BTP Stage-1

Single Photon Emitters with Strain Engineered Monolayer Hexagonal Boron Nitride

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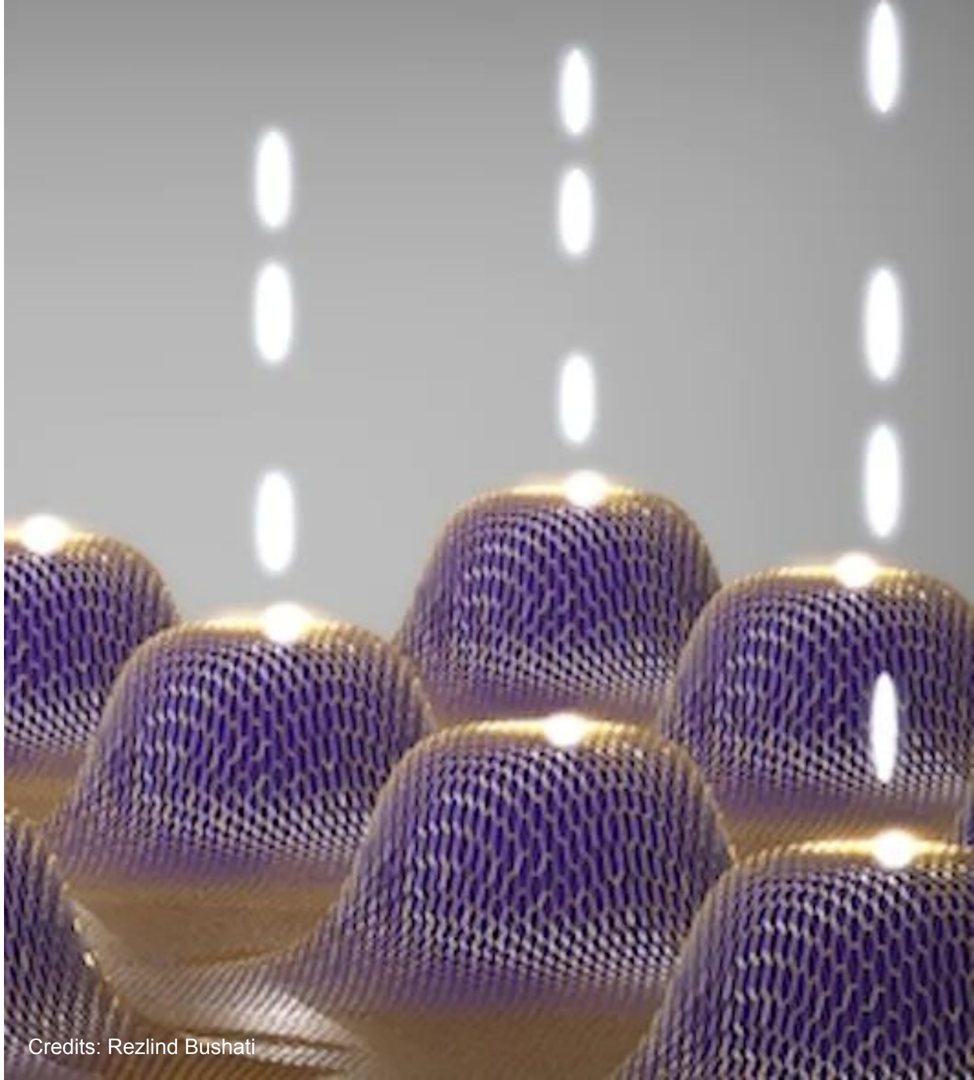
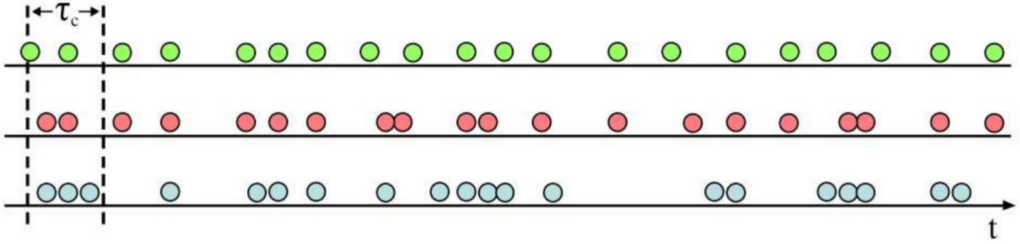
Introduction



Single Photon Sources: Anti-bunching and $g^{(2)}(\tau)$



Photon detections as a function of time for a) antibunched, b)random, and c) bunched light

Second order coherence function:

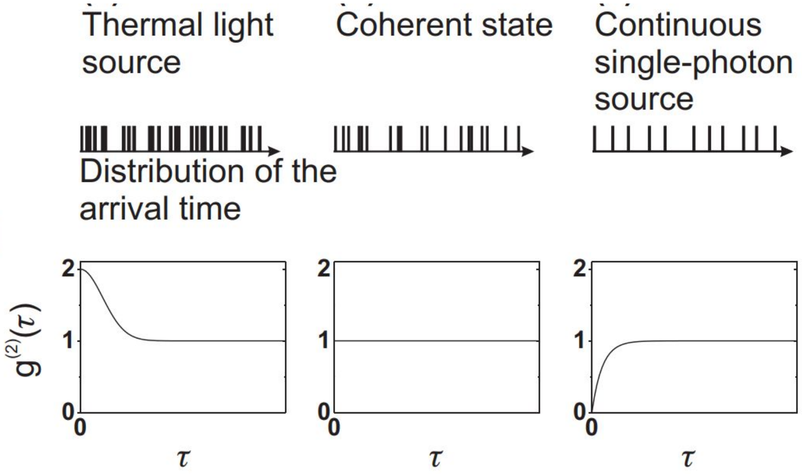
$$g^{(2)}(\tau) = \frac{\langle n(t)n(t+\tau)\rangle}{\langle n(t)\rangle^2}$$

Coherent: $g^{(2)}(\tau) \equiv 1$ for all τ .

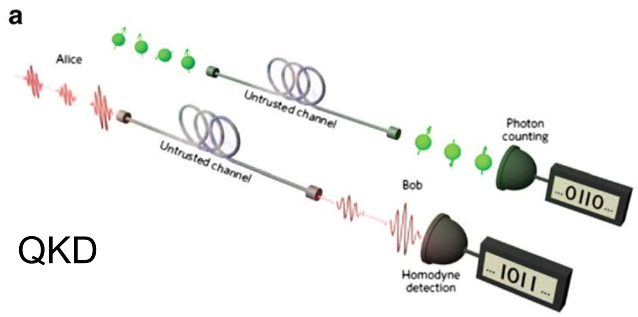
Bunching: (e.g. classical, fluctuating light
(from ensembles of emitters or thermal states))

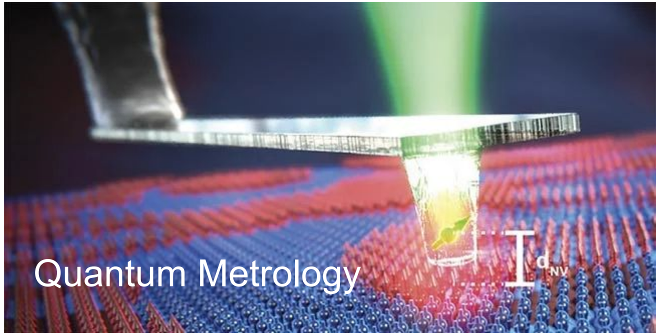
$$g^{(2)}(\tau) \;=\; 1+|g^{(1)}(\tau)|^2 \geq 1 \qquad g^{(2)}(0) \;\geq\; g^{(2)}(\tau)$$

