PhC cavities for the development of a Germanium Vacancy-based spin-photon interface

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We study the coupling between germanium vacancy centers (GeV^-) in diamond and a one-dimensional photonic crystal (PhC) cavity. In such a system, the high values of the Q/V ratio featured by the cavity modes leads to an enhancement of the light-matter interaction of the GeV^- centers, enabling new functionalities such as deterministic generation of single photons, long-distance entanglement distribution or long-term storage of photonic qubits, among others. We compare two different device architectures: freestanding diamond PhC cavities and GaP PhC cavities evanescently coupled to a diamond substrate. In both cases, the cavity mode is formed by adiabatically increasing the cavity period from a central region where light is confined to the mirror region where light is reflected. We find that despite the lower refractive index, diamond-based cavities exhibit lower modal volumes than GaP-based cavities. This finding, when combined with the fact that in diamond-based cavities the GeV^-centers are closer to the mode maximum, makes them a better candidate over the GaP-based devices.

Introduction

Over the past two decades color centers in diamond have drawn the attention of researchers for their potential applications as solid state qubits and their role in the development of quantum technologies thanks to their outstanding optical and spin properties [1, 2]. When color centers are integrated with nanophotonic structures, their light-matter interactions are enhanced leading to new functionalities that can further extend their potential applications [1, 2]. In consequence, several integration approaches combining color centers with nanophotonic structures such as waveguides or nanocavities have been widely studied [1, 2, 3, 4, 5].
Here, we study the coupling between negatively charged germanium-vacancy (GeV^-) centers and one-dimensional photonic crystal (PhC) cavities. GeV^- were chosen over the more commonly studied NV centers due to the stronger and less sensitive zero phonon line that group IV-vacancies exhibit [2]. Additionally, GeV^- were chosen over other group IV color centers because of their moderate zero level splitting of $\sim$150 GHz, which is a middle ground when both the qubit operation temperature and the availability of the RF source required to control the qubit state are taken into account [2].
Two different device architectures were studied: freestanding diamond PhC cavities (Fig 1 a) and GaP PhC cavities evanescently coupled to color centers located in a diamond substrate (Fig 1 b). Due to the evanescent nature of the coupling in GaP-based devices, it is expected that they exhibit lower coupling rates than freestanding diamond cavities. However, the possibility of avoiding the complex diamond nanofabrication processes required for the diamond patterning has already motivated some works exploring hybrid device architectures similar to the ones considered in the present work [3].

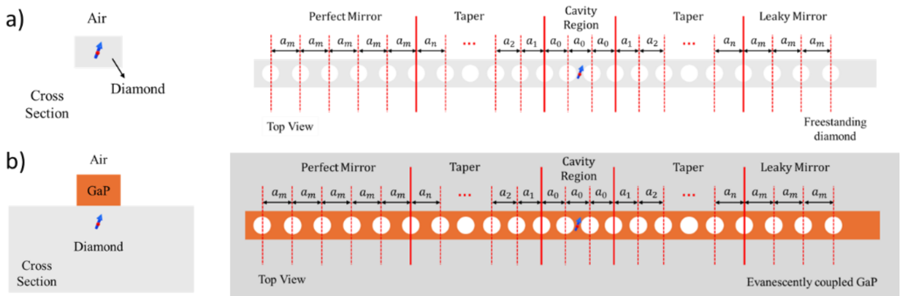

Fig 1. Sketch of the two architectures considered: (a) freestanding diamond PhC cavities and (b) GaP PhC cavities deposited on top of a diamond substrate with GeV^- centers placed close to its surface.

Dynamics of the GeV^--cavity system

The system considered for this work is formed by a single GeV^- and a one-sided open optical cavity. Under the electric-dipolar approximation, all the interactions occurring in the system are summarized in Fig 2 a, and the dynamics of the system can be described in terms of the Jaynes-Cummings Hamiltonian with the addition of the coupling terms between the cavity and the emitter to the radiation modes [3]. In this figure, γ is the decay rate of the emitter into the radiation modes, κ_r and κ_w are the decay rates of the cavity into the radiation and waveguide modes respectively and g is the coupling rate between the cavity and the GeV^-.

In open cavities γ does not differ substantially from the decay rate in a bulk medium (γ_0) [3] and provided that the cavity has sufficient taper holes, the cavity decay rate will be limited by the scattering losses associated with fabrication imperfections [4]. Therefore, the only free cavity QED parameter left to be optimized is g, whose value can be calculated through the following expression [3]:

$$g = \cos(\theta)\frac{1}{4\pi}\frac{E_c^d}{E_c^m}\sqrt{\frac{3\gamma_0\omega_d}{V\left(\frac{n_d}{\lambda_d}\right)^3}}\frac{n_d}{n_m}, \qquad 1$$

where θ is the angle between the electric field and the transition dipole moment, ω_d is the frequency of the emitter, E_c^d and E_c^m are the electric field amplitudes at the emitter position and at the cavity maximum respectively and, finally, n_d and n_m are the refractive indices evaluated also at the emitter position and at the cavity maximum respectively.

Two important effects that emerge from the dipole-cavity coupling are the Purcell effect and the dipole induced transparency (DIT) [2, 6]. The Purcell effect is an enhancement in the spontaneous emission decay rate and can be used to obtain on chip single photon sources [1, 2]. On the other hand, the DIT is an effect that creates an additional dipole-assisted transmission channel into the cavity [6] that can lead into a spin-dependent cavity reflectivity that can be used to build quantum gates and perform non-destructive optical readouts of the qubits [7, 8].

