Visualizing Encapsulated Graphene, its Defects and its Charge Environment by Sub-Micrometer Resolution Electrical Imaging

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Devices made from two-dimensional (2D) materials such as graphene or transition metal dichalcogenides possess interesting electronic properties that can become accessible to experimental probes when the samples are protected from deleterious environmental effects by encapsulating them between hexagonal boron nitride (hBN) layers. While the encapsulated flakes can be detected through post-processing of optical images or confocal Raman mapping, these techniques lack the sub-micrometer scale resolution to identify tears, structural defects or impurities, which is crucial for the fabrication of high-quality devices. Here we demonstrate a simple method to visualize such buried flakes with sub-micrometer resolution, by combining Kelvin force probe microscopy (KPFM) with electrostatic force microscopy (EFM). KPFM, which measures surface potential fluctuations, is extremely effective in spotting charged contaminants within and on top of the heterostructure, making it possible to distinguish contaminated regions in the buried flake. When applying a tip bias larger than the surface potential fluctuations, EFM becomes extremely efficient in highlighting encapsulated flakes and their sub-micron structural defects. We show that these imaging modes, which are standard extensions of atomic force microscopy (AFM), are perfectly suited for locating encapsulated conductors, for visualizing nanometer scale defects and bubbles, and for characterizing their local charge environment.
2D materials can display remarkable electronic properties, but with all the atoms at the surface these properties are easily obscured by scattering off substrate-induced random potentials or adsorbed species. It is therefore desirable to protect these layers by using flat inert substrates or by removing the substrate altogether.\textsuperscript{1-10} Hexagonal boron nitride (hBN) is considered an ideal substrate because of its atomic flatness and its ability to segregate hydrocarbon contaminants into bubbles. Outside these bubbles, hBN provides a pristine surface with significantly reduced charge fluctuations thus providing access to the low energy electronic properties of graphene and other 2D layers.\textsuperscript{11-15} Recent development of methods to pick up and transfer 2D-materials using hBN has led to ultra-clean, high-quality, encapsulated devices such as FETs,\textsuperscript{16} photodetectors,\textsuperscript{17} and light emitters.\textsuperscript{18} Graphene encapsulated in hBN\textsuperscript{19} has provided access to a wide range of intrinsic properties including micron-scale ballistic transport,\textsuperscript{20} electron optics,\textsuperscript{21, 22} magnetic focusing,\textsuperscript{23} and Moiré superlattices which exhibit interesting magneto-transport properties.\textsuperscript{15, 24-26} Despite hBN’s superior qualities as a substrate, protecting the electronic properties of a 2D sample by encapsulation is a delicate process. The quality of such encapsulated devices depends on the location and number of contaminants trapped within the device and on the reliability of the electrical edge contacts. Therefore, knowing the precise location and orientation of the embedded layer makes it possible to avoid the contaminated regions and to achieve precise edge contacts.\textsuperscript{27}

Optical microscopy provides a quick way to identify large bubbles beneath the hBN and, in some cases, the encapsulated flake can be identified through image processing. However, optical microscopy is intrinsically diffraction limited, its contrast is limited to a few percent,\textsuperscript{28} and it is insensitive to charged contaminants. Another common technique, confocal Raman microscopy, can also identify buried graphene flakes, however, the laser spot size of 1-2\textmu m makes it very difficult to detect much smaller defects without time-consuming long integration times.\textsuperscript{29} More
complex scanning-probe methods such as SNOM\textsuperscript{30} and contact-resonance mapping\textsuperscript{31} have been employed previously for this purpose but these techniques require expensive specialized equipment and sophisticated analysis which are not commonly available. Additionally, electron-based imaging such as scanning electron microscopy (SEM) and scanning tunneling microscopy (STM) which require a conductive sample surface are ill-suited to imaging graphene flakes buried under an insulating hBN layer.

