Supporting Information

Nanometer Resolution Elemental Mapping in Graphene-based TEM Liquid Cells

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Keywords: EDX spectrum imaging, in situ TEM, graphene liquid cells, nanoparticles, Van der Waals heterostructures

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**Graphene Liquid Cell Fabrication Procedure**

A step by step outline of the fabrication process is shown in Figure S1, including schematics of the transfer process and optical images at each fabrication stage. To prepare the engineered graphene liquid cells (EGLCs) hexagonal boron nitride (hBN) flakes were first mechanically exfoliated onto oxidized silicon wafers (Figure S1a). A 70 nm oxide thickness was used to maximize the optical contrast of the flakes. The hBN flakes were then patterned using e-beam lithography to form wells for the liquid. To do this the whole flake and substrate were spin-coated with (poly)methyl methacrylate (PMMA). E-beam lithography was then used to define circular holes in the PMMA layer. After development of the resist, reactive ion etching (RIE) with CHF$_3$ was used to transfer the exposed pattern from the resist mask to the hBN flake spacer layer. The PMMA layer was then removed using organic solvents (Figure S1b).

The top layer of few layer graphene was then transferred onto the hBN flake using a dry transfer process. In this procedure the flake is exfoliated onto a dual layer polymer membrane, consisting of PMMA and a water soluble polymer, supported on a silicon substrate (Figure S1c). The PMMA around the flake is scratched away and the underlying polymer dissolved, freeing the flake from the silicon support. It can then be transferred clean-side down onto the hBN membrane (Figure S1d). After the transfer, the graphene and hBN spacer stack were secured with a second supporting PMMA layer allowing the stacked sample to be removed from the substrate by using a weak KOH solution to etch away the underlying silicon oxide.
Figure S1. Schematic showing successive steps in EGLC fabrication process. The right column shows optical images of a specific EGLC sample at the corresponding fabrication stage. (a) hBN flakes are exfoliated onto a silicon oxide substrate. (b) hBN flakes are patterned using electron beam lithography and RIE etching. (c) 2 separate few layer graphene flakes are exfoliated, one onto a polymer layer supported by a silicon substrate and one directly onto oxidised silicon. (d) The few layer graphene flake is lifted from the silicon using the polymer film and is deposited on top of the hBN flake. The inset in the optical image (for this and subsequent steps) shows the locations of the two flakes, with hBN shown in blue/purple and graphene shown in grey. (e) The graphene + hBN spacer flake stack is transferred onto the few layer graphene on silicon oxide. During the transfer a liquid sample is introduced between the sheets. The optical image was captured prior to the removal of the polymer support film. (f) The whole EGLC sample is transferred onto a TEM compatible support. The optical image shows that some of the sample has folded during the transfer, reducing the useful area for imaging.
The top flake and patterned hBN were then transferred onto a mechanically exfoliated few layer graphene flake on silicon oxide which forms the bottom window of the cell. During transfer, the solution of interest was introduced between them using a pipette. Under the effect of van der Waals forces the bottom graphene flake and hBN spacer gradually contact, trapping liquid inside the well areas etched in the hBN spacer (Figure S1e). After the pockets are sealed, the sample is slowly dried at low temperature (~40 °C), to avoid bursting of the pockets.

The final step was to transfer the whole sample onto the support grid, in a second wet transfer process (Figure S1f). After this last transfer, the supporting PMMA can be dissolved using organic solvents, and dried supercritically to avoid damage to the graphene membranes due to surface tension. Critical point drying was performed in a CO₂ atmosphere using a Bal-Tec CPD030 critical point dryer.

**Pressure testing of the EGLCs**

Hencky's solution⁴,⁵ describes the approximate central deflection of a doubly clamped circular thin membrane under uniform pressure loading. The solution for the pressure drop across the membrane ∆P as a function of the perpendicular deflection δ of the central point is⁶,⁷ given by:

\[
\Delta P = \frac{C_1 T}{a^2} \delta + \frac{f(v)E z^D}{a^4(1 - v)} \delta^3
\]
where $T$ is the intrinsic (zero deflection) membrane tension (typically not more than $0.1 \text{ N m}^{-1}$ for exfoliated/transferred monolayer graphene$^8$), $a$ is the membrane radius, $E_{2D}$ is the 2D modulus (units N m$^{-1}$), and $v$ is the Poisson’s Ratio of the membrane material. The constant $C_1$ and function $f(u)$ are unitless and can be determined using numerical techniques.$^9$–$^{12}$ The membrane parameters are illustrated schematically in Figure S2.

