Cavity Quantum Electrodynamics based on Lifetime-Limited Emission in Hexagonal Boron Nitride

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***Abstract*—The coherent interaction between quantum emitters and photonic cavity mode is of utmost importance in quantum science and technology. This study explores the cavity quantum electrodynamics on an emerging quantum material platform, hexagonal boron nitride, that exhibits lifetime-limited single-photon emission at room temperature.**

Keywords*— *hexagonal boron nitride, single-photon quantum emitters, photonic cavities, quantum electrodynamics

I. Introduction

Thanks to the advances in materials science and nanotechnology, a proliferation of quantum entities in solid-state platforms has been witnessed over the past two decades [1,2]. Among them, optically active defect centers in wide-bandgap (WBG) materials, such as diamond and silicon carbide (SiC), have attracted significant attention [3,4], which can be treated as "inverted atoms"—atomic impurities in otherwise perfect crystals associated with quantized optical transitions. The WBG attributes encompassing excellent electronic isolation and thermal and chemical stability promise robust single photon emission and exceptional spin coherence even at room temperature. The wide bandgaps also endorse wide transparent windows from visible to near-infrared, which are desirable for photonic cavities. Hence, these WBG materials offer unique monolithic platforms to explore cavity-emitter coupling and quantum electrodynamics (C-QED).

This work focuses on an emerging quantum photonic material, hexagonal boron nitride (h-BN), a two-dimensional (2D) van der Waals (vdW) layered crystal, which has been primarily employed as atomically smooth gate dielectric and encapsulation layers in 2D nanoelectronics and the structural material in 2D nano-/micro-electromechanical systems (N/MEMS). Distinct from the early hallmarks of 2D materials, semi-metallic graphene (bandgap of 0 eV) and semiconducting molybdenum disulfide (MoS_2, bandgap of 1.9 eV), h-BN possesses an ultrawide bandgap of 5.9 eV. The ultrawide bandgap characteristics have been demonstrated beneficial to hosting photostable and ultra-bright single-photon quantum emitters (QEs) with large emission rates ($>10^6$ counts/s) [5], strong zero-phonon emission (Debye-Waller factor ~0.8), and high quantum efficiency (~87%) [6]. Especially, the defect centers with single-photon emission around 635 nm have been demonstrated to exhibit lifetime-limited linewidth even at room temperature. This work systematically investigates the monolithic integration of this type of h-BN emitters with the whispering gallery mode (WGM) in the microdisk cavity. By optimizing the cavity design, strong coupling between the emitter and cavity has been predicted analytically. Furthermore, coherent manipulation of photons based on cavity-emitter detuning, and spatial position of emitter has been explored and visualized as vacuum Rabi splitting and Rabi oscillation through the Quantum toolbox in Python (QuTiP) simulation. The robust cavity design and methodology developed will provide valuable guidelines for the realization of scalable and integrated quantum photonic circuits based on h-BN defect centers.

II. Photonic Cavity Design

Toward the realization of quantum functionalities based on quantum emitters, efficient coupling to high-quality photonic cavities that can direct emission into a single spatial/spectral mode and enhance the emission rate with unit efficiency is requisite. In the absence of a cavity, the excited state of a two-

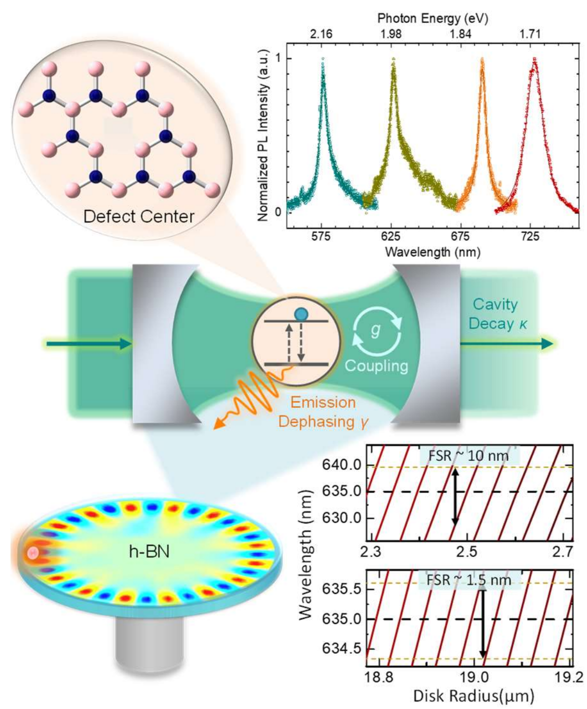

Fig. 1. Schematic illustration of a cavity-emitter coupled system consisting of an h-BN microdisk cavity and embedded defect center, which can serve as an intriguing platform for exploring the quantum light-matter interactions.

level system decays into free space with the emission of a photon. The emission of photons, in this case, would be non-steady with the emission at a random temporal profile. With cavity coupling, if the outcoupling rate of a cavity at a certain propagating mode is greater than the cavity loss, the efficiency of the photon source could be improved.

