EQEP 2023

ENGINEERING OF QUANTUM EMITTER PROPERTIES

THE 9TH INTERNATIONAL WORKSHOP

7-8 DECEMBER

PADERBORN UNIVERSITY

INSTITUTE FOR PHOTONIC QUANTUM SYSTEMS

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Welcome to EQEP 2023

We are very excited to welcome you to the 9th international workshop on Engineering of Quantum Emitter Properties (EQEP), held in Paderborn, December 7-8, 2023.

The two-day workshop program features 21 presentations by the speakers from all over the world. It aims to have live discussion on state-of-the art research results and explore the challenges in engineering of quantum sources in the future.

Institute for Photonic Quantum Systems (PhoQS) combines the expertise of over 30 scientists, including three ERC grant holders, from four disciplines. 13 working groups from the departments of physics, mathematics, computer science and electrical engineering.

We wish that you enjoy the scientific and social exchange during your stay in Paderborn!

Prof. Klaus Jöns

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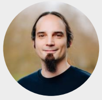

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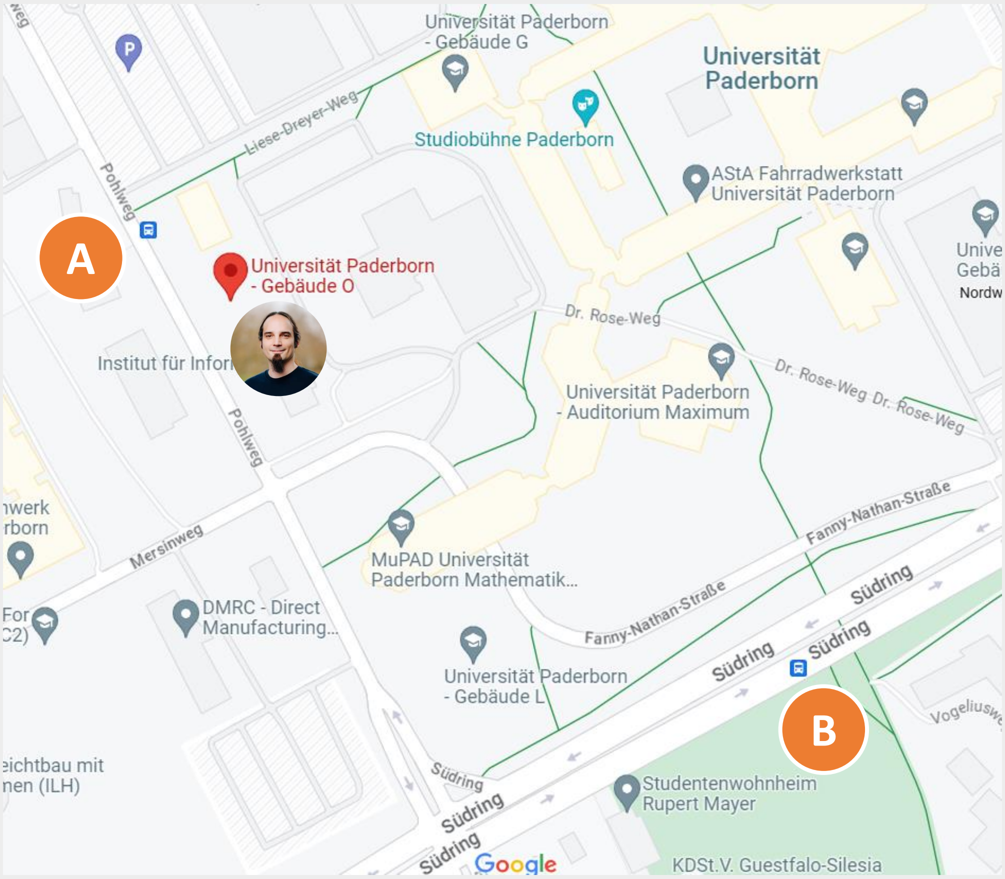

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Invited Session Chairs

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Institute of NanoSciences of Paris

Dr. Simone Portalupi

University Stuttgart

Prof. Jean Michel Gerard

University Grenoble Alpes

Prof. Armando Rastelli

Johannes Kepler University Linz

Program

Time	Thursday 7.12	Friday 8.12
08:00	Venue opening (O building)	
08:45	Opening remarks	
09:00	**Mathias Pont**	**Doris Reiter**
09:30	**Gregor Weihs**	**Peter Michler**
10:00	**Brian Gerardot**	**Tobias Heindel**
10:30	Coffee/Exhibition	Coffee/Exhibition
11:00	**Arne Ludwig**	**Mete Atatüre**
11:30	**Stefan Schulz**	**Tobias Huber-Loyola**
12:00	**Kai-Mei Fu**	**Kai Müller**
12:30	Lunch/Exhibition	Lunch/Exhibition
13:00	Lunch/Exhibition	Lunch/Exhibition/Poster session
13:30	**Tim Schröder**	Exhibition/Poster session
14:00	**Carlos Errando-Herranz**	Exhibition/Poster session
14:30	**Anais Dreau**	**Richard Warburton**
15:00	Coffee/Exhibition	**Christian Schneider**
15:30	**Hanna Le Jeannic**	Coffee/Exhibition
16:00	**Julien Claudon (online)**	**Gediminas Juska**
16:30	Exhibition/Poster session	**Rinaldo Trotta**
17:00	Exhibition/Poster session	Farewell
17:30	Exhibition/Poster session	
18:00	Buffer time	
18:30	Walk to dinner	
19:00	Dinner (Brauhaus)	
21:00	Social event (Gewölbe)	
21:30	Social event (open end)	

Dinner & Event

Brewery House Paderborn - Paderborner Brauhaus

Kisau 2, 33098, Paderborn

GWLB - Gewölbe unter dem Marienplatz

Marienplatz 18, 33098, Paderborn

9th international workshop on "Engineering of Quantum Emitter Properties"– Paderborn, Germany

Quantum information processing with quantum dot single-photon sources.

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After years of fundamental studies and developments, quantum light sources based on semiconductor quantum dots are now reaching a level of maturity compatible with quantum information processing. In the present talk I will review our recent progresses in this direction.

I will first present two recent milestones obtained in strong collaboration with Quandela (www.quandela.com) starting with our efforts to fiber pigtail single-photon sources based on quantum dots in micropillar cavities. We have developed a technique to align a single mode fiber directly on top of the device with sub-micron accuracy and preserve the alignment when going from 300 K to 4K. The apparatus shows an in-fiber single-photon rate of 14.7 MHz with HOM visibility above 96% (indistinguishability above 97%). The performances are stable over hours in multiple standard closed-cycle cryostats [1]. I will then present the general-purpose quantum computing platform based on 6-photons [2] that has recently been made cloud-accessible. The prototype is benchmarked in terms of stability, multi-photon rates and post-selected gate fidelities. We also report on various applications such as a variational quantum eigensolver, a quantum machine learning classification task or the heralded on-chip generation of 3 photon GHZ states starting from 6 photons.

In the near future, to scale-up photonic quantum computing, new resources – namely large multi-photon entangled states- will be needed to implement measurement-based protocols. In this last part, I will show how we have harnessed phonon-assisted excitation schemes to generate spin-photon-photon entanglement in a low magnetic field configuration [3]. The use of a cavity for photon collection allowed to obtain rates that are orders of magnitude higher that previous experimental demonstrations. Many challenges remain to reach longer photonic clusters states – such as the compatibility of spin echo techniques with cluster state generation schemes.

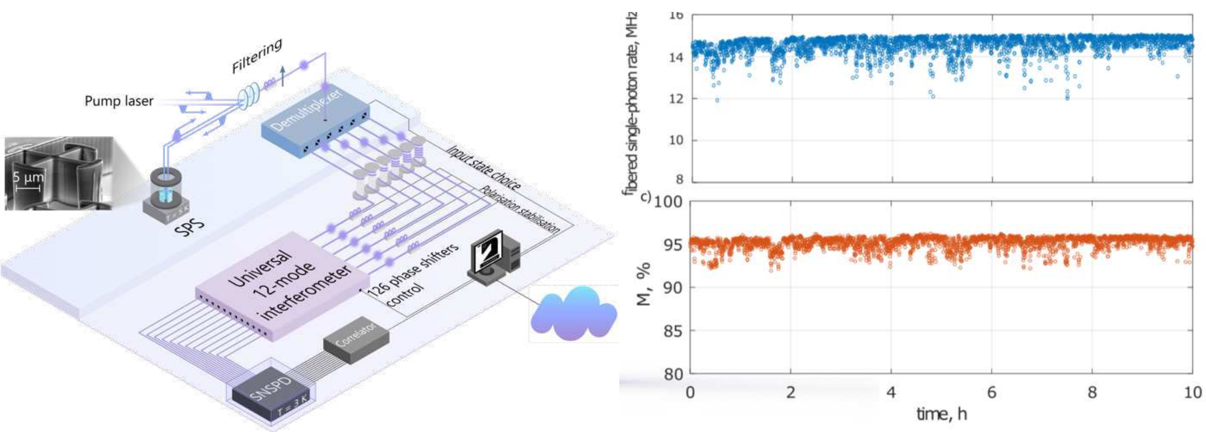

Figure: Left: architecture of the 6-photon quantum computing platform made cloud accessible by Quandela. Right: Performances of a fiber-pigtailed single photon sources inserted in a standard (i.e. vibrating) cryostat.

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Dark Exciton Control for Deterministic Time-Bin Entanglement

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Temporal encodings of quantum information are prevalent in applications because of their suitability for long-distance quantum communication and their compatibility with optical fiber communication networks. Perhaps the simplest temporal encoding is time-bin encoding, i. e. in superpositions of two (or more) temporally separated optical pulses.

Early attempts at generating time-bin entanglement from single quantum emitters was not able to avoid the problem of re-excitation [1] or was converted probabilistically from polarization entangled photon pairs from a quantum dot [2]. Direct generation requires a metastable level [3] to carry the coherence and avoid double pair emission into the desired time bins.

In order to use dark exciton states as metastable states we have worked on their efficient creation and coherent control in the presence of in-plane magnetic fields. Much of this is based on our recent work on advanced excitation schemes using chirped pulses [4]. With chirped pulses we are now able to deterministically populate a dark exciton state and to transfer this population to the biexciton, which can then emit a photon pair.

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V. Remesh, et al., Appl. Phys. Lett. Photon. **8,** 101301 (2023), https://doi.org/10.1063/5.0164222

Cooperative photon emission from multiple indistinguishable quantum dots

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Photon-mediated interactions between atoms can arise via coupling to a common electromagnetic mode or by quantum interference. Here, we engineer and probe cooperative emission arising due to path erasure from multiple distant but indistinguishable quantum dots. The primary signature of cooperative emission, the emergence of "bunching" at zero delay in an intensity correlation experiment, is used to characterize the indistinguishability of the emitters, their dephasing, and the degree of correlation in the joint system that can be coherently controlled [1, 2]. To achieve cooperative emission in a scalable fashion with multiple indistinguishable quantum emitters, we introduce the use of spatial light modulators to independently control the excitation and collection of an arbitrary number of indistinguishable quantum dots. These results establish techniques to rapidly characterize indistinguishability of multiple emitters, to multiplex quantum light sources, to achieve scalable quantum light sources as inputs for programmable quantum circuits [3], and to engineer and manipulate large Dicke states [4].

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Quantum dots for low noise single photon sources

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A key component for photonic quantum devices is a source of high-fidelity photonic qubits, a single photon source. A promising route to create such a device employs semiconductor quantum dots (QDs) in photonic cavities.

However, noise processes hampering solid state emitters [1]. A main contributor to decoherence and low efficiency is random charge rearrangements in the semiconductor environment or the QD itself. A random change of the QD’s charge state from e.g. Auger processes [2] or photoionization [3] can switch the emitter temporarily off [2,4].

One way to efficiently suppress charge noise, is to embed the QDs in the high purity material undoped region of a p-i-n-[5,6] or n-i-n-[7] diode tunnel-coupled to a charge reservoir. We successfully apply this method [8,9] to highly promising strain free local droplet etched GaAs-QDs [10,11] and discuss these QD’s advantages.

We now turn to epitaxial growth control of our QDs. Wafer rotation stop enables material gradient growth. Newly discovered implications of this well-known method like a periodic modulation of the QD density [12] and QD-emission wavelength [13] will be presented.

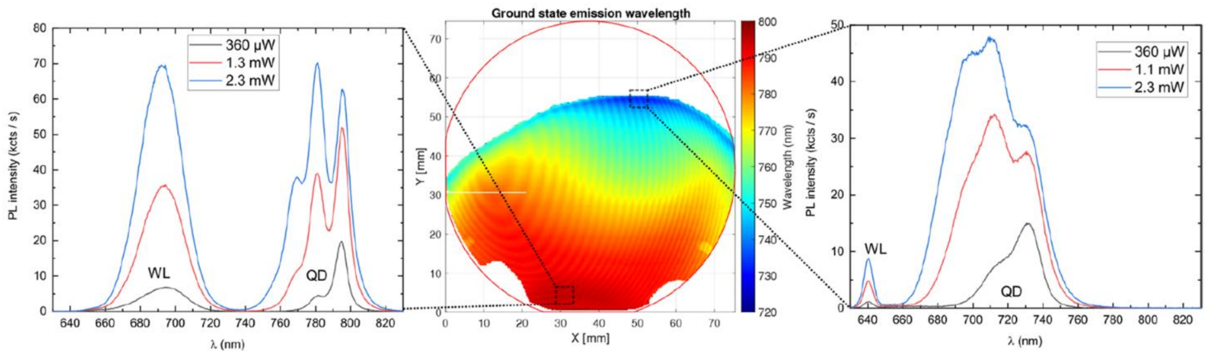

Figure 1: (centre) QD photoluminescence ground state peak emission wavelength recorded on a full 3”-wafer at $T = 100$ K. The emission is modulated due to material gradient deposition. (left and right) Photoluminescence spectra taken at the positions indicated in the centre map measured at the indicated laser power. The QDs show a clear level structure. A thin GaAs quantum well (WL) is emitting in the red spectral range.

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Wurtzite III-N and [111]-oriented zinc blende III-V quantum dots: A theoretical study of similarities and differences in their electronic and optical properties

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The generation of polarisation entangled photon pairs from semiconductor quantum dots via the biexciton-exciton cascade has attracted strong interest over two decades [1]. Utilizing this cascade in [001]-oriented zinc blende (In,Ga)As QDs for such non-classical light emission processes proved difficult due to the fundamental properties of these dots, including aspects related to the combined symmetry of QD geometry and underlying crystal structure [2]. QDs grown in the wurtzite crystal phase or along the [111]-direction of the zinc blende lattice should, in principle, lead to a vanishing excitonic fine structure splitting, thus making them ideal candidates to emit entangled photon pairs [3].

In this work, we will review similarities and differences in wurtzite III-N and [111]-oriented zinc blende QD systems, including piezoelectric polarisation fields, before turning to the electronic and optical properties of such structures. We start our discussion with the electronic structure of [111]-oriented (In,Ga)As dots and present results from atomistic tight-binding (TB) studies to account for alloy disorder in the QD on a microscopic level [4]. Our calculations reveal that random alloy fluctuations in these systems only slightly affects their electronic and optical properties. Equipped with this information we present approaches to construct symmetry adapted continuum-based models, which allow for computationally efficient calculations targeting electronic and optical properties of site-controlled [111]-oriented GaAs zinc blende QDs.

Finally, we present results of atomistic TB investigations for wurtzite (In,Ga)N/GaN QDs [5,6]. In contrast to [111]-oriented (In,Ga)As dots, we find that the alloy disorder significantly affects the electronic structure, leading for instance to strong carrier localisation effects due to random alloy fluctuations inside the QD. Coupling the TB electronic structure with configuration interaction calculations reveals excitonic binding energies larger than the thermal energy at room temperature. However, our calculations also show that when compared to zinc blende III-V QDs, "unconventional" excitonic fine structure splittings and biexcitonic ground states are observed. For instance, the biexcitonic ground state is mainly constructed from electrons in their single-particle ground states while the holes populated ground and excited states ("hybrid" biexcitons). We attribute this aspect to strong hole-hole Coulomb repulsion effects in III-N QD systems.

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9th international workshop on “Engineering of Quantum Emitter Properties”– Paderborn, Germany

Shallow Donors in ZnO for Quantum Information Applications

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Donors in semiconductors have been studied as a qubit platform for over 20 years. Here we present our work on synthesizing and isolating single donors in zinc oxide (ZnO). The direct band gap nature of ZnO enables efficient access to the donor electron via the donor-bound exciton [1,2]. Here we demonstrate synthesis of indium (In) donors via ion implantation and annealing [3] with properties on par with In donors incorporated *in situ* during growth including: a narrow inhomogeneous linewidths (< 10 GHz), spin initialization, and long longitudinal spin relaxation (> 100 ms). Next, we demonstrate single In donor isolation for *in situ* doped In via plasma-enhanced focused ion beam milling [4]. An outlook toward single implanted In isolation, access to the In nuclear spin, and applications in quantum networks, memories and transduction will also be presented.

This presentation is based upon work supported by the Army Research Office MURI Grant on Ab Initio Solid-State Quantum Materials: Design, Production and Characterization at the Atomic Scale (18057522), National Science Foundation under Grant 2212017, and U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Co-design Center for Quantum Advantage (C2QA) under contract number DE-SC0012704.

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Quantum Networking with Spin Defects in Diamond Nanostructures

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Optically active spin defects in diamond have proven to be a promising resource for the implementation of quantum communication and have recently enabled the first demonstration of a 3-node network. In this presentation I bridge ongoing work and proposed concepts in the control, analysis and engineering of single spin defects for applications in quantum communication. I introduce a recent proposal in which we demonstrate theoretically that error corrected quantum communication over 1000 km becomes achievable with solid-state spin qubits that are efficiently coupled to optical nanostructures. These coupled spin defects and their coherent control, however, have complex requirements that go beyond current state-of-the-art. In our work, we focus on understanding the spin qubits' nano- and microscopic noise environment, on coupling to nanostructures, and on system control schemes. To illustrate these efforts, I outline how we coherently control single and multiple diamond spin qubits in a sub-diffraction volume, how we enhance qubit-to-waveguide coupling with the adiabatic Sawfish cavity with efficiencies of up to 99%, and how we mitigate noise in such nanostructures to maintain high photon coherence. Finally, I look into the near future and lay out how we plan to generate multi-qubit entangled states—an important step towards applying solid-state spin defects for the implementation of long-distance quantum communication and quantum networks.

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Integrated quantum photonics with single color centers in silicon

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Color centers are promising candidates for quantum technologies due to their long coherence times and high-quality spin-photon interfaces. Silicon has recently emerged as a host for color centers operating in the telecommunication bands, in a technological platform featuring the world's most advanced manufacturing, electronics, and photonics. In this talk, I will present our recent work on the fabrication and isolation of individual G-centers in silicon photonic waveguides [1], their spectral reconfiguration [1], and the enhancement of their light-matter interaction via coupling to photonic crystal cavities [2].

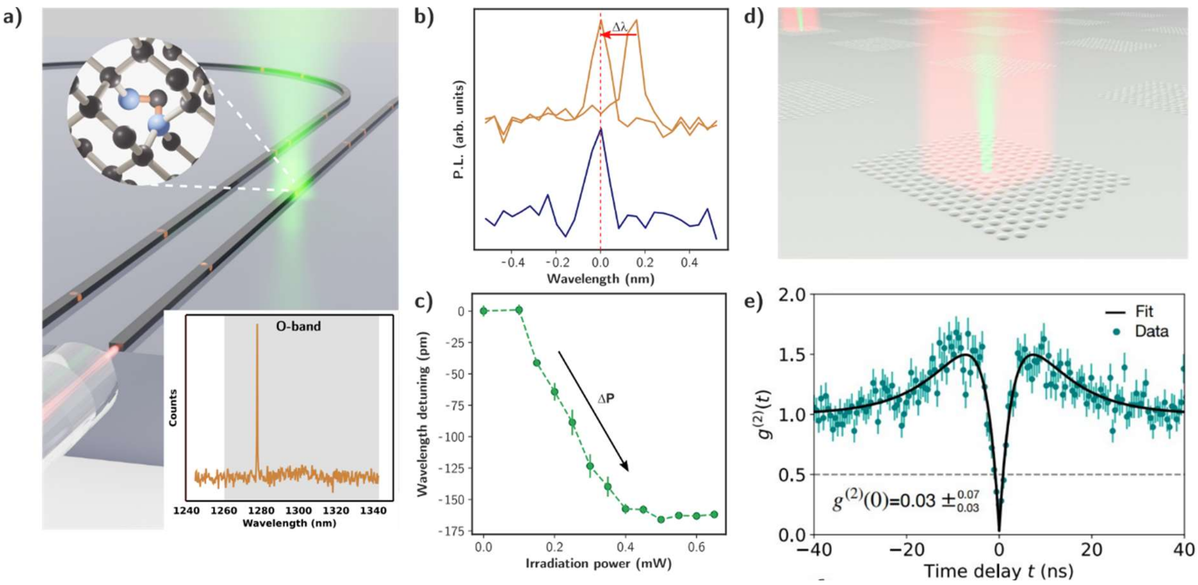

Figure 1: a) We demonstrated coupling of individual G-centers into silicon photonic waveguides and demonstrate waveguide-coupled single-photon emission in the telecom O-band [1]. b) and c) shows their non-volatile spectral tuning via optical irradiation [1]. d) Shows a artist rendering of our inverse-designed photonic crystal cavities coupled to single G-centers, which enabled e) strong single photon emission [2].