This solution is generally a good approximation for circular membranes thinner than a few nm$^{13}$. It depends only on the membrane deformation, $\delta$, and pressure, although the membrane radius, $a$, can change due to partial delamination, as in panel (b) in Figure S2. The value of the pretension term, $T$, is typically $0.1 \text{ N m}^{-1}$,$^8$,$^{14}$ or lower for freshly exfoliated graphene flakes, and is only observed due to partial adhesion of the flakes around the sidewalls of the drum causing additional tension$^{16,17}$. As our samples show a ‘flat’ membrane geometry with no sidewall adhesion, and the pretension is typically lower for the same flakes after transfer due to strain relaxation, we suspect the values for pretension will be smaller for our samples. We use reported values$^{18}$ for the 2D modulus and Poisson’s ratio of

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**Figure S2:** Bowing of a thin membrane due to a pressure drop across it. In case (a), $\Delta P < 0$, and the membrane bows inwards with $a = a_0$, where $a_0$ is the cell radius. In case (b), $\Delta P > 0$ and membrane delamination can occur such that the effective membrane radius $a > a_0$. 

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graphene of $E_{2D} = 340 \pm 20 \text{ N m}^{-1}$ per layer, and $\nu = 0.19 \pm 0.02$ respectively. We assign $C_1 = 4$ and $f(\nu) = 8/3$ following previous studies where these values were shown to accurately predict the shape of graphene bubbles.\textsuperscript{19,20}

The curvature of the cell windows can therefore be used to estimate the pressure inside the cells. Figure 1c in the main text shows an AFM height image of an EGLC sample, with membrane deflections of a few nm. For small deflections such as these (~5 nm and ~2.5 nm for 1250 nm and 800 nm diameter membranes respectively with a 4 layer upper graphene membrane), the first term in equation 1 is dominant. If we assume an upper value for $T$ of 0.1 N m$^{-1}$, measured values of deflection correspond to a pressure drop of smaller than 70 ± 50 mbar. As the top flakes in the EGLC structure are transferred rather than directly exfoliated, the intrinsic tension is likely to be significantly less than the assumed value, which means the pressure drop may be even smaller. This indicates an internal pressure within the cells very close to atmospheric pressure. Indeed, 70 mbar is similar to the range through which atmospheric pressure changes with weather patterns.

To test the robustness of our EGLCs, the sample was coated by a 300 nm thick Au layer using e-beam evaporation under vacuum conditions (Figure S3). After Au evaporation the cells appear to remain intact but the upper graphene membrane had deflected by 90nm for the largest well (as shown by the optical image in Figure S3c, the SEM micrographs in Figure S3d-f and the AFM data in Figure S3g and S3h. The measured values of deflection (90 nm) and diameter (1250 nm) correspond to an internal pressure of $116 \pm 46$ bar. The high pressure is attributed to beam induced heating of the cell during Au deposition. Nevertheless it is encouraging that our cells remain intact for large internal pressures.
Figure S3: Encapsulation and sectioning of a EGLC sample. (a) Optical and (b) AFM images of an EGLC sample. (c) optical differential contrast image and (d) secondary electron SEM of the same area after the evaporation of a 300nm layer of Au on top of the sample under vacuum conditions. In both cases the shape of the cells is clear, with a mixture of filled wells and empty wells. (e) and (f) show cross sectional SEM imaging of the cells after focussed ion beam sectioning. A thick platinum layer was deposited immediately prior to sectioning to protect the imaged area during the cutting process. The location of the profile is indicated in panels (a) and (d). (g) shows a height profile of the Au layer above a membrane taken from the AFM height image in (h), showing a membrane deflection of ~90 nm for the centre of a 1250 nm diameter wells after the Au deposition.
To investigate the response of the EGLC to prolonged external vacuum, we subjected a EGLC sample consisting of a ~30 nm thick hBN flake capped using ~3 nm thick graphene flakes on a silicon oxide support to progressive vacuum cycling. AFM images of the flakes (recorded at ambient external pressure) were captured at various stages during the vacuum cycling process. A set of these images along with an optical reference image of the EGLC sample are shown in Figure S5.

For the larger cells the low aspect ratio (height 30nm, diameters over 1µm) meant that these were usually either ‘ring filled’ (where the top graphene window was able to deflect and adhere to the bottom window in the center of the cell, Figure S4) or empty. For smaller cells (diameters less than 600 nm) this collapsing of the cells was rarely seen, although the top flake would often partially adhere to the sidewalls of the well, creating a ‘half-filled’ structure (see Figure S4c).

