Fabrication of GaP disk resonator arrays coupled to nitrogen-vacancy centers in diamond

Nicole K. Thomas*[a], Russell Barbour[b], Yuncheng Song[c], Minjoo Larry Lee[c], Kai-Mei C. Fu[a,b]
[a]Dept. of Electrical Engineering, University of Washington, 185 Stevens Way, Seattle, WA USA 98195-2500;
[b]Dept. of Physics, University of Washington, 3910 15th Ave. NE, Seattle, WA USA 98195-1560;
[c]Dept. Of Electrical Engineering, Yale University, 15 Prospect St., New Haven, CT USA 06511

ABSTRACT

Nitrogen-vacancy (NV) centers coupled to scalable optical networks have the potential to realize solid-state quantum information processing platforms. Toward this goal, we demonstrate coupling of near-surface NV- centers to an array of GaP optical resonators. The use of GaP as the optical waveguiding materials is appealing due to the possibility of realizing integrated photonic switches based on the linear electro-optic effect. We explore large-area integration of GaP on diamond through two routes: molecular beam deposition directly onto diamond substrates and layer transfer of single-crystalline sheets. While the direct deposition benefits from simpler, monolithic processing, the layer transfer route benefits from higher material quality. In the latter approach, we demonstrate the transfer of submicrometer thick, mm^2-sized GaP sheets from a GaP/AlGaP/GaP substrate to a diamond sample prepared with near-surface NV- centers. We fabricate large arrays of GaP disk resonators with varying diameters (1 to 20 μm) on the diamond substrate via electron beam lithography and dry etching, and show coupling of the NV- center emission to the cavity structures. Quality factors above 10,000 were observed in 5 μm diameter disks on the non-etched diamond substrate. Similar quality factors in smaller sized devices are expected with diamond substrate etching to further confine the optical mode. This approach opens a path towards the integration of coupled optical components in the hybrid GaP/diamond system, an essential step towards large-scale photonic networks utilizing NV- centers in diamond.

Keywords: Nitrogen-vacancy center, diamond, gallium phosphide, disk resonator, microcavity, epitaxial lift-off, layer transfer, nanofabrication.

1. INTRODUCTION

Its optical properties and long spin coherence times present the negatively charged nitrogen-vacancy (NV-) color center in diamond as a candidate quantum bit (qubit) for quantum information processing (QIP) systems. QIP systems which utilize quantum entanglement between qubits as a resource may offer the functionality required for quantum simulation, cryptography, or quantum teleportation applications.[1-4] Entanglement of the electron spins of two spatially separated NV- centers via photon interference and measurement has recently been demonstrated.[5] However, the integration of NV- into solid-state photonic networks is more desirable: solid-state networks potentially allow for device scalability, entanglement of numerous NV- qubits on the same substrate, and Purcell enhancement of the NV- optical emission in microcavities. Diamond nanowires, ring resonators, and photonic crystal cavities have been used to collect and enhance the emission of the optical defect[6-8], and off-chip coupling with diamond grating structures has been achieved[9,10]. The integration of active optical devices, such as optical switches to route the NV- emission through a photonic network, however, may not be possible using this all-diamond approach. The development of thermal diamond switches is underway, though their performance remains challenging.[11]

Integrating a linear electro-optic material, such as gallium phosphide (GaP), with the NV- defects in diamond may be critical for the implementation of active optical switches to facilitate the entanglement of selected, distant NV- on chip.

*correspondence: nkthomas@uw.edu

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Coupling of near-surface NV- optical emission to single GaP optical resonators has been demonstrated.[12] However, the devices were realized by fabrication on a secondary substrate and subsequent release onto a diamond sample from solution. This stochastic approach does not allow for the implementation of scalable photonic networks with coupled GaP cavity-waveguide structures on a diamond substrate with near-surface NV- color centers.