In order to address these challenges, we choose to probe the effect of the graphene layer on the long-range Coulomb forces near the sample surface. The natural probes for this regime are the dynamic AFM modes, KPFM and EFM. Previous KPFM and EFM phase shift measurements on contacted, bare graphene probe graphene’s intrinsic properties such as work function, screening properties, and doping effect.\textsuperscript{32-35} However, upon encapsulation, these properties are no longer directly accessible and details of the embedded graphene’s location and potential variations become obscured. We find that the use of KPFM to map potential variations on the surface of the heterostructure provides access to the local charge environment of the encapsulated graphene flake (e.g. charged defects trapped both between the layers and on the surface). Further, with EFM at large biases, we can suppress the effect of these potential fluctuations to image the graphene structure (e.g. cracks and edges) at the sub-micron scale. We may then determine the position and orientation of the encapsulated layers, avoid defective regions, and probe their quality prior to performing complicated device fabrication steps such as plasma etching, lithography, and attaching metal electrodes.
Figure 1. Measurement setup a) A cartoon depiction of a crucial step in the fabrication process. An hBN flake on a polymer stamp holds a piece of graphene via van der Waals forces as it is being placed onto another hBN flake. b) The final hBN/graphene/hBN stack (side view). A bias voltage, $V_b$, maintains the potential of the metalized AFM tip with respect to a doped Si backgate.

Encapsulated graphene devices are fabricated by mechanical exfoliation of graphene and hBN from bulk crystals onto both Si dioxide (SiO$_2$) substrates and polymer films such as polymethyl methacrylate (PMMA) or polypropylene carbonate (PPC). The optically transparent, thin polymer films enable us to manipulate the flake positions so as to achieve the desired alignment between them via micromanipulators under an optical microscope. Using the van der Waals adhesion between graphene and hBN, a single graphene layer can be lifted from a SiO$_2$ surface. In the final step of the assembly (see figure 1a), a hBN/graphene stack is suspended on a polymer film and placed onto a substrate hBN flake sitting on 300nm thick SiO$_2$ which caps a doped Si backgate.
The final structure consists of a conducting graphene flake protected on both sides by hBN crystals. See Supporting Information figure S1 for optical images of the fabrication steps.

Devices are imaged using non-contact AFM, KPFM, and EFM in a commercial (NT-MDT Solver Next) SPM system using gold coated conducting probes. KPFM and EFM are performed in a two-pass scheme where on the first pass, the sample topography is measured by non-contact AFM and on the second pass, electrical measurements are taken with the tip retracted above the sample surface (typically 10nm) (see figure 1b).

**Kelvin Probe Force Microscopy (KPFM)**

In the second pass of KPFM, the gold-coated AFM cantilever is oscillated near resonance by applying a DC + AC voltage signal. This excitation generates an electrostatic force between the tip and the sample surface:

\[
F_{es}(z) = -\frac{1}{2} \frac{\partial C}{\partial z} (V_b - V_s)^2,
\]

where \(V_b = V_{DC} + V_{AC} \cos \omega t\) is the applied tip bias, \(\omega\) is the AC excitation frequency, \(V_s\) is the potential due to the work function difference between the tip and the sample surface, \(C\) is the local capacitance between the tip and the grounded backgate, and \(z\) is the tip-surface separation distance (10nm). Choosing the AC signal frequency to be near the resonant frequency of the cantilever leads to a large cantilever oscillation amplitude due to the electrostatic force component:

\[
F_{\omega}(z) = -\frac{\partial C}{\partial z} (V_{DC} - V_s) \cdot V_{AC} \cos \omega t.
\]

