Exploring matter at the atomic level

Corrado Spinella

Why electron microscopy

Optical microscopy

$$\lambda = 1000 \div 5000\text{Å}$$

Electron microscopy

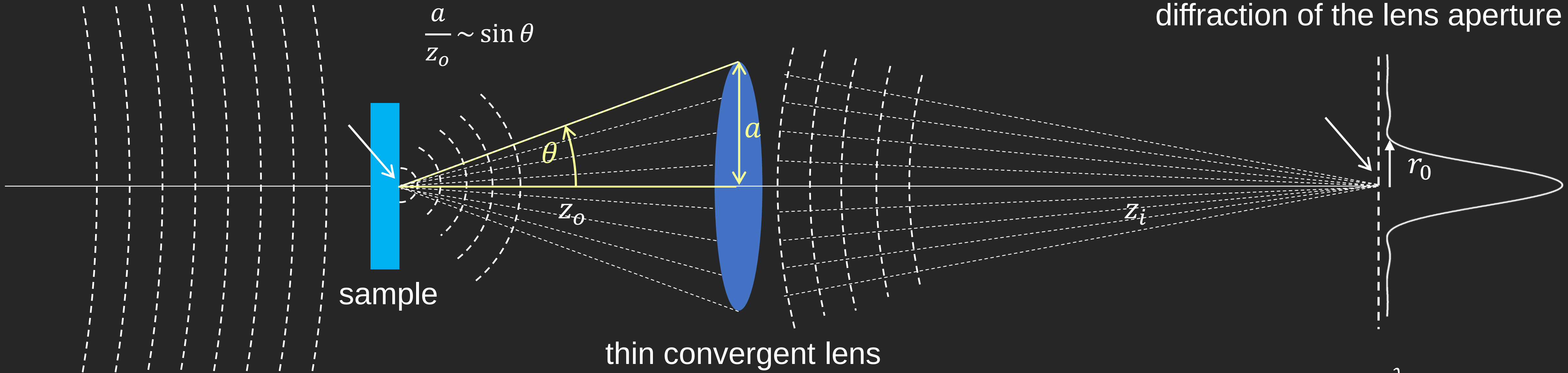
$$\lambda = 0.1 \div 0.5\text{Å}$$

Abbe limit to resolution

corresponding width in the object:

$$\rho_0 = r_0 \frac{z_o}{z_i} = 0.61 \frac{\lambda z_o}{a} \sim 0.61 \frac{\lambda}{\sin\theta}$$

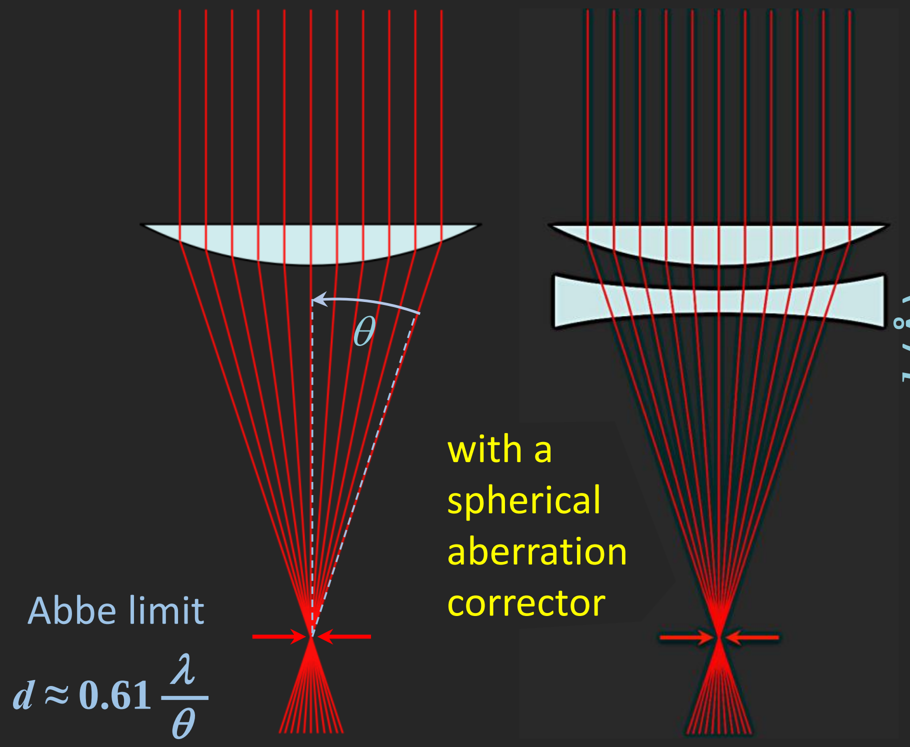
diffraction of the lens aperture

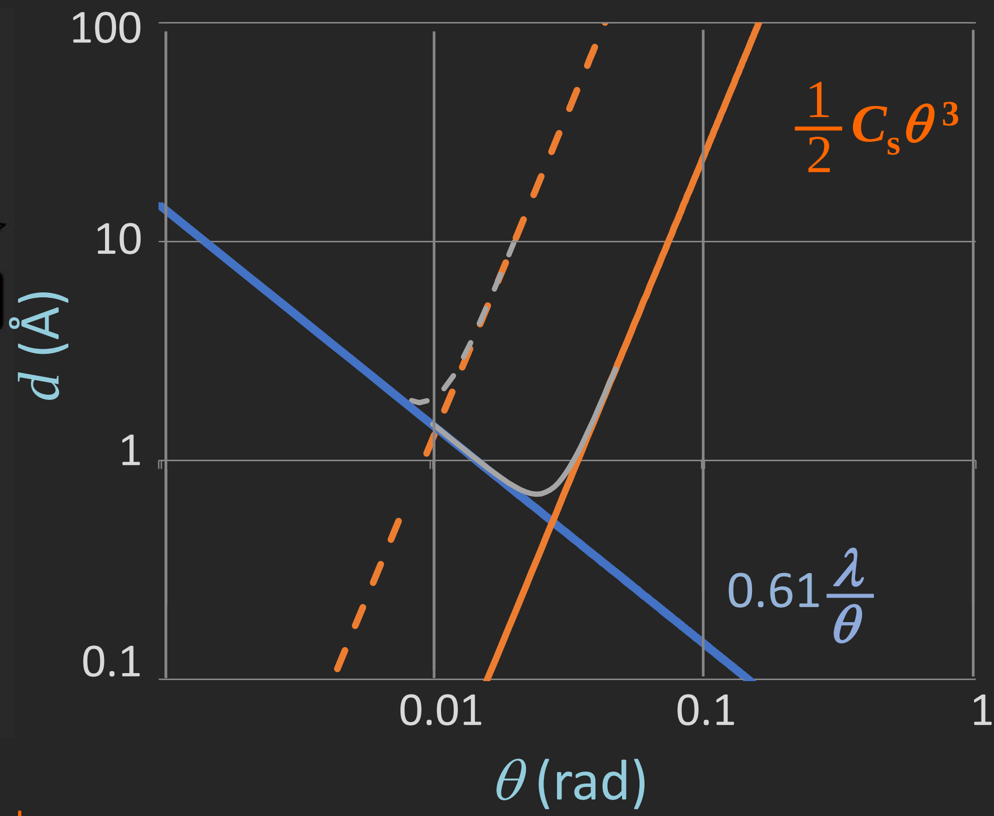


λ

first minimum at $r_0 = 0.61 \frac{\lambda z_i}{a}$

Sub–Ångstrom spatial resolution

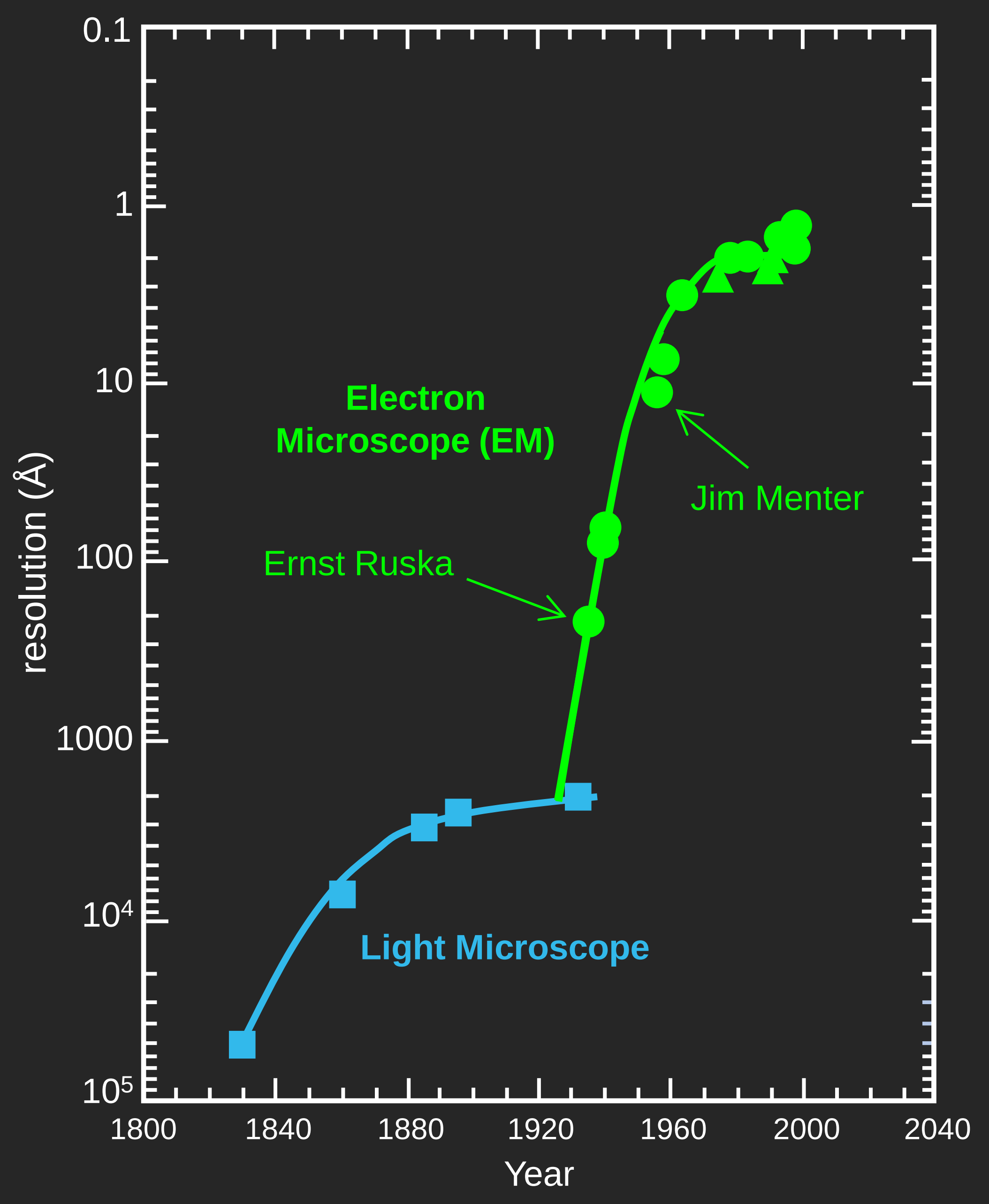




Inherent nature of bending of light/electron waves when passes through an aperture lens of finite size

