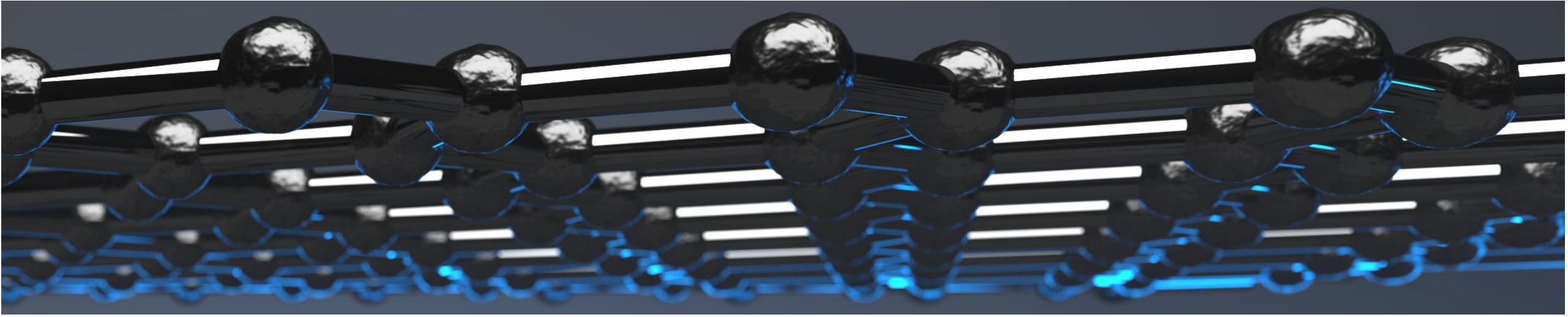

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Proximity-induced electronic states in epitaxial graphene/SiC (0001) via Tin intercalation

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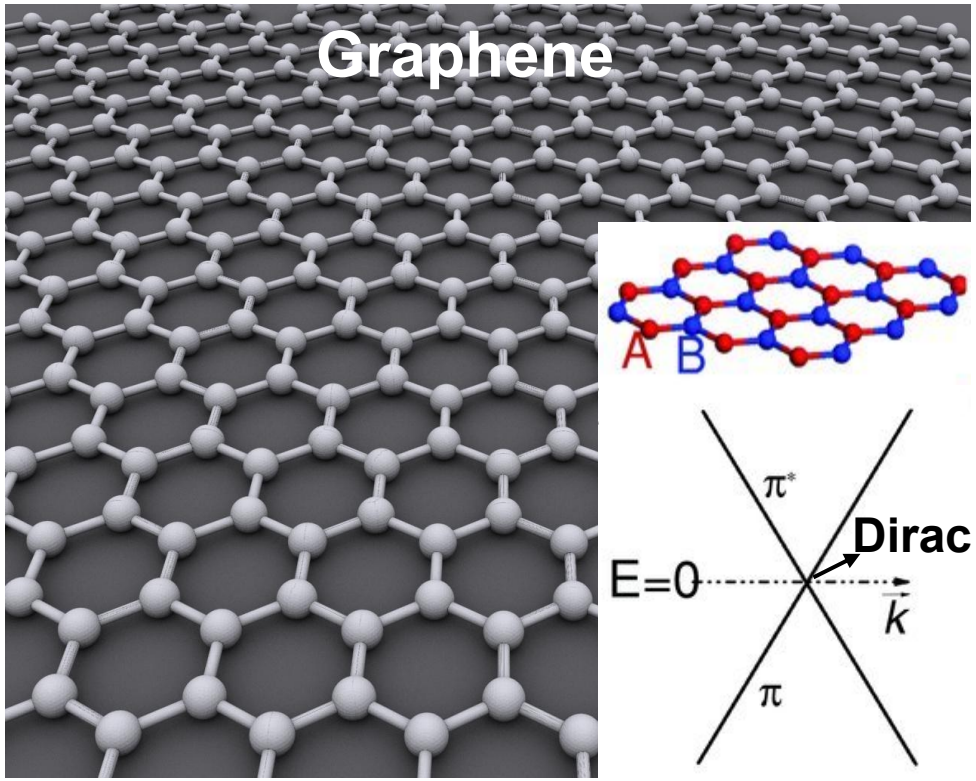
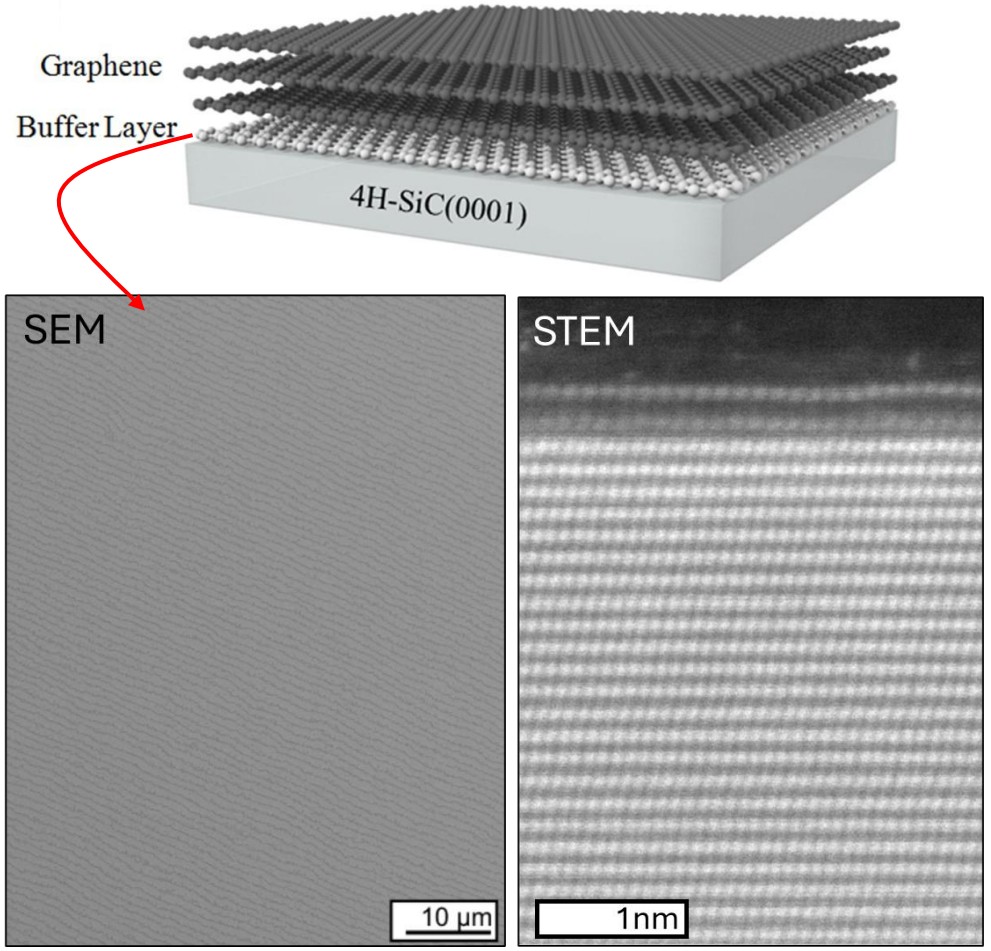
Viet Nam, 9th October 2025

Epitaxial graphene/SiC (0001): outstanding quality



Two symmetric sublattices ➔ Linear band dispersion

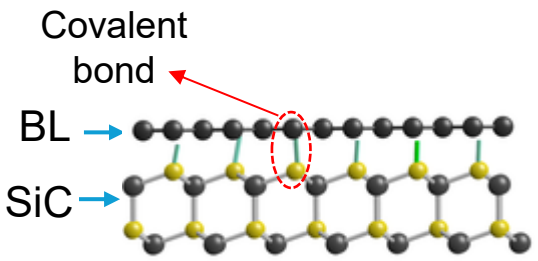


- SiC substrate integration capability
- More scalable and compatible with semiconductor processing.