We explored large-area integration of GaP using two different approaches: molecular beam deposition (MBD) of GaP directly onto diamond and layer transfer of mm^2-sized single-crystalline GaP sheets. While the direct deposition benefits from simpler, monolithic processing, the layer transfer approach benefits from higher material quality since the GaP is epitaxially grown on a native substrate. First, we present the performance of GaP layers directly grown on diamond substrates with near-surface NV- defects. We next present a deterministic fabrication approach for the realization of on-chip hybrid GaP/diamond networks based on the epitaxial lift-off of a submicrometer thick GaP sheet from a trilayer GaP\AlGaP\GaP substrate prepared via molecular beam epitaxy (MBE). Thereafter, we demonstrate coupling of the NV- emission to single-crystalline GaP disk resonators fabricated from GaP sheets transferred onto the diamond from the MBE substrate.

2. MOLECULAR BEAM DEPOSITED GAP WAVEGUIDES ON DIAMOND

GaP was deposited directly on the diamond substrate with near-surface NV- centers using an MBE system. The resulting films appear nano-crystalline, with crystal sizes between 50 nm and 100 nm (Fig.1(a),(b)) and a RMS surface roughness of ~ 4nm (Fig. 1(c)).

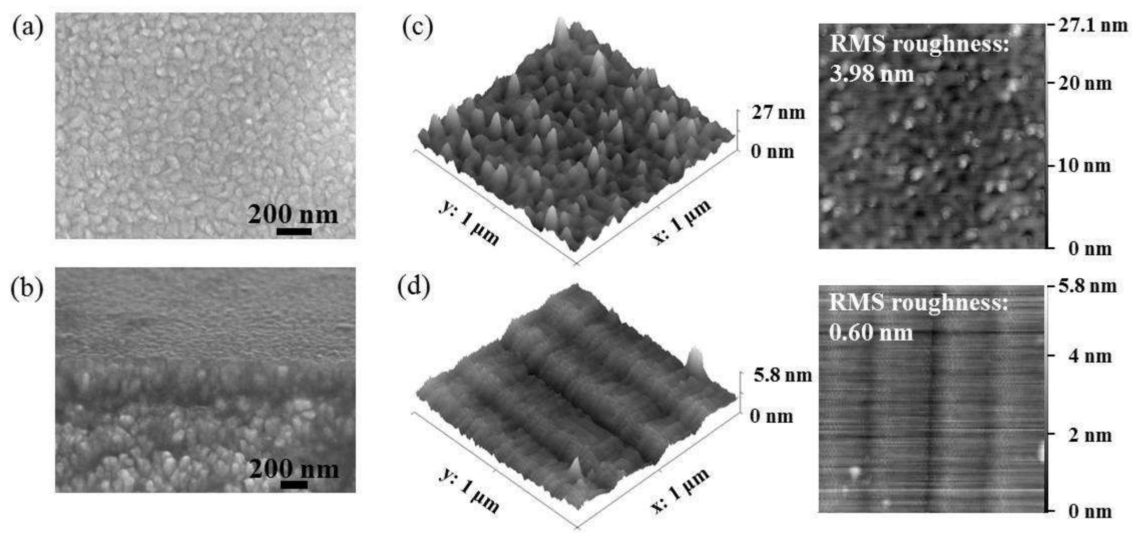

Figure 1. MBD GaP on diamond substrate. (a),(b) Top and side view on nano-crystalline GaP layer on diamond. (c), (d) AFM measurements on MBD GaP on high-pressure-high-temperature (HPHT) diamond substrate and intrinsic HPHT diamond layer, respectively.

0.5/1/2 μm wide GaP waveguides were fabricated via electron beam lithography (EBL), a Cl_2/Ar GaP dry etch and an O_2 diamond dry etch for optical loss measurements. Fig. 2(a) shows a scanning electron micrograph of an exemplary waveguide structures. Fig. 2(b) and (c) display close ups of the top surface and sidewalls, respectively, of optical devices on the diamond substrate.

