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THE BERNAL PROJECT

"Insights into 1D and 2D nano-materials: atomic-scale landscapes, single atom action and collective electron motion revealed by electron microscopy and spectroscopy"

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Motivation

Nano-materials, including carbon nanotubes and graphene have risen enormous interest. Especially in the case of graphene a large number of theoretical and experimental methodologies has been applied to investigate the stunning phenomena promising a huge application potential; less focus has been directed to get 'to the bottom' of emerging and related problems, e.g., via direct visualisation of such phenomena.

Electron Microscopy is vital in this and can reveal

- atomic resolution structure and chemistry determination
- highly localised bandstructure assessment

We have carried out high resolution phase contrast and high angle dark field imaging combined with highly localised energy loss spectroscopy to reveal structure, chemistry and defect / foreign species dynamics as well as plasmonic properties in 1D and 2D carbon on the atomic scale.

We are extending these investigations to other 1D and 2D materials deriving from layered bulk forms (dichalcogenides, MAXenes)

So let's look at

-Atomic landscapes of 2-Ds

-Opto-electronic tailoring of nano-materials by methods used in semiconductor IC: ion implantation

-Tailoring the optical/plasmonic properties of nano-materials

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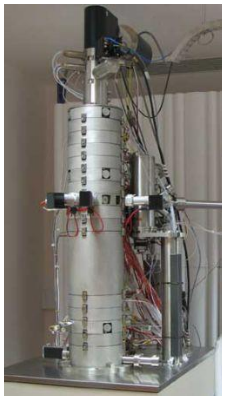
Instrumentation

Instruments used in collaboration with Centres of Expertise

- Daresbury SuperSTEMs - dedicated, probe corrected transmission electron microscopes with analytical facilities: electron energy loss spectroscopy (EELS) and energy dispersive X-ray spectroscopy (EDX)

- Anatytical TEMs (with STEM-mode of the Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons, Forschungszetrum Juelich

- just acquired at UL: analytical TEM/STEM



SuperSTEM
(Nion UltraSTEM)
Probe C_s corrected to 5th

SuperSTEM
DARESBURY

High resolution electron microscopy with aberration corrected lenses achieves down to 50 pm resolution, monochromation achieves 0.1 eV energy resloution

Titan PICO TEM
C_C corrected
Double C_S corrected
Monochromated

JÜLICH
FORSCHUNGSZENTRUM

Titan HOLO TEM,
image C_S corrected, large polepiece gap, two electron biprisms

Titan Themis TEM
monochromated, probe corrected (for scanning mode) and image corrected (for high resolution imaging) transmission electron microscope with energy filter and EDX

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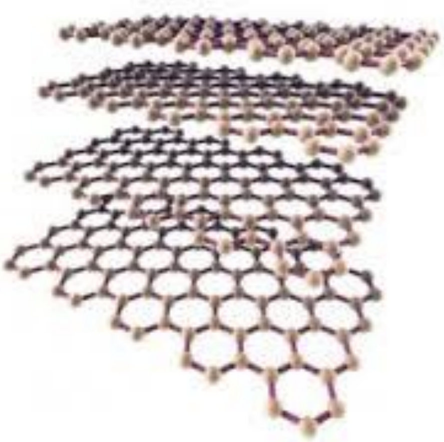
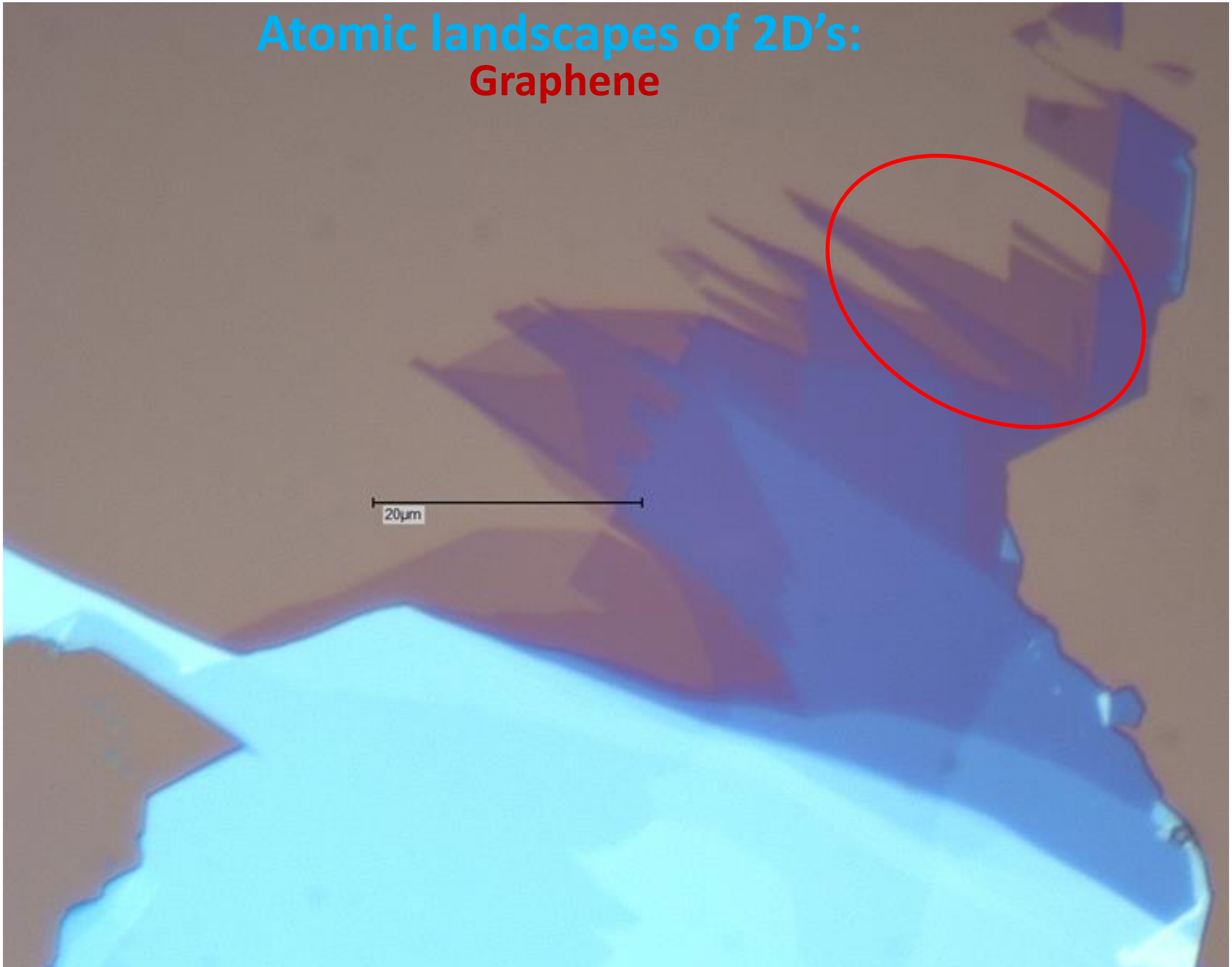
<u>PLUS</u>
-ultrafast acquisition with supersensitive detector/camera
-in-situ experiments (in gas&liquids, under heating/cooling and mechanical &electrial stressing
-tomography and holography ….. ALL ON THE ATOMIC SCALE!

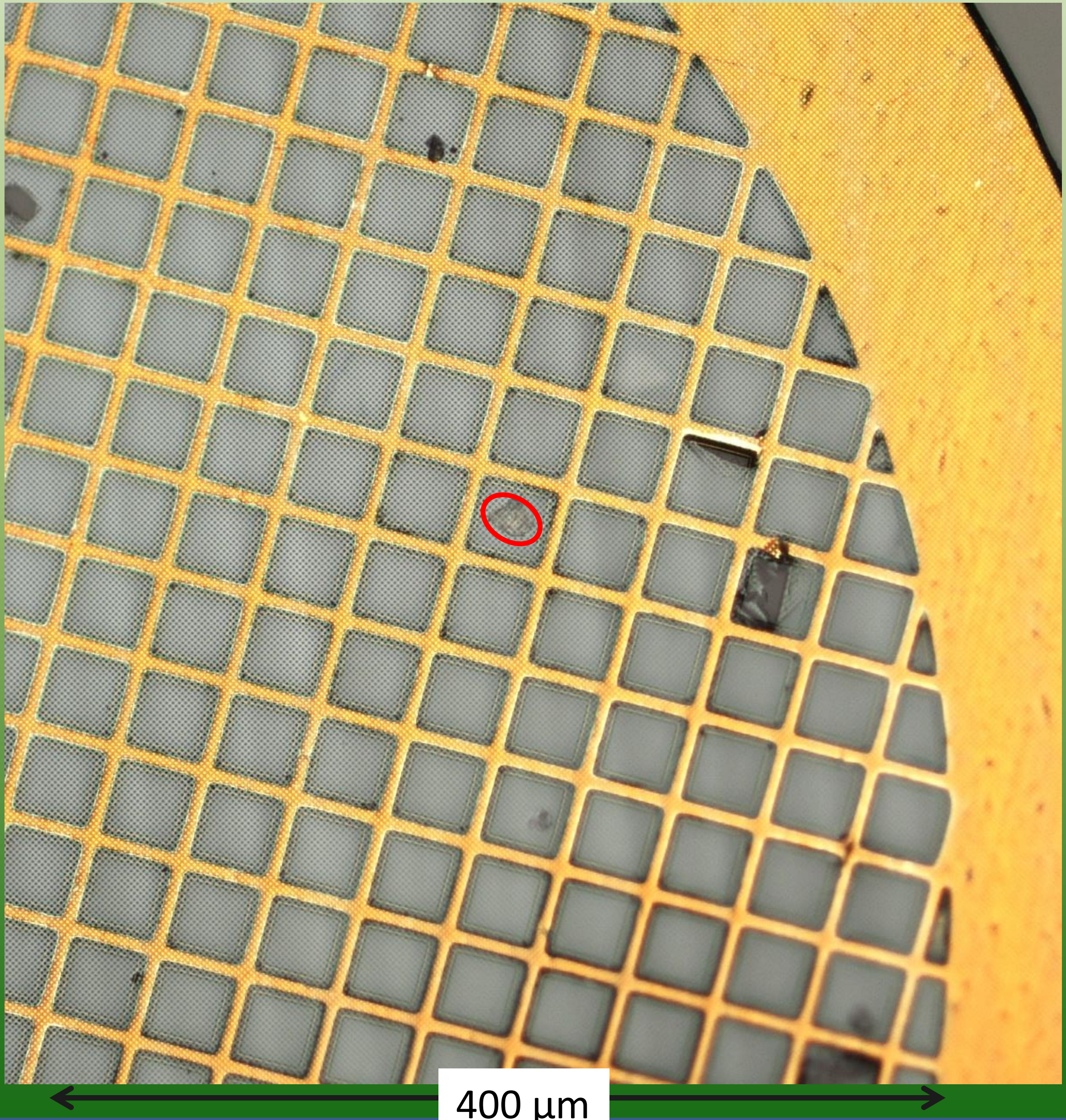
Atomic landscapes of 2D's:
Graphene



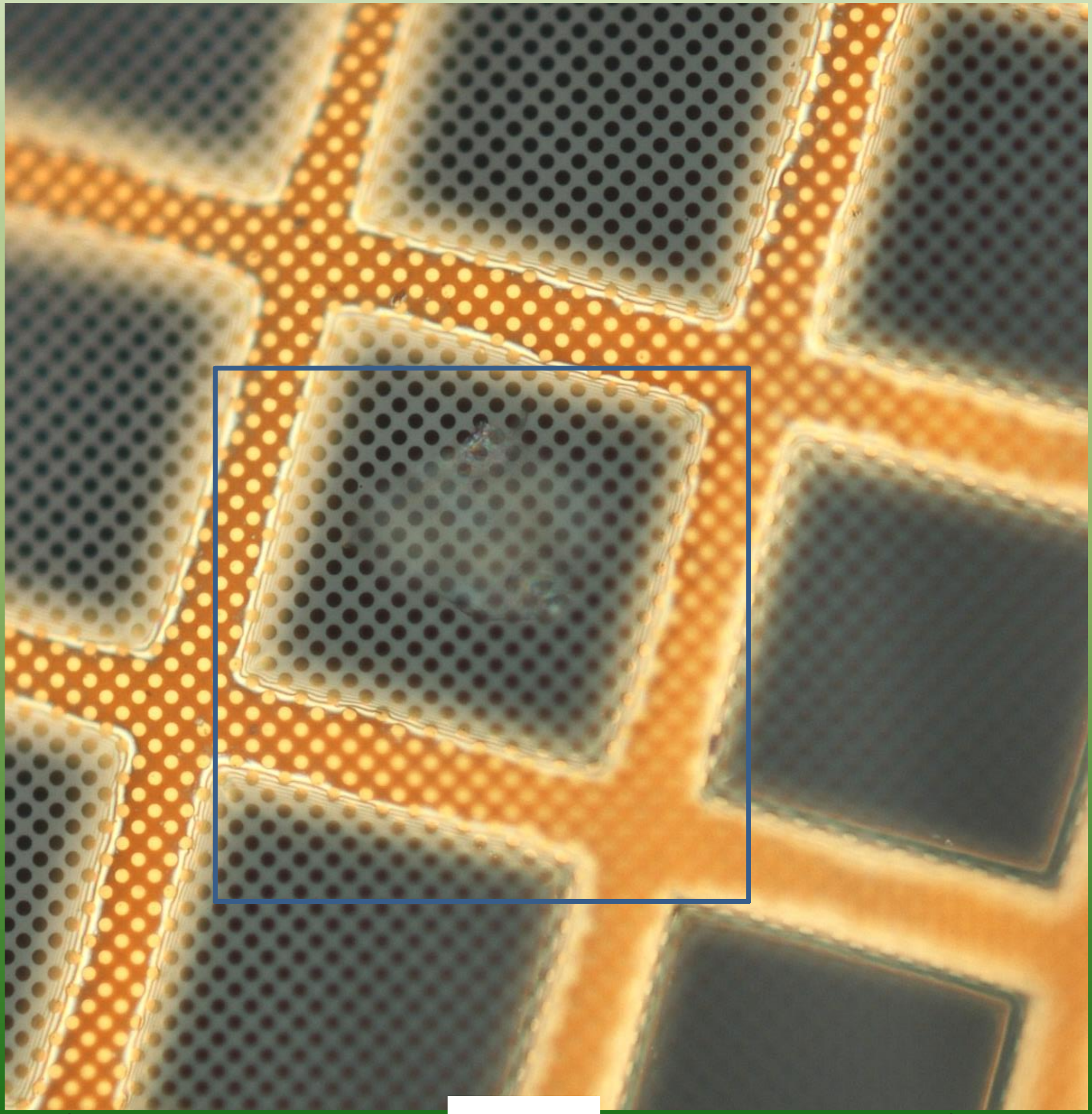
Atomic landscapes of 2D's:
Graphene



Images from 'Graphene-The Virtual Microscope'