Inherent nature of the lens used in the imaging system

λ = 0.025 Å @ 200 kV



0.1
1
10
100
1000
10^4
10^5
resolution (Å)
Electron Microscope (EM)
Jim Menter
Ernst Ruska
Light Microscope
1800
1840
1880
1920
1960
2000
2040
Year

1997: spherical aberration correction. Maximilian Haider, Harald H. Rose, Knut W. Urban

The basic theory of aberration correction for high–resolution imaging was introduced by Dr. Otto Scherzer in the 1940's. Many researchers attempted, but failed, its implementation as an aberration – corrected electron microscope; and experts had questioned its technical feasibility by the time the Haider, Rose and Urban, who thought otherwise, was teamed in 1989.

In 1997 they succeeded in making an aberration-corrected TEM that is capable of high-resolution imaging of atomic structures.

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Full-length paper

Towards 0.1 nm resolution with the first spherically corrected transmission electron microscope

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Abstract A hexapole corrector which compensates for the spherical aberration of the objective lens has been incorporated in a commercial 200 kV transmission electron microscope (TEM) equipped with a field emission gun. The successful correction of the spherical aberration is demonstrated by decreasing the instrumental resolution limit from 0.24 nm down to about 0.13 nm. Images of Si-SiO_2 interfaces obtained with the corrected TEM show a remarkable suppression of artefacts and a strong increase in contrast apart from the improved resolution. The design, alignment and the performance of the corrected instrument are outlined in detail.

Keywords aberration correction, reduction of artefacts, information limit, contrast enhancement, point spread function, high-resolution TEM

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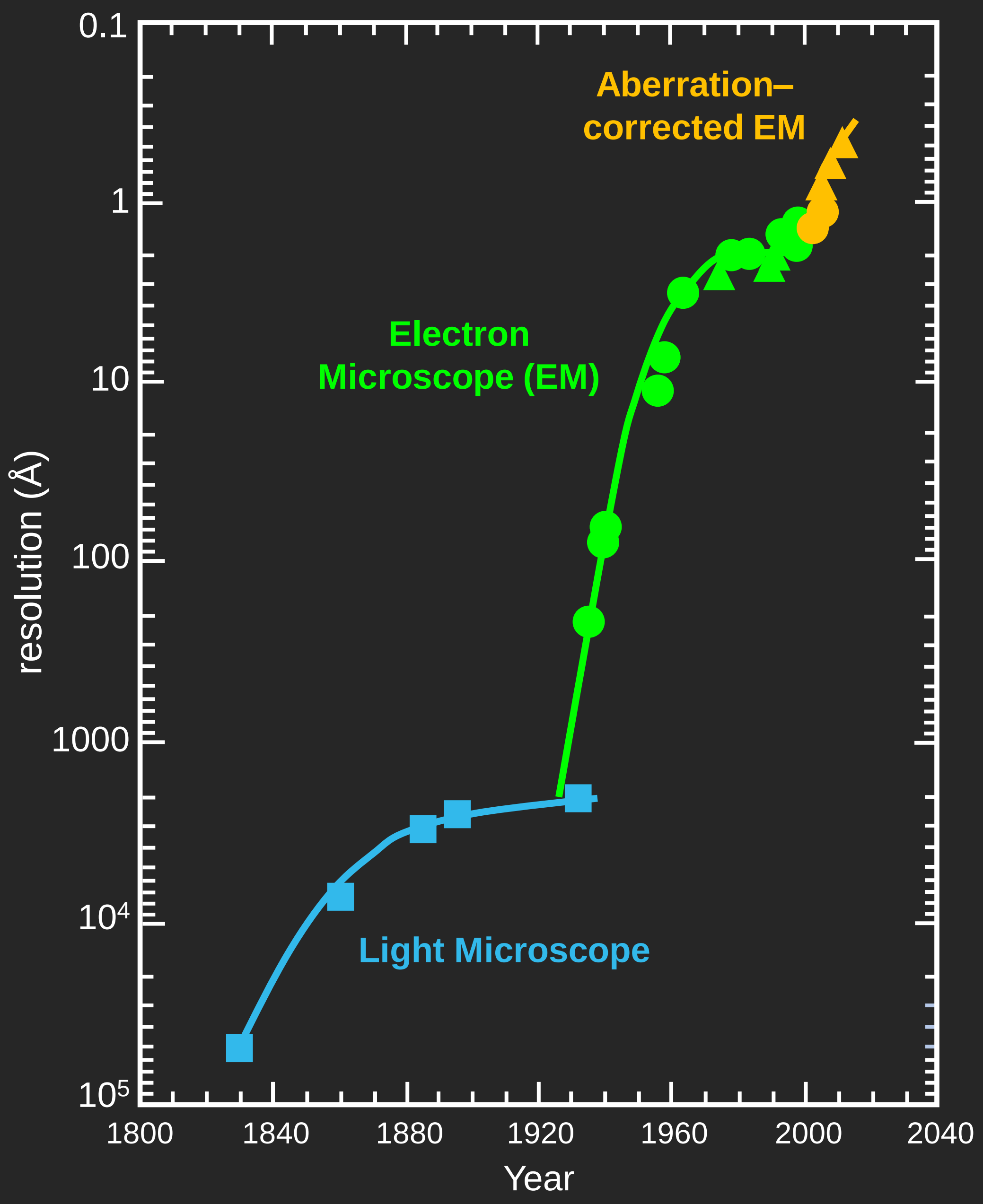
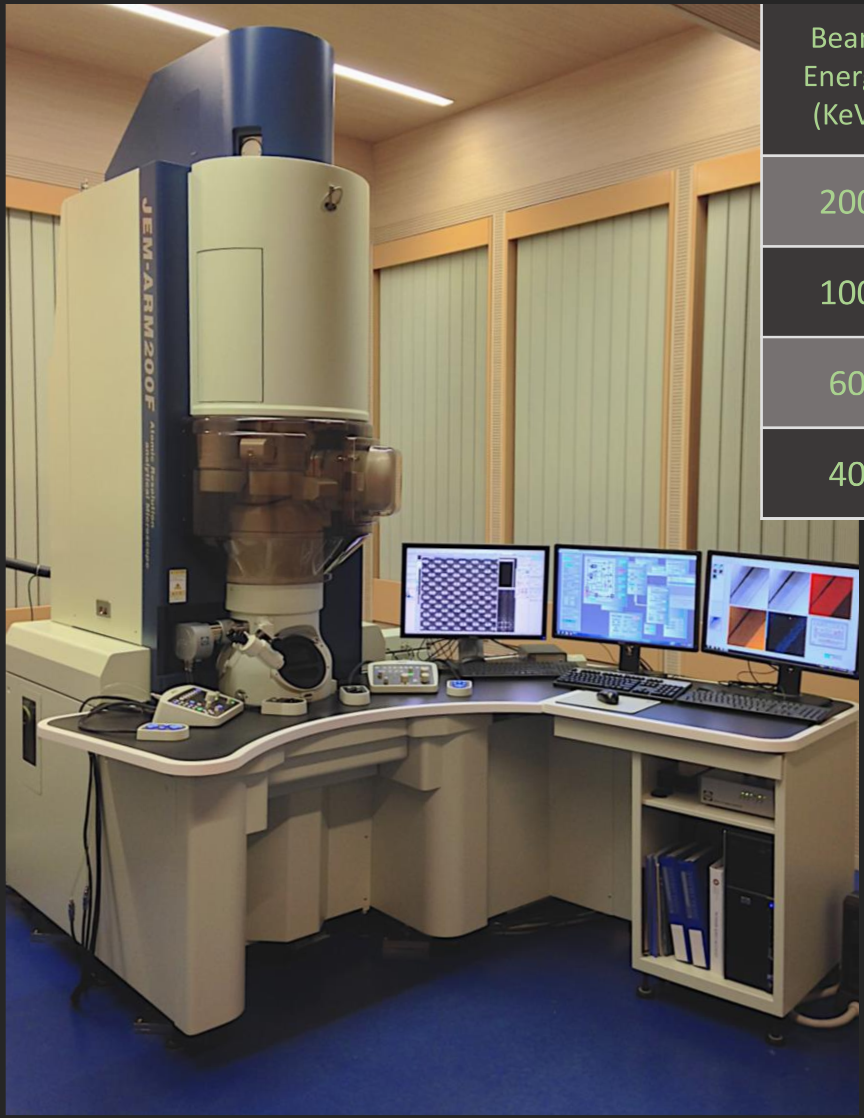
M. Haider, H. Rose, S. Uhlemann, B. Kabius, and K. Urban, Journal of Electron Microscopy 47(5), 395 (1998)

