Abstract Booklet

Quantum Dot Day 2020

6 January 2020

Clarendon Laboratory, University of Oxford, UK

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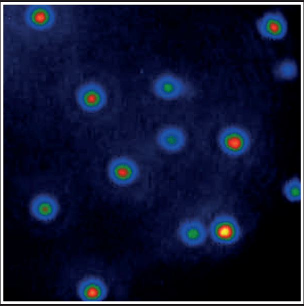

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Programme

10:00	Registration and refreshments
10:30	**(Invited) Design of quantum-dot-based single-photon sources** Niels Gregersen, Technical University of Denmark, Denmark
11:00	**Photon statistics of filtered quantum dot resonance fluorescence** Catherine Phillips, University of Sheffield, UK
11:15	**Fundamental limits to nuclear spin coherence in self-assembled quantum dots due to quantum thermodynamics** Evgeny Chekhovich, University of Sheffield, UK
11:30	Refreshment break, posters and exhibition
11:50	**(Invited) Quantum dot single photon sources: applications and performances reproducibility** Pascale Senellart, University of Sheffield, UK
12:20	**Quantum dots spins in pillar microcavities** Andrew Young, University of Bristol, UK
12:35	**Radiative aager process in the single photon limit on a quantum dot** Matthias Löbl, University of Basel, Switzerland
12:50	Lunch, posters and exhibition
14:10	**(Invited) Quantum dots at telecom wavelengths for single- and entangled photon sources** Peter Michler, Universität Stuttgart, Germany
14:40	**Local anodic oxidation for site-controlled quantum dot growth at telecom wavelengths** Charlotte Ovenden, University of Sheffield, UK
14:55	**Quantum coherent interface of an electron and a nuclear ensemble** Dorian Gangloff, University of Cambridge, UK
15:10	**Single-magnon metrology in quantum dots** Daniel Jackson, University of Cambridge, UK
15:25	Refreshments, posters and exhibition
15:45	**(Invited) GaAs quantum dots as sources of quantum light** Armando Rastelli, Johannes Kepler Universität Linz, Austria
16:15	**Topological photonics with embedded quantum dots** Mahmoud Jalali Mehrabad, University of Sheffield, UK
16:30	**Decreased spectral diffusion rate of a non-polar InGaN quantum dot** Claudius Kocher, University of Oxford, UK
16:45	**Highly tunable quantum light from moiré quantum dots** Hyeonjun Baek, Heriot-Watt University, UK
17:00	Close

Poster programme

P1	**Polarising a nuclear ensemble for a collective quantum memory** Clara Bachorz, University of Cambridge, UK
P2	**Quantum-dot-based optically-pumped vertical-cavity surface-emitting lasers with high-contrast periodic gratings** Edmund Clarke, University of Sheffield, UK
P3	**Influence of vibrational environment on coherent driving of a solid-state two-level system using dichromatic pulses** Zhe Xian Koong, Heriot-Watt University, UK
P4	**Beam the dot up Scotty, laser transfer of chemically formulated nanospheres and quantum dots** Ioannis Metsios, Lumpti Ltd, UK
P5	**Single photon source in the telecommunication C-band via quantum frequency conversion** Christopher Morrison, Heriot-Watt University, UK
P6	**High-yield, low-density InAs/GaAs quantum dots as quantum light sources for 900–1300 nm operation** Pallavi Patil, University of Sheffield, UK
P7	**Droplet epitaxy of InAs/InP quantum dots in MOVPE at the telecom C-band** Elisa Maddalena Sala, University of Sheffiled, UK
P8	**Ultra-fast nanocomposite-based scintillating heterostructures for time-of-flight positron emission tomography** Weronika Serafimowicz, Cranfield University, UK
P9	**Coherent transverse electromagnetic mode lasing in a self-assembled symmetric cavity of perovskite quantum dots** Guanhua Ying, University of Oxford, UK
P10	**Coherent interface to nuclear spins in strain-controlled GaAs quantum dots** Leon Zaporski, University of Cambridge, UK
P11	**Multichromic metal-organic framework via nanoconfinement for multimode photonic sensing technology** Yang Zhang, University of Oxford, UK
P12	**Strain-induced single photon emitters in monolayer TMDs couple to high-index dielectric nano-antennas** Panaiot Zotev, University of Sheffield, UK
P13	**An electrically driving tuneable entangled quantum dot device in cambridge fibre network** Zi-Heng Xiang, Cambridge Research Laboratory, UK

Design of quantum-dot-based single-photon sources

Niels Gregersen

Technical University of Denmark, Denmark

Quantum light sources capable of emitting single photons or entangled photon pairs are key components in optical quantum information processing, and single-photon sources (SPSs) based on quantum dots integrated in photonic microstructures are currently being used in boson sampling experiments and for generating photonic cluster states. The SPS figures of merit include the efficiency ε of the photon collection and the indistinguishability η of the emitted photons, and scalable optical quantum information processing requires that the product $\varepsilon\eta$ is increased very close to unity.

Today, the champion SPS design is the micropillar cavity (Fig. 1a), where Purcell enhancement is used to control the light emission. Here, resonant excitation has been used to demonstrate near-unity indistinguishability [1,2], however for sources emitting unpolarized light, the need for polarization filtering limits the maximum achievable efficiency to 0.5. To improve the efficiency, polarization control must be implemented and this was demonstrated very recently [3] for a pillar with an elliptical cross-section leading to an ε of 0.60 combined with η of 0.97. However, the resulting elliptical output beam profile leads to a trade-off between a high degree of polarization control and a good coupling to a Gaussian mode.

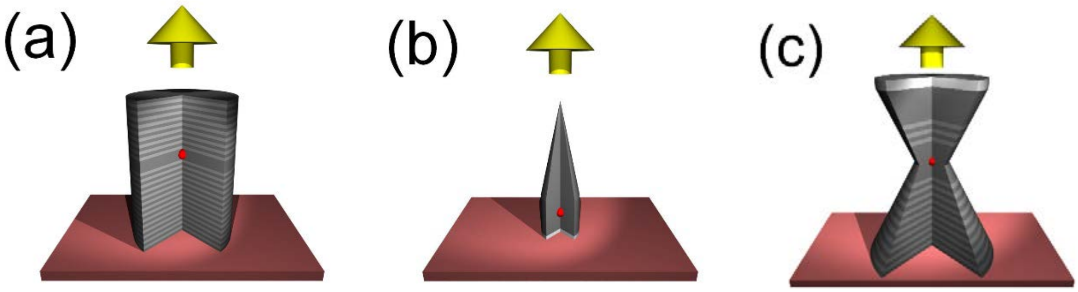

Fig. 1: Single-photon source design strategies: (a) The micropillar cavity, (b) the photonic nanowire and (c) the hybrid photonic hourglass geometry.

An alternative SPS design strategy is based on a quantum dot in a photonic nanowire (Fig. 1b), where dielectric screening effects are used to ensure high efficiency. However, indistinguishable photon emission from photonic nanowires has so far not been demonstrated most likely due to fluctuating charges and slow photon emission due to the lack of Purcell enhancement leading to phonon-induced decoherence.

In this presentation, I will discuss the micropillar and the photonic nanowire designs and their limitations, and I will show that a novel SPS design based on an "hourglass"-shaped pillar [4] illustrated in Fig. 1(c) may overcome these limitations.

[1] N. Somaschi, et al., Nat. Photonics 10, 340–345 (2016)
[2] X. Ding, et al., Phys. Rev. Lett. 116, 020401 (2016)
[3] H. Wang, et al., Nat. Photonics 13, 770–775 (2019)
[4] A. D. Osterkryger, et al., Opt. Lett. 44, 2617–2620 (2019)

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Photon statistics of filtered quantum dot resonance fluorescence

Catherine Phillips[1], Alistair Brash[1], Jake Iles-Smith[1, 2], Dara McCutcheon[3], M Skolnick[1], Mark Fox[1] and Ahsan Nazir[2]

[1]University of Sheffield, UK, [2]University of Manchester, UK, [3]University of Bristol, UK

Filtering around the zero phonon line (ZPL) of quantum dot (QD) resonance fluorescence is widely employed to improve the measured single photon purity (anti-bunching). However, theory [1] suggests that for weak continuous excitation ($^{2} < (\gamma^2 2/)$), filtering below the natural linewidth (γ) on the ZPL reduces the single photon purity. This reduction originates from filtering changing the ratio between coherent scattering and incoherent resonance fluorescence, suggesting that the anti-bunching arises due to interference between coherent and incoherent components.

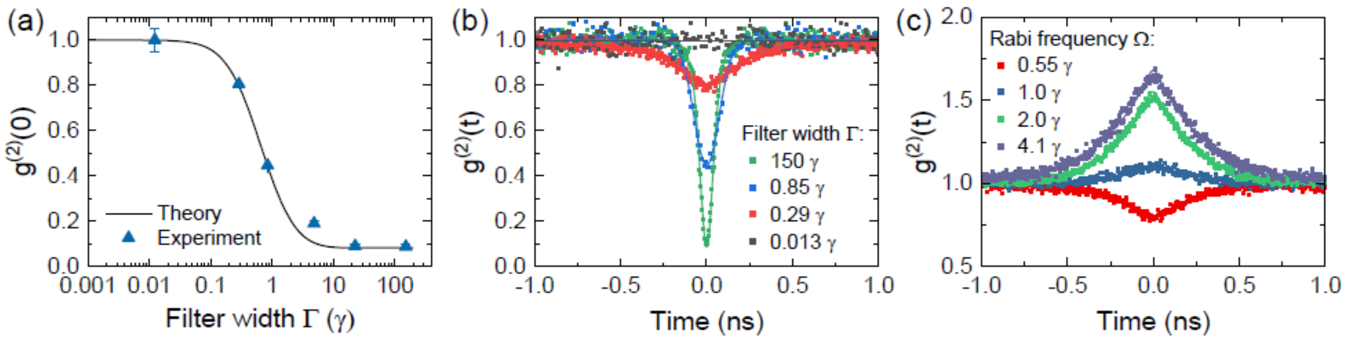


Fig. 1: (a) $g^{(2)}(0)$ measurements (triangles) of weakly driven (Ω = 0.5 γ) QD resonance fluorescence through filters (resonant with the ZPL) of bandwidth Γ. Black line - theoretical prediction. (b) $g^{(2)}(t)$ plots from *(a)*, dip width increases with decreasing Γ. (c) Power-dependent $g^{(2)}(t)$ measured at Γ = 0.29 γ. Increasing Ω causes a transition from anti-bunching to bunching.

In this work we measure the second order correlation function ($g^{(2)}(t)$) of photons emitted from a resonantly excited self-assembled InGaAs QD in a nano-cavity. The signal is passed through one of a range of spectral filters (with bandwidth Γ) prior to the $g^{(2)}(t)$ measurement. Fig 1. (a) shows clearly that as the filter bandwidth reduces below the natural linewidth, the degree of anti-bunching decreases, tending towards Poissonian statistics ($g^{(2)}(0) = 1$). A model derived from sensor theory [1] accurately reproduces experimental results (solid line) with the anti-bunching observed through the broadest filters limited by the detector response. As the filter width decreases, the width of the anti-bunching dip in $g^{(2)}(t)$ also increases (Fig. 1(b)). This broadening is in accordance with the time-bandwidth product, indicating the incompatibility of simultaneously observing both a sub-natural linewidth and anti-bunching from coherently scattered light.

In Fig. 1(c), increasing the driving strength for a fixed filter width Γ = 0.29 γ causes a transition from anti-bunched to bunched photon statistics. This behaviour was previously theoretically predicted [2] and supports the conclusion that the anti-bunching typically observed for QD resonance fluorescence originates from interference between multiple components with different statistics. Our results suggest that care is required when filtering QD emission but also point toward novel methods to generate non-classical light for applications in optical quantum technologies.