Thus, by means of a feedback circuit, we find the value of \(V_{DC}\) which nullifies the cantilever oscillation amplitude \((F_{\omega}(z) = 0)\), providing a direct measure of the surface potential beneath the tip, \(V_s\).
Figure 2. Imaging Encapsulated Graphene  a) Optical micrograph of encapsulated graphene region contacted with an electrically floating gold electrode (bottom right). One can distinguish the top (light blue) and bottom (dark blue) hBN flakes, the bare SiO$_2$ (top left corner), and bubbles (orange spots), but there is not enough contrast to make out the encapsulated graphene layer.  b) AFM topography of graphene encapsulated in hBN region shown in (a). Bubbles between the layers are clearly seen but the graphene flake is invisible. c) KPFM image in the same area shows the variation in surface potential across the sample revealing the charge environment of the embedded graphene layer. Many bubbles appear bright due to trapped charges which affect the KPFM signal.  d) EFM phase difference image taken at $V_b = -6V$ clearly differentiates the region of encapsulated graphene (yellow) from hBN on SiO$_2$ (orange). The graphene flake is left electrically isolated from the tip and stage during these measurements.
When electrical contact is made between the graphene layer and the gold-coated tip, the work function difference between the two materials generates a static charge build-up at the sample surface. In this case, the measured surface potential is simply related to the work function difference between the two materials, \( V_s = \frac{-\Delta \phi}{e} \), where \( \Delta \phi \) is the work function difference between the gold tip and graphene sample and \( e \) is the charge of an electron. In contrast to previous measurements of graphene by KPFM, we measure the surface potential variation without electrical contact to the graphene layer. With this method, we probe the location and properties of the graphene layer before performing any lithography or electrode deposition. Instead, electrical contact and the applied bias is made between the coated tip and the highly doped Si backgate beneath the SiO\(_2\) substrate. Without electrical contact to the graphene layer, the signal depends on a combination of the work function difference between the Au coated tip and the doped Si backgate modified by the charges and conductors between them.\(^{37}\) To account for the presence of the conducting graphene layer and trapped charges between the tip and backgate, we must introduce additional terms to equation (1):

\[
F_s(z) = -\frac{1}{2} \frac{\partial C_{BG}}{\partial z} (V_b - V_{BG})^2 - \frac{1}{2} \frac{\partial C_g}{\partial z} (V_b - V_g)^2 - \sum \frac{1}{2} \frac{\partial C_q}{\partial z} (V_b - V_q)^2.
\]

Here, \( C_{BG} \) (\( V_{BG} \)), \( C_g \) (\( V_g \)), and \( C_q \) (\( V_q \)) are the capacitances (potential differences) between the tip and the doped Si backgate, the buried graphene layer, and the surface charges, \( q \), respectively. Then the KPFM signal, the potential which nullifies the oscillating signal (equation (2)), occurs when:

\[
V_{DC} = V_s = \frac{\frac{\partial C_{BG}}{\partial z} V_{BG} + \frac{\partial C_q}{\partial z} V_q + \sum \frac{\partial C_q}{\partial z} q}{\frac{\partial C_{BG}}{\partial z} + \frac{\partial C_g}{\partial z} + \sum \frac{\partial C_q}{\partial z}}.
\]
The surface potential measured in the same region as figure 2b using KPFM is displayed in figure 2c. As described above, the measured surface potential is determined by the work function difference between the gold-coated AFM tip and the doped Si backgate, by the floating graphene layer and by the trapped charges in the structure (see equation (4)). Due to these terms, the region of encapsulated graphene shows a slightly larger surface potential than the surrounding hBN, however, the edges of the graphene layer are blurred by random variations in the surface potential.

For a metallic buried layer, we would expect the contribution to the KPFM signal, \( \frac{\partial C_g}{\partial z} \) and \( V_g \), to be spatially uniform. However, from figure 2c, we can see that the KPFM signal is non-uniform in this area indicating the presence of potential fluctuations presumably due to graphene’s inability to completely screen trapped charges.\(^{37,38}\)