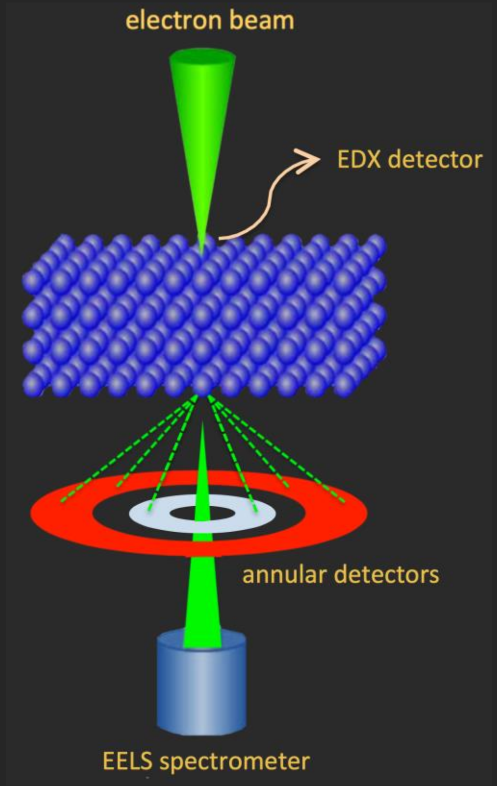


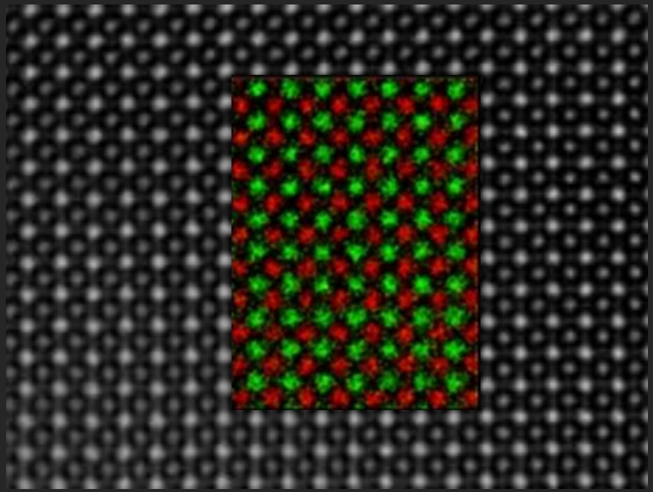
Aberration–
corrected EM
Electron
Microscope (EM)
Light Microscope
0.1
1
10
100
1000
10⁴
10⁵
resolution (Å)
1800
1840
1880
1920
1960
2000
2040
Year

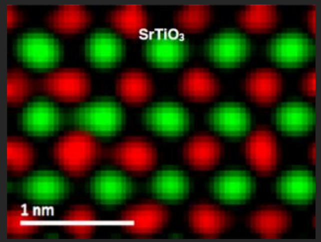
Atomic resolution Scanning Transmission Electron Microscopy



Beam Energy (KeV)	STEM resolution (Å)
200	0.68
100	0.83
60	1.1
40	1.36



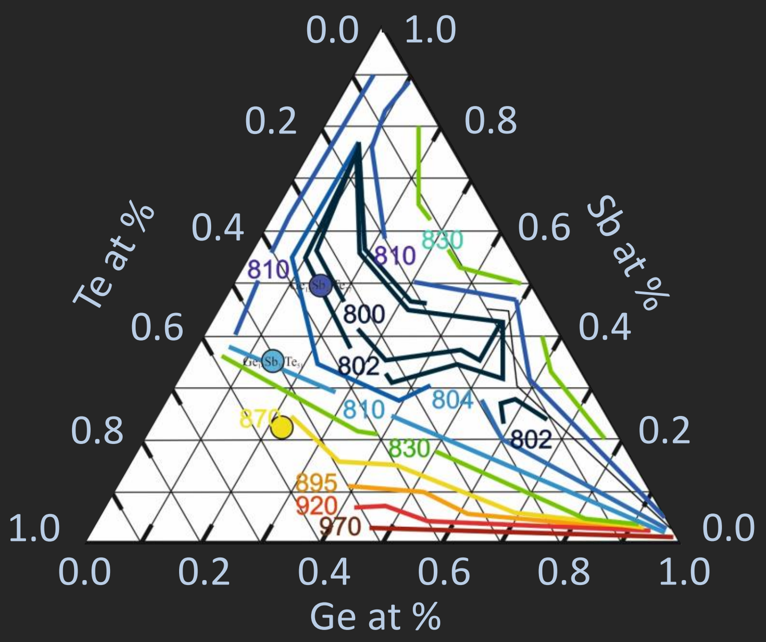


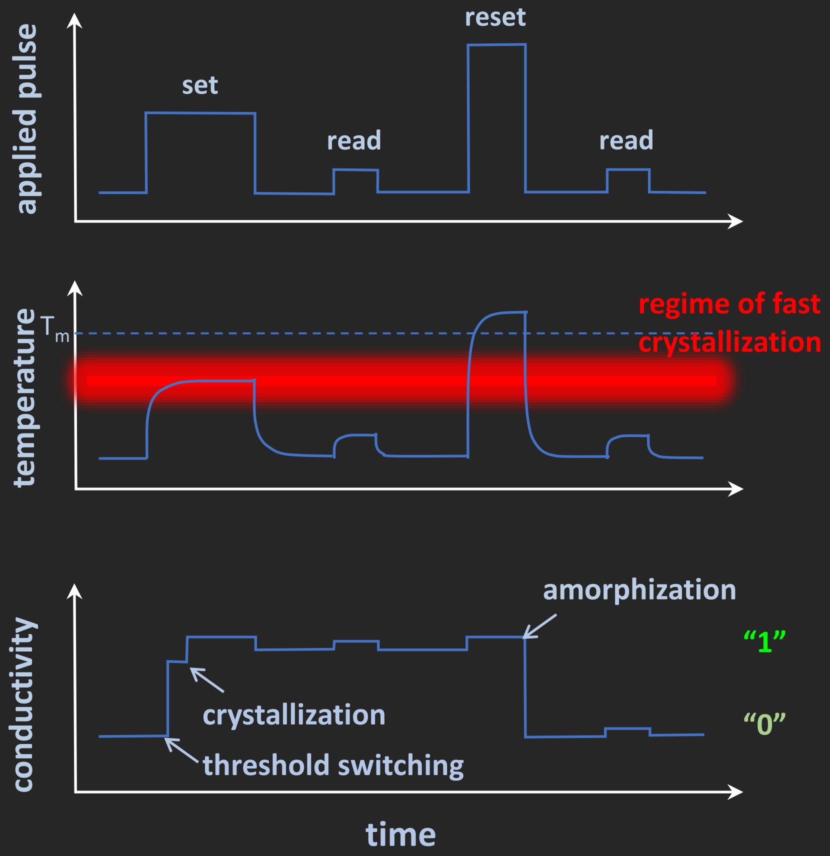


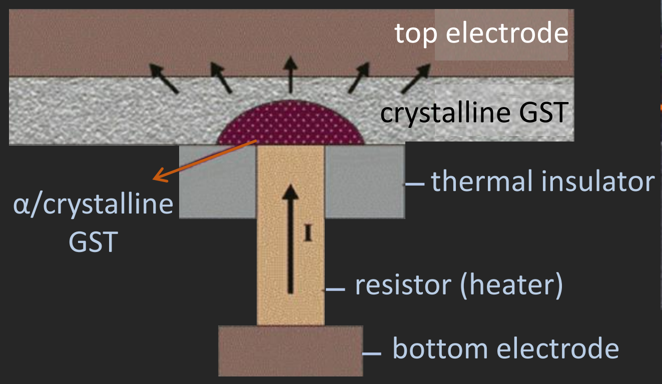
Ti
Sr

More Moore: memory devices based on novel materials

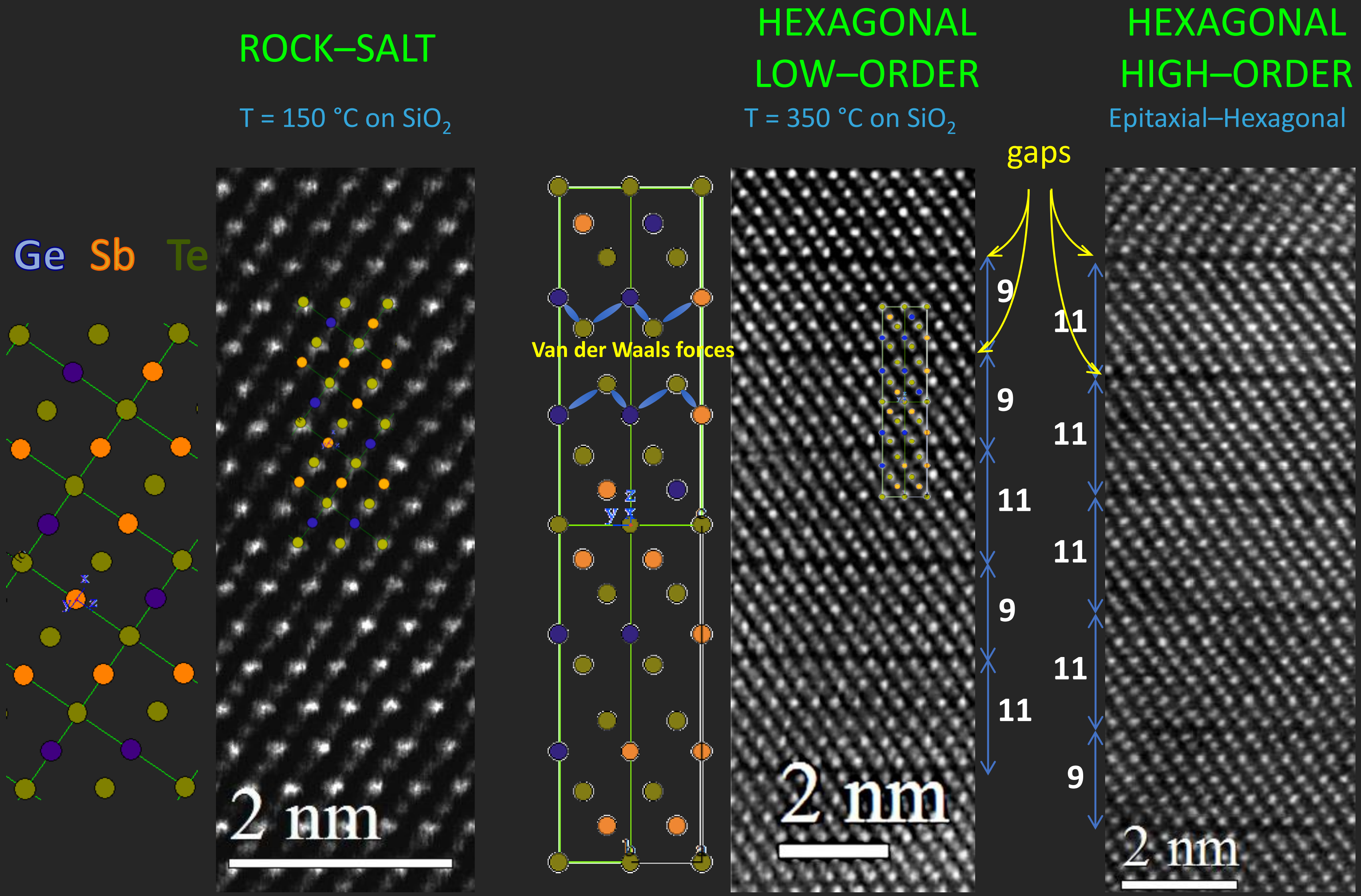
Phase Change Memories based on chalcogenides

