Towards Building a Bright Single-Photon Source with h-BN Defect Emitters

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Principal Investigator(s): Gregory D. Fuchs[1]
User(s): Jialun Luo[2]

Affiliation(s): 1. Applied and Engineering Physics, 2. Department of Physics; Cornell University

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Contact: gdf9@cornell.edu, jl3562@cornell.edu
Website: http://fuchs.research.engineering.cornell.edu

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Abstract:

Single-photons are essential in realizing photon-based quantum technologies [1]. Defect emitters in hexagonal boron nitride (h-BN) have been found to be bright and photostable, making them good candidates for implementing single-photon sources. We developed a fabrication process for an inverse-design cavity device from AlN for efficient photon-extraction from the defect emitters. We present an update on our work-in-progress on the fabrication and characterization of the device.

Summary of Research:

Single-photon sources are important pillars in quantum technologies such as quantum communication protocols [1,2], precision metrology [3], and quantum sensing. Building a single-photon source involves two parts: 1) a single-photon emitter and 2) a photon-extraction method. Hexagonal boron nitride (h-BN) hosts atomic defects that, upon optical excitation, emit bright and photostable fluorescence [5,6]. The zero-phonon line fluorescence from carbon-related h-BN defects falls near 585 nm [6]. Previous publications suggest that carbon ion-implantation can deterministically create these defect emitters [7]. Since h-BN is a van der Waals material that can be prepared into flakes thinner than a tenth of the fluorescence wavelengths, photons emitted from defects hosted within naturally suffer less from total internal reflection. However, the far-field radiation power from these defect emitters typically concentrates at higher angles, which means a high numerical aperture microscope objective is necessary to collect the light.

Our collaborator from the Rodriguez group then calculated a nanostructure to aid the photon collection [8]. The nanostructure shortens a dipole emitter's lifetime when one is placed at the center high field region due to the Purcell effect, and it modifies the near-field dielectric environment of the dipole emitter so that more photons are emitted into a smaller cone for lower numerical aperture lenses to collect (Figure 1).

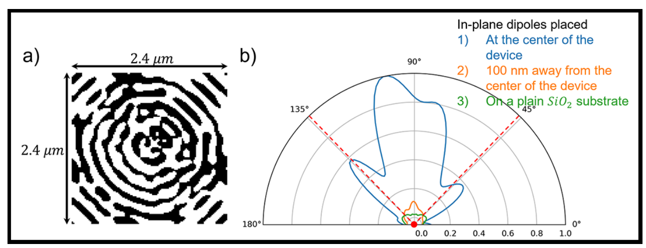

Figure 1: a) Top-down view of an optimized structure pattern for an in-plane dipole emitter. The thickness is 300 nm. b) Far-field radiation patterns comparison among dipole emitters placed at the center of the device, 100 nm shifted away from the center of the device, and placed on a plain SiO_2 substrate. The red dashline indicates the maximum collection angle of a 0.7 NA microscope objective.

In this work, we attempt to build a h-BN defect emitter-based single-photon source integrated with a nanostructure to efficiently extract the single photons.

We fabricated the current generation devices on Si wafer, which allows us to cleave the sample and inspect the cross section. The devices are made from AlN sputtered by the OEM Endeaver M1 AlN sputter system. We chose hydrogen silsesquioxane (HSQ) as our resist layer due to its 10 nm spatial resolution with electron-beam (e-beam) lithography. The nanostructure is patterned by the JEOL 9500 e-beam lithography system. The pattern is transferred to a hard mask layer made of

Ni by ion milling. Then, the devices are etched by reactive ion etch with chlorine/oxygen plasma. While reactive ion etch has high directionality, the device aspect ratio is as high as 5 to 1, so we faced the problem of angled sidewalls. We optimized the etch recipe and reached a sidewall angle of 82 degrees (Figure 2). According to the calculation, such a device can still enhance the photon collection by 7-to-10-fold.

