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Invited Paper

Quantum Meta-Photonics

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ABSTRACT

Photons play a crucial role in quantum applications due to their ability to encode quantum information in various degrees of freedom and transmit it at the speed of light. The quantum states of photons are exceptionally robust against decoherence since photons interact relatively weakly with matter. However, this weak light-matter interaction also limits the rate of quantum photonic operations such as single photon generation or photon-photon interactions. Plasmonic metamaterials can improve light-matter interaction and dramatically speed up quantum photonic processes. In this work, we give an overview of our research efforts regarding the application of plasmonics for spontaneous emission enhancement to enable high-speed bright quantum emitters. The ultimate goal is to enhance the spontaneous emission rate beyond the dephasing rate typical for solid-state quantum emitters at cryo-free temperatures. This would enable the generation of indistinguishable photons without the need of a cryostat. We report on the engineering of solid-state quantum emitters in material platforms such as hexagonal boron nitride and silicon nitride suitable for coupling with plasmonic metamaterials and integrated quantum photonics.

Keywords: Photonics, Quantum information, Single-photon Emitters, Spin-defects, Plasmonics, Metamaterials, Quantum Integrated Photonics, Silicon Nitride, Hexagonal Boron Nitride

1. INTRODUCTION

Photons are indispensable resources for the encoding and secure communication of quantum information. They have found applications in emerging quantum sensing approaches and in the realization of qubits for quantum computing. Recently, impressive results in satellite-based quantum communication as well as quantum computational advantage using photons were demonstrated[1,2]. The weak interactions of photons with matter makes them highly immune to decoherence processes, but also results in the probabilistic nature of most quantum operations, such as the generation of single photons, manipulation of the quantum states of light, and detection. The weak light-matter interaction slows down the success rate of quantum photonic operations. Optical resonators can substantially enhance light-matter interaction, with the enhancement controlled by the Purcell factor, which is proportional to the quality factor Q of the resonator and inversely proportional to the electromagnetic mode volume V. Dielectric optical cavities may have very high quality factors Q; however this results in a slow rate of operation because the higher Q, the slower the response. In contrast, plasmonic cavities with relatively low Q, can have very high rate of operation and in parallel strong enhancement of light-matter coupling because of the exceptionally strong confinement of electromagnetic modes, with volumes V down to the nm-scale. Thus, plasmonic cavities, while enabling as strong enhancement of light matter-coupling as dielectric cavities, can operate at much higher speeds. Importantly, the plasmonic speed-up of quantum photonic processes, such as the spontaneous emission of solid-state quantum emitters, can enable high-speed sources of indistinguishable photons. Quantum emitters typically operate at cryogenic temperatures to suppress decoherence processes responsible for diminishing the indistinguishability of photons. Such emitters typically have low intrinsic spontaneous emission rate (< 1 GHz). Resonant plasmonic nanostructures can offer giant local field enhancement and thus enable the generation of single photons from quantum emitters with high repetition rates outperforming traditional dielectric photonic resonators[3,4]. It was

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predicted that plasmonic cavities may enable an emission rate speed-up into the THz regime[3,5], which is comparable to the decoherence rate of most solid-state emitters at non-cryogenic temperatures. Such single-photon emission rates might be sufficient to overcome quantum decoherence and allow for the generation of indistinguishable photons outside of a cryostat (Fig.1a).[6]

In our previous work, we demonstrated record-bright room temperature single-photon emitters (SPE) with lifetime shortenings of more than 3 orders of magnitude using plasmonics[5,7]. We used a nitrogen vacancy (NV) center in nanodiamonds coupled to low-loss nano-patch antenna (NPA) plasmonic nanocavity. While the coherence time of NV centers is extremely short, using other single-photon sources such as germanium or silicon vacancies in diamond or SPEs in hexagonal boron nitride (hBN) may enable the generation of indistinguishable photons at cryo-free temperatures. In the current work, we applied low-loss NPA plasmonic nanocavities to enhance the brightness of spin-defects in hBN consisting of negatively charged boron vacancy (V_B^-), which has great potential for use in quantum sensing (Fig.1b).[8]