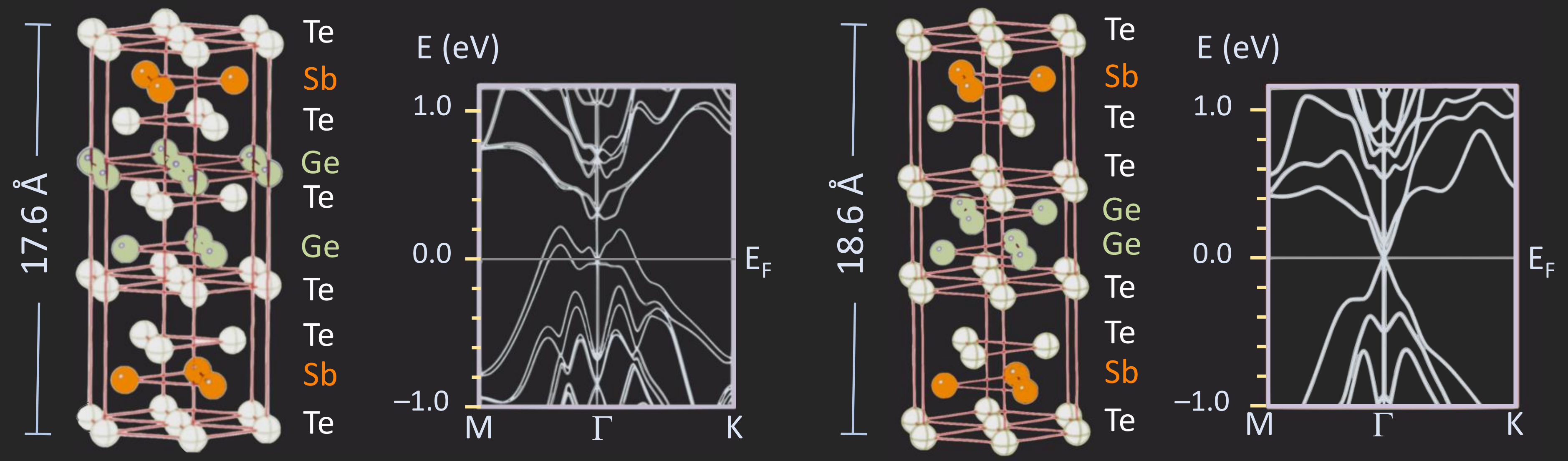






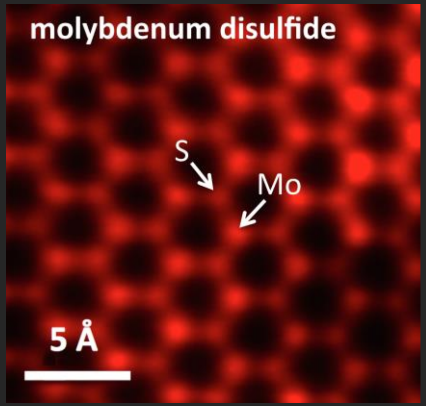
- ✕ Write/Erase velocity
- ✕ Scalability
- ✕ High RESET/SET Contrast
- ✕ Ciclability/Endurance
- ✕ Data Retention


ROCK–SALT
T = 150 °C on SiO2
HEXAGONAL
LOW–ORDER
T = 350 °C on SiO2
HEXAGONAL
HIGH–ORDER
Epitaxial–Hexagonal
gaps
Ge
Sb
Te
Van der Waals forces
2 nm
2 nm
2 nm
9
9
11
9
11
11
11
11
11
9



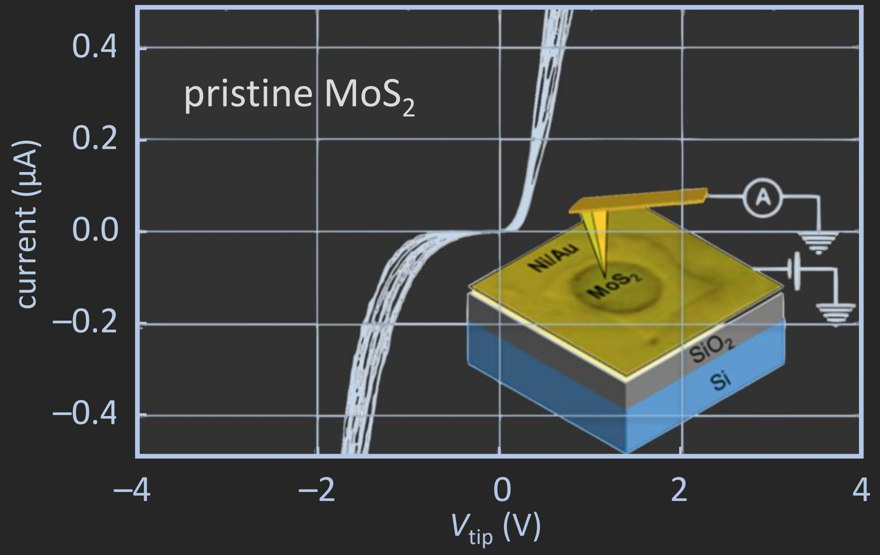
In thin films the local atomic order of chalcogenides is extremely important in determining their electrical properties.

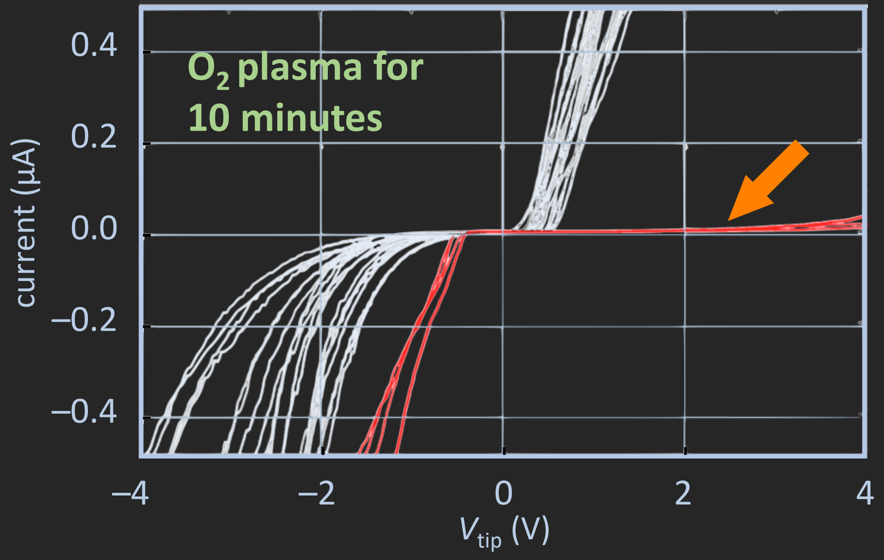
Nanoscale tailoring of Schottky metal/MoS_2 barrier by oxygen plasma functionalization