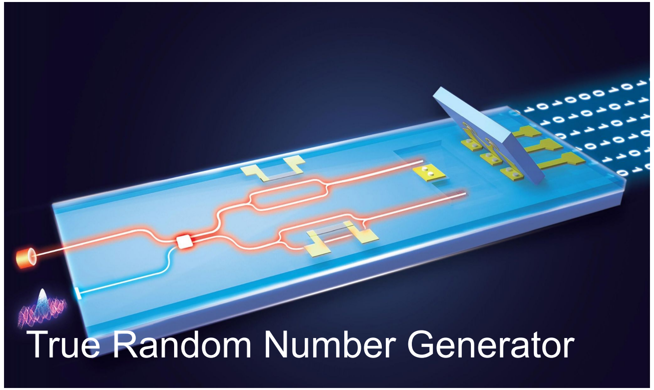
Antibunching: $g^{(2)}(\tau) < 1$

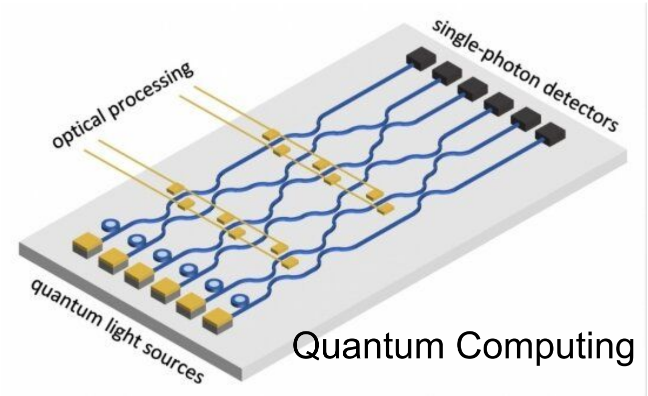


SPE Applications

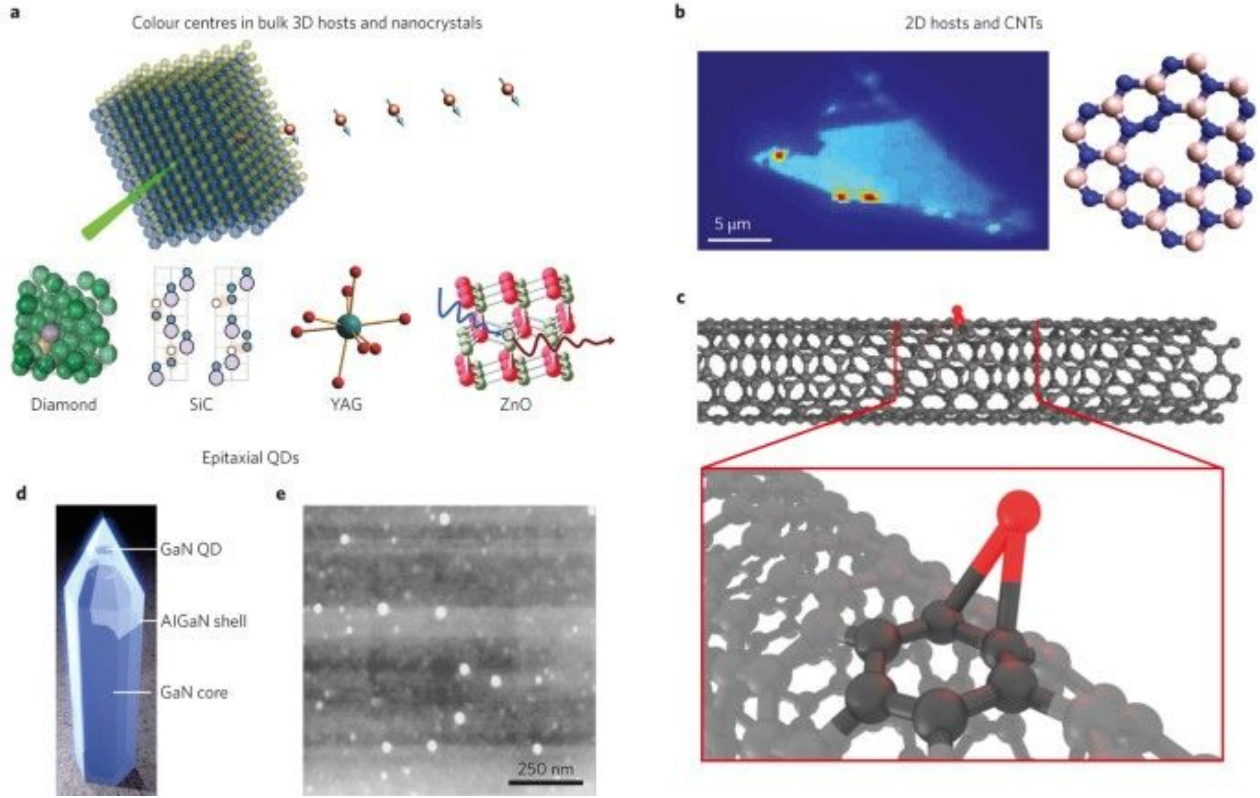






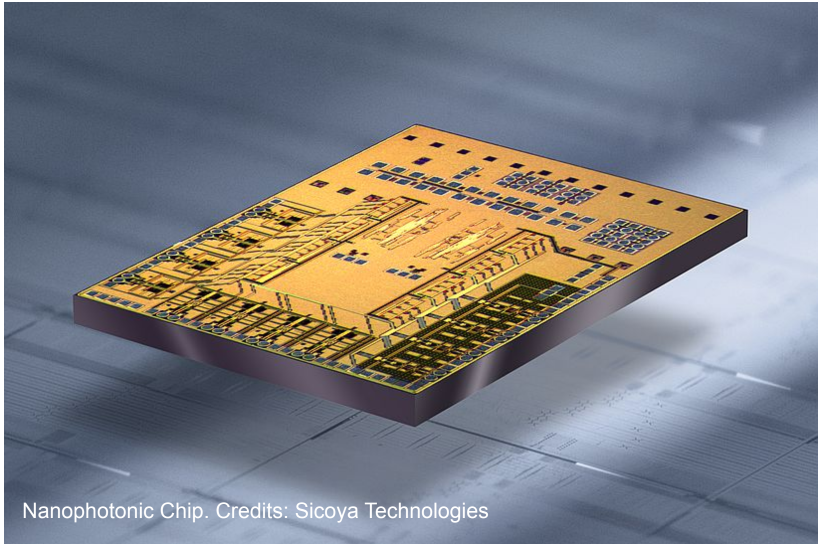


Current SPE candidates



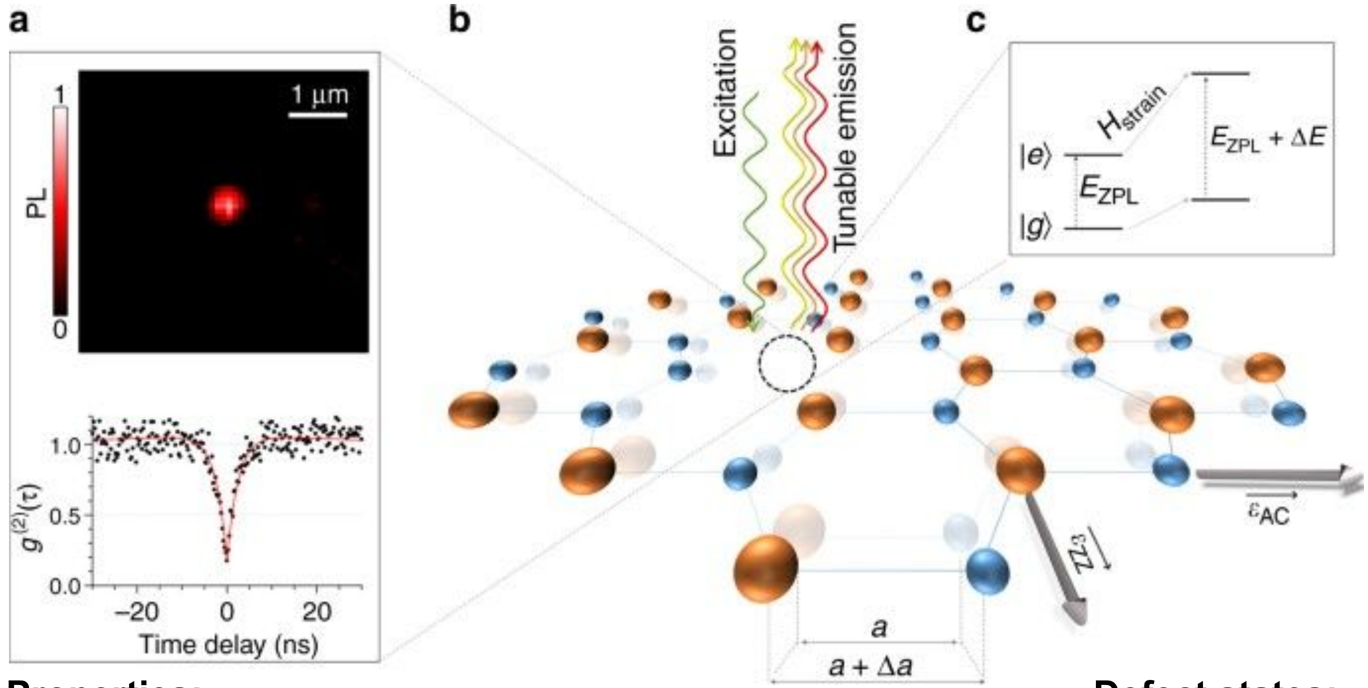
Properties of 2D material based SPEs

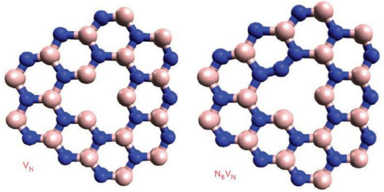
1. Integrability with existing technology.
2. Control over emission properties
