# On-Demand Flying Qubits Using Shaped Laser Pulses and Scalable Semiconductor Emitters

SUMMARY: High-performance single photon sources represent an enabling technology for a whole host of applications in quantum information science, including quantum networks and photonic quantum computers. Here we discuss made-in-Canada efforts to develop laser triggered, solid-state single photon sources, focusing on semiconductor-based approaches that offer the potential for commercial scale fabrication.
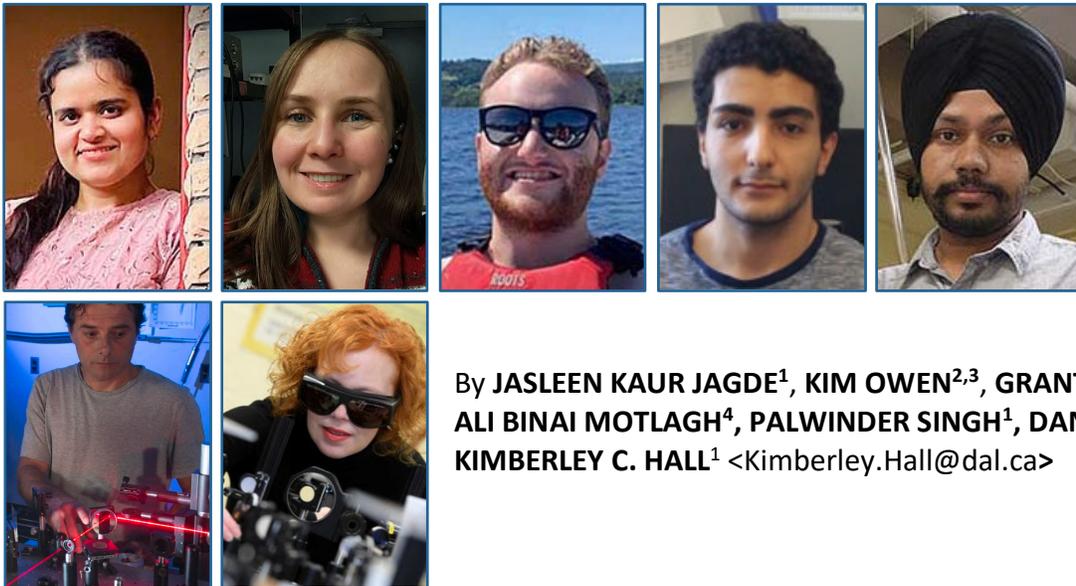
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A single photon can be used to encode quantum information (e.g. within the polarization state, time-bin or path), making it a powerful resource for applications within the field of quantum information science. On-demand single photons may be generated using atom-like transitions in a semiconductor material with confined electrons [1], combining deterministic operation, high brightness and low multiphoton probability. Such solid-state single photon sources (SPSs) may be applied to quantum key distribution for secure communication [2,3], photonic quantum computing [4], and would serve as flying qubits in quantum networks relaying information between quantum memories and simulators [5]. Due to the importance of these applications for a range of areas,

including finance, health and national security, considerable progress has been made in advancing the performance of solid-state SPS systems over the past decade [6].

Researchers at Dalhousie University and the National Research Council Canada (NRC) are pushing the envelope for the development of high-performance, on-demand SPSs based on semiconductor quantum dots (QDs) in nanowire waveguides [7] and strain-induced emitters in 2D semiconductors [8]. Due to their compatibility with semiconductor-based photonic fabrication infrastructure, both approaches offer the potential for commercial-scale fabrication. The Dalhousie group has developed laser triggering schemes for SPSs using laser pulse shaping to optimize the robustness of quantum state inversion and enable the simultaneous optimization of brightness and indistinguishability [9,10]. The NRC and Dalhousie groups are working together with the support of the NRC Quantum Sensors Challenge Program to implement these schemes on promising solid-state SPSs. This article will serve to highlight some of this work within the broader Canadian and international communities working on SPSs.