The NV- defects in the diamond substrate were excited with a 632 nm continuous-wave laser coupled into the waveguides (Fig. 2(c)). The NV- phonon sideband photoluminescence (PL) intensity was recorded as function of distance from waveguide facet for the different waveguide widths, and the inverse 1/e decay length α and the optical loss were extracted from the measurement data. Table 1 displays a summary of the extracted loss data. The optical losses are > 390 $dBmm^{-1}$, and appear to decrease with increasing waveguide width. Hence, sidewall losses may be a significant factor. Even for the wider waveguides, however, the losses remain high. This may indicate absorption, vertical interface scattering, or domain scattering as major loss factors. A systematic study of the optical losses in poly-crystalline GaP\SiO_2 devices is currently underway to determine the dominant loss mechanism. With the maximum expected quality factor (Q) limited to a few hundred, these MBD GaP layers do not appear promising for the realization of hybrid GaP/diamond photonic networks.

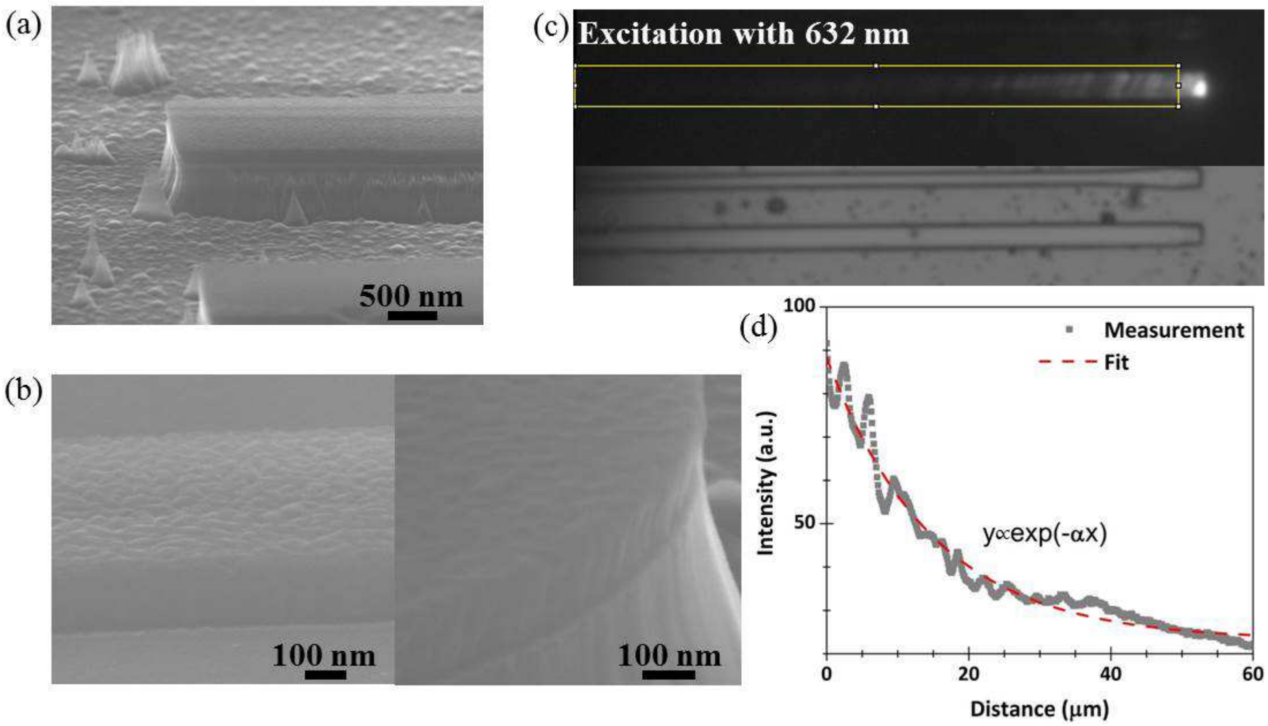

Figure 2. Waveguide loss measurements in MBD GaP. Scanning electron micrographs of (a) GaP waveguides on etched diamond substrate with (b) close-up of the top (left) and sidewall (right). (c) PL (top) and white light (bottom) image of a 2 μm wide waveguide. (d) Extraction of the inverse 1/e decay constant α from the intensity distribution.