   a. van der Waals materials bond structure.
   b. Coupling with plasmonics.
3. Among the brightest SPEs reported so far.
4. Megahertz count rates at the detector have been recorded with a very low excitation power of several hundred microwatts.



Nanophotonic Chip. Credits: Sicoya Technologies

hBN





Properties:

1. High band gap (~6eV).
2. Holds deep defect states that allow SPE operation at room temperature.

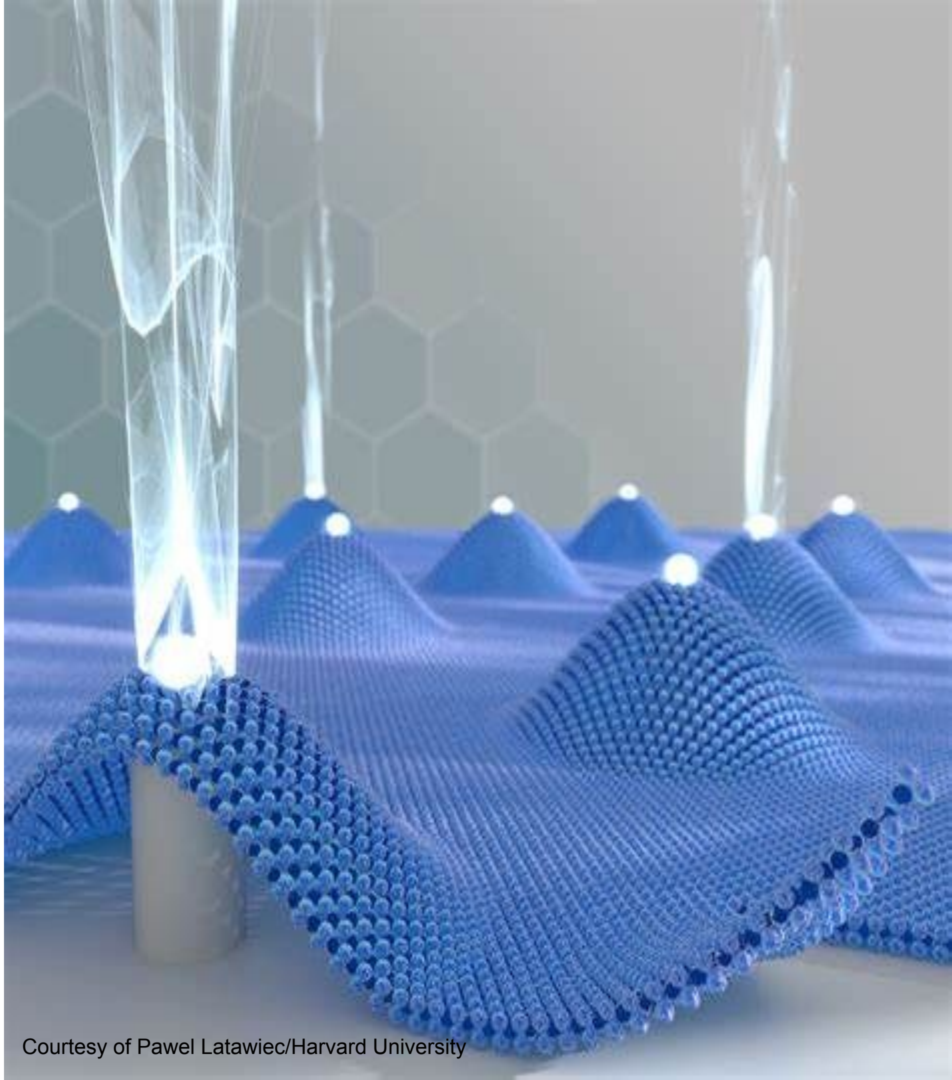
Defect states:

1. VB
2. VN
3. NBVB

Adopted from: https://doi.org/10.1038/s41467-017-00810-2

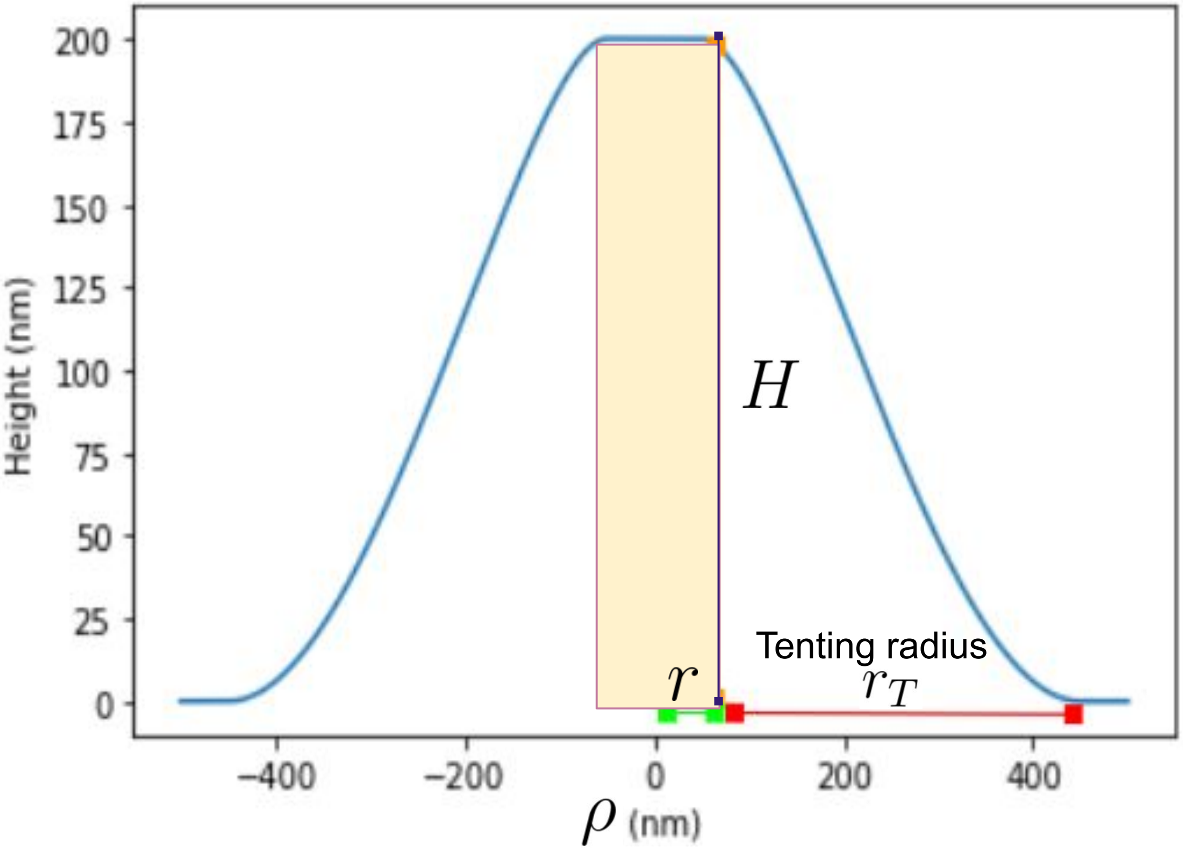
Adopted from: https://doi.org/10.1038/nnano.2015.242

Strain Analysis



Courtesy of Pawel Latawiec/Harvard University

Height Profile



Thin Film Height Profile

The Föppl-von Kármán equations [1]:

$$D\Delta^2\zeta - P = 0 \qquad D = \frac{Eh^3}{12(1-\sigma^2)}$$

E := Young's modulus
σ := Poisson's ratio
h := Thin Film thickness

The P=0 model [2]:

$$\zeta_{\mathrm{P}=0}(\rho) = \frac{H}{\left(r_{\mathrm{T}}^2 - r^2\right)^2 - 4r_{\mathrm{T}}^2 r^2 \ln^2\left[\frac{r_{\mathrm{T}}}{r}\right]} \left\{2r_{\mathrm{T}}^2 \ln[r_{\mathrm{T}}] \left(r^2 + 2r^2 \ln\left[\frac{r}{r_{\mathrm{T}}}\right] - \rho^2\right) + \left(\rho^2 - r_{\mathrm{T}}^2\right)\left(r^2 + 2r^2 \ln[r] - r_{\mathrm{T}}^2\right) + 2\ln[\rho]\left(\rho^2\left(r_{\mathrm{T}}^2 - r^2\right) + 2r_{\mathrm{T}}^2 r^2 \ln\left[\frac{r_{\mathrm{T}}}{r}\right]\right)\right\}$$

Boundary conditions	Parameter values
$\zeta_{P=0}(r) = H$ $\zeta_{P=0}(r_T) = 0$ $\partial_\rho \zeta_{P=0}\vert_{r,r_T} = 0$	$H = 200 \text{ nm}$ $r = 0 \text{ to } 1000 \text{ nm}$ $r_T = 450 \text{ nm} + r$

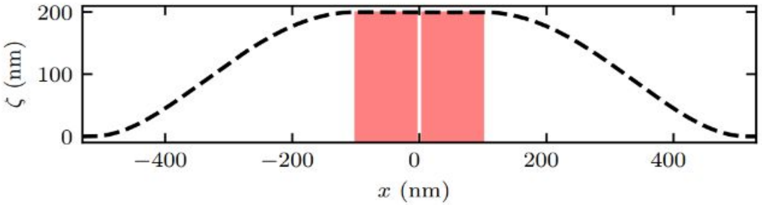
Strain:

$$\mathcal{T} = Tr[\varepsilon_{\mathrm{ij}}] = \frac{(2\sigma - 1)h}{1-\sigma}\Delta\zeta$$

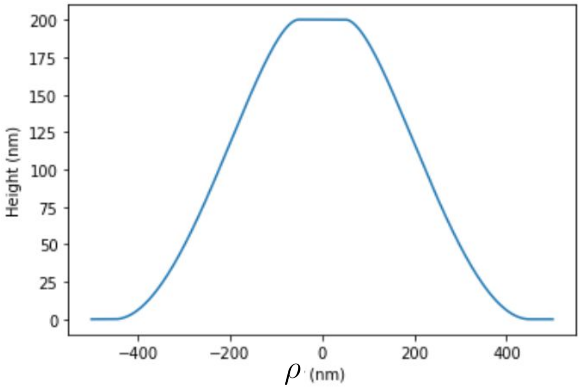
Conduction Band Potential:

$$V = \begin{pmatrix} V_{vb} & 0 \\ 0 & V_{cb} \end{pmatrix} = \begin{pmatrix} \delta_v \mathcal{T} & 0 \\ 0 & \delta_c \mathcal{T} \end{pmatrix}$$