SCALABLE APPROACHES TO SINGLE PHOTON SOURCES

QUANTUM DOTS IN NANOWIRE WAVEGUIDES

Quantum dots are created within a semiconductor by confining electrons and holes to nanoscale dimensions in all three spatial directions, typically achieved through the potential step at the interface between two dissimilar semiconductors (e.g. InAsP inside of InP). Due to the resulting discrete energy level spectrum, the QD possesses a single, spectrally-isolated ground state optical transition. Following excitation of an electron-hole pair in the QD by a laser pulse, one and only one photon is emitted, resulting in a highly pure, on-demand SPS. III-V semiconductor QDs provide the current state-of-the-art for high-performance SPSs [1,6]. Traditionally, QDs are grown via strain-driven self-assembly and nucleate randomly on a semiconductor substrate, however this random positioning makes them unsuitable for large-scale integration into photonic devices. Researchers at NRC have developed a technique to produce QDs integrated within nanowire waveguides [11] (see Figs. 1(a), (b)) using vapour-liquid-solid (VLS) epitaxy [12]. Because the position of the nanowire is deterministically chosen, ordered arrays of nanowires may be produced, providing a scalable solution for QD SPSs. NRC's nanowire SPSs offer excellent single photon emission properties, including ultranarrow emission linewidths under 500 MHz [13], collection efficiencies above 80% [7], and a post-selected two-photon interference visibility over 80% [14]. The latter metric is indicative of a high degree of indistinguishability of successively emitted photons. Nanowire QDs also offer low second-order correlation ($g^{(2)}(0) < 1\%$ [7]), signifying robust antibunching, a key measure of single photon purity.