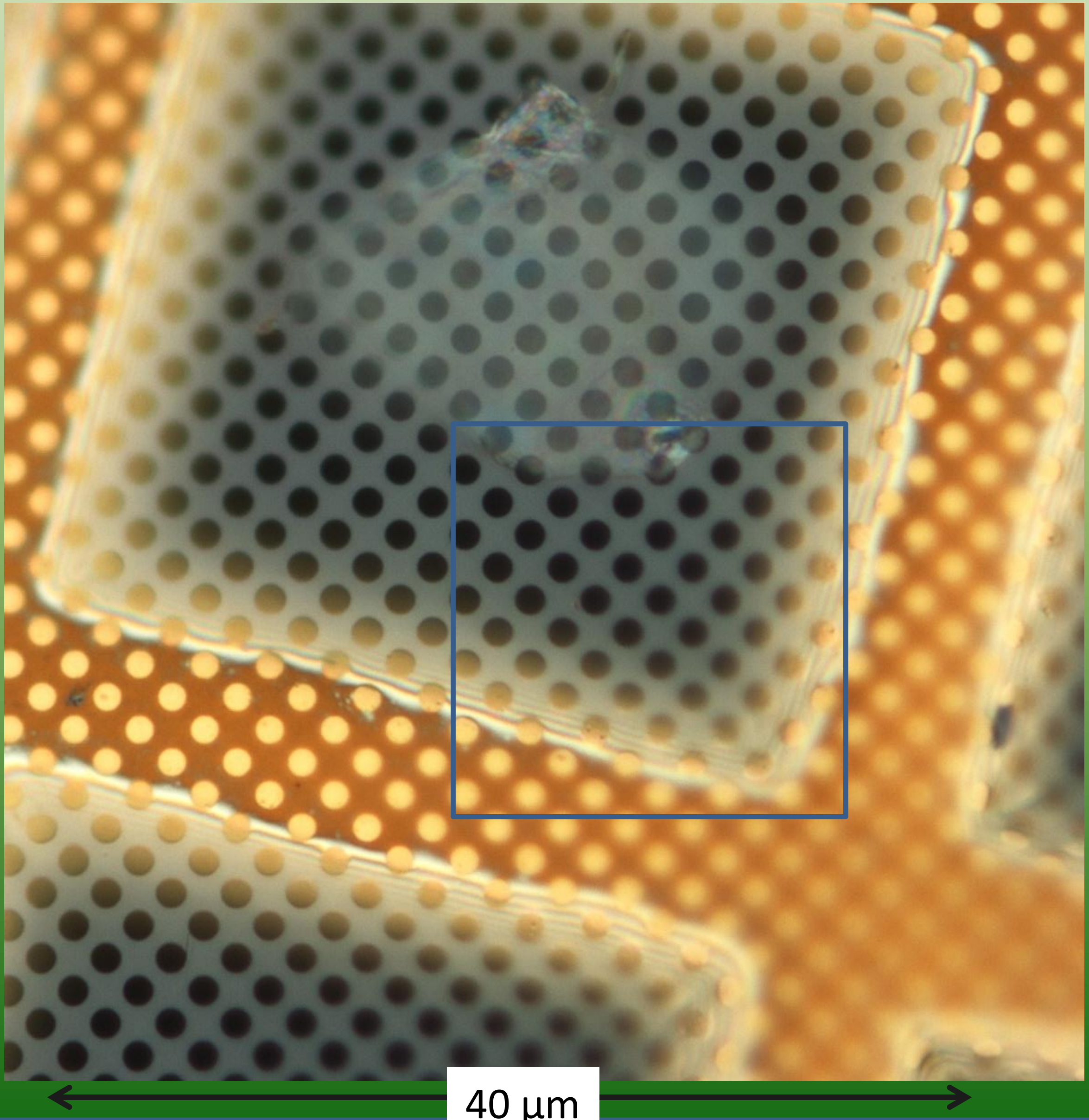


Magnification:
10 x

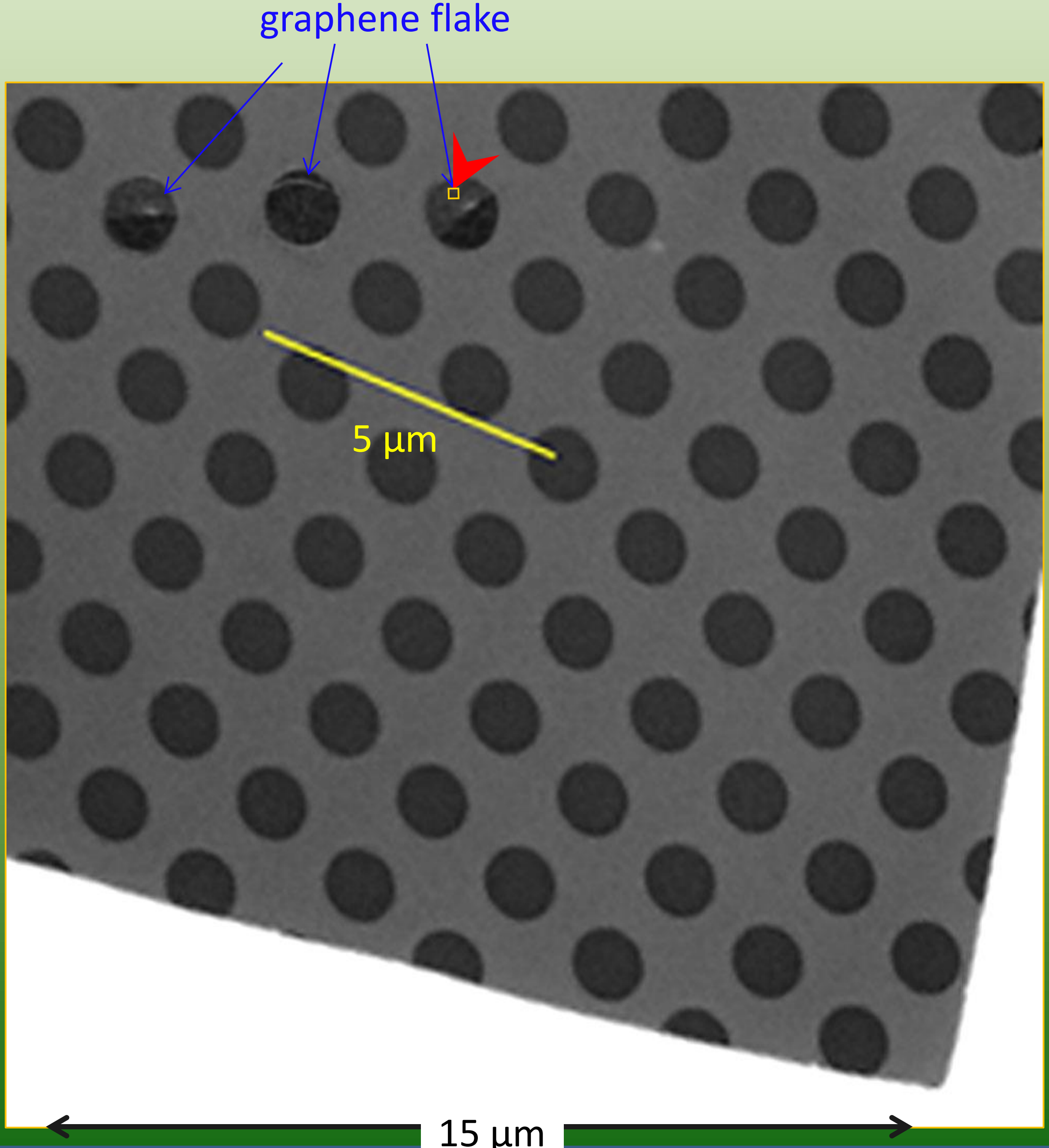


80 µm

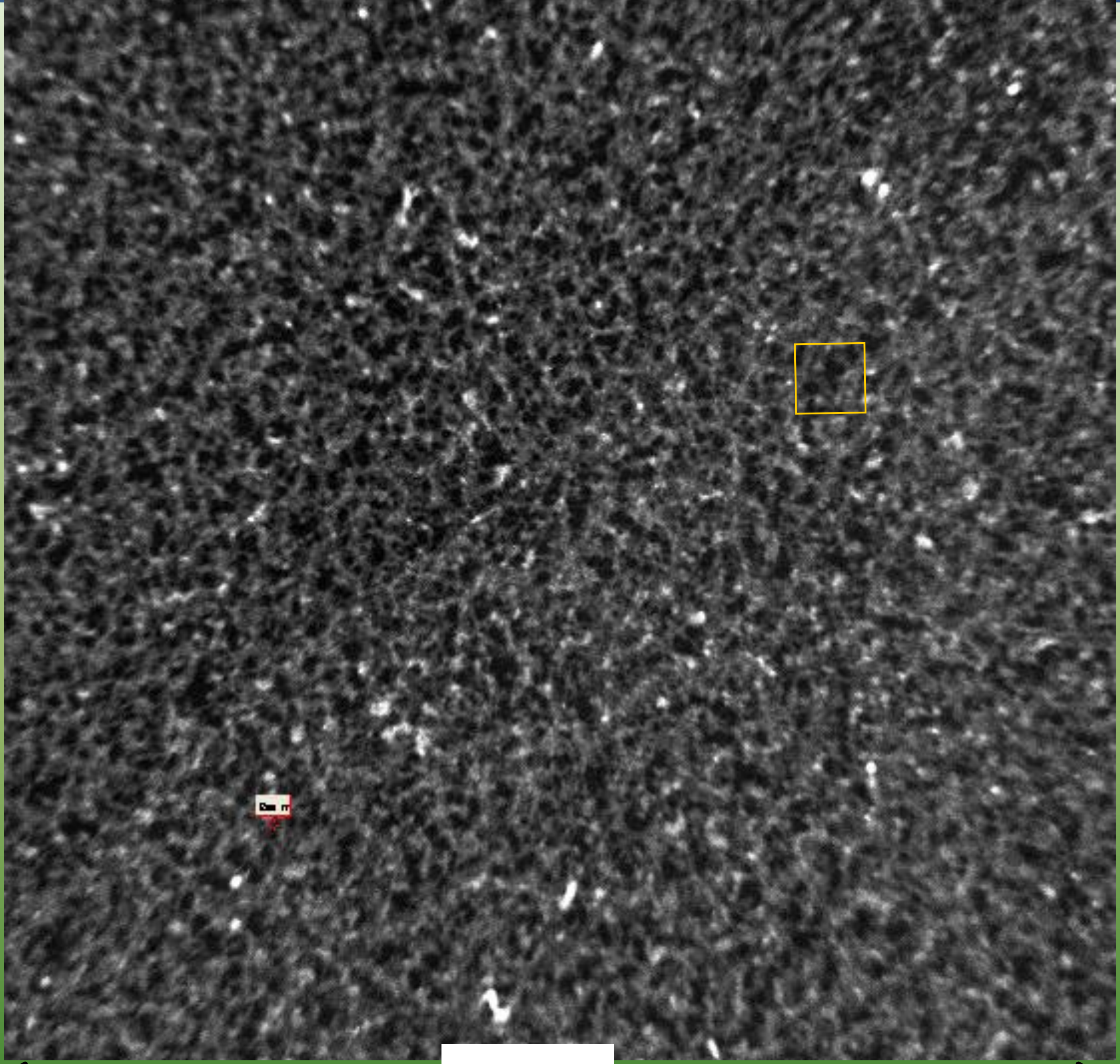
Magnification:
70 x



Magnification:
140 x

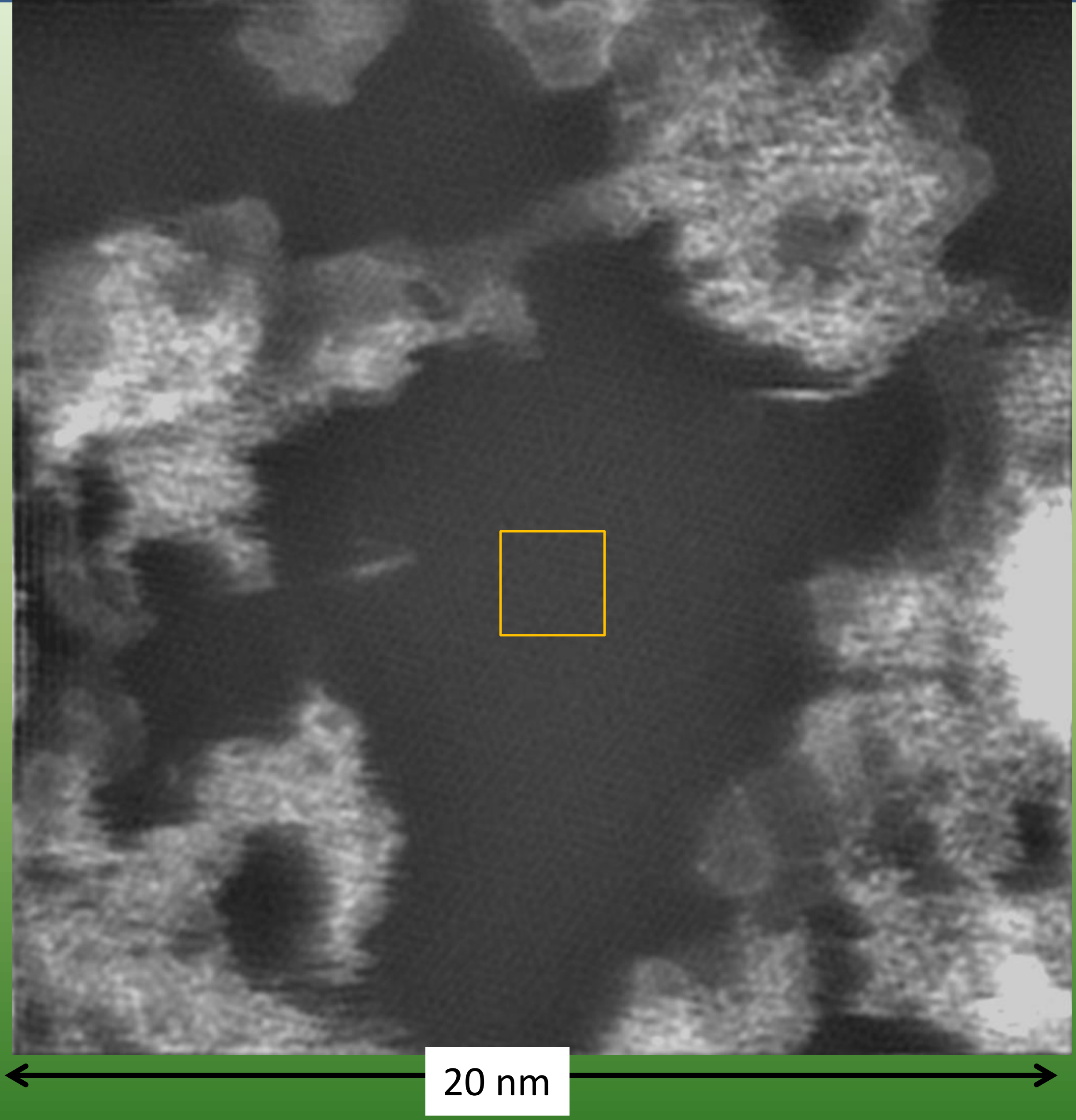


Magnification:
420 x

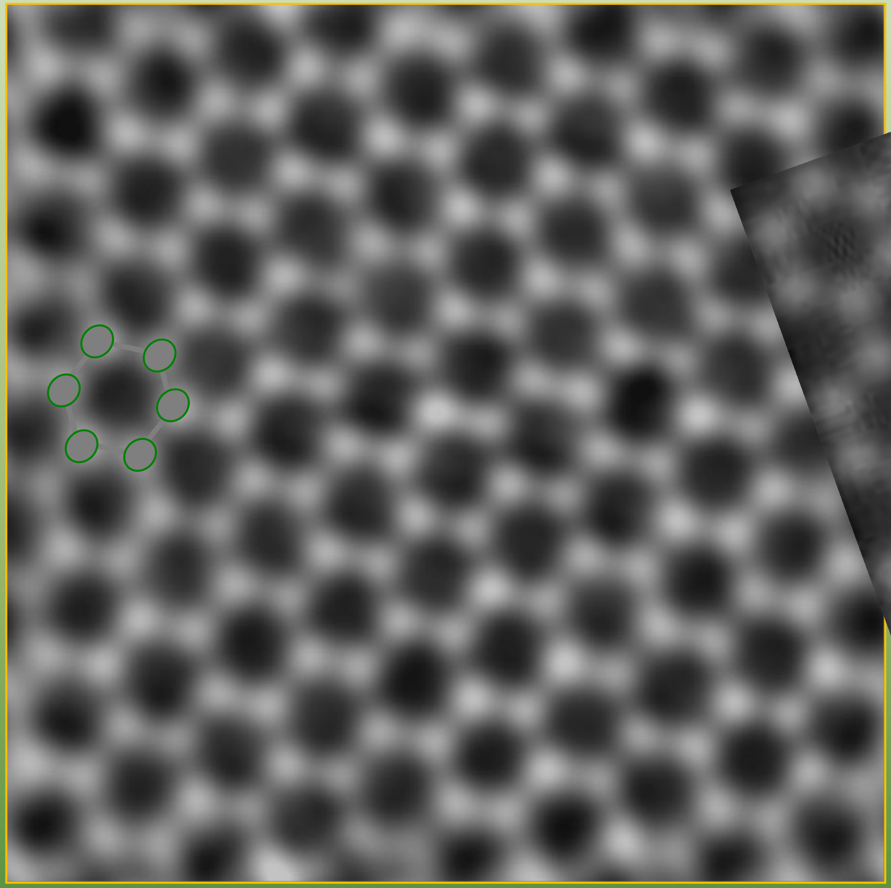


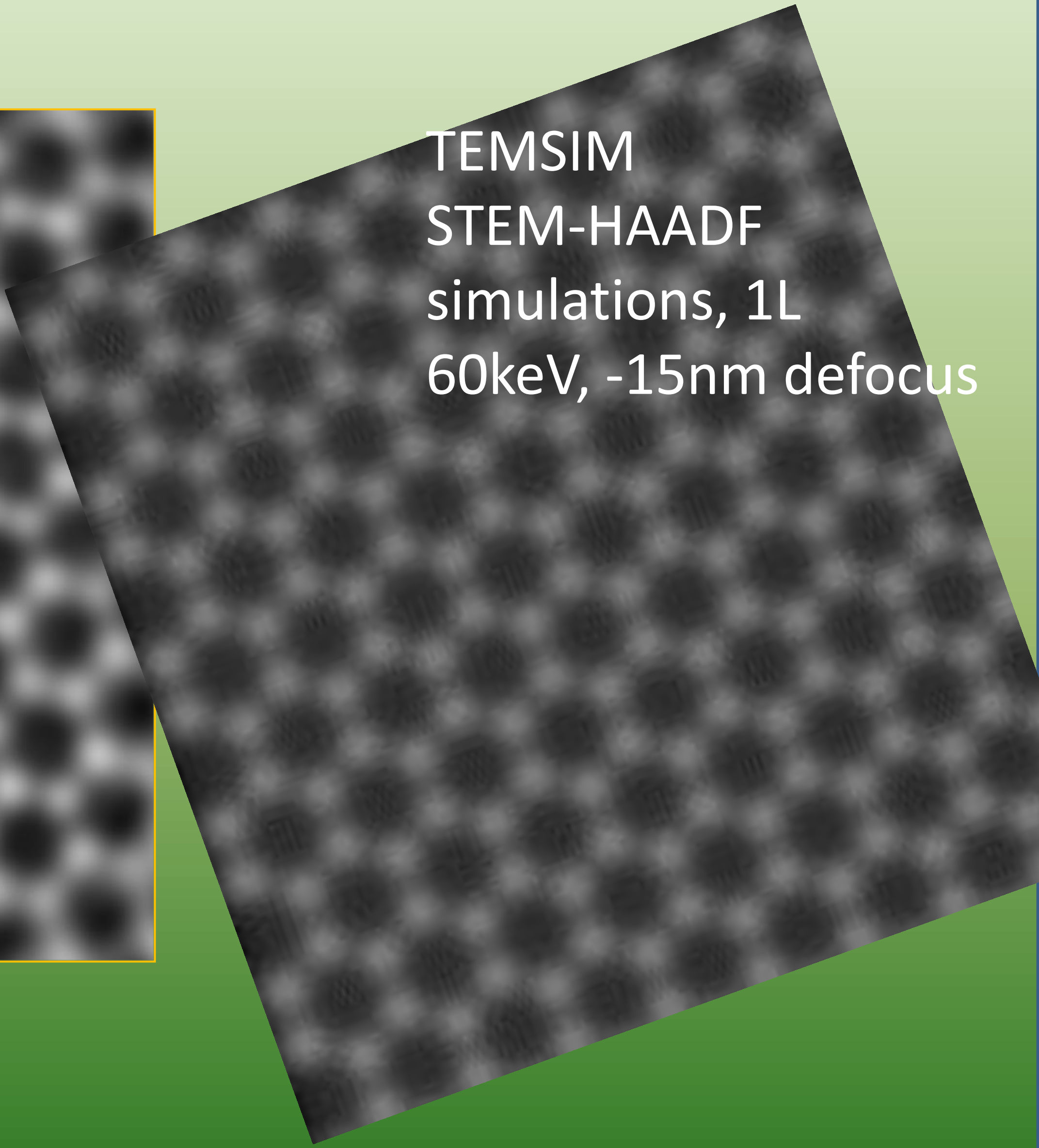
Magnification: 50,000 x

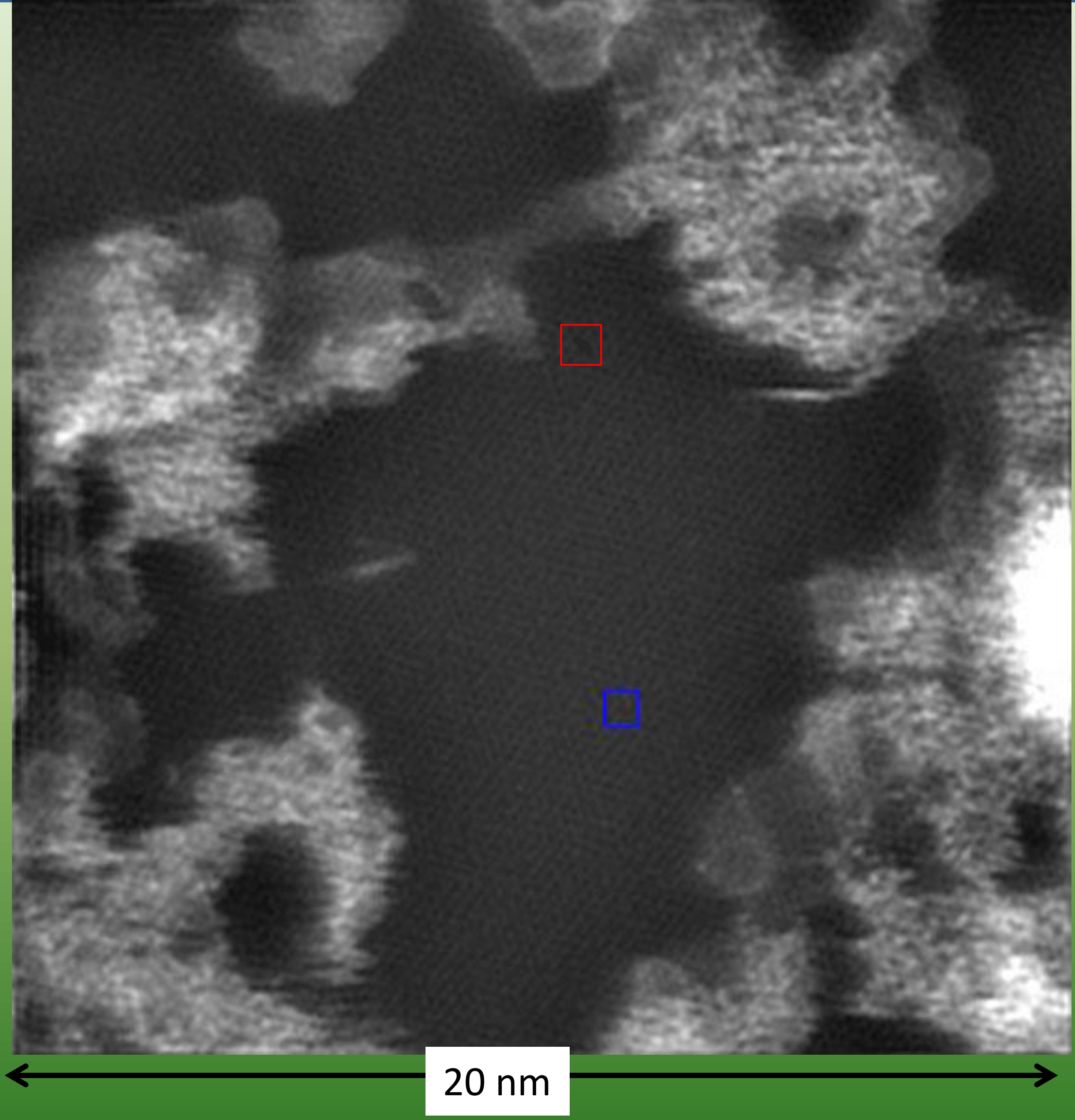
300 nm



Magnification:
750,000 x



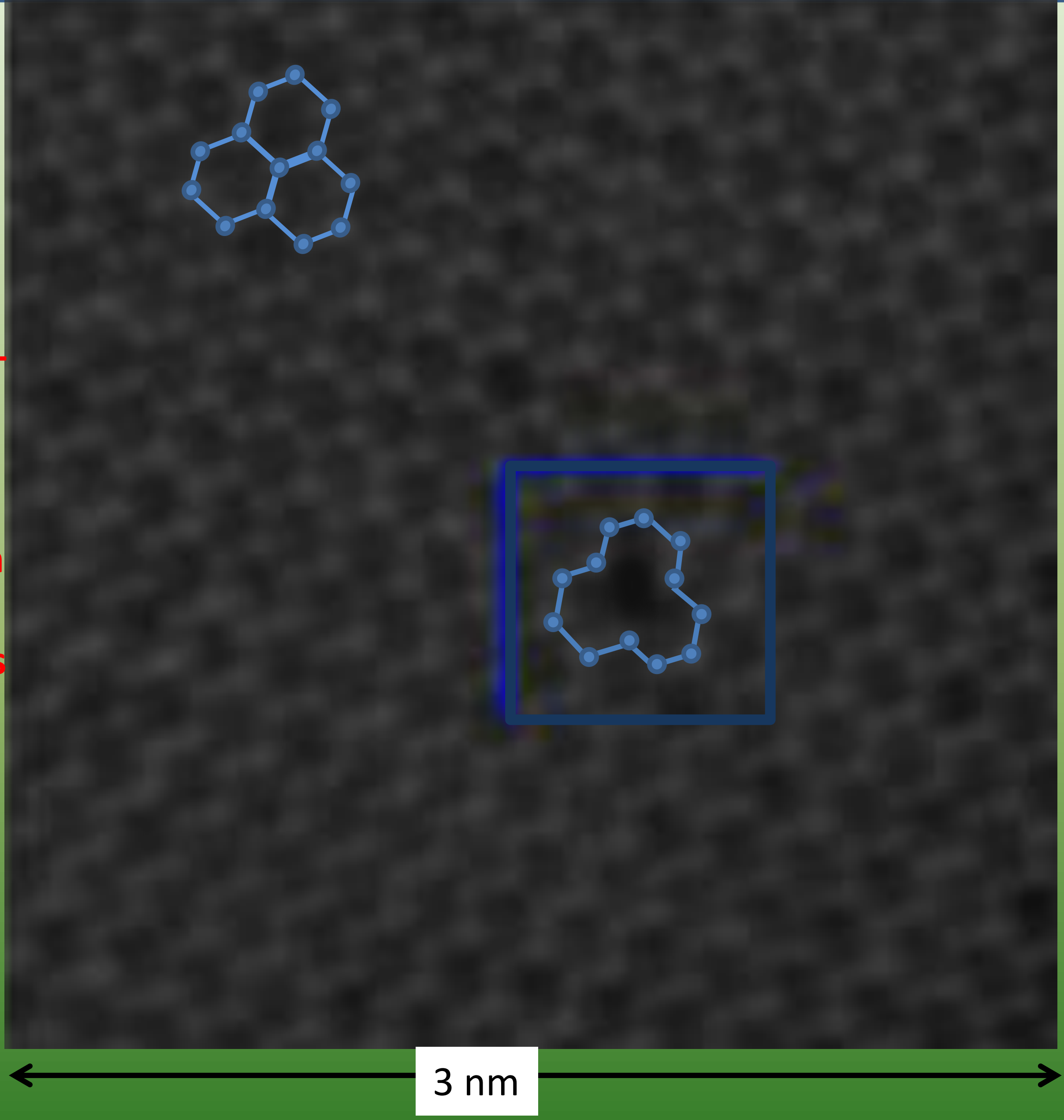

TEMSIM
STEM-HAADF
simulations, 1L
60keV, -15nm defocus



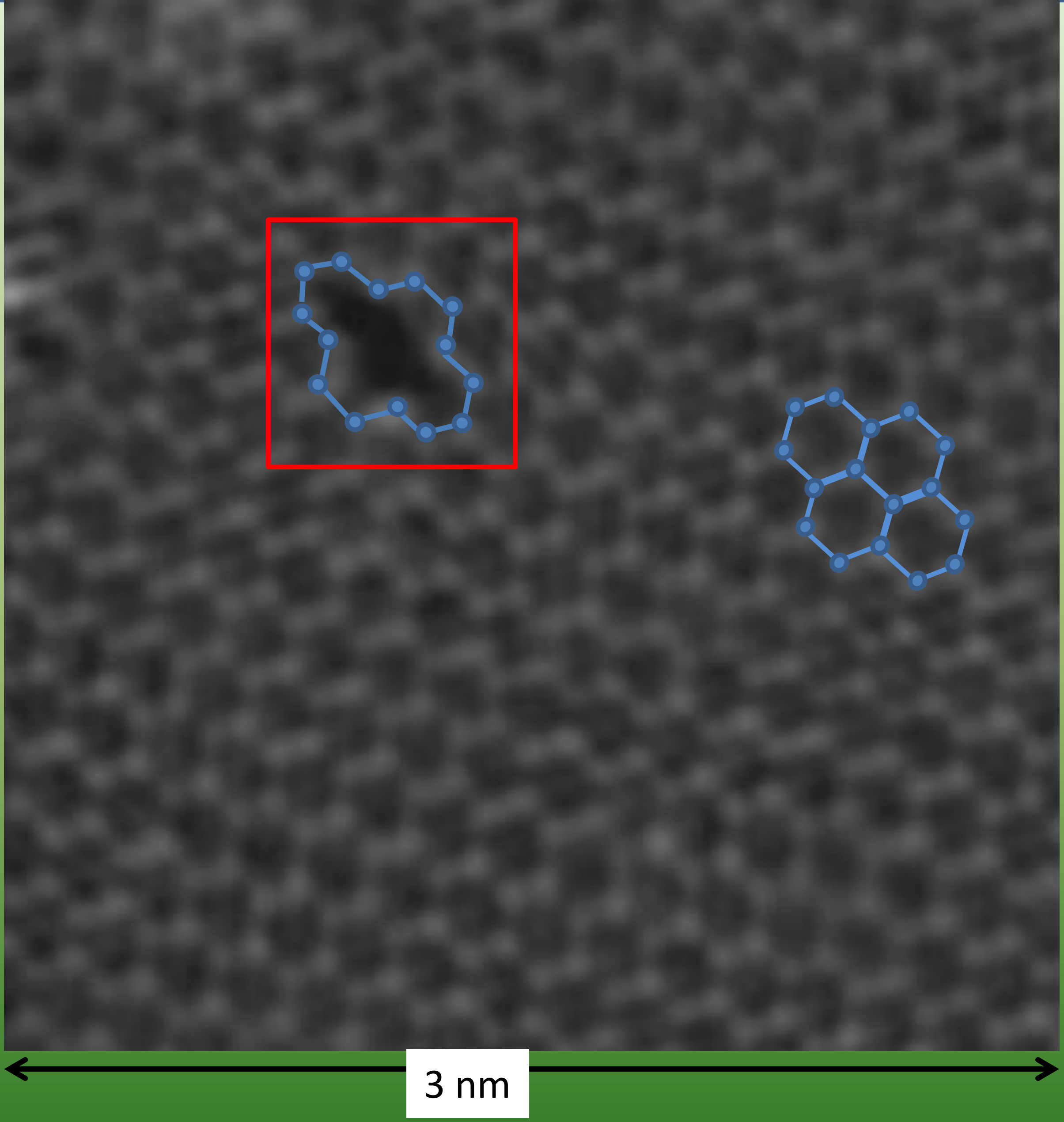
Magnification:
750,000 x

The ball-and-stick model shows the mono-vacancy and the perfect hexagon structure. The 'balls' are carbon atoms, the 'sticks' the bonds between them.

Magnification: 5,000,000 x

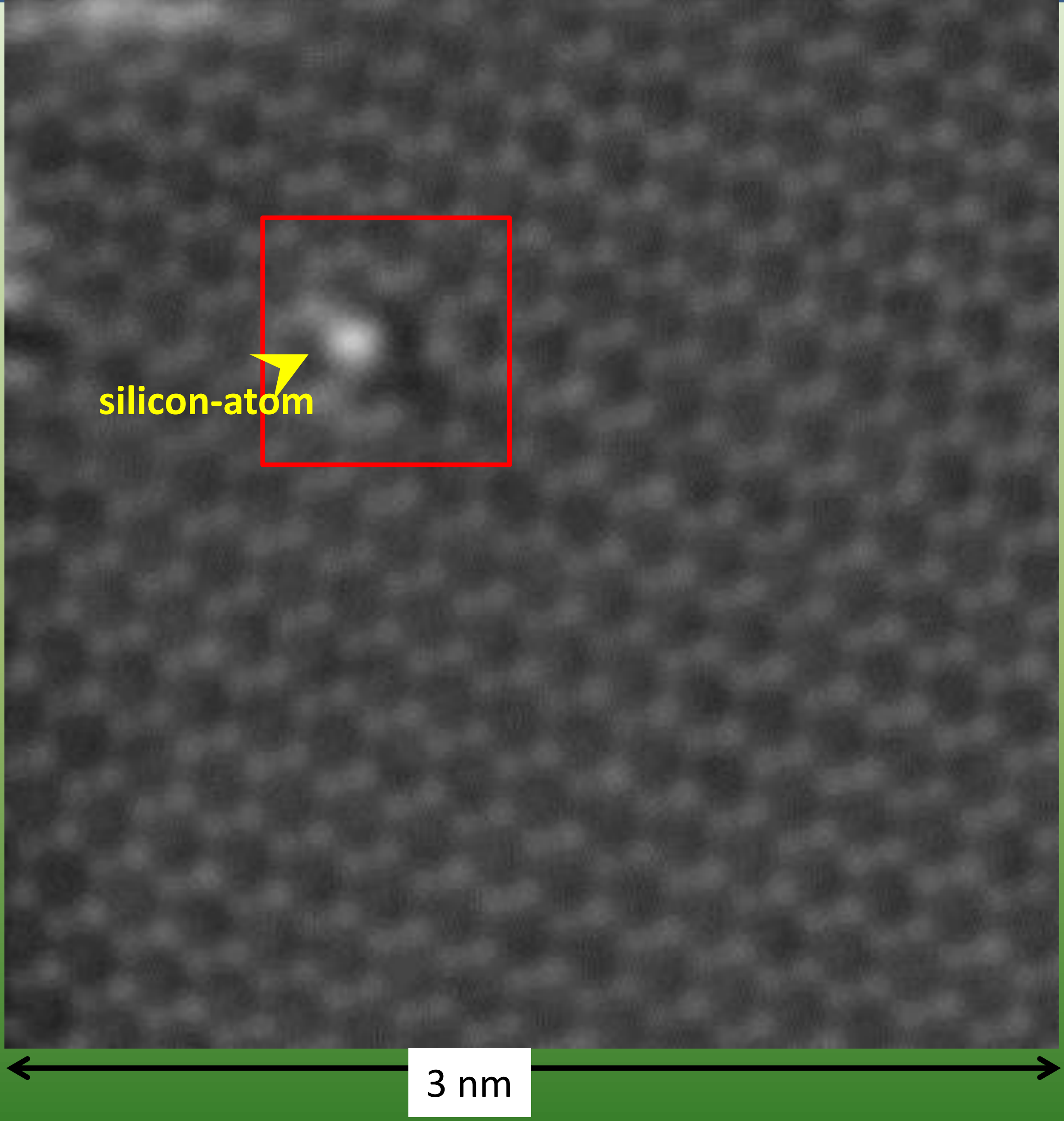


The ball-and-stick model shows the di-vacancy and the perfect hexagon structure. The ‘balls’ are carbon atoms, the ‘sticks’ the bonds between them.



Magnification: 5,000,000 x

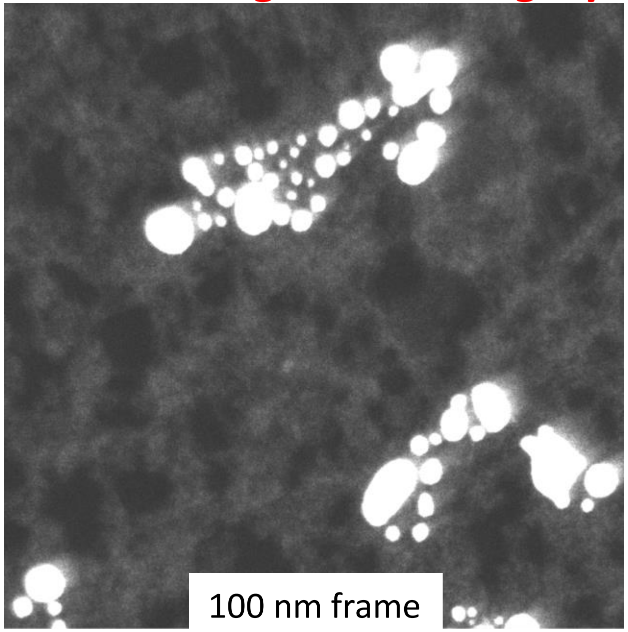
By repeatedly scanning the same area a silicon atom –a common impurity- can be moved to the edge of the defect

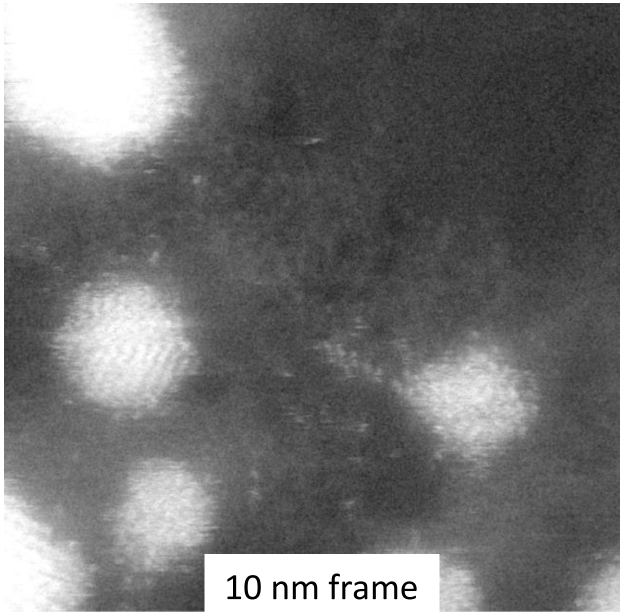


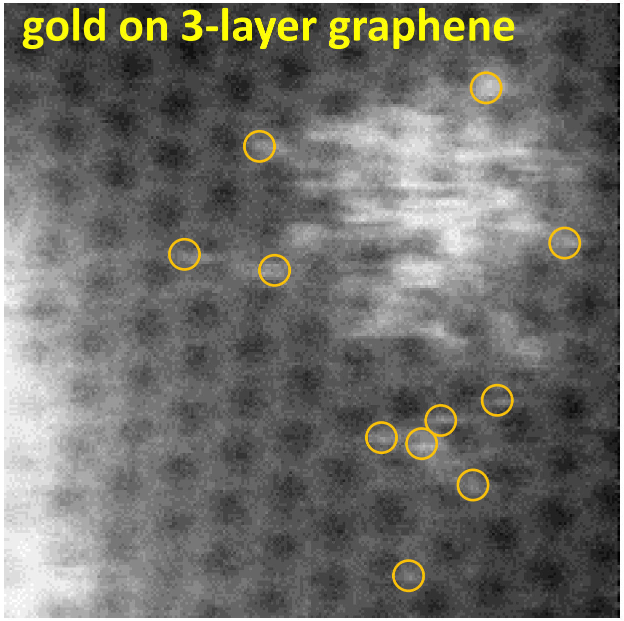
Magnification: 5,000,000 x

Foreign atoms on graphene – noble metals: 0.2 Å gold

understanding the metal-graphene interaction is crucial for devices/electrical contacting!