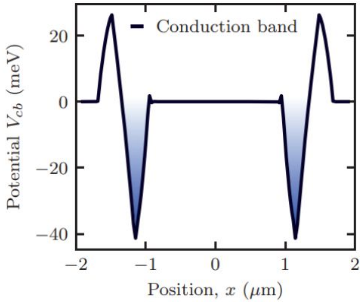
Height Profile

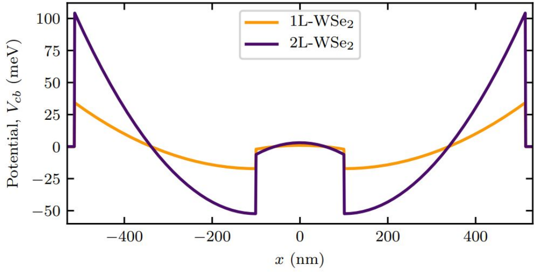


Reference: DOI: 10.1021/acsphotonics.0c00294



Conduction Band Potential





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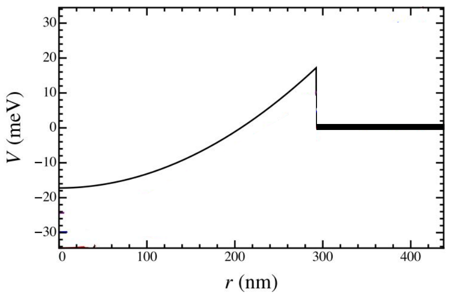
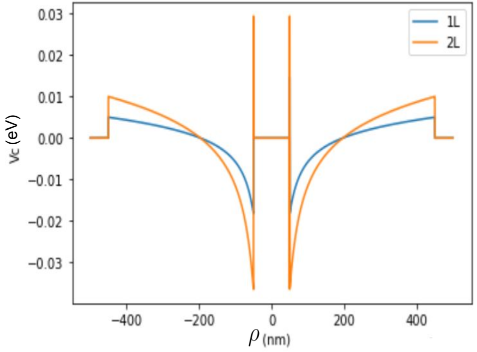


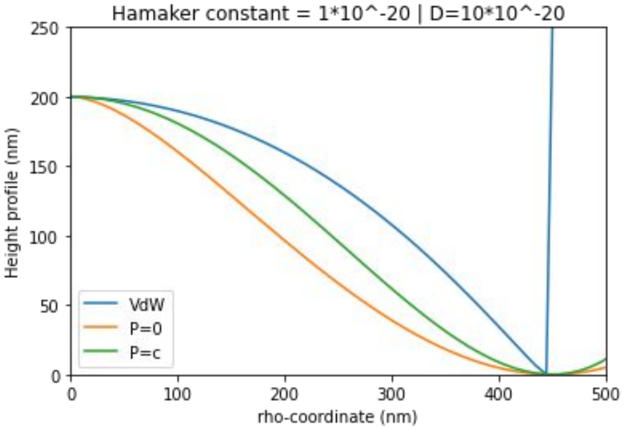


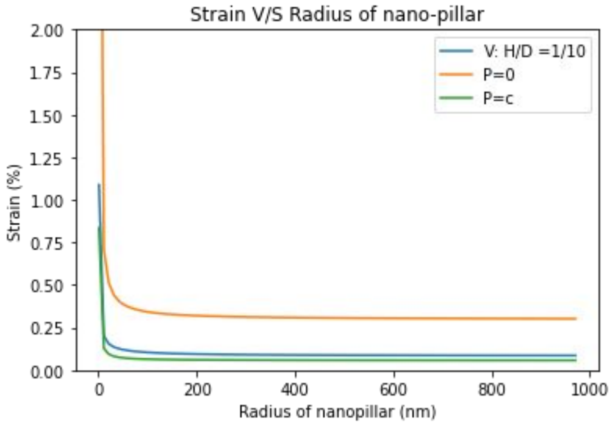
Reference: DOI: 10.1103/PhysRevB.97.195454

Thin Film Height Profile - A comparative study

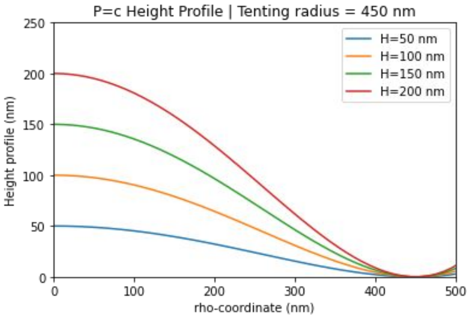
Pressure Model	Pressure Function(P)
Zero	0
Constant	$\frac{64H}{r_T^4}$
van der Waals	$\frac{\mathcal{H}_{\text{TMD-Sub}}}{(h/2+\zeta)^3}$

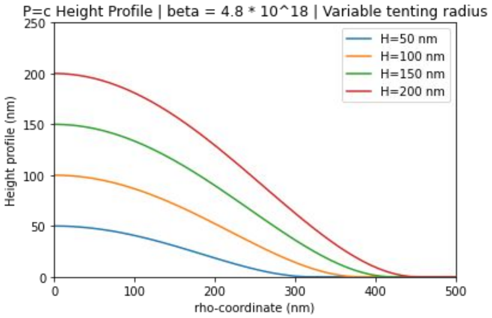
H/D = 1/10



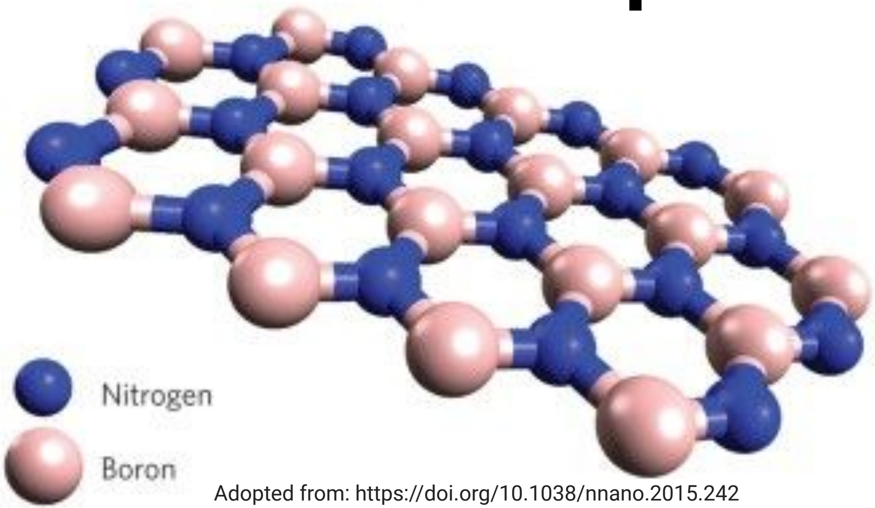


Height Profile P=c





Sample Preparation

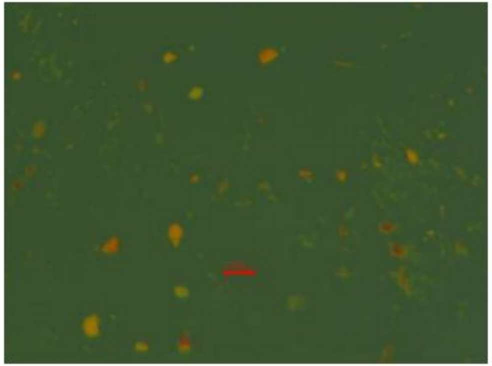


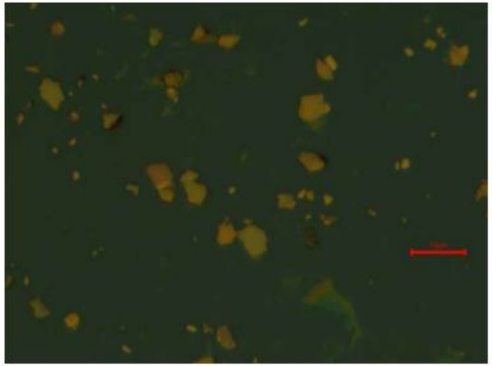
Adopted from: https://doi.org/10.1038/nnano.2015.242