While promising, the above performance metrics are limited by the non-resonant laser excitation scheme used to trigger single photon emission. NRC and Dalhousie are currently working to apply new quantum control protocols developed by the Hall group on these quantum light sources to boost these metrics further, promising ideal, high performance SPSs. NRC is also working to integrate their nanowire SPSs into silicon nitride-based photonic integrated circuits (Fig. 1(d)-(f)). The NRC-Dalhousie
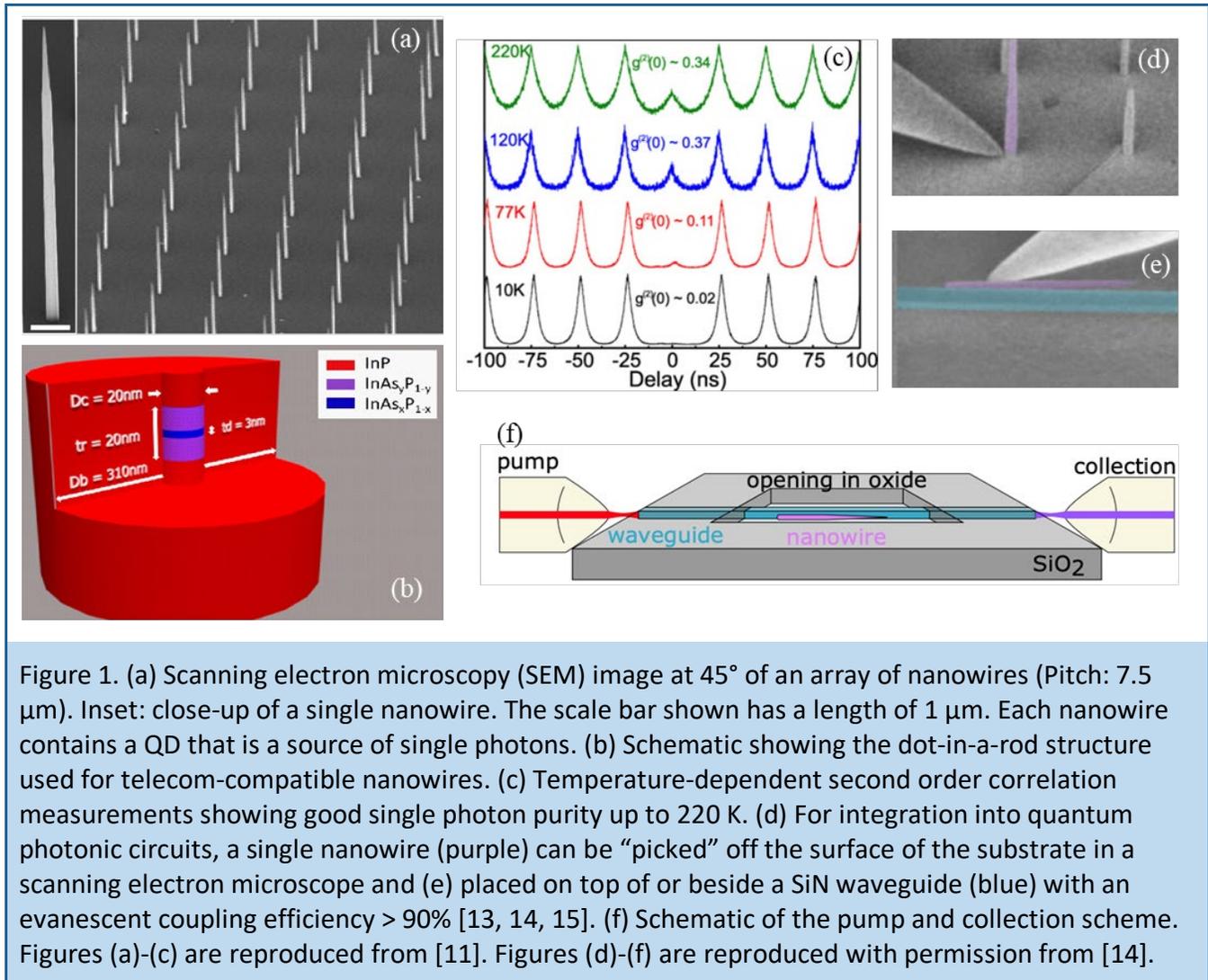
Figure 1. (a) Scanning electron microscopy (SEM) image at 45° of an array of nanowires (Pitch: 7.5 µm). Inset: close-up of a single nanowire. The scale bar shown has a length of 1 µm. Each nanowire contains a QD that is a source of single photons. (b) Schematic showing the dot-in-a-rod structure used for telecom-compatible nanowires. (c) Temperature-dependent second order correlation measurements showing good single photon purity up to 220 K. (d) For integration into quantum photonic circuits, a single nanowire (purple) can be "picked" off the surface of the substrate in a scanning electron microscope and (e) placed on top of or beside a SiN waveguide (blue) with an evanescent coupling efficiency > 90% [13, 14, 15]. (f) Schematic of the pump and collection scheme. Figures (a)-(c) are reproduced from [11]. Figures (d)-(f) are reproduced with permission from [14].

collaboration aims to implement the Hall group's laser triggering schemes in these integrated structures, providing a pathway to a comprehensive high-performance system for quantum photonics.

Emitters in 2D Transition-Metal Dichalogenides

Two-dimensional transition-metal dichalcogenides (TMDs), particularly in their monolayer (ML) and bilayer (BL) forms, have emerged as alternative candidates for solid-state SPSs [15]. These layered materials are composed of strong covalently bonded atomic planes held together by weak van der Waals forces, which enables the use of mechanical exfoliation to obtain pristine, atomically thin flakes from bulk crystals [16]. SPSs may be formed by inducing strain within the thin layer by transferring the exfoliated flakes onto pillars and other structures [17-20], creating an effective QD. Defects such as vacancies combine with strain-induced effects to further localize these states [20], resulting in bright SPSs exhibiting narrow emission peaks and long-term spectral stability [8]. TMDs offer a promising

alternative platform to III-V QDs because emitter site-selectivity and integration into photonic circuits is possible using conventional integrated photonic processing followed by the deposition of the ML or BL [8]. TMD SPSs also offer efficient light extraction without the need for a waveguide because the emitter is localized in the topmost layer, i.e. not embedded in a high index host where extraction is limited by total internal reflection.