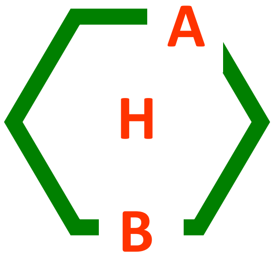






HAADF Z-contrast imaging reveals heavy impurities –single atoms and clusters thereof- additionally to the usual hydro-carbons. In combination with EELS it also reveals their nature

- ***no*** gold found on monolayer graphene -sits exclusively in hydrocarbon contamination in form of nanoclusters
- nanoclusters and some single atoms directly on few-layer graphene
- gold sits on **A-sites**



R Zan, U Bangert, Q Ramasse, K S Novoselov, Nano Letters 11(3) 1087 (2011)

R Zan, U Bangert, Q Ramasse, K S Novoselov, Small, preview (2011)

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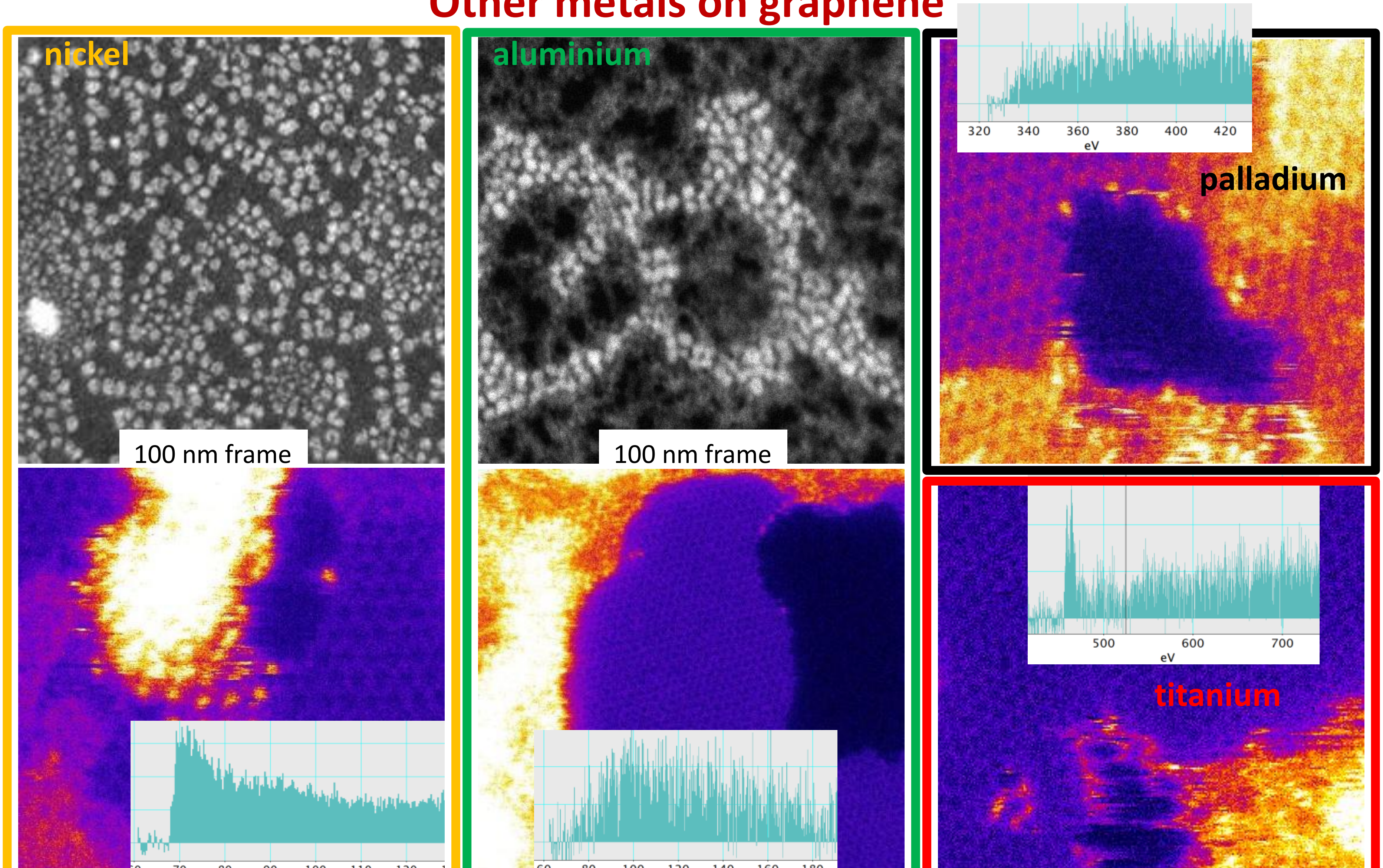
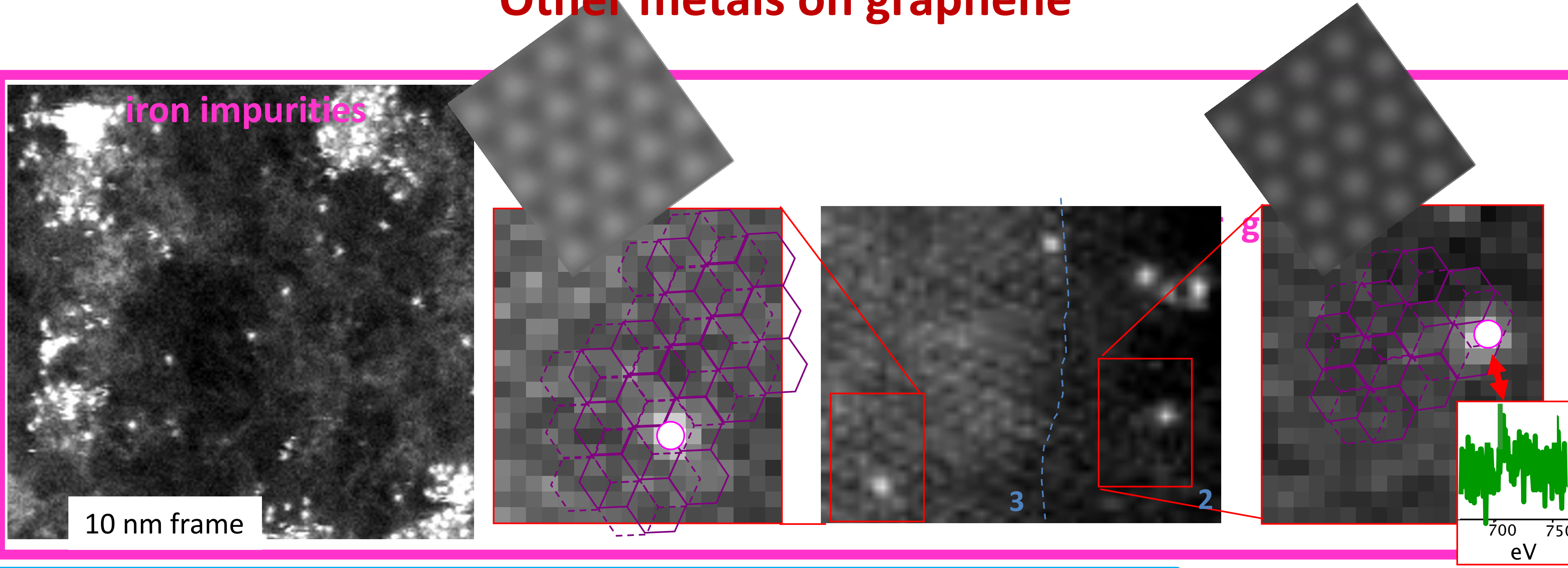
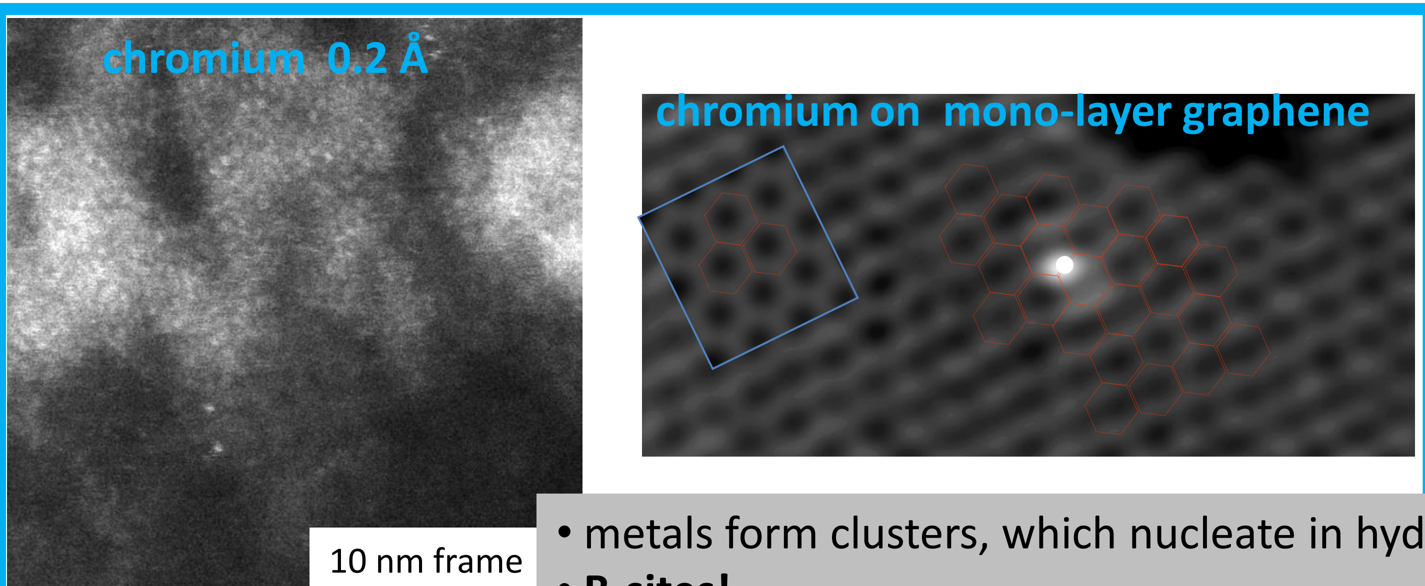
Other metals on graphene

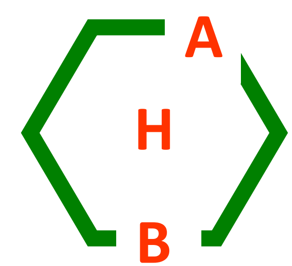


• metals form clusters, which nucleate in hydrocarbon contamination and often move to edge of vacancy aggregates or holes • **A-sites**

Other metals on graphene





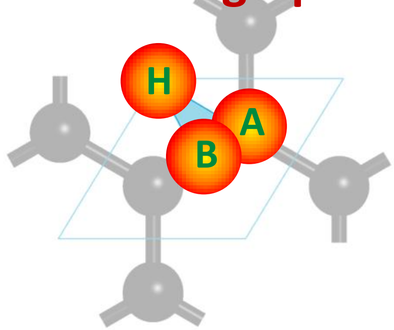


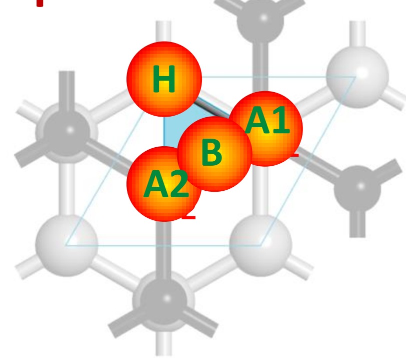
R Zan et al, Nano Letters 11(3) 1087 (2011)

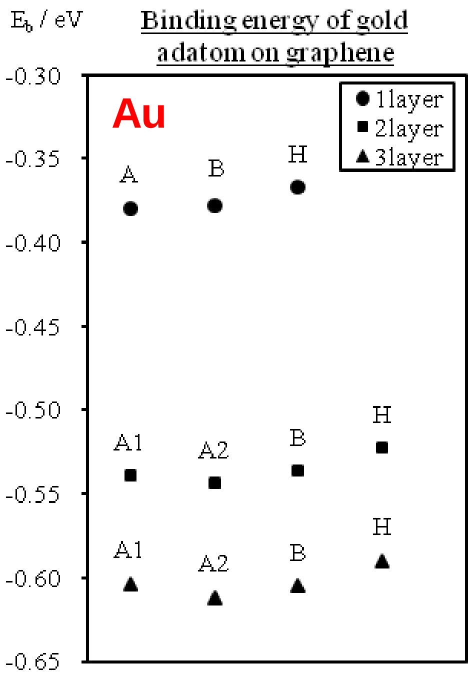
- metals form clusters, which nucleate in hydrocarbon contamination
- **B-sites!**

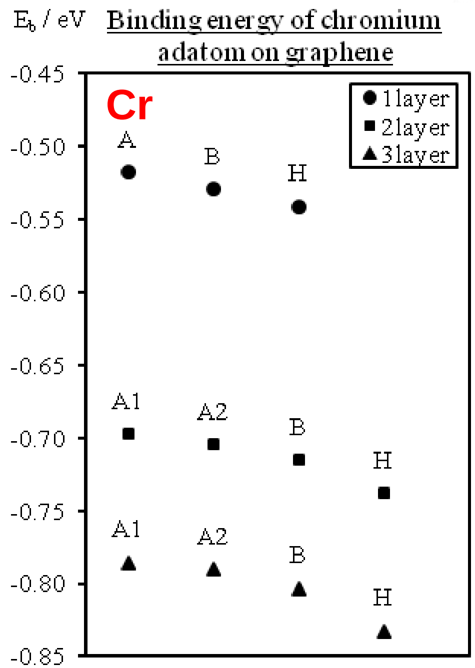
DFT calculations for metal ad-atoms on graphene

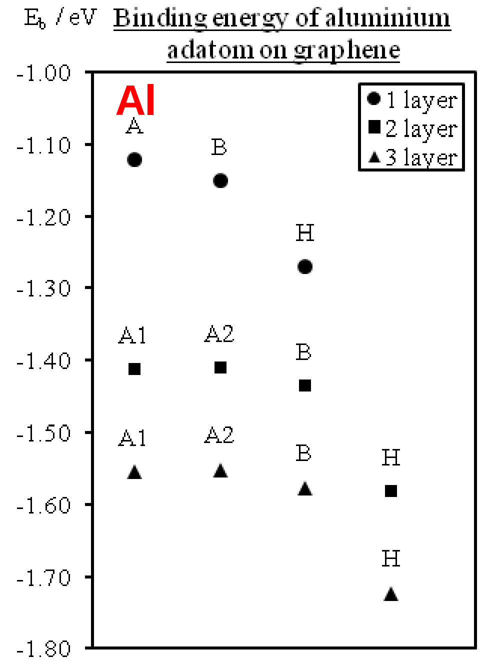
Metal atoms do NOT stick to graphene! Explanation comes from calculations (DFT)











all sites are very similar in energy -> reason for high mobility of ad-atoms

Calculations similarly predict very small migration barrier (of the order of thermal energies)

Hardcastle et al. –PRB 2013

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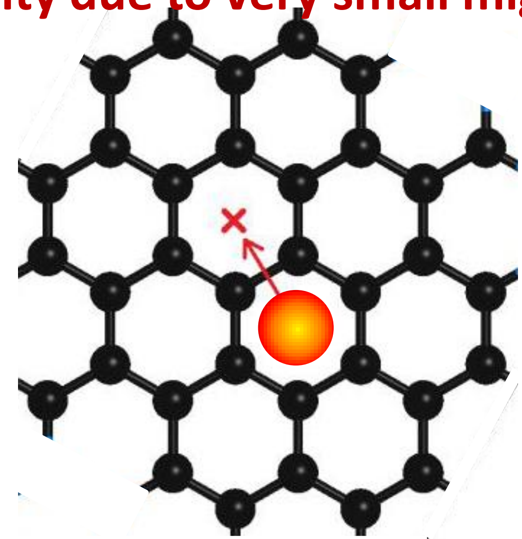
DFT calculations for metal ad-atoms on graphene

high mobility due to very small migration barriers



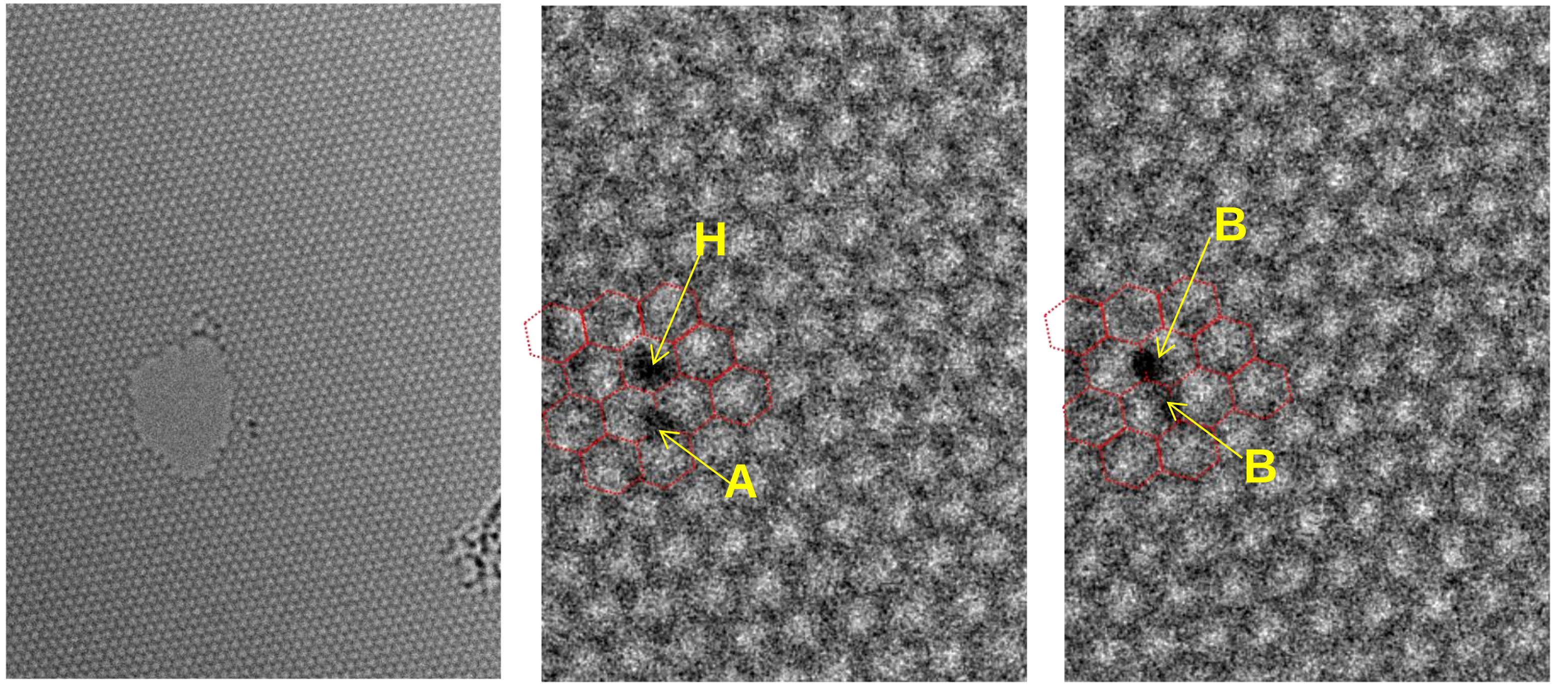
Adatom	Substrate	Path	Migration barrier ΔE / eV (3.d.p.)
Au	1 layer	A → B → A	0.007
	2 layer	A_1 → B → A_2	0.008
		A_2 → B → A_1	0.024
	3 layer	A_1 → B → A_2	0.019
		A_2 → B → A_1	0.025
Cr	1 layer	H → B → H	0.022
	2 layer	H → B → H	0.021
	3 layer	H → B → H	0.022
Al	1 layer	H → B → H	0.166
	2 layer	H → B → H	0.178
	3 layer	H → B → H	0.197

migration barriers of the order of thermal energies (0.03 eV)!

so metal ad-atoms won't stick in one place

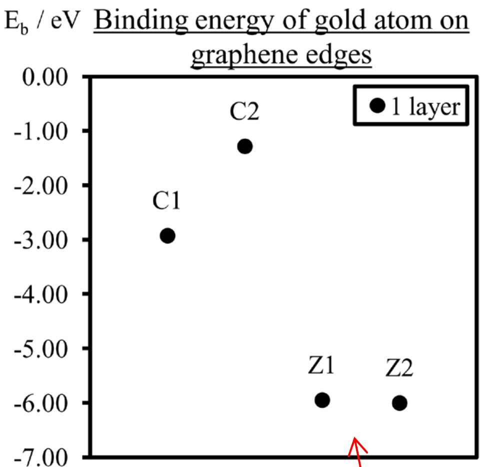
Hardcastle et al. –PRB 2013

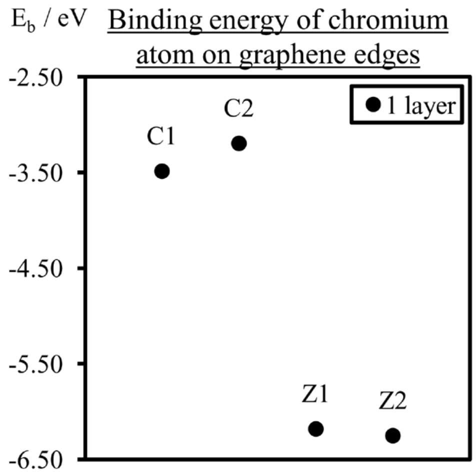
high mobility of metal ad-atoms on graphene (here: Pd)

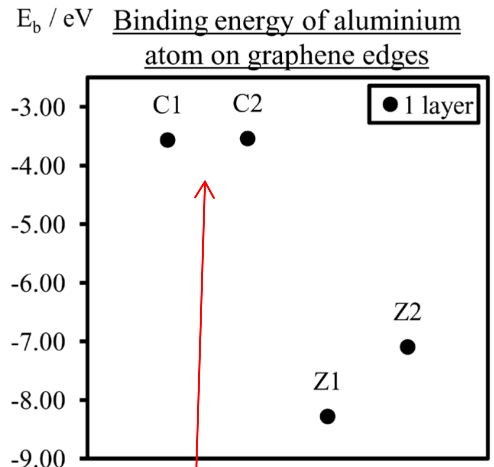


Raw, unprocessed HREM phase contrast images, taken at 50 keV in a Titan PICO, of graphene upon which a layer of nominally 2Å Pd was evaporated. The images are obtained with a defocus of -4nm to reveal atoms as dark and centres of 6-rings as bright contrast; the heavier the atom the darker the contrast. The left hand image shows Pd atoms near a hole. The high mobility of the Pd atoms is revealed in highly magnified, repeated images (middle and right-hand panel) by the fact that there is no apparent preference of their site on the graphene; in the middle image one Pd atom is located in the centre of the 6-ring and the other on a C-atom, whilst after the re-take in the right hand image they both sit on C-C bonds.

DFT calculations for metal ad-atoms at graphene edges

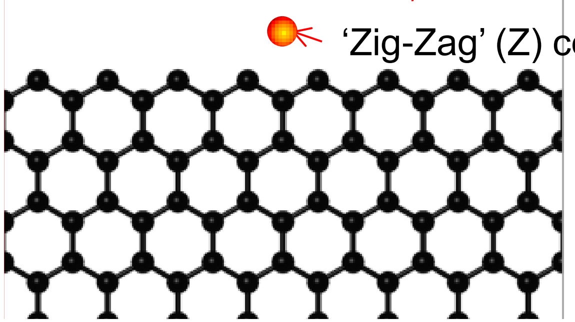




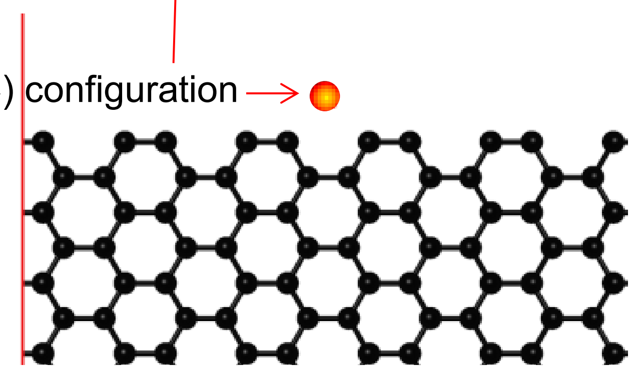


binding energy for atoms to graphene edges much higher than for surface (3 – 10 times)

‘Zig-Zag’ (Z) configuration,



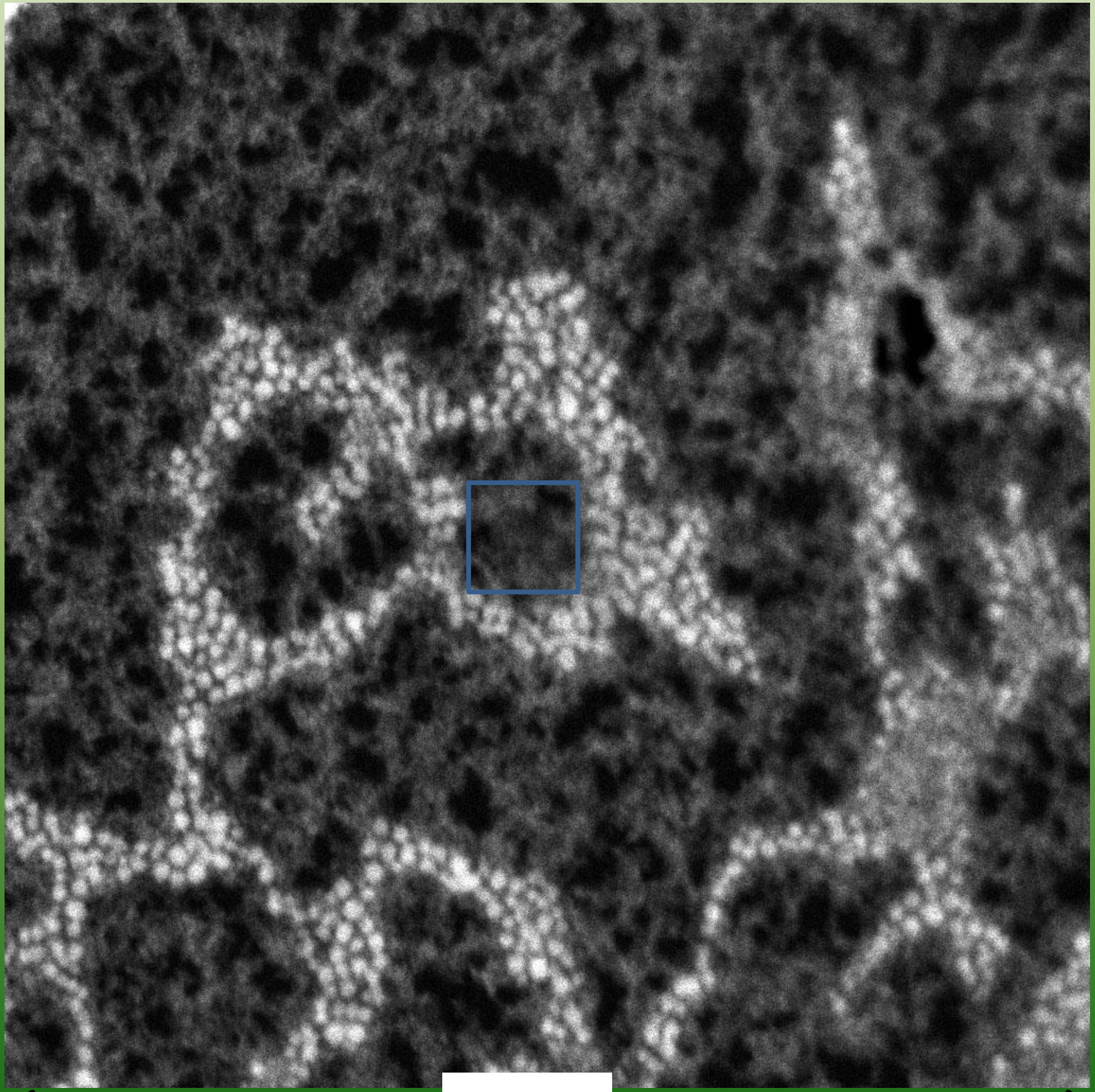
Chair’ (C) configuration



What metals do to graphene

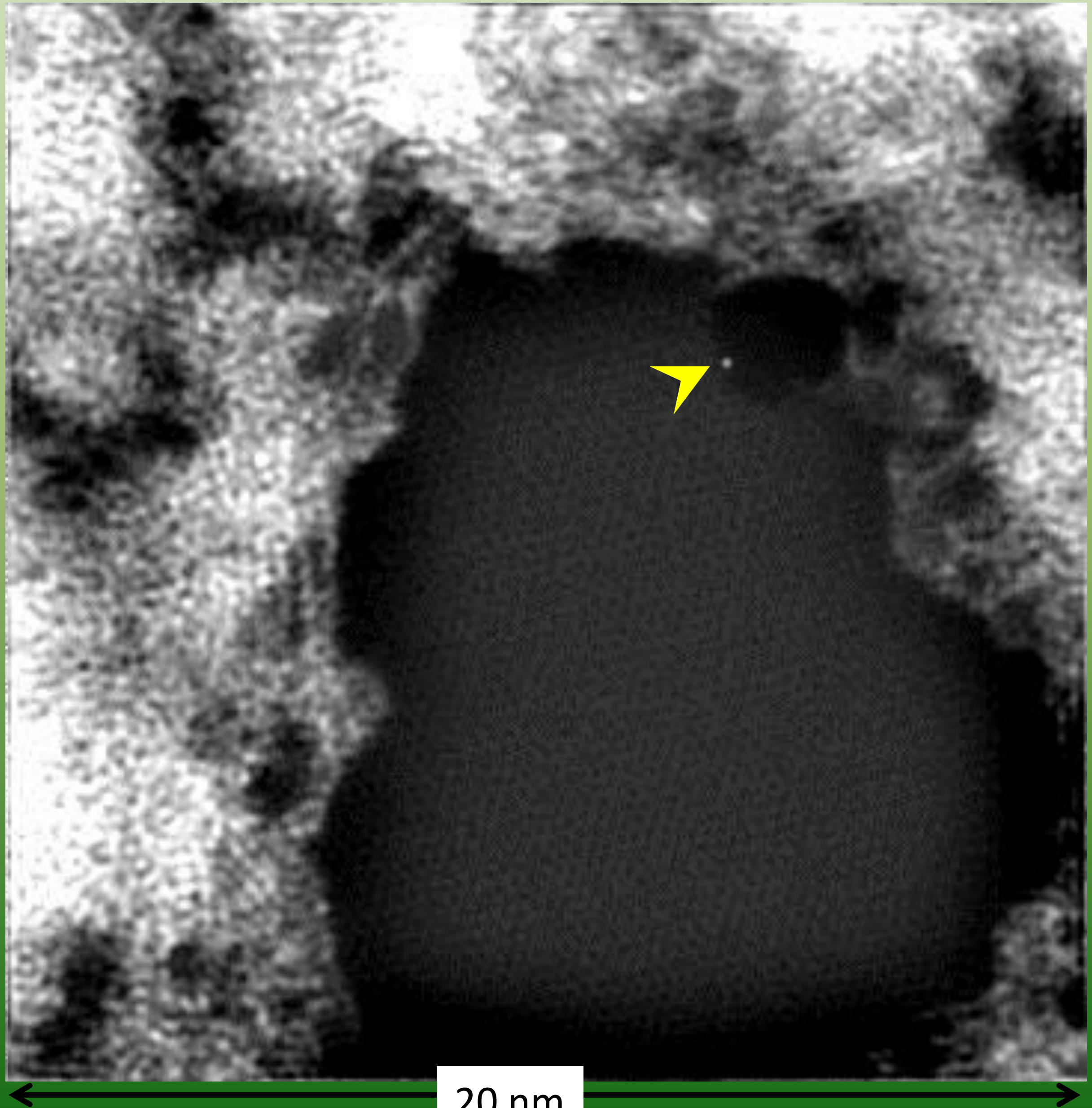
The bright little dots are *aluminium* atom clusters on graphene. Impurity atoms which have a tendency to oxidise in the presence of residual O-atoms, dissociate C-C bonds and cause removal of C-atoms, i.e., cause hole formation in graphene