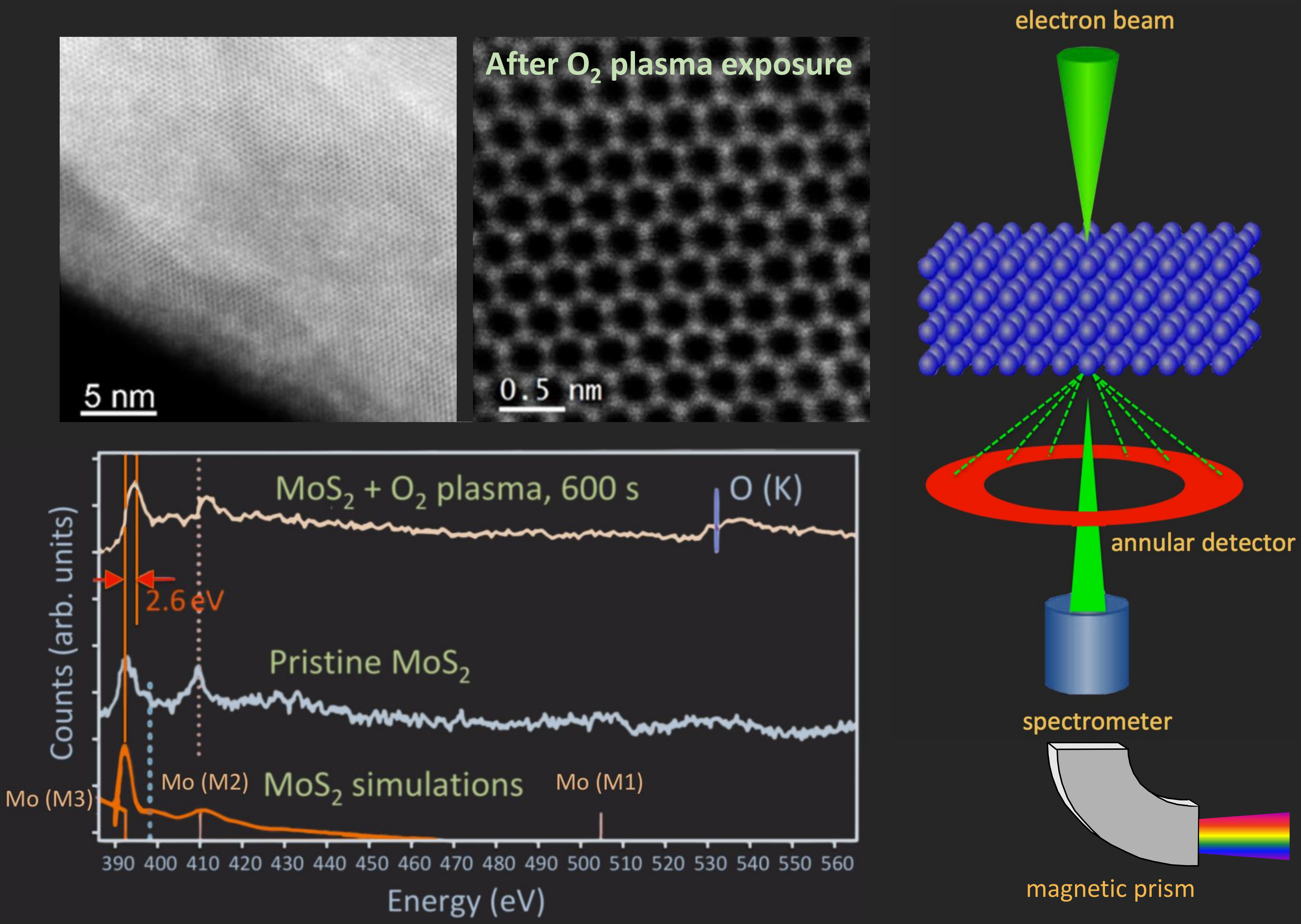


MoS_2 promising material for next generation post–Si CMOS technology

The high effective mass and large bandgap of MoS_2 minimize direct source–drain tunneling, while its atomically thin body maximizes the gate modulation efficiency in ultrashort–channel transistors.



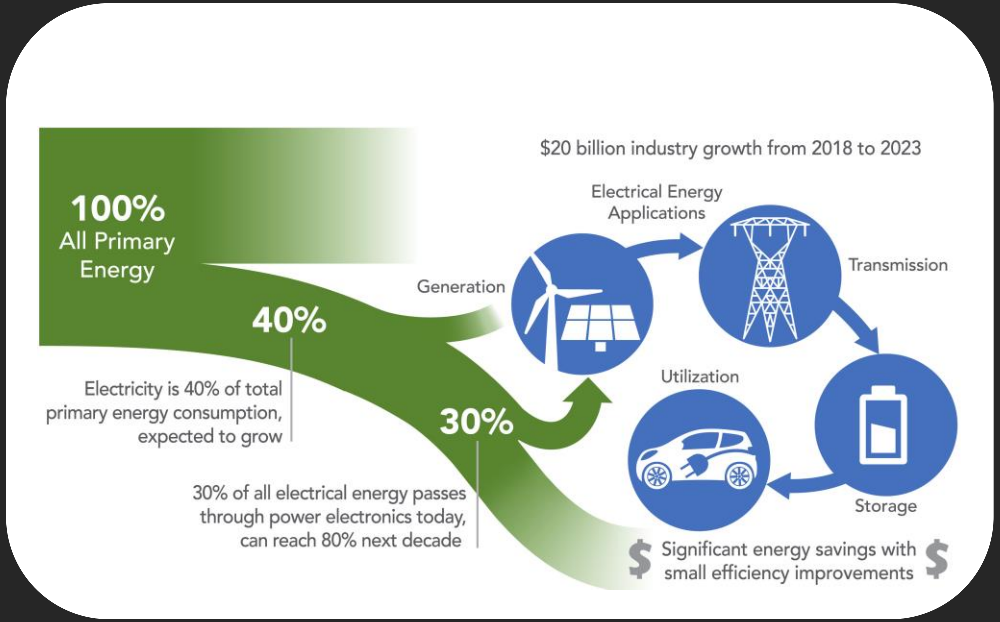


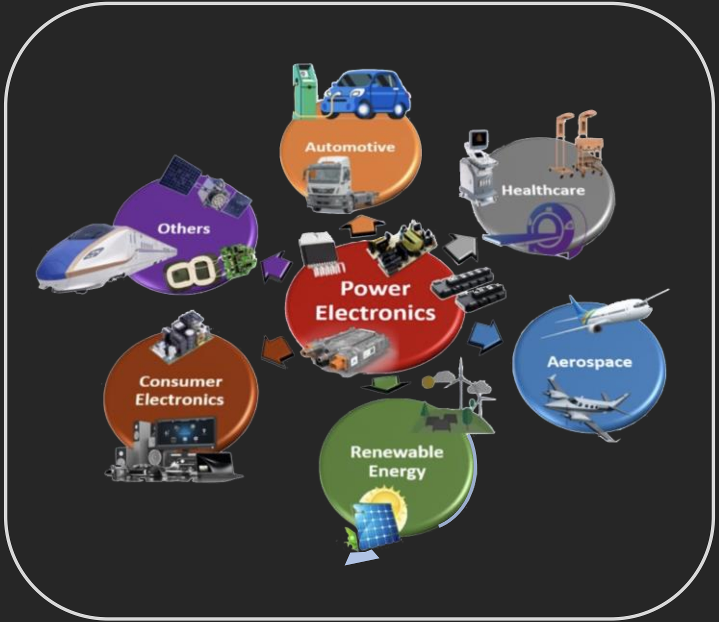


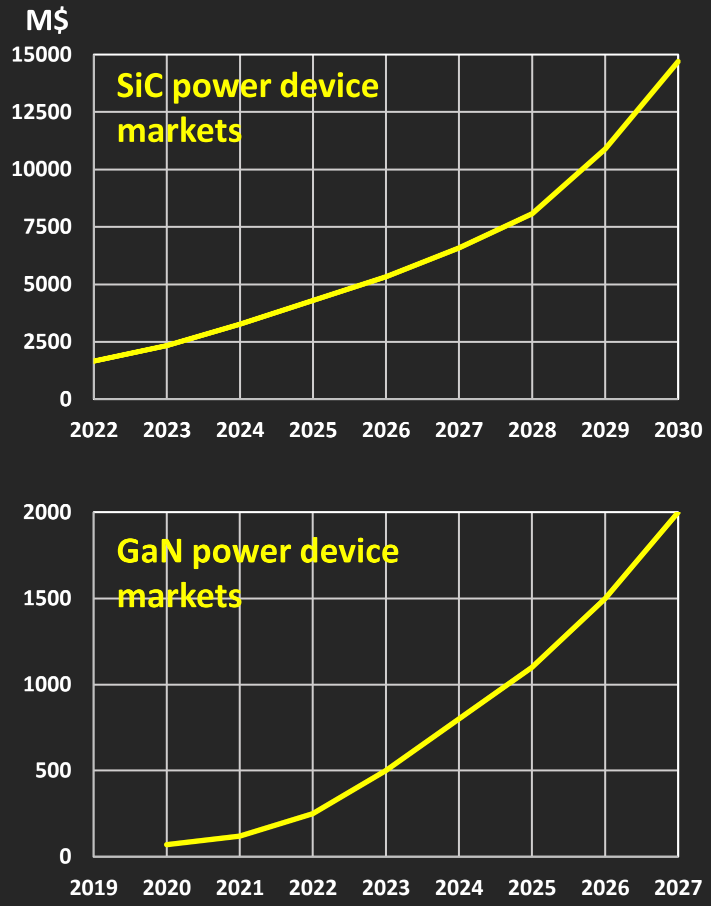
5 nm
After O_2 plasma exposure
0.5 nm
MoS_2 + O_2 plasma, 600 s
O (K)
2.6 eV
Pristine MoS_2
Mo (M3)
Mo (M2)
MoS_2 simulations
Mo (M1)
Counts (arb. units)
390 400 410 420 430 440 450 460 470 480 490 500 510 520 530 540 550 560
Energy (eV)
electron beam
annular detector
spectrometer
magnetic prism

Leverage innovation beyond the Moore's law

Innovation in line with Moore's law (which predicts the continuous shrinking of transistor feature size) will certainly continue, but additional advances are expected from exploring solutions beyond the Moore's law, ***such as those enabled by wide–bandgap semiconductors in the field of power–electronics***

