Sub-surface imaging of atomically thin semiconductors beneath dielectrics based on optical standing wave using PEEM with deep-UV photoexcitation

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Intro, Summary, & Significance

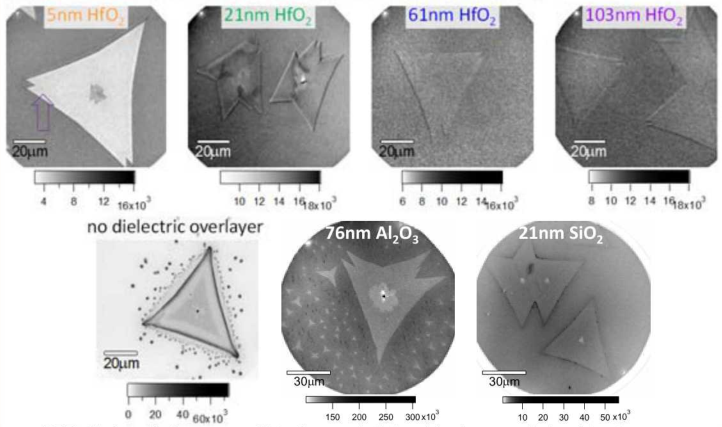
Non-destructive inspection of materials buried beneath dielectrics is sought after for diagnostics of electronics, and is a long lasting technical challenge. Optical microscopy allows for imaging beneath an insulator, while its lateral resolution is limited to the micron scale. Scanning electron microscopy offers sub-nanometer resolution, but often encounters sample charging obscuring the analysis of insulators.

Using photoemission electron microscopy (PEEM) with deep-ultraviolet (deep-UV) photoexcitation, we show sub-surface imaging of MoS_2 flakes sandwiched between dielectric overlayers and underlying SiO_2 films. Comparison of photoemission yield to modelled optical absorption of dielectric stacks demonstrated that optical standing waves contribute to the sub-surface imaging mechanism. The presence of atomically-thin MoS_2 flakes modulates the optical properties of the dielectric stack locally, producing image contrasts of the buried MoS_2 with submicron lateral sensitivity.

The results presented here underscore the role of optical effects in enhancing the depth sensitivity of photoemission images produced using low-energy photons. The benefit of this approach includes ***non-destructive imaging of buried interfaces and sub-surface features*** useful for analysis of microelectronics and of nanomaterial integration into devices.

Sub-surface Imaging of MoS_2: What We Found

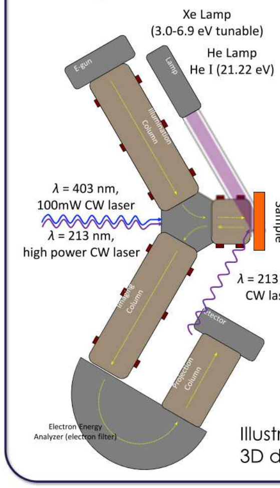
We observed sub-surface MoS_2 flakes sandwiched between dielectric overlayers and underlying SiO_2 films. These surprising results raise the question:
What is the main mechanism of this sub-surface imaging?
Where do electrons come from: surface or sub-surface?

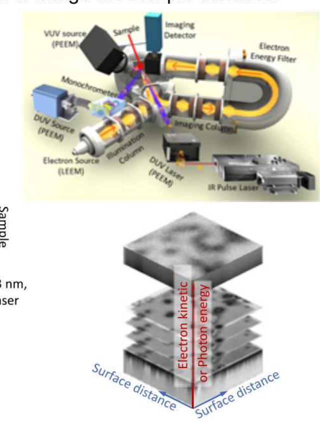


PEEM intensity images of MoS_2 sandwiched between dielectrics layers

PEEM: How We See

Photoemission electron microscopy (PEEM) is cathode electron microscopy, which uses electrons from photoemission process excited by deep-UV irradiation to image the sample surfaces.