Magnification: 40,000 x



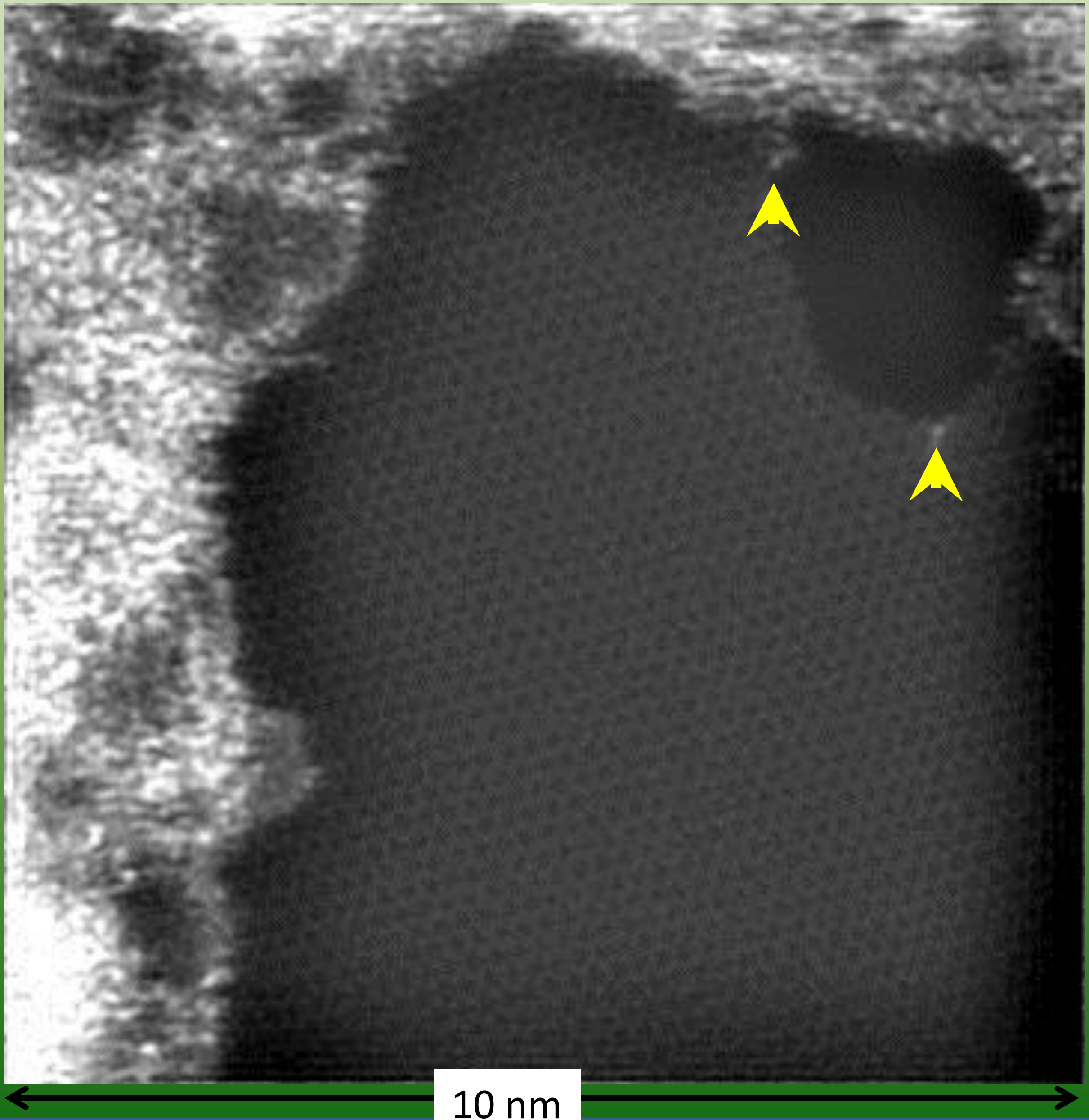
200 nm

Impurity atoms like aluminium and silicon can then catalyse the etching of graphene: a hole starts to form.



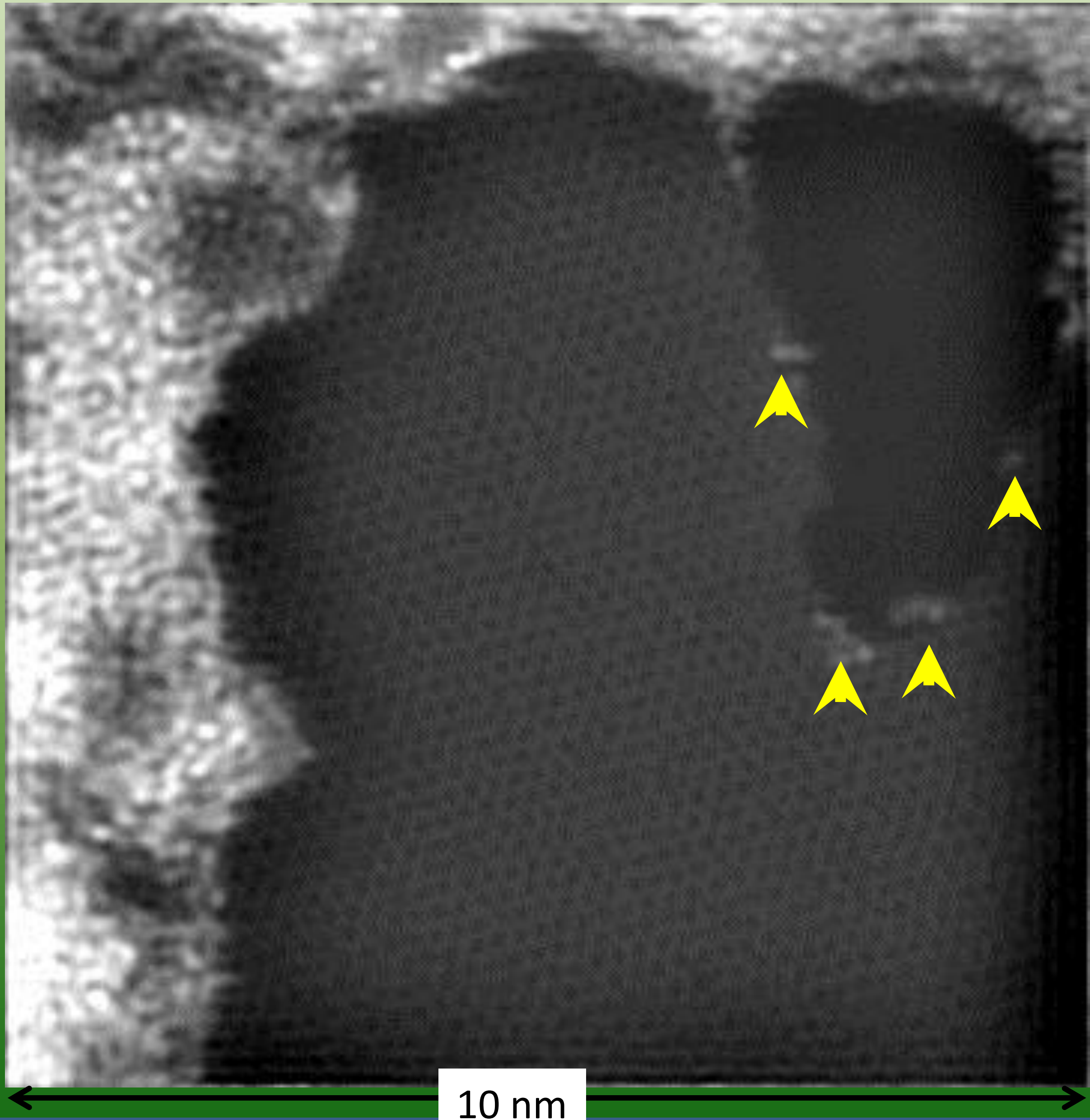
Magnification: 400,000 x

The hole enlarges: impurity atoms ‘zip’ around the edges and help take carbon atoms out.



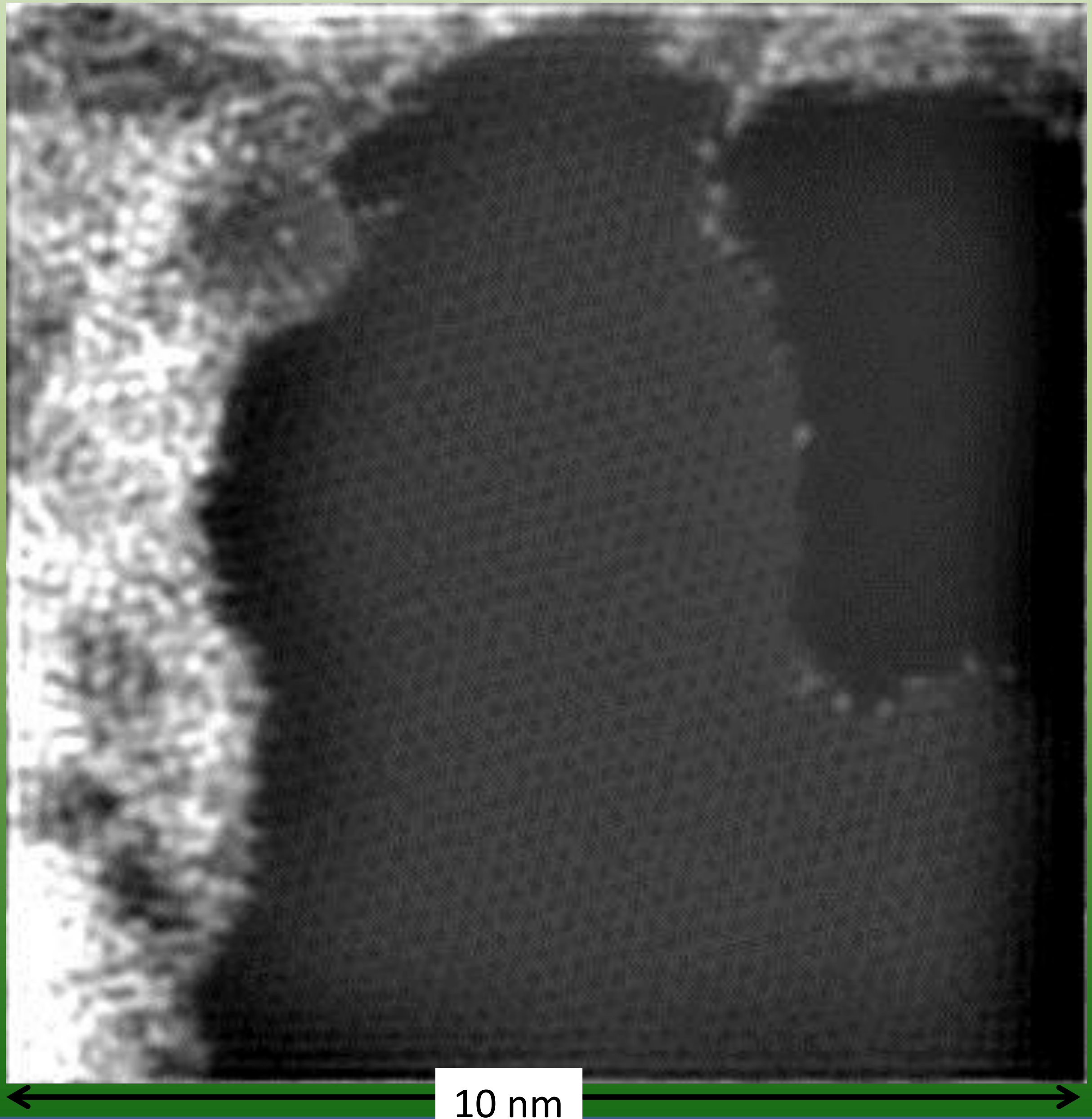
Magnification: 800,000 x

The process carries on…



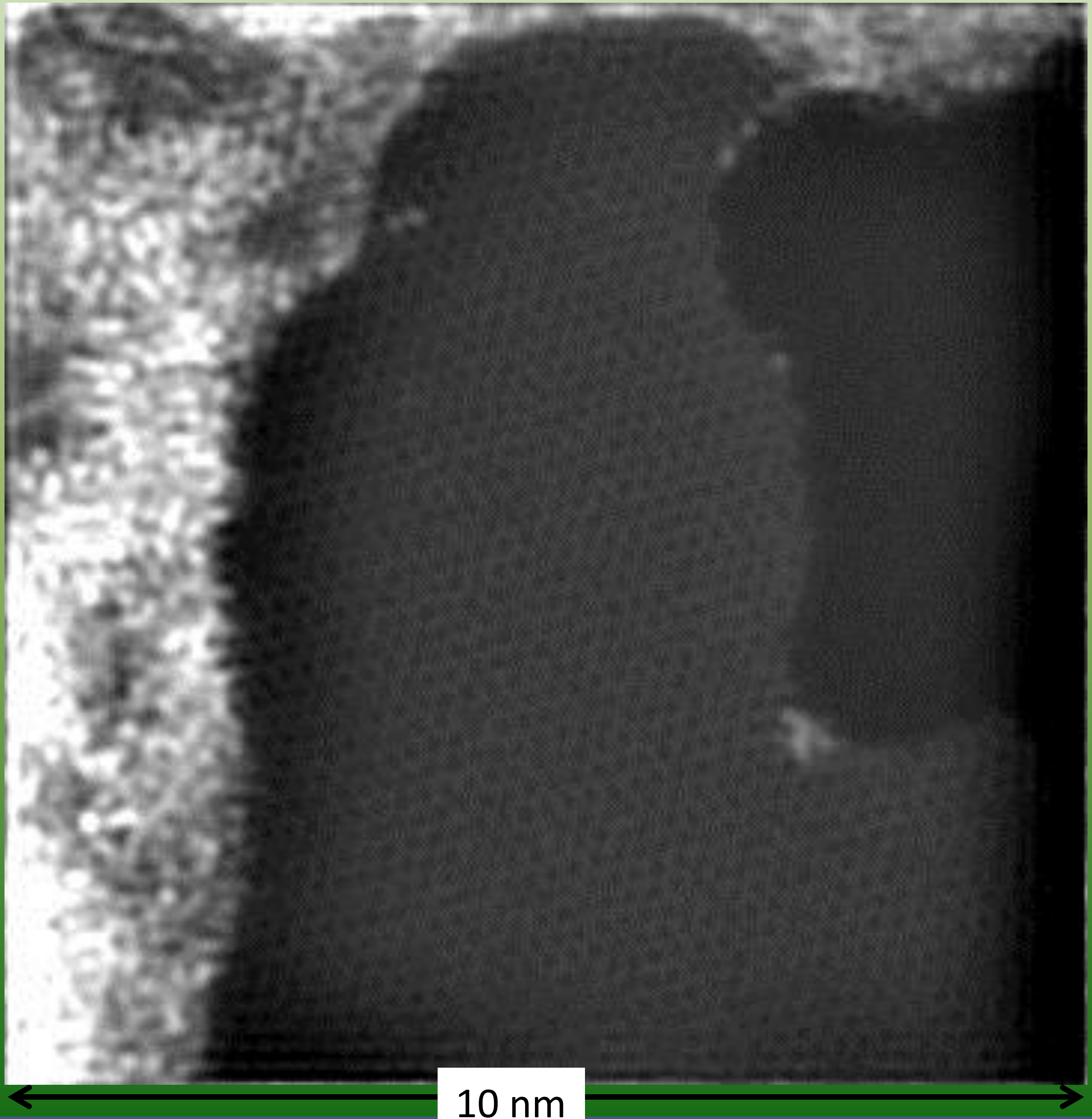
Magnification: 800,000 x

and on…



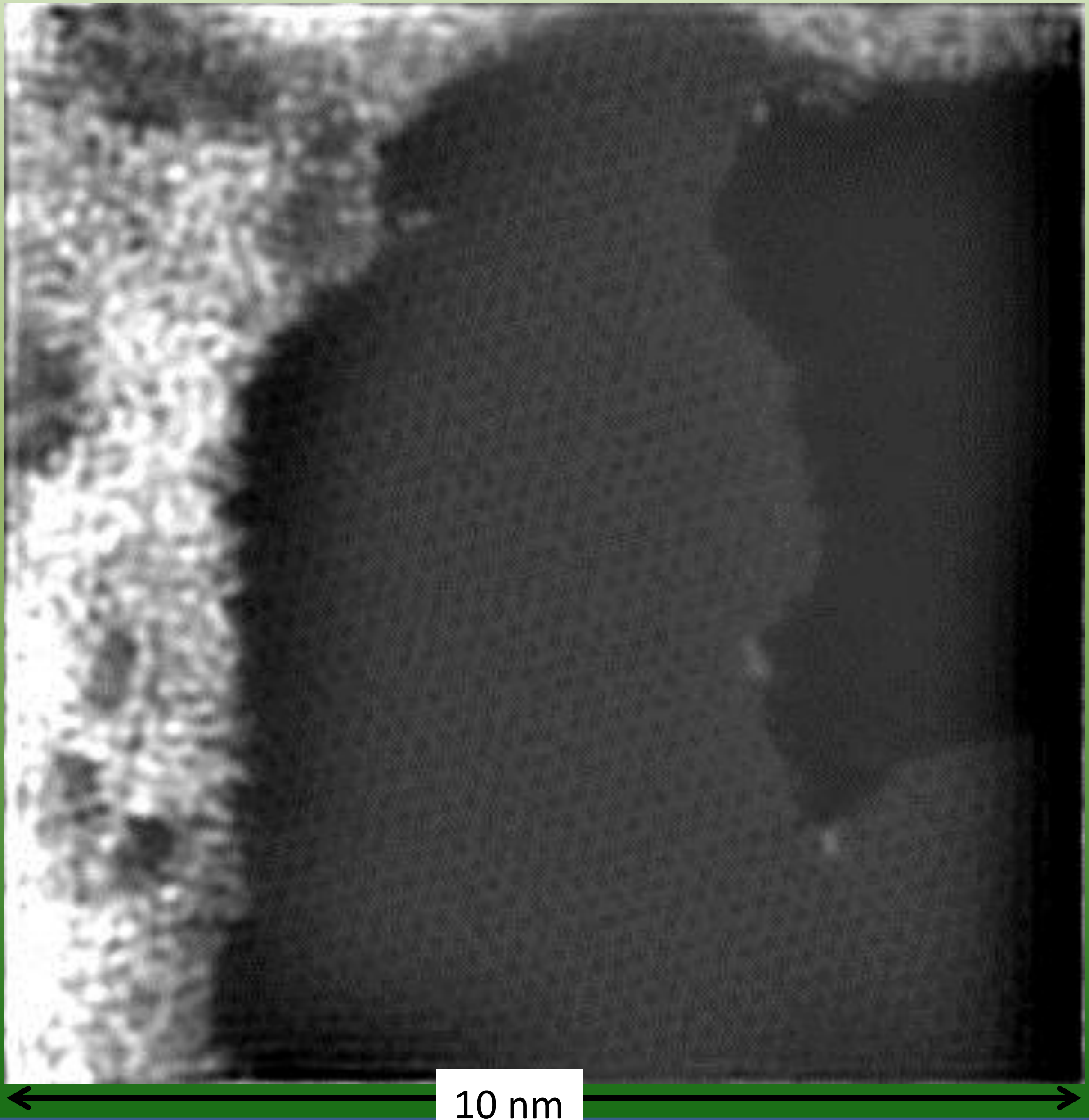
Magnification:
800,000 x

and on…



Magnification: 800,000 x

and on…



Magnification:
800,000 x

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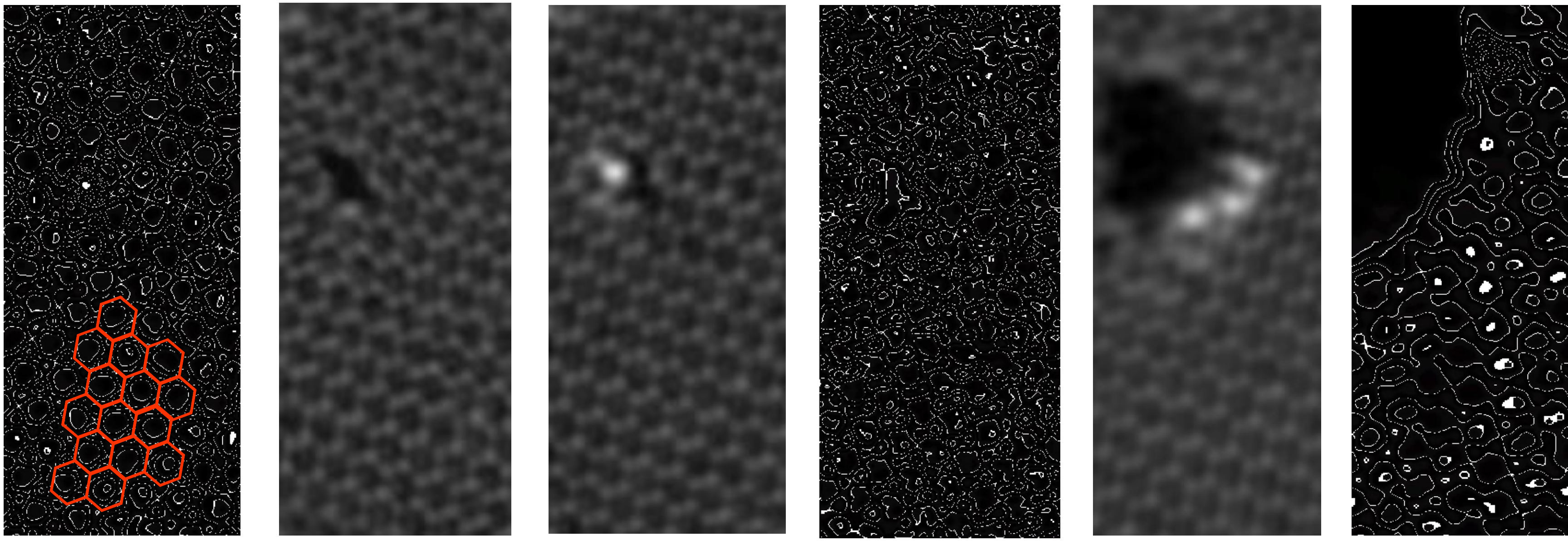
Metal mediated etching of graphene- the ‘drilling’ story in detail



A single impurity atom (in this case chromium) sits on graphene, and reacts with a residual O-gas molecule.

Assisted by the electron beam the Me-atom catalyses carbon-bond dissociation and thus removal of two carbon atoms in form of CO occurs

A new impurity atom moves to the edge of the newly formed di-vacancy.