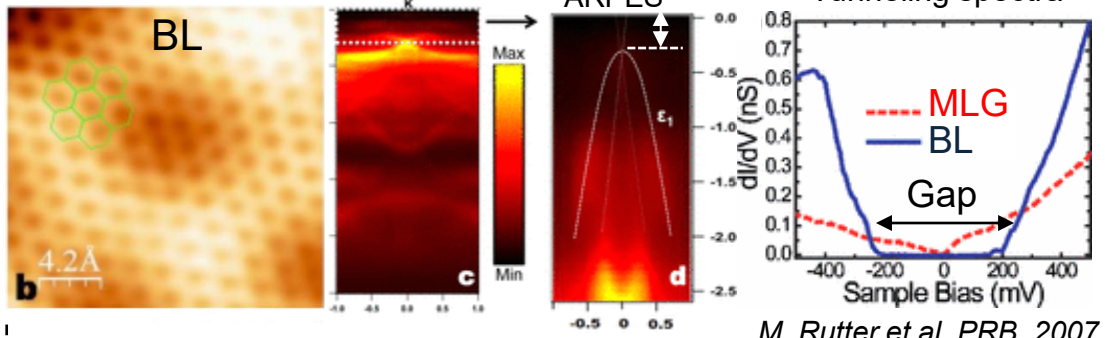
Hajlaoui, M. Sci Rep 6, 18791 (2016)

Buffer layer (BL) or Zero-layer graphene (ZLG)

Motivation: Heavy-element intercalation into the buffer layer



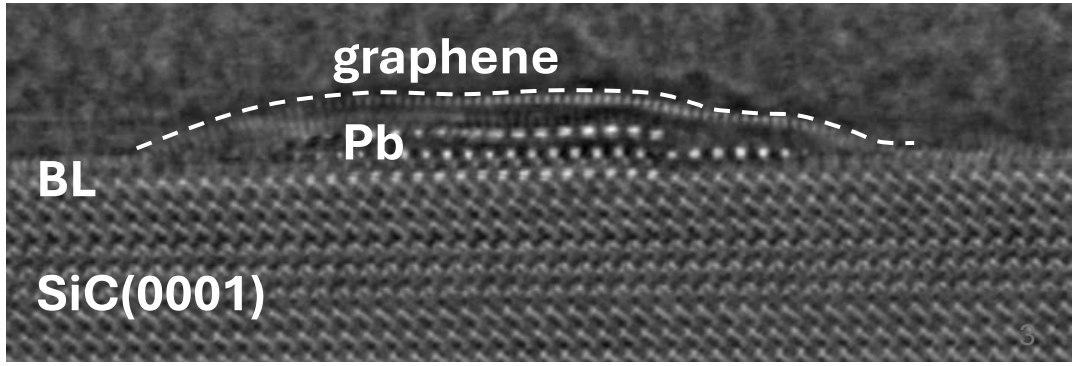
N. Nair et la, Nano Lett. 2017

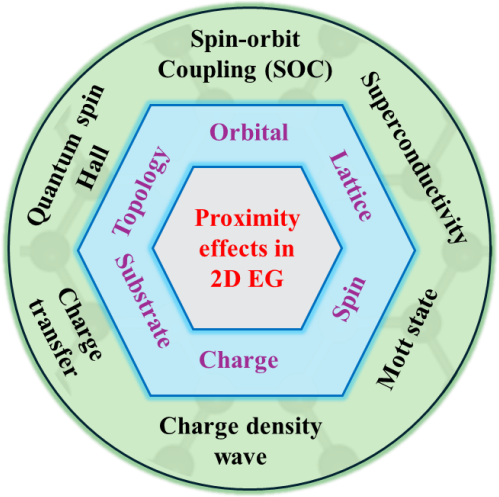


M. Rutter et al, PRB, 2007

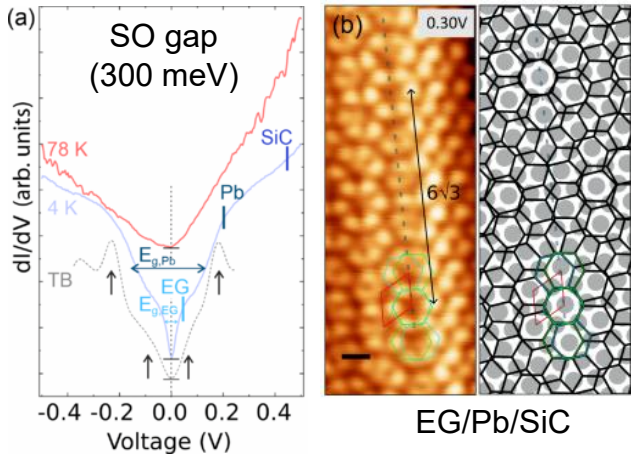
Band gap: ≥400 meV

Quasi-free-standing monolayer graphene (QFSMLG)