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9th international workshop on "Engineering of Quantum Emitter Properties"– Paderborn, Germany

Single color centers in silicon

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The boom of silicon in semiconductor technologies was closely tied to the ability to control its density of lattice defects [1]. After being regarded as detrimental to the crystal quality in the first half of the 20th century [2], point defects have become an essential tool to tune the electrical properties of this semiconductor, leading to the development of a flourishing silicon industry [1]. At the turn of the 21st century, progress in Si-fabrication and implantation processes has triggered a radical change by enabling the control of these defects at the single level [3]. This paradigm shift has brought silicon into the quantum age, where individual dopants are nowadays used as robust electrical quantum bits to encode and process quantum information [4]. Fluorescent defects recently isolated at single-defect scale in silicon [5,6] could follow suit. These new artificial atoms in silicon have the advantage of an optical interface at telecom wavelengths, and for some, combined with a non-zero electron spin state that could be used to locally store quantum information [7].

In this talk, we will present our latest developments on the isolation and control of single fluorescent defects in silicon [8-10]. Despite its small band gap, this semiconductor hosts a large variety of emitters that can be optically detected at single scale at 10K and featuring single-photon emission directly in the telecom bands adapted for long-distance propagation in optical fibers. We will discuss the prospects and challenges of these promising systems for Si-based quantum technologies, including integrated quantum photonics and quantum communications.

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Photon-photon interactions from a two-level emitter coupled to nanophotonic waveguides

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In this conference presentation, we investigate the coupling of single quantum emitters to nanowaveguides, focusing enabling highly efficient photon-photon interactions mediated by quantum emitters. Specifically, I will first discuss the case of self-assembled InGaAs quantum dots integrated into photonic waveguides for highly efficient light matter interaction [1]. Such a platform contains highly rich physics and enables to explore the potential for giant nonlinearities, such as single photon phase shift [2], and consequent advanced photon-photon operations [3]. Finally, I will share insights from my new research group on the enhancement of the coupling of single solid-state quantum emitters to nanofibers, in particular at room temperature [4].

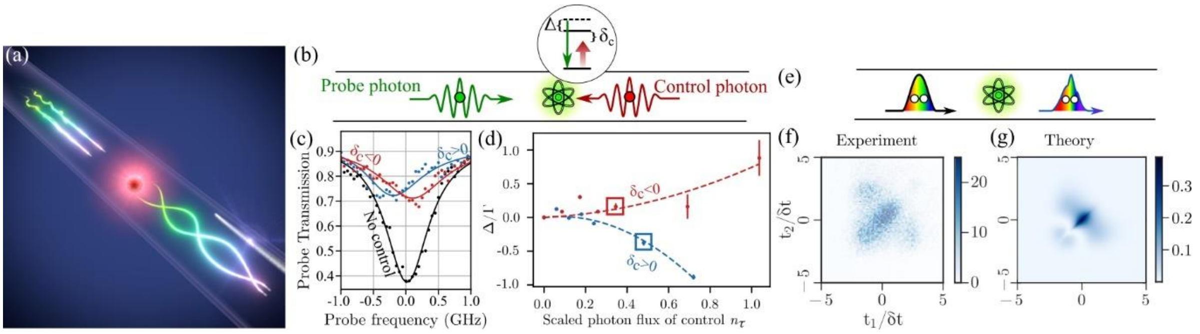

Figure 1: (a) Conceptual illustration of two-photon pulsed nonlinear interaction mediated by a quantum emitter in a nanophotonic waveguide inducing strong quantum correlations between the photon wavepackets. (b,c,d) AC-Stark shift induced by single photon on a quantum emitter and control of the transmission of a signal photon. (e) Illustration of, (f) experimentally recorded, and (f) calculated, temporal quantum correlations induced by the interaction of two single photons via the quantum emitter.

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High-frequency hybrid nanomechanics with a quantum dot strained-coupled to a vibrating microwire

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Hybrid mechanical systems are composite devices, which couple a two-level quantum system to a mechanical resonator. They enable a fundamental exploration of the quantum/classical boundaries and could find applications in sensing or in quantum information technologies. Together with colleagues in Grenoble, we developed a hybrid system based on a semiconductor InAs quantum dot (QD) that is strain-coupled to the fundamental flexural vibration of a GaAs microwire [1]. Whereas it led to many pioneering contributions [2,3], further developments call for a massive increase of the resonator frequency (from the sub-MHz up to the GHz range).

Here, we report on the mechanical spectroscopy of the higher-order vibration modes of the microwire [4], by leveraging a new on-chip actuation technique [5] (see figure). We detected so far flexural resonances up to 200 MHz, an increase by three orders of magnitude compared to the fundamental mode. Surprisingly, large mechanical quality factors (~10^3) are preserved at high frequencies. Moreover, the hybrid coupling strength increases with the mode order and reaches 4 MHz, the highest value reported so far a QD hybrid nanomechanical system.

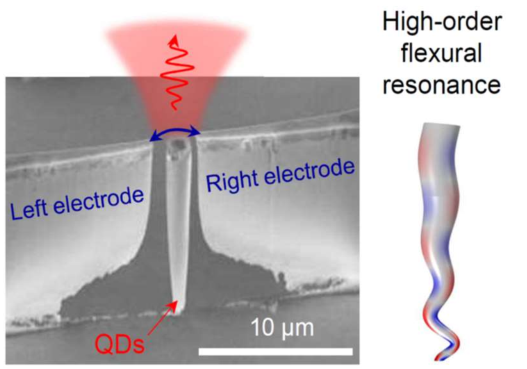

Figure 1. Left: SEM image of the device. Right: mode profile of the flexural resonance F_7.

Since the radiative limit of the QD emission linewidth is on the order of 160 MHz, the resolved-sideband regime is within reach in this system. These results thus open appealing prospects for the – possibly coherent – optical manipulation of the mechanical state and for the realization of photon-phonon interfaces.

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Quantum dots in Bullseye resonators

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Using quantum dots inside resonator structures has been a successful route towards efficient single[1] and entangled photon sources[2]. The generated photons can potentially be used in quantum information technologies[3].

Recently, the circular Bragg grating, or Bullseye, resonator has gotten a lot of attention[4] due to its relatively easy growth, broadband operation at simultaneous high Purcell factors, which is relaxing the conditions on frequency matching between quantum dots and resonator mode, and high extraction efficiencies.

I will show our latest findings on bullseye resonators. First, I will show the polarization properties of quantum dots coupled to Bullseye resonators[5] and its implications for the generation of single photons as well as entangled states, such as polarization encoded Bell pairs or the direct generation of cluster-states. Second I will show recent results on transferring the technology from the 900 nm range to the telecom C-band [6].

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Entangled Photons from Hot Quantum Dots

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Semiconductor quantum dots offer great potential as sources of entangled photons. As solid-state objects, quantum dots are subject to the interaction with phonons. With increasing temperature, the phonon interaction becomes more efficient and often more detrimental. Therefore, most experiments are performed at cryogenic temperatures below 4K. An alternative would be Sterling coolers which operate at about 30K. This raises the question: Can hot quantum dots still produce entangled photons emitted with high quality?

For a quantum dot initially prepared in the biexciton state, phonons do not affect the entanglement fidelity of the emitted photons [1]. However, when an excitation with a finite pulse takes place, an optical Stark shift is induced during the pulse [2]. This unlocks the possibility for phonons-induced transitions leading to a further degradation of the entanglement. In this talk, I will present numerically exact simulations to quantify the loss of concurrence as function of temperature [3].

To obtain high concurrence, even at elevated temperatures, the situation of an initially prepared biexciton state should be restored. I will show that this can be achieved by exciting with a pair of red-detuned pulses making use of the SUPER effect and placing the quantum dot in a cavity [4]. The results show a promising pathway to generate high quality entangled photons from hot quantum dots.

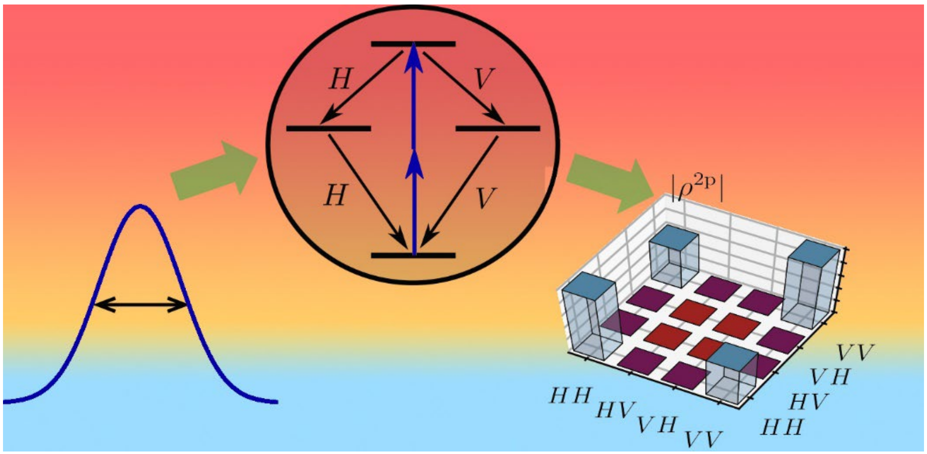

Figure 1: Sketch of the excitation using a finite pulse on a semiconductor quantum dot. Via the biexciton-exciton cascade a pair of polarization entangled photons is emitted. The interaction with phonons results in a temperature dependence of the obtained concurrence of the entanglement.

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Quantum-Dot Quantum Light Sources for Quantum Photonic Networks

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Quantum photonic networks require sources of single, indistinguishable and entangled photon pairs with high brightness. Semiconductor quantum dots (QDs) hold great promise to meet these requirements. In many foreseen implementations of quantum photonic networks, photons must be able to propagate over long distances in silica fibers with limited absorption and wave packet dispersion. When propagating into silica fibers, photons in the so-called telecom C-band (1530 – 1565 nm) will experience the absolute minimum of absorption whereas in the O-band (1260 – 1360 nm) they can travel with vanishing dispersion together with limited absorption.

In this talk, we report on the performance of quantum-dot quantum light sources emitting in the telecom O- and C-band [1-3]. Among them are ultra-bright, triggered circular Bragg grating cavities with embedded QDs, which emit highly polarized single photons. They show simultaneously high single-photon purity ($g^{(2)}(0)=0.005$) and fiber-coupled single-photon count rates of 13.9 MHz for an excitation repetition rate of 228 MHz. We further compare coherent and incoherent pumping schemes of telecom C-band single-photon sources and relate the respective achievable photon indistinguishabilities. In addition, we present recent highlights, which have been achieved with these sources, e.g. intercity QKD [4].

Furthermore, we report on the optical and quantum optical properties of one exemplary polarization entangled QD photon pair source emitting at 780 nm, which is frequency converted to the telecom band. We demonstrate preservation of high-fidelity entanglement during quantum frequency conversion to 1515 nm and back-conversion to the original wavelength (780 nm). Finally, we analyze the quantum optical properties (e.g. entanglement fidelity) after 30 km of fiber transmission.

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9th international workshop on "Engineering of Quantum Emitter Properties"– Paderborn, Germany

Advances in Quantum Light Generation for Quantum Networking

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In recent years, tremendous progress has been achieved in the field of quantum information, fostered by the advent of quantum technologies. In this context, the generation and precise control of qubits, whether photonic or embedded in the solid-state, lies at the heart of groundbreaking applications holding the potential to transform our society.

In this talk, I will review the recent progress in the fields of quantum light generation in the solid-state and physical implementations of quantum information, ultimately striving towards quantum networking at the global scale [1] (see Fig. 1). One focus will be on the development of novel building blocks, including quantum photonics devices [2] and plug-&-play benchtop single-photon quantum key distribution (QKD) systems [3] - devices to be deployed in local quantum communication networks in Berlin city as well as inter-city links. I present routines to certify and optimize the performance of QKD systems [4] and report on recent efforts in transferring our knowledge to advanced protocols, different technology platforms (e.g. 2D quantum materials [5]), and telecom C-band wavelengths suitable for long-haul quantum communication [6]. In this context, we demonstrate record-high photon-indistinguishabilities at C-band wavelengths by exploiting advanced coherent excitation schemes. Not least, prospects for further advances, required for practical quantum networking, are discussed.

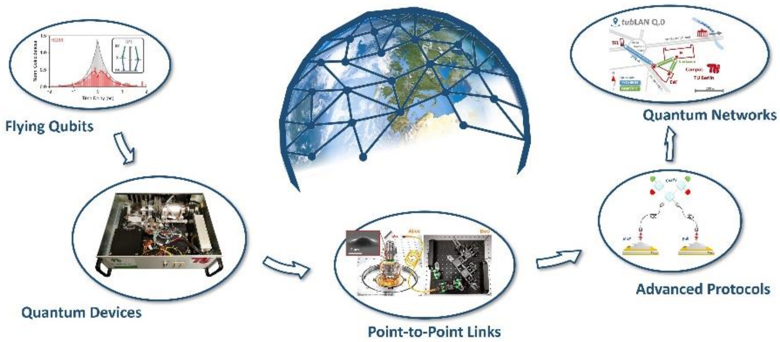

Figure 1: The research and visions of our group build the bridge from fundamental aspects of quantum optics to applications in quantum networking.

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Engineering of Resonance Fluorescence Properties

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A qubit is the simplest quantum emitter and its *fluorescence* under the *resonant* excitation of a laser is the most fundamental quantum light: a stream of single photons that produce perfect antibunching. Its intrinsic emission, however, can be tweaked by external operations such as frequency filtering [1], detection [2], or interference with another laser (homodyning) [3,4].

Paying attention to the dressed-state structure at the multiphoton level, we can choose to select photons from the spectral sidebands only, that form a cascaded emission, obtaining frequency-time entangled pairs [5], as has been long-time proposed, but also harness [6] or enhance [7] N-photon emission from non-emitting parts of the spectrum.

On the other hand, closer inspection of perfect single photon emission from resonance fluorescence shows that it is not actually compatible with a narrow emission line in frequency (sub-natural linewidth) due to the interference origin of antibunching [8]. Fortunately, we can still reconcile these two highly desirable properties through homodyning [9].

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Signatures of dynamically dressed states

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The interaction of a resonant light field with a quantum two-level system is of key interest both for fundamental quantum optics and quantum technological applications employing resonant excitation. While emission under resonant continuous-wave excitation has been well-studied, the more complex emission spectrum of dynamically dressed states – a quantum two-level system driven by resonant pulsed excitation - has so far been investigated in detail only theoretically.

Here, we present the first experimental observation of the complete resonance fluorescence emission spectrum of a single quantum two-level system, in form of an excitonic transition in a semiconductor quantum dot, driven by finite Gaussian pulses [1]. We observe multiple emerging sidebands as predicted by theory with an increase of their number and spectral detuning with excitation pulse intensity and a dependence of their spectral shape and intensity on the pulse length. Detuning-dependent measurements provide additional insights into the emission features. The experimental results are in excellent agreement with theoretical calculations of the emission spectra, corroborating our findings.

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A semiconductor quantum dot in an open microcavity

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A semiconductor quantum dot is an excellent source of single photons: the radiative lifetime is sub-nanosecond, just tens of picoseconds following Purcell enhancement in a cavity, allowing the creation of billions of photons per second; the interaction with phonons is relatively weak such that successively emitted photons exhibit a high degree of two-photon interference. Significant challenges are to create an efficient source, and to reduce the noise such that photons created far apart in time also exhibit two-photon interference. To create more complex quantum states in which the photons are entangled, a quantum dot can be equipped with a single electron or hole. The spin degree of freedom can then be exploited. A further challenge is to ensure that the spin retains its coherence as a string of photons is generated. Potentially, these challenges can be met by embedding a gated quantum-dot in an open microcavity.

In gated devices, quantum dots exhibit near transform-limited linewidths, both at wavelengths in the near infrared (InGaAs quantum dots, wavelength 920-950 nm) and in the near-red (GaAs quantum dots, wavelength around 780 nm). A microcavity is constructed using a planar semiconductor "bottom" mirror (part of the semiconductor heterostructure) and a curved "top" mirror. With a very high-reflectivity top mirror, a single quantum-dot enters the strong-coupling regime of cavity-QED with a cooperativity exceeding 100 [1]. Clear vacuum Rabi-oscillations are observed. With a modest-reflectivity top mirror, an efficient single-photon source is demonstrated [2]. The end-to-end efficiency, the probability of creating a single photon at the output of the experiment's final optical-fibre following a trigger, is 57%; the photon purity ($1-g^{(2)}(0)$) is 97.9%; the two-photon interference visibility is 97.5% and is maintained even on interfering photons far apart in time. The spin coherence is limited by the magnetic noise arising from the "hot" host-nuclei of the quantum dot. However, this noise can be drastically reduced by optically cooling the nuclei, equivalently, by "narrowing" the distribution [3,4]. These schemes were implemented on both InGaAs and GaAs quantum dots and a decoherence time (T_2^*) of about 500 ns was achieved [5].

The potential of this platform both as a realisation of the canonical "one-dimensional atom" and as a source of entangled photonic states will be discussed.

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Controlling Excitons in van-der-Waals materials via tunable optical cavities

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Monolayer transition metal dichalcogenides (TMDC) have emerged as a new and interesting platform for studies of tightly bound exciton in ultimately thin materials. Their giant dipole coupling to optical fields makes them very appealing for implementing novel photonic devices, and for fundamental, as well as quantum photonic investigations in the framework of cavity quantum electrodynamics [1]. In TMDC mono- and multilayers, exciton trapping can be straintronically and twisttronically engineered, which yields a very large flexibility in engineering quantum emitters [2].

Since the deterministic coupling of emitters to optical cavities is critical for quantum applications, yet highly non-trivial in its implementation, I will discuss our effort to realize open optical cavities in liquid helium free optical cryostats [3], which are ideally suited for the study of quantum emitters as well as free excitons in the weak and strong coupling regime. Our study involves the cavity control of TMDC quantum dots, which can be operated as very efficient single photon sources, but is extended to the investigation of the cavity-controlled Moiré trapped excitons in the weak coupling regime, as well as the magnetic properties of charge-correlated exciton-polaritons in the regime of strong light-matter interaction.

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Recent developments of site-controlled pyramidal quantum dots as spin and photon qubit sources

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GaAs quantum dots (QDs) produced by droplet etching epitaxy have been recently making a remarkable progress as state-of-the-art sources of single, indistinguishable, polarization-entangled photons and as a low-noise environment for single charge carriers [1,2]. Herein we present the results of the endeavour to transfer these outstanding properties and advantages to GaAs QDs fabricated by conceptually different approach – metalorganic vapour-phase epitaxy growth on (111)B oriented GaAs substrates pre-patterned by the micrometre-scale tetrahedron recesses. As we will demonstrate, this method enables much higher degree of QD engineering flexibility (Fig. 1a) and ticks site-control property off the bucket list [3].

Within the bigger picture, this new generation of site-controlled QDs is being researched as a potential resource of photonic cluster states. The cluster construction procedure is underpinned by comprehensive studies of the QD energetic structure, various coherence aspects, and spin physics and dynamics. As results, we will demonstrate identification and a remarkable excitonic spectral uniformity of the energetic structure of these QDs. Notably polarisation-resolved resonant excitation and single-photon correlation methods reveal a fundamentally interesting case of excited hole states of a nearly dominant light hole-like character. These states, as we show, in principle, can be used to initialize a QD to a specific trion and eventually to a hole spin state with high fidelity (Fig. 1b).