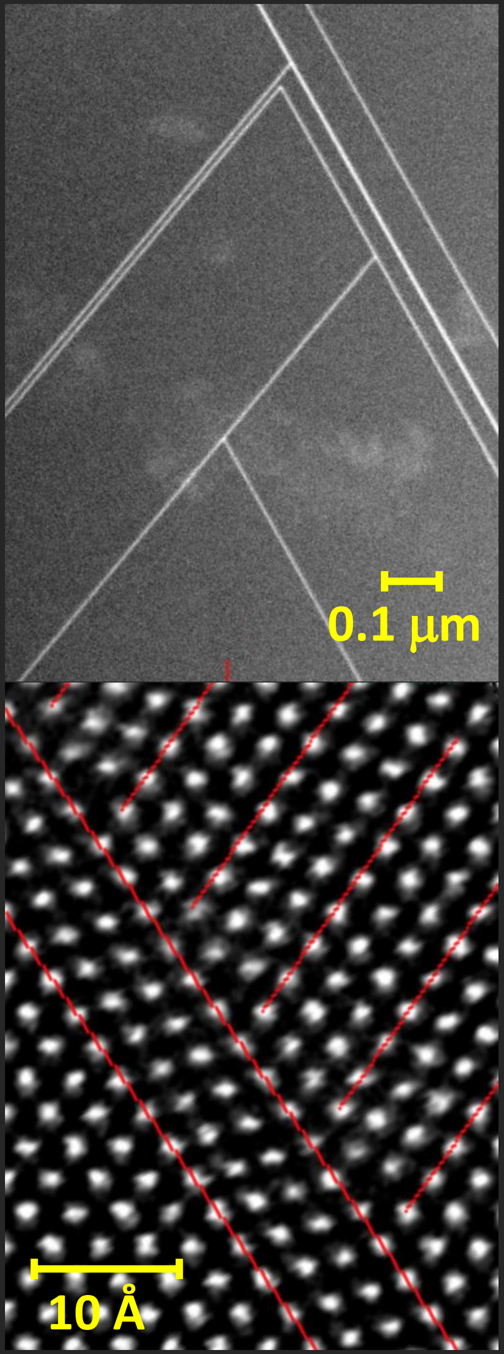


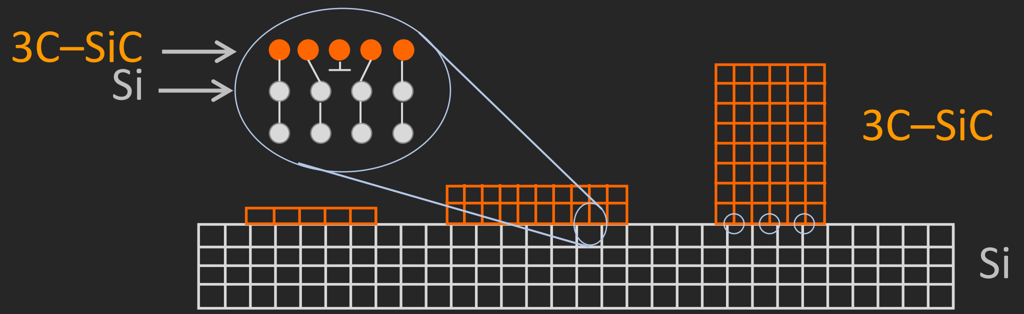


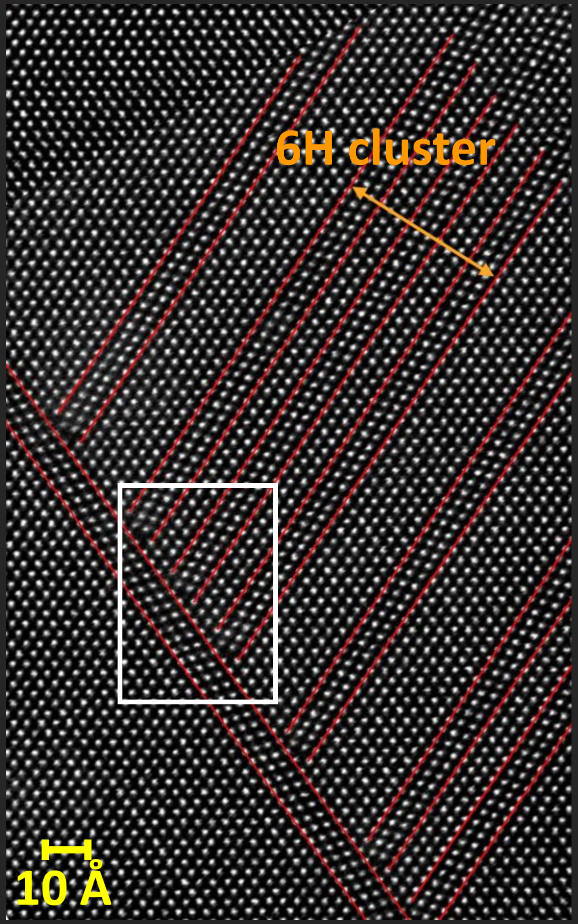


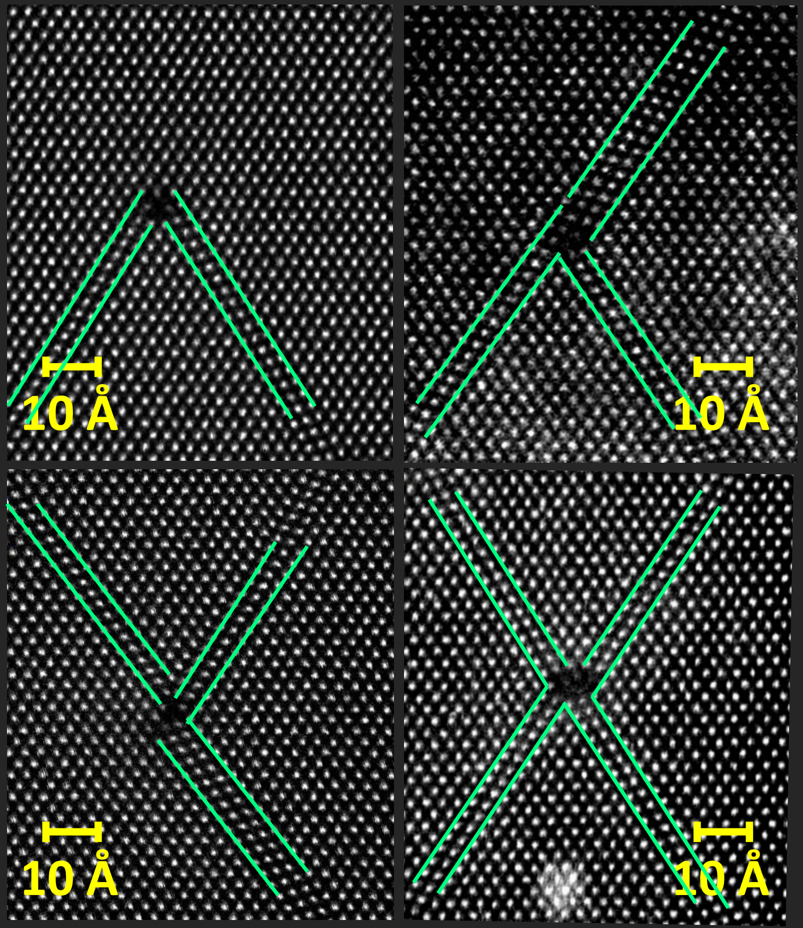
Yole' forecast for SiC and GaN device markets