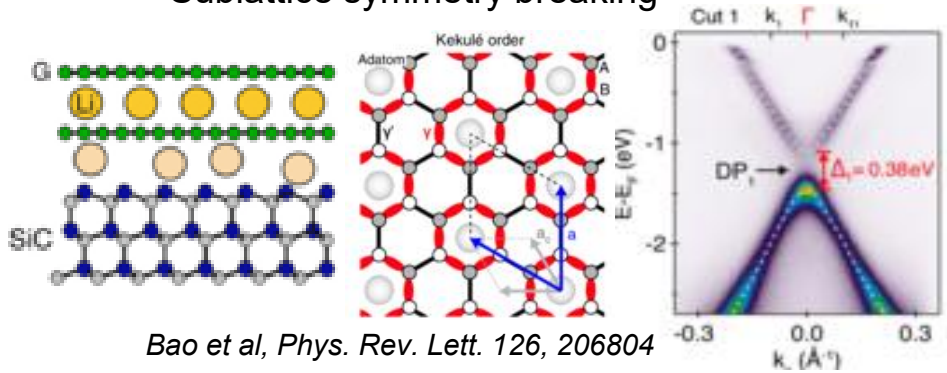
Spin-orbit coupling (SOC) enhancement



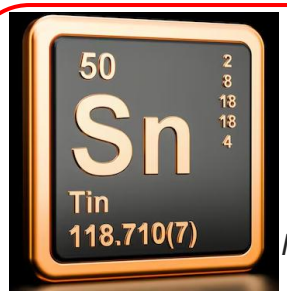
EG/Pb/SiC

Ghosal et al, PRL, 2022

Sublattice symmetry breaking



Bao et al, Phys. Rev. Lett. 126, 206804

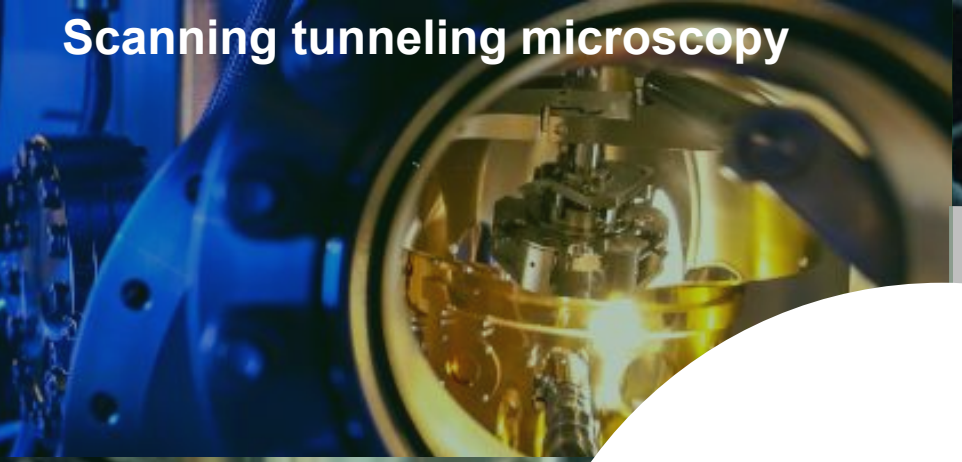


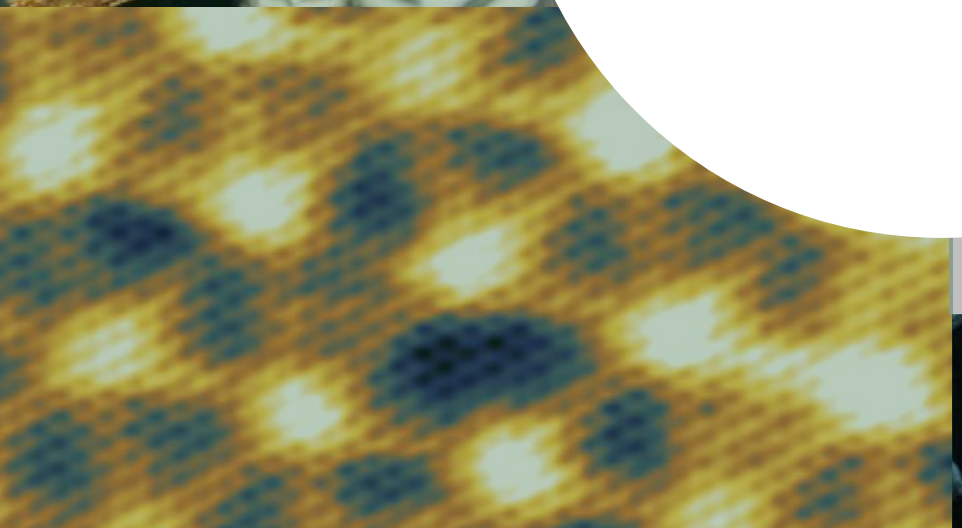
SOC: 72-461 meV

QSH effect (stanene)

Nat Rev Phys **7**, 255–269 (2025).

Novel electronic & Structural properties?





Content

01 **Sn intercalation-driven metal-insulator transition in epitaxial graphene**

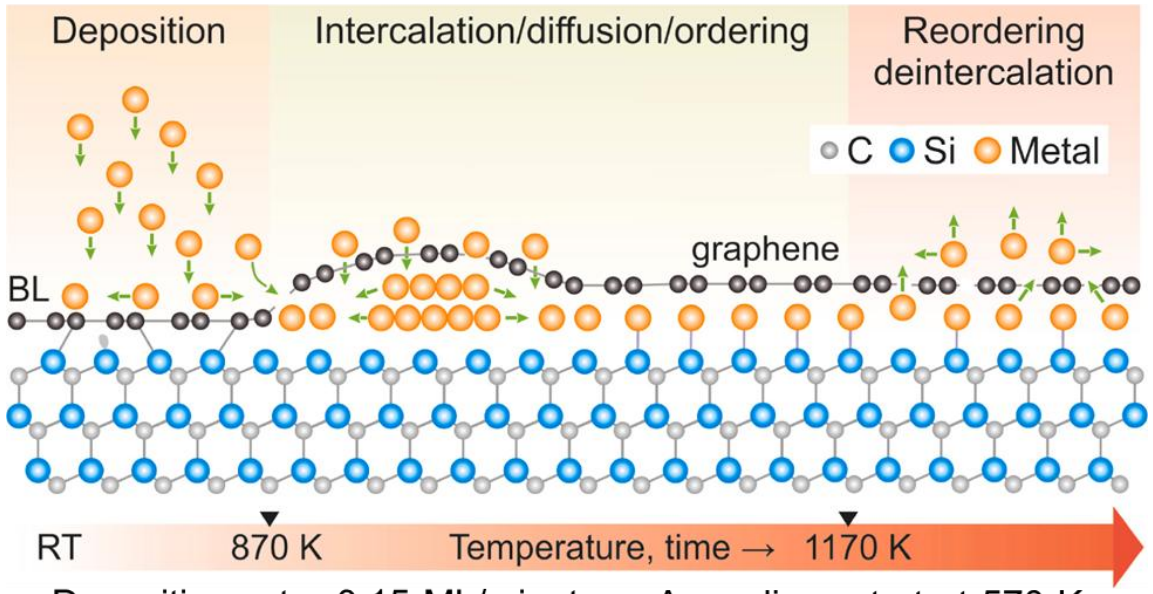
Keywords: Scanning tunneling microscopy/spectroscopy (STM/STS), Low Energy Electron Diffraction, Kekulé-graphene, sublattice symmetry breaking, gap opening, charge-neutral graphene, buffer layer (BL), quasi-free-standing monolayer graphene (QFSMGL)

02 **Mott states proximitized to a relativistic electron gas in epitaxial graphene**

Keywords: $(\sqrt{3}\times\sqrt{3})\mathrm{Sn}$, proximity effects, Mott insulating states, STM/STS, electron energy loss spectroscopy (EELS), pair correlation function (PCF), Dynamical mean-field theory (DMFT) calculations,

1. Sn intercalation-driven metal-insulator transition in epitaxial graphene

Sn(1x1) intercalation into the buffer layer/SiC interface



Deposition rate: 0.15 ML/minute Annealing: start at 570 K

"S": first-order diffraction spots of SiC(1x1)

