

Hexagonal boron nitride as an ideal substrate for carbon nanotube photonics

Nan Fang^{1,2}, Keigo Otsuka¹, Takashi Taniguchi³, Kenji Watanabe³, Kosuke Nagashio⁴, Yuichiro K. Kato^{1,2}

¹RIKEN CPR

Hirosawa, Wako, Saitama 351-0198, Japan

Phone: +81-48-462-1449 E-mail: yuichiro.kato@riken.jp

²RIKEN RAP

Hirosawa, Wako, Saitama 351-0198, Japan

³NIMS

Namiki, Tsukuba, Ibaraki 305-0044, Japan

⁴Univ. of Tokyo

Hongo, Bunkyo-ku, Tokyo 113-8654, Japan

Abstract

Hexagonal boron nitride is widely used as a substrate for two-dimensional materials in both electronic and photonic devices. Here, we demonstrate that two-dimensional hexagonal boron nitride is also an ideal substrate for one-dimensional single-walled carbon nanotubes. Nanotubes directly attached to hexagonal boron nitride show bright photoluminescence with narrow linewidth at room temperature, comparable to air-suspended nanotubes. Although hexagonal boron nitride has a low dielectric constant and is attached to only one side of the nanotubes, we observe that optical transition energies are redshifted ~50 meV from the air-suspended nanotubes. This work opens up new possibilities for all-solid-state carbon nanotube photonic devices by utilizing hexagonal boron nitride substrates.

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.^[1,2] 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 SiO₂/Si, however, suffers from the strong substrate quenching effect, hindering applications in all-solid-state optical devices.^[3] 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.

Here we investigate two different types of heterostructures consisting of *h*-BN and CNT by using PL excitation (PLE) spectroscopy. In samples where *h*-BN flakes are transferred on individual air-suspended CNTs, the chiralities are unambiguously assigned and the same tubes are tracked for

h-BN effects. Bright luminescence with a narrow linewidth is observed from the CNTs directly attached to *h*-BN at room temperature, indicating weak quenching and small broadening effect from *h*-BN. Excitonic energies are found to exhibit considerable redshifts as well. The results demonstrate the ideal properties of *h*-BN as a substrate for CNT photonic devices.

2. Experiments

We begin by studying *h*-BN/CNT heterostructures consisting of an *h*-BN flake on top of an individual air-suspended CNT as shown in Fig. 1(a).^[4] First, the air-suspended CNTs are prepared on silicon substrates. Next, an *h*-BN flake is transferred on top of a CNT with the help of the marks on the substrate using a micromanipulator system. A typical *h*-BN/CNT sample is shown in Fig. 1(b). The *h*-BN/CNT structures are investigated with a home-built confocal PL microscopy system at room temperature. We characterize the *h*-BN effects on the CNTs by comparing PLE maps of individual CNTs before and after the transfer of *h*-BN [Fig. 1(c,d)]. A clean PLE map can be obtained even after the transfer, since the PL intensity remains sufficiently strong. The reduction ratio of PL intensity after transfer compared to before transfer averages to 0.48 over 8 tubes, while the PL reduction ratio is typically less than 0.01 in the current solid-state substrates such as SiO₂/Si, quartz, and metals. The modest reduction of PL after the transfer of *h*-BN indicates the quenching effect from *h*-BN is weak, making *h*-BN a promising substrate for light-emitting CNT devices.

We point out that the full width at half maximum for *E*₁₁ emission shows only a slight increase by 2.2 meV. The linewidth of *h*-BN/CNT is much smaller than CNTs on other solid-state substrates, while the inhomogeneous linewidth broadening of the ground exciton of WS₂ (WSe₂) in 2D WS₂ (WSe₂)/*h*-BN heterostructures is reported to be ~2 meV at low temperatures. The small change in the linewidth at room temperature suggest that our 1D/2D heterostructures show comparable interfacial properties to 2D/2D heterostructures.