In many encapsulated graphene devices, the accumulation of surface contaminants within the structure is common due to the presence ambient adsorbates and residues from tape, transfer polymers, and solvents. Hydrocarbon residues have been shown to coalesce into localized bubbles within the heterostructure.\(^{39,40}\) Large bubbles (>0.5um) can be seen optically in Figure 2a and appear in the AFM topograph (Figure 2b) as protrusions from the hBN surface. The KPFM map, Figure 2c, reveals that charges within these large bubbles are not uniformly distributed but are denser near the edges of the bubble and connect between bubbles through thin filaments. Smaller bubbles (<0.5um) are also observed in AFM topography but cannot be seen in the optical image Figure 2a. The small bubbles exist both within the encapsulated graphene region as well as sandwiched between the top and bottom hBN layers. These potential fluctuations in the vicinity of the buried graphene flake are detrimental to device quality but through KPFM imaging, we are able to select regions of uniform potential as well as assess the charge environment of each device.
Electric Force Microscopy (EFM)

We now turn to EFM. In this measurement mode the tip is mechanically resonated using a piezoelectric block with an excitation signal near the fundamental resonant frequency of the cantilever while a DC bias, $V_b$, is applied to the tip. As a result of the electrostatic force between the tip and the sample, a phase difference is established between the driving signal of the cantilever and the measured oscillation. The phase shift is related to the electrostatic force gradient by

$$\Delta \phi = -\arcsin \left( \frac{Q}{k} \frac{\partial F_{es}(V_b)}{\partial z} \right) = -\arcsin \left( -\frac{Q}{k} \frac{1}{2} \frac{\partial^2 C}{\partial z^2} (V_b - V_s)^2 \right).$$

(5)

Where $Q$ and $k$ are the AFM cantilever quality factor and stiffness, respectively, and $F_{es}(V_b)$ is the electrostatic force between the tip and sample surface given by equation (1) with $V_{AC} = 0$. Thus, the variation of the electrostatic force gradient as a function of applied bias can be mapped across a surface.36-38

As an imaging technique, EFM has the advantage of a higher intrinsic lateral resolution than KPFM. Because EFM measures the force gradient rather than the force itself, it is less susceptible to stray signals than KPFM and therefore can achieve better spatial resolution. This is a direct consequence of the fact that the second derivative $\left( \frac{\partial^2 C}{\partial z^2} \right)$ is more tightly focused at the tip apex than the first $\left( \frac{\partial C}{\partial z} \right)$.36-38, 41, 42 The fact that the EFM signal is nearly quadratic in the applied bias makes it possible to easily tune the measurement sensitivity and image contrast.

As shown in Figure 2d, the encapsulated graphene layer is clearly distinguishable by measuring the EFM phase difference at a finite bias. When the tip bias is chosen to be larger than the surface potential fluctuations observed by KPFM, the graphene is observed through the top layer of hBN as a region of larger phase shift. The electrostatic force in this region follows equation (3), while outside the graphene region, only the first term in equation (3) contributes. At this bias, bubbles
and charges in the vicinity have a smaller effect on the phase signal allowing clear visualization of the graphene beneath.

**Bias Control**

To probe the sensitivity of the contrast in EFM imaging, we measure the EFM phase difference between the encapsulated graphene region and the nearby hBN stack on SiO$_2$ as a function of bias voltage (see Figure 3a-c). In this measurement, a small region at the edge of the encapsulated monolayer graphene region is imaged at various bias voltages and the average phase shift and standard deviation of the phase is recorded in both the region of encapsulated graphene and on bare hBN on SiO$_2$. Following equation (5), we fit the phase shift at low bias (solid grey lines in Figure 3d). In the absence of bias voltage, the phase shifts in the two regions nearly coincide making it impossible to see the graphene location by mapping the EFM phase shift. Due to the close proximity of the tip to the graphene layer we have $\frac{\partial^2 C_g}{\partial z^2} > \frac{\partial^2 C_{BG}}{\partial z^2}$, and the application of a bias quickly increases the phase shift difference between the two regions (See Figure 3a-c,e). As the applied bias increases, the phase shift of the cantilever quickly becomes large and equation (5), which assumes Hookian behavior of the cantilever, no longer holds. As a result, the measured phase shift vs bias deviates from the expected behavior given in equation (5). This effect was observed previously at similar phase shifts$^{43, 44}$ and is not thought to be the result of charging or polarization of the embedded graphene layer.