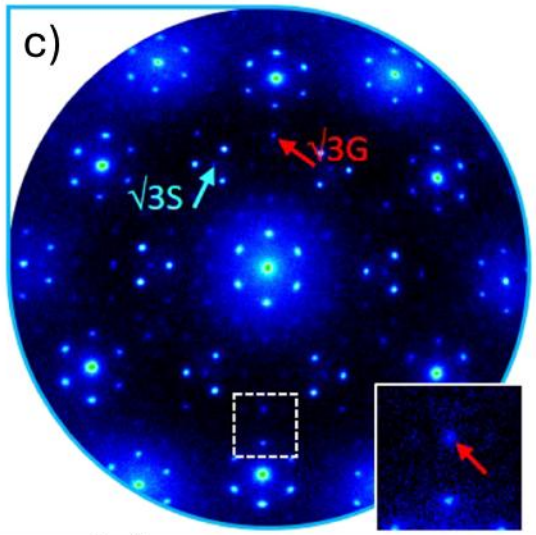
"G": first-order diffraction spots of EG (1x1)

"$\sqrt{3}G$": superlattice of graphene (a = 4.25 Å)

At 1120 K: Quasi-free-standing MLG

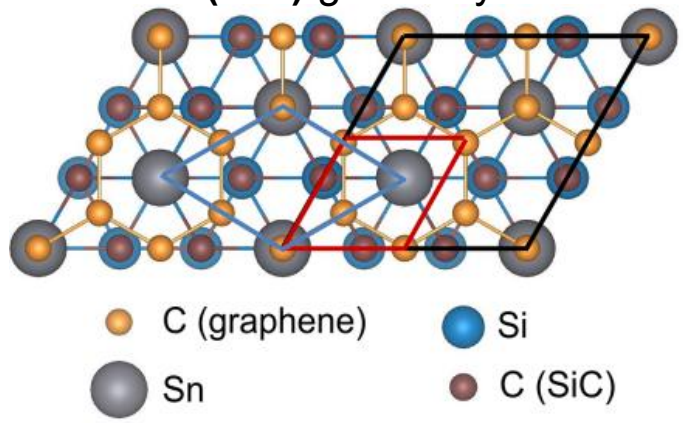
At 1320 K: $(\sqrt{3} \times \sqrt{3}G)R30$ wrt Graphene

Spot Profile Analysis Low Energy Electron Diffraction (SPA-LEED)

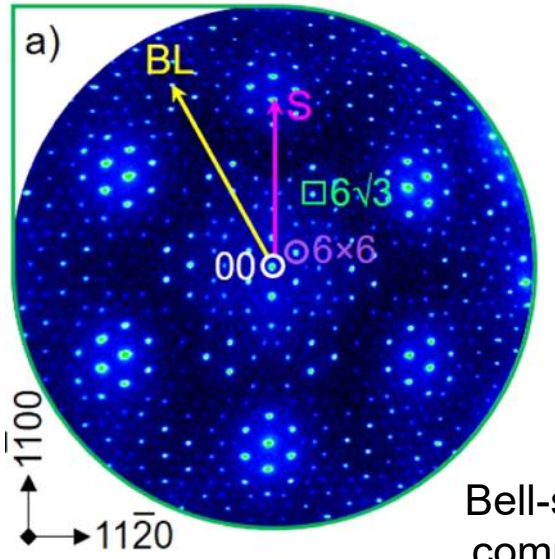


Annealing at 1320 K

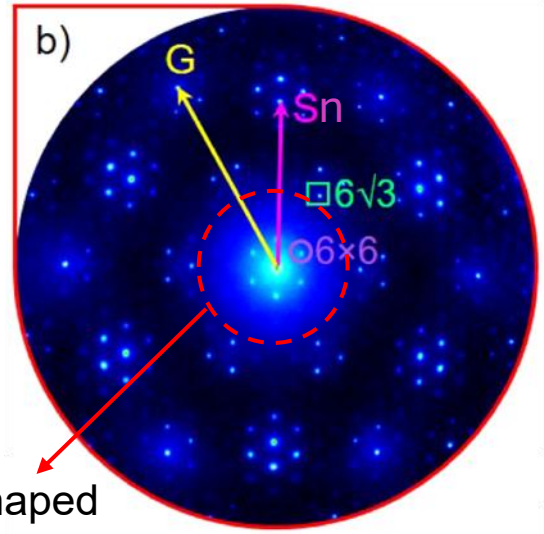
Sn(1×1) geometry on SiC



Federl et al, PRB, 111, 125158 (2025)



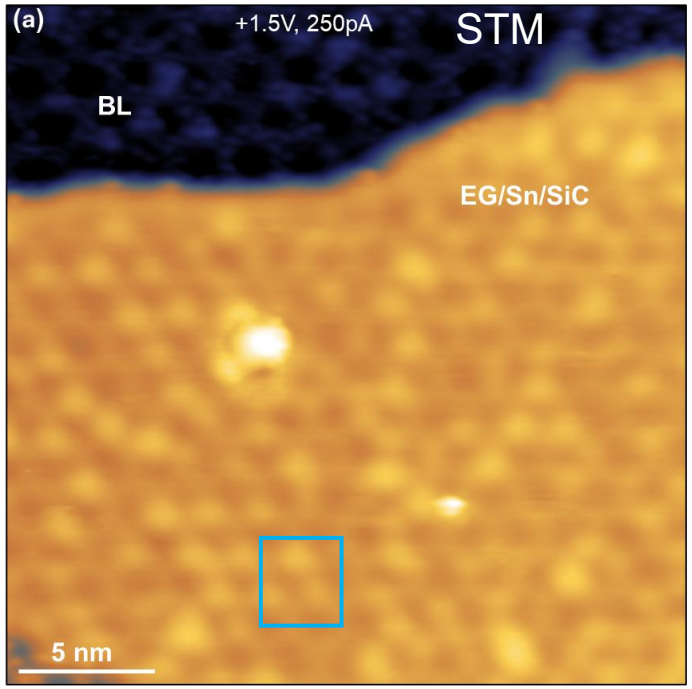
Buffer layer

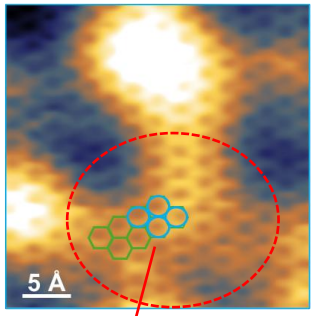


Bell-shaped component

After Sn(1x1) intercalation at 1120 K

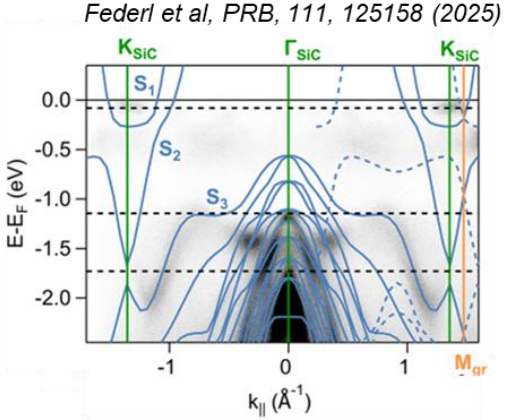
Scanning tunneling microscopy/spectroscopy (STM/STS) at 4.5 K