Scotch tape exfoliation

hBN on SiO2-Si crystal

1. Crystals <10 µm in size.
2. Monolayers are quite rare.
3. Large amount of tape residue on substrate

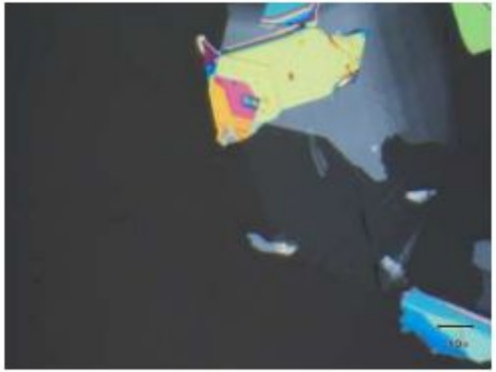


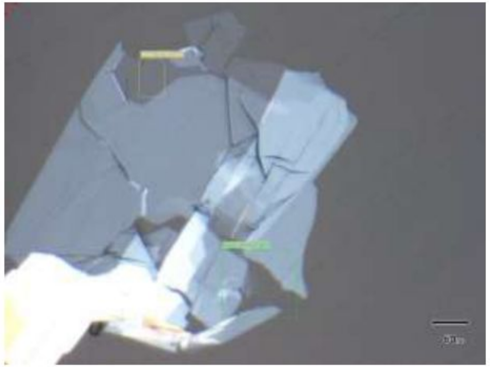


Nitto tape exfoliation

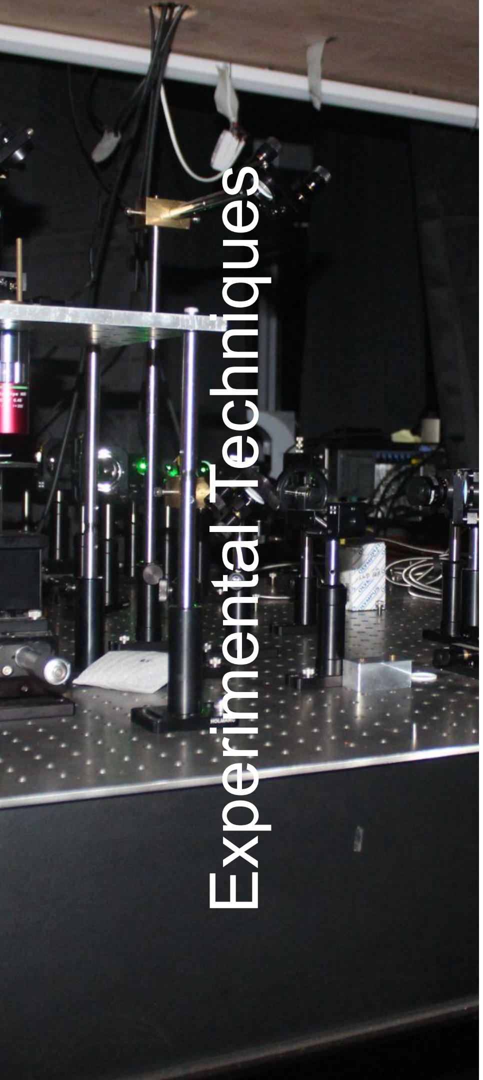
hBN on PDMS

1. Monolayers between 10 - 20 µm in size.
2. Monolayers are rather easy to obtain, given a good parent crystal.
3. No tape residue on PDMS