[1] Carreño et al. Quantum Science and Technology, 2018, 3, 045001
[2] Gonzalez-Tudela et al. New Journal of Physics, 2013, 15, 033036

Fundamental limits to nuclear spin coherence in self-assembled quantum dots due to quantum thermodynamics

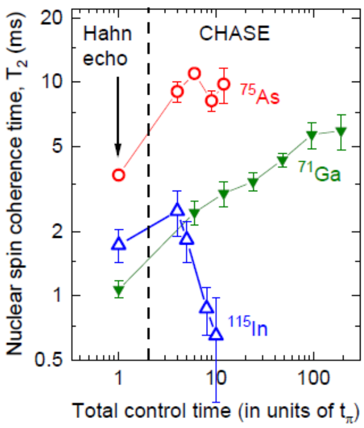
Evgeny Chekhovich[1], A Waeber[1], G Gillard[1], G Ragunathan[1], M Hopkinson[1], P Spencer[2], D Ritchie[2] and M Skolnick[1]

[1]University of Sheffield, UK, [2]University of Cambridge, UK

The excellent spin-photon interface of confined charges in III-V semiconductor quantum dots (QDs) has recently attracted attention for potential applications in photon-mediated quantum networks. However, the coherence properties of the electron or hole spin qubit are strongly affected by hyperfine interaction with the fluctuating nuclear spin bath. Although hyperfine-induced qubit dephasing can be reduced using dynamical decoupling, this approach requires a significant number of additional qubit manipulations and rapidly loses efficiency with increasing spin bath inhomogeneity, induced e.g. by nuclear quadrupolar effects.

Here we examine the complementary pathway of controlling the nuclear spin bath itself with pulsed nuclear magnetic resonance. We introduce pulse sequences which combine the features of Hahn echo decoupling with those of solid echoes. These combined Hahn and solid echo (CHASE) pulse sequences are designed to preserve coherence of an arbitrary quantum state and are tested on neutral InGaAs/GaAs self-assembled QDs [1]. The Figure shows the measured Hahn echo nuclear spin coherence time T_2 compared to T_2 under increasing number of CHASE control cycles. A 5-fold increase in T_2 is achieved for spin-3/2 ^{71}Ga nuclei, while coherence improvement is less prominent for spin-3/2 ^{75}As due to its larger quadrupolar inhomogeneous broadening. Surprisingly, for spin-9/2 ^{115}In, application of CHASE leads to deterioration of coherence even though its inhomogeneous broadening is smaller than in ^{75}As.

Using average Hamiltonian theory and first-principle numerical simulations we explain these results by showing that many-body decoherence emerges naturally under unitary evolution: similar to the second law of thermodynamics, where useful energy is irreversibly dissipated into wasteful heat, the coherence is irreversibly converted into multipartite spin-spin entanglement. The ability to suppress entanglement growth and preserve coherence via global control is inherently limited by disorder (inhomogeneous resonance broadening), which is particularly prominent in a strongly-correlated ^{115}In spin bath with its strong flip-flop coupling of the 9/2 spins. It has been shown previously that interaction with a central (electron) spin reduces nuclear spin coherence [2], while our results show that indium nuclei set a limit to achievable coherence even in a bare nuclear spin bath. This highlights the advantages of spin qubits with homogeneous spin environments, such as dilute donor spins, defect centres, or strain-free GaAs/AlGaAs quantum dots [3]. For such homogeneous baths, calculations predict up to a 100-fold increase in nuclear spin coherence under CHASE control, which can be used for example to preserve the quantum information transferred to the nuclei from the electron spin [4].



[1] A. M. Waeber et al., Nature Communications 10, 3157 (2019)
[2] G. Wust et al., Nature Nanotechnology 11, 885 (2016)
[3] E. A. Chekhovich et al., Nature Materials 19, 982 (2017)
[4] D. A. Gangloff et al., Science 364, 62 (2019)

Quantum dot single photon sources: applications and performances reproducibility

Pascale Senellart

Université Paris Saclay, France

Single photon sources based on semiconductor quantum dots have emerged as an excellent platform for high efficiency quantum light generation [1,2] with promising applications in quantum computing and quantum networks. In this talk, we report on several steps that we have taken to investigate the source potential for scaling-up optical quantum technologies.

First, we have developed a quantum dot based multi-photon source and interfaced it with a reconfigurable photonic chip. We actively demultiplex the temporal train of single photons obtained from a single quantum dot to generate a $3.8 \times 103\ s^{-1}$ three-photon source, which is then sent to the input of a laser written glass circuit. We demonstrate the on-chip quantum interference of three indistinguishable single photons. This first combination of sources and photonic circuits compares favorably in performance with respect to previous implementations. The loss-budget shows that 10-photon experiments on chip at $\sim 40\ s^{-1}$ rate are foreseeable in a near future [3].

Second, we have explored the potential of the source to generate photonic linear cluster states-that are key ingredients for measurement-based quantum computing and quantum networks. We couple a quantum-dot source to a delay loop-based, all-fibered, entanglement apparatus. Such scheme is ideally suited to the quantum dot sources, that deliver long trains of indistinguishable photons. We report on the generation of photonic cluster states up to four photons in a single mode fiber [4].

Finally, we have investigated the scalability of our source technology. We benchmark the performances of fifteen deterministically fabricated single photon sources in terms of brightness, single photon purity, indistinguishability as well as operation wavelength and temporal shape [5]. Various techniques are used to identify the nature of the emitting state— a neutral exciton or a charged exciton— which influences the source characteristics and performances. All sources display state-of-the art brightness, average indistinguishability of 90% and nice homogeneity in operation wavelength and temporal profiles. While the highest brightness is obtained with a charged quantum dot, the highest single photon purity is obtained with neutral ones.

[1] N. Somaschi et al., « Near-optimal single-photon sources in the solid state", Nat. Photon. 10, 340 (2016)

[2] P. Senellart, G Solomon, A White, "High-performance semiconductor quantum-dot singlephoton sources", Nature Nanotechnology 12 (11), (2017).

[3] C. Anton, et al., « Interfacing scalable photonic platforms: Solid-state based multi-photon interference in a reconfigurable glass chip", Optica 6 (12), 1471-1477 (2019)

[4] D. Istrati et al., « Sequential generation of linear cluster states from a single photon emitter", arXiv 2019

[5] H. Ollivier et al., "Reproducibility of high-performance quantum dot single-photon sources", arXiv:1910.08863

Quantum dots spins in pillar microcavities

Andrew Young[1], Petros Androvitsaneas[1] , Thomas Nutz[1,2], J.M. Lennon[1], C. Schneider[3], S. Maier[3], J Hinchliff[1], E Harbord[1], M Kamp[3], D Mcutcheon[1], Sven Höfling[3,4] John Rarity[1] and Ruth Oulton[1]

[1]University of Bristol, UK, [2]Imperial College London, UK, [3]Universität Würzburg, Germany, [4]University of St Andrews, UK

The idea of using quantum dots to generate entangled states was first proposed over ten years ago[1]. The so called "machine gun protocol" relies on generating entanglement between the ground state of a resident electron spin in a QD and single photons as they are emitted. The protocol proposes using an electron spin, whose state coherently evolves in an applied magnetic field (Voigt geometry). The system is then inverted (optically) to the exited state to produce photons at specific time intervals. The result is the emission on an entangled chain of photons emitted from the QD, whose length is then limited by the collection efficiency of the photons and the coherence time of the electron spin. A key feature of the protocol is that the electron spin precession must be slower that the rate that photons are emitted by the QD. For QD's this necessitates the application of a low (in plane) magnetic field (typically <100mT). This poses some interesting questions as not much is known about the behaviour of QD spins in low in plane magnetic fields. This is mainly due to the challenge of measuring the spin in such B-fields. The optical transitions are, by definition, not spectrally resolvable so cannot be spectrally filtered. Further since excitation is resonant, cross polarisers are typically deployed to filter the pump, hence polarisation cannot be used to distinguish the spin states. This means standard approaches to characterisation of the electron spin are not applicable. In this talk I will present a novel method to measure the behaviour of a QD electron spin in a low magnetic field. Using this we can accurately determine several key figures of merit for the electron spin, such as the Lamour frequency, the g-factor and the coherence time. Further there is the possibility to use the ideas as a modification to the machine gun protocol to generate strings of entangled photons.

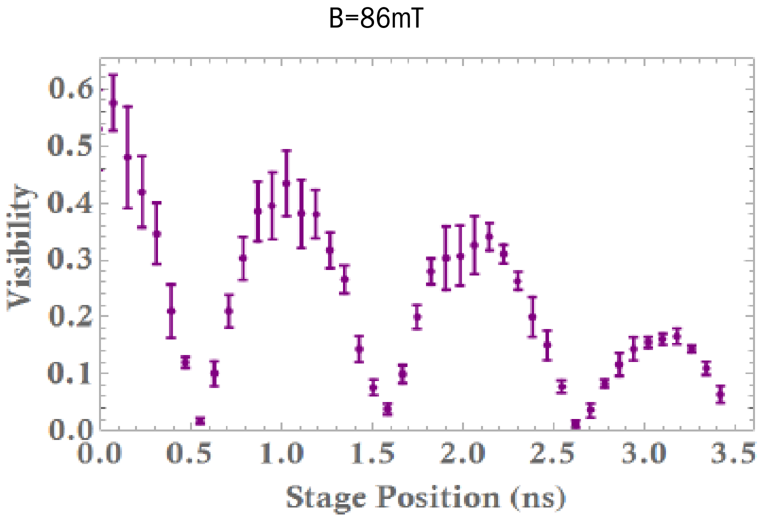


Fig 1: Measurement of a QD electron spin in a low magnetic field

[1] Netanel H. Lindner and Terry Rudolph, Phys. Rev. Lett. 103, 113602 (2008)

Radiative auger process in the single photon limit on a quantum dot

Matthias Löbl[1], Clemens Spinnler[1], Alisa Javadi[1], Liang Zhai[1], Giang Nguyen[1, 2], Julian Ritzmann[2], Leonardo Midolo[3], Peter Lodahl[3], Andreas Wieck[2], Arne Ludwig[2] and Richard J. Warburton[1]

[1]University of Basel, Switzerland, [2]Ruhr-Universität Bochum, Germany, [3]University of Copenhagen, Denmark

In a multi-electron atom, an excited electron can decay by emitting a photon. In a radiative Auger process, the leftover electrons are in an excited state, and a red-shifted photon is created [1]. In a quantum dot, radiative Auger is predicted for charged excitons [2]. However, radiative Auger has not been observed on single quantum dots. Here, we report radiative Auger on trions in individual quantum dots (Fig. 1(a, b)). For the trion, just one electron is left after the optical recombination. In a radiative Auger process, this Auger electron is promoted to a higher shell of the quantum dot, and the emitted photon is red-shifted. We show that radiative Auger directly measures the quantization energies of the single electron [3], information which is otherwise difficult to acquire. We measure the radiative Auger process on two types of charge-tuneable quantum dots: InGaAs, GaAs quantum dots [4], in both cases using resonant excitation. We rigorously prove the radiative Auger mechanism by measuring the photon statistics and the magnetic field dispersion of the emission [3]. Going beyond original proposals, we apply quantum optics techniques to the radiative Auger photons (Fig. 1(c)). We show how quantum optics gives access to the single-electron dynamics, notably relaxation and tunnelling rates [3]. All these properties of radiative Auger can be exploited on other semiconductor nanostructures and potentially colour centres.

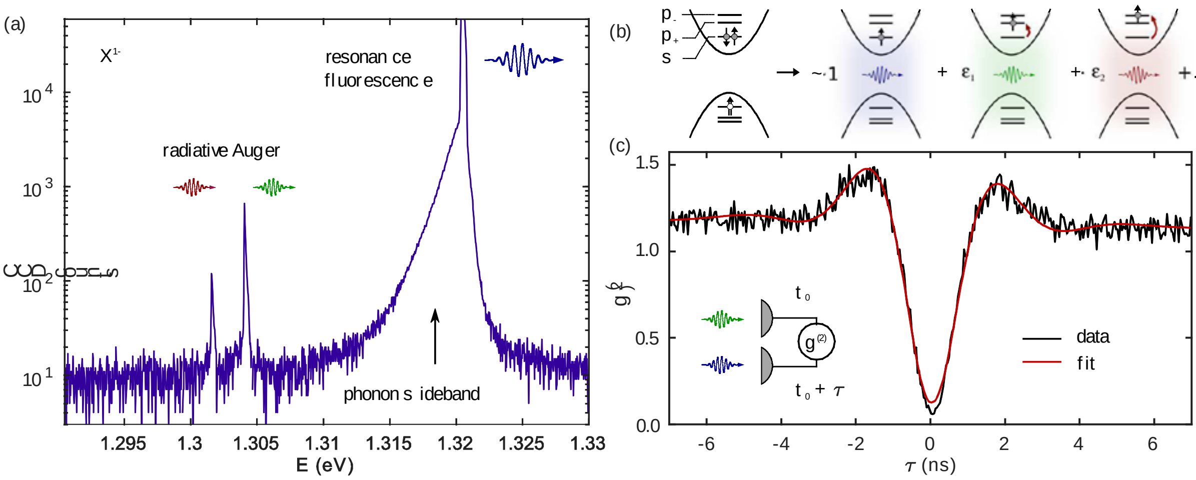


Fig. 1: (a) Resonance fluorescence and radiative Auger emission from the trion. Compared to the resonance fluorescence, the radiative Auger emission is red-shifted by ~17meV. (b) Radiative decay of the trion. With small probabilities, the second electron of the trion is promoted to a higher shell of the quantum dot. The emitted photon is red-shifted by the energy which the Auger electron gains. (c) Cross-correlation between radiative Auger and resonance fluorescence. The antibunching at zero time delay shows that resonance fluorescence and radiative Auger are emitted by the same quantum dot.