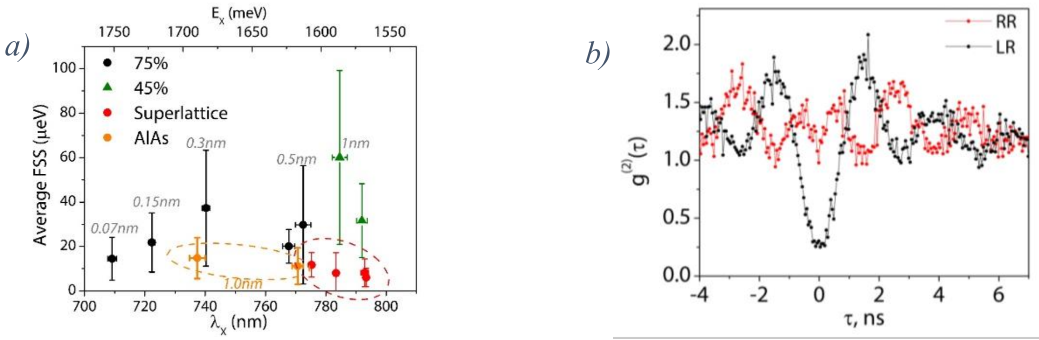

Figure 1: (a) Engineering QD properties – emission wavelength and fine structure splitting – by confinement barrier design and nominal QD thickness, (b) Ground hole state precession in a small in-plane magnetic field (~0.3T) probed by polarization-resolved two-photon correlations.

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Faster, brighter, ever more entangled: how far can we push quantum-dot emitters?

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The development of quantum networks for secure communication requires many outstanding challenges to be overcome. One challenge is to fabricate quantum light sources that deliver photon-pairs with ultra-high brightness and with near-unity level of entanglement. Semiconductors quantum dots can in principle fulfil these *desiderata*, but new roadblocks and open questions appear whenever their performances are pushed to the levels required by the envisioned applications.

In this talk, I will first present our first steps towards the construction of a quantum-dot based quantum network for secure communication within the campus of Sapienza University of Rome [1, 2]. The *desiderata* set by entanglement-based quantum key distribution protocols – in particular for what concerns brightness and degree of entanglement – will be reviewed. Then, I will illustrate our efforts to fabricate a device based on strain-tunable quantum dots in photonic cavities that aims at optimizing both figures of merit [3]. Finally, I will discuss the different physical mechanisms [4, 5, 6] that potentially prevent quantum dots from emitting photons with entanglement fidelities larger than 99%, and I will highlight the role of so-far neglected degrees of freedom [7].

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Coupling novel GaAs site-controlled QDs

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Coupled QDs (CQDs) systems represent a pragmatic actualization of the so-called measurement-based quantum computation [1]. Proposals have been put forward to utilize transitions between CQDs spin-states as a means of generating cluster states [2] [3]. We discuss a preliminary study of GaAs in AlAs Coupled QDs using polarization and time resolved photoluminescence: two GaAs QDs 1.3nm nominally thick are stacked one on top of the other separated by a 10nm nominally thick AlAs spacer. AlAs barriers grown on the self-limiting profile of an $Al_{65}Ga_{35}As$ cladding surround the CQD system. We show the pattern reproducibility of the transitions among different dots of the same sample and a narrow energy distributions of the spectral features. Two groups of peaks separated by ~20meV are seen: an efficient population of higher energy group peaks demonstrates either unusually strong bottleneck of carrier relaxation from the excited states, or presence of a very different energetic structure in comparison to a SQD. Moreover, single-photon correlation measurements have been performed revealing bunching behavior around zero delay for a couple of peaks, clear sign of a recombination cascade, and a very slow anti-bunching curve for another couple, suggesting the absence of a population mechanism that links the two transitions. These results clearly demonstrate reproducible but very different energetic structure and charge carrier dynamics within stacked QD structures in comparison to SQDs.

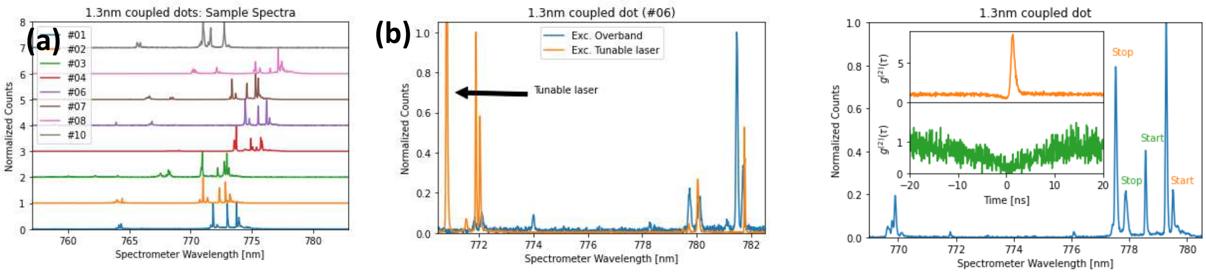

Fig.2. (a) CQDs sample spectra (b) CQD spectrum under different excitation conditions (c) Correlation measurement

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Design of circular Bragg resonators in the telecom band for efficient emission of entangled and indistinguishable photons from semiconductor quantum dots

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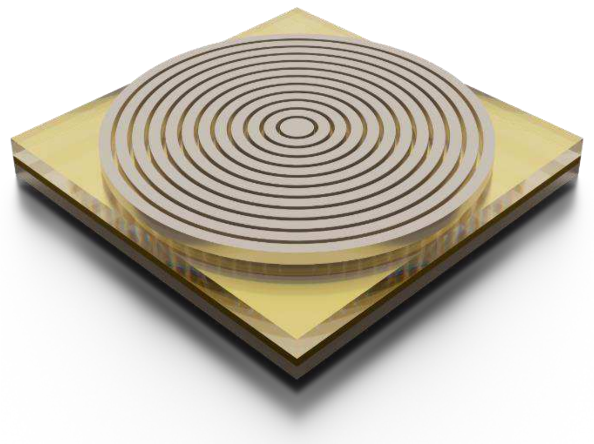
One key technology for quantum communication and quantum computing is the generation of indistinguishable and entangled photons. An idea for this in semiconductor quantum dots is the biexciton-exciton cascade tuned by a photonic environment which increases both the indistinguishability and the entanglement of the photons. We show that a cavity exhibiting low quality factors, a moderate Purcell enhancement and a high coupling strength is the goal for this approach. Since circular Bragg grating (CBG) resonators can fulfill these requirements, we introduce a powerful optimization scheme to find feasible configurations of those structures accurately emitting photons at a target wavelength of 1.55 μm in the telecom C-band.



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Integration of single photon emitters with 1D photonic crystal nanobeam cavities

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Achieving fully operational quantum photonic integrated circuits, it is of great importance to develop a scalable platform capable of supplying an efficient coupling between single-photon emitters and photonic circuitry. In terms of integrating single-photon emitters with other on-chip components, a hybrid approach is the most favorable since the advantages of each individual material platform are exploited [1].

In this work, quantum dots (QDs) at 934 nm are the chosen emitters due to their promising features: low g^2 [2] and Fourier-limited line widths [3]. Nevertheless, due to the interactions of the QDs with the surrounding environment of the cavity, the QDs must be placed at least 150 nm away from any air boundary inside the photonic crystal (PC) [4]. This limitation pushed us forward to develop a new design approach, based on mirror strength optimization, for 1D PC cavities which are efficiently coupled to waveguide modes and possess high-quality factors and small mode volumes, thus resulting in large Purcell factors.

Here we present our design approach alongside preliminary fabrication results and an alternative design based on reference [5] that employs a topological mode inside a 1D photonic crystal.

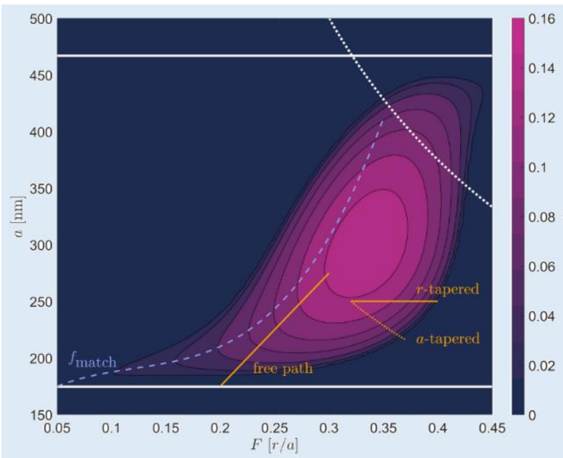

Figure 1: Mirror strength map showing possible designs.

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A Versatile transfer printing toolbox for device stacking

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To scale up photonic quantum technologies such as quantum communication, or quantum computing, integration in photonic circuits is required [1]. One challenge is the efficient integration of single-photon emitters into photonic integrated circuits (PIC).

The integration approaches of single photon emitters can be categorized into monolithic, heterogeneous and hybrid methods. Monolithic integration is the fastest in terms of fabrication overhead, while heterogeneous, and especially hybrid integration offers a diverse choice of materials and properties to be combined [2].

Here we use molecular beam epitaxy-grown $In_xGa_{1-x}As/GaAs$ quantum dots integrated into a nanobeam cavity. The resulting nanophotonic device is transferred via a pick-and-place technique into a Lithium niobate on insulator (LNOI) waveguides which we fabricate using a triple-layer nanofabrication approach. We employ a thermal release transfer method with polypropylene carbonate as a release agent. The transfer stage's translational, rotational, and azimuthal degrees of freedom enable deterministic positioning and control in the fabrication process. Our nanobeam cavity-to-waveguide coupling scheme is based on an evanescent field approach [3]. Here we present our simulation results regarding the efficiency of our coupling scheme conducted with a finite element technique.

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Near Fourier-Transform Limited Blinking Free Quantum Dots

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Tailored quantum light sources are essential building blocks in quantum technology applications. Aluminum droplet-etched GaAs quantum dots are highly promising candidates for such sources as they exhibit excellent features concerning single-photon purity and indistinguishability. On short time scales, entanglement fidelity is high. Nonetheless, these quantum dots generally exhibit an unstable charge environment, which results in reduced coherence on long timescales, broadened linewidths and blinking. The integration of the quantum dots into a p-i-n diode structure enables the tuning of energy via the Stark effect and the charge environment is stabilized. Here, we present a solid-state single-photon source that exhibits no indications of blinking on timescales of up to milliseconds and has a linewidth near the Fourier-transform limit. This creates opportunities for experiments that allow for a fundamentally deeper comprehension of quantum-level schemes. Additionally, it could facilitate the development of a quantum network, where quantum interference between separate sources is required.

Optimising the interference of classical and quantum fields

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Semiconductor quantum dots (QDs) are excellent for generating quantum light. Most efforts in the QD community have aimed at processing Discrete Variable (DV) quantum information by using efficient and high-rate single and entangled photons [1, 2], but the nonlinearity provided by QDs and their ability to generate photon-number superpositions [3, 4] enable their use in a continuous variable (CV) paradigm [5]. A cornerstone of CV is homodyne detection, requiring an excellent mean wave-packet overlap M in the interference between classical and quantum light [6]. Such overlap is crucial to observe non-Gaussianity and negativity in Wigner function [5] reconstructions. This work reports on two methods to assess M based on measuring Hanbury-Brown and Twiss second-order correlations [7] between a coherent state, LO, $|\alpha_{\mathrm{LO}}\rangle$ with mean photon number $\mu_{\mathrm{LO}} = |\alpha_{\mathrm{LO}}|^2$, and a single photon (SP) from a QD source.

Fig.1(a) depicts the experimental setup, where LO and SP are combined in a fibre beam splitter (FBS) with transmissivity T and reflectivity R. $g^{(2)}_{\mathrm{auto}}(\tau)$, the auto-correlation function, exhibits bunching (Fig. (1c)) for $R\mu_{\mathrm{LO}} \geq T\eta = (7.5 \pm 0.2) \times 10^{-2}$, with η the overall end-to-end efficiency of the QD source. When introducing a mode mismatch by changing the polarisation of $|\alpha_{\mathrm{LO}}\rangle$, M decreases from 0.82 (red) to 0 (black). The overlap is independently estimated using cross-correlation $g^{(2)}_{\mathrm{cross}}(\tau)$ measurements [9]. Owing to high emission rates, M can be optimised in real time, constituting a first step to use QD devices for CV schemes harnessing the interference between quantum and classical light, such as twin field QKD.

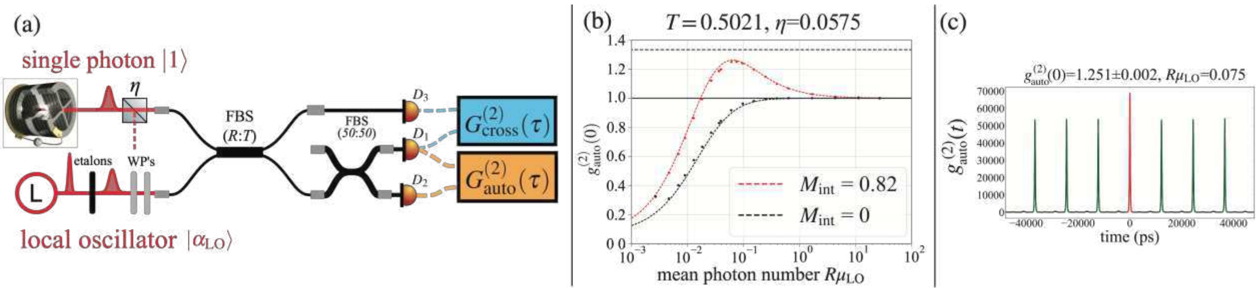

Figure 1: (a) Experimental setup for the interference between $|\alpha_{\mathrm{LO}}\rangle$ and $|1\rangle$ in an R:T FBS. The output is analysed in auto- and cross-correlations. (b) Experimental (dots) and theoretical (dashed) normalised auto-correlation function $g^{(2)}_{\mathrm{auto}}(0)$ for different values of μ_{LO}. (c) $g^{(2)}_{\mathrm{auto}}(\tau)$ shows bunching for $R\mu_{\mathrm{LO}} = (7.5 \pm 0.2) \times 10^{-2}$.

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Controlling the generation of large cluster states with residual visibility measurements

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Entanglement is a key resource to scale up photonic quantum technologies pertaining to quantum computing or quantum communications [1]. We present a resource-efficient way to generate large states of entangled photons, known as photonic linear cluster (LC) states. We use a bright single photon source, here an InGaAs quantum dot embedded within a micropillar cavity [2], and a fibered entangler (See Fig. 1a) [3], composed of a polarizing beamsplitter and a fiber delay loop. To increase the number of photons in the LC state, we develop a practical optimization of the experimental setup, based on residual visibility measurements i.e. scattershot like measurements. By changing the phase in the delay loop, we extract a visibility measurement that is directly related to the quality of the generated state. We usually post-select on measuring the same number of input and output photons. The residual visibility method consists in looking at the visibility measurements of 2 to n-1 photons entangled together, in a n-photon experiment – measurement that require much smaller acquisition time. Optimizing the residual visibilities attests the high level of alignment of the experiment and allows to extract information on the system comprised of the source and the loop. Using this method, we demonstrate entanglement of up to 6 photons in a linear cluster state.

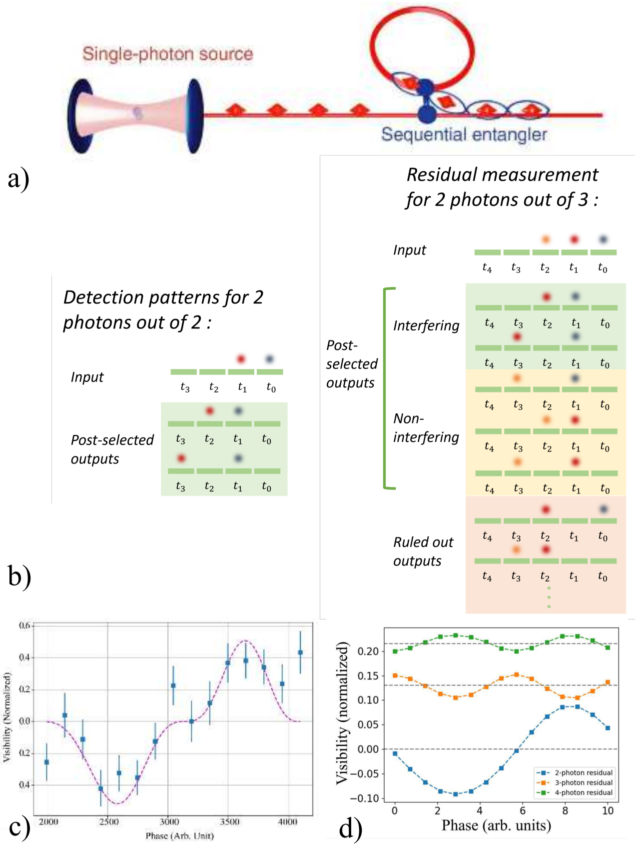

Figure 1: a) Principle of our resource efficient linear cluster state generation protocol [3] b) Principle of residual visibility measurement – We look at patterns in the temporal modes, removing 1 or more photons adds lead to a global addition of interfering and non-interfering events to the measurement – c) 6-photon entanglement measurement - A visibility higher than 0.3 ensures genuine 6-photon entanglement - Experimental value of 0.5±0.1 in agreement with the theoretical model considering 86% Hong-Ou-Mandel d) Residual visibility measurement of 2, 3, 4 photons out of the 6-photon experiment.

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Ultra-stable open micro-cavity platform for closed cycle cryostats

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High-finesse, open-access, mechanically tunable, optical micro-cavities offer a compelling system to enhance light matter interaction in numerous systems, e.g. for quantum repeaters, single-photon sources, quantum computation, and spectroscopy of nanoscale solid-state systems. Combining a scannable microscopic fiber-based mirror and a macroscopic planar mirror creates a versatile experimental platform [1]. A large variety of solid-state quantum systems can be brought onto the planar mirror [2,3], analyzed, addressed individually, and (strongly) coupled to the cavity [4]. We present a fully 3D-scannable, yet highly stable micro-cavity setup, which features a stability on the sub-pm scale under ambient conditions and unprecedented stability inside closed-cycle cryostats. An optimized mechanical geometry, custom built stiff micro-positioning, vibration isolation and fast active locking enables quantum optics experiments even in the strongly vibrating environment of closed-cycle cryostats.

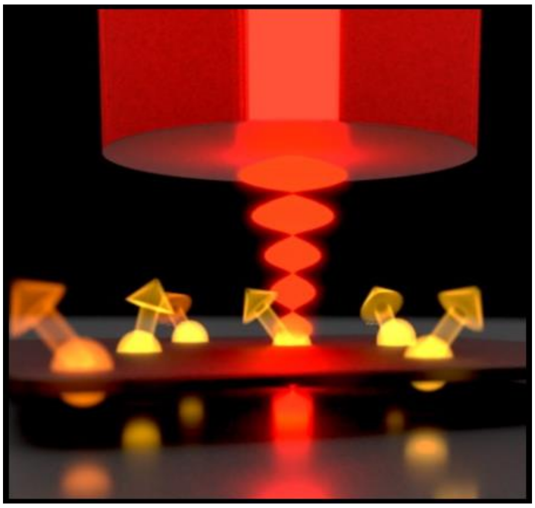

Figure 1: Artistic impression of a fiber micro-cavity facing a planar mirror with embedded quantum systems.

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SUPER Excitation and Generation of Ideal Photons with Quantum-Dot Cavity Systems

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Driven by the quest for high-quality single photons and entangled photon pairs, in our investigation we apply the SUPER (Swing-UP of the quantum EmitteR population) excitation scheme [1,2,3] to a semiconductor quantum dot (QD) inside an optical cavity. The scheme utilizes two off-resonant, red-detuned laser pulses that excite the quantum emitter inside the resonant optical cavity, avoiding the need for complex laser stray light suppression. As a crucial result, we demonstrate that the SUPER scheme eliminates re-excitation of the quantum emitter even in high quality cavities, which optimizes single photon purity and preserves high photon indistinguishability. We further show that driving the biexciton with the SUPER scheme allows generation of high-quality polarization entangled photons in a cavity-mediated photon-pair emission, without the optical excitation reducing the quality of the emitted photons [4].

In the second part of our study we tackle the generation of entangled photon pairs with high photon indistinguishability. Our strategy is based on selectively reducing the biexciton lifetime [5,6] by Purcell enhanced resonant emission into a circular Bragg reflector mode. Through combined Maxwell optimization of the photonic structure and microscopic simulations of the QD excitation dynamics and quantum properties of emitted photons, we shine light onto the complex interplay of the parameters governing the quantum-dot cavity excitation and emission dynamics. In particular we identify the optimal range of Purcell enhancement, resulting in simultaneous near-unity values of indistinguishability and entanglement, here specifically for the telecom C-band at 1550 nm [7].