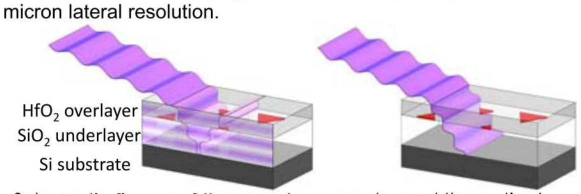




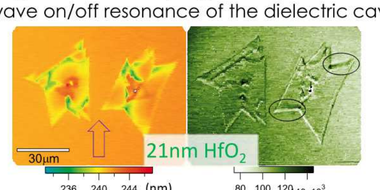
Illustrations of PEEM with light sources and 3D dataset that we acquire

Optical Standing Wave Resonance – Experiment & Modeling: Why We Can See Sub-surface MoS_2

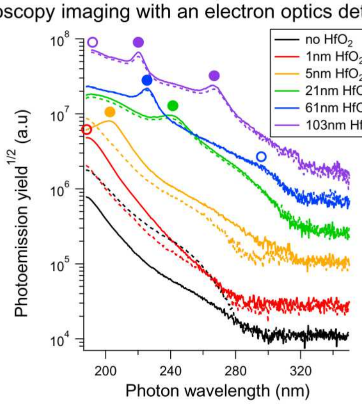
The photoemission yield (PEY) spectra show the resonance-like peaks. To understand the contribution of optical cavity effects, we modeled HfO_2/SiO_2/silicon structure based on transfer matrix method. The experiment and modeling results show excellent agreement indicating that the formation of optical standing waves enables the sub-surface imaging of atomically-thin materials sandwiched between two insulating dielectrics. In other words, PEEM-based sub-surface imaging is equivalent to optical phase contrast microscopy imaging with an electron optics detection scheme, which inherently has sub-micron lateral resolution.

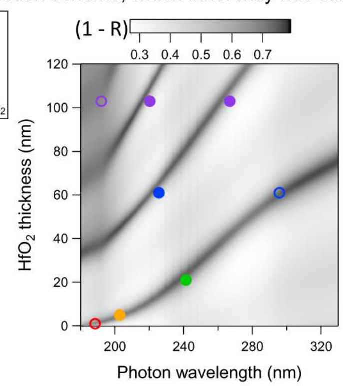


Schematic figures of the sample geometry and the optical standing wave on/off resonance of the dielectric cavities



Spatial mapping of cavity mode resonance peak wavelengths and total peak areas. The arrow indicates the in-plane direction of deep-UV sample illumination

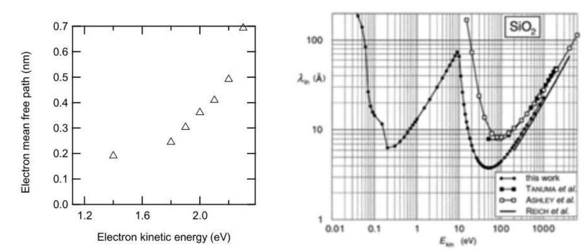




(left) PEY spectra as a function of photon energy obtained at sample locations over MoS_2 flakes (dotted lines) and SiO_2 (solid lines). (right) Total optical absorption (1-R) calculated for dielectric cavities. The solid and open circles depict the positions of resonance peaks in PEY spectra (left).

Electron Mean Free Path: Understanding Where Electrons Come from

Analysis of the photoemission intensity attenuation shows the very short electron mean free path in agreement with recent modeling, but in contrast to the widely-accepted "universal curve." This result supports the notion that the photoelectrons originate close to the dielectrics' surfaces in our photoemission condition.



(left) Experimentally-derived photoelectron mean free path as a function of electron kinetic energy. (right) Inelastic mean free path of electrons with kinetic energy E_{kin} in SiO_2; the interaction with phonons leads to a second characteristic minimum between the electronic band gap and the phonon energy scales. Reproduced from Kuhr & Fitting, J. Electron. Spectrosc. Relat. Phenom. 105, 257 (1999).

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