Growht of 3C–SiC on Si



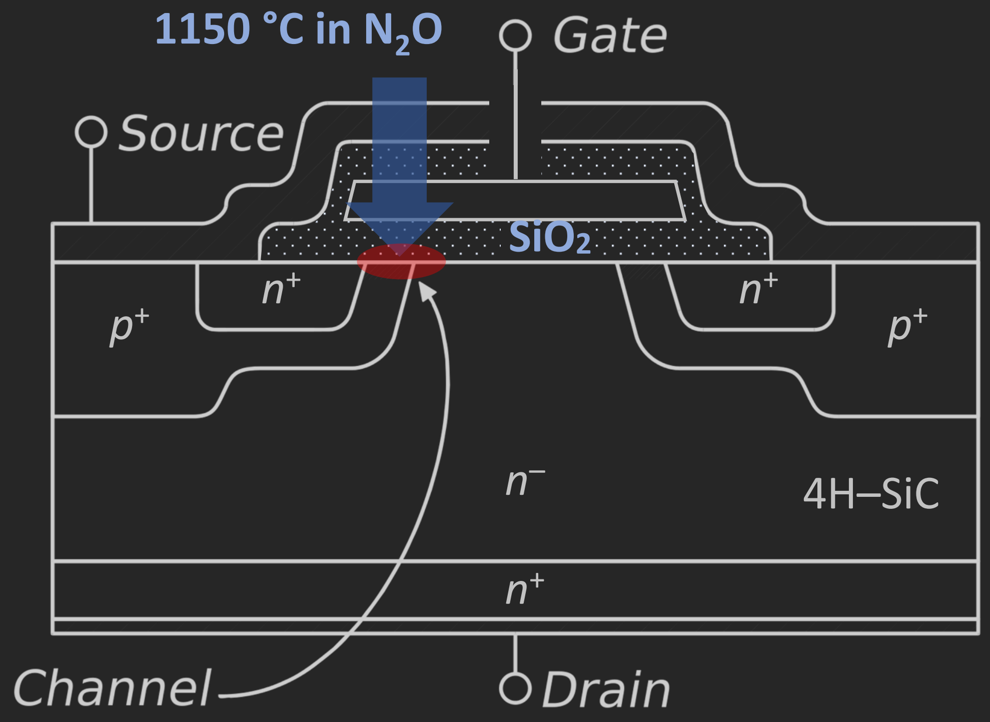


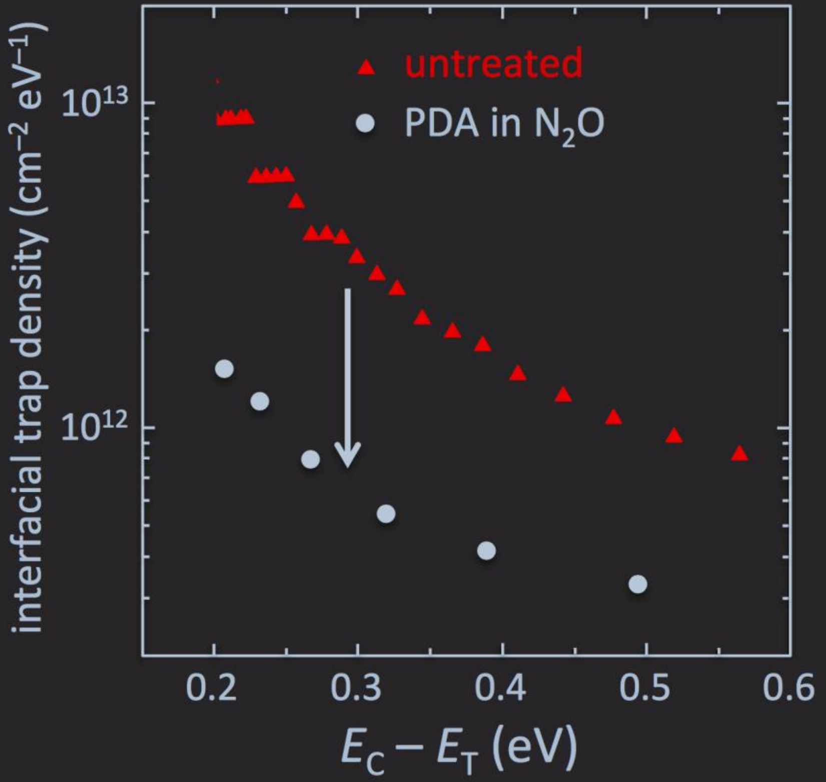




4H–SiC Power MOSFET

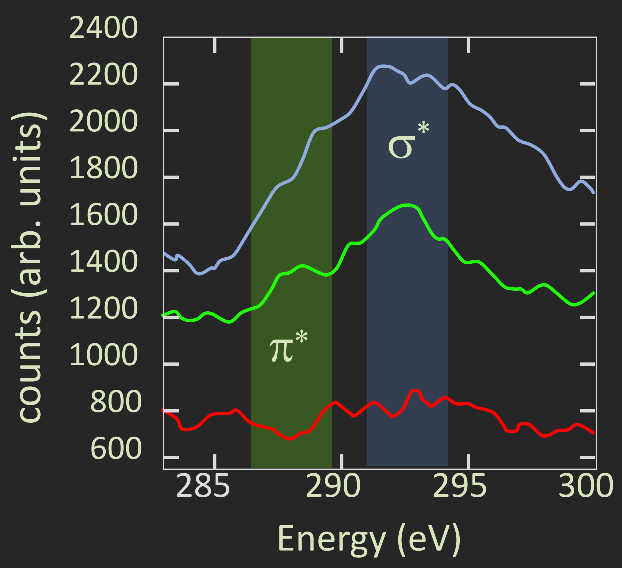
Issues:
High density of traps at SiO_2/SiC interface, low channel mobility

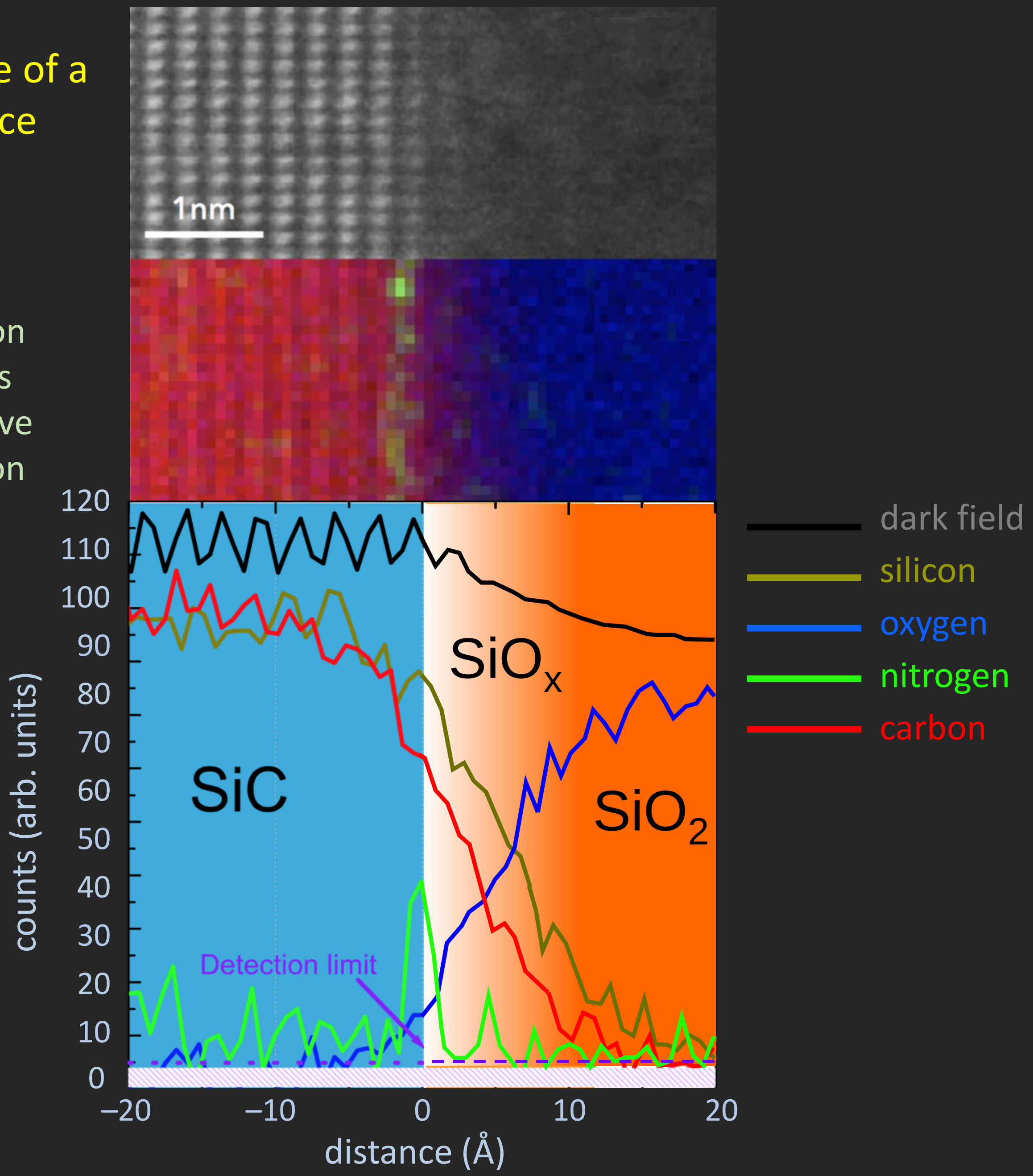




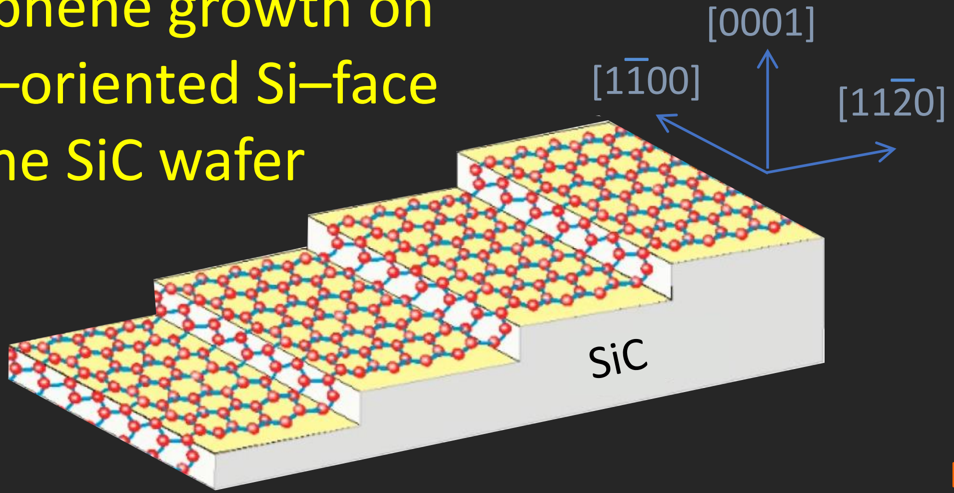
STEM–EELS reveals the presence of a non–abrupt SiO_2/4H–SiC interface

A mixed sp2/sp3 carbon hybridization in the non–abrupt interface suggests that the interfacial carbon atoms have lost their tetrahedral SiC coordination

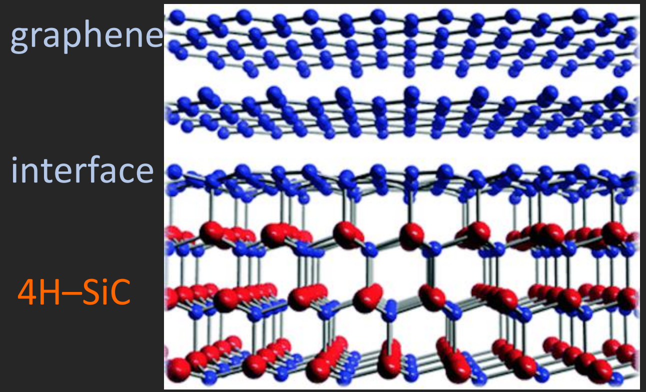




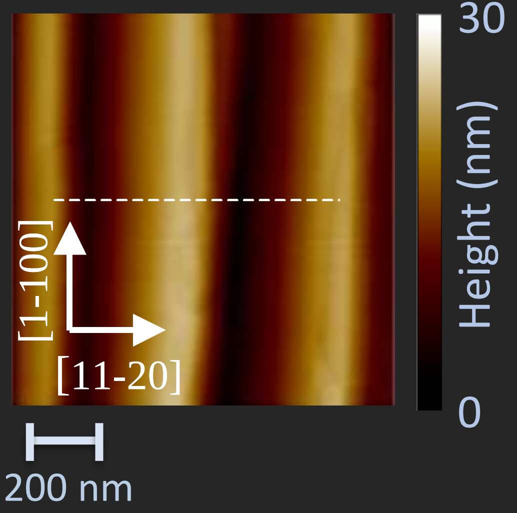
Graphene growth on mis–oriented Si–face of the SiC wafer

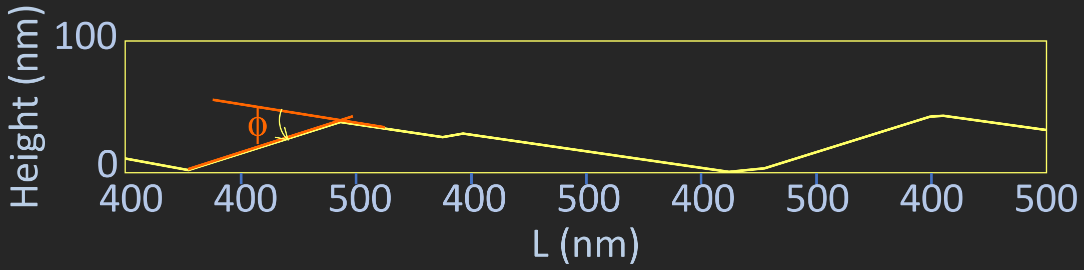


Si terminated 4H–SiC (0001) substrates 8° off–axis miscut angle in the [11$\bar{2}$0] direction



