

# Hexagonal boron nitride as an ideal substrate for carbon nanotube photonics

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## 1. Introduction

Hexagonal boron nitride (*h*-BN), a two-dimensional (2D) material, is atomically flat with low defect density, which is widely used to support other 2D materials for both electronics and photonics.<sup>[1,2]</sup> We expect that the advantages of *h*-BN can also be utilized in mixed dimensional heterostructures, and single-walled carbon nanotubes (CNTs) would provide a unique opportunity in this context. The one-dimensional nature of CNTs results in enhanced Coulomb interactions, giving rise to tightly bound excitons that show photoluminescence (PL) at room temperature. CNTs directly attached on solid-state substrates such as SiO<sub>2</sub>/Si, however, suffers from the strong substrate quenching effect, hindering applications in all-solid-state optical devices.<sup>[3]</sup> By using *h*-BN as a substrate, the quenching effect is expected to be suppressed. Moreover, excitons in CNTs are sensitive to the dielectric environment, and intimate contact with the 2D *h*-BN substrate could result in large modifications in excitonic energies.

## 2. Experiments

We study *h*-BN effects on PL excitation (PLE) spectra of CNTs by transferring CNTs on *h*-BN flakes.<sup>[4]</sup> CNTs are first grown on a SiO<sub>2</sub>/Si substrate, and we prepare *h*-BN flakes on another SiO<sub>2</sub>/Si substrate by mechanical exfoliation. The CNTs are picked up by using a PDMS/anthracene stamp and transferred on the target *h*-BN flake by using the micromanipulator system. PDMS is peeled off and anthracene is sublimated at 110°C, leaving a clean surface for CNTs. It is noted that CNTs are transferred on the surrounding SiO<sub>2</sub>/Si substrate simultaneously due to the large area of the PDMS/anthracene stamp. An atomic force microscopy (AFM) phase image of CNTs on both *h*-BN and the SiO<sub>2</sub>/Si substrate is shown in Figure 1(a), and it is observed that many randomly oriented CNTs are firmly attached to both *h*-BN and the SiO<sub>2</sub>/Si substrate without showing any loose ends or segments.

Integrated PL images are taken in the same region as the AFM image and shown in Figure 1(b). Although CNTs are transferred on both the *h*-BN flake and the SiO<sub>2</sub>/Si substrate, only CNTs on *h*-BN show bright PL. Compared with conventional substrates, the *h*-BN substrate is atomically flat with no dangling bonds and low defects density, which might contribute to the considerable suppression of the

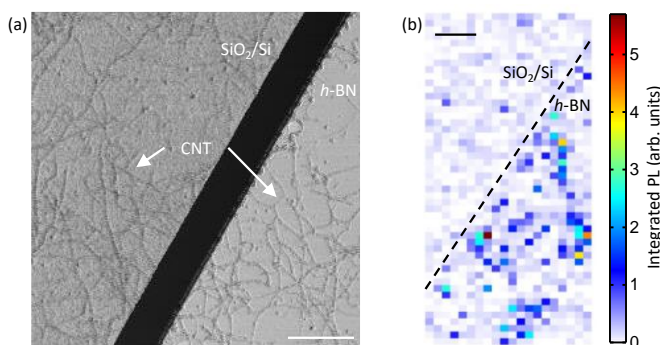


Figure 1. (a) An AFM phase image at the edge of the *h*-BN flake. (b) An integrated PL image at the edge of the *h*-BN flake. Scale bars in (a), (b) are 2, 4  $\mu\text{m}$ , respectively.

substrate quenching effect. Moreover, the large redshifts in  $E_{11}$  and  $E_{22}$  of  $\sim 50$  meV are observed, which is attributed to the dielectric screening effect.

## 3. Conclusions

We have demonstrated that CNTs directly attached to *h*-BN are highly luminescent with narrow linewidths, which is comparable to air-suspended CNTs.

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## References

- [1] K. F. Mak, K. He, J. Shan, T. F. Heinz, *Nature Nanotechnol.* **7**, 494 (2012).
- [2] N. Fang, S. Toyoda, T. Taniguchi, K. Watanabe, K. Nagashio, *Adv. Funct.* **29**, 1904465 (2019).
- [3] J. Lefebvre, Y. Homma, P. Finnie, *Phys. Rev. Lett.* **90**, 217401 (2003).
- [4] N. Fang, K. Otsuka, A. Ishii, T. Taniguchi, K. Watanabe, K. Nagashio, Y. K. Kato, *ACS Photonics* (2020). DOI:10.1021/acsphotonics.0c00406.