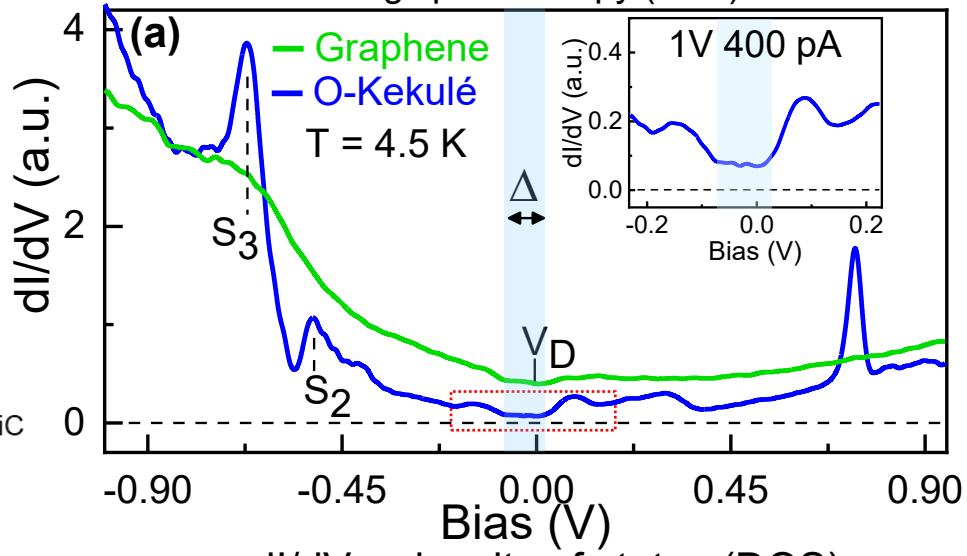
Kekulé-distorted graphene

Federl et al, PRB, 111, 125158 (2025)

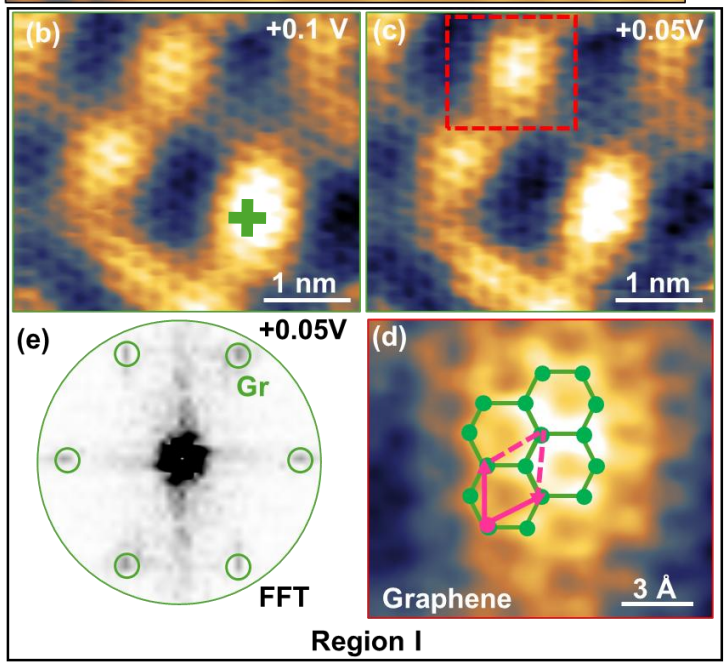


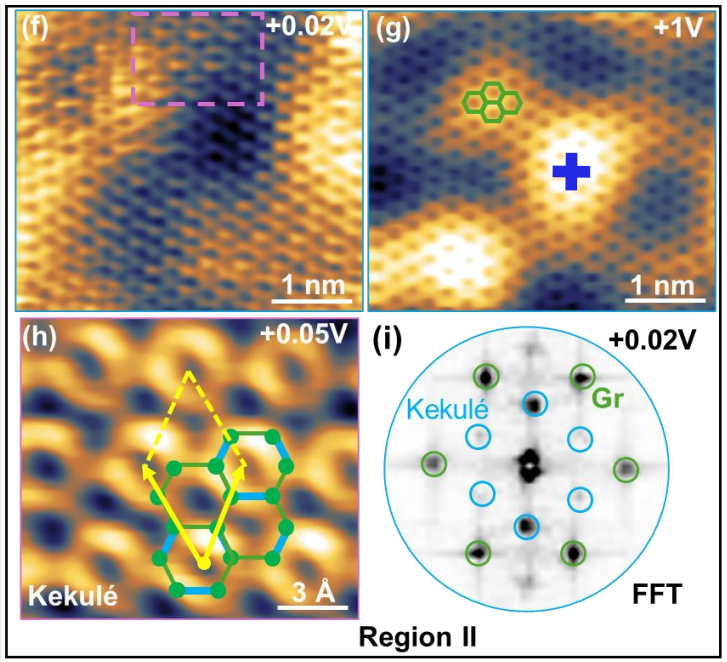
ARPES+DFT calculation for Sn (1x1)/SiC

Tunneling spectroscopy (STS)



dI/dV = density of states (DOS)