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Telecom C-band emission from droplet etched quantum dots in the InP/$In_yAl_{1-y}As$/$In_xGa_{1-x}As$ system

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Semiconductor quantum dots (QDs) have been established as promising sources for on-demand single photon and entangled photon pair generation for quantum communication applications. [1] In the case of entangled photons it is possible to utilize the biexciton-exciton cascade of a QD system. Here GaAs/$Al_xGa_{1-x}As$ QDs grown via local droplet etching (LDE) have been proven to be excellent candidates, as they show very low fine-structure splitting (fss) due to their negligible strain and good in-plane symmetry. [2] However, for the GaAs/$Al_xGa_{1-x}As$ system one is limited to photon emission around 780 nm. In this contribution we present the adaptation of the LDE technique to the InP/$In_yAl_{1-y}As$/$In_xGa_{1-x}As$ system for photon emission in the optical C-band. We show that by optimizing the parameters for the etching process we can produce nanoholes that show very good symmetry when measured with atomic force microscopy (AFM) and that these nanoholes can be filled with $In_xGa_{1-x}As$ when utilizing an As_4 environment. Finally, we demonstrate that the filled nanoholes emit light when embedded in an $In_{0.52}Al_{0.48}As$ matrix, where the wavelength redshifts with increasing filling height and that ultimately, we were able to create QDs that show emission up into the optical C-band.

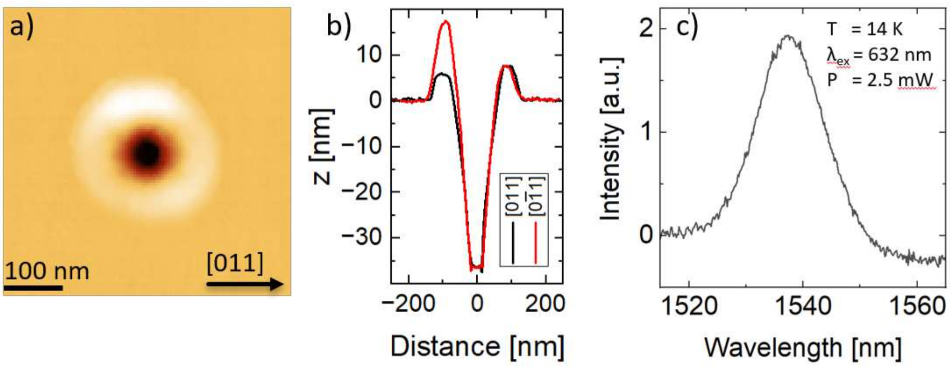

Figure 1: a) Exemplary AFM image of a nanohole etched into an $In_{0.52}Al_{0.48}As$ layer by depositing InAl droplets. b) Corresponding line scans in the two main crystalline directions. c) Ensemble photoluminscence signal from $In_{0.56}Ga_{0.44}As$ QDs embedded in an $In_{0.52}Al_{0.48}As$ matrix, grown by filling nanoholes produced with the same parameters as in a) and overgrown with $In_{0.52}Al_{0.48}As$.

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On-chip Generation and Dynamic Optomechanical Rotation of Single Photons

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Integrated photonic circuits (IPCs) are a promising platform to realize photonic quantum technologies on a chip [1]. However, the underlying schemes require reconfigurable devices which demand versatile tuning mechanisms. Here, we report on an acousto-optically tunable IPCs with integrated quantum emitters and demonstrate dynamic rotations of an on-chip initialized photonic qubit [2].

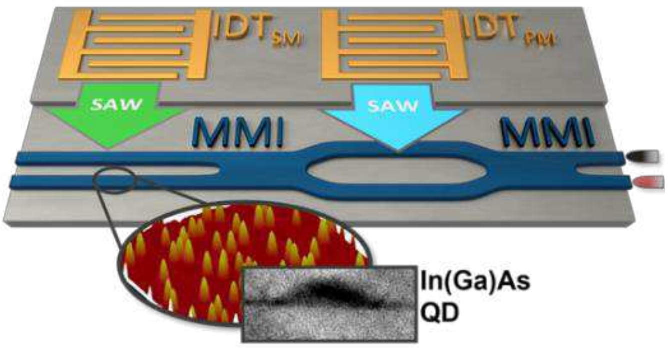

Fig.1. Schematic of SAW-tunable Mach-Zehnder IPC with integrated QDs. IDT-SM and IDT-IM allow for the dynamic control of the QDs and the MZI. A photonic qubit is initialized by a single photon emitted by a QD.

Figure 1 shows a schematic of our device which is monolithically fabricated on a III-V heterostructure containing a layer of quantum dots (QDs). The IPC comprises a pair of ridge waveguides connecting two multimode interference (MMI) beamsplitters forming a Mach-Zehnder interferometer (MZI). Interdigital transducers (IDTs) allow for the generation of two beams of ≈ 500MHz surface acoustic waves (SAWs) to dynamically control the optical properties of the QDs (IDT-SM) [3] and the optical phase in the two arms of the MZI (IDT-PM) [4]. We initialize a rail-encoded photonic qubit by selective excitation of single QDs in one of the two waveguides. When we apply a SAW via IDT-PM, we dynamically modulate the optical phase in the MZI and, thus, perform a coherent rotation on the qubit. The angle is set simply by the electrical power applied to IDT-IM. Finally, we demonstrate programmable dynamic spectral multiplexing and demultiplexing of the photonic qubit in our device by simultaneously modulating the QD by a SAW generated by IDT-SM.

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Enhanced Spin Coherence in a GaAs Quantum Dot

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Semiconductor quantum dots are promising candidates for photonic quantum technologies such as cluster state generation or distant spin-spin entanglement. However, the magnetic noise from the host nuclei poses a drawback for spin-photon applications as it leads to fast spin decoherence. Progress has been made recently on droplet-etched GaAs quantum dots. On the one hand, the demonstration of two-photon interference with indistinguishability V > 90% for photons created by completely separate quantum dots validates the excellent photonic properties [1]. On the other hand, success on electron spin decoupling from the host nuclei affirms a highly homogeneous nuclear ensemble and $T_2^{CPMG} > 100$ µs [2].

In this work, we use all-optical cooling [3,4] of the host nuclei of a GaAs quantum dot to tackle the problem of a short electron spin coherence time T_2^*. Ramsey interferometry probes the electron coherence time, acting simultaneously as a gauge of the nuclei’s temperature. We find a 20-fold increase in coherence time from 3.9 ns to 78.0 ns after Rabi cooling and a 155-fold increase up to $T_2^* = 608$ ns after feedback cooling [5] (see Fig. 1).

Our work shows that a GaAs quantum dot produces coherent photons and hosts a coherent spin. The coherence is maintained for times much longer than the radiative decay time, all at a convenient wavelength. These are ideal properties for a coherent spin-photon interface.

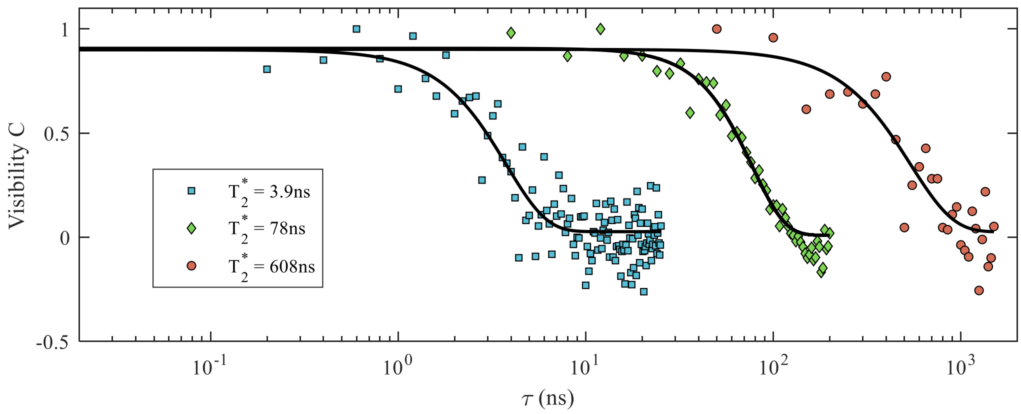

Figure 1: Ramsey visibility before cooling (blue), after Rabi cooling (green), and after feedback cooling (red).

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9th international workshop on “Engineering of Quantum Emitter Properties”– Paderborn, Germany

Cavity-enhanced single-shot readout of a quantum dot spin within 3 nanoseconds

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Rapid, high-fidelity single-shot readout of quantum states is a ubiquitous requirement in quantum information technologies, playing a crucial role in quantum computation, quantum error correction [1], and fundamental tests of non-locality [2].

Here, we demonstrate single-shot optical readout of a semiconductor quantum dot (QD) spin state, achieving a readout time of only a few nanoseconds. Our approach involves embedding a gated InGaAs QD device within an open microcavity architecture (Fig. 1a) [3]. Singly charged InGaAs QDs exhibit strong optical transitions, which become non-degenerate under an applied magnetic field. By resonantly driving one optical transition with short pulses (Fig. 1b), we can determine the spin state of the charge carrier based on the presence or absence of emitted photons. In our design, the Purcell enhancement increases the QD emission rate and efficiently directs emitted photons into a well-defined mode, facilitating high-speed and accurate detection. We achieve single-shot readout of an electron spin-state in 3 ns with a fidelity of (95.2 ± 0.7)%, and observe quantum jumps using repeated single-shot measurements (Fig. 1c) [4]. Our work significantly reduces the spin readout time well below the achievable spin T_1 and T_2^* times in InGaAs QDs, rendering our platform a promising candidate for measurement-based protocols.

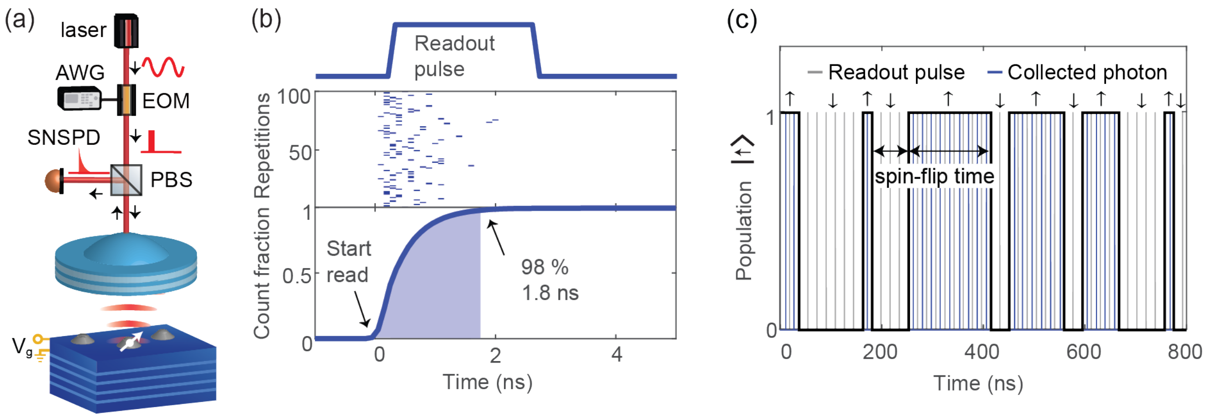

Figure 1: (a) Experimental setup. (b) Readout characterisation at zero magnetic field: The readout pulses are set to 2 ns (top panel). Photons from the QD are detected and arrival times recorded for 100,000 repetitions. In 98% of repetitions, a photon is detected within 1.8 ns (middle panel). In a non-zero magnetic field, a similar pulse sequence facilitates the determination of the spin state within 3 nanoseconds. (c) Repeated single-shot readout experiments, showing real-time quantum jumps of the electron spin state.

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Higher-order supermodes for evanescent coupling of quantum emitters with an optical nanofiber

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To achieve highly efficient light matter interactions for quantum operations, the quantum optics community has long focused on the coupling of atoms or solid state emitters to nanostructures to enhance coupling efficiency. Among them, nanofibers have attracted considerable attention due to their ease of fabrication and their very high transmission. The optical property of the tapered optical nanofiber guiding fundamental HE^{11} mode has been well explored and used in the application involving light-matter interaction, especially the quantum communication systems with atoms trapped around optical nanofibers. However, limited works have been done on exploring the interaction of neutral atoms or single emitters with higher order modes of optical nanofibers [1-4]. For a tapered optical nanofiber with the propagation of higher order modes, the evanescent field around the nanofiber waist shows different optical properties from the HE^{11} mode.

In this work, we managed to experimentally and on demand couple a variety of supermodes generated with higher-order modes in our nanofiber, as shown in Figure.1, including the Hermite-Gaussian-like and Laguerre-Gaussian-like (azimuthally and radially polarized) beam generated by the mixed mode of LP^{11} mode family. Due to the spatial intensity and polarization distribution of different supermodes, it shows interesting potential in the spatial disposition of the electric field when coupling with quantum emitters.

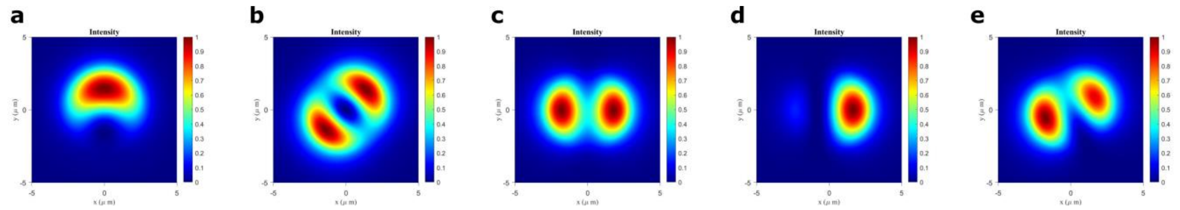

Figure 1: Supermodes generated with LP^{01} and LP^{11} family. a, HE^{11} coupled with TE^{01} or TM^{01}. b, HE^{21} coupled with TE^{01} or TM^{01} but with unequal proportion. c,d, HE^{21} coupled with TE^{01} or TM^{01} with influence of HE^{11} (different polarization orientation). e, HE^{11} coupled with LP^{11} family.

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Plasmonic Bull's eye resonators as a platform for directed single-photon emission from TMDC monolayers

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Secure, scalable quantum networks rely on single-photon sources that are bright, easy to fabricate and offer an easy integration into photonic networks. Integrating single photon sources into optical cavities increases their brightness and can lead to a high directivity of the emitted photons. Even though semiconductor quantum dots are so far the most advanced quantum light sources, monolayers of transition metal dichalcogenides (TMDCs) show great potential as quantum light sources.

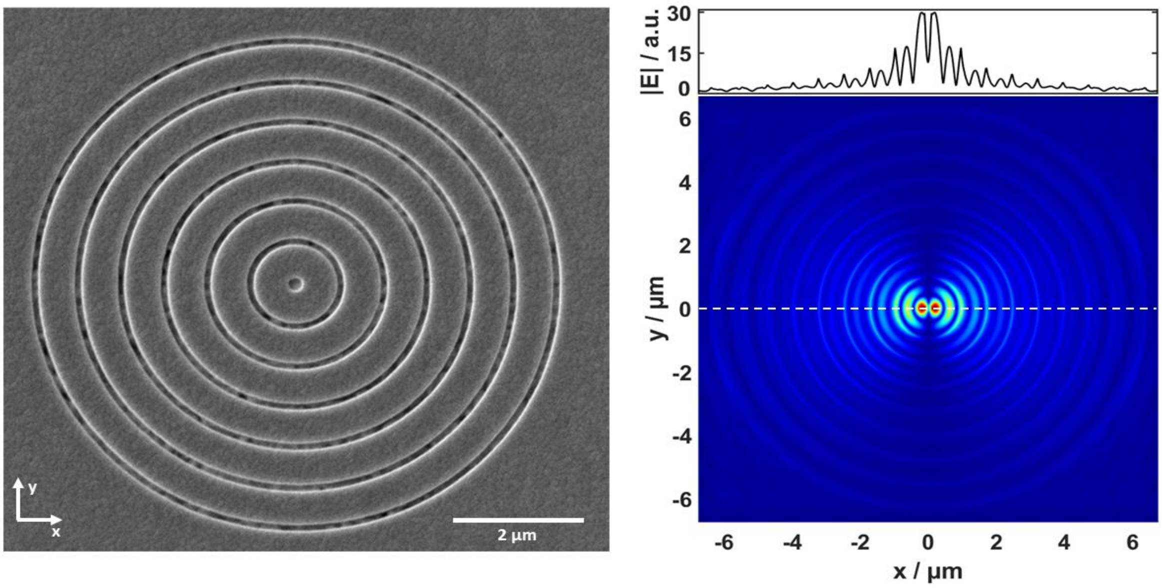

Figure 1: (left) SEM micrograph of a plasmonic Bull's eye resonator consisting of circular grooves written into a gold film and a central hole. (right) FDTD simulation of the absolute value of the electric field 30 nm above the surface of the structure shown on the left.

Here, we show the versatility of plasmonic Bull's eye cavities which feature a strong field enhancement and Purcell factor. A dipolar emitter in the center of such cavity also experiences optical beaming leading to a directed emission of photons. The latter leads to a high collection efficiency even with low numerical apertures.

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Purcell-Enhanced Emission of Single-Photons in the Telecom-C Band from Quantum Dots in Circular Bragg Grating Resonators

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As high-performant sources of single photons, epitaxial quantum dots can be considered as a semiconductor launchpad for quantum photonic technologies [1], such as applications in quantum metrology, biology and the foundations of quantum physics [2], as well as in quantum communications and computing [3]. Of particular interest are quantum dot single-photon sources that emit light at the telecommunication wavelengths window between 1530-1565 nm (the so-called Telecom-C band).

In this work [4], we show Purcell enhancement of quantum dot emission in the Telecom-C band. InAs quantum dots are grown with molecular beam epitaxy on an InP substrate and are embedded in an InAlGaAs bulk environment. In a post-growth flip-chip process with subsequent substrate removal and electron-beam lithography, circular Bragg grating ('bullseye') resonators are defined. Micro-photoluminescence at cryogenic temperatures of $T = 4.5$ K reveals individual quantum dot emission lines into a pronounced cavity mode. Time-resolved single-photon counting experiments are performed to measure exciton lifetimes, and the second order autocorrelation function of the emitted photon stream. When in resonance with the bullseye mode, the exciton lifetime is significantly reduced compared to emission from bulk quantum dots, indicating a Purcell enhancement of $F_P = 6.7 \pm 0.6$. A background limited $g^{(2)}(0) = 0.057 \pm 0.004$ is found, which reveals single photon character of the studied source.

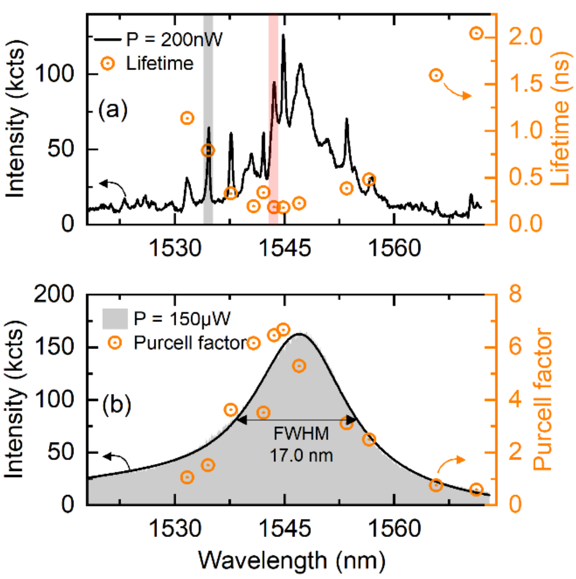

Figure 1. (a) μPL measurement with lifetime (b) Bullseye mode and corresponding Purcell factor

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GaSb Quantum Dot Single-Photon Emitters in the Telecom S-band grown by Local Droplet Etching

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GaSb quantum dots (QDs) grown by local droplet etching in an AlGaSb matrix are investigated. Compared to other typical QD materials like InAs, this material platform has several advantages, as it does not contain indium, which has a high nuclear spin of 9/2. Recent work has shown that the spin coherence times of electrons or holes are larger in the indium-free material system GaAs [1]. It is hypothized that the larger charge carrier spin coherence comes from the reduced interaction with the nuclear spins. Additionally GaSb QDs show an indirect-direct bandgap crossover in the telecom wavelength range, making these suitable for emission of non-classical light in the telecom S-band at around 1.5 µm [2].
We discuss the epitaxial growth of GaSb QDs by etching nanoholes in an AlGaSb matrix using Al droplets. The dimensions of these nanoholes can be varied by changing the substrate temperature during the local droplet etching process as well as the Sb pressure [3,4]. The nanoholes are subsequently filled with GaSb by overgrowing a quantum well, which ensures confinement of carriers inside the filled nanohole. Polarization resolved micro-PL studies reveal an excitonic charge complex in the telecom S-band with a small fine structure splitting of 12 µeV [2]. Time-resolved measurements in an Hanbury Brown Twiss setup yield a second order autocorrelation of $g^2(0) = 0.16$ [2] at zero time delay, demonstrating single-photon emission.