[1] F. Bloch et al., Phys. Rev. 47, 884-885 (1935); T. Åberg et al., PRL 22, 1346-1348 (1969)
[2] P. Hawrylak, Single quantum dots 90 (editor: P. Michler, Springer Science, 2003)
[3] M. C. Löbl et al., arxiv:1911.11784 (2019)
[4] Y. H. Huo, A. Rastelli, O. G. Schmidt, Appl. Phys. Lett. 102, 152105 (2013)

Quantum dots at telecom wavelengths for single- and entangled photon sources

Peter Michler

University of Stuttgart, Germany

The emission of semiconductor quantum dots (QDs) has been shown to exhibit excellent properties in terms of single photon purity, photon indistinguishability and entanglement fidelity, i.e. essential prerequisites for quantum communication. Emission in the telecom O- or C-band will boost the range of communication schemes due to the favorable absorption and dispersion properties of silica fibers employed in the existing global fiber network.

By metal-organic vapor-phase epitaxy, we have fabricated InAs quantum dots on InGaAs/GaAs metamorphic buffer layers on a GaAs substrate with area densities that allow addressing single quantum dots. The photoluminescence emission from the quantum dots is shifted to the telecom C-band at 1.55 µm with a high yield due to the reduced stress in the quantum dots. Single- and polarization-entangled photon emission is demonstrated [1, 2]. Furthermore, the coherence properties of photons emitted by InAs/InGaAs QDs emitting directly in the telecom C-band, are examined under above-band excitation and in resonance fluorescence [3]. The average linewidth is reduced from 9.74 GHz in above-band excitation to 3.5 GHz in resonance fluorescence. Two-photon excitation of the biexciton is investigated as a resonant pumping scheme. A de-convoluted single-photon purity value of $g^{(2)}(0) = 0.07$ and a post-selected degree of indistinguishability of $V_{HOM} = 0.89$ are determined for the biexciton transitions (see Fig.1).

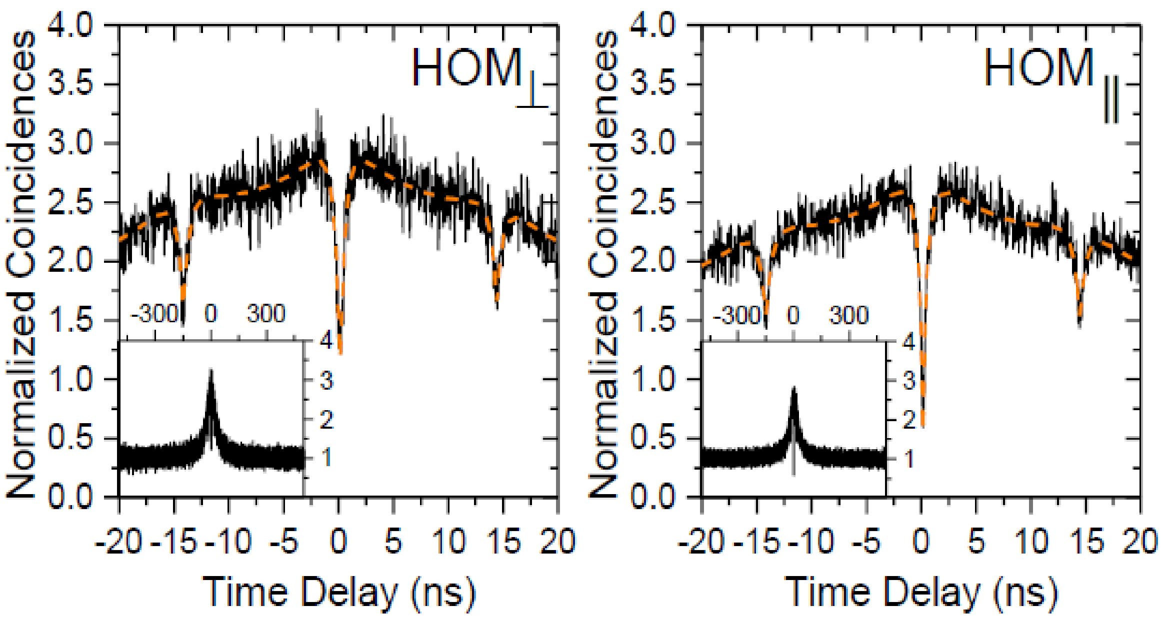


Fig. 1: Two-photon interference of distinguishable and indistinguishable photons after two-photon excitation of the quantum dot with the respective fit functions (orange). The insets show the same data with a correlation window of ± 500 ns.

Finally, to boost the extraction efficiency, the applicability of an approach combining a nano-membrane containing QDs, with a GaP hemispherical lens is presented for a sample emitting in the telecom O-band.

[1] M. Paul et al., Appl. Phys. Lett. 111, 033102 (2017)
[2] F. Olbrich et al., Appl. Phys. Lett. 111, 133106 (2017)
[3] C. Nawrath et al., Appl. Phys. Lett. 115, 023103 (2019)

Local anodic oxidation for site-controlled quantum dot growth at telecom wavelengths

Charlotte Ovenden, Ian Farrer, Maurice Skolnick and Jon Heffernan

[1]University of Sheffield, UK

To achieve integration of on-chip photonic devices suitable for quantum cryptography into existing commercial communication networks, single-photon sources emitting at 1.55 μm are required. High numbers of identical single-photon sources can be produced in a scalable fashion by using site-controlled quantum dot growth (QD) to deterministically place the emitters. Fabricated features, such as nanoholes, control the nucleation position and emission wavelength of the QDs, in addition to decreasing spectral inhomogeneity.

Low linewidths for site-controlled QDs have been achieved using electron-beam lithography (EBL) and wet chemical etching to fabricate nanoholes (18 nm depth), and a stacked QD growth system [1]. The purpose of the stacked QD layers was to increase total re-growth buffer thickness and so distance the optically active QD from the re-growth interface and any residual surface contaminants, such as organic EBL resist. An alternative nanohole fabrication technique is atomic force microscopy (AFM)-assisted local anodic oxidation (LAO) [2]. The nanoholes produced in this way have previously been shallow (<5nm) [3], which limits re-growth buffer depth. However, the technique has the advantage that it doesn't require the use of organic resist. Using this method and no re-growth buffer, site-controlled QDs emitting at telecom wavelengths were produced with linewidths of 0.8 meV [4]. At 900 nm it was reported that using a re-growth buffer thickness of 15 nm and by optimising growth conditions, linewidths were reduced from 870 μeV to 156 μeV [5].

We propose that by developing a method to create deep LAO formed nanoholes (> 10 nm) with optimised growth conditions, wavelength controlled, low linewidth QDs can be grown. We report best mean depths of 16 ± 1 nm on InP, which are significantly deeper than typically reported. Nanohole depth and radius was controlled via applied AFM tip bias and humidity, and doping type effect over nano-oxide dimensions was also investigated.

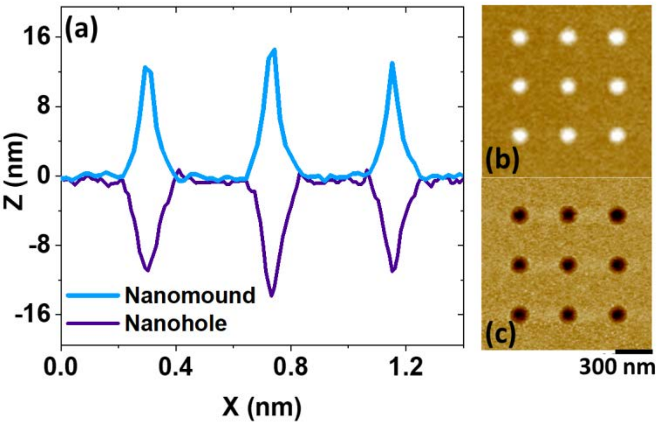


Fig. 1: (a) Section through nano-oxide mounds and nanoholes fabricated by LAO; (b) AFM image of nano-oxide mounds; (c) AFM image of nanoholes.

[1] K. D. Jöns et al., Nano Lett. 13, 126-130 (2013)
[2] J. Herranz et al., Cryst. Growth Des. 15, 666-672 (2015)
[3] E. Tranvouez et al., Superlattices Microstruct. 36, 325-333 (2004)
[4] H. Z. Song et al., Appl. Phys. Lett. 86, 113118 (2005)
[5] J. Herranz et al., Nanotechnology 26, 195301 (2015)

Quantum coherent interface of an electron and a nuclear ensemble

Dorian Gangloff[1], Jonathan Bodey[1], Daniel Jackson[1], Emil Denning[2], Gabriel Éthier-Majcher[1], Robert Stockill[1], Constantin Lang[1], Jesper Mørk[2], Claire Le Gall[1] and Mete Atatüre[1]

[1]University of Cambridge, UK, [2]Technical University of Denmark, Denmark

Coherent excitation of an ensemble of quantum objects offers the opportunity to realise robust entanglement generation and information storage in a quantum memory [1]. In quantum dots, a single electron spin qubit is a coherent interface to an isolated nuclear spin ensemble (Fig. 1). Recently, we have developed an all-optical electron spin resonance technique that, together with our ability to optically cool the nuclear ensemble [2], has allowed us to perform complex single qubit manipulations on the electron spin, such as a spin-locking sequence [3], and to coherently probe and excite spin-wave modes in the nuclear spin ensemble [4]. Combined, these results open a promising avenue for quantum state engineering of a mesoscopic ensemble, and we have recently proposed a realistic path to a nuclear quantum memory based on electronactivated spin waves in GaAs quantum dots [5]. In my talk, I will briefly summarise these recent experimental results and theoretical proposals for the future.

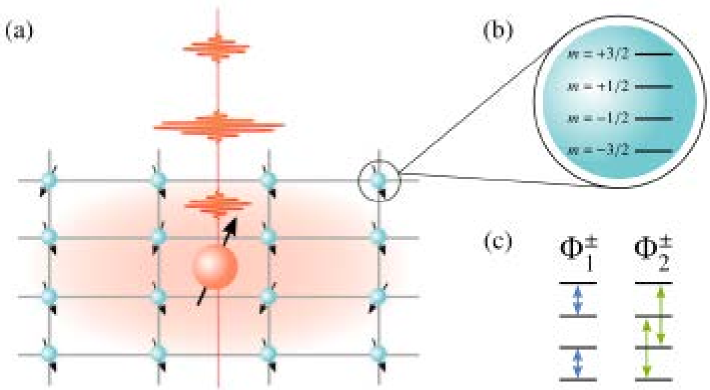


Fig 1: (a) Quantum interface between an electron and a nuclear ensemble with light. (b) Nuclear spin eigenstates for Gallium and Arsenic nuclei. (c) Allowed nuclear spin wave modes.