Following the Aharonovich group result [7], we send exfoliated h-BN flakes with thicknesses ranging from tens to hundreds of nm for carbon ion-implantation process. However, the resulting flakes contain mostly short-lived emitters with broad emission spectra (Figure 3), rendering h-BN flakes not suitable for single-photon sources. We also found that the thin h-BN flakes become much harder, if not impossible, to pick up with our 2D material transfer techniques.

We tried characterizing the inverse-design cavity nanostructures by transferring a 100-nm sized h-BN flake over (Figure 4), however, the fluorescence and the collected spectra showed no enhancement, likely because the h-BN flake drastically changed the dielectric environment and broke the nanostructure design assumption that only a thin layer of h-BN is placed on it.

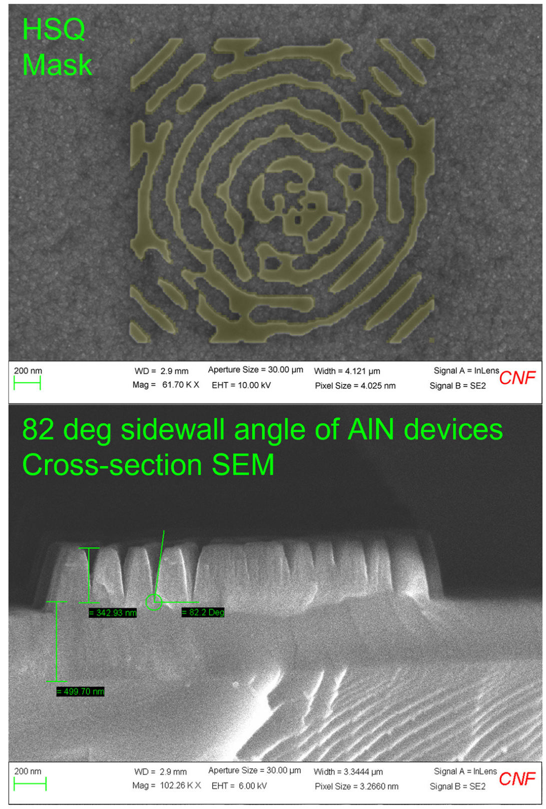

Figure 2: Upper: Developed HSQ mask overlayed with the design pattern (in yellow) Lower: The cross-section SEM of etched AlN devices showing an 82-degree sidewall angle.

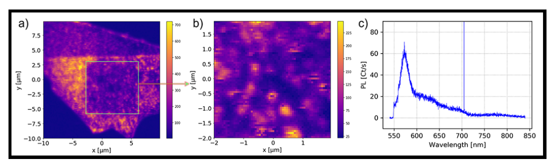

Figure 3: a) A typical fluorescence map under 532-nm laser excitation. b) A finer fluorescence map zoomed into the boxed region in a), there are point-like emitters in general. c) Typical spectrum of the point-like emitters. While the zero-phonon line centers around 585 nm, the linewidth is broad (~20 nm).

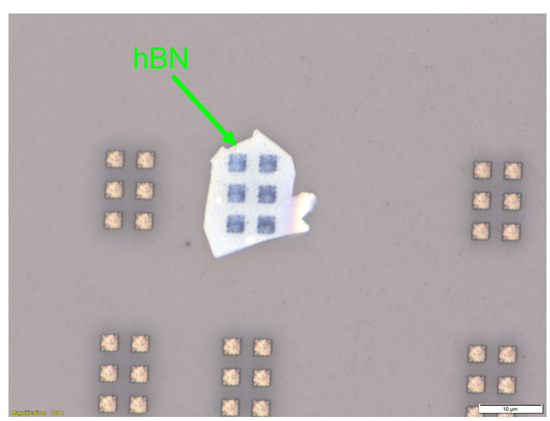

Figure 4: An optical image of a 100 nm thick h-BN flake placed over six inverse-design cavity devices.

Future Work:

We are trying to characterize the inverse-design cavity nano-structures with commercially available CdSe quantum dots which are of 10 nm in size. The characterization result can provide guidance for the next steps.

Acknowledgements:

We would like to thank members of the Rodriguez Group on the discussion on and their designs of the inverse-design cavity nanostructures.

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