How Clean Is Clean? Recipes for van der Waals Heterostructure Cleanliness Assessment

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ABSTRACT: Van der Waals (vdW) heterostructures, artificial stacks of two-dimensional materials, present an exciting platform to explore new physical phenomena and unique applications. An important and increasingly recognized factor limiting the electrical and optical performance of heterostructure samples is the presence of interfacial contamination. In published work reporting various heterostructure fabrication methods, evidence for the cleanliness of samples is often presented as optical and atomic force microscopy images, typically exhibiting a completely flat topography. In this work, we demonstrate that such samples may nonetheless contain a uniformly thin layer of contaminants at the heterostructure interface. As alternatives, we propose two robust visualization methods that are highly sensitive to such residues, based on photoluminescence mapping and on selective solvent diffusion. The detection capability and straightforward implementation of these two imaging techniques make them powerful tools to assess and improve the cleanliness of a wide variety of fabrication techniques for heterostructures comprising any combination of vdW materials.

KEYWORDS: van der Waals heterostructures, organic residues, contaminant visualization, photoluminescence, solvent diffusion

INTRODUCTION

In parallel with the rapid expansion of the library of available two-dimensional (2D) materials, van der Waals (vdW) heterostructures, artificial stacks of atomically thin 2D crystals, have emerged as a promising and extremely active research field.1,2 The first demonstration of a vdW heterostructure involved monolayer graphene transferred onto hexagonal boron nitride (hBN), resulting in a significant improvement in the electronic properties of the graphene monolayer.3 Since then, vdW heterostructures have enabled the exploration of intricate physical phenomena such as Coulomb drag in bilayer graphene structures,4,5 the giant Stark effect in black phosphorus,6 and more.7−11

Methods for the large-scale fabrication of vdW heterostructures include the roll-to-roll assembly of large-area thin films,12,13 and direct heterostructure growth.14,15 However, these approaches are presently limited to relatively few 2D materials, and transfer stacking of exfoliated and chemical vapor deposition-grown materials remains the most widely used mode of heterostructure assembly. A typical transfer procedure involves the deposition of a polymer onto the vdW flake to be transferred, such as polymethylmethacrylate (PMMA)8 or poly(lactic acid).16 This is followed by the removal of the original substrate, aligned transfer to form the heterostructure, and polymer dissolution in organic solvent. Samples with improved cleanliness were achieved by so-called dry methods, which involve the direct exfoliation of vdW materials onto a polymeric stamp17 or heat-assisted pickup of a flake deposited on a SiO2 substrate18 and subsequent deposition onto the target material, without the involvement of solvents. Hybrid methods that utilize solvents for only part of the procedure (pickup or deposition) are referred to as semi-dry,19 which is the fabrication approach chosen for samples discussed in this work.

Resulting vdW heterostructures often contain organic residues that originate from exfoliation and/or transfer steps. Frequently, residues manifest themselves in the form of blisters or bubbles that are trapped at the interface between vdW layers.20 Such interfacial contaminants are increasingly recognized as a limiting factor of sample quality, as they contribute to an inhomogeneous surface potential associated with impurity scattering,21 and they have been demonstrated to lead to spatial variability in the interlayer coupling.22 Recipes that are successful in cleaning the surface of 2D materials, such as the drastic reduction of PMMA residue adhering to the surface by heat treatment in a partial hydrogen atmosphere,23−25 frequently do not extrapolate easily to the...
Figure 1. Benchmarking PL-based visualization method on hBN/hBN stacks with a moderate degree of contamination. (a−f) hBN/hBN stack with contaminant bubbles on top of the sample surface. These residues are not apparent in bright-field microscopy images, but are visible in the AFM topography map. Their location on top of the sample surface is confirmed by AFM phase lag contrast [arrows in panels (d,e)]. (g−l) hBN/hBN stack with contaminant bubbles at the interface. Residues are visible in AFM topography [white arrows in panel (j)], but they are not visible in the AFM phase lag map [corresponding arrows in panel (k)], implying that they are located at the interface. For both stacks, PL mapping [panels (f,l)] detects contaminants throughout the area of the top hBN sheets [hBN #2]. PL intensities are in arbitrary units. Phase-lag images are shown without processing. White and yellow lines: outlines of hBN flakes.