[1] Taylor, Marcus, & Lukin. (2003) Phys. Rev. Lett. 90, 206803
[2] Éthier-Majcher, Gangloff et al., (2017), Phys. Rev. Lett. 119, 130503
[3] Bodey, Stockill, Denning, Gangloff, et al. (2019) npj Quantum Information 5 (95)
[4] Gangloff et al. (2019) Science 364 (6435)
[5] Denning, Gangloff, Atatüre, Mørk, & Le Gall (2019) Phys. Rev. Lett. 123, 140502

Quantum Dot Day 2020

Single-magnon metrology in quantum dots

Daniel Jackson[1], Dorian Gangloff[1], Jonathan Bodey[1], Claire Le Gall[1] and Mete Atatüre[1]

[1]University of Cambridge, UK

InGaAs quantum dots (QDs) are now well established in the community of solid-state single-photon emitters thanks to their excellent photonic properties. Unfortunately, the limited coherence times of the local matter qubit, the electron spin, limit their usefulness in conventional quantum networks. However, recent work from our group has allowed us to harness the nuclear ensemble intrinsic to the QD as a resource for quantum state storage, circumventing electronic coherence problems [1, 2]. Whilst we have demonstrated the most basic state transfer from electron to nuclei, the verification of such transfer remains a challenge, and is the focus of this work.

We propose to use the central electron-spin as a high-precision sensor to detect the writing-in of single magnons into the ensemble. This is possible thanks to the hyperfine interaction, which means that the electron effectively sees a small change in the total magnetic field after a single nuclear spin flip. With a 3.5T external magnetic field, a single magnon amounts to a 1MHz shift in the 25GHz electron-spin resonance (ESR) frequency. This sets the metrological precision we require on the ESR frequency in order to detect a single nuclear-spin excitation. To this end we have built and characterised a Ramsey interferometry sequence which incorporates phase-controllable optical ESR [3]. With this control sequence we can map small precession angles to a change in electron-spin polarisation linearly (figure 1a), becoming maximally sensitive to small magnon-induced ESR shifts. We characterise the precision of the control sequence by experimentally simulating the shift due to a single magnon and demonstrate sub-MHz resolution (figure 1b). Furthermore, we report the successful detection of a single magnon after performing nuclear spin orientation via electron spin locking (NOVEL) [4]. Once again we exploit the phase control of our drive to selectively couple to two distinct magnonic modes and verify this through the magnon-induced ESR shift. Together these results constitute crucial steps towards a technique for the quantum tomography of magnonic superposition states [2].

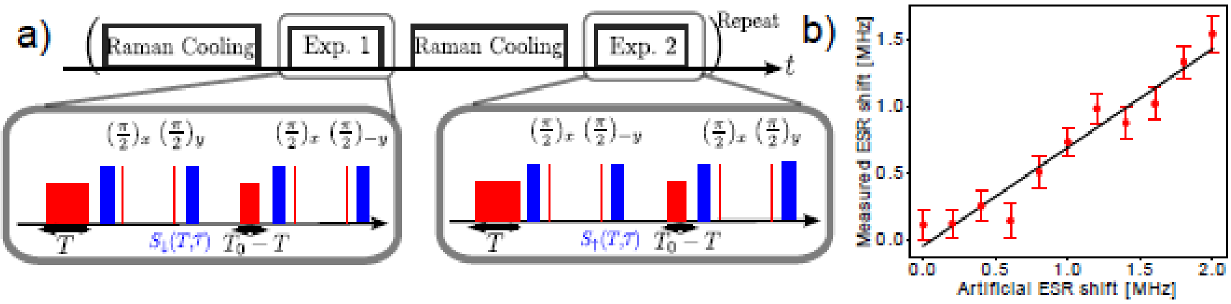


Fig. 1: (a) Control sequence for high-precision Ramsey interferometry. Electron-spin control pulses are in red, spin pumping is in blue. Electron-magnon exchange is driven for a time T, followed by Ramsey interferometry. The two experimental regions differ subtly in the phases of the Ramsey gates, and effectively allow both spin states to be read after a Ramsey sequence. (b) Measured ESR shift after simulating the effect of a single magnon by manually introducing a detuning during the free precession between Ramsey gates.

[1] D. A. Gangloff, et al., Science, 364, 6435 (2019)
[2] E. V. Denning, et al., PRL, 123, 140502 (2019)
[3] J. H. Bodey, et al., npjQI, 5, 95 (2019)

[4] A. Henstra, et al, Journal of Magnetic Resonance, 77, 2 (1988)

GaAs quantum dots as sources of quantum light

Armando Rastelli[1], M Reindl[1], S Filipe Covre da Silva[1], D Huber[1], C Schimpf[1], X Yuan[1], H Huang[1] and R Trotta[1, 2]

[1]Johannes Kepler University, Austria, [2]Sapienza Università di Roma, Italy

Semiconductor quantum dots (QDs) obtained by epitaxial growth are regarded as one of the most promising solid-state sources of triggered single and entangled photons for applications in emerging quantum communication and photonic quantum-information-processing.

In this talk, we will focus on GaAs QDs in AlGaAs matrix [1,2], which show a unique combination of appealing features: fast radiative rates of ~5 GHz, capability of generating near perfectly entangled photon pairs [3] with good indistinguishability [4], ultralow multiphoton emission probability [5], high brightness [6], as well as wavelength (~800 nm) suitable for free-space quantum communication.

Because of the statistical fluctuations in the optical properties of different QDs in an ensemble, scaling up the QD hardware is still an open challenge. Realistic strategies and encouraging results relying on post-growth tuning of the QD properties [7-9] will be discussed.

[1] A. Rastelli et al., Phys. Rev. Lett. 92, 166104 (2004)
[2] Y. Huo et al., Nature Phys. 10, 46 (2014)
[3] D. Huber et al., Phys. Rev. Lett. 121, 033902 (2018)
[4] M. Reindl et al., Phys. Rev. B 100, 155420 (2019)
[5] L. Schweickert et al., Appl. Phys. Lett. 112, 093106 (2018)
[6] J. Liu et al., Nature Nanotech. 14, 586 (2019)
[7] A. Rastelli et al, Phys. Status Solidi (b), 249, 687 (2012)
[8] R. Trotta et al., Nat. Comm. 7, 10375 (2016)
[9] M. Reindl et al., Nano Lett. 17, 4090 (2017)

Topological photonics with embedded quantum dots

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University of Sheffield, UK

The interface between topologically-distinct photonic crystals supports unidirectional photonic modes. Such modes are robust against disorder of the crystal, as well as certain types of defect and corners. This presents opportunities for the development of photonic elements such as ring resonators [1] with robust optical properties. Furthermore, the modes are helical, and are thus of significant interest for the realization of chiral photonic devices. For instance, chiral coupling of a quantum dot (QD) to a spin-Hall topological waveguide was recently demonstrated [2].

We first present our realization of topological photonic ring resonators using both spin- and valley-Hall-type topological interfaces (Fig. 1a). Using embedded QDs as an internal broadband light source, we probe the mode structure of the devices, and through photoluminescence (PL) spatial mapping demonstrate confinement of the optical modes to the resonator interface (Fig. 1b). We then show coupling of the optical modes of a valley-Hall resonator to a bus waveguide, providing a route for the future development of devices such as add-drop filters (Fig. 1c).

Next, we investigate chiral coupling of QDs to the valley-Hall topological interface. Using a magnetic field in the Faraday geometry to lift the degeneracy of QD transitions, we demonstrate directional coupling of a QD to the waveguide, with a chiral contrast of up to 85% (Fig. 1d). Chirality is also observed for a QD embedded inside a ring resonator. Our results highlight the significant promise of topological photonics for applications in chiral quantum optics.

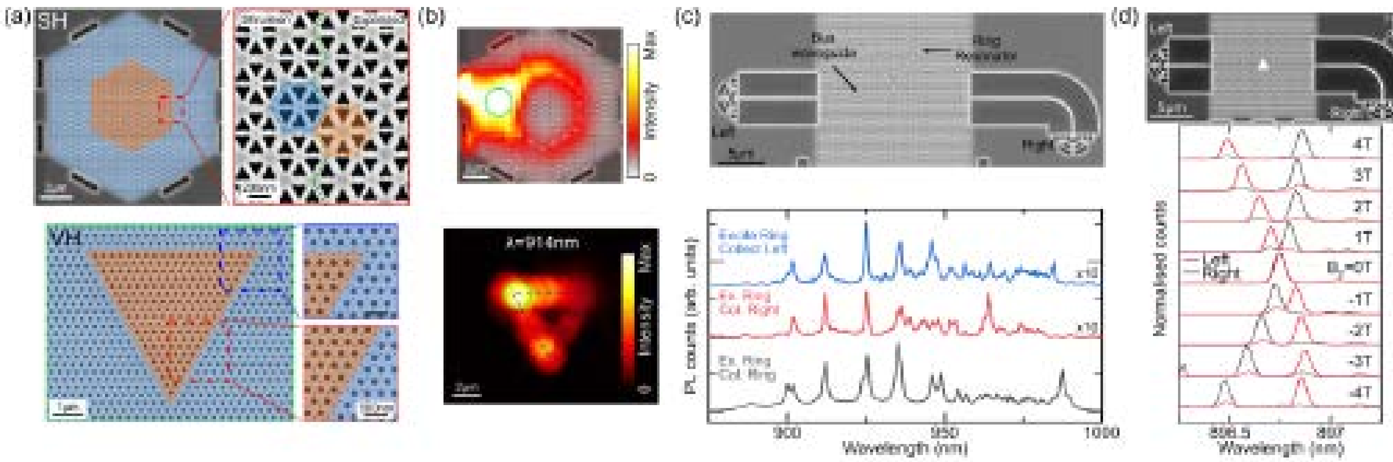

Fig. 1: (a) Scanning electron microscope (SEM) images of (upper) spin-Hall (SH) and (lower) valley-Hall (VH) topological ring resonators; (b) PL maps showing confinement of resonator modes at the (upper) SH and (lower) VH topological interfaces. The excitation position is rastered across the device. The collection location is fixed (green circle); (c) Coupling of a VH resonator to an adjacent bus waveguide. (Upper) SEM image of the device. (Lower) PL spectra revealing resonator modes. The resonator is excited from above and PL collected either from above the resonator, or from the ends of the waveguide; (d) Chiral coupling of a QD to a valley-Hall topological interface. (Upper) SEM image of the device. (Lower) PL spectra from either end of the device as a function of magnetic field.

[1] M. Jalali Mehrabad et al., arXiv.1910.07448 (2019)
[2] S. Barik et al., Science 359, 666-668 (2018)

Quantum Dot Day 2020

Decreased spectral diffusion rate of a non-polar InGaN quantum dot

Claudius Kocher[1], Tongtong Zhu[2], John Jarman[2], Rachel Oliver[2] and Robert Taylor[1]

[1]University of Oxford, UK, [2]University of Cambridge, UK

Traditionally, nitride quantum dots suffer from strong spectral diffusion. This is partly due to their large in-built dipoles resulting from the polar nature of nitride materials. Another reason is the high dislocation density compared to the more mature arsenide material system, which gives carriers a multitude of opportunities to get trapped in the materials surrounding the dots. As a result, fast time scale spectral diffusion broadens linewidths of nitride dots up to more than 1 meV for integration times on the scale of seconds.

This presents a large obstacle for the generation of indistinguishable photons. However, recent publications reported a spectral diffusion time of ~22 ns for a polar GaN/AlGaN QD [1], and ~230 ns for a polar InGaN/GaN QD [2]. This puts an upper limit to the time scale in which indistinguishable photons could be generated; other mechanisms are likely to reduce the coherence further.

In contrast to these nitride dots conventionally grown along the polar direction, we studied a quantum dot grown on a non-polar plane. These have been shown to exhibit an increased oscillator strength by a factor of ~10 [3]. Furthermore, a theoretical analysis revealed for the special case of non-polar InGaN dots, that the second order piezoelectricity counteracts the first order [4], resulting in a further reduced dipole moment. However, along with the change of the growth plane comes an increased density of defects.

Here, we present a study of the fast time-scale spectral diffusion of a non-polar InGaN quantum dot grown by modified droplet epitaxy [3]. Its spectrum is shown in Fig. 1 (a). We conducted autocorrelation measurements for a range of different excitation powers. By restricting the signal to half of the emission peak width, bunching originating from fast spectral diffusion was observed. Its timescale varied approximately linearly with the excitation power, as shown in Fig. 1 (b). The longest spectral diffusion time obtained was ~900 ns for the lowest excitation power. This represents an increase by a factor of 2 to 3 compared to the polar case [2] and increases the chance of successful generation of indistinguishable photons.