Table 1. Waveguide loss measurements in MBD GaP on HPHT diamond.

Waveguide width (μm)	**α (μm^{-1})**	**Loss ($dBmm^{-1}$)**
0.5	0.150 ± 0.010	643 ± 43
1	0.091 ± 0.009	397 ± 39
2	2.100 ± 0.023	433 ± 101

3. SINGLE-CRYSTALLINE GAP RESONATOR ARRAYS ON DIAMOND

High-Q ring and disk resonators fabricated from single-crystalline GaP have previously been demonstrated.[13] The realization of evanescently coupled GaP cavity-waveguide structures on diamond requires large scale GaP sheets on top of the diamond substrate. Hence, further efforts were focused on the transfer of single-crystalline GaP from a MBE grown trilayer substrate using a technique similar to the one developed by Yablonovitch et al. for the release of GaAs[13,14] (Fig. 3). The intermediate AlGaP film is utilized as sacrificial material for the release of the ~ 200 nm thick, mm^2-sized GaP top layer patterned via photolithography and a GaP dry etch. The released GaP sheet is then transferred to the diamond substrate containing near-surface NV- defects, where it binds via van der Waals forces[14].

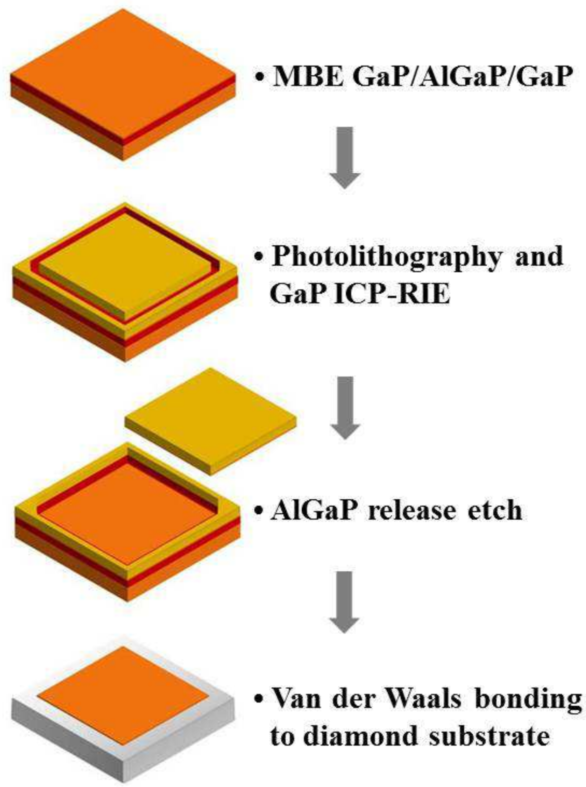

Figure 3. Schematic process flow for epitaxial lift-off and transfer of the release GaP layer onto the diamond substrate.

To attest the suitability of the transfer process for the future realization of large-scale GaP/diamond hybrid networks integrating NV- defects as qubits, we show coupling of the near-surface NV- optical emission to an array of GaP disk resonators fabricated from the transferred GaP sheets. The resonator structures were implemented on the CVD diamond substrates using EBL and a Cl_2/Ar GaP dry etch. Fig. 4(a) shows a scanning electron micrograph of the resonator array with disk diameters between 1 and 20 µm. Due to the EBL pattern overlapping with etch pattern some resonators are partially cut.

The NV- defects were excited with a 532 nm continuous-wave laser. The NV- PL coupled into the disks, and the PL scatter could be collected from the edges of the resonators. Fig. 4(b) shows an exemplary PL spectrum of a 5 µm GaP disk on the diamond substrate with the respective resonance peaks, and the Lorentzian fit of a selected peak. Quality factors > 10^4 were measured in these devices. Upon etching of the diamond substrate, similar results are expected for resonators with smaller diameters due to an enhanced confinement of the optical mode.