AFM images were captured immediately after transfer, but imaging conditions were inhibited by the polymer residue visible on the surface (see left panel in Figure S5d). The sample was therefore exposed to a total of 50 seconds of low power oxygen cleaning to remove this residue. The sample was then repeatedly exposed to high vacuum conditions ($\leq 10^{-7}$ mbar) and imaged. No membrane rupture or leakage was observed after a cumulative 24 hours in vacuum, although changes in some of the well geometries were observed, suggesting that leaking of liquid between cells may have occurred. For example, one of the small holes in the upper part of panel (d) goes from a ‘half-filled’ to a ‘filled’ geometry between the central two panels. Smaller trapped pockets of liquid are visible between the flat hBN surface and the upper graphene window away from the patterned areas, as shown in Figure S5e. They were not observed to move or change shape during the course of the experiment.

The total yields of cells of various geometries after 24 hours in vacuum conditions
sorted by the cell diameter are presented in Table 1. For the smallest cells (with diameters ≤ 100 nm) no empty or ring-filled cells were observed and the cells were believed to be all filled within measurement accuracy. High-magnification TEM imaging was performed using cells with diameters between 400 nm and 600 nm.

**Table 1.** Fabrication yield of EGLCs sorted by cell diameters. The location of the cells recorded here is shown in Figure S5b. Smaller cells were found to be all filled within measurement accuracy.

| Diameter (nm) | Sample Size | ‘Filled’ yield | ‘Ring-filled’ yield | ‘Half-filled’ yield | ‘Empty’ yield |
|---------------|-------------|----------------|---------------------|---------------------|--------------|
| ≈ 1550        | 136         | 0 %           | 52.2 %              | 0 %                 | 47.8 %       |
| ≈ 1050        | 276         | 9.4 %         | 68.5 %              | 0 %                 | 22.1 %       |
| ≈ 600         | 276         | 77.5 %        | 0 %                 | 8.0 %               | 14.5 %       |
| ≈ 475         | 415         | 57.6 %        | 0 %                 | 31.7 %              | 10.7 %       |
| ≈ 220         | 1392        | 43.7 %        | 0 %                 | 56.3 %              | 0 %          |

**Figure S4.** Demonstration of test EGLC cell geometries. (a) AFM height image of an area of an EGLC sample on a solid substrate. The height profiles along the blue and green dotted lines are shown in (b). The apparent slope mismatch between sides of the same hole is due to the asymmetric side angles of the AFM tip. (c, d) illustrates schematically (b, cross section and c, plan view) various membrane geometries seen in our EGLC samples with the cells colour in order to indicate the nature of each cell, as determined from the AFM images. (e) shows an AFM force error image, which makes it simpler to discriminate between ‘empty’ and ‘ring-filled’ holes.
Figure S5. Leak testing of EGLC. (a) Optical image of an EGLC sample illustrating the large number of liquid cells accessible for TEM imaging. The locations of the AFM images shown in (b) to (f) are highlighted. (c,d) AFM height images and showing the cell distribution. Trapped pockets of liquid are visible on top of the hBN flake in the unpatterned regions. (d) shows the cells at different stages after vacuum conditions for up to 24 hours. The left panel was captured immediately after resist removal after the liquid encapsulation. Polymer residue is visible on the membrane surface. The next panel was recorded after the sample was plasma cleaned for 50s, and under vacuum (~$10^{-7}$ mbar) for 1 hour. The right panels were captured after the sample was placed in vacuum for a cumulative 6 hours and 24 hours respectively. (e) shows a region of close to the edge of the boron nitride. Stationary pockets of trapped material are observed on the hBN spacer indicating a hermetic graphene-hBN seal. (f) shows a region at edge of the top graphene flake in which the bottom section of the image shows the full pattern of the hBN spacer layer hBN layer (not covered by graphene).
Figure S6: A TEM micrograph of an EGLC in (a) shows platinum particles in the well area. The diffraction pattern (b) of this area shows both top and bottom graphene layers misaligned by ~21°. A high resolution TEM image of the graphene area is in (c), with a zoom-in showing graphene lattice structure in (d) and corresponding FFT in (e) showing the same orientation revealed by electron diffraction.
Figure S7 shows further examples of HAADF STEM imaging of graphene liquid cells. Where nanoparticles were sputter sputtered on one of the graphene sheets as in Figure S7c the cells were found to be less stable for prolonged imaging. We attribute this to a reduction in the quality of the hermetic seal able to form between the graphene and the hBN spacer.