The Dalhousie and NRC groups have been working to demonstrate site-selective quantum emitters in TMDs using a variety of engineered surfaces, including dielectric nanopillars (see Fig. 2(a), (b)) and the nanowire waveguides described in the preceding section oriented horizontally (Fig. 2(c)). Both structures exhibit bright, spectrally narrow emission lines and good photon purity (Fig. 2(d)-(f)), promising for the future implementation of TMD-based SPS systems. The Hall and NRC groups are working to investigate the nonlinear optical properties of these TMD emitters and to realize fully triggered SPSs using shaped laser pulses.
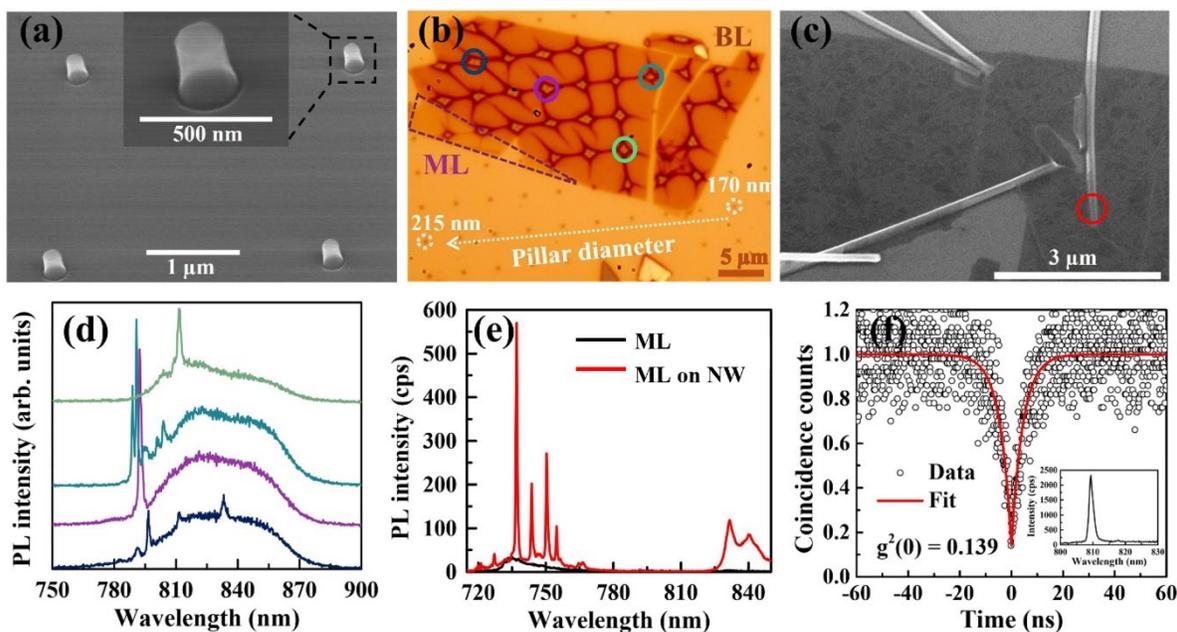

Figure 2. (a) SEM image of a SiO$_2$ nanopillar array (pitch: 3 μm, pillar height: 275 nm). The inset shows a single nanopillar at higher magnification. (b) Optical image of ML and BL WSe$_2$ transferred onto the SiO$_2$ nanopillar array (pitch ≈3.67μm). (c) SEM image of ML WSe$_2$ on InP nanowires. (d) Photoluminescence (PL) spectra obtained from a TMD BL on nanopillars marked with circles in (b). (e) Same as (d) for an unstrained WSe$_2$ ML and a strained ML on a nanowire in the area marked with a circle in (c). (f) Second-order autocorrelation measurement at 809 nm collected from the bilayer covered nanopillar indicated by the light green circle in (b). Open circles represent the raw data; the solid line is a fit showing g$^{(2)}$(0) = 0.139. The inset shows the 809 nm emission line. Figures (a), (b) and (f) are reproduced from [21].