A cavity-emitter coupled system built upon the defect center embedded within the h-BN microdisk (Fig. 1) is proposed in this study. The whispering-gallery nature of the microdisk cavity can elegantly resolve the challenges in aligning the QE with the cavity mode spatially and spectrally, of which cavity resonance can be flexibly engineered by tuning the radial and azimuthal mode indices. The tunability of cavity resonance is exemplified in Fig. 1 for two disk radius ranges. The mode spacing is larger for the smaller disk than for the larger disk, shown as the plot of free spectral range (FSR). The FSR decreases from 10 nm (~8000 GHz) to 1.5 nm (~ 900 GHz) when the disk radius is changed from ~ 2.5 μm to ~ 19 μm. The denser mode allows easier tuning of cavity resonance with the emitter with different approaches. However, if the FSR is too small, the emitter might interact with a large number of modes, resulting in irreversible spontaneous emission in a weak coupling regime.

III. Cavity Quantum Electrodynamics Analysis

Considering a cavity-emitter coupled system in a good emitter regime, the time evolution of the system in a strong coupling regime is shown in Fig. 2. The quantum dynamical simulation was performed by solving the master equation in the quantum toolbox in Python (QuTiP) []. The coherent exchange of energy between the cavity and emitter is visualized as Rabi oscillation. The Rabi oscillation observed with time-resolved measurement is equivalent to the Rabi splitting observed spectroscopically. Spectral splitting and anti-crossing behavior at resonance indicate vacuum Rabi splitting is the signature of strong coherent cavity emitter interaction.

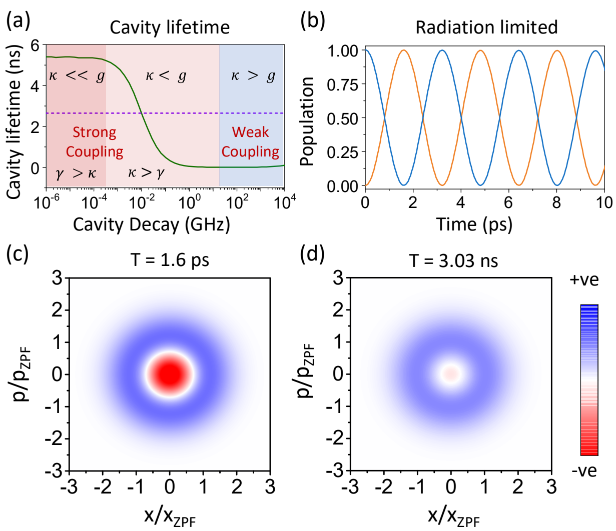

Fig. 2. Cavity quantum electrodynamics description of cavity emitter coupling in h-BN. (a) Photon lifetime inside the cavity as a function of cavity decay in strong (g> γ,κ) and weak coupling (g< γ,κ) regimes. (b) Rabi oscillation with radiation-limited cavity decay for the microdisk cavity. Cavity Wigner function/Wigner quasiprobability distribution at (c) T ~ 1.6 ps and (d) T ~ 3 ns indicating the coherence for the cavity, which is limited by the radiation limited quality factor.

The maximum decay rate an emitter can achieve for the strong coupling regime is $(\frac{\kappa+\gamma}{2})$, where κ is the cavity decay rate and γ is the spontaneous emission dephasing rate. For a good cavity ($\kappa \ll \gamma$), the maximum decay rate would be $\gamma/2$ (30.05 MHz for the lifetime-limited QEs at 635 nm) [6], corresponding to a cavity photon lifetime of 5.3 ns. Meanwhile, as there is a coherent exchange of energy between the cavity and emitter before the photon escapes the system, the photon lifetime inside the cavity can be determined quantitively when the mean photon number reaches a value equivalent to 1/e. The plot for the average photon lifetime inside the cavity as a function of cavity decay is demonstrated in Fig. 2a. The increase in photon lifetime inside the cavity would mitigate the decoherence effects and allows the system to exhibit quantum coherent oscillations as shown in Fig. 2b. The cavity reaches a state close to the single photon state just after the exchange of energy with the emitter at 1.6 ps as demonstrated with the Wigner map in Fig. 2c, which is negative close to the origin in phase space. The decoherence could be visualized from the Wigner map as well, which maintains the non-classical state for a longer time up to 3 ns when the radiation-limited quality factor is considered, as shown in Fig. 2d.

IV. Conclusion

Synergizing numerical simulations and C-QED analysis, we explored the cavity-emitter coupled system based on a microdisk cavity and the lifetime-limited quantum emitter in the monolithic h-BN platform. The methodology developed for investigating the coherent quantum interactions between the cavity and the two-level emitter could be extended to other defect centers and provide valuable guidelines for realizing integrated quantum photonic circuits.

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