The process repeats itself,

After several further repeats a nano-hole has formed

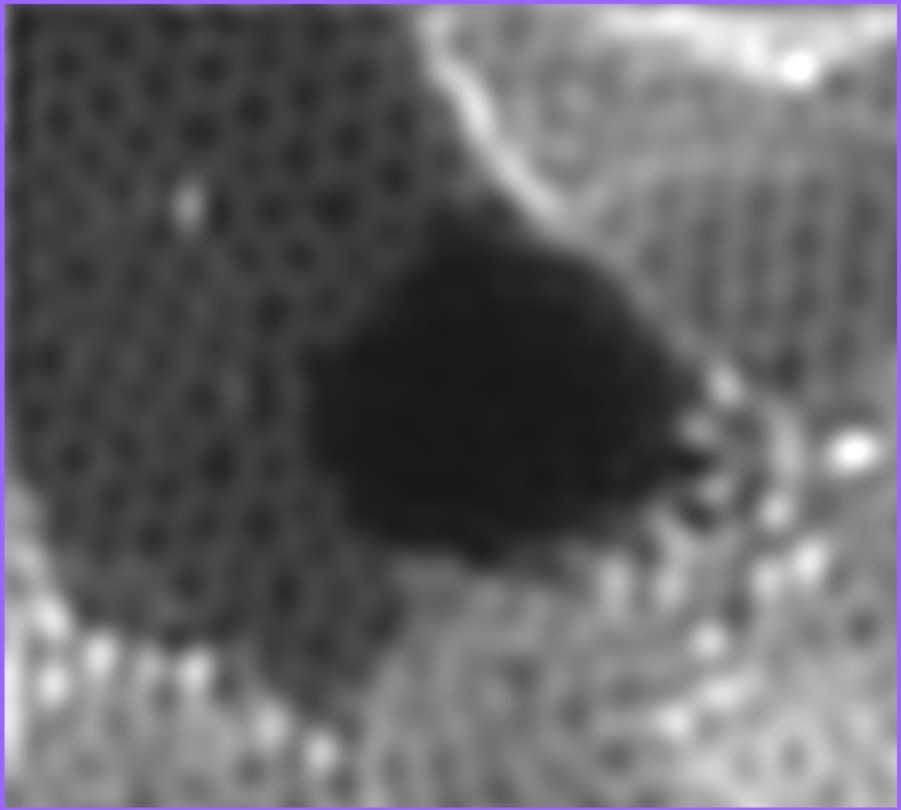
The hole keeps on growing

When the supply of impurity atoms ceases, the hole stays the same in size

Healing: 'filling' story

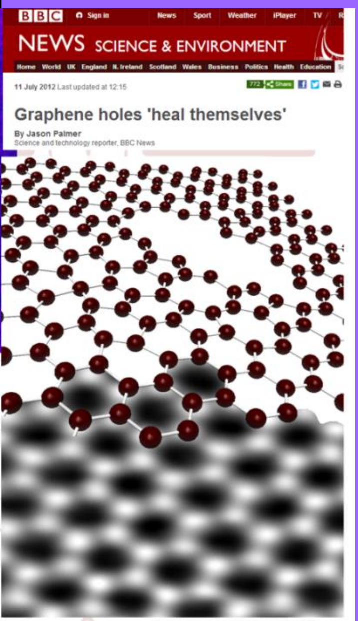
the hole seen here……

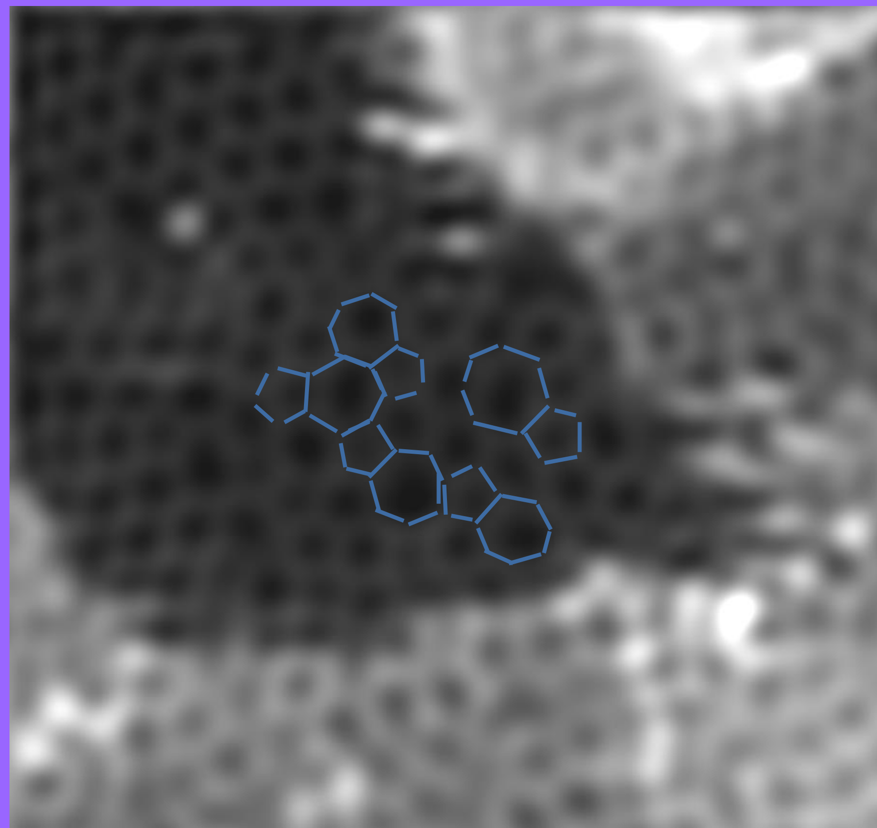
Healing: 'filling' story



… can be observed to close through graphene-like structure (amorphous) under continued scanning, where carbon atoms are supplied by near-by hydrocarbons….

Healing: 'filling' story





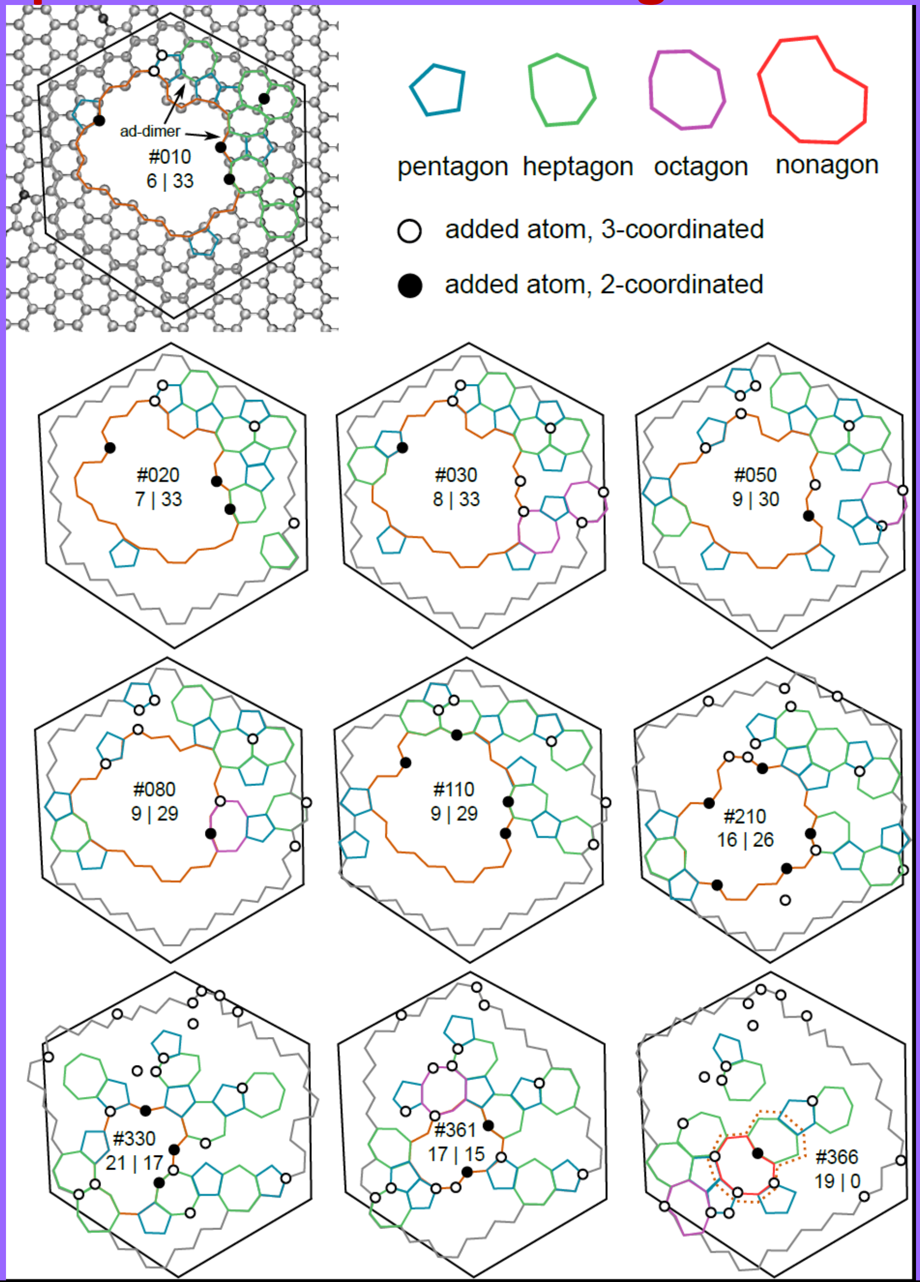
Healing with Pentagons and Heptagons !!!

.... These fill-ins contain many defects, and healing only happens when the supply of Si- and/or metal-impurities ceases. When these impurities are still available, there is a competition between drilling and filling.

Zan et al. – Nano Letters ,12, 3936 (2012)

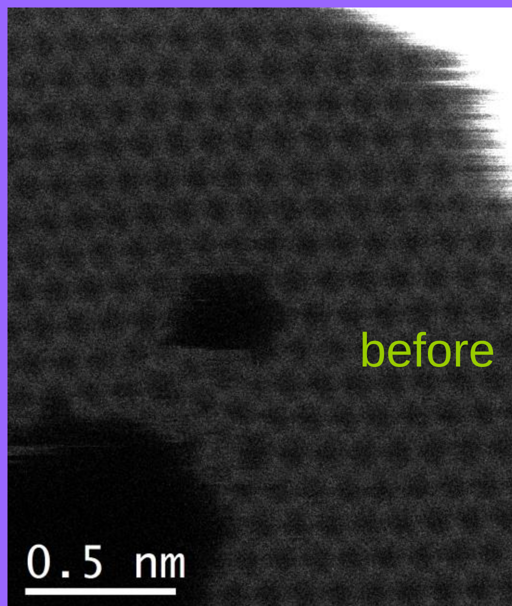
Molecular Dynamics calculations
competition between 'filling' and 'drilling'

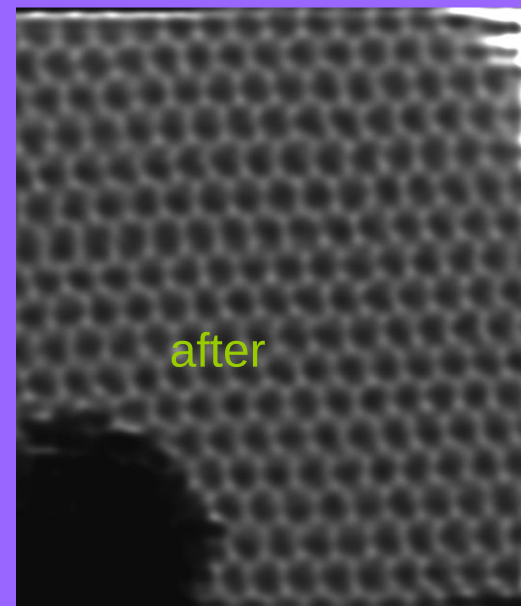
2Å Pd evaporated sample



Molecular Dynamics calculations describe this process well.

There is also perfect healing





Healing with Hexagons!!!

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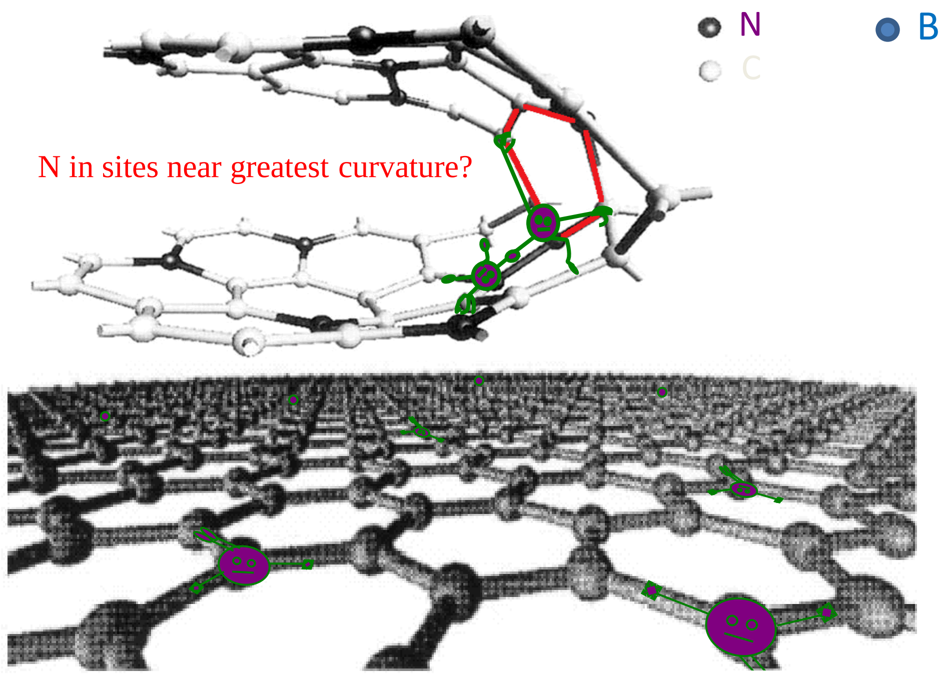
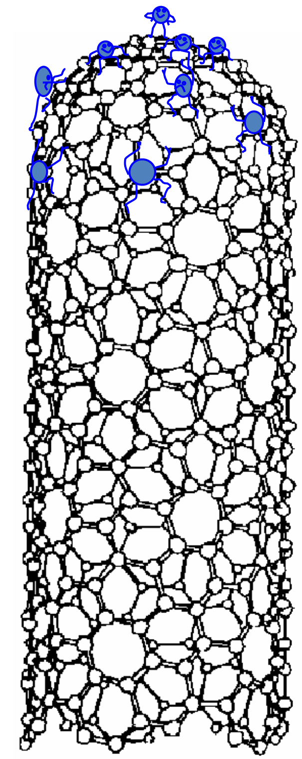
Opto-electronic tailoring of nano-materials by ion implantation

Identifying the nature and behaviour of single atoms by combining Imaging and Electron Energy Loss (EEL) Spectroscopy



substitutional and disperse?



B-segregation to tip?

- fundamental studies of impurities and defects
- application to impurity engineering of functional materials
- experimental proof for theoretical predictions

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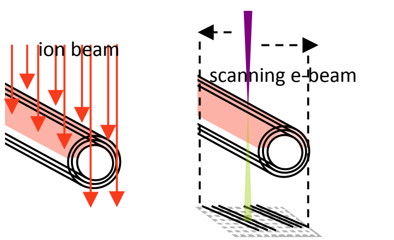
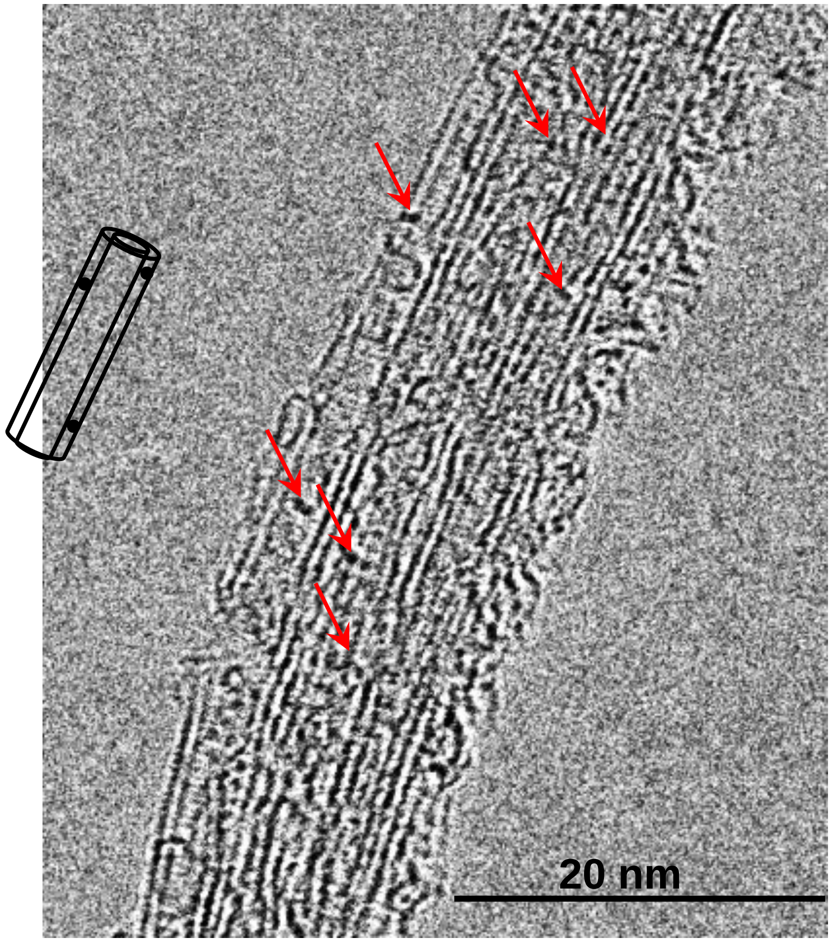
Ion-beam modification of Carbon Nanotubes

K- implantation @ 100 eV, 10^{14} cm^{-2}

Controlled and clean impurity introduction into nano-structures has become a task of prime importance for tailoring for technological applications; ***ion implantation*** appears to be a promising solution.





HREM image of a K-doped (via ion implantation) DWNT bundle; dark dots (some are arrowed) are K-atoms, seen in many cases between the graphene sheets (see sketch), indicating the ***intercalated state***.

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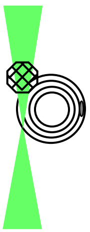
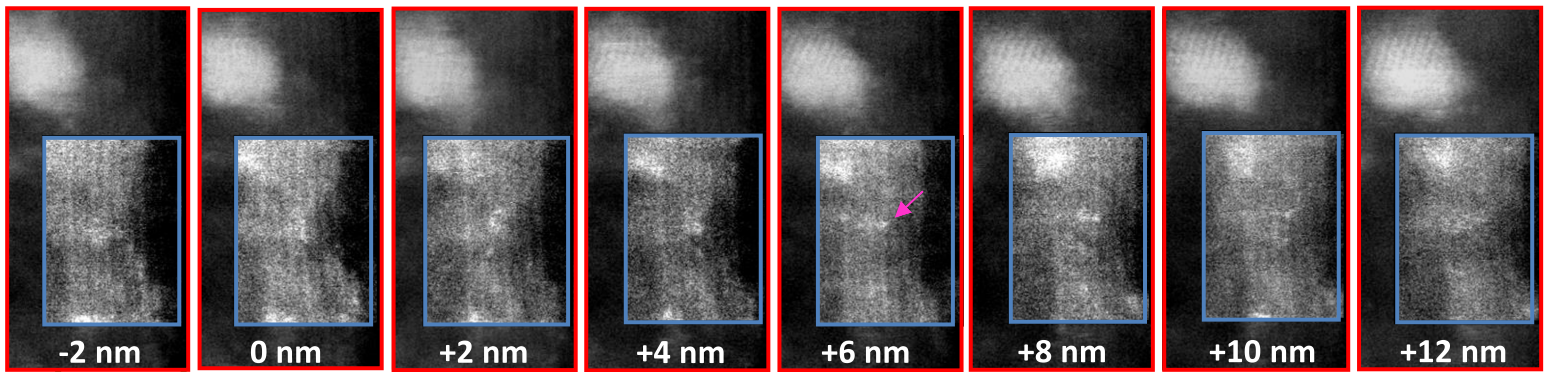
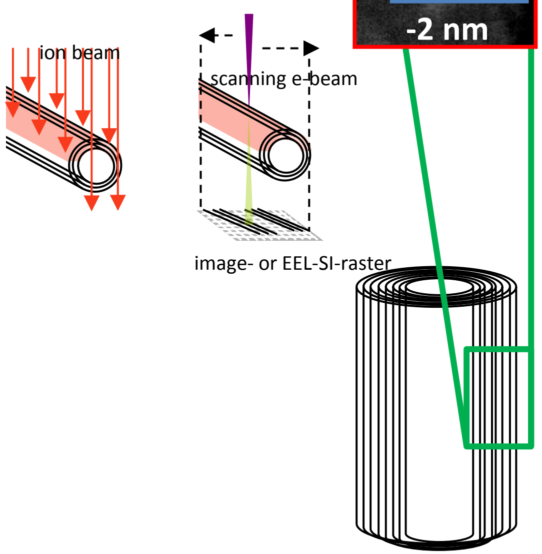
Ion-beam modification of Carbon Nanotubes
Ag implantation – prospects for plasmonics and nano-photonics



electronic and optical functionalisation of nanotubes (e.g., for light absorption and emission) via ion implantation (100 eV Ag-ions at a dose of $2x10^{15}$ atoms/cm^2)





HAADF through-focal series with focus point retracting from left to right in steps of 2 nm. Probe focussed inside the nanotube wall in the left-most image (see sketch above images), and on the top of the peripheral Ag-cluster in the right-most image. In the right-most image the Ag-lattice image can be seen in Ag-cluster (top left). As the probe focus progresses through the Ag-nano-crystal and then into the carbon nanotube (right to left) the nanotube walls come 'into focus' and the Ag-cluster goes out off focus. The nanotube walls can be seen in all but the right-most image, where the probe is focussed above the nanotube onto the Ag-cluster. The arrow denotes a single Ag-atom (green arrow) coming into focus and vanishing again -> the atom is embedded in the nanotube wall between 2 graphene sheets, making minute movements in each scan.

-> ***intercalated atom***

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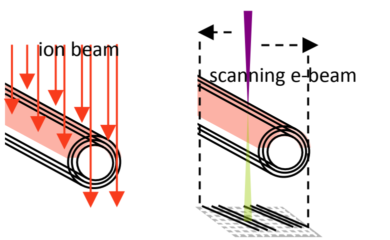
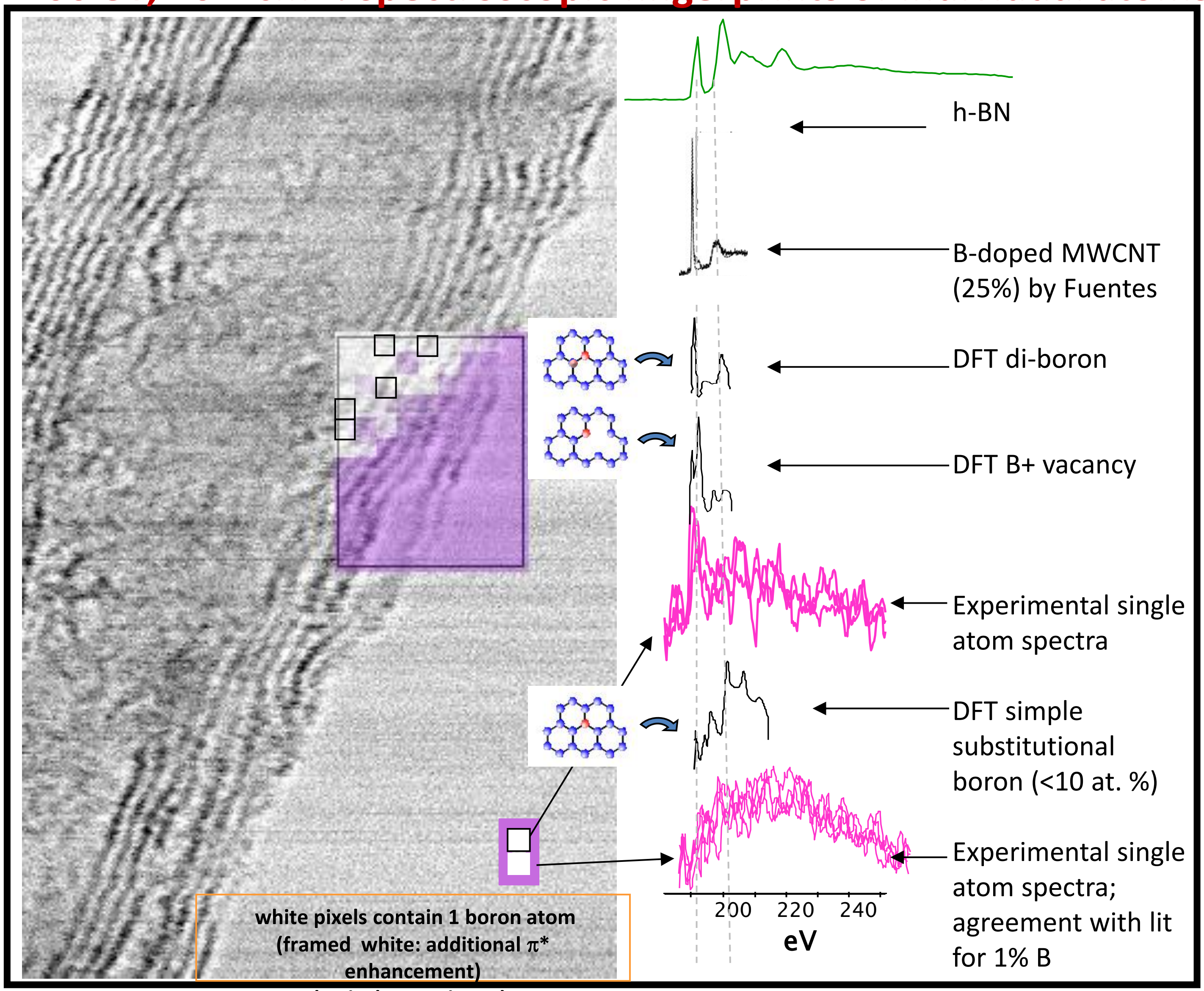
Ion-beam modification of Carbon Nanotubes

B implantation @ 100 eV, 10^{14} cm^{-2}: spectroscopic fingerprints of individual atoms





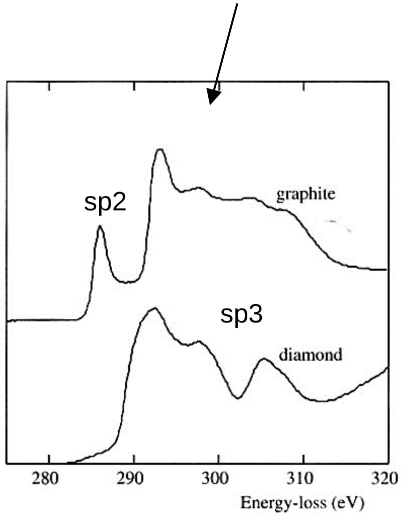
U. Bangert, A. Bleloch, M. H. Gass, A. Seepujak and J. van den Berg, Phys Rev B 81, 245423 (2010)

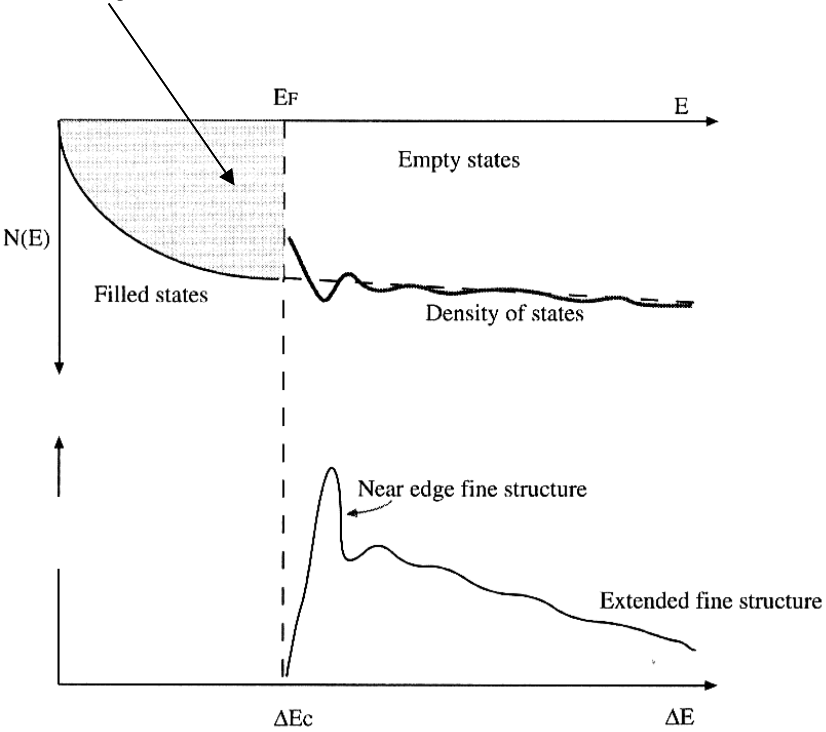
Some general remarks about EEL spectra:

- inner shell electrons are scattered into empty states around Fermi level
  -> absorption spectroscopy

- scattering probability is proportional to the *density of states*

- energy loss near edge structure (ELNES) is extremely sensitive to changes in the bonding or the valence state of the atom