Quantum Control for Laser Triggered Emitters

The parameters of the laser pulse used to excite the QD have a dramatic impact on the quality of the emitted stream of photons [9,22-27]. Optimized values for single photon purity and indistinguishability for a QD SPS occur when the ground state exciton in the QD is pumped directly. The use of resonant pumping necessitates the development of an effective approach to separate the emitted single photons from the scattered laser light since these occur at the same wavelength. The most common approach relies on polarization-based filtering [23], but the simplicity of this approach comes at the expense of a two-fold reduction in the collection efficiency. Such high losses have the consequence that the single photon source has low brightness and is no longer deterministic. These problems have led the quantum communication community away from pure SPSs and instead towards decoy state protocols employing attenuated coherent states.

To overcome this limitation, the Hall group recently developed a new scheme for triggering SPSs called Notch-Filtered Adiabatic Rapid Passage (NARP) [9]. It utilizes a chirped trigger pulse whose spectrum has a notch resonant with the ground state exciton transition in the QD (see Fig. 3). The NARP scheme builds upon existing adiabatic control protocols for single and multiple qubit systems developed by the Hall group [9,10,22,28]. Since the photon and the pump spectrum do not overlap, the pump can be spectrally filtered, allowing for near-unity collection efficiency limited only by the quality of the spectral filters used. With this advance, QD sources of pure single photons can become competitive with the decoy state methods**.** The NARP scheme is also robust to experimental fluctuations, unlike many competing schemes [23-26], making it suitable for field-deployed applications outside the laboratory setting. The Hall and NRC groups are working to demonstrate the NARP protocol on both TMD-based quantum emitters and nanowire QD SPSs.