Cleanliness Assessment in Heterostructures: How Clean is Clean? We first present a method to analyze the cleanliness of heterostructure fabrication techniques that exploits PL measurements on hBN/hBN stacks as its platform. While such hBN/hBN stacks are unlikely to hold any intrinsic interest, we have found them to be a very useful tool, for the following reasons: first, the chemical inertness of hBN enables us to completely eliminate polymer residues introduced during mechanical exfoliation using an aggressive thermal treatment (see Supporting Information), such that contaminants detected after stack assembly can be clearly assigned to the transfer step. Second, hBN is known to exhibit strong PL in the presence of hydrocarbon residues, and we utilize this effect to visualize contaminants that are not detectable by other means. This approach is underpinned by the reasonable assumption that the degree of contamination that a fabrication technique introduces into heterostructures comprising arbitrary vdW materials, which is often difficult to assess, will closely parallel the extent of residues it introduces in hBN/hBN stacks, which our method excels at detecting.

Our study utilizes hBN/hBN stacks prepared via a transfer method utilizing polydimethylsiloxane (PDMS) sheets as stamps, in a semi-dry variation of the procedure introduced by Castellanos-Gomez et al. (see Supporting Information for details). In Figure 1, we benchmark our PL-based visualization approach on two representative hBN/hBN stacks that feature a modest degree of contamination. Both samples have contamination levels that are sufficiently small to be undetectable in bright-field microscopy images (Figure 1b,h). In contrast, AFM topographic scans in both cases readily detect small bubble-like features located in the overlapping case of interfacial residue which is located less accessibly. This has motivated the development of other techniques to remove/reduce contamination bubbles, such as directional compression of the polymeric stamp at elevated temperature during assembly in order to induce the migration of the bubbles out of the heterostructure area, or removal of residue bubbles by scanning the assembled heterostructure with an atomic force microscopy (AFM) tip in contact-mode. Analysis of the chemical composition of trapped interfacial residues by spectroscopic means has been demonstrated recently, but is only possible when relatively sizable accumulations of residue are present. Most commonly, assessment techniques for sample quality pre-screening are limited to bright-field optical microscopy and AFM topography mapping, with the underlying assumption that an apparently flat heterostructure surface corresponds to a clean interface. There is no doubt that the absence of visible contamination features is a necessary condition for a clean interface, but is it a sufficient condition, too?

In this work, we show that this is not the case. Specifically, we demonstrate that contaminants can form a thin uniform layer at the heterostructure interface. Such layers of uniform height are hidden in plain sight, in the sense that they are not detectable by optical microscopy or AFM. We note that we have found this particularly difficult-to-detect case to be very common. Further, we propose two straightforward but powerful characterization techniques that are highly sensitive to the presence of contaminants: (1) visualization of hidden organic residues by exploiting their intense PL when in contact with hBN and (2) contaminant visualization by selective organic solvent diffusion, which induces migration and agglomeration of hidden residues, resulting in features that are also visible by optical microscopy and AFM.

These approaches are not intended as pre-screening methods for individual heterostructures. The value of our methods lies in their ability to accurately assess the degree to which a heterostructure fabrication technique introduces interfacial contamination, even in circumstances where conventionally used approaches do not detect any residues, thus enabling the rational selection and/or development of cleaner assembly protocols.
regions (Figure 1c,d,i,j). This observation alone provides no information on the vertical location of residues within the heterostructure; however, insight on the precise vertical position of contaminants is desirable because interface contamination is far more detrimental to heterostructure quality than contaminants located on the surface only. We resolve this question by utilizing the phase-lag signal of ac-mode AFM that is collected simultaneously with AFM topography data. The AFM phase-lag signal is sensitive to chemical surface contrast. It has been used extensively to visualize surface chemical heterogeneity, but it does not seem to be utilized routinely in the contamination assessment of vdW heterostructures. In the case of the hBN/hBN stacks discussed here, in one sample the presence of phase-lag features clearly locates contaminants on the sample surface (Figure 1e), whereas in the other sample the absence of such features demonstrates that residue bubbles are trapped at the interface (Figure 1k). In Figure 1f,l, we show PL acquired on these two samples, representing the visualization method that is the focus of this section. In both cases, the presence of intense PL visualizes heterogeneous distributions of organic residues throughout extended sample regions. Comparison between AFM topography and PL scans shows clearly that PL is highly sensitive to organic contaminants located on or within hBN stacks.

