# ScanWave: Examples of Scanning Microwave Impedance Microscopy on Graphene

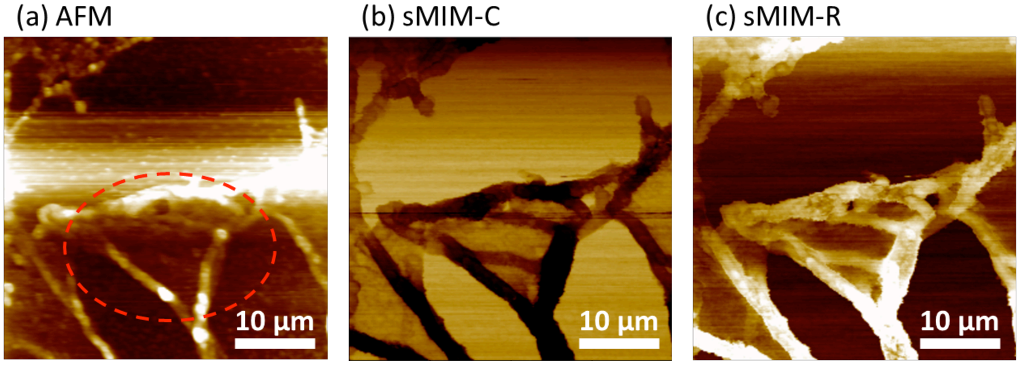
## sMIM Analysis of Graphene

Graphene has attracted enormous interest and intense research activities due to its rich physical properties in fundamental research and versatile potentiality to revolutionize many applications, especially in electronics and opto-electronics1,2,3. The unique properties of graphene for electrical applications makes it a focal point for next generation microelectronics. imaging the electrical properties of graphene presents specific challenges to researchers. MIM reduces the technical difficulties of preparing often small flakes or films on non-conducting substrates for electrical measurement by eliminating the need for a conductive path. MIM directly probes the grain structures and local variations in conductivity differentiating between conductive, semi conductive, and insulating regions. Below are presented several examples of sMIM measurements on differently prepared graphene.

---

## Exfoliated Graphene

Exfoliated graphene is one of the more common and easier forms of graphene to prepare and a common sample type in the investigation of novel graphene properties. Figure 1 show the results of AFM measurements on a graphene flake[4]. The exfoliated flake is loosely attached to a glass substrate with no special preparation for grounding or in any way providing an electrical path for the sample imaged. Figure 1. a) is the topographical image of a known graphed region. The area of interest is 40 um x 40 um. There are no visible features in the area highlighted in the topography region. Figure b)  and figure c) sMIM-C and sMIM-R respectively show substructure in the graphene flake. These ribbons show regions of higher conductivity and lower conductivity with high level of order. These regions are not able to be imaged using traditional electrical methods without complicated sample preparation. The images presented are work done at Nanjing University courtesy of Prof. Minghua Lu.


(a) AFM
(b) sMIM-C
(c) sMIM-R

---

## Single Layer Graphene CVD deposited on BN layer

MIM has shown particular value in visualizing regions where the conductivity or permittivity vary but not necessarily with physical features. A single monolayer of graphene grown using CVD and deposited on h-BN seed layer on a quartz substrate. Figure 2 shows the a) topography and b) the sMIM-R image. The topography image shows no specific variation in the 1um scan area. The sMIM image shows variation in the conductivity of the 3 graphene domains. A line profile along one transition boundary shows over 15nm distance a large contrast in the conductivity signal, 100's of mV.

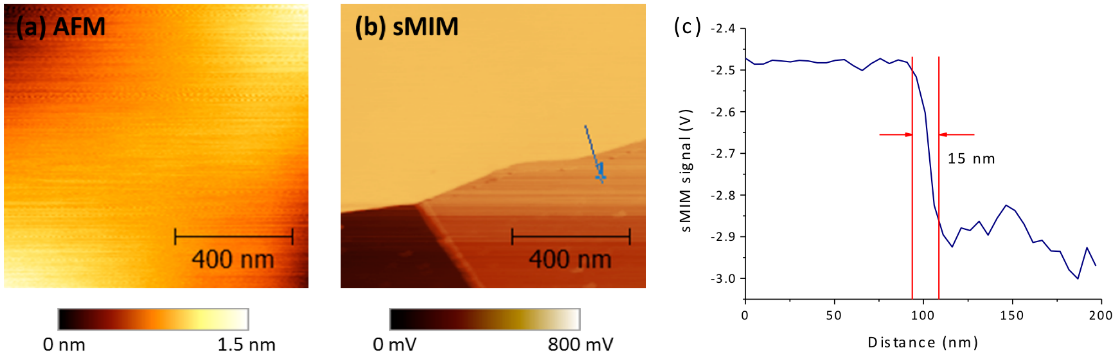


Figure 2. (a) AFM topography. (b) sMIM image, (c) profile of blue line in (b) show the spatial resolution of sMIM. Courtesy Haomin Wang, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences.