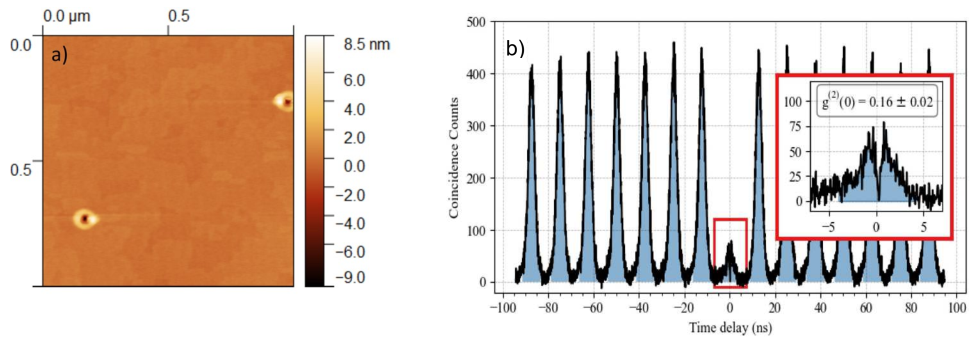

Figure 1: a) Atomic force micrograph of etched nanoholes. b) Autocorrelation measurement showing single photon emission [2].

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A tunable open-fiber cavity system for cluster state generation

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Entangled photon states are a key resource for quantum information technology. These nonlocally correlated states enable us to establish concepts like quantum links between two parties, or one-way quantum computing [1, 2]. A simple quantum link can be established by distributing the photons of a prepared Bell-pair to two parties [3]. However, a two-photon entangled state has certain limitations in transmission distance, since the quantum link is not established if one of the photons gets lost. One concept to overcome this limitation is by larger multiphoton entangled states, so-called cluster states [4]. These states have a higher loss tolerance due to redundancy in the system [5, 6].

Efficient photon sources are crucial for generating entangled states of photons at high rates [4]. Self-assembled quantum dots have been proven to be a promising platform for delivering on demand streams of entangled photons when embedded into photonic resonators [7, 8]. With a carefully designed cavity, a directed emission of the photons is achieved. Furthermore, the introduced Purcell effect reduces decay times, which can be used to achieve high rates of entangled photons.

The extent of the enhancement strongly depends on the manufacturing accuracy of the resonators with respect to randomly grown quantum dots. Modern devices are therefore deterministically placed on preselected quantum dots. However, this process is technologically challenging and still requires hand selection of the best performing devices.

For this reason, open cavity systems have been developed to navigate to each position on the wafer and tune the cavity energetically into resonance with the quantum dot [9]. Here, we present our realization of an open fiber-cavity system for cluster state generation.

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Recent Developments in the Engineering of Practical Single-Photon Sources made from Semiconductor Quantum Dots

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As high-performant sources of single photons, epitaxial quantum dots can be considered as a semiconductor launchpad for quantum photonic technologies.[1] Luckily enough for engineers and scientists, there is still a variety of challenges to tackle on the road to an ideal single-photon source. This poster presents an overview of recent developments in the engineering of practical single-photon sources made from III-V semiconductor quantum dots grown by molecular beam epitaxy:

Photonic wire-bonding of a quantum dot distributed Bragg grating waveguide was used to demonstrate a true plug-and-play fiber-coupled single-photon source, which allows for resonant-frequency pumping without the need of any additional cross-polarization filtering.[2]

By integrating InAs/InP quantum dots into circular Bragg grating resonators, Purcell-enhanced single-photon emission with $F_P \approx 7$ in the telecom C-band was achieved. [3]

We demonstrated that GaSb quantum dots are a scientifically rich alternative material system for the generation of single-photons in the telecom S-band. [4]

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Cryogenic Coupling of Site-controlled Quantum Dots with Photonic Integrated Circuits

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Routing and control of quantum photonic states using photonic integrated circuits (PICs) is one of the major paths towards a scalable quantum-computing platform. Here we utilize site-controlled InGaAs quantum dots (QDs) as the source of photons [1], which are then coupled to and operated on by a custom SiN PIC, developed to operate at cryogenic temperatures (12 K).

The QD arrays are processed to produce a variety of nanostructures with improved optical qualities and potential for hybrid integration. Free-space coupling (Fig. 1a) has already enabled quantum correlations of multiple QDs (Fig. 1b).

A major requirement of a functional chip is the ability to tune circuit elements and thereby implement photonic gates. Here we have improved upon previous cryogenic SiN work [2] to show filter tuning across a full free spectral range (FSR) at 12 K (Fig. 1c).

Now with the second iteration of the chip, we plan to demonstrate a greater range of photonic control and quantum gate operations up to and including entanglement swapping [3].

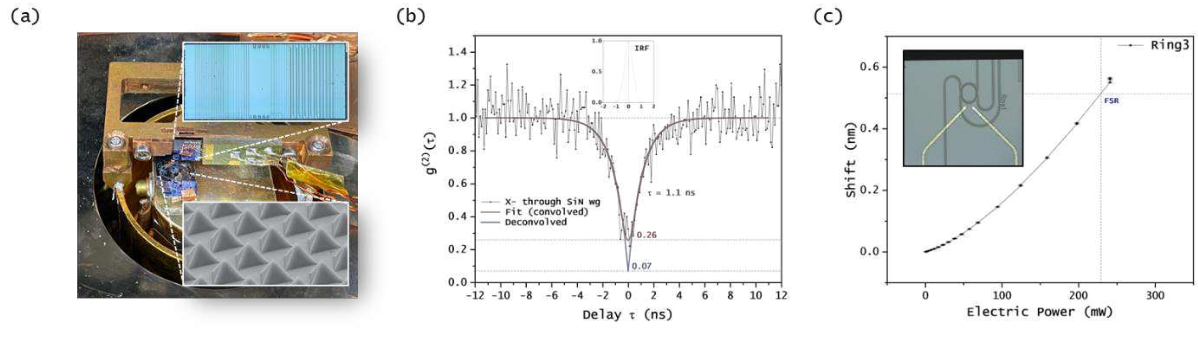

Figure 1. (a) Experimental scheme for free-space coupling of QD arrays (bottom inset) to prototype SiN chips (top inset). (b) Cross-correlation of QD coupled through SiN chip. (c) Tuning of SiN ring resonator (example inset) across a full FSR at 12 K.

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9th international workshop on "Engineering of Quantum Emitter Properties"– Paderborn, Germany

Cavity-enhanced linearly polarized single-photon emission from localized excitonic quantum emitters in WSe_2 monolayer

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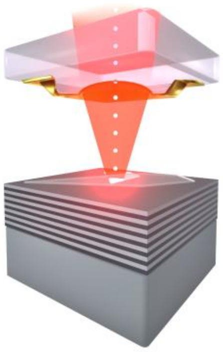
The bright and ease-to-fabricate single-photon source is at the heart of scalable quantum communication where the data is safely encrypted using quantum nature of the light. To date semiconductor quantum dots are the most advanced quantum light source in solids. However recent research show that strongly localized excitons in two-dimensional semiconductors act as a bright quantum emitters possessing narrow spectral lines and pronounced antibunching feature.



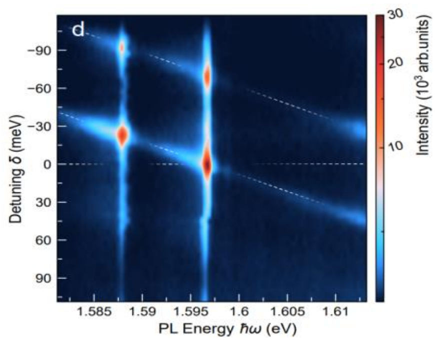


Figure 1: (left) Schematical of a WSe2 nanosheet embedded in an open cavity with distributed Bragg bottom mirror and gold plano-concave microlens as a top mirror. (right) Quantum dot photoluminescence spectrum as a function of cavity detuning.

Here we report that implementation of microresonators such as open cavity or plasmonic circular Bragg grating leads to dramatic improvement of SPE performance in WSe_2 nanosheets. Second-order correlation study revealed purity of linearly polarized single photons with $g^{(2)} =$ = 4.7 ± 0.7% Owing to record high first-lens brightness of 65 % we managed to observe true quantum interference in Hong-Ou-Mandel experiment with a visibility of 2% which makes WSe_2 monolayers prospective platform for scalable quantum information processing.

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Dynamically Dressed States of a Quantum Four-Level System

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The realization of photonic quantum applications requires a profound understanding of the fundamental interaction of a light field with quantum few-level systems. In recent years semiconductor quantum dots have taken a pivotal role in experimental studies of fundamental quantum optics due to their tunable few-level structure, excellent optical properties and strong light-matter interaction.

Resonant continuous-wave excitation of excitonic transitions in quantum dots has been well-studied both theoretically and experimentally over the past decades [1, 2, 3], while recently the less investigated dynamically dressed emission spectrum under resonant pulsed excitation of a quantum two-level system, driven by Gaussian pulses of finite pulse durations, was experimentally observed for the first time [4, 5].

In this contribution, the study of a dynamically dressed quantum two-level system is extended to the quantum four-level system formed by the biexciton-exciton cascade under resonant pulsed two-photon excitation. In the emission spectra, we make two main observations: First, we observe both the biexciton and exciton undergoing coherent Rabi oscillations with increasing pulse area. Second, we observe multiple sidepeaks emerging from the biexciton transition, with their quantity and spectral detuning increasing with excitation pulse intensity. Furthermore, a clear dependence of the spectral shape of the sidepeaks on the pulse duration is observed. These findings indicate a dynamical dressing of both ground and biexciton state during the finite pulse duration that is induced by the light field resonant on the two-photon transition.

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Stimulated Generation of Indistinguishable Single Photons from a Quantum Ladder System

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Single photons play a key role for applications in photonic quantum technologies, with semiconductor quantum dots as one of the most promising platforms for their on-demand generation. This stems from their excellent optical properties, such as almost exclusive emission into the zero-phonon line, near transform-limited linewidth, high emission rates and their integrability into nanophotonic structures.

A wealth of different excitation schemes for the generation of single photons have been developed, each with their specific advantages and disadvantages. Both resonant and phonon-assisted excitation allow for the generation of highly indistinguishable photons, while the single-photon purity is limited by reexcitation. In contrast, two-photon excitation of the biexciton suppresses reexcitation, resulting in ultra-low multi-photon errors. However, the indistinguishability of emitted photons is inherently limited by the timing jitter of the cascaded decay.

Here, we propose, model and demonstrate a scheme that combines the advantages of all previously established excitation methods [1]. The scheme is based on the resonant two-photon excitation of a biexciton, followed by the stimulation of the biexciton-exciton transition to selectively prepare an exciton. The subsequently emitted photon from the exciton recombination inherits the excellent purity from the two-photon excitation, while the precisely timed stimulation laser removes the timing jitter of the cascaded decay, thus restoring high indistinguishability. In addition, the emission energy is spectrally detuned from both driving laser fields, removing the necessity for polarization filtering, which enables high brightness. Via the polarization of the stimulation laser field, one of the two fine structure split branches of the cascaded decay can be selectively coupled, thus deterministically programming the polarization of the emitted photons (H/V).

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Spin and Optical Properties of Shallow Donors in ZnO: From Ensembles to Singles

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Neutral shallow donors (D^0) in ZnO, such as Al, Ga, or In substituting a Zn site, are strong candidates as donor qubits due to their efficient optical access, narrow inhomogeneous linewidths (~10 GHz), and long longitudinal spin relaxation times (T_1) by virtue of weak spin orbit coupling.

Using all-optical control on D^0 ensembles, we observe efficient spin initialization via optical pumping [1], T_1 up to ~0.5 s [2], and a moderate coherence time (T_2) of ~50 µs which is limited by substrate purity [1]. On ensembles of implanted In donors, we reveal the hyperfine coupling of the In electron spin-1/2 to the In nuclear spin-9/2, promising the potential for an electron-spin qubit with access to a nuclear-spin memory. Moreover, we find that a single 1 h anneal in oxygen recovers the donors favorable spin and optical properties which had been diminished by implantation-induced damage. Motivated by this resilience to radiation damage, we isolate single In donors by using plasma focused ion beam milling (PFIB) to confine a small volume of ZnO, revealing charge stable emission, near lifetime-limited linewidths, and a ten-fold reduction in lifetime compared to bulk donors which we ascribe to surface-related non-radiative recombination.

This work bolsters the potential for deterministically implanted In-donor qubits integrated with nanophotonic structures fabricated directly in ZnO using PFIB.

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Towards a quantitative understanding of quantum dot ensemble capacitance-voltage spectroscopy

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The quantum dot (QD) is a promising candidate for the technological step toward quantum processing. Coupling to a charge reservoir can help control the charge state of the QDs and reduce charge noise. Scaling up technology to devices with multiple QDs may require controlling an inhomogeneous ensemble coupled to a single charge reservoir.

In previous work by Brinks et al., a thermal shift of the tunnel current resonance associated with the ground states of the QDs was observed. An applied model consisted of an equilibrium condition between in- and out-tunneling [1]. The work of Valentin et al. introduced a master equation approach and successfully described non-equilibrium states in illuminated QD systems [2]. However, energy dependence in tunneling and inhomogeneous QD ensembles were so far not considered.

We investigate such reservoir-coupled QD ensembles experimentally (Fig. 1) and extend the master equation approach of Valentin et al. [2]. The elaborate theoretical model best describes the experimental data when considering an energy-dependent tunnel coupling. Ensemble broadening effects dominate the spectral response at low temperatures and measurement frequencies comparable to the tunneling rate between the QD and charge reservoir. At elevated temperatures, we observe a peak shift of a completely different origin, best described by optimizing the conditional probability of the successive events of in and out-tunneling.

Our findings have important implications for the development of QD-ensemble systems for applications such as single-photon sources or spin qubit resources and highlight the need for further research into the physical properties of these systems under different conditions.

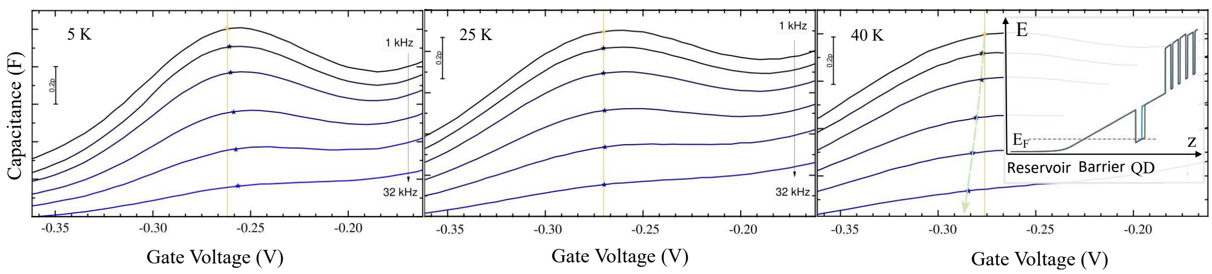

Figure 1: Experimental C-V spectrum of a QD ensemble for different temperatures and ac-frequencies. <u>Inset on the right:</u> Schematic representation of the band structure of the relevant region in the experiment.

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Signatures of the Optical Stark Effect on Entangled Photon Pairs from Resonantly Pumped Quantum Dots

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Semiconductor quantum dots (QDs) are emerging as one of the main building blocks of the newborn field of quantum networks. Their peculiar electronic structure can be exploited for the generation of single and polarization entangled photons (EPs). In particular, EPs are crucial for the realization of entanglement based quantum protocols [**1**]. Two-photon resonant excitation (TPE) of the biexciton-exciton (XX-X) cascade in a quantum dot generates highly polarization EPs in a near-deterministic way. However, the ultimate level of achievable entanglement is still a debate. Recently, it has been proved how the integration of a cavity enhanced QD based device on a strain-tuning piezoelectric actuator meet the demand for both high brightness and high entanglement degree [**2**]. However, the shortening of both X and XX lifetimes via Purcell effect due to the presence of the cavity brought to light a detrimental effect that was only theoretically predicted [**3**]. Here [**4**], we experimentally investigated for the first time the impact of the laser induced optical Stark effect on cavity enhanced GaAs QDs emission spectra and photon pairs entanglement degree. Even for a perfect in-plane symmetry, resulting in a degeneracy of the bright X states, the laser pulse exploited for TPE couples with the X state aligned to its polarization. This results in a transient energy shift between the X states energies, depending on the pulse intensity, and on the ratio between the pulse duration (τ_L) and the XX lifetime (τ_{XX}), lowering the entanglement degree of the photons emitted during the XX-X cascade while the pulse is still shining the QD. We investigated this phenomenon for two different QDs, featuring different XX lifetimes, while varying the laser pulse duration, observing how the concurrence decreases for increasing pulse duration and, for a fixed laser pulse, is lower for faster XX recombination.

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Entanglement-based quantum key distribution using a deterministic quantum dot photon source

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Entanglement-based protocols for quantum key distribution (QKD) provide additional layers of security compared to single-photon prepare-and-measure approaches, despite presenting the challenge of a less immediate hardware implementation. As remarkable technical achievements have been used to demonstrate entanglement-based QKD over longer and longer distances [1], the main opportunity for further development is related to multiphoton emission. This is a fundamental limitation for state-of-the-art photon sources based on spontaneous parametric down-conversion, which can be solved using deterministic quantum emitters. Here we focus on semiconductor quantum dots, which can generate nearly on-demand photon pairs with record-low multiphoton emission [2] and Bell state fidelity currently up to 98% [3].

We experimentally demonstrate the viability of this technology in a realistic urban communication scenario [4]. We employ a modified asymmetric Ekert protocol and perform QKD comparing two choices of quantum channel: over a 250 m single-mode fiber and in free-space between two buildings across the campus of the Sapienza University of Rome. The key exchange is successfully performed with error rates of 3–4%, well below the protocol threshold, and with substantial violations of the Bell inequality. By filtering spatially and spectrally the sunlight, the communication can be maintained continuously throughout the day and even withstanding moderate rain [5]. The results are discussed in relation to the technical solutions employed for transferring the signal and to the current state of development of the source. In this regard, an outlook is presented based on the latest and foreseen advances in source design that can lead to unprecedented pair emission rates and boost secure key exchange over long distances.

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Building the quantum repeater: advancements in the entangled-photon sources based on GaAs epitaxial quantum dots

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Entangled-photon sources are at the base of the quantum repeater, i.e., one of the building blocks of future quantum networks [1]. Semiconductor quantum dots proved to be one of the best sources of entangled photons due to their ability to emit entangled light on demand and to tune their light emission properties via strain engineering [2]. Still, the potential of quantum dots remains partially unexploited due to a few current limitations such as the low extraction efficiency due to refractive index mismatch and entanglement degradation due to asymmetries in the quantum dot shape. In this poster, I will show the advancements in the fabrication of an entangled-photon source based on a strain-tunable cavity-enhanced GaAs epitaxial quantum dot. This device combines for the first time high entanglement fidelity, high extraction efficiency, and energy tuning. However, there is still a long road to walk before using these sources in a real-life quantum repeater and here we will highlight what is still missing to complete this journey and some viable solutions to make it possible.

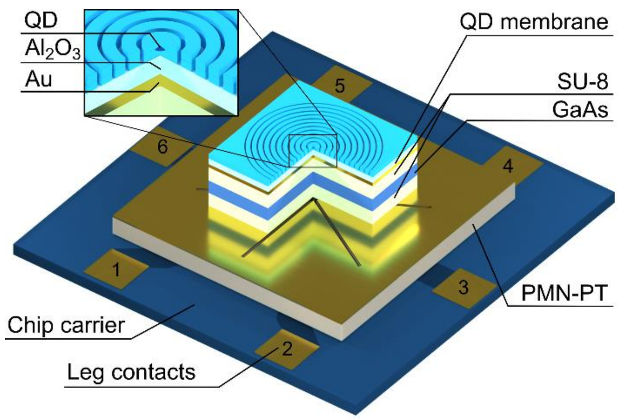

Figure 1: Sketch of the entangled photon emitter device. A single QD is sitting in the centre of a Bullseye photonic cavity. The semiconductor membrane sits on a micromachined piezoelectric for strain tuning.

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Exciton redistribution in 2D WSe_2 via external strain field

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Monolayer Transition-Metal Dichalcogenides (ML-TMDs) are two-dimensional semiconductors materials exhibiting unique optical and electronic properties. In addition to their easiness in fabrication, ML-TMDs can withstand up to 10% strain without breaking, being then feasible to exploit deformations to control their transport and optical properties. Furthermore, localized excitons in ML-TMDs provide single photons with high brightness[1]. Since both impurities and spatial strain gradients induce quantum emitters (QEs) in ML-TMDs[2], dynamic control over the strain field enables to engineer the QEs properties and exploit their full potential for quantum technologies. Our piezoelectric device bursts into this context. It is a gold-covered piezoelectric material with a micro-pillars array covered by dry-transferred ML-WSe2. The QEs nucleation sites are arranged around the pillars, providing control of their position over a few microns[3]. Furthermore, deforming the piezoelectric substrate we can explore the QEs response to external strain fields. We demonstrated that the QEs energy can be precisely tuned across a spectral range as large as tens of meV without changing the multi-photon emission probability[3]. We also observed that the external strain field reversibly modifies the QEs brightness, providing theoretical simulations based on an exciton diffusion model. We found good agreement between the theory and the experimental results, confirming that strain is a valuable tool even for brightening one specific emitter rather than another[4]. We also investigated the QEs response in magnetic field. Measuring the g-factor of several single-photon lines as a function of the applied external stress, we found that despite changes in energy up to 10 meV, the variations in the g-factor always remain between the experimental errors[5]. This result ensures the robustness of the QEs spin degree of freedom, opening future possibilities in hybrid spintronic devices or photonic interfaces.