We note that we deliberately do not study hBN stacks in which contamination bubbles are evident in bright-field optical images because samples with such extensive contamination do not require special visualization techniques. Having benchmarked our visualization technique using hBN samples of moderate cleanliness, we will now demonstrate its utility on the case of a much higher-quality hBN/hBN stack that has no evident residue bubbles. Figure 2 presents the characterization of two individual hBN sheets (Figure 2a–j) and of the resulting stack (Figure 2k–o). Bright-field images as well as AFM topography and phase-lag maps of the individual hBN sheets and their assembly show surfaces of uniform height and without any chemical contrast (see Figure S5 for further magnification); judged by these conventionally used techniques, this hBN/hBN stack would appear to be free from residues. An AFM topographic roughness characterization (Figure S6) finds that the surface roughness before versus after stacking is indistinguishable. PL maps confirm that prior to assembly, the individual hBN sheets have no organic contamination, except along linear folds where the residue from mechanical exfoliation could not be fully removed (Figure 2j). In contrast, the PL map of the hBN/hBN stack reveals finite PL intensity throughout the area of the top hBN sheet (Figure 2o, yellow outline). Taken together, our characterizations clearly demonstrate the presence of a contaminant film of uniform thickness along the entire stack interface, and the introduction of these residues can be clearly assigned to the stack assembly step. These observations also provide an unambiguous example for our notion that a flat sample topography alone is not sufficient evidence that a heterostructure is contamination-free. Furthermore, even when isolated bubble-like features are detected in AFM topography images, such as in Figure 1i,j, this observation on its own may...
greatly underestimate the amount of the residue present, as demonstrated by the PL map of the same sample (Figure 1l.) Figures 3 and S8 show the procedure of cleanliness assessment described above in the form of a decision flow-chart.

Quantifying the sensitivity of this method in detecting contaminants is complicated by the absence of an independent, similarly sensitive measure for the amount of residue present. Using a data set in which topographic and PL features can be clearly correlated, we have established an upper bound for the sensitivity of $1.1 \times 10^{-16} \text{g} (110 \text{ ag})$, corresponding to $1.5 \times 10^{-18} \text{mol} (1.5 \text{ amol})$ of PDMS (see Supporting Information for details). The actual detection limit is likely significantly better than this bound.

The characterizations presented so far centered on vdW stacks that were fabricated using an uncommon semi-dry PDMS-based protocol. However, our technique to detect minute amounts of residue functions equally well for samples assembled via the more common all-dry methods. Figure S7 presents an hBN/hBN stack fabricated with all-dry PDMS stamping. On AFM topography and phase-lag images, the portion of the samples in which the two hBN sheets overlap appears largely contamination-free. In contrast, the PL map shows finite PL intensity throughout the overlapping area, demonstrating the presence of residues that would have otherwise remained hidden.

We now briefly discuss the mechanism that may underlie the PL emission from contaminated areas. We begin by noting that residues have an intense PL signature only in the presence of hBN, but not for semimetallic vdW materials such as graphene, or semiconductors like molybdenum disulfide ($\text{MoS}_2$). A plausible mechanism for the generation of PL in the presence of hBN would be that the contaminants need to possess some degree of intrinsic fluorescence. In this picture, hBN is distinguished by its wide bandgap which prevents it from causing fluorescence quenching, unlike other 2D materials. However, we cannot exclude the possibility that other mechanisms contribute. Of note, we do not observe comparable PL on the SiO$_2$ substrate, even though the bandgap of SiO$_2$ is even wider than that of hBN. We also remark that the match between topographic and PL features is rarely perfect; for example, whereas Figure 2l reveals an extremely flat surface, the PL map in Figure 2o shows a patchy intensity distribution. The origin of these slight discrepancies is an open question.

Regarding contaminant species that can be visualized in this manner, from Figure 2 it is clear that residues were introduced during the transfer step. This implicates the PDMS stamp as the source of contaminants, suggesting that the latter may be incompletely polymerized methylsiloxane oligomers (see Supporting Information for discussion). Additionally, earlier work covering cleaning recipes for hBN has shown that both adhesive residues from mechanical exfoliation and photoresist residues similarly lead to intense PL. Together, these substances cover a large fraction of the organic contaminants encountered in practice when processing 2D materials. We remark that all these residue sources are complex organic mixtures and their precise compositions are not publicly available, and the factors that determine PL emission are not yet fully understood. These uncertainties notwithstanding, our visualization method clearly represents a highly sensitive means to detect minute amounts of common interfacial contaminants, and as such it provides a powerful tool to assess the cleanliness of a wide variety of heterostructure assembly protocols.