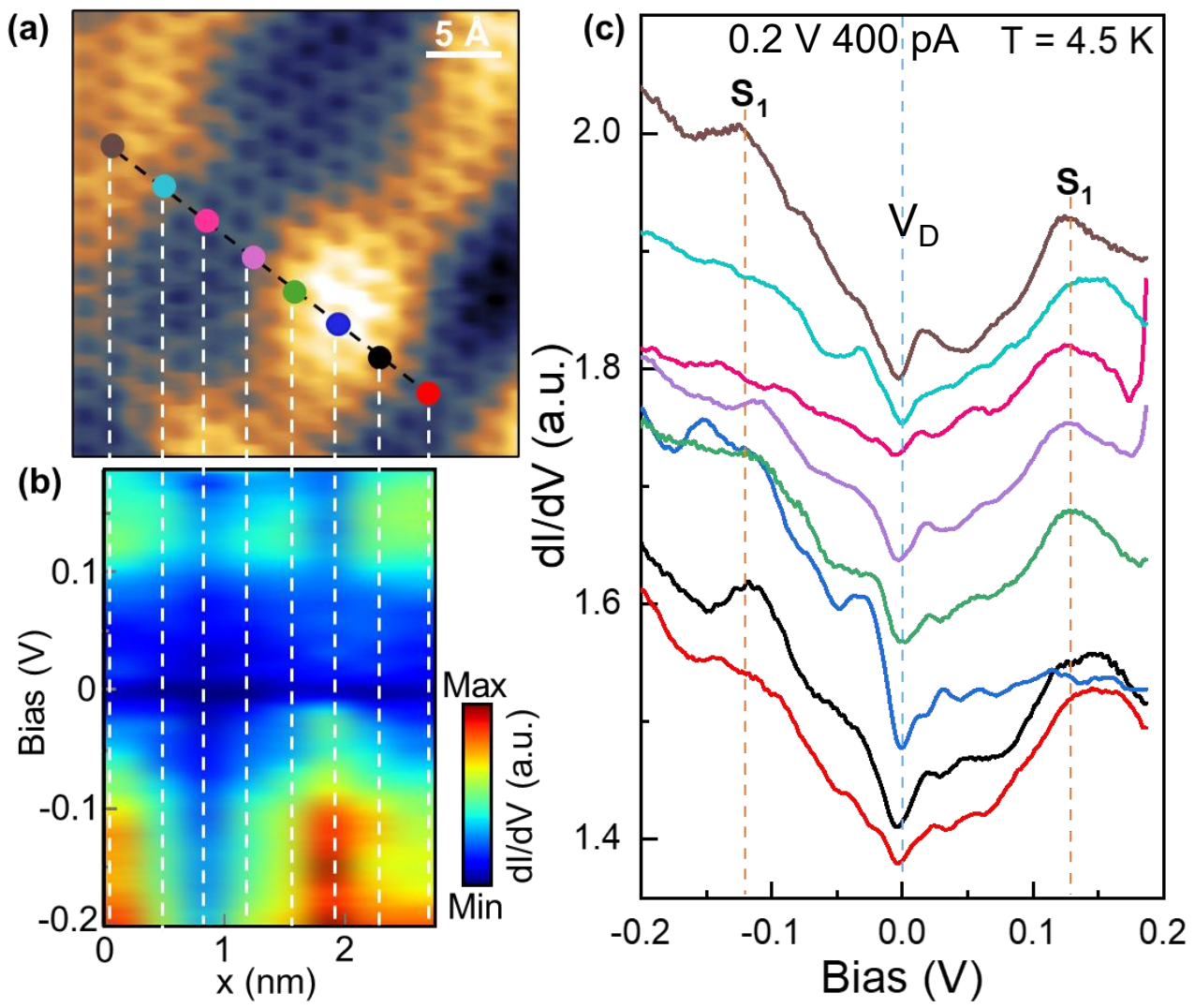
- Linear band dispersion (R1)
- DOS > 0➔ Metallic Sn (1x1) phase (RI)
- Gap opening at the DP (Kekulé-O)

Hidden Sn states hint at hybridization with graphene

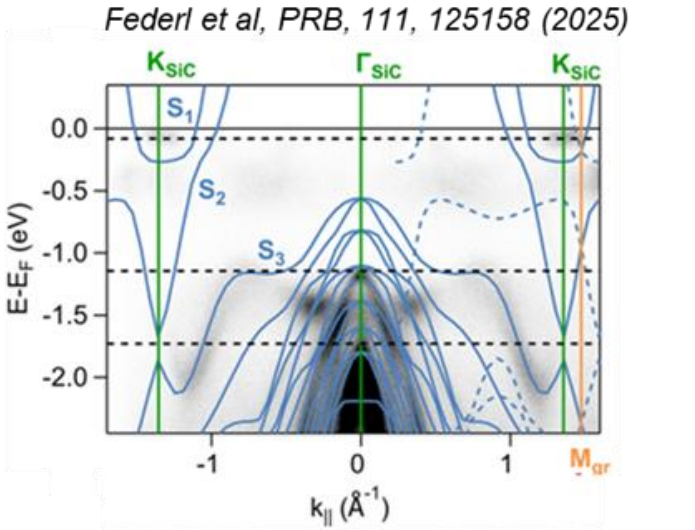
- Kekulé-lattice = 4.25 Å = $\sqrt{3}\times a_{Gr}$
- RII: Kekulé-O graphene (+0.02 V)
- RI: graphene + bubble-like features

Sn intercalant-induced charge-neutral graphene probed by STS

Region I: Sn-intercalated buffer layer (no Kekulé)