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Increasing the brightness of site controlled QD with chip scale processing

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Site-controlled quantum dots (QD) grown in pyramidal patterned substrates give access to hundreds of thousand of single photon emitters, with highly uniform emission wavelength, that also act as entangled photon pair source [1,2]. Here, we demonstrate a chip scale processing that largely increases the extraction efficiency from these sources and their coupling into waveguides.

Firstly, we produce a regular array of sub-micron triangular pillars with a self-aligned process that ensures a single QD inside each pillar, positioned along its axis. Subsequently, multiple cycles of chemical vapor deposition are used to create quasi-conformal dielectric shells that encapsulate the pillar. While the emitted light is guided by the GaAs pillar, the dielectric layers reduce the internal reflection at the pillar end, and create a convex surface that partially focus the output beam, acting as a lens.

We succeed in increasing the extraction efficiency into a 0.8 NA objective to ≥14% obtaining raw single photon count rate ≥1MHz under continuous wave excitation of the QD. The dielectric coating also induces a shift of the emitted wavelength possibly due to materials strain.

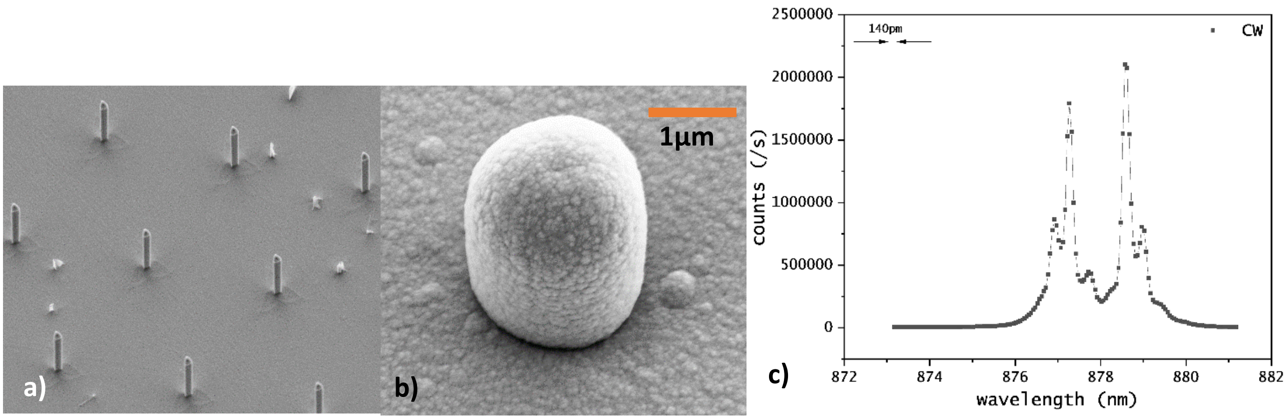

Figure 1: a) Array of nanopillars obtained with a self-aligned process. b) A single nanopillar coated with thick SiN_x and SiO_2 layers. c) Single photon count rate spectrum recorded on an avalanche single photon detector placed at the output of a spectrometer.

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QDs, Stranski-Krastanov and origins: the journey for the invention of epitaxial quantum dots

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Epitaxial semiconductor quantum dots have been, in the last 40 years or so, at the center of the research effort of a large community. The focus being on "semiconductor physics and devices", in view of the broad applications and potential, e.g., for efficient temperature insensitive lasers at telecom wavelengths, or as "artificial atoms" for quantum information processing. Our work aims at addressing, with an historical perspective, the specifics of (III-V) epitaxial quantum dot early developments (largely for light emitting) and subsequent years. We will not only highlight the variety of epitaxial structures and methods, but also, intentionally glancing a didactic approach, discuss aspects that are, in general, little acknowledged or debated in the present literature. Some surprises also are highlighted: for example, the Stranski-Krastanov (SK) process was not introduced historically for describing the physics of the current SK dot formation. In many ways we will show that the semiconductor community re-defined over the years the meaning itself of SK processes.

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Two-photon emission from single-photon sources

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The most fundamental source of quantum light is, without any doubt, the two-level system (2LS). Since it cannot hold more than one excitation, it always produces perfectly antibunched light, thus qualifying as the most straightforward realisation of a single-photon source. Even when considering more complex structures, such a basic picture provides further opportunities along similar lines [1].

Under weak coherent excitation, the antibunching of a 2LS is a consequence of the interference between the coherent (mean field) and incoherent (fluctuations) fractions of the emission [2]. Suppressing the former through homodyning shows that the fluctuations are strongly correlated [3], which reveals the multiphoton structure hidden behind the resonance fluorescence. This has been recently confirmed experimentally by various and complementary approaches, partially suppressing either the incoherent [4] or the coherent [5] photons through frequency filtering.

When the laser-emitter detuning is large, the spectrum consists of two symmetric sidebands around the Rayleigh peak. Using frequency filtering [6], we can correlate the signal from these peaks and show that two photons, one from each band, are emitted in a cascade [7]. Additionally, the quality of the process considerably improves when the Rayleigh peak is subtracted using homodyning.

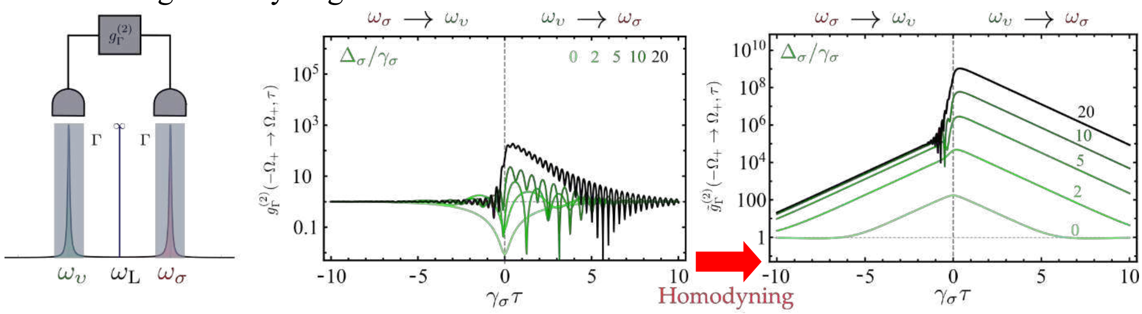

Fig. 1: The cross correlations between the sidebands reveals the cascade emission ($\omega_\upsilon \to \omega_\sigma$) that improves if: (a) the detuning Δ_σ increases and (b) the Rayleigh peak (Dirac delta) is suppressed through homodyning.

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Towards twin photon emission from (In,Ga)N quantum dots: Tailoring their multi-excitonic properties via external electric fields

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Semiconductor quantum dots (QDs) have drawn significant attention due to their potential for non-classical light emission (NCLE), e.g., single photons [1], polarization entangled photon pairs [2] or twin photons [3]. Thanks to their fundamental material properties (e.g., large band offsets), nitride-based QDs have been considered for high temperature applications and GaN-based dots have shown single photon emission up to and beyond room temperature [4]. While these emitters operate in the ultra violet (UV) spectral range, (In,Ga)N-based dots offer, in principle, NCLE in the visible. However, alloy disorder can strongly impact the electronic and optical properties of (In,Ga)N-based emitters [5].

To target the electronic and optical properties of (In,Ga)N/GaN QDs, we have developed an atomistic model based on tight-binding theory [6]. This model accounts for fluctuations in strain and internal built-in polarization fields due to the presence of alloy disorder in the dot. Our calculations reveal that in comparison to [001]-oriented arsenide-based QDs, (In,Ga)N systems exhibit “unconventional” biexcitonic ground states. An example of a resulting multi-excitonic spectra is shown in Fig.1, indicating different “decay channels” for the biexciton.

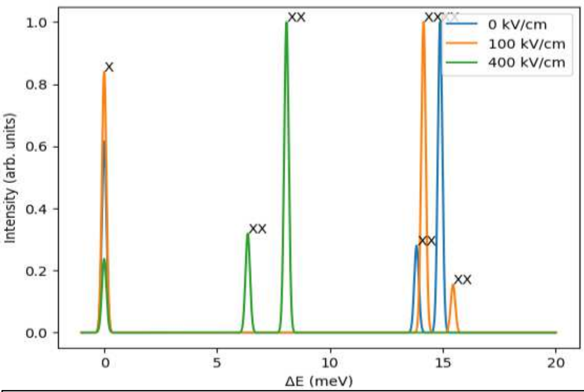

Figure 1: Calculated multiexciton emission spectra for an $In_{0.2}Ga_{0.8}N$/GaN QD. The spectra are shown for different electric field strengths namely 0 kV/cm (no field), 100 kV/cm and 400 kV/cm. The results are normalized to the respective exciton ground state emission peak.

Our recent calculations [7] also reveal that while polarization entanglement may be prohibited due to alloy disorder in the system, (In,Ga)N dots could be potential candidates for twin photon emission due to the polarization characteristic of the emitted photons. To explore these properties further, we here present results when tailoring the electronic and excitonic properties of (In,Ga)N QDs via external electric fields. Our studies indicate that the biexciton binding energy decreases with increasing external field (see Fig. 1) as one may expect. However, we also find that the level to which the excitonic properties can be tailored strongly depends on the alloy microstructure of the QD.

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Electronic and excitonic properties of [111]-oriented site-controlled GaAs quantum dots: Insights from symmetry adapted calculations.

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Scaling laboratory systems for quantum information processing (QIP) and quantum computing to accommodate large numbers of qubits is challenging. A potential solution to this issue is found through using multi-dimensional photonic cluster states (PCS) as a substrate for quantum computation [1]. However, generating these cluster states on-demand at large scales faces significant challenges.

Recent literature has targeted semiconductor quantum dots (QDs) for production of PCS. While Stranski-Krastanov (SK) growth of QDs does in general not offer the level of precision required for multi-dimensional PCS generation, site-controlled [111]-oriented GaAs QDs [2] offer an attractive option for such applications. However, in comparison to SK QDs grown along the [001]-direction, far less attention has been directed to their electronic and optical properties. Moreover, due to changes in symmetry, understanding from [001]-oriented dots cannot necessarily be carried over to these site-controlled structures. In this work we target this question and present results on electronic and excitonic properties of [111]-oriented site-controlled GaAs QDs from a symmetry-adapted framework.

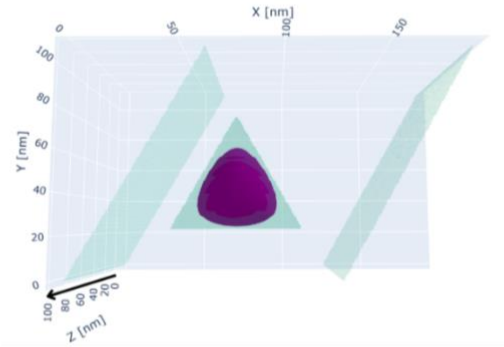

Figure 1: Hole ground state charge density for a GaAs QD. The dot base length is 18nm its height 2nm. The isosurface of the charge density is plotted @ 60% of its maximum value.

More specifically we employ an 8-band **k.p** model to model the electronic structure of experimentally relevant triangular prism shaped GaAs/$Al_{0.08}Ga_{0.92}As$ QDs. The model accounts for strain and polarization fields and the underlying C_{3v} symmetry. Our calculations reveal several bound hole states (example shown in Fig 1) but almost no confinement for electrons. Interestingly we find that the first excited hole state has significant p_z-like character, indicative of a light-hole like state, which is usually not found in SK dots grown along the [001]-direction.

To gain access to excitonic and biexcitonic properties, the symmetry adapted **k.p** model is connected to configuration interaction (CI) calculations, thus accounting for exchange and correlation effects in the many body wave functions. Here, we investigate the impact of the specific dot geometry on excitonic properties, showing that the excitonic binding energy increases with increasing dot height.

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Full Wafer Property Control of Local Droplet Etched GaAs Quantum Dots

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Local droplet-etched GaAs quantum dots (LDE-QDs) are excellent sources for single and entangled photons [1,2]. In contrast to self-assembled InGaAs Stranski-Krastanov quantum dots (SK-QDs), GaAs QDs are strain-free and have a typical emission wavelength between 700 nm and 800 nm. This is desirable for quantum memory systems such as Rubidium atom vapor and Silicon-vacancies [1,3].

It is crucial to control the electronic and photonic properties of these QDs to build new devices for quantum photonics and advanced opto-electronics. We demonstrate a method to compensate for non-ideal growth conditions in a conventional molecular beam epitaxy (MBE) system. By stopping the sample rotation, a flux gradient is induced which leads to a gradual change of the deposited material. As a result, the emitter wavelength can be adjusted. The QD density remains largely unaffected until it drops to zero beyond a critical amount. Another consequence is a surface roughness modulation across the whole wafer, which has been demonstrated as a simple and efficient method to control the density of low-noise, high-quality InAs SK-QDs [4]. Applying this method to LDE-QDs also results in a periodic modulation of the ground state, with an approximate 3 nm variation on a millimeter scale [5].

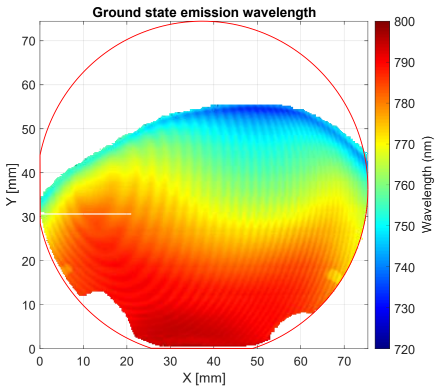

Figure 1: Wafer-map showing the ground state QD-emission obtained by applying Gaussian fits to the PL spectra.

References:

[1] L. Zhai et al., Low-noise GaAs quantum dots for quantum photonics, Nat. Com. **11**, 4745 (2020).
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In Depth Study of Pyramidal GaAs Quantum Dots Optical Transitions

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Over the last decades Quantum Dots (QD) have emerged as promising sources of qubits for quantum computing application due to their optical properties (single photon emission, short lifetimes of states etc.)[1].

In the poster we present an in depth study of epitaxially grown pyramidal GaAs QDs spectrum; these are a new generation of site-controlled QDs grown in a pyramidal recess of a patterned GaAs substrate using Metalorganic Vapour-Phase Epitaxy (MOVPE). These QDs are characterized by a remarkable spectral uniformity[2] and, like their InGaAs counterparts[3], have been demonstrated as entangled photons emitters[2].

Recombination cascades have been identified with polarization resolved correlations and the excited state orbitals have been characterized with polarization resolved spectroscopy and resonant fluorescence.

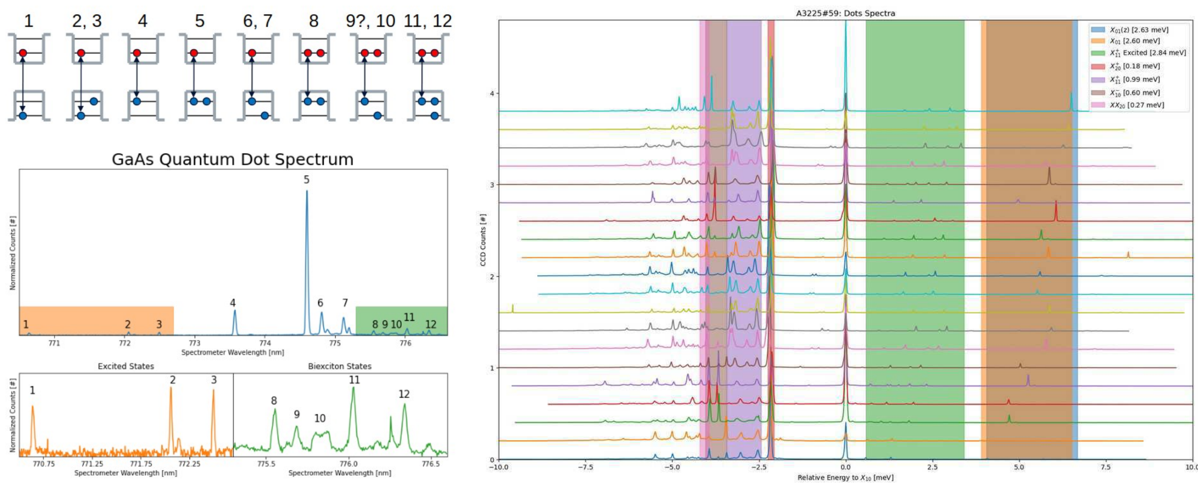

Figure 1: a) Optical transitions and charge configurations of a typical Pyramidal GaAs QDs b) Relative energy distribution of QDs optical transitions.

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Generation of single and indistinguishable photons with an InAs quantum dot embedded in a GaAs nanopost cavity

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On-demand single photon sources are key devices for photonic quantum technologies. Among various approaches, semiconductor quantum dots embedded in a tailored photonic environment offer remarkable performance. However, photonic structures that combine Purcell acceleration with broadband operation are relatively scarce.

In this poster, we present a single-photon source based on a self-assembled InAs quantum dot that is embedded in a GaAs nanopost cavity [1]. Despite its apparent simplicity, this design offers a pronounced Purcell acceleration of spontaneous emission (up to 6) over a large operation bandwidth (30 nm). We focus on a charged exciton, that experiences a Purcell acceleration of 5. The transition is driven by pulsed, phonon assisted excitation. We measure a Hong-Ou-Mandel visibility that exceeds 90% (after correction for the imperfect $g^{(2)}(0)$=19.6%), which shows that photons emitted consecutively, with a 2 ns delay, are highly indistinguishable. The same device was investigated under strictly resonant, continuous excitation, in the frame of a collaboration with the group of Professor R. Warburton. The data show an excellent single-photon purity, but also reveal non-idealities of the source: a slow spectral wandering and a blinking of the emission. These processes can be partially tamed by an additional, weak, non-resonant laser pump.

The results presented in this poster, combined with further improvements of the device, pave the way for the realization of a broadly-tunable source of single and indistinguishable photons.

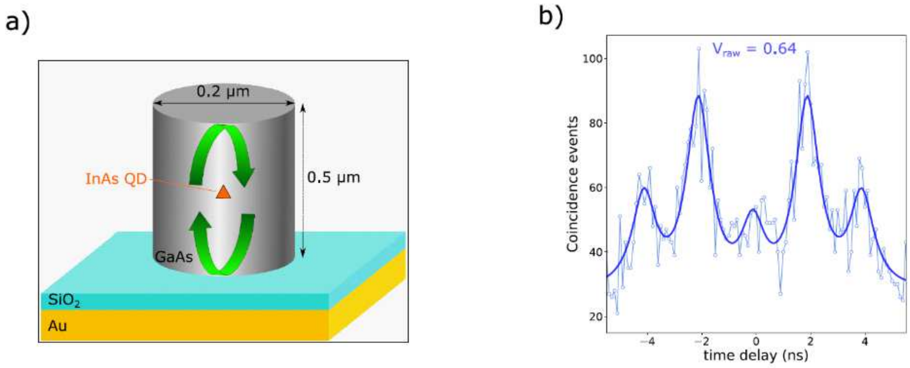

Figure 1: a) Scheme of the nanocavity. The optical cavity is formed by the bottom gold mirror and the Fresnel reflexion at the top interface. The modest quality factor of Q = 30 is compensated by an ultrasmall mode volume. b) HOM coincidence histogram for the charged exciton presented in this work. The raw HOM visibility is V_{raw} = 0.64.

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Photonic Integration of Diamond Qubits into Hybrid Circuits

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Quantum photonic circuits are fundamental building blocks for quantum information applications, like secure communication or quantum computing. Hybrid photonic systems combine different materials to leverage their individual strengths. We focus on devices, which are based on an AlGaN guiding layer on top of an AlN on sapphire substrate. This material has a strong second order susceptibility $\chi^{(2)}$ enabling on-chip nonlinear optics. Color centers in diamond have excellent properties to serve as qubits in our circuits. To maximize the collection of photons we use a "Sawfish" photonic crystal cavity, which enhances the color center's emission rate by means of the Purcell effect and raises the collection efficiency close to unity [1].