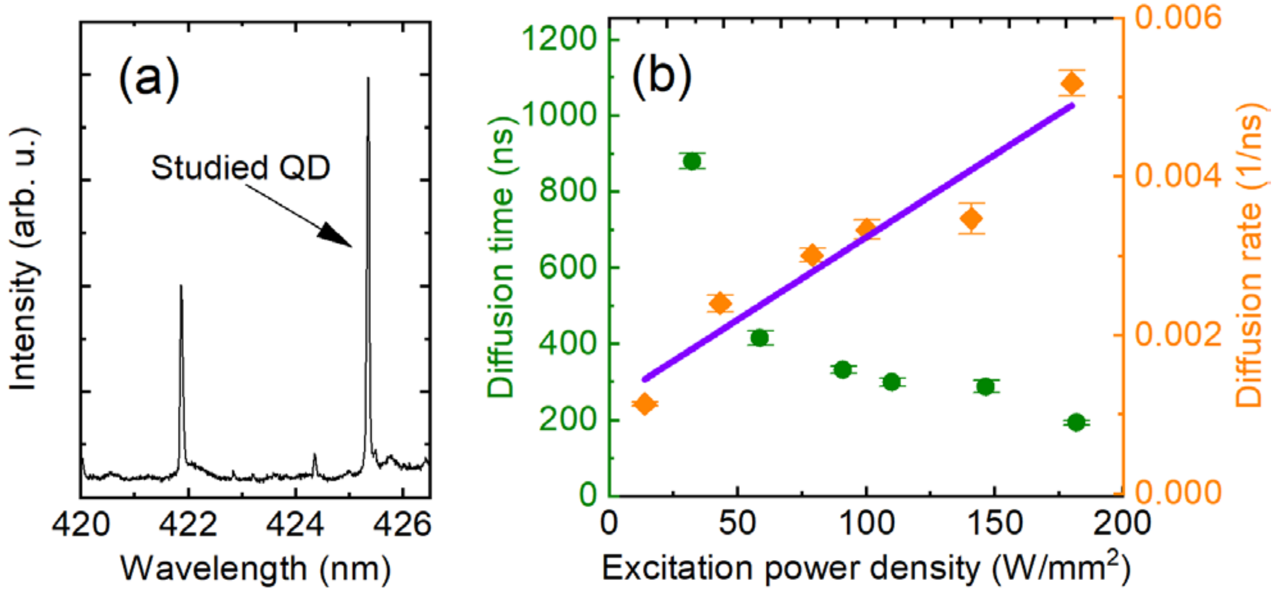

Fig. 1: (a) Spectrum of the QD. (b) Power dependence of the diffusion time/diffusion rate.

[1] K. Gao, et al., AIP Advances. 7, 125216 (2017)
[2] K. Gap, et al., Appl. Phys. Lett. 114, 112109 (2019)
[3] T. Zhu, et al., Appl. Phys. Lett. 102, 251905 (2013)
[4] S. Patra, S. Schulz, Phys. Rev. B 96, 155307 (2017)

Highly tunable quantum light from moiré quantum dots

Hyeonjun Baek[1], Mauro Brotons-Gisbert[1], Zhe Xian Koong[1], Aidan Campbell[1], Markus Rambach[1], K Watanabe[2], T Takashi[2] and Brian Gerardot[1]

[1]Heriot-Watt University, UK, [2]National Institute for Materials Science, Japan

Photon antibunching, a hallmark of quantum light, has been observed in the correlations of light from isolated atomic and atomic-like solid-state systems like quantum dots or wide-bandgap defects. Recently, quantum emitters in two-dimensional materials which resemble conventional atomic defects in wide-bandgap materials or semiconductor quantum dots have been discovered. Beyond these archetypical systems, the ability to stack unlimited combinations of atomic layers with arbitrary crystal angle opens a new paradigm in quantum material design. For example, two-dimensional semiconductor heterostructures offer an original approach to create quantum emitter arrays: a small lattice mismatch or relative twist in a heterobilayer can create moiré trapping potentials for band-edge electrons and holes. This can create uniform high-density arrays of quantum emitters or topological bands whose properties can be manipulated by electric or strain fields.

Absorption and photoluminescence (PL) of molybdenum diselenide ($MoSe_2$)/tungsten diselenide (WSe_2) heterobilayer samples have recently been investigated to probe for quantum emitters formed from moiré trapped interlayer excitons (IXs). [1,2] In the limit of low temperature and weak excitation, discrete PL spectra have been observed to exhibit strong helical polarization and an absence of fine-structure splitting due to the intrinsic $\hat{C}_3$ symmetry of the constituent crystal lattices. In addition, highly uniform g-factors dependent on the relative layer twist are observed, clear fingerprints of the spin and valley configurations for excitons composed of band-edge electrons and holes at the ±K points. Finally, the helical polarization appears to be determined by selection rules dictated by atomic registry. Combined, these observations provide compelling evidence for moiré trapped IXs. Nevertheless, ambiguity remains about their precise attributes. Here we demonstrate photon antibunching from a single moiré trapped IX, affirming their quantum nature. This raises the prospect to investigate second-order correlations among the inhomogeneous spectral features to understand their relationship. Furthermore, the emission energy from moiré trapped IX could be highly tunable using Stark shift, which is promising further applications.

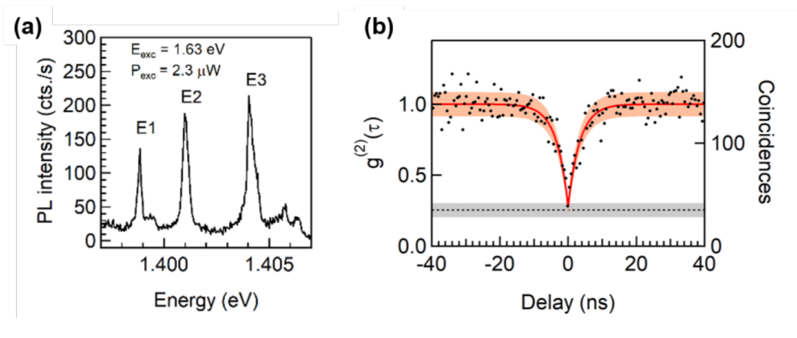

Fig. 1: (a) PL spectrum of IXs trapped in the moiré potentials (b) Second-order photon correlation statistics from emitter E2 under CW excitation

[1] K. L. Seyler, P. Rivera, H. Y. Yu, N. P. Wilson, E. L. Ray, D. G. Mandrus, J. Q. Yan, W. Yao, and X. D. Xu, Nature 567, 66 (2019)

[2] M. Brotons-Gisbert, H. Baek, A. Molina-Sánchez, D. Sceri, D. White, K. Watanabe, T. Taniguchi, C. Bonato, and B. D. Gerardot, arXiv:1908.03778 (2019)

P1 Polarising a nuclear ensemble for a collective quantum memory

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University of Cambridge, UK

Establishing a successful long-lived quantum memory is an essential stepping stone to many quantum communications applications. Quantum dots have been an increasingly attractive platform for this implementation, due to their exceptional optical properties. The recent demonstration of a deterministic and coherent control interface between a single electron confined in a quantum dot and a nuclear bath [1] has further motivated efforts in this direction. Combining this state transfer with the millisecond-scale coherence times offered by the nuclear environment would be an extremely attractive capability.

To-date high-fidelity state transfer remain an elusive goal as the competition between various nuclear modes places a constraint on what operations can be performed. One way to address this is to polarise the nuclear ensemble, thus introducing selectivity between the nuclear modes. Here, we propose to make use of the widely studied quantum dot phenomenon, known as dynamic nuclear spin polarisation. This effect (Fig. 1) allows the nuclear environment of a quantum dot to be modified by optical excitation, due to its feedback effect on the electron. Using a polarisation protocol, even up to experimentally achievable levels of 50%, promises to dramatically enhance the state transfer fidelity to over 90% (Fig. 2).

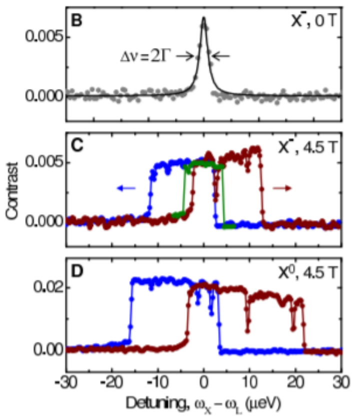

Fig 1: When a magnetic field is applied, the nuclear bath polarises to ‘follow’ the optical transition, thus widening it. This can be used to drag and polarise the nuclear bath [2].

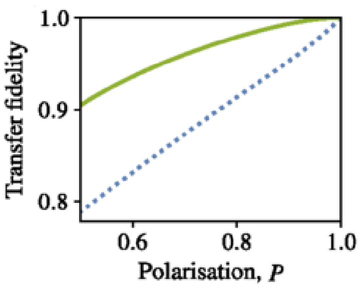

Fig 2: The nuclear state polarisation as a function of state transfer fidelity, for two different magnon modes [3].

[1] D. A. Gangloff, et al., Science 364, 6435 (2019)
[2] C. Latta, et al., Nature Phys 5, 758–763 (2009)
[3] E. V. Denning, et al., Phys. Rev. Lett. 123, 140502 (2019)

P2 Quantum-dot-based optically-pumped vertical-cavity surface-emitting lasers with high-contrast periodic gratings

Edmund Clarke[1], Tibor Fördös[1, 2], Pallavi Patil[1], Robert Airey[1], Nasser Babazadeh[1], Charlotte Ovenden[1], B Cemlyn[3], M Adams[5], I Henning[3] and J Heffernan[1]

[1]University of Sheffield, UK, [2]VŠB - Technical University of Ostrava, Czech Republic, [3]University of Essex, UK

Research on quantum dot-based vertical-cavity surface-emitting lasers (QD-VCSELs) for O-band telecoms window applications is a relatively new direction within optoelectronics [1]. The use of QD gain materials in VCSELs provides advantages such as lower threshold and longer spin lifetime, which plays a crucial role in challenging spin-controlled lasers. Here we demonstrate room temperature lasing at 1285 nm (figure 1a) from a QD-based optically pumped VCSEL, with a cavity using top and bottom GaAs/AlAs Distributed Bragg Reflectors (DBR) and an active region consisting of quantum dot-in-a-well (DWELL) layers.

There are advantages for device fabrication if the thickness of the top mirror is reduced. We discuss possible strategies for reducing the top mirror thickness by using silicon-rich silicon nitride for SiN_x/SiO_2 DBRs, which provide high refractive index contrast. Reflectivity and ellipsometry measurements show a reduction of >50% in the number of SiN_x/SiO_2 DBR pairs required to obtain reflectivity equivalent to standard GaAs/AlAs DBR designs. The thickness of the top mirror can be reduced further by using a high-contrast periodic grating, which also allows polarization-selection of optical modes [2]. SiN_x/SiO_2 grating structures, designed for high reflectivity of TE-emission and fabricated directly onto the QD active region, show a narrow (2 nm FWHM) TE-polarised photoluminescence peak at 1310 nm (figure 1b), which is highly promising for realization of novel VCSEL designs.

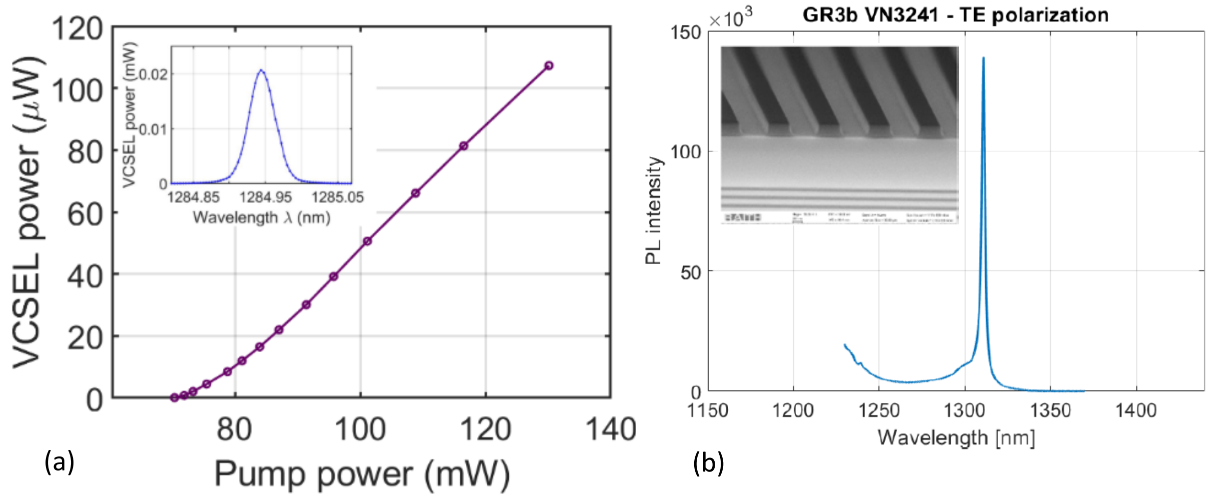

Fig 1: (a) Output QD-VCSEL power versus optical pump power, with output spectrum inset. (b) TE-polarised photoluminescence obtained from QD VCSEL with dielectric grating, inset: scanning electron microscopy image of VCSEL structure with grating.