The ability to resolve the graphene layer can be quantified by the image contrast-to-noise ratio (CNR) given by the difference of the average phase $(\Delta \phi_g - \Delta \phi_{hBN})$ divided by the average of the standard deviation of the phase in each region, $(\sigma_g + \sigma_{hBN})/2$.

$$\text{CNR} = \frac{2|\Delta \phi_g - \Delta \phi_{hBN}|}{\sigma_g + \sigma_{hBN}} \quad (6)$$
FIGURE 3. Bias Dependence of Graphene Contrast a-c) EFM phase shift scans at the edge of an encapsulated graphene device with individually adjusted scale bars (scan size: 1.4µmx1.4µm). This region shows both encapsulated graphene (lower right) and bare hBN (upper left) at different bias voltages. d) EFM phase shift as a function of bias voltage in the regions of bare hBN on SiO$_2$ (black) and hBN encapsulated graphene (red). Error bars represent RMS phase noise in the region measured. Grey lines plot the fit to equation (2) at low bias. e) Contrast-to-noise ratio is plotted as a function of bias voltage.
Figure 3e plots the CNR as a function of bias voltage. At zero bias, CNR is less than 1, indicating that the two regions cannot be distinguished. As the bias is increased or decreased, CNR initially increases quickly before beginning to saturate. The phase shift in the graphene region grows more rapidly because the capacitance gradient is very sensitive to the distance of the tip to the metallic plane; in one region this is the graphene flake underneath the 37nm thick hBN layer and in the other it is the doped Si layer underneath the 300nm thick SiO2 layer. We find that controlling the bias makes it easy to resolve the encapsulated graphene layer regardless of surface quality, nearby contaminants, and electrical contact to the graphene layer itself.

**hBN Thickness Dependence**

The use of solvents during the device fabrication introduces some sample-dependent unintentional doping of the graphene layer which, in turn, contributes to contrast differences between samples. In Figure 4 we show the results for an encapsulated graphene device with a folded hBN flake on top. This device provides the opportunity to observe the effect of varying the top hBN layer thickness on the image contrast without worrying about work function differences between different samples due to electrostatic charging. Figure 4a,b displays an AFM topography image and height profile of the folded top hBN flake. We identify 3 regions of different encapsulant thicknesses: 9.3nm, 19.3nm, and 28.3nm. As expected, the EFM phase shift decreases with increasing thickness of the top hBN due to a smaller capacitance between the graphene layer and the tip (see Figure 4c,d). Because the graphene layer sits between the Si backgate and the tip, there will always be a larger capacitance between the tip and graphene than the tip-backgate.
FIGURE 4. hBN Thickness Dependence  a) AFM topography of an encapsulated graphene flake with a 37nm thick bottom hBN and 9.3nm thick top hBN that is folded on top of the graphene region twice. b) A linecut through the AFM topography image shown in (a) exhibiting several steps where the top hBN flake has folded onto itself. c) EFM phase shift image taken 10nm from the surface shown in (a) at a tip bias $V_b = -5V$. d) A linecut through the EFM phase image in (c) (along blue line) showing 3 different regions where the graphene is encapsulated by different thicknesses of boron nitride.
Thus, for finite biases, there should always be a contrast between the encapsulated graphene region and the surrounding hBN in EFM phase shift. For each device, the amount of contrast depends on the value of the bias and the distance between the tip and the surface. We note that changes in the hBN thickness have a less pronounced effect on the surface potential measured by KPFM. While a small shift of measured surface potential due to differences in the tip-graphene capacitance, \( C_g \), may be expected, this effect is not clearly observed in our measurement (see Supporting Information, S4).