The PLE maps also show substantial modifications of the excitonic energies. We identify the nanotube chirality from

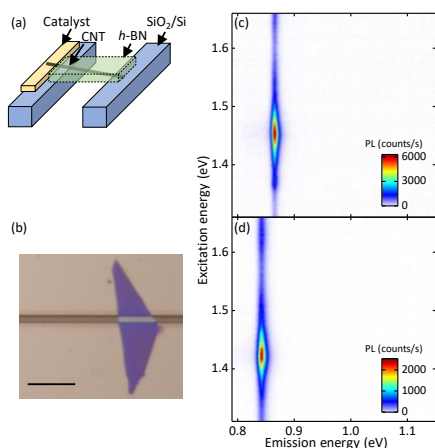


Fig. 1 (a) A device schematic of an air-suspended CNT with an *h*-BN flake transferred on top. (b) An optical microscope image of a typical *h*-BN/CNT sample. Scale bar is 20 μm . (c) and (d) PLE maps of an air-suspended (10,8) CNT before and after the transfer of a *h*-BN flake, respectively.

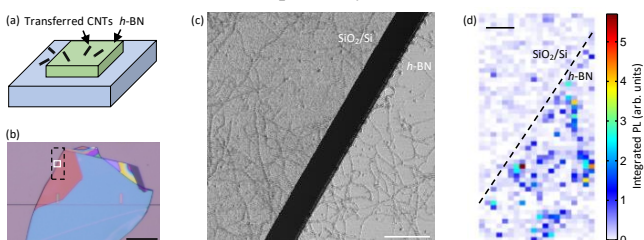


Fig. 2 (a) A schematic of CNTs transferred on an *h*-BN flake. (b) An optical microscope image of the CNT/*h*-BN sample. White and black boxes indicate the areas measured in (c) and (d), respectively. (c) An AFM phase image at the edge of the *h*-BN flake. (d) An integrated PL image at the edge of the *h*-BN flake. Scale bars in (b), (c), and (d) are 50, 2, and 4 μm , respectively.

the PLE map before transfer [Fig. 1(c)] to be (10,8) by extracting the E_{11} and the E_{22} energies from the emission and the excitation resonances, respectively. After the transfer of *h*-BN, we observe redshifts of 21 and 30 meV for E_{11} and E_{22} , respectively. We measured 18 more samples with different chiralities, and all the samples show redshifts for both E_{11} and E_{22} . Dielectric screening from *h*-BN is expected to cause some redshift, but the observed shifts are large considering the fact that *h*-BN is only attached to one side of the CNT.

Up to this point, we have been focusing on *h*-BN/CNT samples with individual nanotubes that allow for chirality identification before *h*-BN transfer. Now that we understand the general behavior of the CNTs upon contact with *h*-BN, we are in a good position to study an ensemble of CNTs directly transferred onto *h*-BN without prior characterization. CNTs are first grown on a SiO_2/Si substrate, and we prepare *h*-BN flakes on another SiO_2/Si substrate by mechanical exfoliation. The CNTs are picked up and transferred on the target *h*-BN flake by using the micromanipulator system. We will refer to this structure as CNT/*h*-BN, and the corresponding schematic and optical microscope image are shown in Fig. 2 (a,b), respectively. It is noted that CNTs are transferred on the surrounding SiO_2/Si substrate simultaneously due to the large area of the PDMS/antracene stamp. An atomic force microscope (AFM) phase image of CNTs on both *h*-BN and the

SiO_2/Si substrate is shown in Fig. 2(c), and it is observed that many randomly oriented CNTs are firmly attached to both *h*-BN and the SiO_2/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 Fig. 2(d). Although CNTs are transferred on both the *h*-BN flake and the SiO_2/Si substrate, only CNTs on *h*-BN show bright PL. In previous reports of transferred CNTs on quartz or glass substrates, the dominant factor that affects the PL intensity was pointed out not to be the substrate itself but the elimination of interaction between substrates and CNTs by the transfer process. In contrast, our results reveal that the PL quenching effect is significantly affected by the substrate itself and indicate the superior compatibility between 1D and 2D materials. 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 substrate quenching effect.

3. Conclusions

In summary, we have investigated *h*-BN effects on the optical properties of CNTs by performing PL spectroscopy on *h*-BN/CNT and CNT/*h*-BN heterostructures at room temperature. We have demonstrated that CNTs directly attached to *h*-BN are highly luminescent with narrow linewidths of ~ 12 meV, which is comparable to air-suspended CNTs. The substrate quenching and broadening effects on the *h*-BN substrates are found to be much weaker than those in conventional substrates such as quartz and SiO_2/Si . In addition, the anomalously large redshifts in E_{11} and E_{22} are observed despite the fact that *h*-BN has a low dielectric constant and is only attached to one side of the CNT. These findings highlight the superior properties of *h*-BN for 1D/2D hybrid-dimensional photonics and open a new pathway for manipulating excitons in CNTs.

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