[1] S. S. Alharthi, E. Clarke, I. D. Henning, M. J. Adams, IEEE Photon. Technol. Lett. 27, 1489 (2015)

[2] C. J. Chang-Hasnain, W. Yang, Adv. Opt. Photon. 4, 379 (2012)

Quantum Dot Day 2020

P3 Influence of vibrational environment on coherent driving of a solid-state two-level system using dichromatic pulses

Zhe-Xian Koong1, Dale Scerri[1], Markus Rambach[1, 3], Suk-In Park[2], Jin-Dong Song[2] and Brian Gerardot[1]

[1]Heriot-Watt University, UK, [2]KIST, Korea, [3]University of Queensland, Australia

On-demand, bright and indistinguishable single photons are key building blocks for any photonic-based quantum information processes. Resonant driving of a Quantum Dot (QD) generates near perfect (>99%) indistinguishability and purity [1, 2] single photons, but with low brightness due to the reliant on polarization filtering. Recent work [3] introduces a background-free resonant excitation scheme, whereby the use of a phase-locked dichromatic pulse on a QD embedded in a micropillar cavity demonstrate simultaneous coherent, bright single photon generation without polarization filtering. This scheme, in principle could be applied to any less sophisticated sample architecture, e.g. bulk samples. Here, we study the dynamics of the scattered photons generated from a solid-state two-level system (negatively charged exciton) in a planar cavity QD sample [4] via dichromatic pulse excitation (DPE). We show that in the absence of a "good cavity", contribution from the exciton-phonon coupling reduces the fidelity of population transfer to approximately 50%. We then show that we could recover up to 95% of the population inversion by modifying the weightage (pulse contrast) of the red and blue components of the dichromatic pulses. By doing so, we observe multi-photon suppression of 1.6% and a HOM visibility of 81% when exciting with a π-pulse. We discuss the role of the emitter-cavity coupling in dichromatic driving by perform numerical simulation on the effective population transfer as a function of emitter-cavity coupling strength. We conclude that for a QD operating in the bad cavity limit, the efficiency and the indistinguishability of the photons generated from the DPE scheme suffers from phonon-induced dephasing.

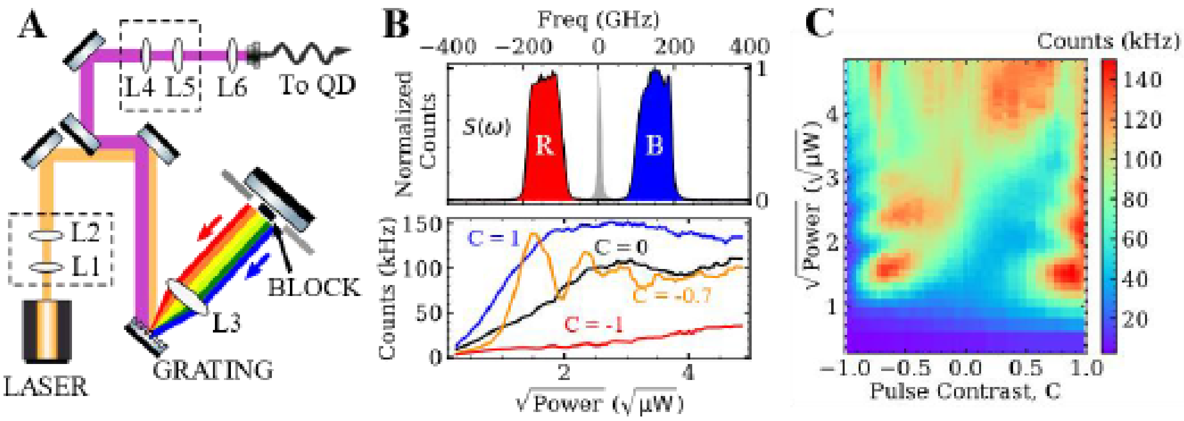

Fig. 1: (A) Experimental schematic for the generation of dichromatic pulses. (B) Example excitation spectra S(ω) and the emission count rate (C- full) as a function of square root of excitation power at different pulse contrasts, C=(B-R)/(B+R). The prescence of electron-phonon coupling degrades the net population change resulting in lower count rate at C=0, compared to the case at C=1

[1] X. Ding, et al., Phys. Rev. Letters 116, 020401 (2016)
[2] N. Somaschi, et al., Nature Photonics 10, 340 (2016)
[3] Y.-M. He, et al., Nature Physics 15, 941 (2019). [4] Y. Ma et al., Journal of Applied Physics 115, 023106 (2014)
[4] Y. Ma et al., Journal of Applied Physics 115, 023106 (2014)

P4 Beam the dot up Scotty, laser transfer of chemically formulated nanospheres & quantum dots

Ioannis Metsios[1], David Sands[2] and Nigel Young[3]

[1]Lumpi Ltd, UK, [2]University of Hull, UK

Fabrication of quantum dots at low cost is a luxury that the industry may not still know it is in need of. Comparing between established methods, chemical fabrication is by far the lowest cost approach. The low control typically encountered in the chemical process dynamics can however be prohibitive to industrially adopting it for mass manufacturing. Results are presented in chemical preparation of II-VI semiconductor nanosized particles in a chemical bath. Process optimization to significantly improve control of particle size formation is then achieved by the use of micro-reactor technology. Synthesising the nanoparticles in the micro-reactor facilitates the reduction of particle size distribution and also the size control of the particles. The center of size distribution can be shifted to sizes between 5 and 80 nm, thus obtaining quantum confinement effects, observed in emission spectra, when exciting the materials photonically to a variety of identified emissive states. In order to place the synthesised particles onto suitable substrates, e.g. semiconductor excitation sources, etc, a technique called Laser Induced Forward Transfer (LIFT). The particles are transferred from a transparent substrate by exploiting a precursor underlying layer, to candidate substrates in a vacuum chamber, using a KrF laser at 248nm or a 4nd harmonic Nd:YAG laser at 266nm. The LIFT process ensures that the target candidate substrates are not exposed to chemical and thermal fabrication conditions that generate the quantum dots. The quantum confinement effects on the excited emission of the quantum dots is verified again after LIFT redeposition.

P5 Single photon source in the telecommunication c-band via quantum frequency conversion

Christopher Morrison, Zhe Xian Koong, M Rambach, Francesco Graffitti, F Thorburn, A Kar, Alessandro Fedrizzi and Brian Gerardot

Heriot-Watt University, UK

Self-assembled quantum dots are a leading technology for bright and indistinguishable single photon sources. There has been significant progress in extending their emission range to the telecommunication bands, for example [1]. This spectral region is desirable for applications such as fiber-based quantum key distribution over metropolitan scale networks.

To date the highest performing quantum dots emit in the near-infrared region [2]. One possible route to a high-performance source in the telecommunication region is to frequency convert the near-infrared single photons using three-wave-mixing in a nonlinear medium [3]. Frequency conversion can be a noiseless process and therefore can preserve the quantum statistics of the near-infrared photon.

We demonstrate low-noise conversion of photons emitted from an InGaAs quantum dot at 939 nm to 1550 nm by difference frequency generation (DFG) in a periodically poled Lithium Niobate (ppLN) waveguide. The DFG process is driven by a home-built 2380 nm laser which can provide over 2 W of continuous wave output power over a tuning range of approximately 400 nm.

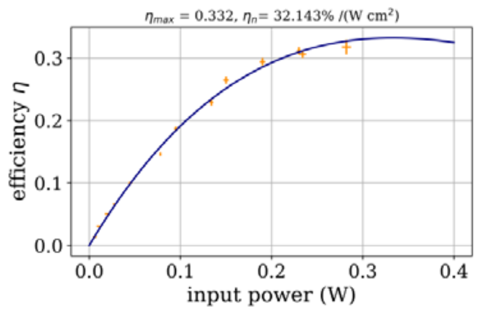

Fig. 1: Conversion efficiency from 939 nm to 1550 nm in the ppLN waveguide. The maximum conversion efficiency is 33% at a coupled pump power of 335 mW. The total fiber-to-fiber system efficiency is greater than 10%.

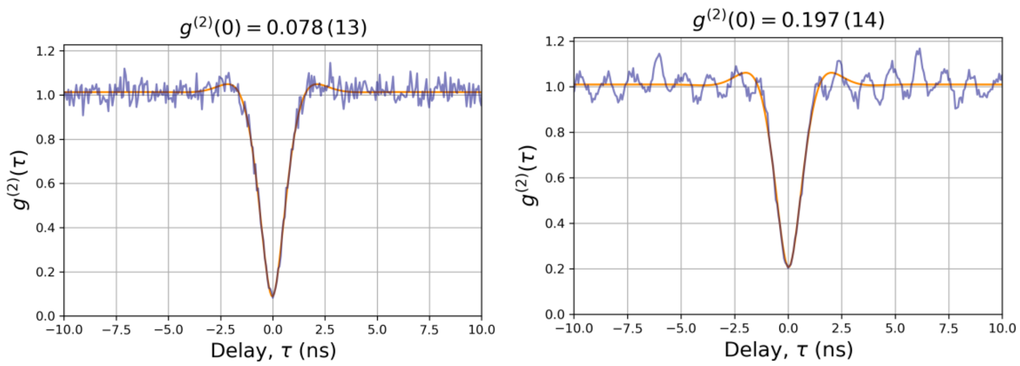

Fig. 2: (a) Second order correlation measurement of the 939 nm photon (b) Second order correlation measurement of converted 1550 nm photon.

[1] C. Nawrath. et al., Appl. Phys. Lett. 115, 023103 (2019)
[2] H. Wang, et al., arXiv:1910.09930 (2019)
[3] J.H. Weber, B. Kambs, et al., Nature. Nanotech. 14, 23-26 (2019)

Quantum Dot Day 2020

P6 High-yield, low-density InAs/GaAs quantum dots as quantum light sources for 900-1300 nm operation

Pallavi Patil[1], Edmund Clarke[1]. Ian Farrer[1,2], Aristotelis Trapalis[1], Charlotte Ovenden[2], A. Foster[3], M Makhonin[1], D Hallett[1], B Royall[1], R Döst[1], I Griffiths[1], E Chekhovich[1], I Itskevich[2], L Wilson[3], A Fox[3], M Skolnick[3]and Jon Heffernan[1]

[1]EPSRC National Epitaxy Facility, University of Sheffield, UK, [2]Department of Electrical and Electronic Engineering, University of Sheffield, UK, [3]Department of Physics, University of Sheffield, UK, [4] University of Hull, UK

Single InAs/GaAs quantum dots (QDs) are promising as sources of on-demand non-classical light, due to their stable, sharp emission lines and the ability for on-chip integration into GaAs-based devices and quantum optical circuits. However this places new demands on the optical properties of the QD, particularly its emission linewidth. We present strategies for growth of high-quality InAs/GaAs QDs and their incorporation into device structures. Use of very low InAs growth rates or close control of the InAs coverage around the 2D-3D transition provides QDs with uniform low density across a whole wafer while maintaining a narrow emission linewidth. Wavelength control can be achieved either by partial capping then annealing to truncate the QDs or including InGaAs-capping layers, giving QDs with a range of low temperature emission wavelengths from 900 to >1300 nm.