**Sub-Optical Wavelength Resolution**

The spatial dependence of the EFM phase shift has its largest contribution at the tip apex; as a result, the phase shift observed above the encapsulated graphene sample decays quickly away from the graphene edge. In Figure 5b, we display an EFM phase shift map of the edge of the encapsulated graphene monolayer between a 37nm hBN substrate and a 9.3nm hBN encapsulating layer at a tip height of 10nm. Assuming an exponential decay away from the graphene edge, we find a characteristic decay length of \( 104 \pm 3 \text{nm} \) (see Supporting Information). The quick spatial decay of the signal is responsible for the superior edge resolution of buried graphene flakes attainable by EFM, as shown in Figure 5c. Additionally, we occasionally notice small cracks in the encapsulated layer as shown in Figure 5a,d. These cannot be seen in the optical image of the heterostructure (see S4a) however, the crack can be located and its width is estimated by measuring the variation of the EFM phase shift, Figure 5e. Thus, EFM enables imaging of deleterious nanometer-sized cracks that which would otherwise go unnoticed.
FIGURE 5. Sub-Optical Wavelength Resolution  

a) An EFM phase map of a region of the device shown in Figure 4 taken with $V_b = -5V$ and $z=10\text{nm}$ above the surface.  
b) Zoomed in image of the region in (a) (marked by a blue box) displaying the edge of encapsulated graphene beneath a 9.3nm thick top hBN layer. Scale bar is 200nm.  
c) A linecut along the blue line shown in the EFM phase shift map in (b). Red line traces an exponential fit to the observed graphene edge.  
d) A zoomed in image of the region in (a) (outlined with a red box) showing a crack in the buried graphene layer beneath 19.3nm hBN.  
e) A linecut along the blue line running across the crack observed in (d). The feature is observed as an approximately 150nm wide dip in phase shift.
In conclusion, we have shown that EFM and KPFM make it possible to image and characterize graphene layers buried within 2D heterostructures. These methods enable to visualize the precise boundaries of the graphene flake, the structural defects, and trapped contaminants; which are crucial for developing high quality encapsulated graphene devices. Surface-adsorbed contaminants and the graphene flake are clearly resolved using KPFM and EFM respectively, even if the graphene flake is not electrically contacted or resolved optically. Furthermore, we demonstrate that that EFM imaging provides a tunable contrast-to-noise ratio and higher intrinsic lateral resolution than both KPFM and standard optical imaging. We obtain a clearer image of the graphene position, identification of sub-micrometer cracks in the embedded graphene layer, as well as sensitivity to its local charge environment.

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AFM topography images are tilt corrected using Gwyddion.

**Supporting Information** Optical images of a device during and after fabrication, backgate influence on the EFM signal, height dependence of EFM, hBN thickness dependence on KPFM, and techniques to estimate the graphene edge are given online in the Supporting Information.
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Device Fabrication Images

**Figure S1** a) Optical micrograph of the hBN flake used to pick up and cover the graphene layer imaged in figure 2 of the main text. b) hBN substrate where the graphene/hBN stack was placed. c) Graphene flake on SiO₂ prior to being picked up by the top hBN. d) The same region as (c) after lifting the desired graphene flake. e) The final heterostructure with the graphene that was lifted from SiO₂ is marked by the dashed red line. The region of monolayer graphene is to the right of the solid red line.
Backgate Dependence

\[ V_g = -2V \]

\[ V_g = 0V \]

\[ V_g = 2V \]

**FIGURE S2.** Phase shift dependence on bias is shown for 3 different gate voltages. The voltage is applied to the doped Si backgate with the graphene flake grounded. The insulating hBN region follows the backgate potential while the grounded graphene layer changes by a marginal amount.