Nanocrystal motion in the HAADF images was analysed using the spot detection and tracking capabilities available in Icy software, where the positions of nanocrystals over a HAADF time-series were recorded and compiled to form particle trajectories. The algorithms used for particle detection involve application of a Laplacian of a Gaussian (LoG) filter for edge detection, followed by segmentation and thresholding to determine particle properties such as size and position. Tracking scripts then link particles with similar features across consecutive frames using user-defined
probability functions and spatial limitations. In some cases manual adjustment of particle tracks was required where coalescence or cross-over events occurred. Several image series were acquired with the hBN spacer layer at the edge of the image. This provided a reference from which sample drift (unwanted movement of the whole TEM sample) could be corrected. The removal of sample drift is important as this could otherwise be mistaken for collective motion of the nanoparticles through the liquid. Sample drift was corrected for using the ImageJ plug-in: StackReg\textsuperscript{22} and irregular contrast changes over time were adjusted for using another ImageJ plug-in: Stack Contrast Adjustment.\textsuperscript{23} Note that sample drift is indistinguishable from ‘superdiffusional motion’ reported in previous studies.\textsuperscript{24} The aligned image series from which the data in main text Figure 2 was obtained is reproduced in Supplementary Video 1. This video shows tungsten nanocrystal motion in a water/IPA mixture captured in HAADF STEM mode at a rate of 2.5 seconds per frame. The particles are located at the edge of liquid well (600 nm diameter with a 30 nm hBN spacer). The original 512 × 512 pixel data has been cropped to focus on the region of interest. Video plays at 20 times real time: 8 frames per second. Scale bar is 10 nm.

The aligned image series (Supplementary Video 1) allow the details of nanoparticle coalescence to be studied in the EGLCs (Figure 2 of the main text and Figure S8). For example, two 0.6nm diameter particles in close proximity demonstrate correlated motion, circling about each other with constant interparticle distances (marked by blue lines in main text Figure 2g). The particles are also able to pass over/under each other in the projected direction during this rotation (giving a zero interparticle distance for a few frames). These two particles coalesce later in the video to form a larger particle (t =500s).
A further analysis of particle coalescence seen in these videos is shown in Figure S8. Huang thresholding by minimization of fuzziness\textsuperscript{25} was used to determine projected areas for individual particles. Four particles were studied and their projected areas monitored as a function of time. Small size fluctuations are a result of the particles rotating in the liquid environment. Two smaller particles merged into a single larger particle following a period of correlated motion similar to that observed for different particles in main text Figure 2g, which then gradually reduced its projected area. The size reduction observed for this large particle later in the video we attribute to both the particles being closer than can be resolved using the measurement method and also the initially conjoined particles restructuring to become more spherical, minimising the projected area without significantly changing the volume.

The random motion of nanoparticles observed in an intact cell (Supplementary Video 1, main text Figure 2) is very different to the case when a cell has been punctured by an intense electron beam. Supplementary Video 2, shows the case of a leaking cell where particles move very quickly along the direction of liquid flow. Video set at 20 times real time: 4 frames per second. Scale bar in Video 2 is 50 nm.
Figure S8: Monitoring of nanoparticle projected areas extracted from the image series presented as supplementary video 1. Graph shows the size of individual particles (colour coded in the HAADF STEM image at t=0, inset left). By 100 s the small yellow particle has dissolved and the blue and green particles have coalesced into the largest (red) particle. Inset right is the final frame at t = 498 s where, only the red particle remains of the four particles originally measured. Schematic diagrams illustrating the coalescence process are shown above. Interestingly, after the initial coalescence the area of the largest (red) particle reduces from 150 s until a steady state is reached at 400 s. We attribute the size reduction to a period of densification after the particles initially touch. The data for the area of the red particle has been averaged over the nearest 5 frames to reduce noise. Scale bar is 2 nm.
Energy Dispersive X-ray Spectroscopy

Figure S9 compares summed spectra for areas of the spectrum image inside and outside the liquid well region of the EGLC. As expected outside the well there is a strong nitrogen signal due to the presence of the hBN spacer layer. Inside the well we see an enhanced oxygen signal, consistent with the presence of water. The ratio of oxygen counts in and outside the cell was measured to be $O_{\text{wet}}/O_{\text{dry}} = 3.05$.