dI/dV = density of states (DOS)
V_D : Dirac point voltage



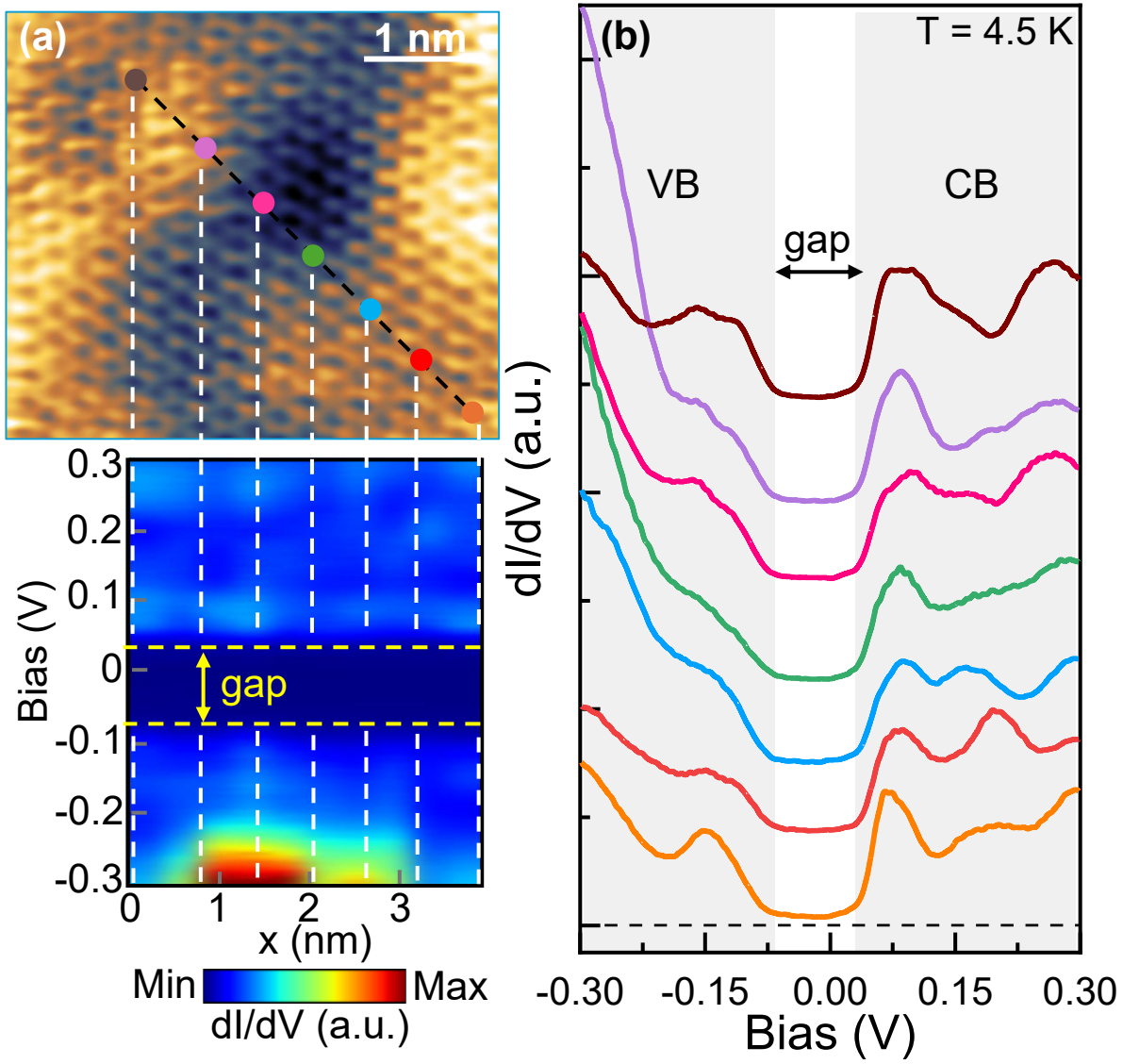
ARPES+DFT calculation for Sn (1x1)/SiC

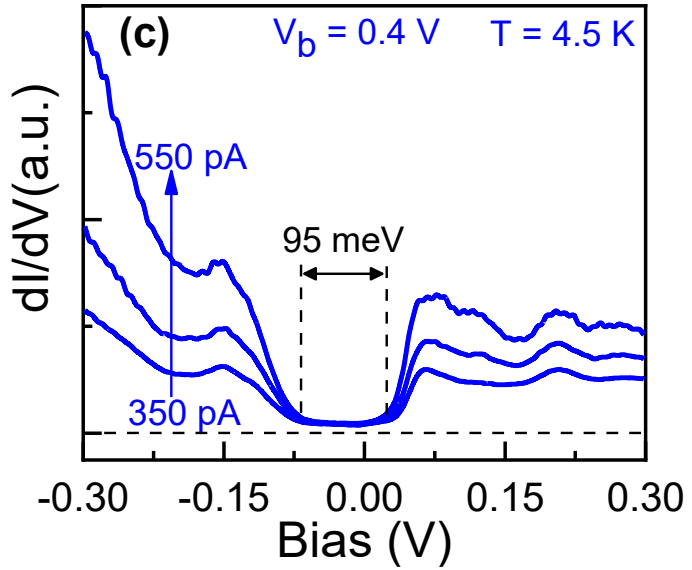
- Charge-neutral graphene (V_D at 0V)
- DOS > 0 ➔ Metallic Sn(1x1) phase
- Peaks at ±0.12 V (S_1 band of Sn layer)

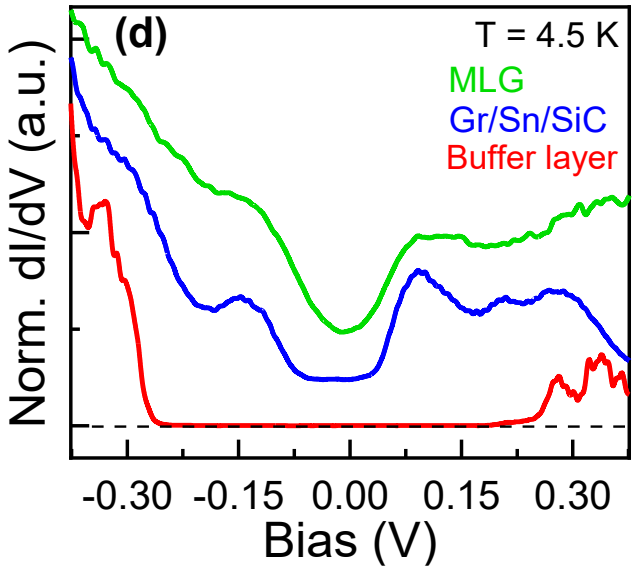
Charge-neutral graphene

Electronic band structure of Kekulé-O graphene probed by STS

Region II: Sn-intercalated buffer layer with Kekulé-O graphene





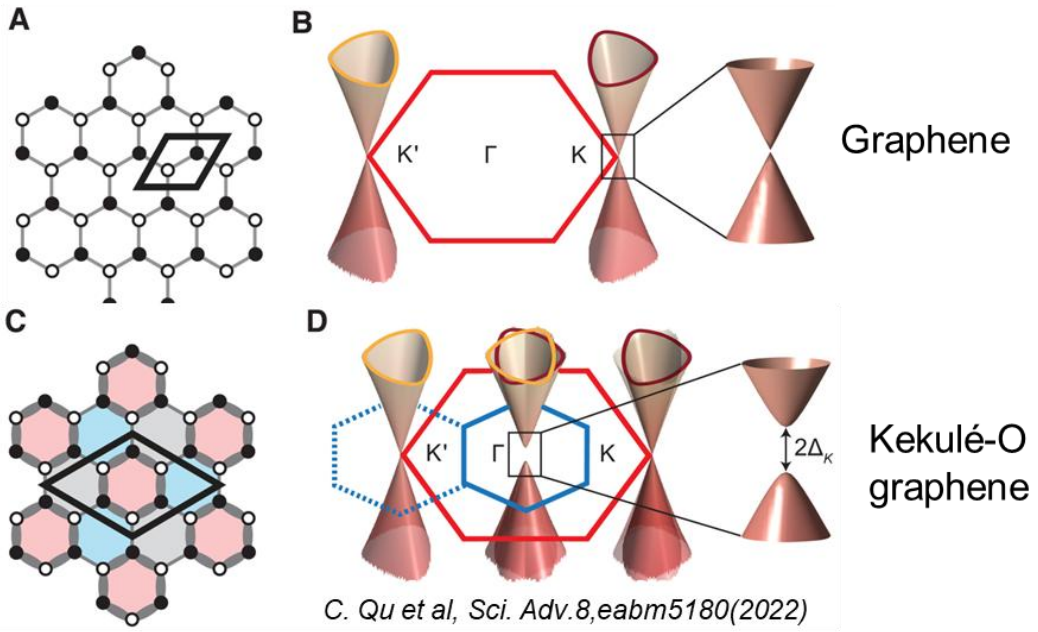


- An apparent gap of 95 meV
- Stable electronic states
- MLG: phonon gap (40 meV)
- BL gap of 600 meV

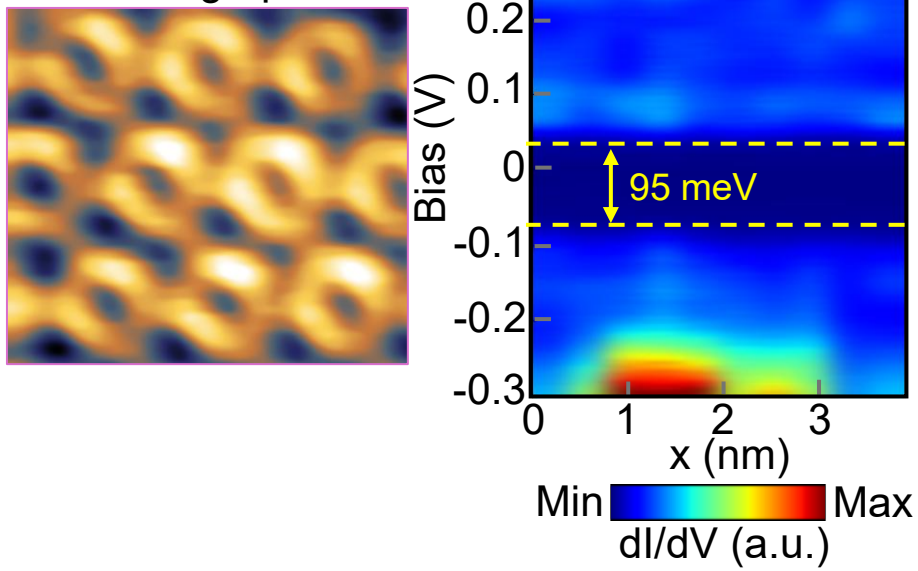
Sn intercalant-induced sublattice symmetry breaking

dI/dV = density of states (DOS)

