Quantum dot single photon sources: blinking and deterministic device fabrication

(Invited)

Marcelo Davanço$^{1,2}$, Luca Sapienza$^{1,2}$, C. Stephen Hellberg$^3$, Serkan Ates$^{1,2}$, Krishna C. Balram$^{1,2}$, Antonio Badolato$^4$, and Kartik Srinivasan$^1$

$^1$Center for Nanoscale Science and Technology, National Institute of Standards and Technology, Gaithersburg, MD 20899
$^2$Maryland Nanocenter, University of Maryland, College Park, MD 20742
$^3$Center for Computational Materials Science, Code 6390, Naval Research Laboratory, Washington, DC 20735
$^4$Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627

Abstract—We discuss both multiple-time-scale blinking and deterministic device fabrication based on quantum dot registration through optical positioning, each within the context of creating bright, high efficiency single photon sources based on self-assembled InAs/GaAs quantum dots.

I. INTRODUCTION

For many applications and experiments in photonic quantum information science, a single photon source operating at high (near-GHz) triggering rates with near unity radiative efficiency into a single mode collection channel would be a valuable resource [1]. Single InAs/GaAs quantum dots grown by molecular beam epitaxy have been viewed as a promising candidate for the creation of such sources for over a decade [2]. Their short radiative lifetime ($\approx 1$ ns) suggests that GHz triggering rates should be achievable, with higher rates possible through Purcell enhancement in suitably engineering photonic environments. Near-unity radiative efficiency into a single desired collection channel also seems feasible, provided the following can be achieved: (1) near-unity radiative recombination efficiency when an electron and a hole (for the neutral exciton state) are simultaneously confined within the quantum dot, and (2) near-unity coupling of the emitted light due to radiative recombination into the desired optical mode.

Here, we discuss two topics of relevance to the creation of such single photon sources. First, we present measurements of multiple-time-scale blinking in these devices, which can limit the quantum radiative efficiency [3]. Next, we discuss a camera-based optical positioning approach, similar to that described in Ref [4], that we are developing in order to deterministically fabricate photonic structures in which the quantum dot location in-plane is optimized.

II. MULTIPLE-TIME-SCALE BLINKING IN QUANTUM DOT SINGLE PHOTON SOURCES

In contrast to colloidal quantum dots, epitaxially-grown InAs/GaAs quantum dots grown by MBE typically exhibit stable fluorescence over time, that is, they do not blink. However, the fabrication of nanophotonic geometries, a necessity in order to efficiently extract emission from the quantum dot into a single mode collection channel, may introduce surfaces in close enough proximity to the quantum dot to alter its radiative behavior. To investigate this issue further, we perform measurements on single quantum dots embedded in circular grating and microdisk cavities (Fig. 1(a)-(b)) that have been operated as bright single photon sources [5], [6]. We use a Hanbury-Brown and Twiss setup (Fig. 1(c)) to measure the photon intensity autocorrelation function $g^{(2)}(\tau)$ over 12 decades in time. In contrast to direct time-trace analysis, $g^{(2)}(\tau)$ is known to have superior characteristics for analyzing blinking in certain respects - namely, no arbitrary choice of time bin width or threshold value is required [7].

Data from one studied device is shown in Fig. 1(e), where the usual antibunching at $\tau=0$ is followed by photon bunching and decay towards unity punctuated by a series of steps. This behavior is indicative of blinking - in contrast, a truly non-blinking structure would show antibunching followed by a monotonic rise in $g^{(2)}(\tau)$ towards unity over a timescale on the order of the radiative lifetime of the system. We find that the blinking occurs over a wide range of timescales - hundreds of nanoseconds to hundreds of milliseconds - and can be well-fit to a model (Fig. 1(d)) in which the radiative transition is coupled to multiple independent dark states. The fit (Fig. 1(e)) yields transition rates and occupancies for all of the dark states, and thus enables an estimate of the radiative efficiency of the quantum dot, which in this case is 78 %. The physical mechanism that causes the blinking cannot be conclusively determined from these measurements alone, though they are consistent with a model in which blinking is caused by tunneling of carriers out of the quantum dot and into nearby (< 50 nm) traps. We are currently trying to understand if the device fabrication process used to create the photonic cavities might be at the root of this blinking behavior.

III. QUANTUM DOT REGISTRATION BY OPTICAL POSITIONING

For nanophotonic geometries such as those shown in Fig. 1(a)-(b), precise location of the quantum dot within the structure is a requirement to achieve optimal performance, both in terms of Purcell enhancement and the fraction of light emission directed into the desired collection channel.
Researchers have developed a number of techniques to determine the location of self-assembled quantum dots with respect to alignment features, including atomic force microscopy [8], scanning confocal photoluminescence microscopy [9], cryogenic photoluminescence spectroscopy and lithography [10], and camera-based photoluminescence microscopy [4]. Here, we adopt the latter technique.

Figure 2 shows a microphotoluminescence image acquired on an electron multiplied CCD camera from a sample illuminated simultaneously by 635 nm and 940 nm wavelength LEDs. The sample consists of a matrix of 2 μm wide gold alignment marks, and the image shows both the fluorescence from a single quantum dot at ~940 nm (excited by the 635 nm LED) and the reflected 940 nm LED light off the alignment marks. Horizontal and vertical line cuts are fit to determine the centers of the markers and the quantum dot. Their separation is determined with an accuracy as good as 20 nm, which is on par with that demonstrated in previous optical positioning work [9], [4]. We will discuss the factors limiting this accuracy, and present results on circular grating cavities fabricated with such optically positioned quantum dots.

**REFERENCES**