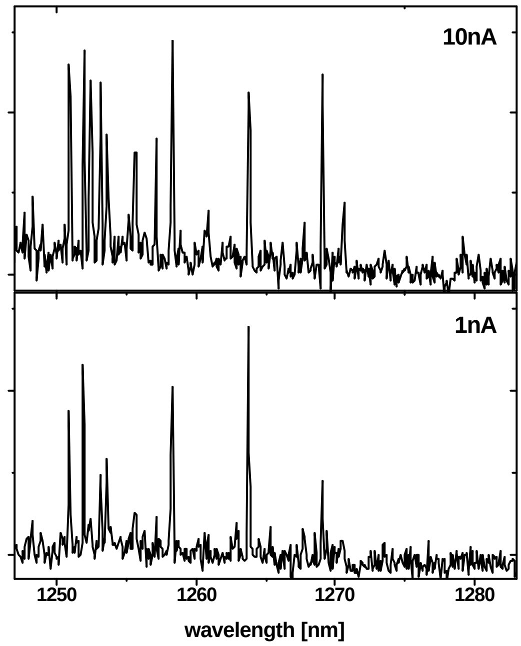

Figure 4 : Electroluminescence spectra of individual quantum dots emitting near 1.3 µm.

avoids the need for a pump laser and its costly alignment with the quantum dot. Potentially this source could be mass produced by photo-lithography on a wafer scale and thus be relatively cheap.

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