As discussed earlier, the residue visualization protocol demonstrated so far depends on hBN as a tool because of the unique property of hBN to enable high intensity PL when organic contaminants are present. In the following, we propose a separate, complementary method for the detection of interfacial contaminants, based on a different mechanism that
Visualizing Contaminants: Selective Solvent Diffusion at vdW Interfaces. Here, we propose an alternative method for the visualization of "hidden" contaminants that are frequently present as uniformly thin films inside vdW heterostructures, based on selective solvent penetration along the heterostructure interface. Figure 4a schematically depicts our approach: when the vdW stack to be examined is immersed in organic solvent, the solvent is able to diffuse along the interface, especially when the adhesion between flakes is reduced by the presence of residues and/or imperfect lattice matching. As the solvent reaches organic contaminants, polymeric chains of the latter can migrate along the interface and redistribute, often accumulating and forming bubble-like objects at energetically preferred sites such as sheet edges or steps. When the solvent is subsequently cleared, the top vdW sheet of the heterostructure conformally envelops the contaminant bubbles, thus rendering them detectable by optical microscopy and/or AFM.

Our approach is described in Figure 3b in the form of a flow-chart, and demonstrated in Figure 4 on a stacked hBN/hBN sample. The as-made sample (previously shown in Figure 2) is characterized by brightfield optical microscopy, AFM topography and phase-lag imaging, and PL mapping (Figure 4b–e). As discussed above, this vdW stack contains a uniformly thin layer of contaminants trapped under the top hBN sheet which is not detectable by optical microscopy and AFM characterization, and it may thus be erroneously categorized as contamination-free. The sample is then immersed into a solvent (TCE) for 30 min, left to dry thoroughly, and then characterized again in the same manner. Post solvent treatment, prominent new features are visible in the AFM topography in the form of bubbles and line-shaped wrinkles (Figure 4g, arrows, and Figure S9). These features also have high visibility in the AFM phase-lag image (Figure 4h).

Since this particular sample is a hBN/hBN stack, we also present PL intensity maps before and after solvent immersion (Figure 4e,i), and we use them to establish that the newly created topographic features reflect the rearrangement of organic residues and are not caused by the mechanical action of the solvent alone. In the PL map shown in Figure 4i, line-like features of high intensity closely match those detected by AFM, showing clearly that residues are present within all topographic wrinkles. In addition, contaminants have accumulated along all sheet edges and steps. We remark that here we present PL maps for additional analysis only—the express purpose of developing this technique is to enable contaminant detection also for vdW heterostructures that do not comprise hBN, and the utility of the method presented here lies primarily in the sizable, contaminant-induced features that AFM can detect.

A potential reservation with respect to the method presented here is that it is not clear a priori that the line-like topographic features visible in AFM scans after immersion in solvent are necessarily due to rearranged polymeric contaminants, as these features could also reflect the presence of residual solvent instead. We argue that it is indeed polymer residue causing these features, based on the high vapor pressure of TCE. The PL intensity scan shown in Figure 4i was acquired approximately 6 h before AFM measurements (Figure 4g,h) were performed; in the intervening time the sample was stored at room temperature. Despite the delay of several hours, the...
prominent line-like features in AFM images clearly correspond to high-intensity features of identical shape and location in the PL map. Due to TCE’s high vapor pressure, it would have most likely diffused out of the heterostructure by the time we performed AFM measurements, which would have led to strongly altered topographic features. Furthermore, when liquids are present under vdW sheets, scan-to-scan variations are typically observed during AFM data acquisition. We did not observe any such variability.

We note that besides TCE, we have also found DMF to be effective in visualizing contaminants originally located at the vdW interface.

