Dynamic Emission Characteristics of Single-Photons and Photon Pairs from Color Centers Tuned by Thermally Induced Strain Fields

Dr. Frank D. Bello
School of Physics and CRANN
Trinity College Dublin
Dublin 2, Ireland
fbello@tcd.ie

Dr. Saeid Asgarnezhadzorgabad
School of Physics and CRANN
Trinity College Dublin
Dublin 2, Ireland
ASGARNES@tcd.ie

Dr. Zahra Jalali-mola
School of Physics and CRANN
Trinity College Dublin
Dublin 2, Ireland
JALALIMZ@tcd.ie

Dr. Daniel D. A. Clarke
School of Physics and CRANN
Trinity College Dublin
Dublin 2, Ireland
CLARKED5@tcd.ie

Prof. Ortwin Hess
School of Physics, CRANN, and Center for Advanced Materials and Bioengineering Research (AMBER)
Trinity College Dublin
Dublin 2, Ireland
Ortwin.Hess@tcd.ie

***Abstract*—Photonic quantum networks frequently demand a consistent and reliable source for generating single photons and entangled photon pairs, which function as quintessential encoders of quantum information. However, many experiments demonstrating quantum algorithms using photons have necessarily been performed at cryogenic temperatures (milli to a few Kelvin), in order to mitigate the adverse effects of temperature dephasing. Encouraged by the relatively long lifetimes of group-IV color centers, we show that subdiffracted heating produced by a near-field plasmonic transducer can control the resonant behavior of individual quantum emitters and, consequently, their emission. Our theoretical analysis establishes the ability to control antibunching and superbunching effects at elevated temperatures via highly manipulable, thermally-induced strain fields. Furthermore, our work raises encouraging prospects for the application of color centers in on-chip quantum photonics, while elevating technologies for solid-state quantum information processing towards ever higher temperatures.**

Keywords—single photon emission, near-field transducer, color center, quantum network

I. Introduction

Single photon sources have long been recognized as a fundamental resource for applications within photonic quantum technologies, quantum cryptography, and remote sensing to name but a few[1]. On-demand sources of single photons are therefore highly desired with numerous architectures, such as quantum dots, color centers, or atoms/molecules, capable of producing the required antibunching of light. In addition, these architectures have been shown to simultaneously emit photon pairs, also heavily used within photonic quantum technologies, which may be entangled in, for instance, path or time-bin degrees of freedom. Herein, we focus on the use of silicon vacancy centers (VCs), a type of color center, for the emission of single photons or photon pairs, demonstrating that the emission can be dynamically controlled by the strain field induced via near-field plasmonic heating. This advancement is crucial given the proposed use of color centers for quantum information processing at elevated temperatures. Given the relatively long lifetimes (> 6 ns) for optical transitions at the zero-phonon line (ZPL) of SiC color centers[2], we show that one can control emission on a time scale much shorter than is required for temperature-related dephasing to decohere the system at 20-70 K. Our research specifically focuses on negatively charged silicon VCs (V_{Si}^{-}) within 4H-SiC, in part, due to silicon carbide's substantive absorption coefficient suitable for heating control. Furthermore, resonant wavelengths of Si VCs within 4H-SiC lie within the near infrared range (~861 nm), making them applicable for multimode fiber communication systems. Plasmonic nanoheating is provided by a near-field transducer (NFT) under excitation from a laser, which is on resonance with the color centers' ZPL (c.f. Ref. [3] for details of the NFT). The NFT is able to raster above the 4H-SiC media and therefore maneuver accordingly above the VCs. This is vital to manipulate the heating in the vicinity of each VC, and hence control the tuning of energy levels via induced strain. Our model focuses on two VCs located within the near-field heated region of the 4H-SiC, where dynamic switching between single-photon emission and the emission of two simultaneous photons is possible depending on the extent of thermal-induced strain and concomitant energy-level tuning.

II. Results and Methods

We quantify the correlation properties of the light emitted from the VCs via calculation of the two-time, second-order correlation function at zero-time delay, $g^{(2)}(\tau = 0)$. This is equivalent to a measurement taken within a Hanbury-Brown-Twiss experiment for detecting antibunched or bunched light and defined as,

$$g^{(2)}(0) = \frac{\langle \rho \sigma_1^\dagger \sigma_2^\dagger \sigma_2 \sigma_1 \rangle}{\langle \rho \sigma_1^\dagger \sigma_1 \rangle \langle \rho \sigma_2^\dagger \sigma_2 \rangle}, \quad (1)$$

where ρ is the density matrix and $\sigma_i^\dagger$ (σ_i) represents the raising (lowering) operator for each emitter ($i = 1, 2$)[4]. The VCs are modelled using a bipartite 4-level system with $g^{(2)}(0)$ calculated via time-dependent density matrix theory. The Hamiltonian for our system is defined as,

$$H = \sum \hbar\omega_i \, \sigma_i^+ \sigma_i - 2S\hbar\omega_{ph} \langle n_{ph}(T) \rangle \sigma_i^+ \sigma_i + \hat{\mu} E_i (\sigma_i^+ + \sigma_i), \quad (2)$$