Incorporation of low density QDs into freestanding, air-clad GaAs waveguides allows the demonstration of elements for a quantum optical circuit. Resonance fluorescence from QDs embedded in a photonic crystal waveguide show linewidths <4 μeV at 4 K [1]. Correlation measurements have demonstrated anti-bunching of emitted photons from the QD and propagation of single photons in the waveguide, allowing for demonstration of on-chip single-photon beam splitting and Hong-Ou-Mandel interference [2]. Schottky diodes containing QDs grown with the low coverage method to obtain ultralow QD densities (~1 μm^2) exhibit controllable charging of single QD states with resonance fluorescence linewidths <2 μeV at 4 K, and electron spin lifetimes T_1 up to 1 ms, suitable for utilization of electron spin in quantum information applications.

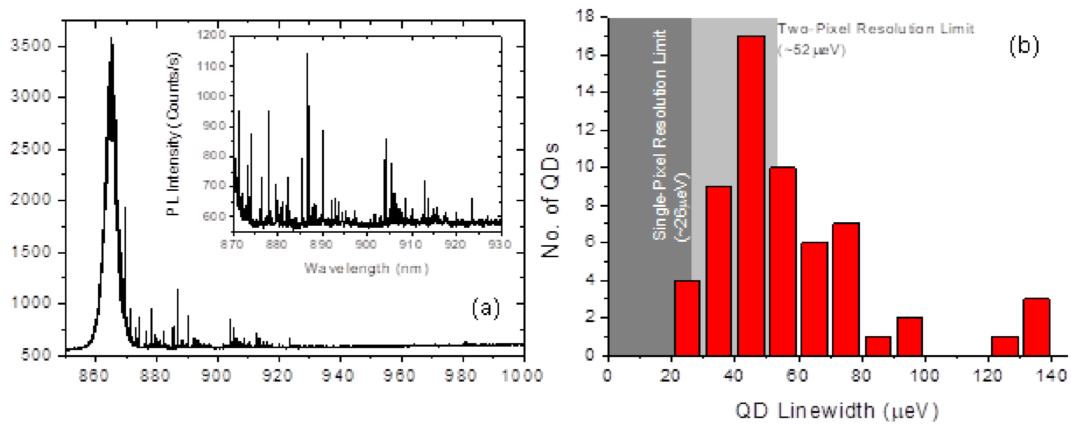

Fig. 1 (a) Photoluminescence spectrum obtained from QDs in waveguide pin diode structure (inset: zoom into QD emission), (b) histogram of single QD PL emission linewidths, showing a significant proportion close to the resolution limit.

[1] D. Hallett, A. P. Foster, D. L. Hurst, B. Royall, P. Kok, E. Clarke, I. E. Itskevich, A. M. Fox, M. S. Skolnick. L. R. Wilson, Optica 5, 644 (2018)

[2] N. Prtljaga, C. Bentham, J. O'Hara, B. Royall, E. Clarke, L. R. Wilson, M. S. Skolnick, A. M. Fox, Appl. Phys. Lett. 108, 251101 (2016)

P7 Droplet epitaxy of InAs/InP quantum dots in MOVPE at the telecom c-band

Elisa Sala, Young In Na, Max Godsland, Aristotelis Trapalis and Jon Heffernan

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We investigate the Droplet Epitaxy (DE) of InAs quantum dots (QDs) on InP(001) substrates. DE relies on the self-assembly of group III droplets, which are subsequently crystallized into QDs by the supply of a group V flow, as discovered by N. Koguchi *et al*. [1] in a Molecular Beam Epitaxy (MBE) environment. Here, we employ DE in Metal Organic Vapor Phase Epitaxy (MOVPE), the cost effective and large-scale growth technique for semiconductor materials. Among III-V QDs, InAs/InP QDs are to date very attractive for applications in the quantum information technologies, since they are compatible with the low-loss telecom C-band [2,3]. Recently, InAs/InP QDs grown via DE in MOVPE led to the demonstration of the first Quantum Light-Emitting Diode (QLED) operating around 1.55 µm [2]. Here, we study the In droplet formation on bare InP and employ a multi-step growth procedure in order to crystallize the In droplets into InAs QDs. Depending on the crystallization conditions, the QD morphology is remarkably affected. In particular, at temperatures greater than 500ºC, a local material removal takes place in the QD vicinity, leading to QDs positioned in etched pits, as shown in Fig.1. Such structures represent thus a combination of Droplet Epitaxy and Droplet Etching [4], and controlling this mechanism could lead to a reduction of the fine-structure splitting (FSS) of DE QDs, a key parameter for achieving a higher entanglement degree [4].

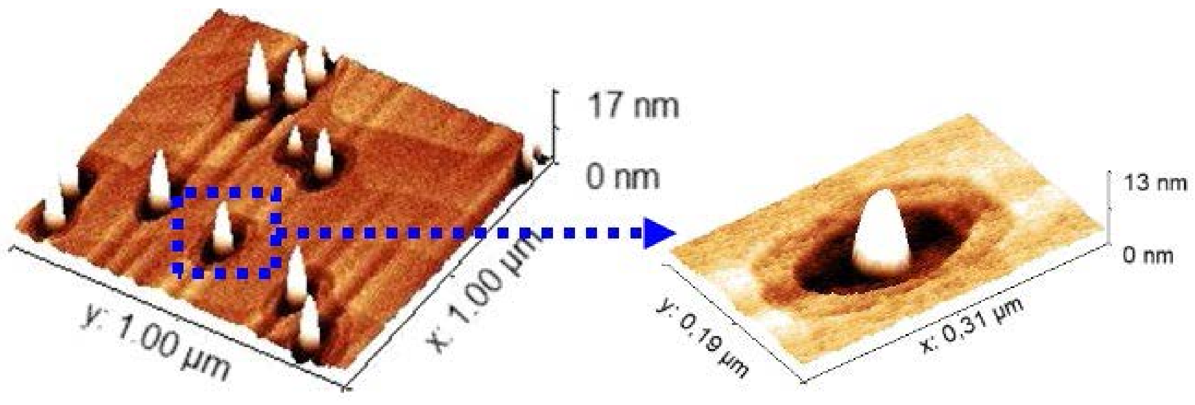

Fig. 1: AFM micrographs of free-standing InAs/InP QDs crystallized at 520ºC. On the right-hand side a single QD placed in an etched pit is shown.

As suggested in [3], an InAsxP1-x 'quasi wetting layer' (WL) is formed as a result of exposing the InP surface to As during droplet crystallization. Optical investigations show a clear correlation between the etching depth of the area around the QDs and the emission intensities of QD and WL bands, suggesting that the local etching disrupts the WL, leading to a more efficient carrier capture into QDs. Additionally, micro-photoluminescence investigations show emission of single QDs around 1.55 µm, confirming their good optical quality. This study opens up to the possibility to apply the flexibility of the droplet epitaxy in MOVPE environment to the large-scale fabrication of a broad range of high-quality nanostructures for applications in quantum information technologies at the telecom C-band.

[1] N. Koguchi, S. Takahashi and T. Chikyow, Journal of Crystal Growth 111, 688–692 (1991)
[2] T. Müller, J. Skiba-Szymanska, A.B. Krysa, J. Huwer, M. Felle, M. Anderson, R. M. Stevenson, J. Heffernan, D.A. Ritchie, and A. J. Shields, Nature communications 9, 862 (2018)

[3] J. Skiba-Szymanska, R. M. Stevenson, C. Varnava, M. Felle, J. Huwer, T. Müller, A. J. Bennett, J. P. Lee, I. Farrer, A. B. Krysa, P. Spencer, L. E. Goff, D. A. Ritchie, J. Heffernan, and A. J. Shields, Phys Rev. Appl. 8, 014013 (2017)
[4] M. Gurioli, Z. Wang, A. Rastelli, T. Kuroda, and S. Sanguinetti, Nature Materials 18, 799–810 (2019)

P8 Ultra-fast nanocomposite-based scintillating heterostructures for time-of-flight positron emission tomography

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Time-of-Flight Positron Emission Tomography (ToF-PET) is a well-established and key healthcare examination technique. Its unique capability to provide functional information at the cellular level has become invaluable for early diagnosis and staging of multiple diseases. However, there is still a wide gap between the current technology's performance and the clinical end user's needs, which could be achieved by establishing ToF-PET imaging as a less invasive, more flexible and high diagnostic power technology. The application requirements for ToF-PET detectors are well defined - i) short attenuation length, ii) ultra-fast response time (sub-nanosecond) and iii) decent energy conversion efficiency (light output). Conventional single crystal scintillators such as $Lu_2SiO_5:Ce^{3+}$ (LSO) or $Bi_4Ge_3O_{12}$ (BGO), the current materials of choice for ToF-PET, represent a technical compromise, especially in terms of the reachable timing. We propose to address the limitations of the single detector material approach, by developing a novel family of radiation sensing heterostructures in which multiple materials work in synergy to achieve unparalleled performance - and in turn, enable the production of ultra-fast and short attenuation length alternatives to the currently inherently limited ToF-PET detectors.

In this context, a heterostructure (Fig. 1 - a) consists of a single crystal body called the matrix, in which a nanocomposite component is embedded in the form of a highly loaded quantum dot (QD) polymer [1] called the filler. The matrix, in our case BGO single crystal, acts as the main radiation absorber to maintain the overall high stopping power of the heterostructure, while the QD-loaded polymer adds an ultra-fast component to the standard BGO time response. The presentation will focus on three parts; i) heterostructure design versus performance, ii) nanocomposite filler synthesis (Fig. 1 - b) and iii) heterostructure manufacturing. The emphasis will be given to filler production including challenges associated with a high loading of QDs (>10 wt%) into a polymer and the optical performance of the monolith. Results for commercially available CdS/ZnS QDs and in-house synthesized perovskite QDs, both chosen for their high atomic number and fast decay times, will be presented. Finally, preliminary results for the manufactured heterostructure (precision machining of single crystal, QD loading into the polymer and in situ polymerization of the nanocomposite) will be presented.

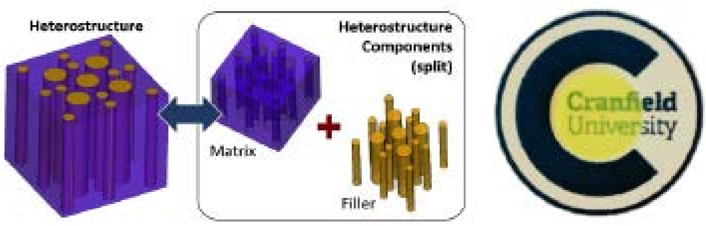

Fig. 1: (a) Schematic example of a 2-material heterostructure for ToF-PET; (b) Picture of the CdS/ZnS QD-loaded polymer (14 wt%).

[1] C. Liu, et al., ACS Nano, 11, 6, 6422-6430 (2017)

P9 Coherent transverse electromagnetic mode lasing in a self-assembled symmetric cavity of perovskite quantum dots

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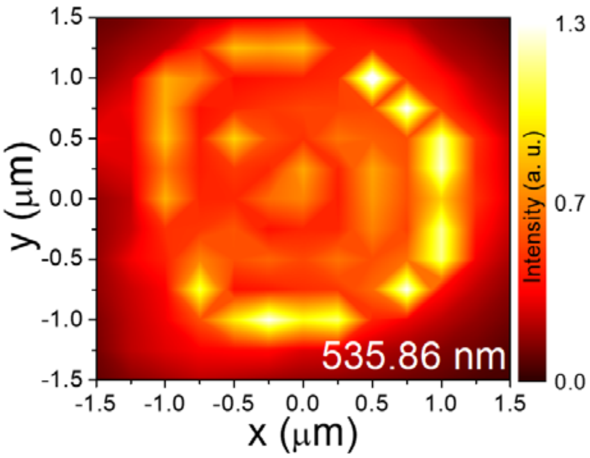
Highly promising inorganic perovskites are expected to enable the next generation of optoelectronic devices, offering properties vital for technological deployment and scalability, including stability and robustness, reproducibility and cost-effective synthesis. Inorganic perovskite lasers are of particular interest and recent work has focused on Fabry-Pérot cavity-forming nanostructures.

Our work has demonstrated lasing from a coupled quantum dot system based on $CsPbBr_3$ that dispenses with an external cavity resonator. The quantum dots are encapsulated in nanocrystals which in turn are distributed homogeneously inside a self-assembled cluster. Planar symmetric facets of the cluster naturally provide the configuration of an optical resonator supporting Gaussian modes which give rise to transverse electromagnetic (TEM) modes (figure 1) seen for the first time in a perovskite quantum dot system. Moreover, power control of the optical pump can induce a dynamic shift of the background spontaneous emission which picks up different TEM modes (fig 2) revealing the potential for mode switching. The coherence time of our lasing signal is about ~9.5ps, setting a benchmark for the collective emission from perovskite quantum dot system. The onset of lasing in our devices is attained at low excitation powers, promising a new class of highly efficient lasers for applications in visible-range ultrafast spectroscopy.



