

Supporting information

Solvent-Exfoliated Hexagonal Boron Nitride Nanoflakes for Quantum Emitters

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S1. Solvent exfoliation of hBN powder

Hexagonal boron nitride powders were obtained from five commercially available sources: MicroLubrol™, Hagen Automation™, Plasma Chem™, Graphene Supermarket™ and Sigma Aldrich™ and used as is.

In a typical exfoliation experiment, 0.444 g of polyvinylpyrrolidone (PVP) was dissolved in 40 mL of ultrapure water (18.2 MΩ-cm) to create a 0.1 M PVP ($M_w = 40$ kDa) solution in a 100 mL beaker. Two hundred milligrams of the hBN powder was then added to the aqueous solution under continuous stirring. A probe-based ultrasonicator (Ultrasonics™, FS-150N, 72W, 20 KHz) was inserted into the solution and was operated with a 50% duty cycle for 30 minutes to induce exfoliation of the hBN nanoflakes. The resulting solution was left to sediment for 24 hours before being stored in a plastic test tube for further characterization.

S2. Structural and elemental characterization of hBN powder and hBN flakes

X-ray diffraction

The crystal structures of the hBN powder were characterized with X-ray diffraction (XRD, Bruker D8 Discover™) in the θ -2 θ configuration with a range of 20-90° and a rate of 2.3°/minute.

Raman spectroscopy

Raman spectra of the hBN powder were acquired using a confocal Raman setup (Renishaw inVia™ confocal Raman) with a 633-nm excitation laser at 1mW for 10 seconds.

Scanning electron microscopy

Electron micrographs were obtained with a scanning electron microscope (Zeiss Supra 55VP SEM) at 5 keV beam energy.

Atomic force microscopy

Atomic force microscopy (AFM) images were acquired using a commercially available AFM system (Park XE7 AFM) with a standard silicon probe (radius of curvature of the tip <10 nm). The purpose of gathering information about the flake dimension is to understand the physical aspect of the flakes hosting quantum emitters. Specifically, we want to know if there are significant differences among the different hBN starting powders since a major difference in the resultant flake dimension could strongly affect the optical performance of the embedded quantum emitters via effects such as totally internal refraction (TIR), light scattering among others.

Inductively Coupled Plasma Mass Spectrometry

Ultrapure nitric acid (Seastar Baseline 67 – 70% HNO₃, Choice Analytical, Thornleigh, NSW, Australia) was used for a room-temperature overnight digestion of hBN powders using a 5:1 weight ratio acid to powder; the samples were then diluted 1 in 10 with reverse osmosis water (MilliQ, Merck, Macquarie Park, Australia). External calibration standards were made up from a 10 ppm 48 component multi-elemental standard (ICP-MS68A-500, Choice Analytical, Thornleigh, NSW, Australia) diluted in 5% HNO₃ at 5, 10, 100, 500 and 1000 ppb.

Solution analysis was performed on an Agilent 8900 ICP-MS, (Agilent, Mulgrave, Australia) equipped with a Scott type double pass spray chamber cooled to 2 °C for sample introduction. Platinum sampling and skimmer cones were used. Solution ICP-MS was used to analyse digested standards. An Agilent SPS4 autosampler was loaded with digested standard materials for analysis. Solutions were transferred to the ICP-MS using a 1.02 mm internal diameter Tygon tubing and a three-channel peristaltic pump. The solution was pumped at a continuous flow of 0.1 mL min⁻¹. A 100 ppb Rhodium solution in 1 HNO₃ was used as an internal standard and introduced into the analyte flow via a T connector post-pump. The solution was delivered to the plasma of the ICP via a Micromist nebulizer and Scott type double pass spray chamber. The typical ICP-MS conditions are shown in Table 1.

Table 1 Typical Agilent 8900 ICP-MS parameters used for solution analysis.

| Agilent 8900 | |
|--------------|------|
| RF Power (W) | 1500 |

| | |
|---|------------|
| Carrier gas flow rate (L min ⁻¹) | 0.85 |
| Makeup gas flow rate (L min ⁻¹) | 0.3 |
| Sample depth, mm | 9.0 |
| Extracts 1,2 (V) | -7.5, -250 |
| Omega bias, lens (V) | -145 |
| Cell entrance, exit (V) | -50.0 |
| Octopole RF (V) | -1.0 |
| Octopole bias (V) | -20 |

S3. Optical characterization of quantum emitters in hBN

Ten microliter of the five-fold diluted solution was drop-cast on a marked thermal oxide silicon substrate. The silicon substrate was then annealed at 850 °C for 1 hour in a tube furnace (Lindberg/Blue MTM) in argon (1 Torr) to activate the quantum emitters. The substrate was cooled to room temperature overnight.