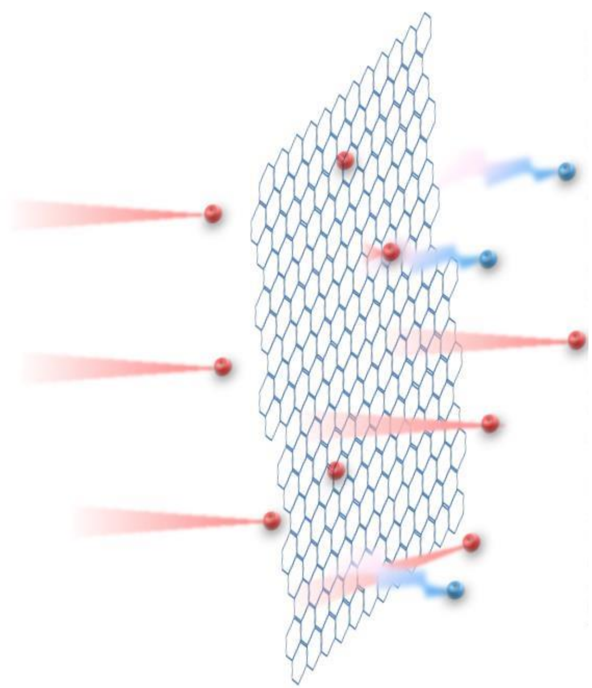




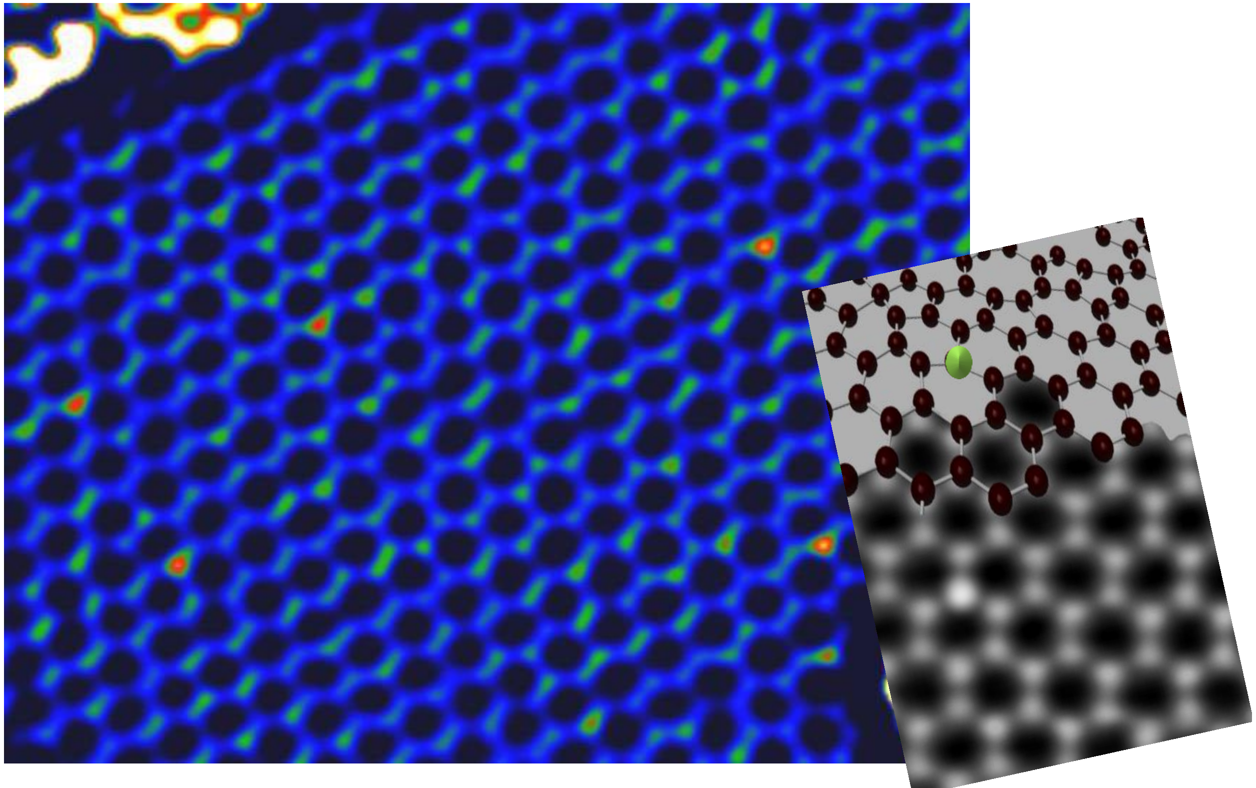
Ion-beam modification of graphene: controlled in-lattice functionalisation

Introducing impurities controllably into graphene is a big goal. We explored ion-implantation at very low energies (25 eV with **B** and **N**) for electronic doping **-> work function and bandgap tailoring**. This would move graphene technology towards scalable technologies, integratable with semiconductor technologies.

We have now proof that the implants are present in the graphene lattice, mostly substitutional, with retention of typically ~15% of the original dose

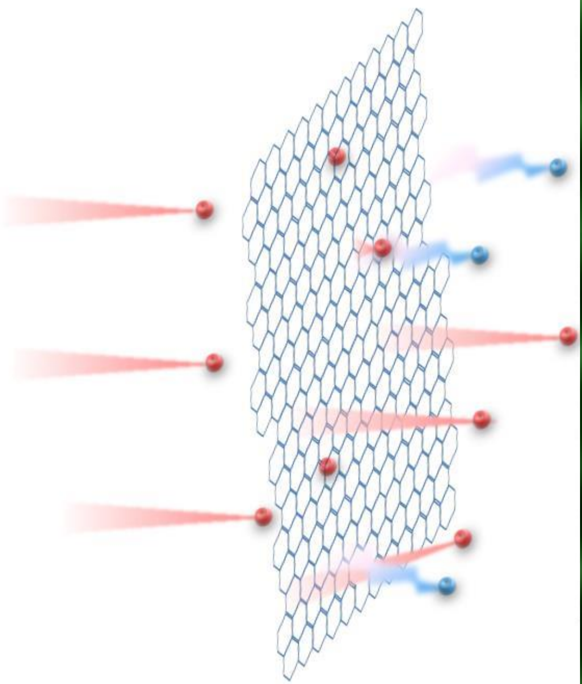


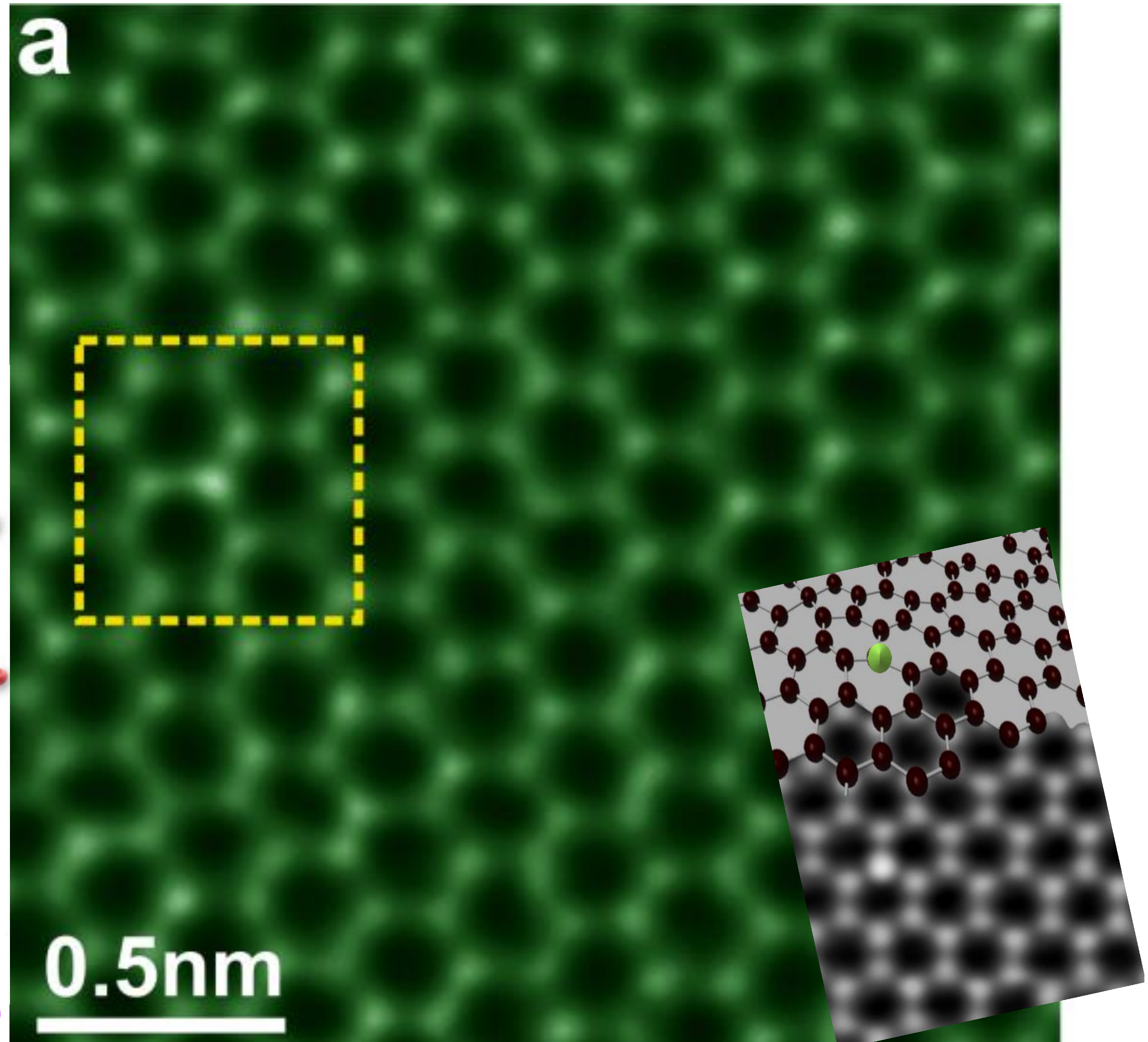
Graphene with substitutionally implanted N-atoms



Ion-beam modification of graphene: controlled in-lattice functionalisation

Substitutional N-implants in graphene:
a) HAADF lattice image showing substitutional, implanted atoms…





Bangert et al, Nano Lett. 13 (10), 4902 (2013)

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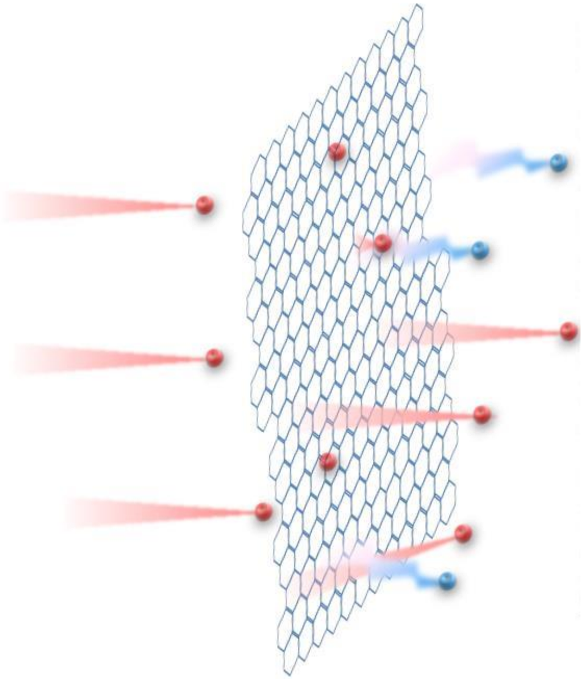
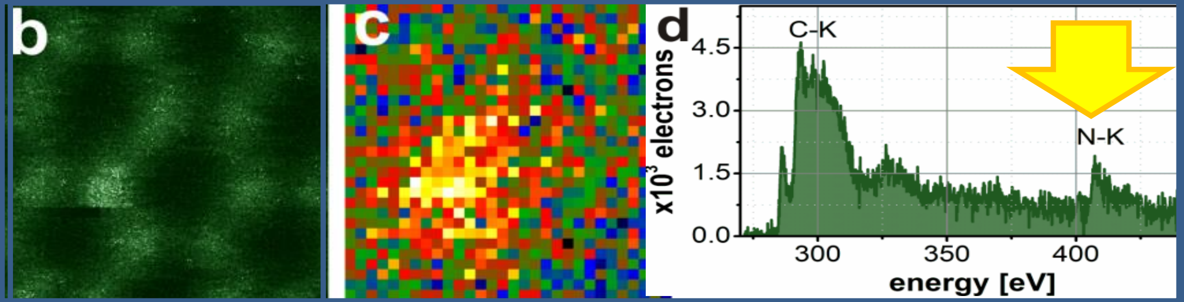
Ion-beam modification of graphene: controlled in-lattice functionalisation

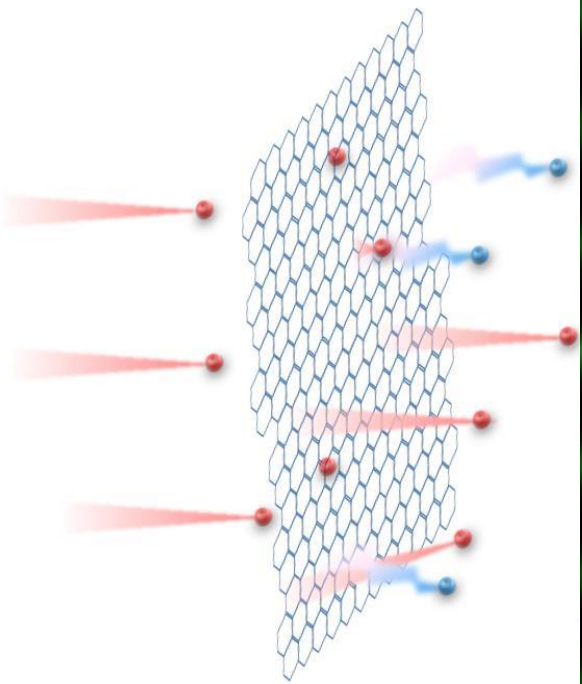
Substitutional N-implants in graphene:
… b) area in (a) with c) simultaneously acquired N K-edge intensity map and d) EEL spectrum extracted from an EEL spectrum image of the frame area

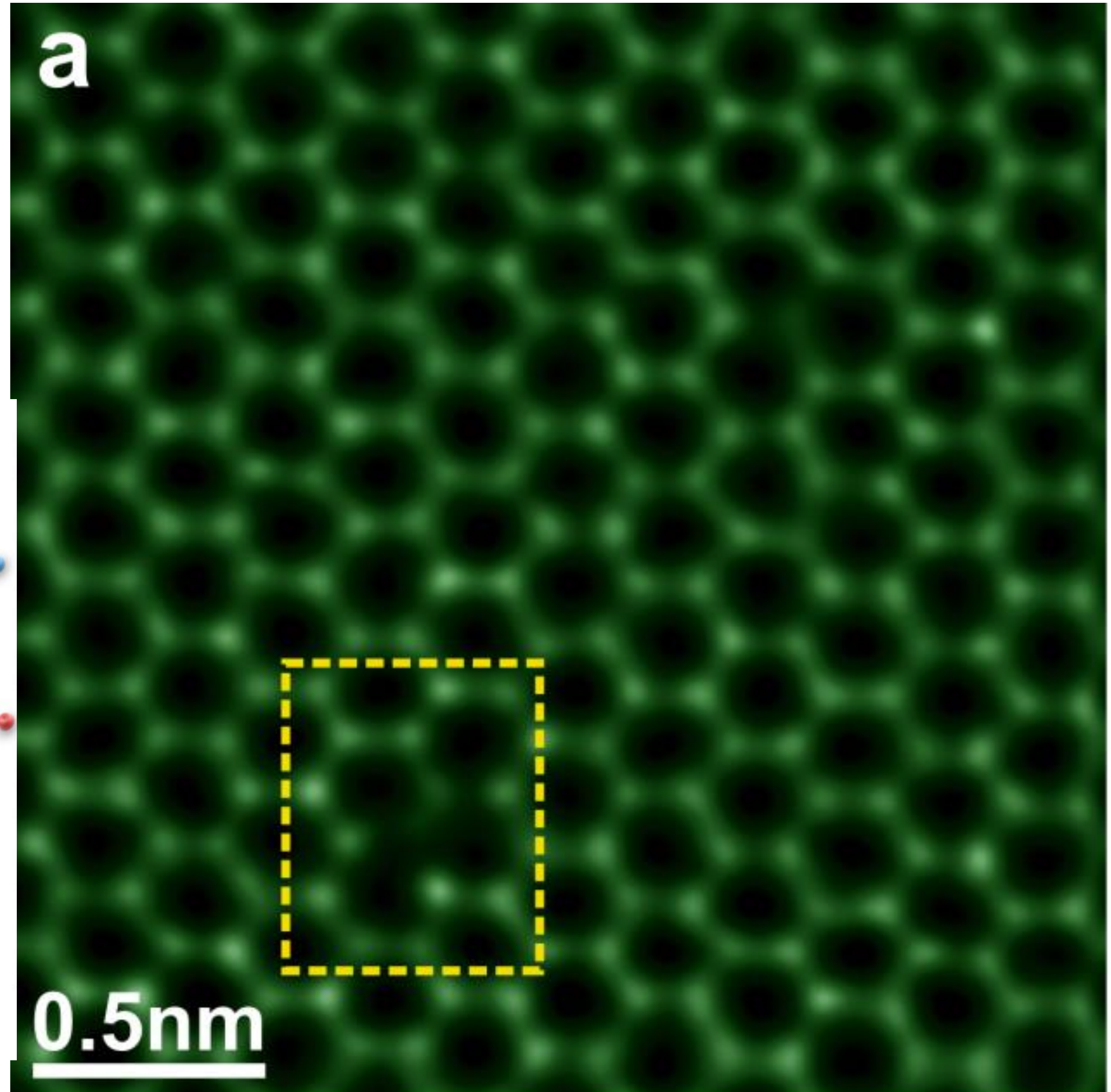




Ion-beam modification of graphene: controlled in-lattice functionalisation

Substitutional B-implants in graphene:
a) HAADF lattice image showing substitutional, implanted atoms…





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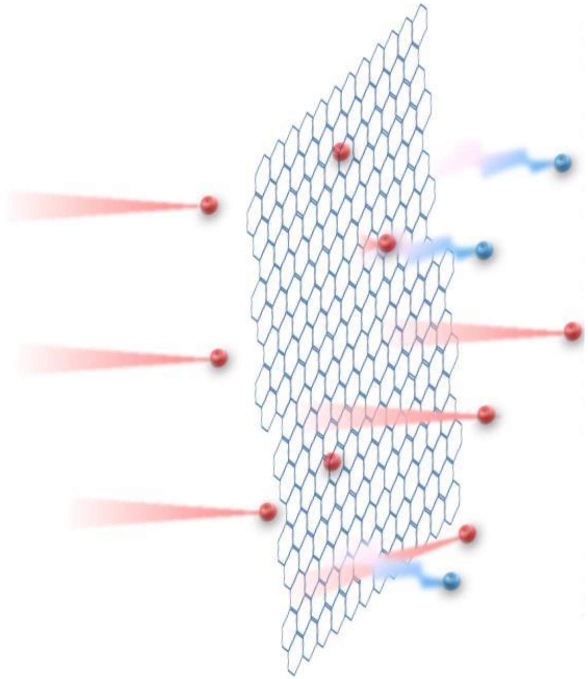
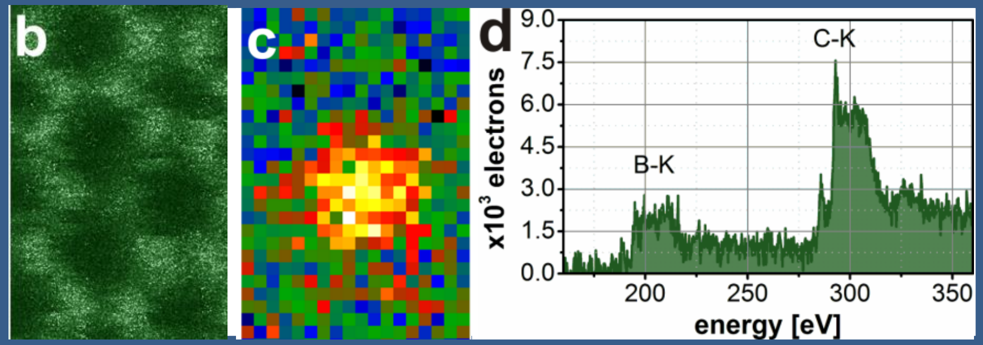
Ion-beam modification of graphene: controlled in-lattice functionalisation

Substitutional B-implants in graphene:
… b) enlarged frame of (a) with c) simultaneously acquired B K-edge intensity map and d) EEL spectrum extracted from an EEL spectrum image of the frame area



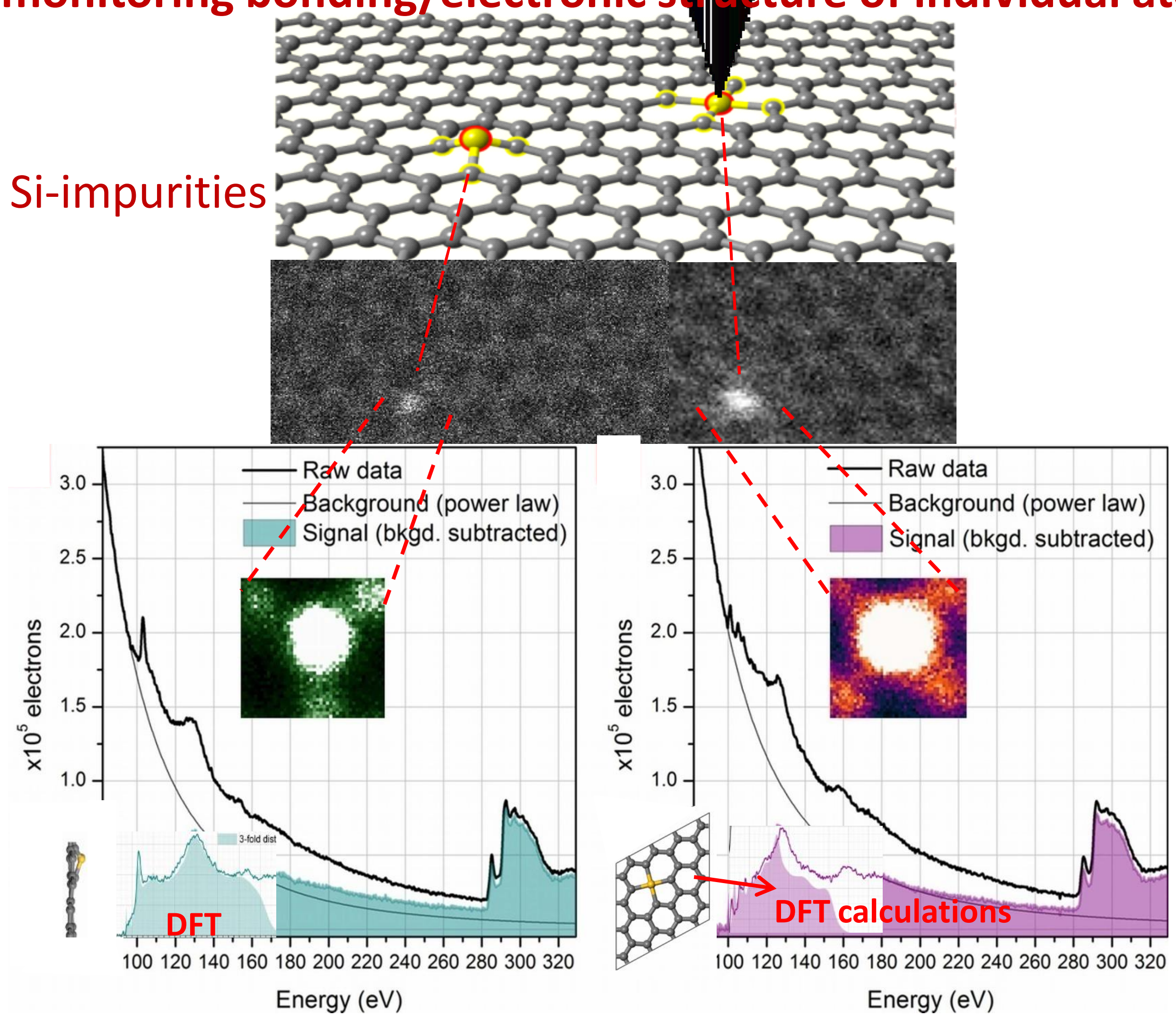


Bangert et al, Nano Lett. 13 (10), 4902 (2013)

Ion-beam modification of graphene: controlled in-lattice functionalisation

monitoring bonding/electronic structure of individual atoms

Si-impurities



-> electron energy loss spectroscopy

Ramasse et al , Nanoletters Dec 2012

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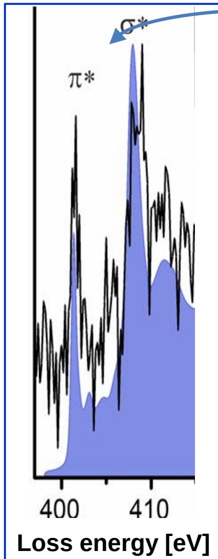
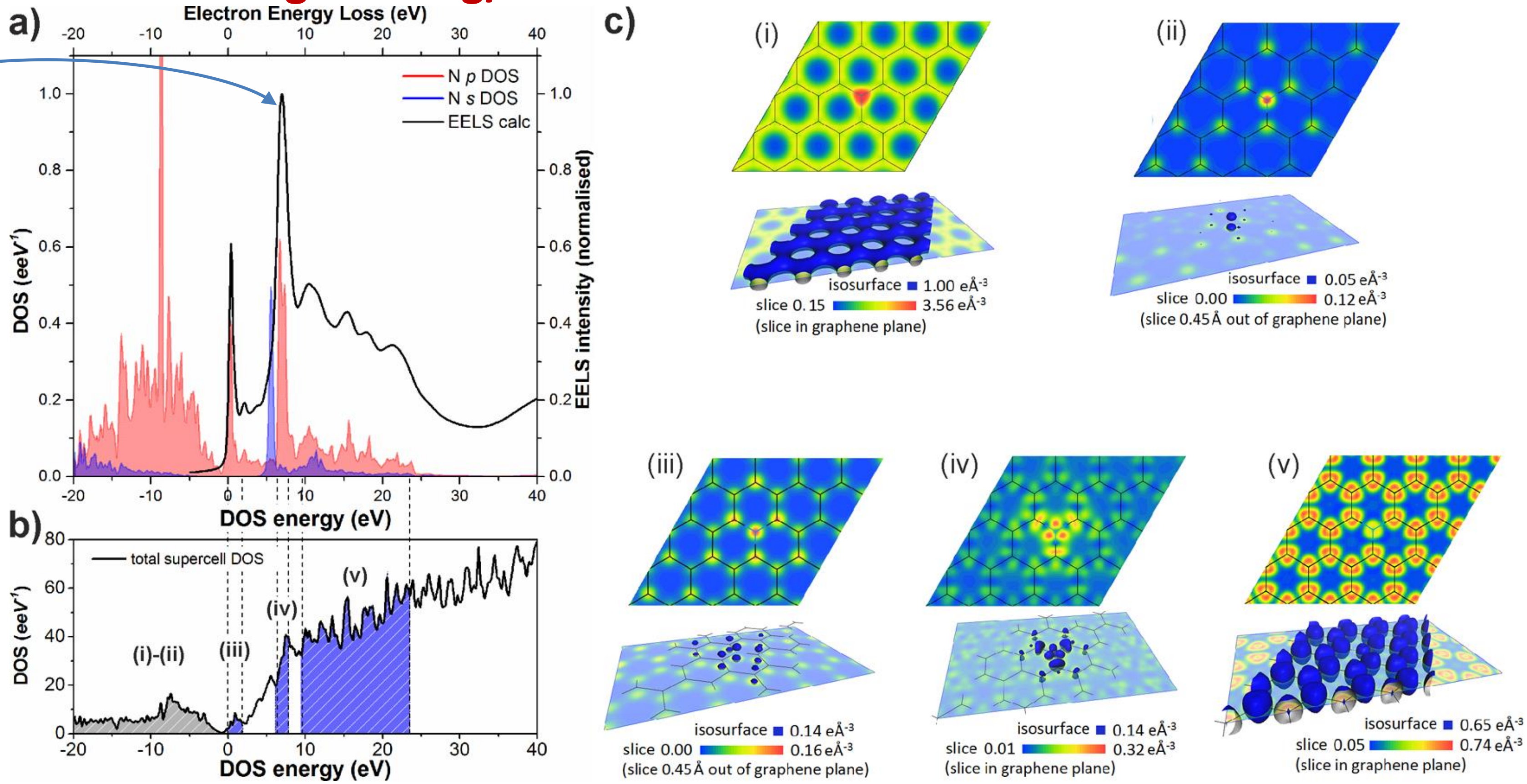
Ion-beam modification of graphene: controlled in-lattice functionalisation

monitoring bonding/electronic structure of individual atoms



The blue-filled curve is the calculated EEL-spectrum (black-line curve in (a)); the black spectrum is the experimental EEL spectrum of the N-atom



Calculated electronic states for single substitutional N dopants in graphene. (a) Overlaid p DOS, p DOS and calculated N K EELS spectrum; (b) total DOS: all states lying within a chosen energy window are highlighted in the shaded areas. The states that lie within that energy window are populated and the density is plotted and displayed as 2D slices from above the lattice: (c)(i and ii) excess density on the N dopant and density slice showing the single state constituting the negative charge carrier which has the appearance of a pz-like orbital and is occupied in the ground state; (iii and v) unoccupied states attributable to EELS peaks of interest in (a). Specifically: (iii) π*-like states, (iv) σ*-like states both highly localized on the dopant, and (v) high-energy states localized on the C nuclei.