Semiconductor Emitters Applied to Quantum Technology

On-demand SPSs are required for a whole host of applications in quantum technology, including quantum communication, simulation and metrology. With demonstrated photon indistinguishability of 99.5% [23] and single-photon purity as low as 8×10^{-5} [29], QDs have outpaced TMDs in technological maturity and considerable progress has been made in advancing QD-based SPSs for a range of applications. The nearest-term use case for these SPSs is the development of secure communication immune to classical eavesdropping [30]. QD based SPSs are starting to become competitive with conventional quantum key distribution (QKD) sources using attenuated coherent light, with large collection efficiencies enabling higher generated key rates [31]. A telecom-compatible QD SPS was recently used to generate secure keys in a QKD experiment, achieving communication over 175 km of fiber [32]. In Canada, the quantum cryptography satellite QEYSSat is expected to launch in 2026 and could ultimately rely on quantum dot SPSs [33]. Deterministic SPSs can also be applied to quantum computing using an all-photonic architecture [34-36]. Boson sampling using 20 pure single photons from a QD SPS, enough to enter the genuine sampling regime, was recently demonstrated [37]. In the area of quantum metrology, QD SPSs have been applied to intensity squeezing for sub-shot-noise measurements [38], the development of absolute calibration standards for single-photon detectors [39], and super-resolution phase measurements [40,41]. The foundational role played by SPSs in these
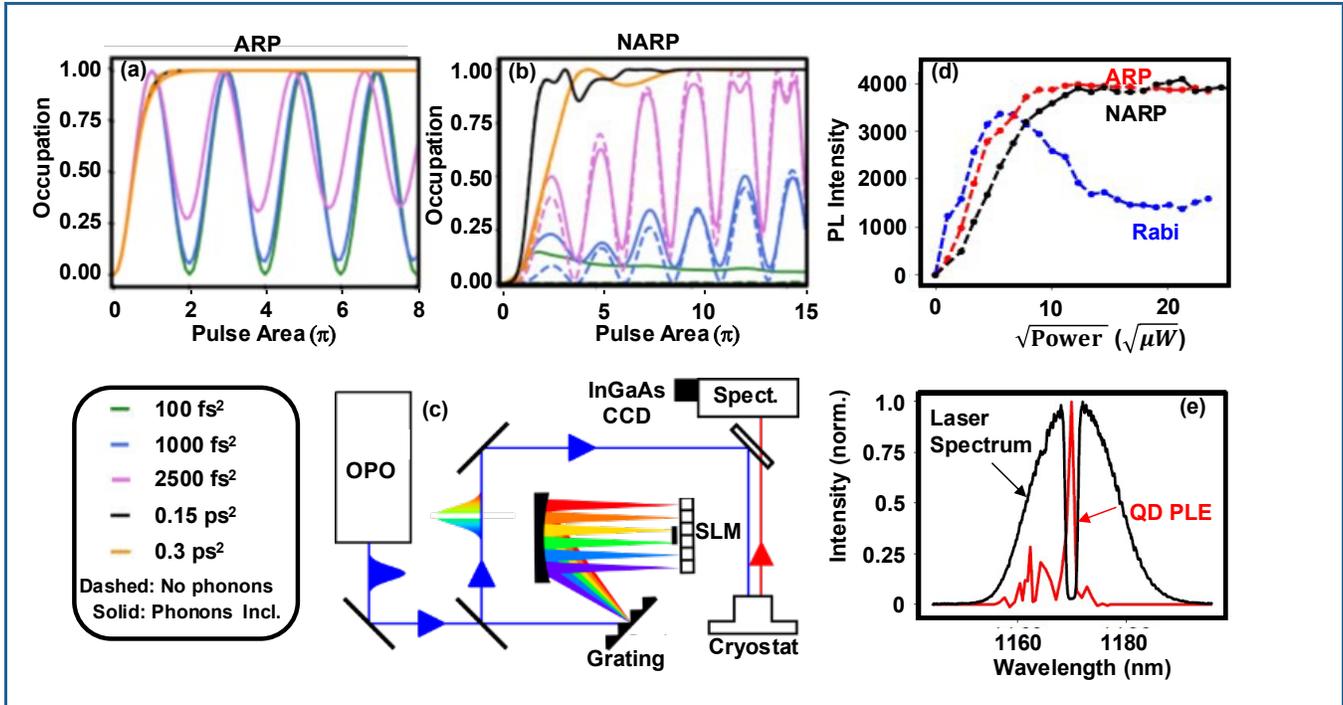
Figure 3. NARP scheme for triggering SPSs. (a) Results of calculations of the quantum state dynamics for optical driving of a single semiconductor QD with an unfiltered Gaussian laser pulse for different values of spectral chirp ϕ'', illustrating the transition from the Rabi rotation regime to the traditional adiabatic rapid passage (ARP) regime. (b) Same as (a) for NARP using a spectral hole pulse with $2\delta = 2.1$ meV. For chirps above the threshold for adiabatic state transfer (ϕ'' larger than 0.1 ps^2), the system inverts via ARP in (a) and NARP in (b). In (a) and (b), the solid (dashed) curves indicate the calculated state dynamics with (without) coupling to longitudinal acoustic phonons. (c) Schematic diagram of the quantum control apparatus. (d) Measured PL intensity from a single semiconductor QD versus pulse area for a Rabi rotation (blue symbols), traditional ARP (red symbols) and NARP (black symbols) applied to the p-shell transition. (e) Laser spectrum for the NARP pulse used for the experiments in (d) (black curve) together with the photoluminescence excitation (PLE) spectrum of the QD (red curve). Adapted from [9].

and other quantum technologies highlights the urgent need to develop scalable solid-state systems using a range of platforms, including the semiconductor-based SPSs being explored by the Dalhousie-NRC team.

CONCLUSION

The Dalhousie and NRC groups are making a key contribution to international efforts to develop high-performance SPSs based on solid-state platforms. By developing systems that offer compatibility with existing telecommunications and integrated photonic circuit technology, their research promises long-term scalable quantum photonic systems and will have knock-on benefits in many areas of quantum

technology where on-demand sources of quantum light are needed. This research will lead to world-leading, made-in-Canada solutions for on-demand sources of flying qubits.

Acknowledgements

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