Here we report on the characterization of recently fabricated "Sawfish" cavities and the deterministic coupling of color centers to nanostructures. The "Sawfish" cavities show high quality factors and fundamental mode resonances that precisely follow the behavior expected from the corresponding design parameters. For the scalable fabrication of "Sawfish" cavities coupled to single color centers we are working on the development of a deterministic coupling method. This method is based on the localization of color centers and subsequent fabrication of nanocavities around them [2]. Furthermore, we numerically optimized the photon transfer between diamond and AlGaN/AlN waveguides. Using tapered regions in both materials, an efficient coupling is achievable. Combining these methods facilitates the assembly of fully integrated quantum photonic circuits.

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Temperature dependent exciton dynamics in GaAs quantum dots

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Epitaxially grown semiconductor quantum dots have shown to be one of the best performing single-photon emitters in the solid-state. Here, the best results have been achieved at a temperature of around 4 K, where the excitonic transitions can well be modeled by a two-level system. However, with higher temperatures the two-level model fails to describe the exciton decay dynamics accurately, which is attributed to a phonon mediated intermediate population of energetically close states [1]. Still, the full mechanism behind the change in decay dynamics is not fully understood, and an inspection using resonance fluorescence could improve the currently used model. This might then be beneficial in fabricating quantum dots suitable for higher temperature operation using Stirling coolers [2]. In this work, we show temperature dependent decay dynamics measurements of the neutral exciton and trion under different excitation and photon collection conditions. These measurements can act as a basis to further understand the mechanisms at play when the temperature is increased and the effects they have on photon indistinguishability.

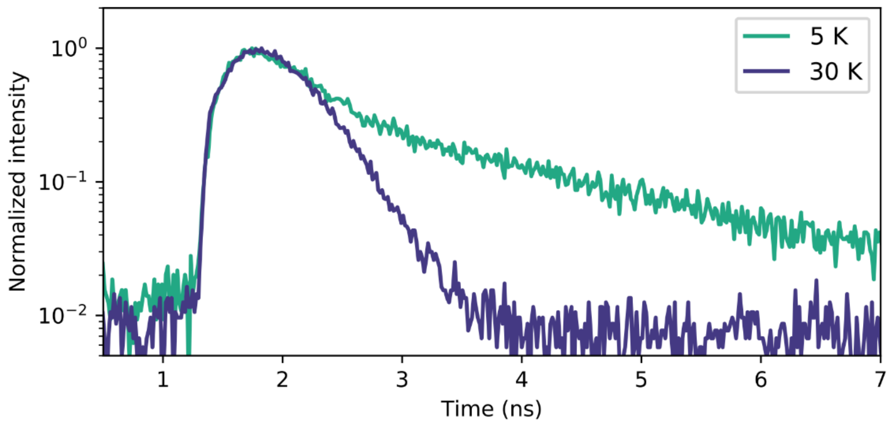

Figure 1: Decay time measurement data of the neutral exciton under resonant excitation at a temperature of 5 K and 30 K. The latter shows a long tail in the photon detections, indicating the intermediate population of energetically close states.

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Stimulated excitation and coherent control of dark exciton state population in a quantum dot

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Semiconductor quantum dots, with their capability of confining charge carriers and various spin configurations resulting from it, can be regarded as a highly versatile platform for generating non-classical light. While the generation of single photons or entangled photon pairs from quantum dots utilizes the so-called bright excitons and biexcitons respectively, quantum dots can also host optically dark excitons. Such states are optically inactive due to the spin-selection rules. Due to their longer coherence times, a direct and coherent optical excitation and control of dark states are of great interest in modern quantum information protocols [1]. In this work we demonstrate a stimulated excitation and coherent control of the dark exciton population via the biexciton state in a GaAs/AlGaAs quantum dot in presence of an in-plane magnetic field. The versatility of our scheme allows not only a deterministic preparation, but storage and a temporal retrieval of the dark state population, giving rise to a programmed single photon/photon pair emission [2].

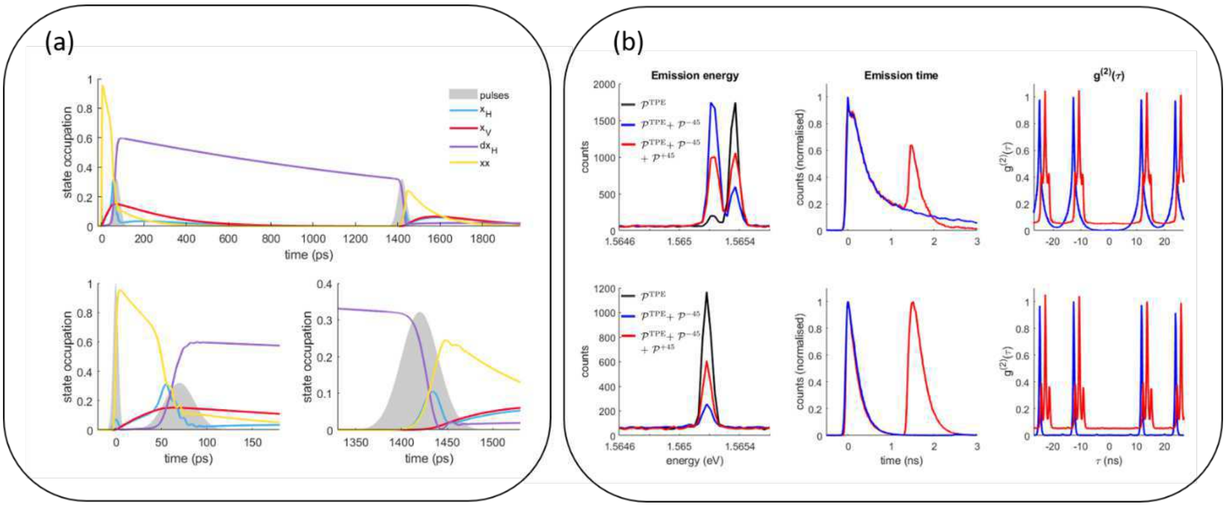

Figure 1: (a) Simulated quantum dot state dynamics under a three-pulse excitation. (b) Energy and time-resolved photon emission as a function of excitation polarization. Top: collection polarization parallel to stimulation pulse polarization. Bottom: collection polarization orthogonal to stimulation pulse polarization.

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[2] Kappe et al., *in preparation*

Magneto-optical generation and characterization of dark exciton state in a quantum dot

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Semiconductor quantum dots are arguably the most promising platform for future quantum technologies. Due to the confinement of charge carriers, a variety of photon states can be generated, making them a highly adaptable quantum platform. While the most common optical excitation methods target the so-called bright excitons or biexcitons for the generation of single or entangled photon states, quantum dots also accommodate optically dark excitons, which are not directly accessible via optical excitation methods. The dark exciton states exhibit significantly slower decay rates compared to their bright counterparts, making them potential candidates for application in quantum information protocols that demand the control of quantum coherence over long time scales [1]. In this work, we generate the dark exciton states in a single GaAs/AlGaAs quantum dot emitting ~ 800 nm under a magneto-optical excitation (in-plane magnetic field ~ 3.2 T), and characterize the emission energy splitting, lifetime variation and polarization response.

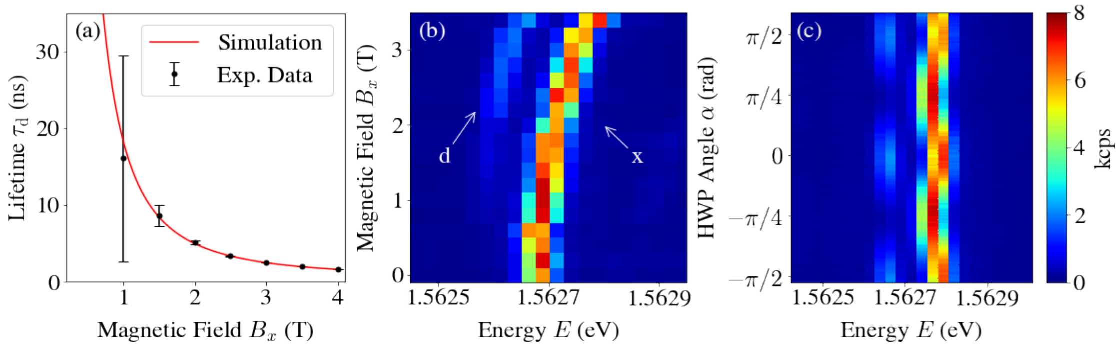

Figure 1: (a) Lifetime of the generated dark exciton state in the QD as a function of the applied in-plane magnetic field. (b) Magnetoluminescence spectrum as a function of the in-plane magnetic field, with the bright exciton (x) and the dark exciton (d) lines indicated. (c) Polarization-resolved response of the magnetoluminescence spectra, indicating amplitude oscillations of the dark state as well as both orthogonally polarized bright states.

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Compact chirped fiber Bragg gratings for single-photon generation from quantum dots

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To realize a scalable source of frequency-multiplexed single photons, it is important to have an ensemble of quantum emitters that can be collectively excited with high efficiency. Semiconductor quantum dots hold great potential here, due to their excellent photophysical properties. The most efficient scheme to excite a quantum dot ensemble employs chirped laser pulses, relying on the so-called adiabatic rapid passage, is due to its robustness against spectral and intensity fluctuations. Yet, the existing methods to generate chirped laser pulses coupled to a quantum emitter are bulky, lossy, less flexible, and mechanically unstable, which severely hampers the prospects of a practical quantum dot device. Here, we present a compact, robust, and high-efficiency alternative for chirped pulse excitation of solid-state quantum emitters. Our simple plug-and-play module consists of chirped fiber Bragg gratings (CFBGs) that provide high dispersion, tailored to ~ 800 nm with a ~ 5 nm bandwidth that accommodates the quantum dot spectral variability. To characterize and benchmark the performance of our method, we demonstrate the chirped excitation of a GaAs/AlGaAs quantum dot that shows excellent agreement with theoretical simulations and establish high-fidelity single-photon generation. Our method can be tailored for a wide spectral range and dispersion requirements and is a significant milestone toward realizing a direct fiber-coupled, plug-and-play quantum dot photon source.

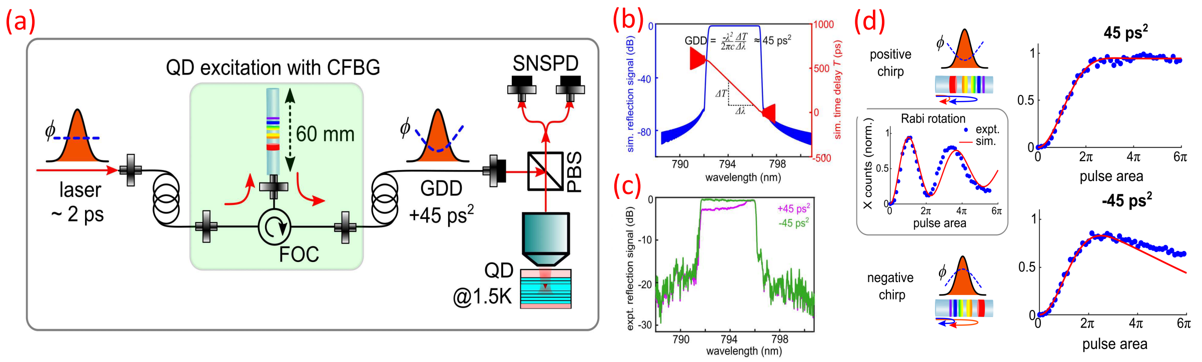

Figure 1: Sketch of the plug-and-play chirping method. The chirped fiber Bragg grating (CFBG) tailored for 45ps² dispersion is directly coupled to the quantum dot (QD) sample. (b) Design parameters of CFBG (c) Measured reflectivity of CFBG (c) Results of QD excitation using chirped pulses, compared to the resonant Rabi rotations.

References:

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Magneto-optical time-resolved photoluminescence experiments on G-center ensembles in silicon

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Silicon is the major semiconductor of the information society. It is at the heart of devices in microelectronics and computer technology, and as such one of the most desired platforms for the development of next-generation applications in quantum technologies. On one hand, individual dopants and gate-defined quantum dots have already emerged for implementing electrical qubits in silicon. On the other hand, the literature is still very sparse on silicon-based quantum devices harnessing individual optically active qubits for quantum communications and quantum integrated photonics. Recent studies demonstrating the single-photon emission from several families of isolated individual near-infrared color centers in silicon [1–4] including single spin initialization through optical pumping [5], could open up new perspectives. However, coherent control of a single spin interfaced with light is yet to be demonstrated in silicon.

In this work, we focus on the G center in silicon, a well-known defect recently observed at single scale [6], which possesses a telecom emission and a metastable electron spin triplet that has been detected optically on ensembles in the 80s [7]. Here we present magneto-optical time-resolved experiments carried out on G center ensembles to investigate the energy structure of the metastable spin triplet level. These results are a first step towards the optical detection of the magnetic resonance of the G center in silicon down to the single defect scale.

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9th international workshop on "Engineering of Quantum Emitter Properties"– Paderborn, Germany

Purcell enhancement of W color centers in silicon optical microcavities

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Silicon is a major material platform for large-scale quantum photonics, with the integration of hundreds of components in cm²-scale programmable chips. However, further expansion is challenged by the difficulty to generate single photons on demand in silicon. An ideal solution would be the direct integration of all-silicon single photon emitters into a chip. In this context, the isolation of individual color centers in silicon provides a diversity of candidates to build such a source. [1] By placing a color center inside a silicon-on-insulator (SOI) microcavity, one expects to control its spontaneous emission to build a source of single photons into a well-defined optical mode.

Here, we present cavity quantum electrodynamics (CQED) experiments with an ensemble of W centers in circular Bragg grating (CBG) cavities. The W center is a tri-interstitial silicon color center created upon self-ion implantation and thermal annealing. [2] We demonstrate an enhancement of the zero-phonon line (ZPL) intensity by a factor of 20 and Purcell acceleration of the decay by a factor of 2. [3] These results are promising for further CQED experiments with individual W centers in SOI microcavities.

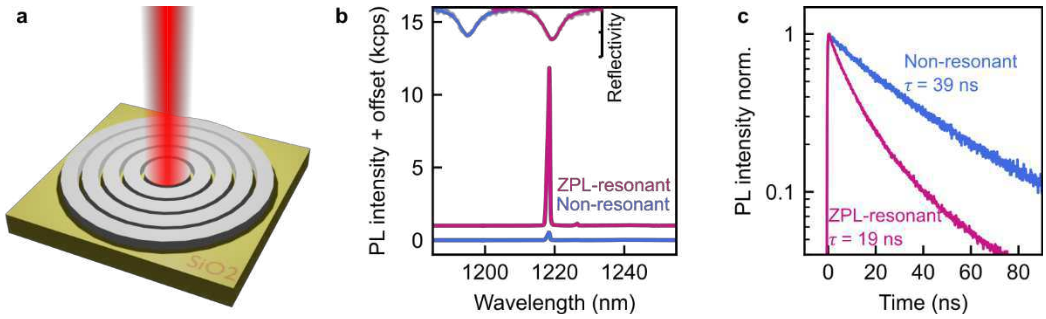

Figure 1: Purcell enhancement of W centers in a CBG cavity. **a.** Illustration of a CBG cavity. **b.** PL spectra and **c.** PL decay curves of an non-resonant cavity (blue) and ZPL-resonant cavity (pink).

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Towards Low Temperature Imaging of Telecom Wavelength InGaAs Quantum Dots

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Semiconductor quantum dots (QDs) are a promising non-classical light source for quantum information technology. To boost the fabrication yield of bright single and entangled photon pair sources, deterministic fabrication techniques can be employed. For this purpose, three techniques have been developed: low temperature deterministic optical lithography, low temperature deterministic electron beam lithography, and low temperature imaging, with recent interesting results also at telecommunication wavelengths

Exemplary, figure 1(a) shows a µ-PL map of a preselected QD in between deterministically fabricated alignment markers, which have been used to further combine 3D-printing and e-beam lithography for the fabrication of photonic structures [1, 2]. This technique has been demonstrated also at telecommunication wavelengths. Furthermore, we will discuss the progress towards an imaging setup operating at telecom wavelengths. An approach similar to T. M. Kriegers (operated at 780nm, figure 1(b)) will be followed [3]. The aim is reaching comparable performances at telecommunication wavelengths.

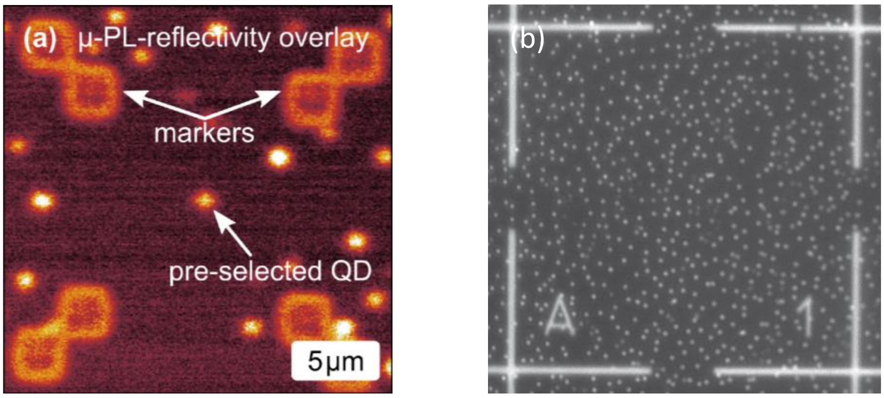

Figure 1: (a) Low temperature µ-PL map of a preselected QD with markers written through low-temperature deterministic optical lithography [1, 2]. (b) Image from Linz [3] of a 50x50 µm sample area framed by gold markers. The individual QDs are clearly distinguishable und can be selected for further processing.

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Excitonic Lifetime Tuning of GaAs Quantum Dots under High Electric Fields

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In order to be used for quantum communication and computation, entangled photon pairs featuring simultaneously a high degree of entanglement as well as a high single photon indistinguishability are desired. GaAs QDs embedded in diodes have shown to both be able to emit highly polarization entangled photon pairs from the Biexciton-Exciton decay cascade [1] as well as highly indistinguishable single photons [2]. However, the indistinguishability of photons emitted from a decay cascade is fundamentally limited by the relative lifetimes of the two decay paths due to an unwanted temporal coupling [3]. Therefore, using the photons from the decay cascade for the aforementioned applications hinges on the ability to independently tune the lifetime of the two decays. Here we present a novel approach which allows this by operating the diode at high fields.

Usually, these kinds of samples are used in the regime, where the Fermi Energy is resonant to the excitation of interest, be it the neutral state or different charged states. For the sample used here (see figure 1a)), the charge state of the QD can be set to neutral around +0.9V. Increasing the voltage further to the positive leads to a flat band and to a flow of current. Applying a negative voltage on the other hand will increase the total field and thereby increase the band bending. The resulting triangular shape of the potential wells of the conduction and the valence will lead to wave function of the electrons and holes being asymmetric and shifted away from one another, increasing the lifetime of the states[4].

As can be seen in figure 1b), we could excite the biexciton state using two photon absorption in the negative voltage range. One noticeable feature is that the binding energy of the biexciton state decreases towards higher fields, which can be seen in figure 1c). Additionally, a second line appears next to the exciton as well as the biexciton. We attribute those emission lines can be explained by a positive charge which is indicated in the inset of figure 1c) in the small well created by the tunneling barrier of the diode structure as already shown in a similar structure[5].

In figure 1d) the results of the lifetime measurements are presented. While the exciton lifetime increases towards higher fields, the lifetime of the biexciton seems largely unaffected. This is very positive as the theoretical limit of the indistinguishability for the highest measured change in lifetime is increased from about 64% to about 76%.