*Kepatsoglou et al., ACSNano, **9** (11) 11398 (2015)*

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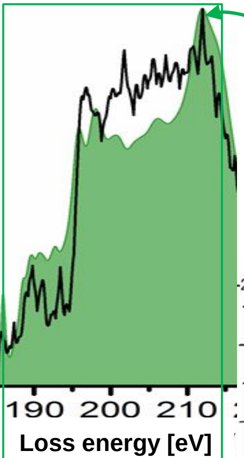
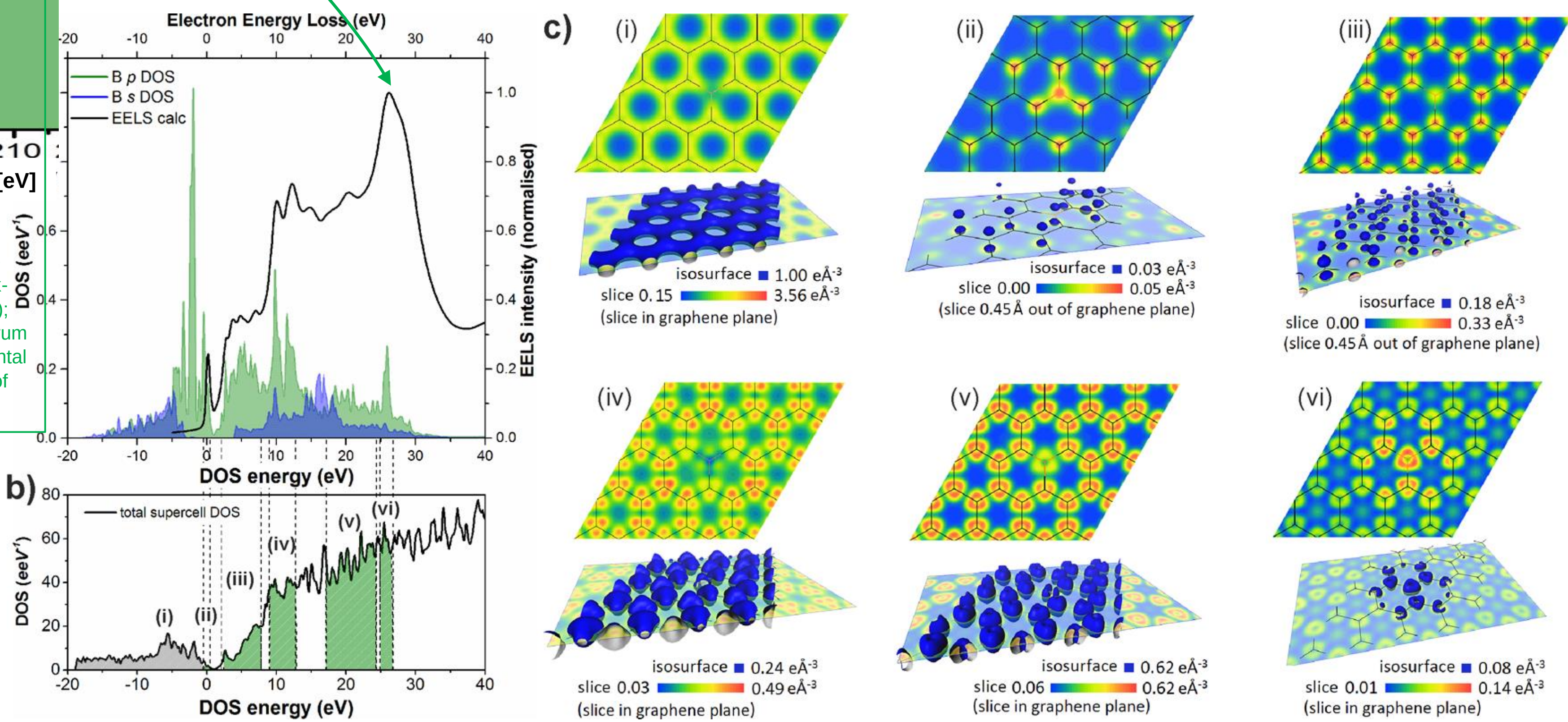
Ion-beam modification of graphene: controlled in-lattice functionalisation

monitoring bonding/electronic structure of individual atoms



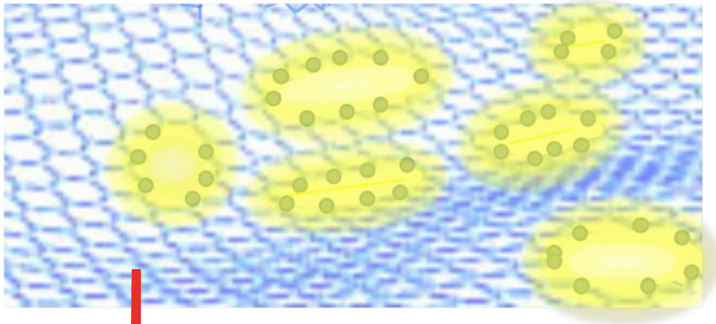
The green-filled curve is the calculated EEL-spectrum (black-line curve in (a)); the black spectrum is the experimental EEL spectrum of the B-atom



Calculated electronic states for single substitutional B dopants in graphene. (a) Overlaid p DOS, s DOS and calculated B K EELS spectrum; (b) total DOS: all states lying within a chosen energy window are highlighted in the shaded areas. The states that lie within that energy window are populated and the density is plotted and displayed as 2D slices from above the lattice in (c). (i) Ground states, showing the missing charge density on the dopant causing the Fermi energy to sink into the π band, constituting the hole; (ii) the π state occupying the charge carrier hole, (iii) π*-like states and (iv) σ*-like states both mostly localized around the C nuclei with a noticeably lower accumulation of charge around the dopant; (v) high energy σ*-like states localized on the C nuclei and (vi) high energy σ*-like states localized on the dopant.

*Kepatsoglou et al., ACSNano, **9** (11) 11398 (2015)*

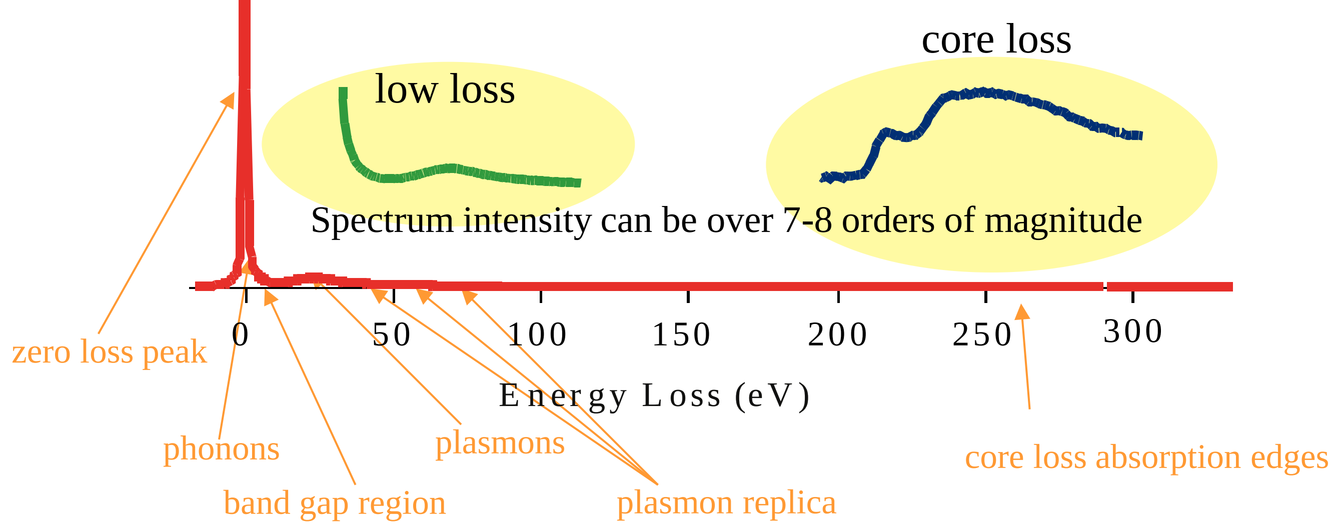
Tailoring the optical/plasmonic properties of nano-materials

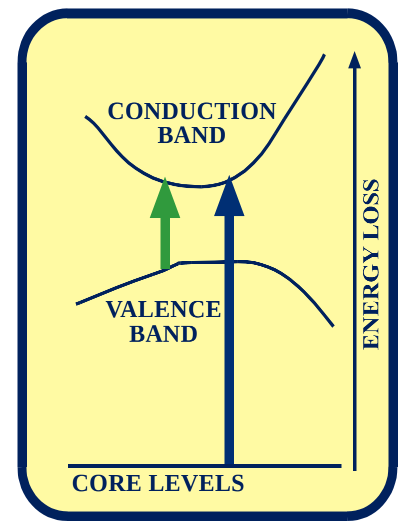


We now investigate, using electron energy loss spectroscopy in the low loss regime, the possibility of creating plasmons in the visible wavelength regime in carbon-nanotubes and graphene (-> atomic antennae?)

General remarks about EEL spectra: The EEL spectrum is proportional to the loss function which is the imaginary part of the inverse longitudinal dielectric constant ε.

$$I_{EELS} \propto Im(-1/\varepsilon_{ij})$$





In scanning mode highly spatially resolved! Nm-scale! Can even go to do spectroscopy on single atoms!

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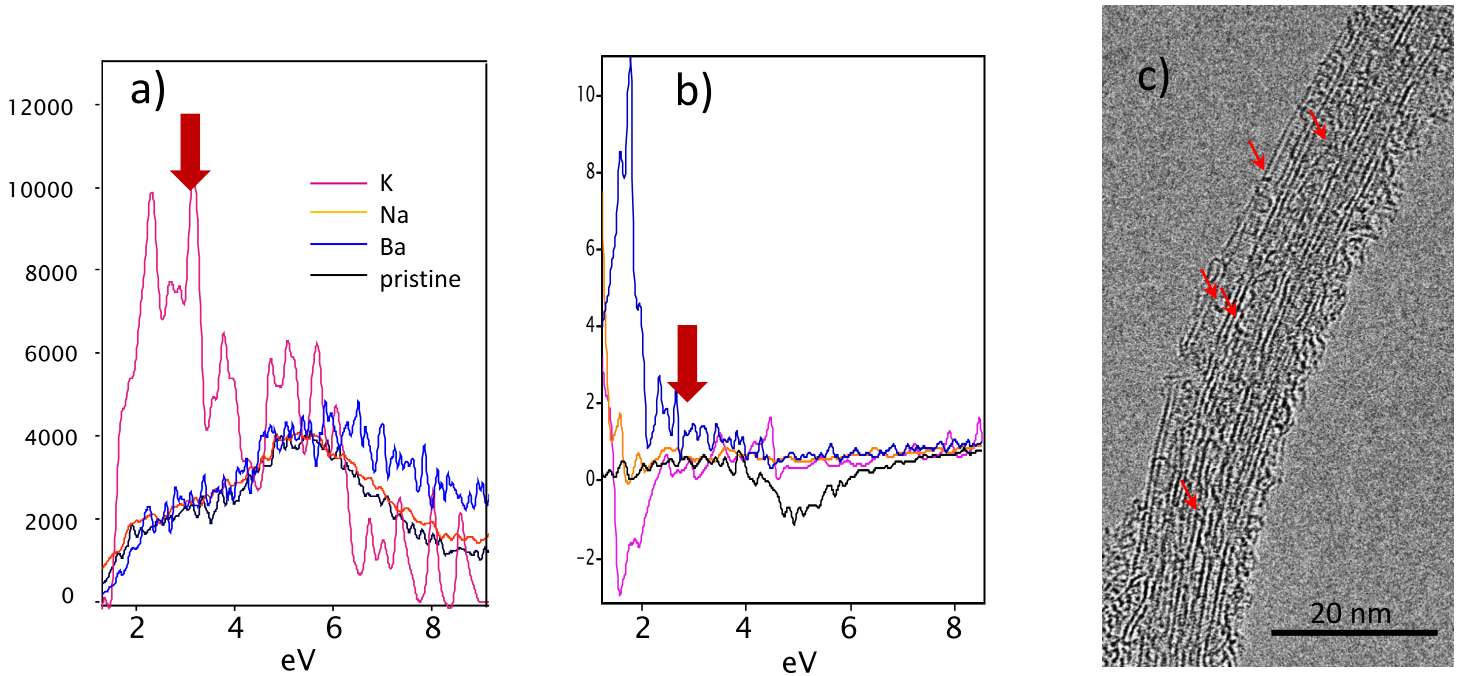
Carbon Nanotubes-
Controlled impurity introduction
-> ion implantation: alkali metals

experimental spectra and dielectric function

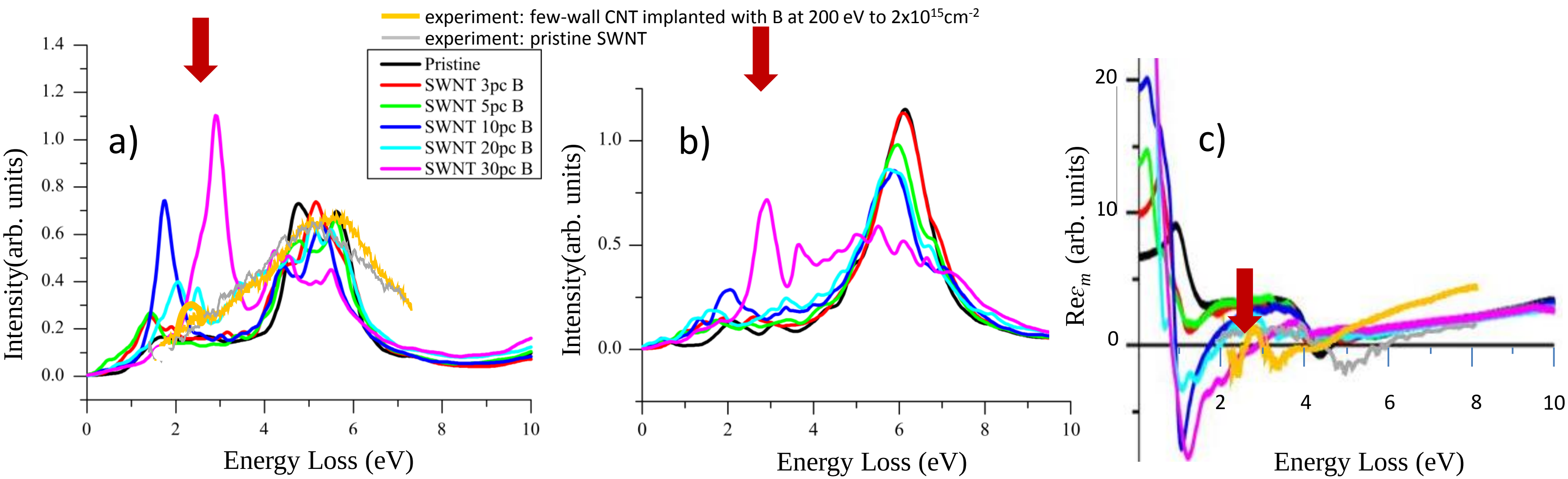


a) low loss EEL spectra of DWNTs and SWNT bundles implanted with alkali and earth-alkali metals and B. The spectrum intensity is normalised to the feature at ~5 eV (pi-plasmon). Doping with the metals was achieved by ion implantation at 200 eV to a dose of $10^{15}cm^{-2}$; **b)** Reε_m of the dielectric function extracted via Kraemers- Kroenig analyisis from the experimental spectra (smoothed with a low pass filter with w= 0.2 eV); **c)** HREM image (TitanPICO) of K-doped DWNT bundle; dark dots (some are arrowed) are K-atoms

~3 eV feature !

Carbon Nanotubes-
Controlled impurity introduction
-> ion implantation: B

Wien2k calculations- spectra and dielectric function



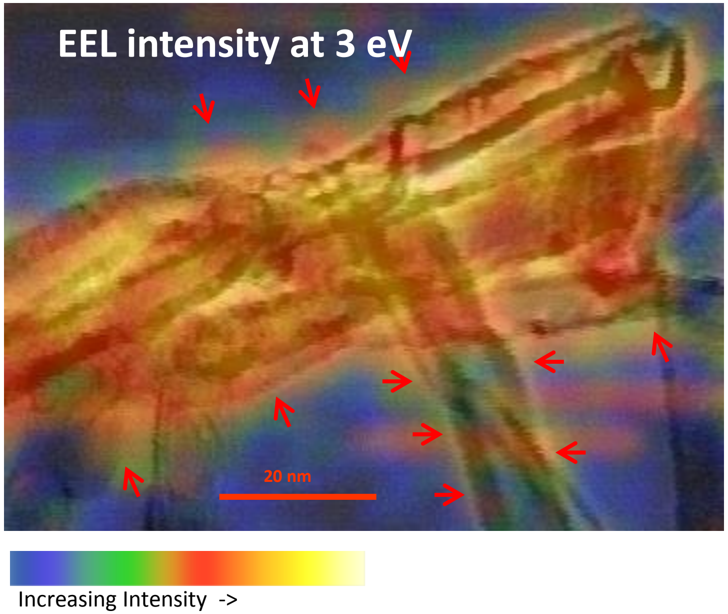
a) Calculated electron energy loss spectra of a boron doped (10,10) SWNT bundle in the out-of-plane and **b)** the in-plane direction, **c)** calculated out-of-plane component of the real part of the dielectric function. The calculations were performed using Wien2k. Also overlaid in (a) and (c) are experimental spectra of a heavily B-doped and a pristine carbon nanotube

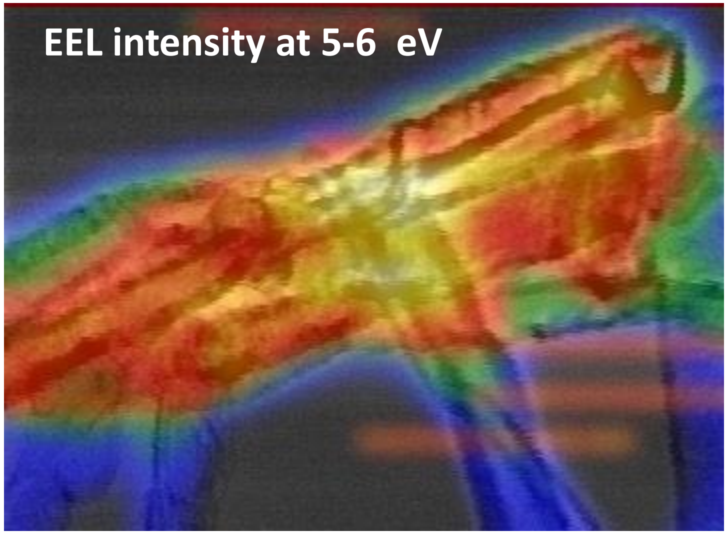
experiments show B incorporates substitutionally!

~3 eV feature !

Carbon Nanotubes-
Controlled impurity introduction
-> ion implantation: B

low loss intensity maps





Background subtracted EEL signal of a DWNT and few-layer CNTs agglomerate at 2-3.5 eV (left) and 4.7-6.5 eV (right) from and SI obtained in a NionUltraSTEM. The CNTs were ion-implanted at an energy of 200 eV, to a dose of $2x10^{15}$ cm^{-2} (Surrey Ion Beam Centre). The EEL map is overlaid on the Bright Field STEM image of the tubes (black shapes).
Arrows in the left-hand image mark positions that indicate that the lower energy signal is less localised than the π-bulk plasmon (right) and more concentrated on the surface of the tubes; relatively higher intensity is seen here in the vacuum.

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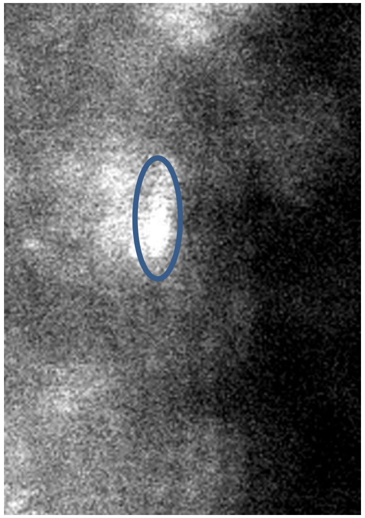
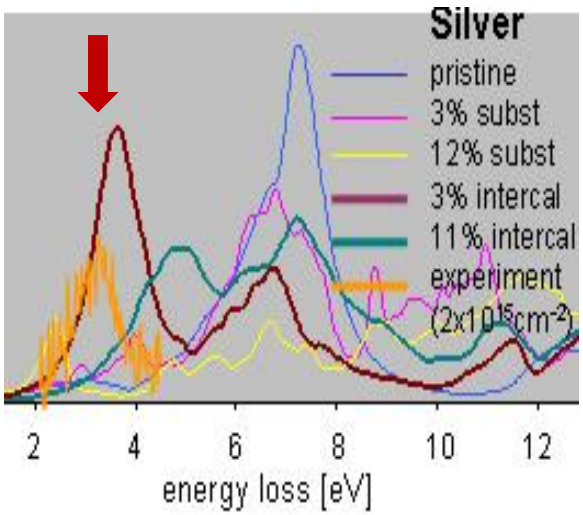
Carbon Nanotubes-
Controlled impurity introduction
-> ion implantation: Ag

HAADF through-focal series of intercalated Ag platelet and calculated and experimental low loss spectra



+2 nm



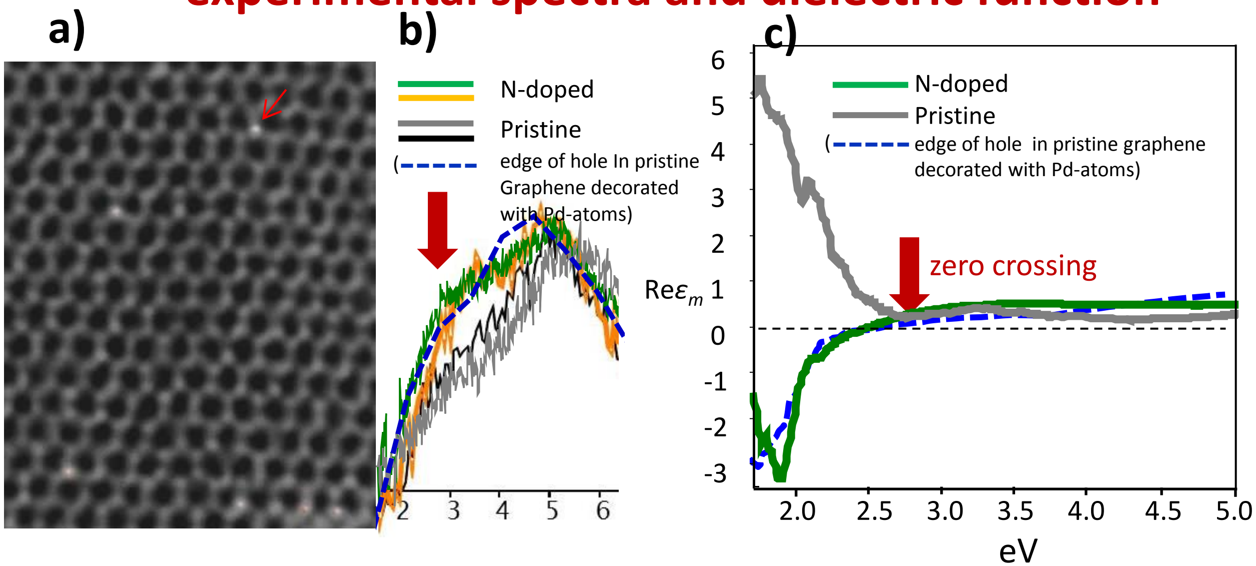
aggregate of Ag-atoms, which stays in focus over a longer range of foci, indicating an extended platelet confined between two graphene sheets of the tube wall

*U. Bangert, A. Bleloch, M. H. Gass, A. Seepujak and J. van den Berg, Phys Rev B **81**, 245423 (2010)*

3 eV feature !

Graphene-
Controlled impurity introduction
-> ion implantation: N

experimental spectra and dielectric function



a) HAADF image of N-implanted graphene, N-atoms are revealed by their brighter contrast- substitutional!

b) low loss spectra, of N-doped and pristine graphene. The spectrum intensity is normalised to the feature at ~5 eV. N-doping was achieved by N-ion implantation at 25 eV to a dose of 10^{15} cm^{-2}.

c) Reε_m of the dielectric function extracted via Kraemers- Kroenig analyisis from the experimental spectra.

The blue curve shows the of Reε_m of an EEL spectrum from the edge of a hole in pristine graphene decorated with Pd atoms, after Pd-evapration.

~3 eV feature !