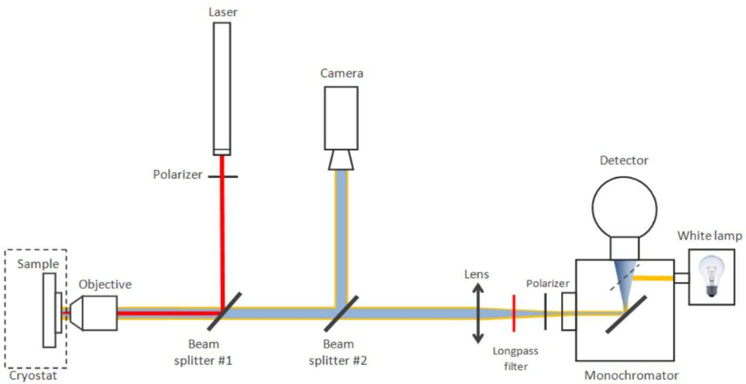




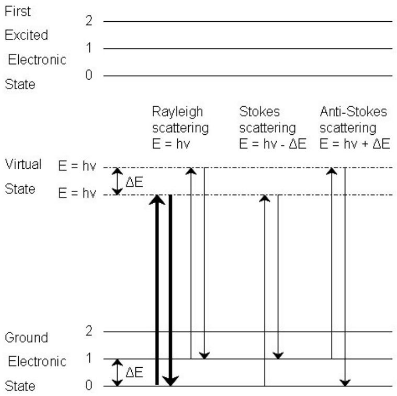
Experimental Techniques

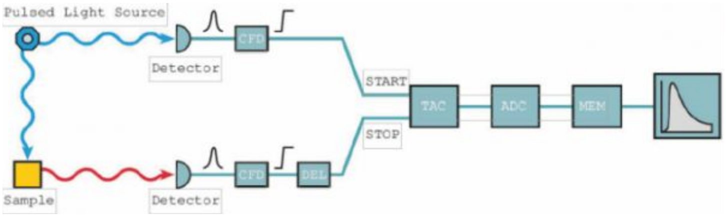


PL Spectroscopy

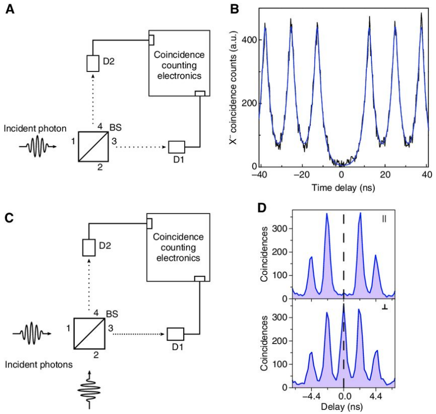


Raman Spectroscopy



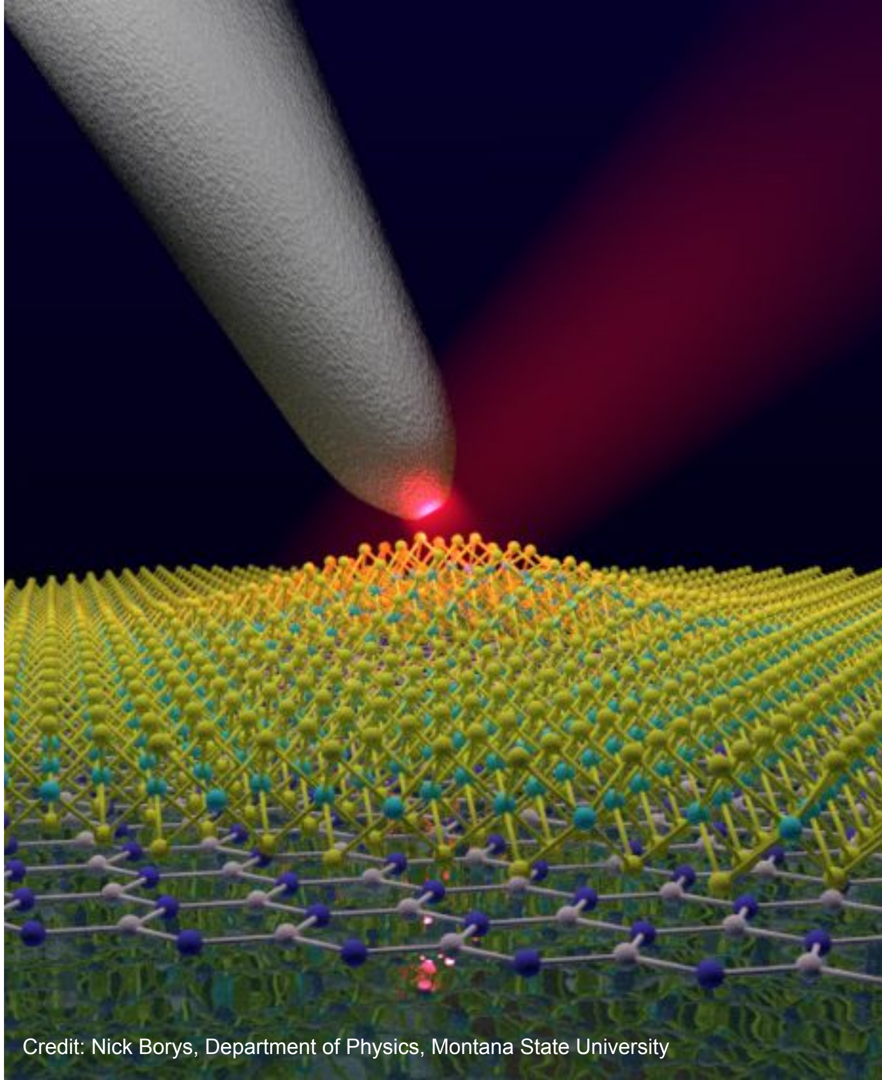


Lifetime Measurement Setup

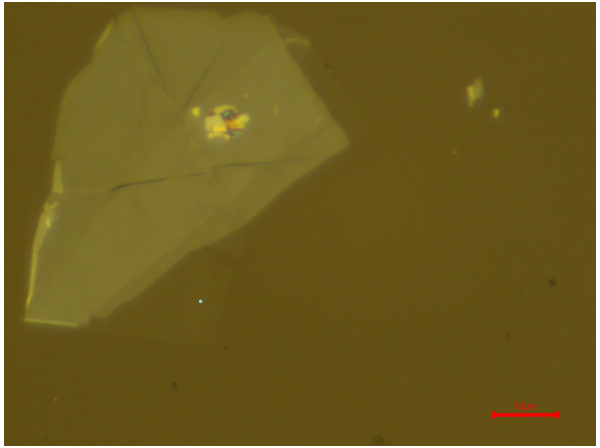


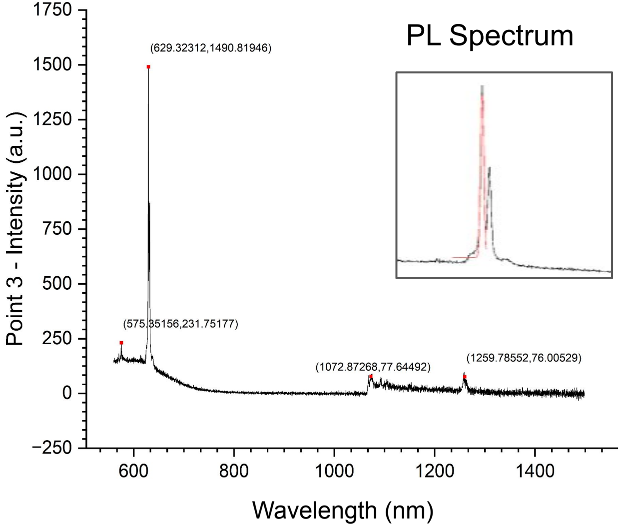
HBT Setup ($g^{(2)}$)

Spectroscopy Results

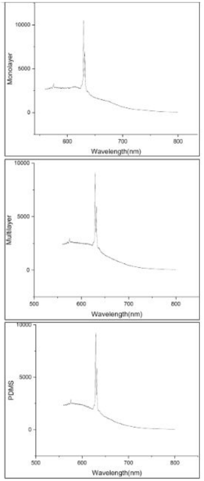


PL Spectra





PL Results



xc1: 629.26165 ± 0.00385 nm
w1 : 0.9812 ± 0.0125 nm

xc2: 631.66114±0.00601 nm
w2 : 0.87009±0.02869 nm

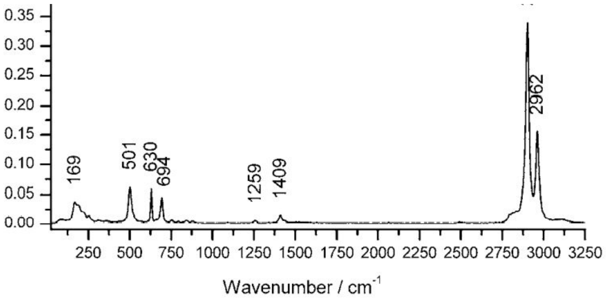
xc1: 629.26365 ± 0.00314 nm
w1 : 0.94061±0.01086 nm

xc2: 631.66979 ± 0.00998 nm
w2 : 0.8489 ± 0.04494 nm

xc1: 629.24349 ± 0.0039 nm
w1 : 0.99073 ± 0.0129 nm

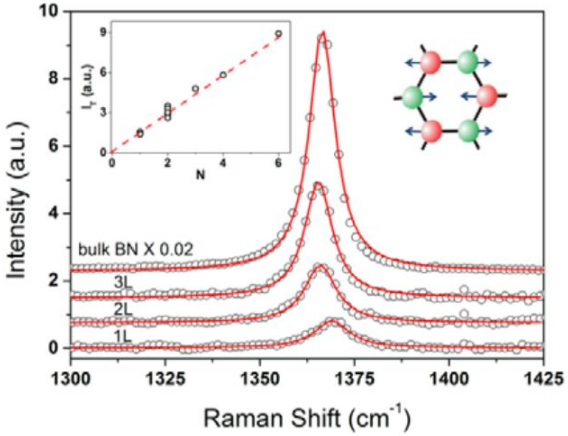
xc2: 631.64241 ± 0.00738 nm
w2 : 0.9519 +0.05944 nm

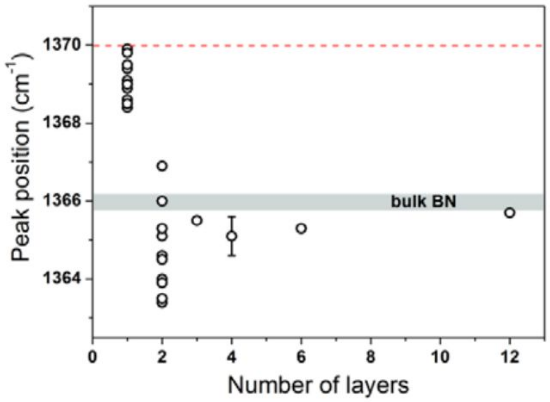
PDMS Raman spectrum[3]