Energy gap opening in Kekulé-O graphene (Theory)



Kekulé-O graphene



- The energy bands of the Hamiltonian (graphene, K point)

$$\boldsymbol{E(\mathbf{k}) = \pm\hbar\vartheta_F\left|\vec{k}\right|}$$

sublattice symmetry breaking

- Fold K, K' into the Γ point in the Brillouin zone (kekulé-O)

$$\boldsymbol{E(\mathbf{k}) = \pm\sqrt{(\hbar\vartheta_F\left|\vec{k}\right|)^2 + \Delta^2}}$$ → mass term

$$\Rightarrow \boldsymbol{E_{gap} = 2|\Delta|}$$

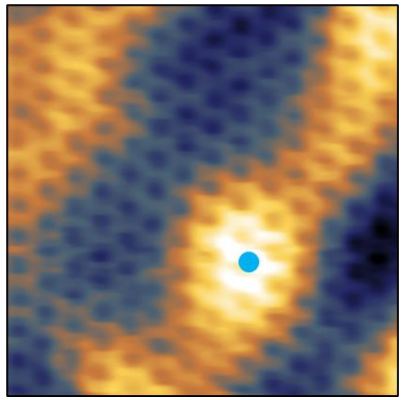
Effective mass of electrons: $m = e^{i\frac{2\pi}{3}}\Delta/(\vartheta_F)^2$

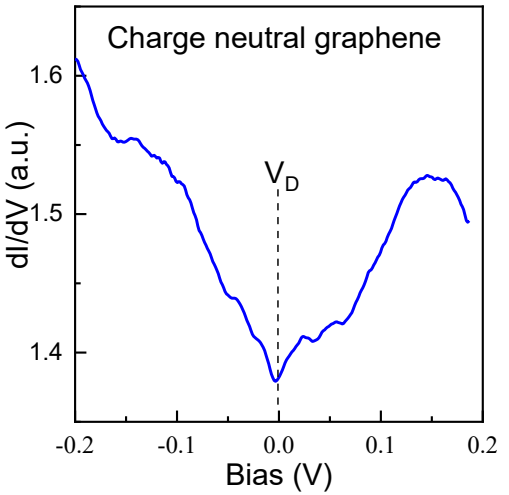
Galván y García et al, Nano Lett. 2024, 24, 7, 2322–2327

Proximity-induced electronic states in epitaxial graphene/SiC (0001) via Tin intercalation

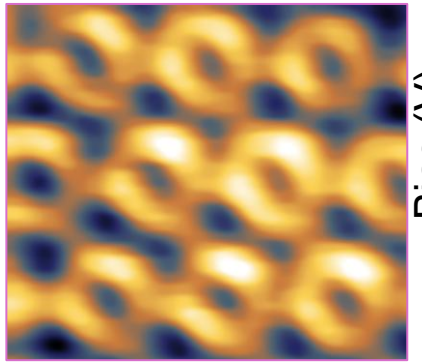
❑ Intercalation of Sn into the buffer layer/SiC interface

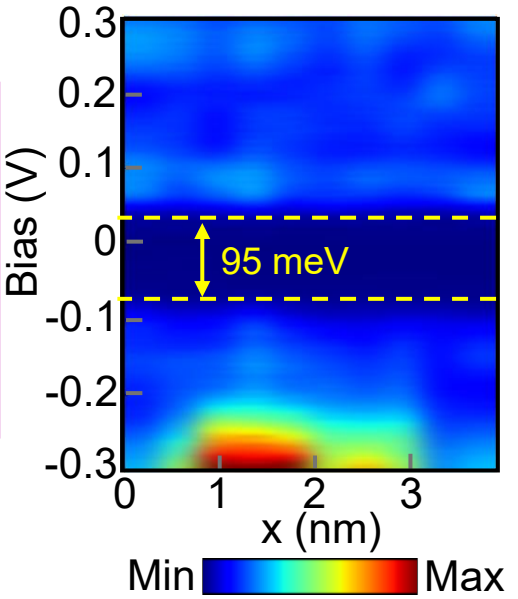
- Buffer layer is transformed into charge-neutral graphene via the effective charge transfer from Sn intercalants
- Sn(1x1) phase causes the instability of graphene, forming Kekulé-O graphene
- An energy gap (95 meV) opening in Kekulé-O graphene





Kekulé-O graphene





Acknowledgement

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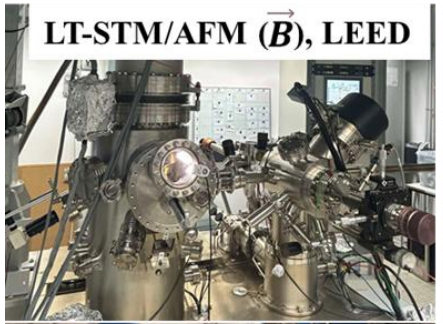

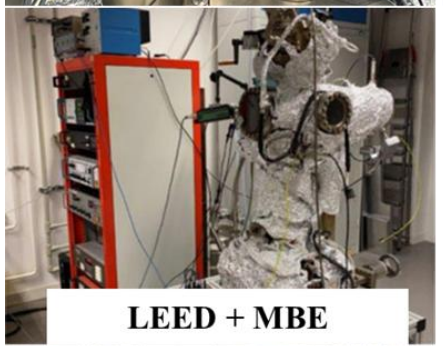

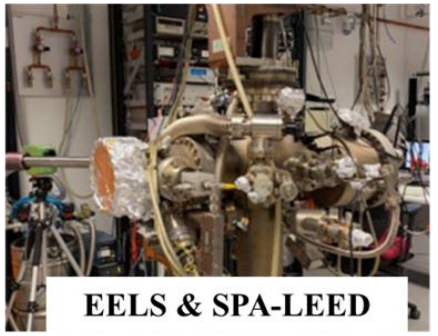

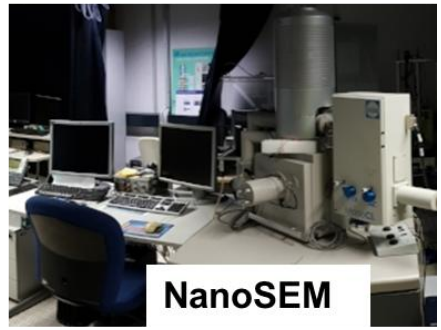

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