The visualization method presented here applies equally well to vdW materials other than hBN. We demonstrate this for the case of MoS2 as a prototypical TMD material. In Figure S10, we present a MoS2/hBN heterostructure, assembled using the same semi-dry transfer protocol. Comparing the AFM topography maps before versus after immersion in TCE, it is evident that significant rearrangement of interfacial residues has taken place, resulting in features with high topographic contrast post-immersion. Furthermore, we expect the utility of this visualization method to extend to a wide class of 2D materials: quantitative information on the solubility parameters that govern the interaction with polymers and solvents is available for graphene, as well as MoS2, MoSe2, MoTe2, and WS2, and the numerical parameter values are extremely similar for all these materials (see Table S1 in Supporting Information). Moreover, extrapolating from these four TMD materials, we expect that solubility parameters will also be similar for other vdW materials in which individual layers are bounded by sheets of chalcogens (X = S, Se, and Te), for example, all layered TMD (MX2) and phosphorus trichalcogenides (MPX3).

For completeness, we note that instead of solvent immersion, heat treatment of vdW stacks can be effective in visualizing residues because elevated temperature enables polymeric contaminants to migrate and aggregate. However, depending on the details of the annealing protocol, topographic and chemical modification of the organic residues can be rather complex, making this approach less helpful (Figure S11; refer to Supporting Information for a more detailed discussion).

While the above results unambiguously demonstrate that immersion of vdW samples in organic solvent can visualize hidden contaminants, the proposed mechanism of aggregation via solvent diffusion along the vdW interface was presented above as a conjecture. The fact that DMF and other solvents are frequently used to perform liquid exfoliation of bulk vdW materials suggests that solvents can also propagate along the interface of vdW stacks. Besides, we support our conjecture with additional experimental evidence for solvent diffusion along a vdW interface in the following. For this demonstration, we choose exfoliated monolayer graphene deposited on an oxidized silicon substrate, taking advantage of the well-known facts that (i) after heat treatment, thin graphene sheets conformally adhere to the SiO2 substrate, leading to enhanced interaction with the substrate and strong p-type doping; (ii) the Raman spectrum of monolayer graphene is highly sensitive to doping, the degree of which can be inferred from the positions of the G- and 2D-bands; and (iii) when solvent diffuses between the graphene monolayer and the substrate, doping is reversed. It was shown previously that water slowly diffuses along the monolayer graphene/SiO2 interface, on a time-scale of weeks. Here, we show that organic solvent similarly undercut the monolayer graphene sheet, albeit on a much shorter time-scale.

Our experimental procedure is schematically depicted in Figure S5a. After mechanically exfoliating graphene onto a SiO2 substrate, we pre-clean the sample by immersion in TCE for 30 min and perform a heat treatment at 400 °C in an argon atmosphere for 2 h. While undoped monolayer graphene has its G-band located at ∼1585 cm⁻¹, a blue shift of the G-band of the sample’s monolayer portion by ∼10 cm⁻¹ to ∼1595 cm⁻¹ is clearly visible, corresponding to a doping level of ∼10¹³ cm⁻². The G-band upshift is accompanied by a broadening of the 2D-band, which is another known signature of doping. Next, the sample is immersed in organic solvent (DMF) and then left to dry thoroughly. Subsequent Raman spectral characterization (Figure S5c,d) reveals the return of the graphene monolayer’s G-band to ∼1585 cm⁻¹, accompanied by a re-sharpening of the 2D-band, demonstrating that solvent immersion results in a reversal of substrate-induced doping due to solvent undercutting and associated weakening of the graphene/substrate interaction. We remark that the solvent film temporarily formed under the graphene flake must be very thin (comparable to monolayer) because the flake’s position remained unchanged during immersion. (Full Raman spectra...
are shown in Figure S12; the absence of a D-band shows that the graphene sample did not sustain any damage during heat treatment and solvent immersion.)

Since the Raman peak positions of graphene are sensitive to both doping and strain, we perform a more detailed analysis of G- and 2D-band positions in order to exclude sample strain as the origin of the peak shifts described above. In Figure S5e, we summarize all data points acquired by Raman spectral mapping in the monolayer portion of the graphene sample, plotting the 2D-band position versus the G-band position for every pixel within the monolayer area. Our analysis utilizes that a strain-induced band shift leads to a slope $\partial \text{pos}(2D)/\partial \text{pos}(G) = 2.2$, whereas doping leads to $\partial \text{pos}(2D)/\partial \text{pos}(G) = 0.7$.35 In Figure S5e, the spread of data points acquired for the heat-treated sample precisely matches the expectation for a graphene substrate-induced doping, and its reversal caused by solvent immersion in organic solvent can be clearly assigned to interface which does not leave a topographic signature. In this work, we show that commonly used methods for the detection of such contaminants, typically limited to bright-field optical microscopy and AFM topography measurements, are insensitive to such uniformly thin residue films. Further, we present two methods that are far more sensitive tools for the visualization of interfacial contaminants, and that successfully address the troublesome case of thin, flat residue films: non-invasive PL mapping visualizes organic residues by utilizing their intense PL emission when in contact with hBN; and selective solvent diffusion along vdW interfaces results in the collection of residues in agglomerates that can be detected by topographic measurements. Our characterization approaches are not intended for the pre-screening of individual samples. Rather, they provide workers with two powerful tools to perform cleanliness assessments of arbitrary vdW heterostructure fabrication techniques, to aid in the informed selection of the most appropriate technique or the development of new protocols. We anticipate that the systematic application of our visualization techniques will assist the development of cleaner transfer procedures and thereby contribute to the ongoing quest for new physical phenomena in higher-quality vdW heterostructures.