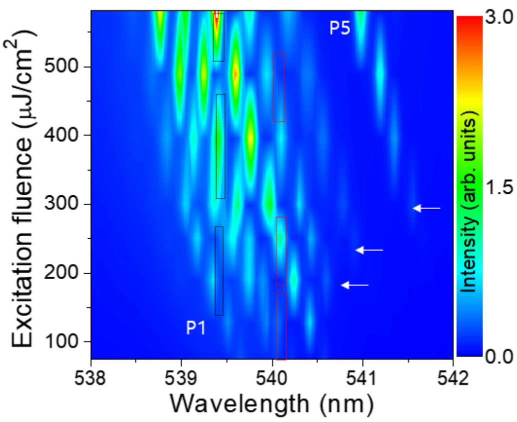


Fig. 1: (Left) Spatial luminescence map of emission showing one transverse electromagnetic mode structure

Fig. 2: (Right) Power-dependent 2D contour map of emission spectra taken over a region of a QD cluster. The black and red rectangles are visual guides showing lasing modes at fixed wavelengths. The white arrows indicate the onset of new peaks

P10 Coherent interface to nuclear spins in strain-controlled GaAs quantum dots

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In our previous work, we achieved the coherent control of electronic-nuclear transitions within an InGaAs quantum dot through all-optical control of the electron [1]. This suggests that the nuclear spin ensemble in a quantum dot is a strong candidate for a quantum memory.

Recent theoretical work done in our group [2] suggests the possibility of an all-optical memory write-in and read-out protocol, inspired by the Dynamic Nuclear Polarisation (DNP) sequence from ref. [3]. In particular, it predicts the possibility of high fidelity information transfer at experimentally achievable nuclear polarisation. However, it also shows that the transfer fidelity can be severely affected by nuclear ensemble inhomogeneities.

The effective interaction between the electron and the ensemble of nuclear spins originates from the coupling of nuclear quadrupolar moments to the electric field gradients caused by strain within the quantum dot. For InGaAs quantum dots, the strains built-in during growth are large and inhomogeneous. Instead, we plan on using GaAs quantum dots where the intrinsic strain is reduced because of no lattice mismatch between the quantum dot and the host semiconductor. To induce the quadrupolar interaction the sample has to be strained externally, which is the next intended step of our research.

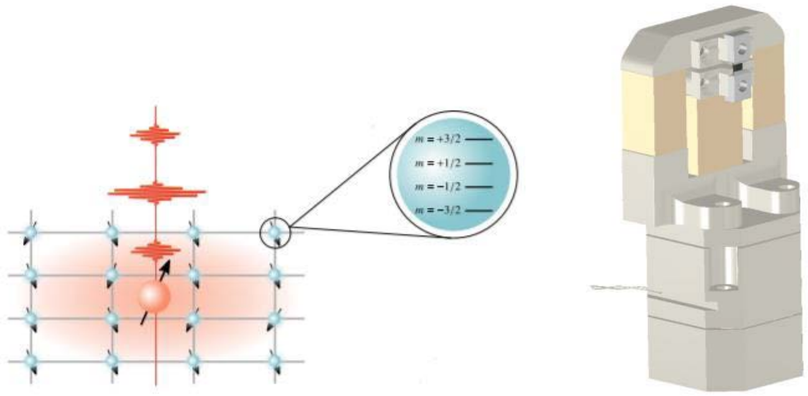

Fig. 1: (Left) Optically controlled central electron spin interacting with a nuclear spin ensemble within a GaAs quantum dot; (Right) Design of the device applying uniaxial strain to GaAs Quantum Dots

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[2] E. V. Denning, et al., PRL, 123, 140502 (2019)
[3] I. Schwartz, et al., Science advances, 4, eaat8978 (2018)

P11 Multichromic metal-organic framework via nanoconfinement for multimode photonic sensing technology

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The luminescent properties of Metal-Organic Frameworks (MOFs) have attracted considerable attention in recent years. One of the most important reasons is that MOFs have high porous and long-range crystalline network structure giving themselves the ability to 'capture', isolate and stabilize other emitter molecules, namely 'guest'. Because many possible interactions may happen when introducing guest into MOFs, this host-guest combination can result in various intriguing luminescent performances which are not commonly observed in conventional materials, such as mechanochromism, solvatochromism, etc [1]. Furthermore, the isolation of guest in MOFs structure can significantly overcome aggregation-caused quenching (ACQ) effect, allowing many materials that only show luminescence in a dilute solution can fully exhibit their properties in the solid state [2]. These characteristics make this kind of material can be used in many advanced fields, such as LED and sensor.

In this work, we used a very simple way to synthesize a multi-stimuli responsive luminescent material by embedding commonly used rhodamine B (RhB) into zeolitic imidazolate framework-71 (ZIF-71). This material could exhibit good mechanochromism, thermochromism, and solvatochromism (Fig. 1). We found the multichromic response are closely related to the nanoscale confinement effect that ZIF-71 imposes on the RhB monomers, H-type, and J-type aggregates, which provides a new strategy for the preparation and design of novel multi-stimuli responsive sensors.

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[2] A. K. Chaudhari, J. C. Tan, Nanoscale. 10, 3953-3960 (2018)

P12 Strain-induced single photon emitters in monolayer TMDs couple to high-index dielectric nano-antennas

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[1]University of Sheffield, UK, [2]Imperial College London, UK, [3]Ludwig-Maximilians-Universitat Munchen, Germany

The search for reliable single photon sources integrated with on-chip photonic structures for use in quantum information processing has motivated the study of different material systems. Desirable characteristics include high positioning precision within a photonic circuit, high purity, brightness and indistinguishability. In the past, efforts to achieve quantum emitters within a solid-state system have been led by research in III-V quantum dots and NV centres in diamond. Recently, the discovery of quantum emission in 2D materials [1] has brought transition metal dichalcogenides (TMDs) towards active single photon source research.

The simple fabrication of strain-induced single photon emitters (SPEs) in TMDs with intrinsic positioning precision to < 50nm [2] makes them attractive for further research into quantum light emission. The use of arrays of polymer [3] or SiO_2 [54] pillars as stressors for the formation of TMD single photon sources paved the way for the formation of precisely positioned SPEs.

In our work, we use this ability to produce strain-induced SPEs in TMDs by placing a monolayer of WSe_2 onto high refractive index dielectric nano-antennas (NAs) made of gallium phosphide in order to couple their emission to photonic modes, which coincide with the region of highest strain. This approach is based on our recent demonstration of strong photoluminescence enhancement in monolayer and bilayer WSe_2 placed on such antennas [5]. Here the NAs act as both stressor and nano-photonic structures enhancing the optical properties of SPEs. We observe bright, narrow linewidth, single photon emission at nano-antenna sites. We have recorded the brightest (>30 000 cts/s), highest purity ($g^2(0) = 0.00135$) and longest lifetime (200 ns) emission reported for TMD single photon sources to date. For the first time, we have also been able to measure the coherence time of single photon emission in TMDs, which we found to be 2.7 ps.

Coupling SPEs to dielectric nano-antennas could lead the way to integrating TMD single photon sources on-chip in order to be utilized in quantum technology applications.

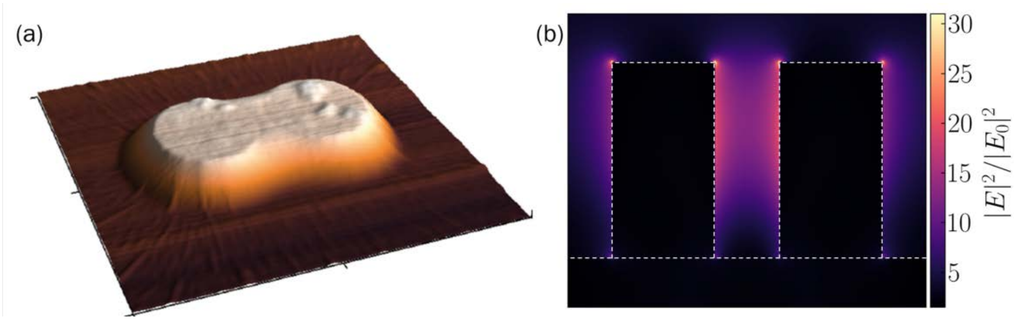

Fig. 1: (a) AFM scan of WSe_2 monolayer strained by a nano-antenna, (b) Electric field enhancement due to a photonic mode. The electric field enhancement is co-located with the region of highest strain.

[1] P. Tonndorf et al., Optica 2(4):347 (2015)
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[3] A. Branny et al., Nature Comm. 8, 15053 (2017)

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[5] L. Sortino et al., Nature Comm. 10, 5119 (2019)

P13 An electrically driving tuneable entangled quantum dot device in cambridge fibre network

Zi-Heng Xiang[1, 2], Jan Huwer[1], Joanna Skiba-Szymanska[1], Mark Stevenson[1], David Ellis[1], Ian Farrer[2, 3], Martin Ward[1], David Ritchie[2] and Andrew J Shields[1]

[1]Cambridge Research Laboratory, UK, [2]Cavendish Laboratory, UK, [3]University of Sheffield, UK

Quantum dot entangled photon pair sources are one of the most promising devices for secure quantum networks, due to their low probability of multi-photon-pair generation. The application of quantum dot devices in an urban fibre-based quantum network would require emission in telecom-wavelength region. Despite recent progress on pushing the quantum dot emission wavelength to telecom O and C-band [1], no work has fully has illustrated its network integrability yet. A practical network environment would prefer a full electrical operation of the device, with wavelength tuneability for multiplexing purposes. For the above purposes, we have designed an electrically operated telecom quantum dot device, and deployed it in the Cambridge Fibre Network [2].

Figure 1 shows a schematic of the new tuneable device design. It consists of two parts: a pumping diode and a tuning device. The pumping diode is electrically excited by a current injected from the metal contact on the left. The emitted light from it optically excites the quantum dots located at the centre of the tuning diode, where a bias could be applied from the right metal contact for tuning the wavelength and fine structure splitting. Wavelength of emitted biexciton/exciton photons could be tuned both over 25 nm in the telecom O-band.

We deployed the device in West Cambridge (CAM). One photon of each entangled pair is measured at CAM with a polarization analyser. Its partner photon is sent to Toshiba Cambridge Research Laboratory (CRL) over 15km optical fibre in the Cambridge Network. A polarization stabilization system was used to compensate for fibre birefringence variation [3], and classical data traffic was multiplexed over the same fibre for classical communication between CAM and CRL. An entanglement fidelity over 95% has been maintained for the entire measurement duration (40 hours).

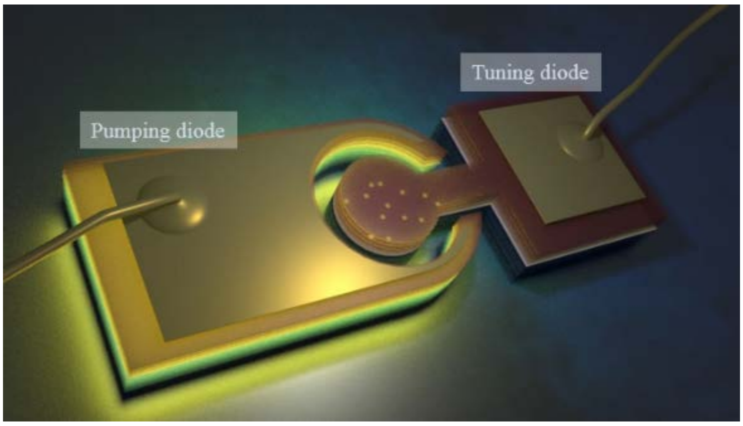

Fig. 1: A schematic of the electrical telecom quantum dot device

[1] Anderson, M., et al. arXiv preprint arXiv:1901.02260 (2019)

[2] Xiang, Z-H., et al. "A tuneable telecom-wavelength entangled light emitting diode." arXiv preprint arXiv:1909.12222 (2019)

[3] Xiang, Zi-Heng, et al. Scientific reports 9.1 (2019): 4111

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