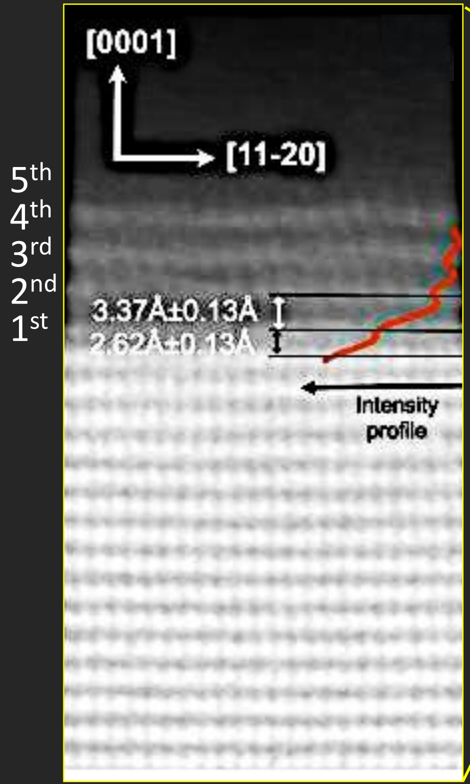
Epitaxial graphene: solution for integration of high power and high frequency functions on a SiC substrate

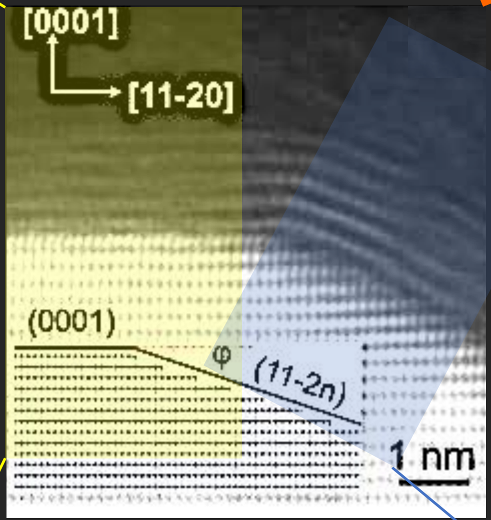




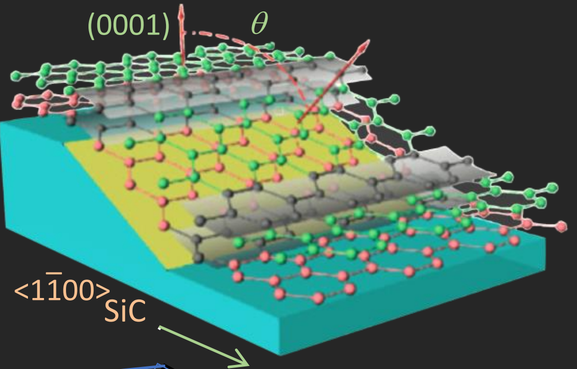
Atomic resolution HAADF–STEM

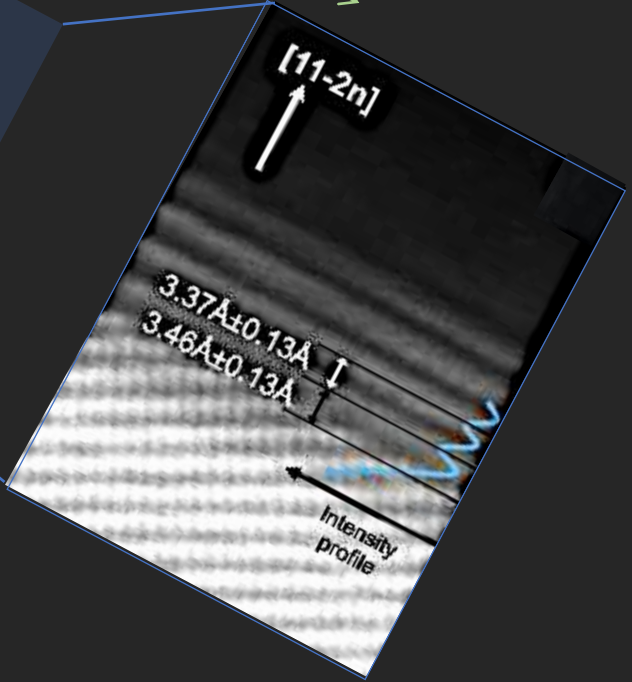
@ 60 keV primary electron beam

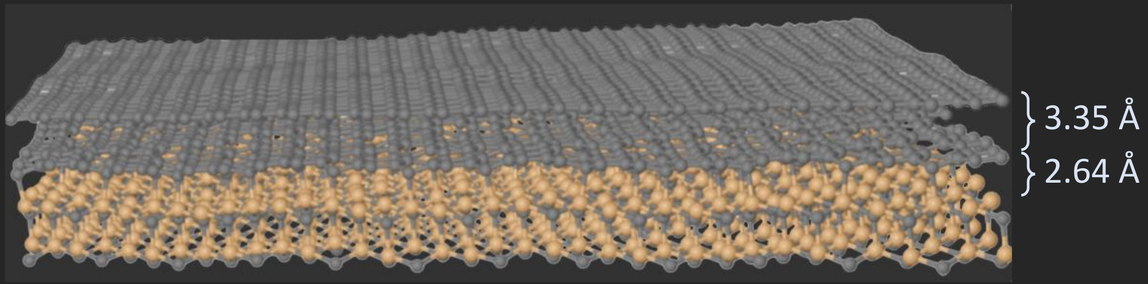




Cross section perpendicular to [0001] direction

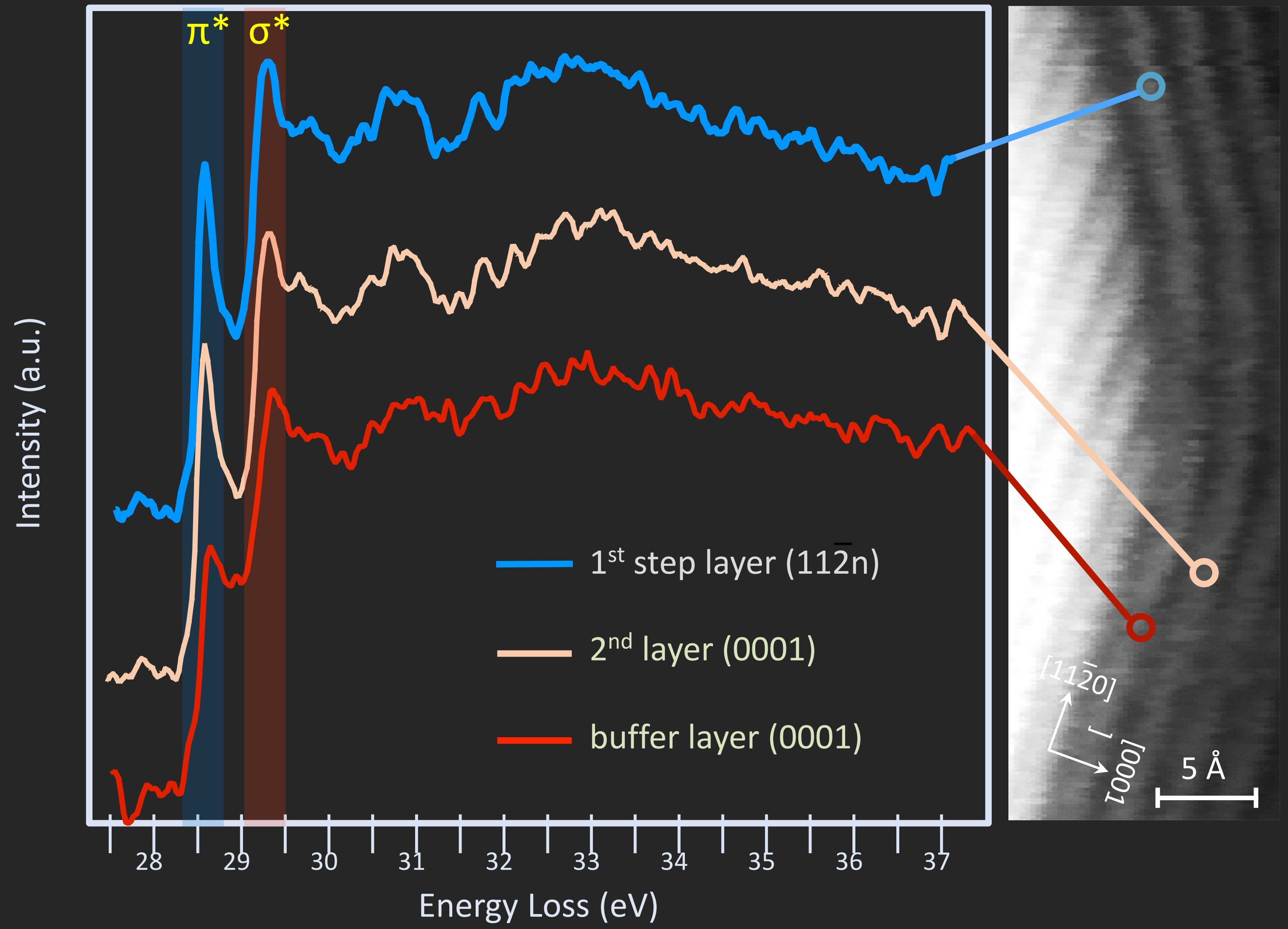






Ab initio simulations showing the equilibrium average atomic distances

The buffer layer on the planar (0001) surface gets detached from the (11$\bar{2}$n) surface



The buffer layer present on the planar (0001) face gets detached from the substrate on the (112̄n) facets of the steps, turning into a quasi–freestanding graphene film

Conclusions

Fulfilling Feyman's Dream

*… I would like to try and impress upon you while I am talking about all of these things on a small scale, **the importance of improving the electron microscope by a hundred times**. It is not impossible; it is not against the laws of diffraction of the electron … **What good would it be to see individual atoms distinctly?***

December 29th 1959 at the annual meeting of the American Physical Society at California Institute of Technology