These results indicate that coupling of the NV- optical emission to resonator structures fabricated from the single-crystalline MBE GaP layers on diamond is feasible. We expect the availability of large-area GaP sheet on diamond to allow for the realization of coupled GaP resonator-waveguide structures which are integral for the potential realization of scalable QIP networks.

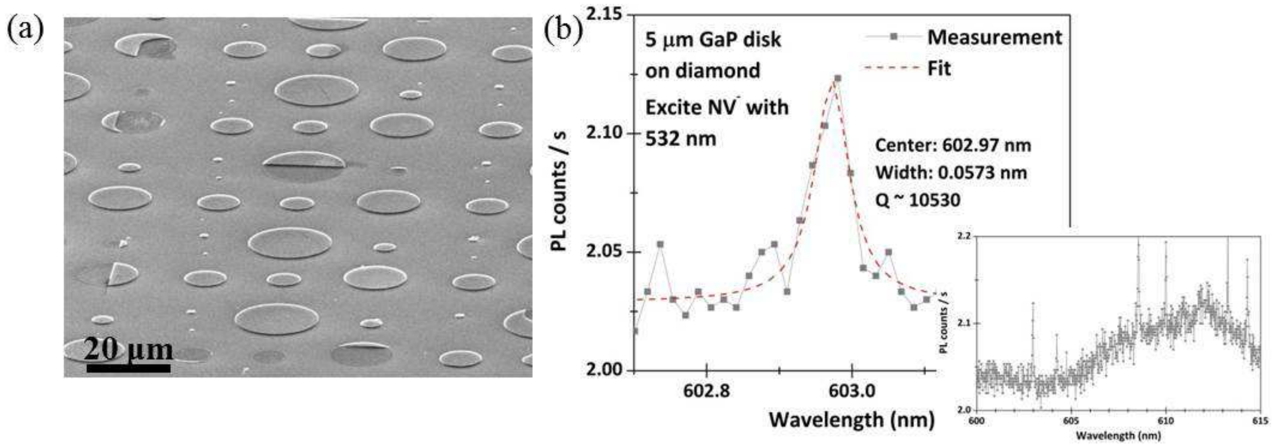

Figure 4. Coupling of NV- emission to GaP disk resonator array. (a) Scanning electron micrograph of disk resonator array. (b) PL spectrum for a 5 µm diameter GaP disk on diamond with a Q factor > 10^4.

4. CONCLUSION

We evaluated the potential of directly grown GaP layers and single-crystalline GaP sheets released from a secondary substrate onto the diamond with regard to their optical properties for their possible integration in hybrid GaP/diamond photonic networks.

The nano-crystalline MBD GaP layers exhibit high optical losses and do not appear suitable for the integration into hybrid GaP/diamond networks. In contrast, submicrometer thick, mm^2-sized GaP sheets released from an MBE GaP/AlGaP/GaP substrate and subsequently transferred to a diamond sample facilitate the realization of functional GaP disk resonator arrays with high quality factors on diamond. Cavity structures with varying disk diameters were fabricated via EBL and dry etching. We demonstrate coupling of the optical emission of near-surface NV- defects to the microcavities. Even on the non-etched diamond substrates, quality factors > 10^4 could be observed in 5 µm diameter disks. Smaller sized devices may show similar performance upon etching of the diamond substrate, leading to improved confinement of the optical modes. Hence, the release and transfer of single-crystalline GaP sheets via epitaxial lift-off can be considered a viable path for the fabrication of integrated diamond/GaP photonic devices.

We expect the developed transfer process to allow for an integration of coupled GaP cavity-waveguide structures with NV- defects in diamond for the prospective realization of large-scale QIP networks with active device capabilities.

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