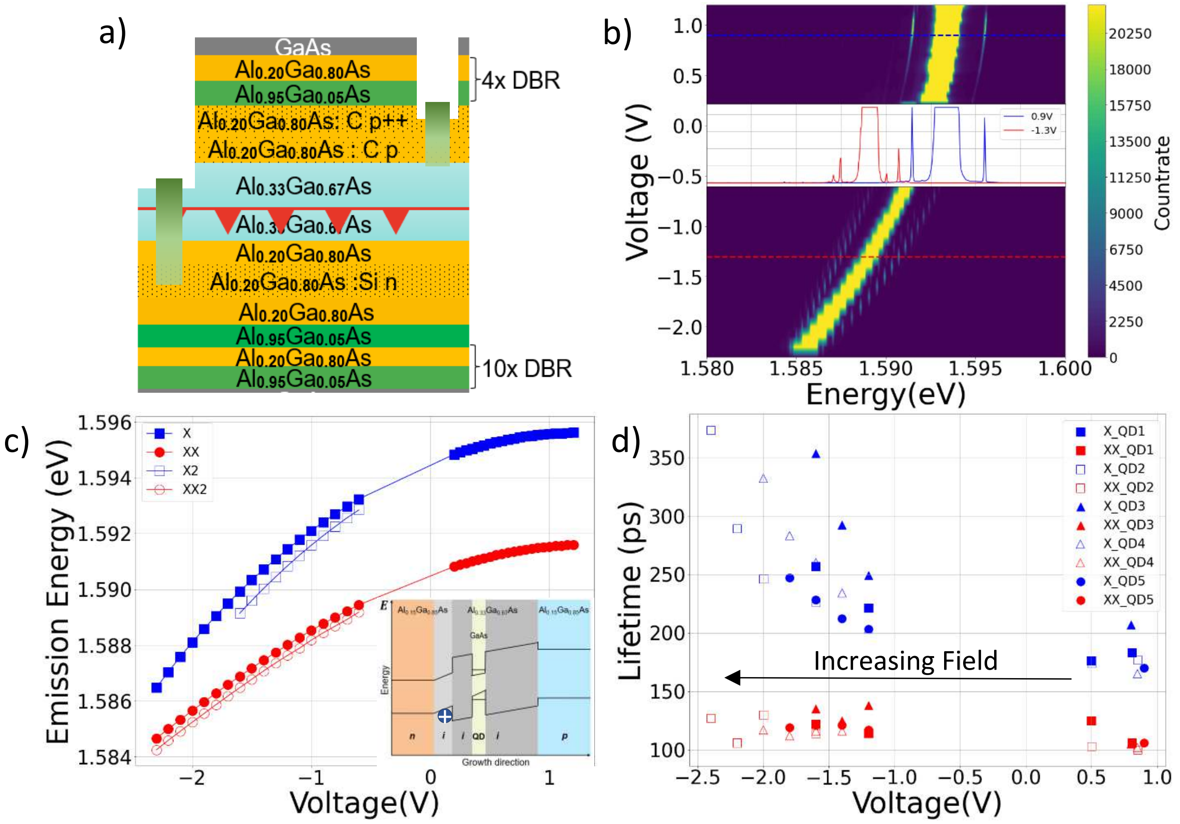

Figure 1: a) Sample structure with GaAs QDs embedded in a p-i-n-diode and the dots placed at the center of a planar cavity structure, b) voltage sweep with two-photon excitation with adjustment of the excitation laser, c) emission energy of exciton and biexciton confined in a representative QD as well of satellite emission lines (attributed to positive charges localized at the Al0.3Ga0.7A/Al0.2Ga0.8As interface in the tunneling barrier, as shown in the inset, d) independent tuning of the lifetime of the exciton and biexciton for 5 different dots by moving towards higher fields

The change in lifetime measured is high enough to already see a clear difference in the indistinguishability. There is however still room for improvement. One can see clearly that the change in lifetime is very strongly dependent on the chosen QD. Additionally, some experimental factors limited the ability to excite the QD via the two-photon absorption at even higher negative voltages, which would lead to a larger change in lifetime of the exciton, further increasing the achievable indistinguishability.

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9th international workshop on "Engineering of Quantum Emitter Properties"– Paderborn, Germany

On-demand Generation of Indistinguishable Photons in the Telecom C-Band using Quantum Dot Devices

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Semiconductor quantum dots (QDs) generate single and entangled photons for applications in quantum information and quantum communication [1]. While QDs emitting in the 780-950 nm spectral range feature close-to-ideal single-photon purity and indistinguishability, they are not the best choice in fiber networks, due to the high optical losses in this spectral range. Thus, QDs operating in the low-loss spectral window near 1550 nm (telecom C-band) are desirable.

In this work [2], we demonstrate the coherent on-demand generation of indistinguishable photons at telecom C-band wavelengths from single QD devices. The latter consist of InAs/InP QDs in mesa structures heterogeneously integrated on silicon [3]. Using pulsed two-photon resonant excitation (TPE) of the biexciton-exciton (XX-X) radiative cascade, we show for the first time, for this material system, pulsed Rabi rotations up to 4π yielding preparation fidelities > 80%, as also confirmed in independent cross-correlation experiments. Analyzing the radiative decay times, we find a 4-times faster decay of the biexciton compared to the exciton state. By performing pulsed Hong-Ou-Mandel experiments and comparing co- and cross-polarized coincidences in a 4 ns time window, we obtain a photon-indistinguishability of $V_{4ns} = 35(1)\%$ for XX photons, a record for this wavelength range.

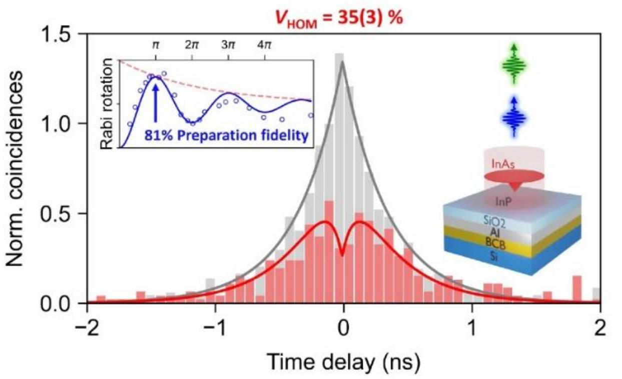

Figure 1: HOM measurement of two-photon-resonantly, coherently excited (left inset) an InAs/InP Quantum Dot device (right inset) emitting in the Telecom C-band.

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9th international workshop on "Engineering of Quantum Emitter Properties"– Paderborn, Germany

Towards fiber-pigtailed Quantum Dot Circular Bragg Grating Microcavities: Design & Deterministic Fabrication

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Hybrid circular Bragg gratings (hCBGs) have attracted much interest as photonic structures to enhance the performance of semiconductor quantum dot (QD) based quantum light sources due to significant Purcell enhanced emission rates and broadband coupling efficiencies into free space optics [1-3]. Additionally, hCBGs promise greatly enhanced performances of (directly) fiber-coupled "plug-and-play" QD based devices [4].

In this contribution, we present our recent progress in realizing a directly fiber-compatible hCBG device that enables electrical control of embedded QD emitters via a capacitor approach [5]. By using cathodoluminescence mapping combined with marker alignment, we realize consistent 100% integration yields of QDs into the hCBGs, which allows for benchmarking of spatial and spectral integration accuracy directly by the achieved Purcell enhancement. Finally, we show first results towards a high-performance, directly-fiber coupled hCBG device for "plug-and-play" generation of indistinguishable photons, enabling practical realizations of emerging quantum technologies requiring state-of the art quantum light performance.

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Spectroscopy of spin states in anisotropic droplet-etched GaAs QDs.

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Epitaxial QDs fabricated by infilling of in-situ droplet etched nanoholes have several advantages over QDs fabricated by the Stranski-Krastanov growth technique. In particular, the density and anisotropy of the dots can be determined by the choice of growth conditions for the first droplet deposition and etching step which is independent from the second, infilling, step which determines the emission wavelength. Relatively small droplets yield symmetric, shallow nanoholes that when completely infilled with GaAs result in dots with highly symmetric carrier wavefunctions and emission with small fine-structure-splitting. In contrast, deposition of larger droplets, due to droplet motion during the etching process, results in highly asymmetric nanoholes. When partially infilled, these dots have a broken Cs symmetry, resulting in brightening of the dark exciton emission (fig 1a) [1].

We have embedded these dots both in charge control diode structures (fig 1b) [2] and ridge waveguide structures [1,3]. We will discuss here the voltage control of the circular polarisation of the X^- state, and the use of resonant two-photon excitation to study the singlet-triplet states of the excited biexcitonic state, where the electron-hole pairs are in different energy levels of the dot (fig 1c) [3].

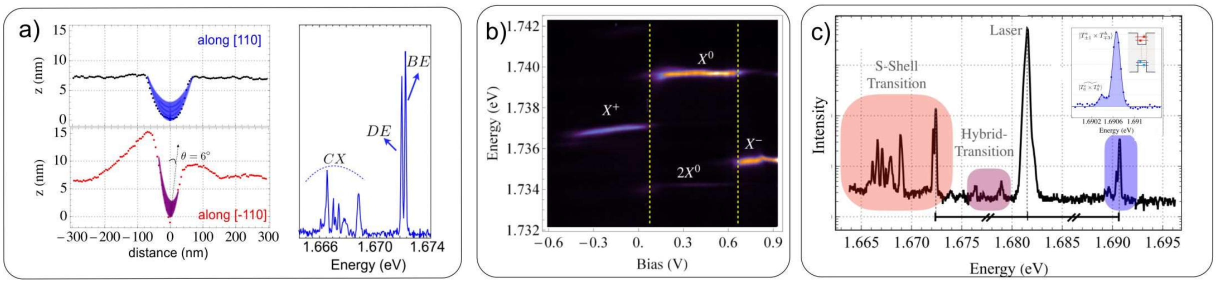

Figure 1: a) AFM line profiles along the [110] and [-110] directions of the original nanohole and after partial infilling showing the in-plane and out-of-plane asymmetry of the QD. Micro-PL showing brightening of the dark exciton [1]; b) charge control of a GaAs QD embedded in a schottky diode [2]; c) broad PL spectrum with the laser at the TPE resonance condition between the neutral exciton and the excited biexciton $s^1_e s^1_h p^2_e p^2_h$. Inset – zoom on the p-shell emission.

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Coherent dynamics of the swing-up excitation technique

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Finding a suitable excitation method for quantum two-level systems in the solid state is a widely investigated research area in quantum technologies. The challenge of combining (1) efficient filtering of quantum emission from residual excitation laser leakage, (2) spin- and polarization preservation and (3) coherence of the technique, as well as (4) good quality of the emitted photons has led to a variety of excitation methods. However, each of these schemes has specific disadvantages, such as being suitable only for specific level schemes or setup configurations. Recently, Bracht et al. proposed a promising technique based on two red-detuned excitation pulses which enable a high-fidelity swing-up effect of the population from the ground- to the excited state in a coherent manner [1], with successful experimental demonstration of its functionality by Karli et al. [2].

In this contribution, we extend the analysis of this method and explore the coherent dynamics of the swing-up technique with an InGaAs quantum dot [3]. We investigate the multidimensional parameter-space of the excitation to study their impact on the scheme and to find optimal conditions for high-fidelity population inversion, where we find several resonances and investigate the effects of the interdependence of the excitation parameters - both in experiments and numerical simulations.

Furthermore, we analyze the single-photon performance of our two-level system under swing-up excitation. We find near perfect single-photon purity with a raw value of $g^2_{\mathrm{swing,\ raw}}(0) = 0.033$. In contrast, the measured indistinguishability is limited to $v_{\mathrm{HOM,\ swing}} = 0.439$, which can be attributed mostly to the impact of the high laser intensities on the semiconductor environment of the quantum dot. Therefore, we conclude that the method is very promising, although further engineering is required to make it suitable for applications.

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9th international workshop on “Engineering of Quantum Emitter Properties”– Paderborn, Germany

Towards optically coherent color centers in diamond nanocavities

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Entanglement-based quantum networks have the potential to enable secure communication and distributed quantum computing over long distances. Such a network is composed of spin qubits which are interconnected by photon-mediated entanglement. The nitrogen-vacancy color center in diamond (NV) is an especially promising qubit candidate system thanks to its formidable spin coherence time. However, scalable quantum networks based on the NV continue to remain out of reach due to an insufficient yield of indistinguishable photons from the quantum emitter.

Functional diamond nanostructures offer a way to improve the performance of spin-photon interfaces. We recently proposed a novel ‘Sawfish’ nanocavity design with a fiber interface, for enhanced light-matter interaction and highly efficient photon collection [1]. However, especially in nanostructures, electric field fluctuations can broaden the NV photon emission spectrum and thereby reduce the entanglement success rate. Our recent work shows that it is possible to integrate NVs into nanostructures with strongly enhanced spectral stability up to optical coherence on the time scale of a second [2]. We explore if further stabilization is possible through a controlled preparation of the surface of etched diamond nanostructures, where a major part of charge noise is widely believed to originate from. Based on our findings, we propose entanglement schemes that can increase spin-photon entanglement rates by up to four orders of magnitude.

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SUPER in the Jaynes-Cummings Model

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The excitation of quantum emitters (QE) plays a huge role in quantum information technology. QEs can be easily excited using resonant pulses, yielding Rabi oscillations. This leads to difficulties distinguishing between the photons used to excite the QE and those emitted by it. To overcome this several off-resonant excitation schemes have recently been proposed. Among those is the Swing UP of quantum EmitteR (SUPER)-Scheme [1,2] using a pair of off-resonant pulses.

Here, we present a fully quantum mechanical description of the effect used in SUPER, by examining an extended Jaynes-Cummings model. We consider the coupling of two photon modes with different detunings to a two-level system with different detunings. Our model could be realized by a QE placed in a two-mode cavity. We show that specific resonance conditions yield occupations of the two-level system being close to unity. The dynamics display oscillatory behavior, as expected for SUPER. We discuss the conditions necessary to achieve a high inversion.

Our studies give new insight in the fundamental problem of the interaction of a two-level system strongly coupled to photon modes.

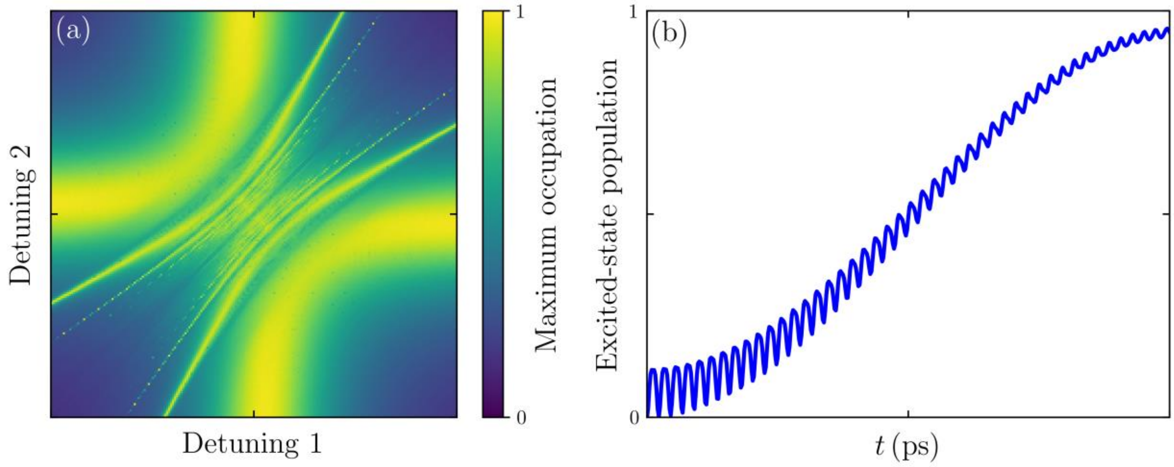

Figure 1: (a) Maximum occupation of the two-level system for different pairs of detuning. (b) Example dynamics of the excited state population for the off-resonant case.

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Correlation Functions describing Time-Bin Entangled Photons from Quantum Emitters with Metastable States

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For long-distance quantum communication, a source of entangled photon pairs is essential for the implementation and usage of quantum information protocols such as quantum teleportation and quantum key distribution. In time-bin entangled photon pairs, the photons are entangled with respect to the time-bin in which they are created. In this scenario, two time-bins named *early* and *late* correspond to the bits 0 or 1.
For the generation of these photon pairs, semiconductor quantum dots are our system of choice, as they provide on-demand generation of photon pairs with a high yield. Extensive effort has already been put into utilizing the biexciton-exciton cascade of a semiconductor quantum dot for the generation of polarization-entangled photon pairs. However, photons sent through optical fibers suffer from decoherence due to polarization mode dispersion, which results in a gradual loss of entanglement when polarization-entangled photon pairs are used. In contrast, time-bin entangled photons pairs are more robust in optical fibers.

Several proposals exist on how to create time-bin entangled photons from a quantum dot. Using a metastable dark-state that can be addressed using tilted magnetic fields [1], the entangled state can be deterministically prepared, allowing for the construction of an on-demand source for entanglement [2]. An experimentally simpler approach relies on probabilistic generation, using direct excitation of the biexciton state, addressing the biexciton in a two-photon resonant process [3].
Here, we present how the photon state can be extracted from numerical simulations of the optical excitation of the quantum dot using multi-time correlation functions, including the interaction with the phonon environment, i.e., the vibrations of the crystal lattice of the host material. We then use these tools to analyze both the deterministic and the probabilistic generation scheme, discussing their respective advantages and drawbacks.

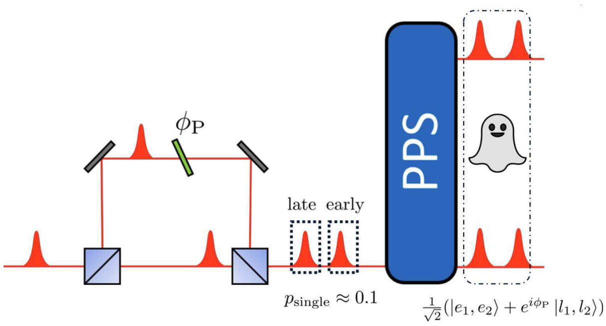

Fig. 1. Generation of time-bin entangled photon pairs using a photon-pair source (PPS) and an unbalanced Michelson-Interferometer, splitting the excitation pulse in the early and late time-bins.

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Integration of droplet-etched GaAs quantum dots in photonic integrated circuits as a source of highly indistinguishable photons

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Droplet-etched GaAs quantum dots (QDs) are a promising source of single and highly indistinguishable photons. A narrow wavelength distribution, short decay times, linewidths near to the Fourier limit and the resulting highly indistinguishable photons make them promising for several quantum technologies [1]. Therefore, integrating these QDs into photonic integrated circuits is highly appealing. We demonstrate the first integration of these QDs in photonic integrated circuits consisting out of single-mode waveguides and multi-mode interference splitters [2]. In this regard, we investigate the statistical distribution of wavelength, linewidth and decay times of the excitonic line of multiple QDs. Also, the quantum optical properties of individual emitters including the single-photon purity and indistinguishability of the emitted photons, shown in Figure 1, are discussed.

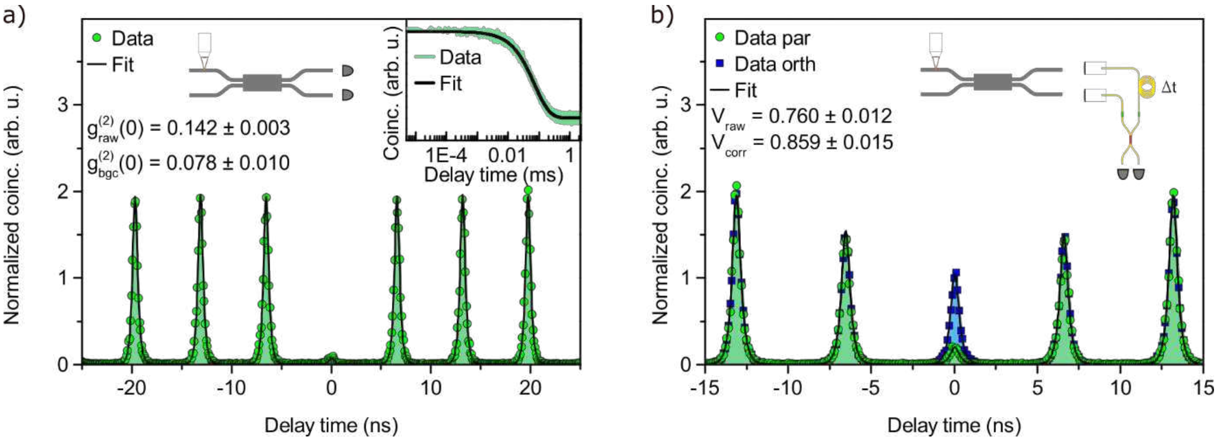

Figure 1: a) Second-order correlation measurement of the exciton under pulsed excitation using the on-chip beamsplitter. b) Hong-Ou-Mandel measurement of the exciton using the on-chip beamsplitter to divide the photon stream and a fiber-beamsplitter to let the photons interfere afterwards with each other [2].

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9th international workshop on "Engineering of Quantum Emitter Properties"– Paderborn, Germany

Single quantum emitters in silicon

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A future quantum internet could be used for fundamentally secure information exchange, distributed quantum computing, and possibly many other applications still unknown [1]. Color centers in silicon function as an interface between solid-state spin qubits and photons at telecom wavelengths [2]. This could allow us to combine the long coherence times of spin qubits with the connectivity of photons. Existing silicon photonics can enable the on-chip integration of these color centers in large numbers [3]. Direct emission in the telecom O-band allows for use of the fiber networks currently used for classical communication, along with having low loss over large distances [4]. This project is about identifying various color centers in silicon and exploring their properties and potential use in quantum technologies.

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