![Figure S9](image)

**Figure S9:** Comparison of the summed EDX spectra from areas inside the well (wet) and outside the well on the hBN spacer (dry): brown trace (wet) and blue (dry) with an inset showing closer view of peak difference for oxygen Kα. The spectra are taken from areas marked on the HAADF image (below left). A nitrogen EDX elemental map shows the location of the boron nitride spacer. Scale bar is 30 nm.

Figure S10 shows STEM EDX spectrum imaging of nanoparticles inside the EGLCs. A smoothing filter was applied to the elemental maps in Figure 4 of the main text. All other spectral maps are unprocessed. Line profiles in Figure S10 have the width shown on the elemental map above and were horizontally averaged over 3 pixels to improve signal to noise ratio. The particles were monitored during spectrum imaging and mapping ceased if noticeable changes in shape or morphology occurred.
Consequently shorter acquisition times had to be used for the mapping of tungsten nanocrystals compared to the AuFe. The line profiles extracted from the elemental maps in Figure S10 reveal elemental features with widths of ~1 nm in the form of coatings and gaps between particles.

Figure S10: Left: Composite elemental map (top) and line scan (below) for two FeAu particles in the EGLC (see main text figure 3), where a 1 nm gap between the particles can be discerned. Red is Fe K-α X-ray signal and blue is Au K-α X-ray signal. Right: Elemental map for W K-α X-ray signal showing two tungsten particles in the EGLC with diameters of 2 nm and 2.5 nm for the left and right particles respectively. The scales of both elemental maps are the same as those for the line scans shown below (full width 16 nm and 14 nm respectively).

In some cells the graphene windows were sputtered with gold prior to closing the cell, in order to produce metal nanoparticles which provide nucleation sites for the formation of core-shell particles (main text Figure 4, Figure S11). For these cells a greater degree of leakage was observed, both during prolonged imaging and when stored for months in ambient conditions. After 5 months stored at room temperature all wells appeared dry. We explain this by the presence of sputtered particles which deleteriously affect the graphene-boron nitride seal, creating microchannels which allow liquid to escape. This effect could be reduced by lowering the seed crystal
concentration, or by avoiding sputtering as a deposition technique and working only with particles in solution or formed in situ by beam induced reduction of metal salts. Drying could also be produced by piercing the graphene window with an intense electron beam (Supplementary video 2). Interestingly, cells where the liquid had been removed appeared less stable to prolonged imaging with the electron beam (Figure S11). The as made EGLC was imaged for extended periods (30 minutes at 80 kV, beam current 240 pA) without any signification morphological changes to the particles, while particle sintering was observed after just 5 minutes, (200 kV, beam current 100 pA) in dry cells. Particle bridging was seen across iron-coated faces creating single elongated nanocrystal. Here imaging of the empty cells was performed at 200 kV to achieve higher spatial resolution with our microscope).

Nevertheless, similar sintering behavior was observed in dried cells imaged at 80kV.

Figure S11: Iron-coated gold nanoparticles featured in main text figure 4. (a) shows an unfiltered EDX map acquired in liquid. High-resolution STEM image of specific particles in 'dried' cell in (b) with labelled Fourier transforms for each in (c) and (d). Sequential HAADF micrographs (e)-(h) were acquired after damaging graphene using 200kV to release liquid. In the empty cells the particles show necking and coalescence between adjacent crystals and eventual formation of nanorod. An EDX map in (i) shows the elemental distribution in the final nanorod configuration. Scale bar is (a) 5 nm, (b) 2 nm, (c) 2 nm⁻¹, (d) 2 nm⁻¹, (e) 5 nm, and (i) 5 nm.
The electron beam quickly induced rapid changes in the nanoparticles’ morphology causing coalescence to form nanorods. This change in behavior can be attributed to passivation of nanocrystals by a layer of water molecules, possibly a solvation shell or electrostatic layer that provides a barrier to sintering. Initial iron beam induced deposition in the cells appeared to occur preferentially on vertices rather than facets of the Au particles, particularly at vertices in close proximity to other Au particles (main text Figure 4, Figure S11). During sintering, redistribution of the iron occurred such that it still appeared to be associated with vertices and the nanoparticle surface. Understanding the preferential colocation of different metallic phases in solution is very relevant to colloidal nanoparticle synthesis but has previously been impossible to investigate without dismantling the liquid cell. This is a rich area of further work made possible by our new EGLCs.

Supplementary References:

(1) Gorbachev, R. V.; Riaz, I.; Nair, R. R.; Jalil, R.; Britnell, L.; Belle, B. D.; Hill, E. W.; Novoselov, K. S.; Watanabe, K.; Taniguchi, T.; Geim, A. K.; Blake, P. Small 2011, 7 (4), 465–468.