CONCLUSIONS

Growing awareness of the detrimental effects that interfacial contamination can have on the properties and performance of vdW heterostructures has stimulated the development of cleaner stacking techniques. The quality of resulting heterostructure samples has increased to the point that they may not feature contamination bubbles. However, such samples may nonetheless contain a uniformly thin residue film at the interface which does not leave a topographic signature. In this work, we show that commonly used methods for the detection of such contaminants, typically limited to bright-field optical microscopy and AFM topography measurements, are insensitive to such uniformly thin residue films. Further, we present two methods that are far more sensitive tools for the visualization of interfacial contaminants, and that successfully address the troublesome case of thin, flat residue films: non-invasive PL mapping visualizes organic residues by utilizing their intense PL emission when in contact with hBN; and selective solvent diffusion along vdW interfaces results in the collection of residues in agglomerates that can be detected by topographic measurements. Our characterization approaches are not intended for the pre-screening of individual samples. Rather, they provide workers with two powerful tools to perform cleanliness assessments of arbitrary vdW heterostructure fabrication techniques, to aid in the informed selection of the most appropriate technique or the development of new protocols. We anticipate that the systematic application of our visualization techniques will assist the development of cleaner transfer procedures and thereby contribute to the ongoing quest for new physical phenomena in higher-quality vdW heterostructures.

Sample Preparation. Bulk crystals of natural graphite are obtained commercially (NaturGraphit GmbH); we grow hBN crystals using the method previously described by Watanabe et al.46 All solvents are purchased from Daejung Chemicals. As substrates, we use silicon wafer pieces with 300 nm SiO$_2$, which are pre-cleaned by immersion in TCE for 30 min in order to remove any pre-existing organic contaminants. Mechanical exfoliation of bulk crystals is performed using Ultron 1007R wafer dicing tape (Ultron Systems Inc.). In order to remove adhesive residues from exfoliated vdW flakes, we immerse samples in TCE for 30 min after exfoliation.45 On hBN flakes, we perform an additional thermal treatment (700 °C in 10% O$_2$/Ar atmosphere, 1 bar pressure, for 3 h) in a tube furnace (MTI Corp.) for the complete removal of hydrocarbon contamination. The procedure by which we subsequently prepare vdW stacks is described in detail in Supporting Information.

Sample Characterization. Optical brightfield images were acquired on a Leica DM2700M optical microscope. We characterize pristine samples and completed vdW stacks using Raman/PL spectroscopy and ac-mode AFM. Optical spectra are collected on a WITec alpha-300 microscope, using a 100X objective and a Nd:YAG-laser of wavelength 532 nm, at low laser power ~0.5 mW to avoid heating and sample damage. PL intensity data shown in this work refer to an integration range of 1.91–2.16 eV. We collect ac-mode AFM data on a Park Systems XE-7 AFM, using silicon cantilevers of spring constant 40 N/m and tip radius $r < 10$ nm. The cantilever amplitude setpoint is chosen appropriately to maximize phase-lag surface contrast. AFM data are processed using the Gwyddion software package.46 No corrections have been applied to phase-lag images. The AFM and scanning Raman/PL microscope are located inside an inert-gas glovebox with H$_2$O and O$_2$ concentrations below 1 ppm.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsami.9b18821.

Heterostructure assembly protocol based on solvent-assisted PDMS pickup; additional PL and AFM characterizations of hBN/hBN vdW stacks; contaminant visualization by heat treatment; and discussion of vdW flake pickup efficiency as a function of solvent choice (PDF)

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Notes
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