In addition to speed-up of spontaneous emission for generation of indistinguishable photons at high repetition rate, on-chip integration of quantum emitters is a major necessity for enabling practical and scalable quantum photonic technologies[9,10]. Here, we report on engineering of solid-state SPEs in various material platforms suitable for integration with quantum photonic circuitry. We demonstrated high yield site-controlled creation of single-photon emitters in hBN by nanoindentation with an atomic force microscopy (AFM) probe[11]. Also, we recently discovered the formation of intrinsic SPEs in low-autofluorescence SiN films[12]. The high brightness and single-photon purity of these emitters even at room temperature combined with capability of monolithic integration with SiN photonics[13] make them particularly attractive for quantum applications (Fig.1c). We outline our results of integration of these emitters with SiN waveguides and the temperature-dependent study of their properties. The photophysics of these single-photon emitters in hBN and SiN, their potential applications, and optimization approach using plasmonics is discussed.

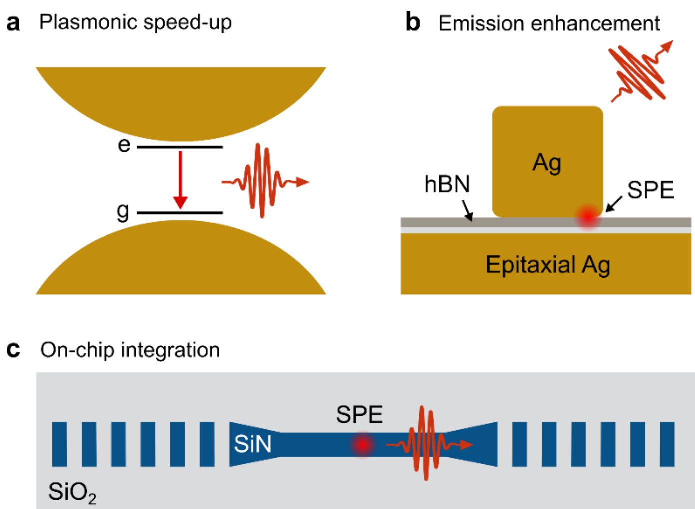

Figure 1. (a) Light-matter interaction enhancement with plasmonics – toward faster operation. (b) Enhancement of emission from spin-defects in 2D hBN using the plasmonic nanocavity. (c) Engineering of single-photon emitters in material platforms for quantum integrated photonics.

2. SPEED-UP OF QUANTUM PHOTONICS WITH PLASMONIC METAMATERIALS

The negatively charged boron vacancy (V_B^-) centers in hBN have received increasing attention in recent years as optically active spin defects[14]. The atomic scale thickness of few-layer hBN allows for the placement of such spin defects within nanometers range of the object of study, potentially enabling advanced nanoscale sensing. However, V_B^- centers exhibit low quantum efficiency, which is a critical parameter limiting their sensitivity as sensors. In our work, we demonstrated photoluminescence enhancement from V_B^- spin defects of more than 3 orders of magnitude by coupling these emitters to a resonant nanoplasmonic cavity[8]. We realized the plasmonic resonator in the nano-patch antenna (NPA) configuration consisting of exceptionally low-loss epitaxial silver films and single-crystalline silver nanocubes. The substantial enhancement of the emission was achieved by carefully optimizing the hBN flake thickness and the V_B^- defect implantation depth. Importantly, we found that the optically detected magnetic resonance contrast of V_B^- centers was preserved under such enhancement in the plasmonic environment. The NPA-enhanced V_B^- defects address the low quantum efficiency limitations, making them particularly promising for quantum sensing applications. Moreover, the strategy of coupling to low-loss resonant nanoplasmonic cavities can be also applied for isolating single V_B^- defects, which has not been realized so far.