(2) Kretinin, A. V.; Cao, Y.; Tu, J. S.; Yu, G. L.; Jalil, R.; Novoselov, K. S.; Haigh, S. J.; Gholinia, A.; Mishchenko, A.; Lozada, M.; Georgiou, T.; Woods, C. R.; Withers, F.; Blake, P.; Eda, G.; Wirsig, A.; Hucho, C.; Watanabe, K.; Taniguchi, T.; Geim, A. K.; Gorbachev, R. V. Nano Lett. 2014, 14 (6), 3270–3276.

(3) Booth, T. J.; Blake, P.; Nair, R. R.; Jiang, D.; Hill, E. W.; Bangert, U.; Bleloch, A.; Gass, M.; Novoselov, K. S.; Katsnelson, M. I.; Geim, A. K. Nano Lett. 2008, 8 (8), 2442–2446.

(4) Hencky, H. Zeitschrift fuer Math. und Phys. 1915, 63, 311.

(5) Komaragiri, U.; Begley, M. R. J. Appl. Mech. Asme 2005, 72 (2), 203–212.

(6) Vlassak, J. J.; Nix, W. D. J. Mater. Res. 1992, 7 (12), 3242–3249.

(7) Mitchell, J. S.; Zorman, C. A.; Kicher, T.; Roy, S.; Mehregany, M. J. Aerosp. Eng. 2003, 16 (2), 46–54.
(8) Poot, M.; van der Zant, H. S. J. Appl. Phys. Lett. 2008, 92 (6), 3.
(9) Beams, J. W.; Walker, W. E.; Morton, H. S. Phys. Rev. 1952, 87 (3), 524–525.
(10) Small, M. K.; Nix, W. D. J. Mater. Res. 1992, 7 (6), 1553–1563.
(11) Pan, J. Y.; Lin, P.; Maseeh, F.; Senturia, S. D. IEEE 4th Technical Digest on Solid-State Sensor and Actuator Workshop, IEEE: Hilton Head Island, SC, USA. 1990, pp 70–73.
(12) Wei, X.; Fragneaud, B.; Marianetti, C. A.; Kysar, J. W. Phys. Rev. B 2009, 80 (20), 205407.
(13) Castellanos-Gomez, A.; Singh, V.; van der Zant, H. S. J.; Steele, G. A. Ann. Phys. 2015, 527 (1–2), 27–44.
(14) Lee, C.; Wei, X.; Kysar, J. W.; Hone, J. Science (80-. ). 2008, 321, 385–388.
(15) Barton, R. A.; Ilic, B.; van der Zande, A. M.; Whitney, W. S.; McEuen, P. L.; Parpia, J. M.; Craighead, H. G. Nano Lett. 2011, 11 (3), 1232–1236.
(16) Clark, N.; Oikonomou, A.; Vijayaraghavan, A. Phys. Status Solidi B-Basic Solid State Phys. 2013, 250 (12), 2672–2677.
(17) Lee, C.; Wei, X. D.; Kysar, J. W.; Hone, J. Science (80-. ). 2008, 321 (5887), 385–388.
(18) Politano, A.; Chiarello, G. Nano Res. 2015, 8 (6), 1847–1856.
(19) Koenig, S. P.; Boddeti, N. G.; Dunn, M. L.; Bunch, J. S. Nat. Nanotechnol. 2011, 6 (9), 543–546.
(20) Bunch, J. S.; Verbridge, S. S.; Alden, J. S.; Van Der Zande, A. M.; Parpia, J. M.; Craighead, H. G.; McEuen, P. L. Nano Lett. 2008, 8 (8), 2458–2462.
(21) Chenouard, N.; Bloch, I.; Olivo-Marin, J. C. IEEE Trans. Pattern Anal. Mach. Intell. 2013, 35 (11), 2736–2750.
(22) P. Thévenaz, U.E. Ruttimann, M. U. IEEE Trans. Image Process. 1998, 7 (1), 27–41.
(23) Capek, M.; Janacek, J.; Kubinova, L. Microsc. Res. Tech. 2006, 69, 624–635.
(24) Chen, Q.; Smith, J. M.; Park, J.; Kim, K.; Ho, D.; Rasool, H. I.; Zettl, A.; Alivisatos, A. P. Nano Lett. 2013, 13 (9), 4556–4561.
(25) Huang, L. K.; Wang, M. J. J. Pattern Recognit. 1995, 28 (1), 41–51.