---

## Moire Patterns on Single Layer Graphene deposited on BN

Precisely aligned graphene on h-BN without a metal catalyst was found under very specific crystal orientations of the graphene layer to the h-BN layer to result in Moire interference patterns.[1] Results shown in the work by Tang, Wang, and Zhang et al imaging with lateral force microscopy visualized these Moire patterns confirming the specific conditions and tying this to the stress relief of the graphene Van der Waals force between the two epitaxy layers. In follow-up research done at Stanford University and PrimeNano in cooperation with SIMIT' Dr. Wang and Dr. Tang the Moire patterns were reproduced using sMIM.

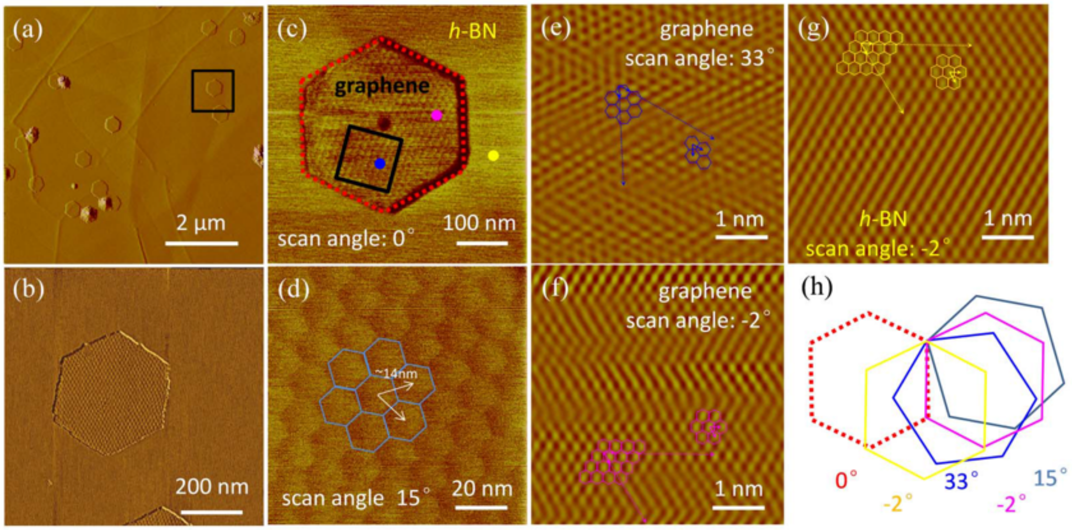
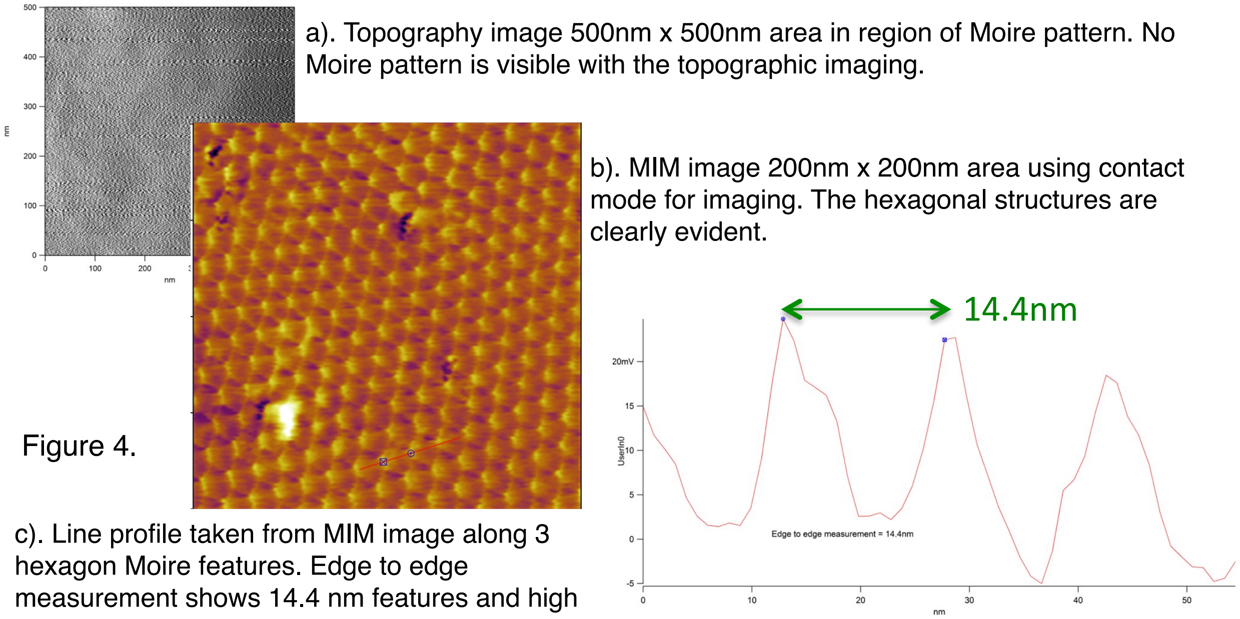