Photoluminescence measurements were conducted using a home-built laser-scanning confocal microscope. A 532-nm excitation laser was used to excite the quantum emitters through a 0.7 numerical aperture (NA) objective lens. The back-reflected light was filtered through a long-pass 568-nm filter (SemrockTM) and was collected into an multimode optical fiber. The signals were then analyzed by either a spectrometer (Princeton InstrumentsTM) or a pair of avalanche photodiodes (APDs, Excelitas TechnologiesTM) that were connected to a time correlator (PicoHarp 300), in a Hanbury Brown and Twiss (HBT) interferometer configuration, allowing for the measurements of second-order autocorrelation function.

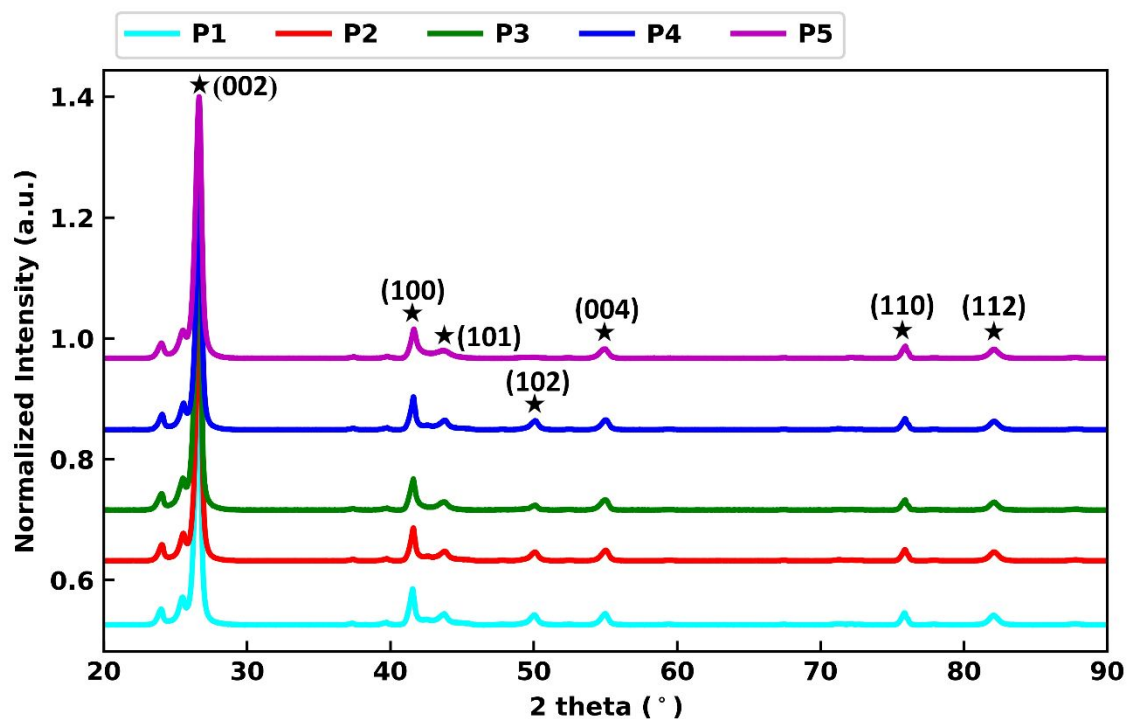


Figure S1. XRD patterns of the different sources of hBN powder.