3. SINGLE-PHOTON EMITTERS FOR INTEGRATED QUANTUM PHOTONICS

3.1 Site-controlled creation of single-photon emitters hBN

Two-dimensional hexagonal boron nitride (hBN) hosts various bright room-temperature single-photon emitters, which have been studied extensively and attracted particular interest from the quantum photonic community.[15] The atomic-scale thickness of hBN enables high-efficiency light extraction and offers unparalleled advantages for integration with quantum photonic circuitry. The practical realization of on-chip integrated SPEs in 2D materials requires on-demand and site-controlled creation of emitters. Significant research effort was devoted to development of such techniques allowing for engineering SPEs in hBN with a certain degree of spatial control.[16] In our work, we developed a novel technique to deterministically activate room-temperature hBN SPEs by nanoindenting hBN with an atomic force microscopy (AFM) probe.[11] The method is demonstrated for hBN flakes exfoliated onto flat SiO_2-coated silicon substrates. AFM probes with diamond-like carbon coatings are used to induce sub-micron scale indents in hBN. Bright quantum emitters are then activated by thermal annealing at the indented positions. Both SPEs and clustered emitters are identified at the indent locations. The yield of SPE formation per spot is ~ 30% for multiple indent sizes, with a maximum of 36% for indents around 400 nm. The efficient creation of hBN SPEs on chip-compatible substrates with high spatial precision paves the way toward the controlled coupling of hBN emitters with quantum photonic circuitry.

3.2 Intrinsic single-photon emitters in Silicon Nitride

We recently discovered the formation of intrinsic single-photon emitters in low-autofluorescence SiN films[12]. These emitters were found to exhibit high brightness and single-photon purity even at room-temperature operation. The substantial reduction of SiN background fluorescence was achieved by growing nitrogen-rich films, which allowed these SPEs to be revealed. The emitters were created by subsequent thermal annealing of as-grown SiN films. We also found that these emitters can be created by both rapid thermal annealing as well as annealing in a conventional furnace. The room-temperature photoluminescence spectra are broad and consist of emission peaks which cluster around specific wavelengths. These peaks were tentatively assigned to the phonon sidebands, while their appearance at similar wavelengths suggests that the emission originates from the same type of defect center. In our most recent work, we studied the photophysics of these emitters at cryogenic temperatures. We found the emergence of narrow zero-phonon lines (ZPL) at low temperatures on top of the broad spectrum observed at room temperature. Also, narrow peaks at longer wavelengths were observed, which we tentatively assign to vibronic states. Inhomogeneous and temperature-dependent homogeneous broadening of the ZPLs from 4.2 – 300K was studied. We found that the main broadening mechanism at 4.2K is spectral diffusion, which exhibits dependence on the excitation power. Time-resolved photoluminescence spectroscopy allowed us to resolve individual emission peaks with instrument-limited linewidth. Pursuing on-chip integration, we demonstrated the first realization of SiN waveguides containing intrinsic quantum emitters and coupling of single-photon emission to the waveguide mode[13]. These emitters were found to survive all the fabrication procedures utilized.

Moreover, we have demonstrated the first site-controlled fabrication process for SiN single-photon emitters[17,18]. By nanostructuring SiN/SiO_2 pillars using electron beam lithography (e-beam) and reactive ion etching (RIE) followed by rapid thermal annealing it was found that SiN single photon emitters are created in the nanopillars with high yield. Additionally, preliminary analysis indicates a site-controlled placement accuracy of less than ~±30nm. Preliminary yield measurements show that ~66% of the nanopillars contain single photon emitters. This yield far exceeds the typical poissonian limit for stochastically integrated emitters hinting that this process is deterministic in addition to being site controlled. The ultimate goal of our work is to enable scalable, technology-ready quantum photonic integrated circuitry efficiently interfaced with solid-state quantum emitters.

4. OUTLOOK

Plasmonic metamaterials hold great promise for applications in quantum photonics. They offer the dramatic enhancement of single photon emission from solid-state quantum emitters. The dramatic speed-up of the spontaneous emission may also allow quantum decoherence to be overcome and the generation of indistinguishable photons even outside of cryostats. The mitigation of losses in plasmonic metamaterials is the subject of further research to harness their full potential for applications in the quantum domain. Our focus is on development of solid-state single-photon emitters in material platforms supporting integration with plasmonic metamaterials and quantum integrated photonic circuitry. In this regard, we will explore applicability of different types of quantum emitters including symmetric germanium and silicon vacancy centers in diamond, optically-addressable spin-defects in hBN, and intrinsic emitters in SiN.

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