We also probe the effect of applying a backgate on the contrast between the encapsulated graphene region and the insulating hBN on SiO\(_2\) region. As a gate voltage is applied to the doped Si layer beneath SiO\(_2\), the parabola minimum shifts with the backgate in the insulating hBN region while the grounded graphene layer does not change much. We expect the phase shift minimum above the graphene layer to shift slightly as the work function of the graphene flake changes with electrostatic doping. In the small range of backgate voltage used in this study, such an effect is not observed. The effect of gating on the graphene layer-dependent work function and screening ability will be addressed in the future. Applying a backgate potential provides a method of generating contrast between the two regions at a fixed bias. Additionally, as seen in figure S2, applying a backgate moves the EFM phase shift minimum in the bare hBN region. Because the phase shift minimum is related to the local surface potential, applying a backgate may provide a mechanism to generate contrast in the KPFM signal.
Height Dependence

**FIGURE S3.** a) Phase shift vs. lift height (the tip-sample distance during EFM measurement) at a constant bias, $V_b = -3V$, in three different sample regions: encapsulated graphene (black), bare hBN (red), and bare gold (blue). Solid lines are fits using a simple tip model. b) Contrast-to-noise ratio between graphene and hBN is plotted as a function of lift height.

We vary the distance between the AFM tip and the device surface (lift height) during EFM measurement and plot the measured phase shift vs. lift height data in Figure S3. Data is taken in three regions of the same sample (shown in figure 2): encapsulated graphene, bare hBN on SiO$_2$, and on an exposed, grounded gold pad at a constant tip bias, $V_b = -3V$. At large tip-sample separation, the phase shift above the encapsulated graphene layer approaches that of bare hBN but quickly grows as the tip approaches the sample. In Figure 5b, we plot the CNR value as a function of lift height. Above a critical height, the CNR value decreases quickly with increasing lift height. Below this critical lift height, the CNR value changes more slowly. We qualitatively observe the critical point at which this behavior changes to be near the thickness of the top hBN flake (37nm) for this sample.
FIGURE S4. a) Optical image of the sample in Figure 4 of the main text with folded hBN layers on top of graphene b) AFM topography of the sample displayed in figure 4 of the main text showing a folded flake of hBN on top of a graphene layer with a 37nm substrate hBN flake beneath. c) KPFM image of the same region as in (b) showing the encapsulated graphene region as having a larger surface potential. Regions of different encapsulating thicknesses are not reflected because the KPFM signal does not change much with changing tip-graphene capacitance, $C_g$ (see equation (4) in the main text).
Graphene Edge Detection

**FIGURE S5.** a,b) Reproduction of figures 4e,f from the main text showing the EFM phase shift at the edge of a monolayer graphene encapsulated between 37nm hBN and 9.3nm hBN flakes. A line marking the edge of the buried graphene flake is added in red. c) Derivative of the phase shift shown in (b) w.r.t. X. The abrupt discontinuity of the graphene edge produces a sharp peak in the derivative of the phase shift signal, used to determine the edge position.

To determine the edge position of the buried graphene flake, we take the derivative of the phase shift signal as the tip passes the edge of the encapsulated region. Because the graphene (and charge distribution) end in a sharp discontinuity, we expect a peak or discontinuity in the derivative of the
signal as well. From figure S5c, we find a maximum at a critical value $X_c = 474.829\, \text{nm}$. We take this position to be approximately the position of the graphene edge and fit both sides of this point using an exponential curve:

$$\Delta \phi = \begin{cases} 
    y_L + A_L \exp \left( \frac{X}{d_L} \right), & X \leq X_c \\
    y_R - A_R \exp \left( - \frac{X - X_c}{d_R} \right), & X > X_c 
\end{cases}$$

We find characteristic decay lengths of $d_L = 104 \pm 3\, \text{nm}$ and $d_R = 36 \pm 2\, \text{nm}$ on the left and right of $X_c$, respectively. We find that the signal decays in a much shorter distance than typical optical diffraction limits (300-500nm). Thus, features which are unable to be resolved by optical methods can be visualized using EFM.