Figure 3. Determination of the rotational orientation of monolayer graphene with respect to h-BN. (a) A typical topography of the graphene grains on h-BN surface. Almost all the grains are in hexagonal shape with the opposite sides parallel. The hexagons are aligned on the whole h-BN surface. It clearly indicates anisotropic growth of graphene; (b)A zoom-in view from the black

box in panel (a). A sizable superstructure with a periodicity much larger than the lattice constant of both graphene and h-BN was observed on graphene; (c) Friction image of a single crystal graphene on h-BN. Dashed red line marks the edges of this grain; (d) A closer view (100 3 100 nm2) in the black box of (c), the superstructure exhibits hexagonal symmetry with lattice constant about 14 nm; Regular hexagons are superimposed on the images to demonstrate the giant lattice. The friction images (e), (f) and (g) show the atomic lattice of 535 nm2 area taken from the blue, pink and orange dot areas in panel(c), regular hexagons demonstrate the lattice of both graphene and h-BN, respectively. Zigzag directions (in dashed line) and lattice vectors (in solid line) are indicated by arrows (extracted from reference 1).



a). Topography image 500nm x 500nm area in region of Moire pattern. No Moire pattern is visible with the topographic imaging.

b). MIM image 200nm x 200nm area using contact mode for imaging. The hexagonal structures are clearly evident.

Figure 4.

c). Line profile taken from MIM image along 3 hexagon Moire features. Edge to edge measurement shows 14.4 nm features and high quality SNR for the electrical measurement. The MIM demonstrates sub 10nm resolution for these highly conductive samples

Figure 4 a) shows an sMIM image of the same Moiré pattern formed by the lattice mismatch of the graphene monolayer and  the h-BN film. sMIM proved to be a an easier and much more repeatable method of visualizing the Moire pattern than with lateral force  (LFM) or topography imaging. The line profile shown below in Figure 4 c) is taken across several of the hexagonal Moire structures. The cross-section measured 14.4nm, matching the LFM measured distance and the calculated values from the previous work. The individual hexagonal features demonstrate that on these very flat highly conductive samples approximately 5nm resolution is achieved.

Analysis of the hexagon Moire structures with MIM shows brighter (more conductive) at the edges of the hexagon. Further work by Tang and Wang of SIMIT focus correlating the conductivity of the graphene to the stress induced by the lattice mismatch between the graphene and h-BN.

## Conclusion

sMIM is shown to be a versatile technique for researchers to probe the electrical properties of graphene. Graphene has proved a challenging material to prepare and study especially for electrical properties where conventional methods require a conductive path or ground. The microwave frequency regime removes the need for a sample to be grounded or provide a conductive path to the instrument. MIM measurements are able to image variations in the sample conductivity over a very large range, a particular property of graphed research, where one region can have very low conductivity and another be orders of magnitude higher. Examples of various graphene measurements using PrimeNano's ScanWave system have been presented in order to demonstrate the versatility and sensitivity of the MIM technology.

## References

1. S. Tang, H. Wang et al, Precisely aligned graphene grown on hexagonal boron nitride by catalyst free chemical vapor deposition, Scientific Reports. 3: 2666 (2013)
2. Geim, A. K. & Novoselov, K. S. The rise of graphene. Nature Mater. 6, 183–191 (2007).
3. Novoselov, K. S. et al. A roadmap for graphene. Nature 490, 192–200 (2012).
4. Katsnelson, M. I. & Geim, A. K. Electron scattering on microscopic corrugations in graphene. Philos. Trans. R. Soc. A-Math. Phys. Eng. Sci. 366, 195–204 (2008).