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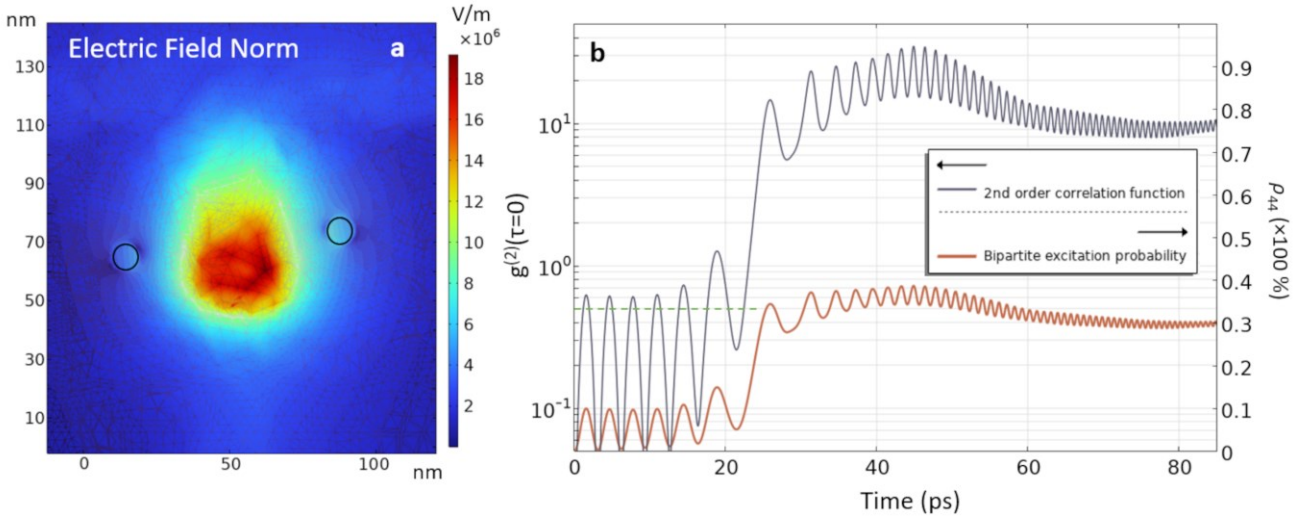

Fig. 1 (a) The incident plasmonic near field is shown, which excites and heats the silicon VCs that serve as the source of single photons or photon pairs (black outline). The electric near-field has previously been demonstrated to facilitate strong coupling with quantum emitters of comparable transition dipole moments (2-5 D)[3]. Finite-element methods (FEM) are used to simulate the system with the conformal mesh superimposed semi-transparently. (b) The second order correlation at zero-time delay along with the probability to excite the bipartite state (ρ_{44}) is presented. Initially, the VCs are slightly detuned from resonance allowing for single-photon emission, with values of $g^{(2)}(0) < 0.5$ predicted (dashed line). As the VCs are brought into resonance, circa 25 ps, via the thermally induced strain field, simultaneous emission from both emitters is predicted with calculated superbunching shown $g^{(2)}(0) > 2$.

where ω_i is the frequency of the zero-phonon line, often designated as V1 and found near 861.5 nm for V_{Si}^- centers located at hexagonal sites in 4H-SiC. It is at this wavelength where single-photon emission or the emission of simultaneous photons is anticipated. S (= 2.8) is the material dependent Huang-Rhys factor and $\langle n_{ph} \rangle$ is the average phonon number with corresponding frequency $\omega_{ph} =$ 17 THz. We assume the lattice deformation, i.e. strain, is induced primarily along the axial direction of the SiC crystal, which thus causes a shift to the ZPL energies of each VC, allowing one to tune their energies with the applied nanoheating. T is the temperature calculated from the thermal diffusion equation and $\hat{\mu}$ is the transition dipole moment, considered to be identical for each VC. A multiscale physics approach is employed which leverages 3D finite element time domain simulations[5] to elucidate the dynamics, solving for the time-dependent local electric field and induced polarization of each color center ($\mathbf{P} = \langle \mathbf{p} \rangle = \eta \mathrm{Tr}(\hat{\mu}\hat{\rho})$) via Maxwell's equations along with the thermal diffusion equation simultaneously. The electric field and temperature are then coupled to the semi-classical master equation for the density matrix in each time step.

Our results are shown in Fig. 1, where temporal values of $g^{(2)}(0)$ are calculated showing excellent antibunching, with dominant single-photon emission ($g^{(2)}(0) < 0.5$) when heating from the plasmonic field is initiated. Here, both VCs initially have equal probability amplitudes where the presence of a finite detuning between the color centers and field (inevitable in practice) is exploited; as such, bipartite excitation is suppressed ($\rho_{44} < 0.1$) as well as coherence between the ground and bipartite levels ($|\rho_{14}| < 0.05$). As heating in the vicinity of each VC continues, they eventually become resonant with the driving field allowing for more effectual emission of photon pairs. In this scenario, the autocorrelation function assumes values for $g^{(2)}(0)$ well above 2, implying superbunching. Such systems have shown promise for superradiance and its reciprocal characteristic, superabsorption, which we plan to investigate for the two-emitter system explored herein, together with photon entanglement at elevated temperatures. Whilst temperature dephasing effects overwhelmingly decohere the system above 80 K, our work seeds a novel approach to generating and controlling quantum photonic signals under experimental temperatures of tens of Kelvin, thereby greatly reducing the cryogenic constraints on current photonic quantum technologies.

To conclude, we present a robust method for producing single photons and photon pairs at elevated temperatures, harnessing native V_{Si}^- color centers in SiC. This is done by manipulating the strain fields produced by plasmonic nanoheating, enabling control over relative energy level detunings and resonant interactions. Our method establishes the possibility of reducing experimental constraints and could be extended to the production of photonic cluster states at higher temperatures. Furthermore, the prospect of superradiance and superabsorption in SiC color centers is promising for advancements in quantum solar energy harvesting and photovoltaic technologies.

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