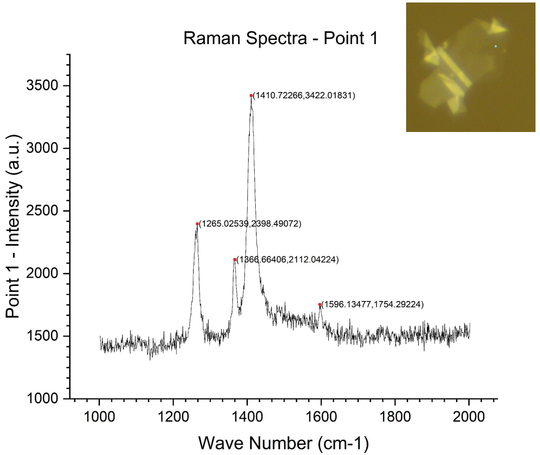


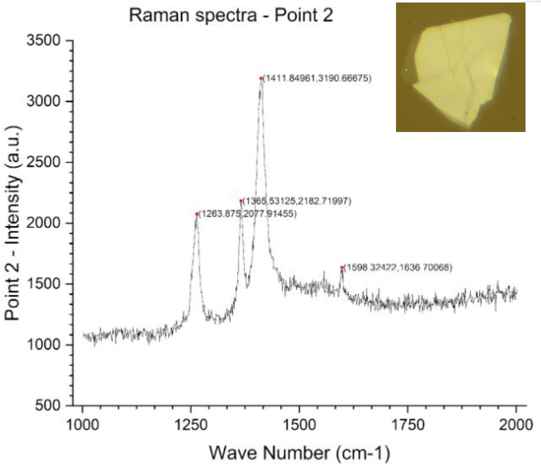
Reference: DOI: 10.1366/000370207780220796

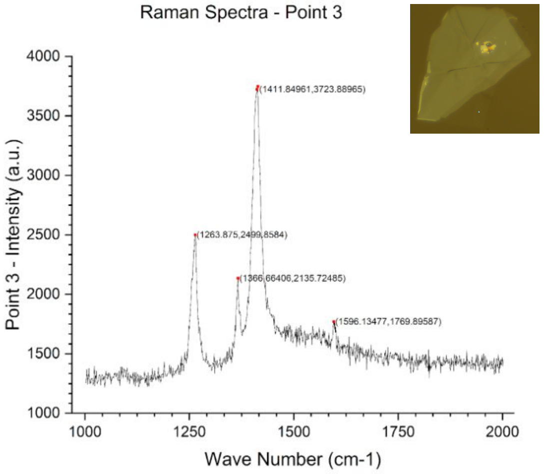
Raman spectra [4]

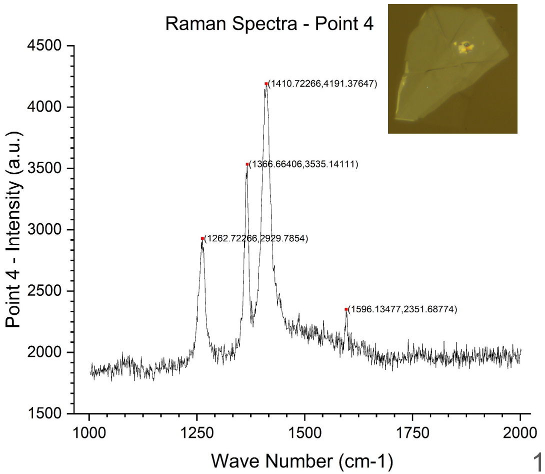






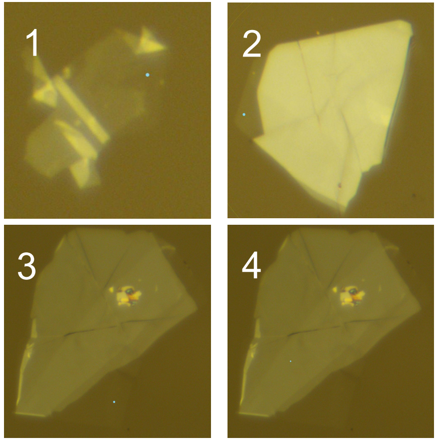




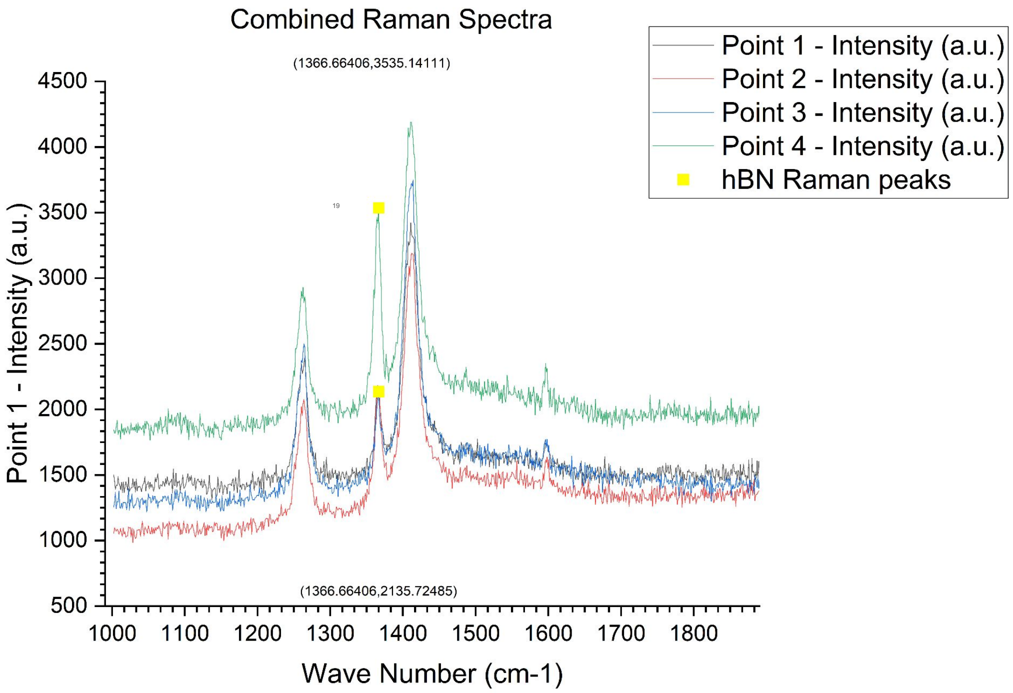


Reference: DOI: 10.1039/c7ra00260b

hBN Peak Positions



Point #	Peak Position hBN	Peak Position - Point 4 Peak position	Peak Position - Avg(~Monolayer peak position)
1	1366.251	0.982	0.03100
2	1366.184	0.915	0.03604
3	1366.225	0.956	0.00504
4	1365.269	0	0.95133



Future Work

Future Work

Goals:

1. hBN monolayers on gold nanoparticles(GNP) on a SiO2 - Si substrate
2. hBN monolayers on gold nanocones(GNC) on a SiO2 - Si substrate

Tasks:

Experimental	**Theoretical / Simulation**
1. Transfer of samples to SiO2 - Si substrate 2. AFM characterisation to ascertain monolayers	FDTD simulations: 1. hBN on SiO2-Si 2. hBN on GNP + SiO2-Si 3. hBN on GNC + SiO2-Si

Thank you

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