Energy-loss spectra - the 3 eV feature

- criterion for a Drude plasmon: zero crossing of Reε from – to +

- 3 eV feature is nearly always present, more or less pronounced, often as part of multiple excitations

- zero crossing of Reε observed in most cases

- DFT calculation reproduce feature, inclusion of local field effects and single particle excitations gives more complex spectra around 3 eV feature

-> 3 eV feature has plasmon component, most likely coupled with single particle excitations

-> observable enhancement at edges over membrane- why?
-> concentration of active impurities higher

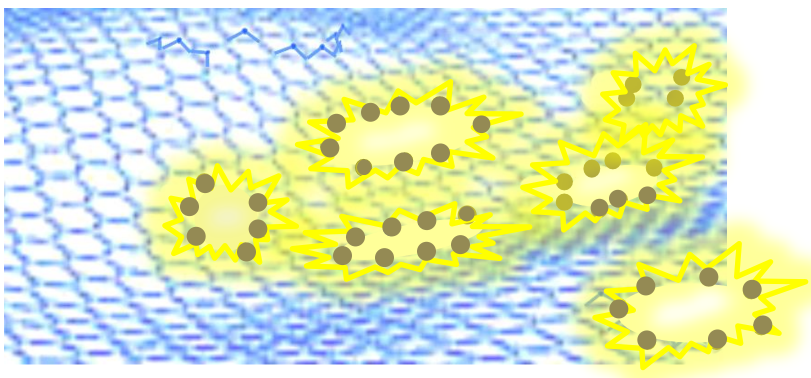
Plasmonic confinement& enhancement

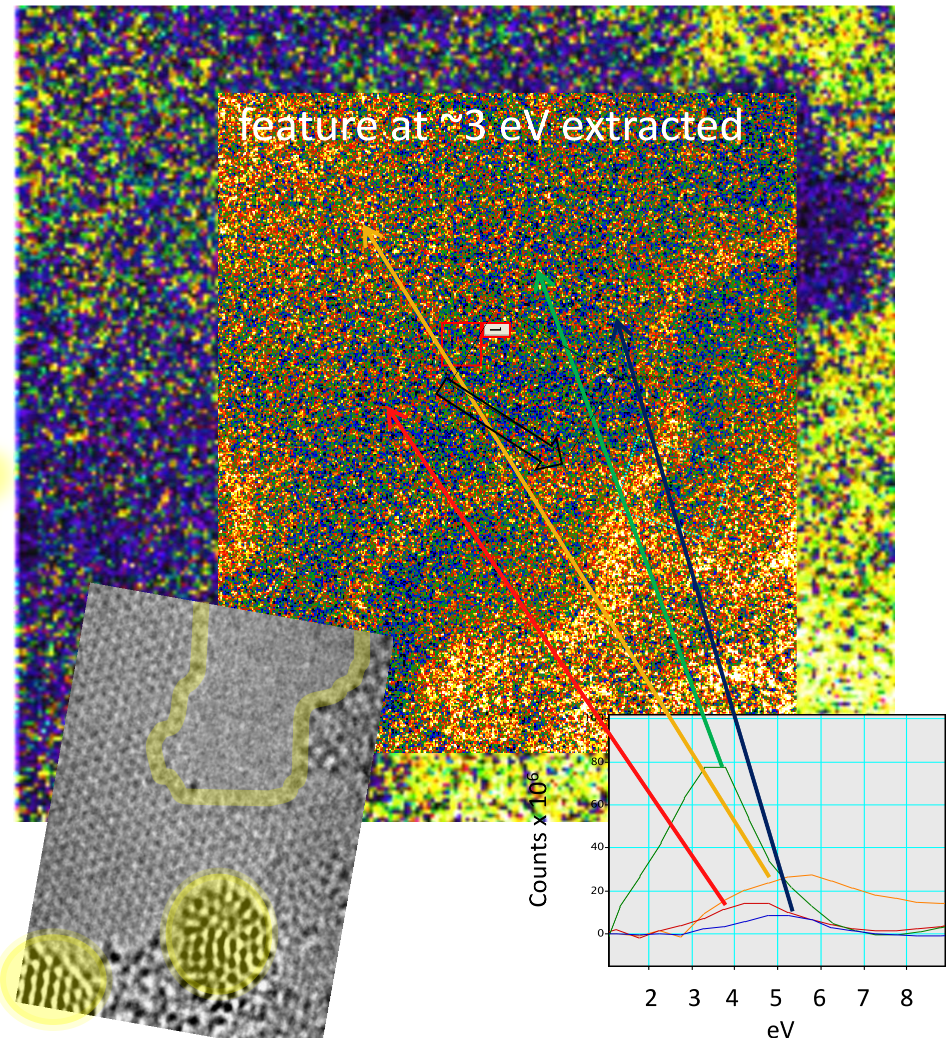
‘glowing Necklaces’ - energy-filtered imaging

Pd deposited on graphene: plasmon image @ 3.5-4.0 eV showing intensity enhancement at edges of holes

energy filtered image obtained in a monochromated triple aberration-corrected Titan-PICO at ER-C Juelich, Germany

Similar results for Ti deposited on graphene





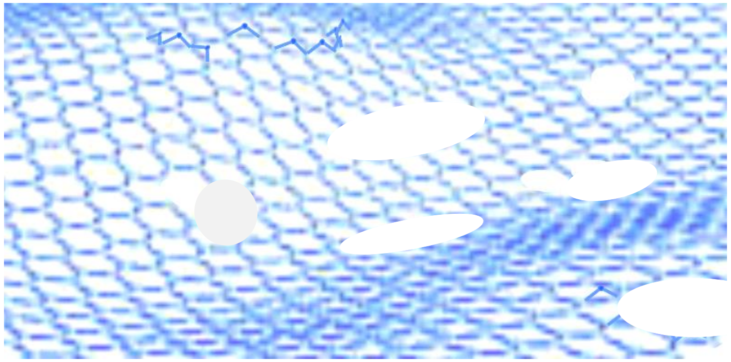
Nano-devices?
Nano-sculpting?

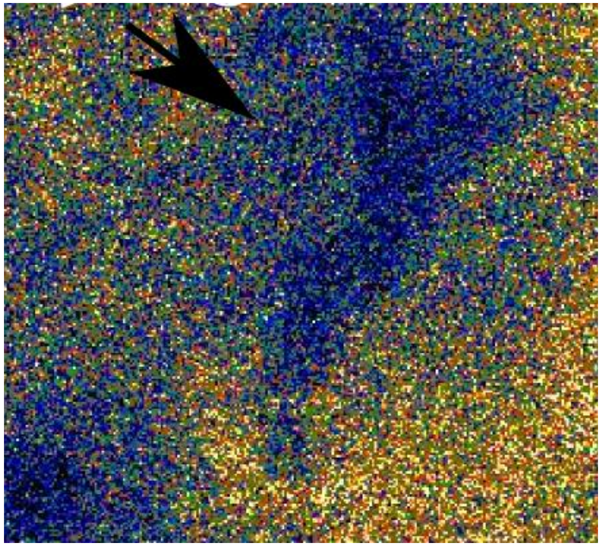
--> Graphene as transparent electrode with tailored workfunction and plasmonic light enhancement for solar cells - (under development)

U. Bangert et al, Nature Sci Reports
www.nature.com/articles/srep27090

Plasmonic confinement& enhancement

‘glowing Necklaces’ - energy-filtered imaging





No intensity enhancement at edges in pristine graphene!

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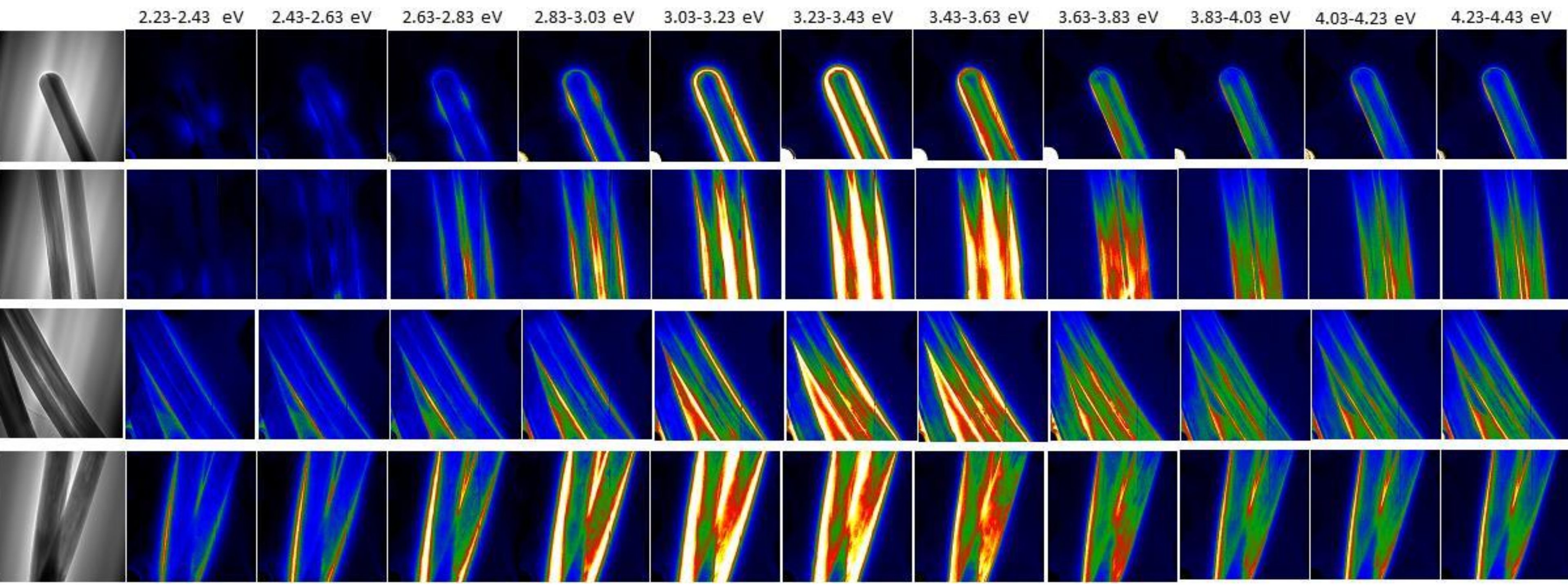
Plasmons in other 1-D nano's

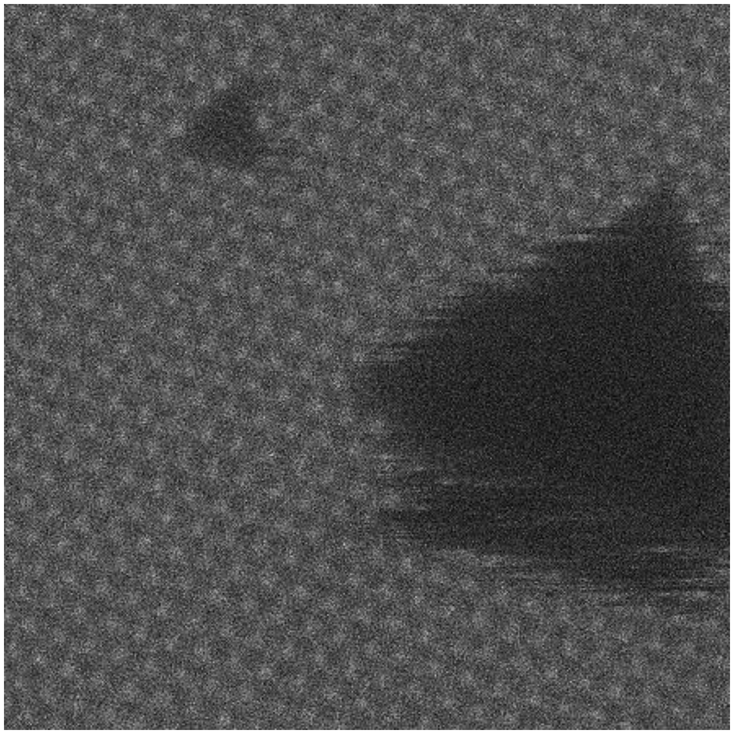
Plasmonic confinement& enhancement in Ag nanowires

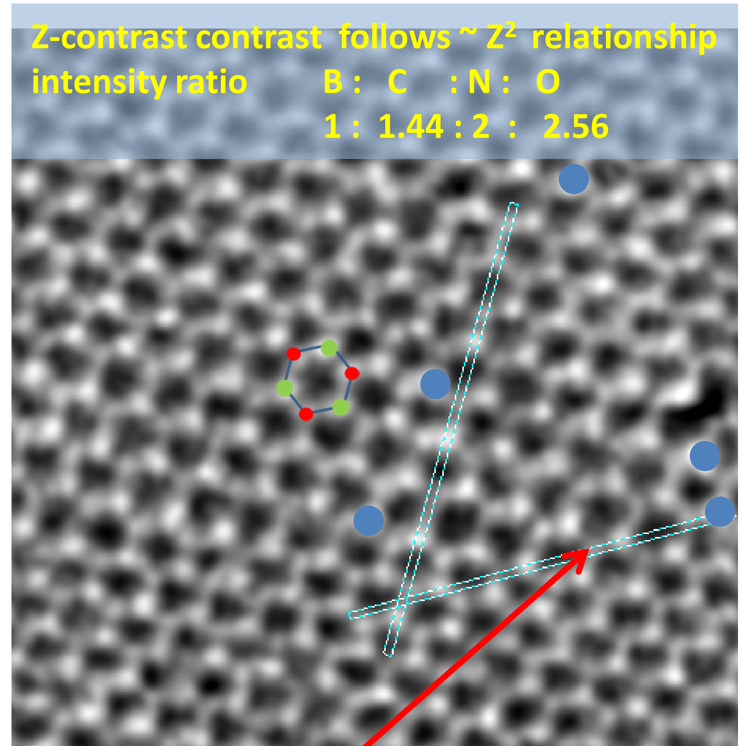


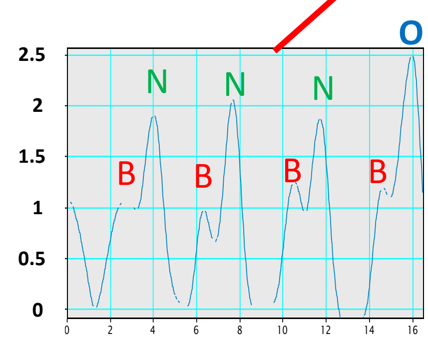
Energy filtered images extracted from an EFTEM cube, representing energy loss intensities in the respective energy windows between 2.2 and 5.5 eV. The images are of a single Ag-nanowire with an end (1st row), of two, parallel Ag nano-wires with a distance between them (2nd row), of two crossing Ag-nano-wires (3rd row) and of two, parallel, touching silver nano-wires (4th row). The silver plasmon is strong at energies between 3 and 3..6 eV. There is an enhancement in the cavity between the wires in the 2nd row images, whereas no such enhancement is observed with touching wires (3rd row). Separate Ag-nanowires (row 1 and 2) appear to have separable surface plasmon nodes below 3 eV, whereas at energies above the Ag-plasmon they cannot be observed as separate nodes any longer in a wire of the given length. No nodes are observed in the touching and the crossed wires. The resonance energy seems to be broader/ shifted downwards in the latter.

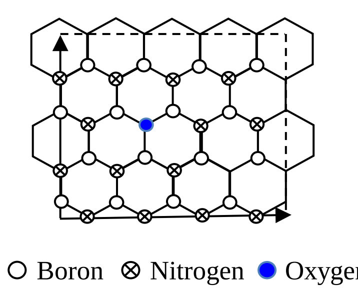
Atomic structure of other novel 2D materials- single layer boron nitride

transparent insulator for graphene hetero-structures









BN does not exhibit the same defects as graphene, instead triangular holes form (on repeated e-beam scanning), B escapes first, then N (SSTEM2 HAADF image)

Pan et al, Phys Rev B, 2012

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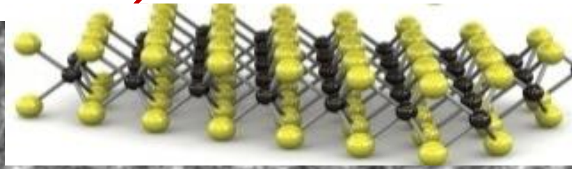
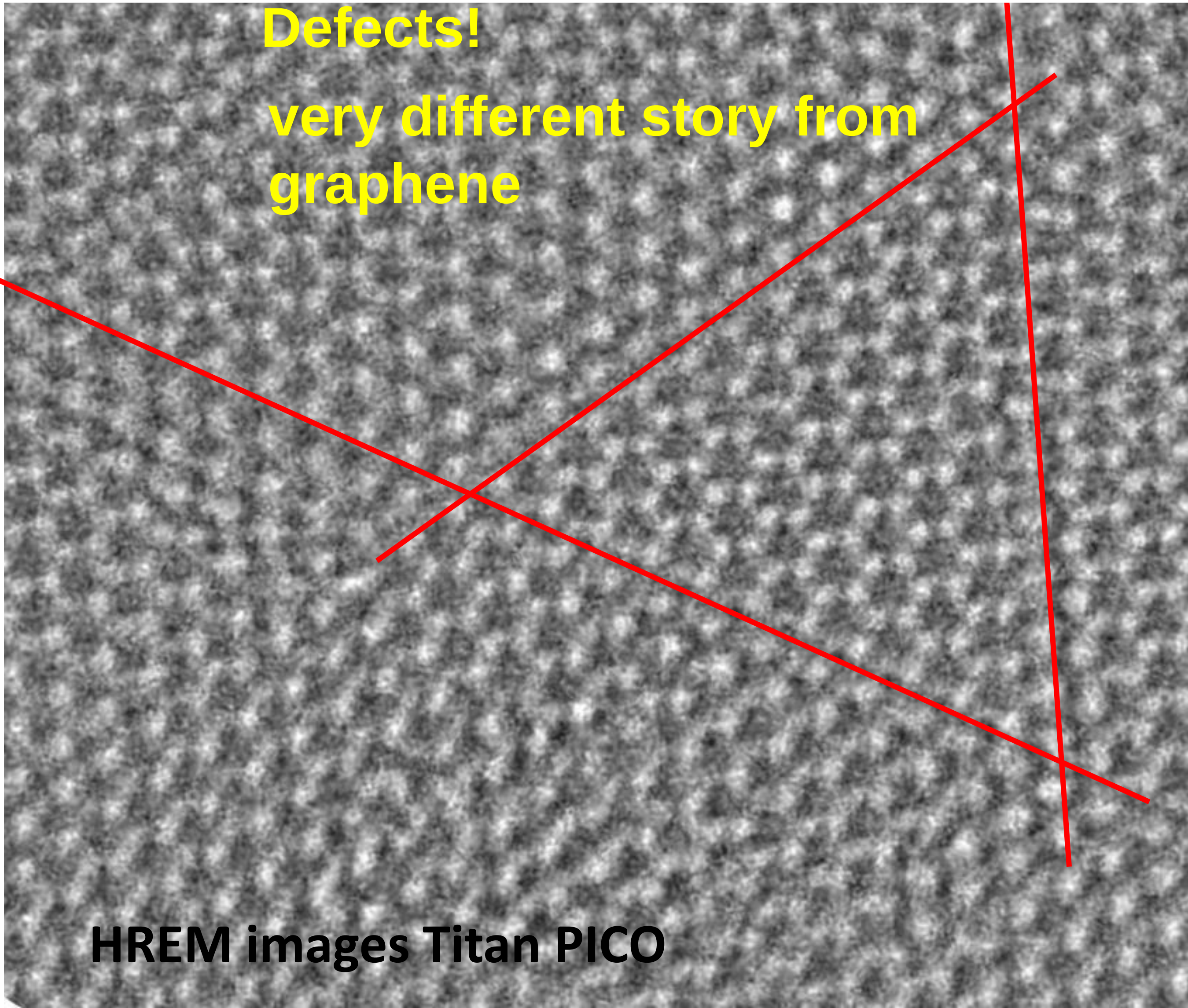
Other 2Ds on the Scene with semiconducting properties-

promising for opto-electronics: single layer MoS_2





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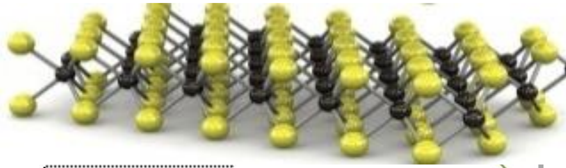
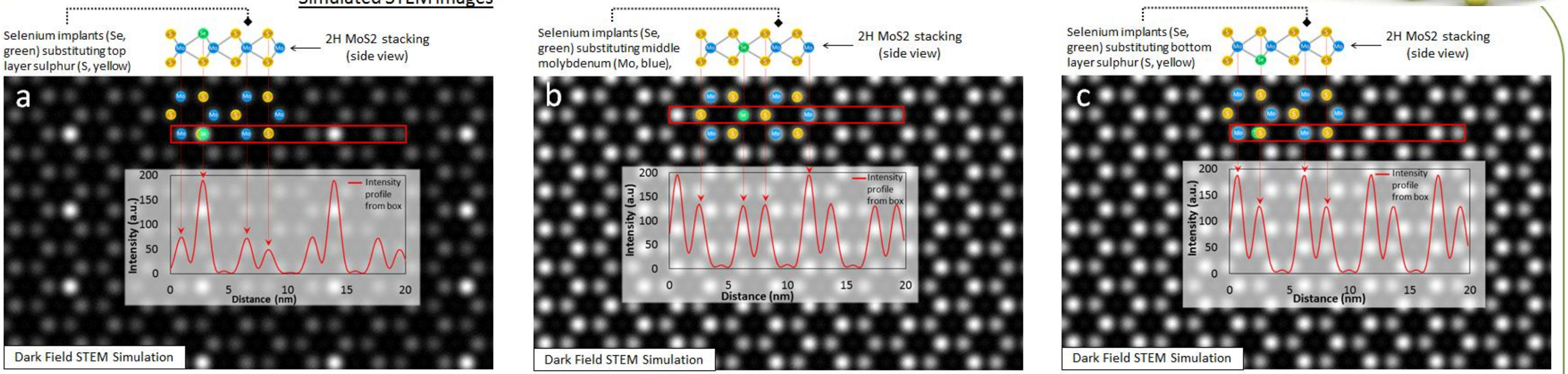
Ion Implantation of MoS_2 with Se:
controlled in-lattice functionalisation for bandgap tailoring and doping



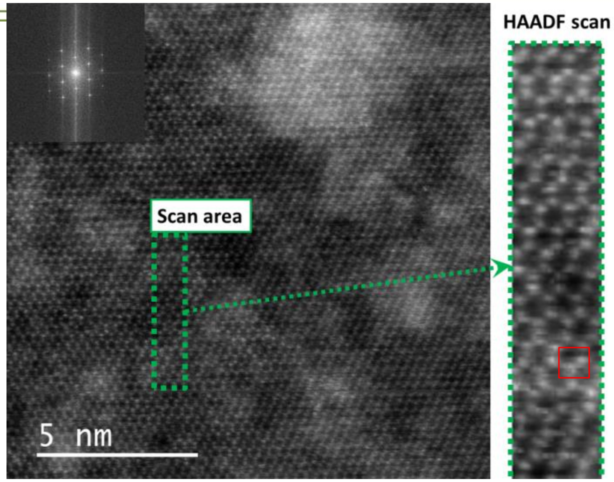
Simulation

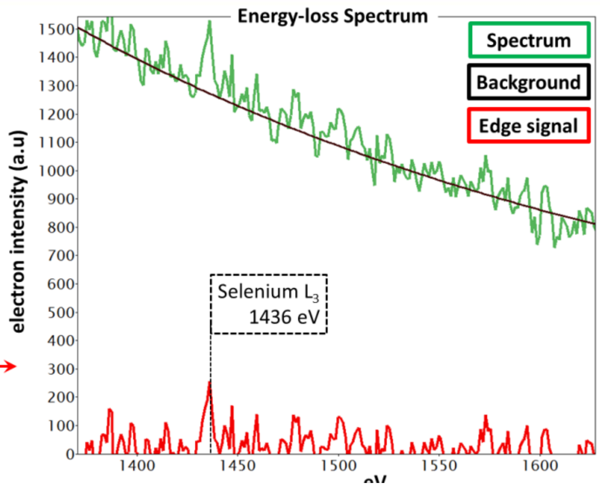
Simulated STEM images



Simulated STEM images of monolayer MoS2 with accompanying atomic model illustration overlaid and inset intensity profile for selenium implants (Se, green) substituting a) top layer sulphur (S, yellow), b) molybdenum (Mo, blue), c) bottom layer sulphur (S, yellow).

The intensity profiles were taken over the red boxes and demonstrate how easily one can identify implantations by eye. It becomes more difficult as the Se implant is placed lower (a – c) in the monolayer MoS2.



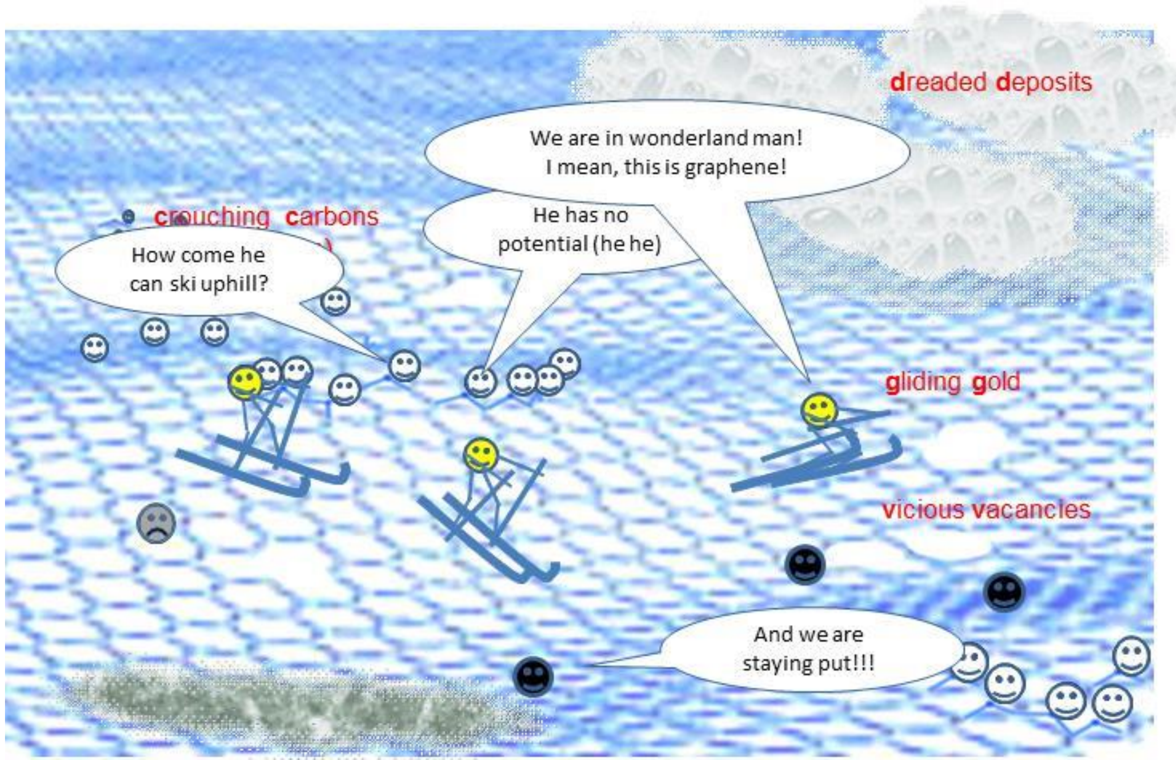


very different and much more complex story than for graphene

Summary points

- Graphene and carbon nanotube characterisation
  -> defects
  -> detection, identification and site specification of *individual* atoms
- Extreme mobility of metals on pristine graphene -> problem for contacting?
- Graphene etching in presence of metals-> prospects for nano-sculpting?
- Healing -> radiation hardness? Perfect material in radiation conditions?
- Controlled impurity introduction via ion implantation in CNTs and graphene
- Substitutional ion implantation at ultra-low energies possible in graphene!
  -> doping & electronic functionalisation -> prospects for scalable technology, integratable with semiconductor technologies
- Tailoring excitations in the uv/vis plasmonic energy regime
  -> feature at ~3 eV: at graphene edges with metal atoms -> nanosculpting,
  -> after alkali- and B-doping in CNTs and N-doping in graphene
- Other 2D's: BN, dichalcogenides (impurities, defects)

Summary points ctd ;)



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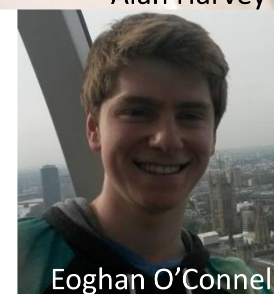
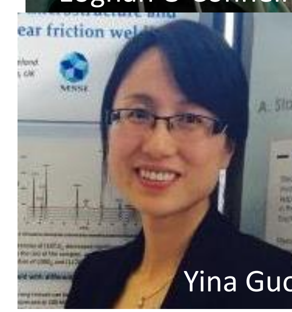
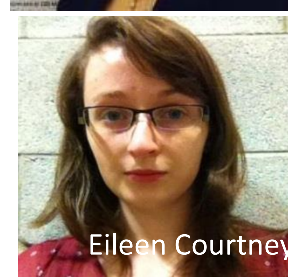
<u>Special thanks and acknowledgements for their strong involvement to</u>

Q Ramasse	SuperSTEM
D Kepaptsoglou	SuperSTEM
W Pierce	Manchester Uni
R Zan	Manchester Uni
C T Pan	Manchester Uni
C Boothroyd	ER-C FZ Juelich
L Houben	ER-C FZ Juelich
K Novoselov	Manchester Uni
A Geim	Manchester Uni
T Hardcastle	Leeds Uni
A Scott	Leeds Uni
C Seabourne	Leeds Uni
H Hofsaess	Goettigen Uni
J Amani	Goettingen Uni
A J Harvey	Limerick Uni
E O'Connell	Limerick Uni
E Courtney	Limerick Uni
C. Jeynes	Surrey Uni
R. Gwilliam	Surrey Uni
J Van den Berg	Salford Uni
R Kashtiban	Warwick Uni
A Stewart	Limerick Uni
J Bangert	Jubjub.co
a. o.	

A great thank you to my group!







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