Design principle and simulation results

The simulations required for the PhC cavity design process were conducted using the software "Ansys Lumerical FDTD". In order to design cavities capable of supporting high Q/V modes, the hole-to hole distance along the cavity is varied following the procedure known as gentle confinement [9]. As it is shown in Fig 1, in both architectures the PhC cavity is formed by three distinguished regions: the mirror, the taper and the cavity region.

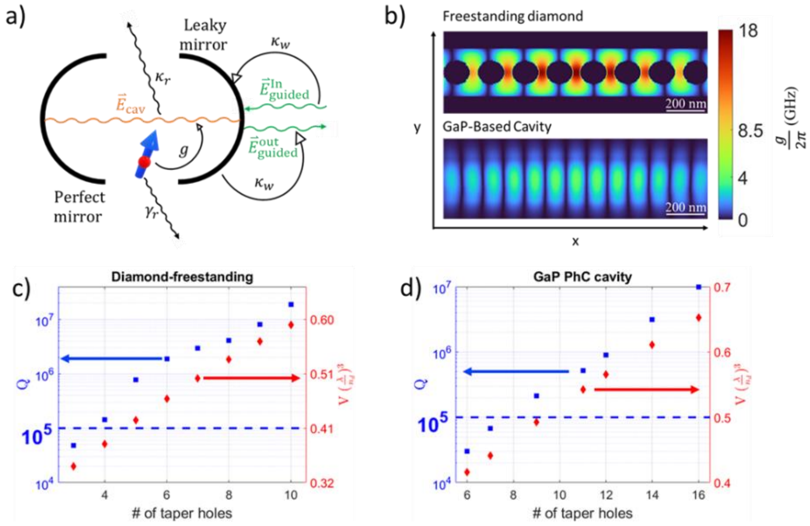

Fig 2. (a) Sketch of the cavity-GeV- system with all the coupling mechanisms considered. (b) Coupling rate of a GeV- as a function of its position in the cavity (x,y) plane. For pure diamond devices, the vertical position is taken at the center of the waveguide while for GaP based devices it is taken 25 nm below the GaP-diamond interface. (c-d) Modal volume and quality factor as a function of the number of taper holes in each of the taper regions for diamond freestanding cavities (c) and for GaP-based structures (d).

The mirror region is a region with a fixed hole-to-hole spacing chosen to maximize the reflection at the GeV- transition frequency. In the cavity region the holes are also evenly spaced, however, this spacing is chosen so that the wavelength of interest can propagate without being scattered. Finally, the taper region is a transition region along which the hole spacing is gradually increased until it matches the period in the mirror region.

As it is shown in Fig 2 c-d, increasing the number of taper holes leads to an increase in both Q and V. While the increase in Q is beneficial for the light-matter interaction enhancement, from Eq 1 it can be seen that the increase in V contributes to a reduction in the coupling rate. Therefore, considering that in practice Q will be limited by the scattering losses associated with the fabrication imperfections, the number of taper holes in each architecture was chosen to target a simulated $Q{\sim}10^6$, which is one order of magnitude higher than the state of the art for 1D PhC cavities in the visible range [4].

The main results of the design process are summarized in Table 1. g_{max} is an upper boundary for the maximum coupling rate that can potentially be achieved in each architecture for an optimal alignment and positioning of the defects within the cavity. In GaP-based devices, this upper boundary was calculated considering GeV- located at 25 nm from the diamond surface. Moreover, when these upper boundaries are compared with the state of the art coupling rates achieved in cavity-coupled diamond color centers, which is $\sim 2\pi \cdot 8.5$ GHz [8], it follows that from the architectures considered in our work, only diamond freestanding PhC cavities can potentially improve current technologies.

Architecture	$V\left(\frac{\lambda_d}{n_d}\right)^3$	$\frac{g_{max}}{2\pi}$ (GHz)
Freestanding Diamond cavities	0.46	18.4
Evanescently coupled GaP cavities	0.59	4.2

Table 1. Modal volume and maximum coupling rate achievable for the optimized devices in each of the considered architectures.

Finally, in order to study the positioning tolerance of the GeV- along the designed devices, in Fig 2 b we represent the coupling rate as a function of the defect position in the cavity.

When analyzing this figure for the diamond freestanding devices, it is observed that they feature a region with a length of around 1.2 microns within which the positioning of a GeV^- would result in coupling rate higher than current state of the art of 8.5 GHz.

Conclusions

In summary, we compared two different device architectures for cavity-coupled GeV^- centers in diamond: diamond freestanding PhC cavities and GaP-PhC evanescently coupled to the color centers present in a diamond substrate. As a result of this study, we find that due to the evanescent nature of the coupling and their higher modal volumes, GaP-based structures are unlikely to achieve the coupling rates of the current state-of-the-art technology. On the other hand, the diamond freestanding PhC cavities have the potential of not only to match the performance of state-of-the-art technologies, but even to outperform them provided that the GeV^- are located within 600 nm from the cavity center. Therefore, despite the increased complexity in the fabrication process, due to their superior performance and capabilities to improve current technologies, diamond-based structures are believed to be a more suitable architecture for both single photon generation and the construction of a quantum network based on solid state qubits.

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