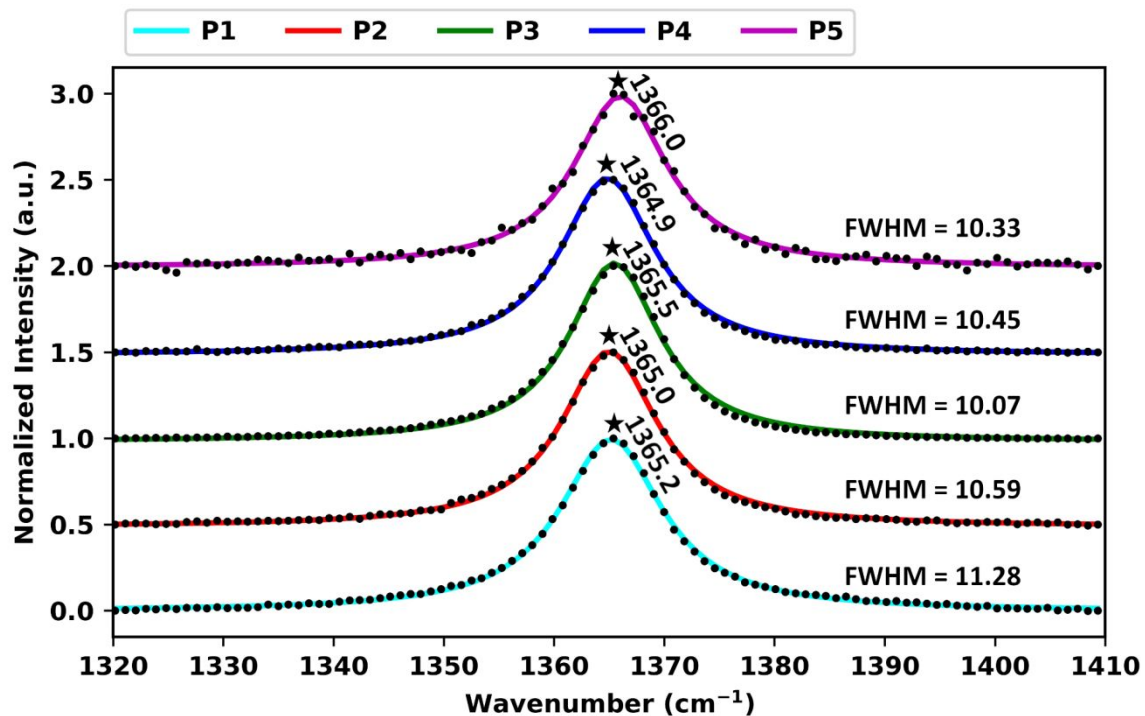


Figure S2. Raman spectra taken from the different sources of hBN powder.

Table S1. Raw data of Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) measurements for forty-eight elements for the five starting powders, P1-P5.

| Element | Blank | P1 | P2 | P3 | P4 | P5 |
|---------|-------|------------|------------|-----------|------------|------------|
| Li | 0.27 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Be | 0.16 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na | 87.22 | 659075.73 | 715825.96 | 35860.67 | 986803.47 | 477556.17 |
| Mg | 10.50 | 646861.77 | 637018.35 | 12405.25 | 692252.10 | 77648.95 |
| Al | 0.73 | 92928.75 | 95412.62 | 605.55 | 123206.39 | 14734.33 |
| Ca | 0.81 | 26463.60 | 24352.20 | 793.99 | 26999.73 | 4858.44 |
| Sc | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ti | 0.64 | 1899993.73 | 2107266.65 | 369186.88 | 3510053.50 | 2414922.25 |
| V | 0.19 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Cr | 0.33 | 667.06 | 2952.60 | 0.00 | 1059.81 | 1485.41 |
| Mn | 0.23 | 2315.46 | 2848.42 | 0.00 | 4452.95 | 224.49 |
| Fe | 0.66 | 86310.82 | 95704.34 | 6254.50 | 96618.68 | 29498.59 |
| Co | 0.17 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ni | 0.28 | 877.93 | 1396.08 | 0.00 | 2051.31 | 3951.11 |
| Cu | 0.18 | 0.00 | 266.71 | 0.00 | 136.61 | 342.35 |
| Zn | 0.88 | 0.00 | 1466.92 | 0.00 | 0.00 | 0.00 |
| Ga | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ge | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| As | 0.56 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Se | 1.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Rb | 1.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sr | 0.26 | 2802.08 | 2535.86 | -241.37 | 2650.62 | 589.30 |
| Y | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Zr | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Nb | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mo | 2.29 | 0.00 | 0.00 | 0.00 | 0.00 | 1152.41 |
| Ag | 1.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Cd | 0.19 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sb | 0.45 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Te | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Cs | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ba | 0.24 | 5703.50 | 6855.37 | 0.00 | 3487.89 | 0.00 |
| La | 2.35 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ce | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pr | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Nd | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sm | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Eu | 0.94 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ho | 0.51 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

| | | | | | | |
|------------------------|---------|------------|------------|------------|------------|------------|
| Yb | 0.44 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| W | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Tl | 0.64 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pb | 1.06 | 944.84 | 0.00 | 0.00 | 0.00 | 0.00 |
| Bi | 2.58 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Th | 3.53 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| U | 0.51 | 1113.13 | 1477.34 | 0.00 | 2328.93 | 0.00 |
| Rh (ISTD) | 2084025 | 2232341.53 | 2231927.73 | 2224496.32 | 2194391.55 | 2253756.29 |