EP2.6.03

Correlation between morphology and transport properties of quasi-free-standing monolayer graphene (QFMLG)

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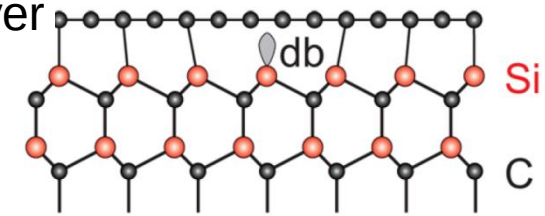
National Enterprise for nanoScience and nanoTechnology

NEST

Introduction

Graphene on silicon carbide (SiC) (0001)

buffer layer

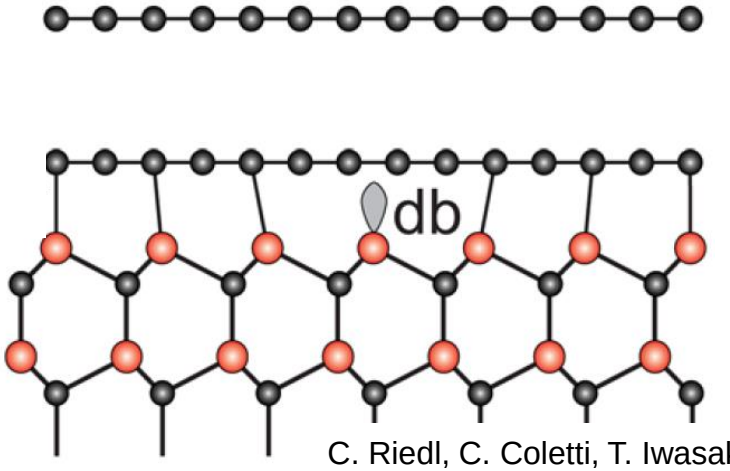


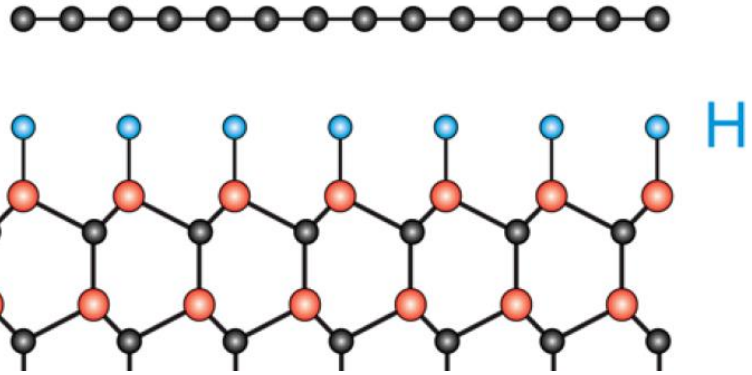
annealing

epitaxial monolayer graphene (EMLG)

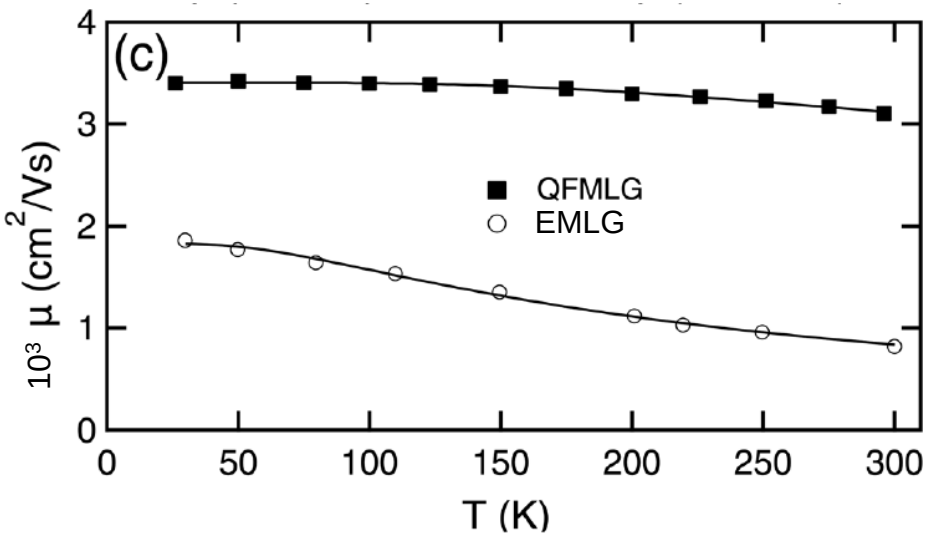
H intercalation

quasi-free-standing monolayer graphene (QFMLG)





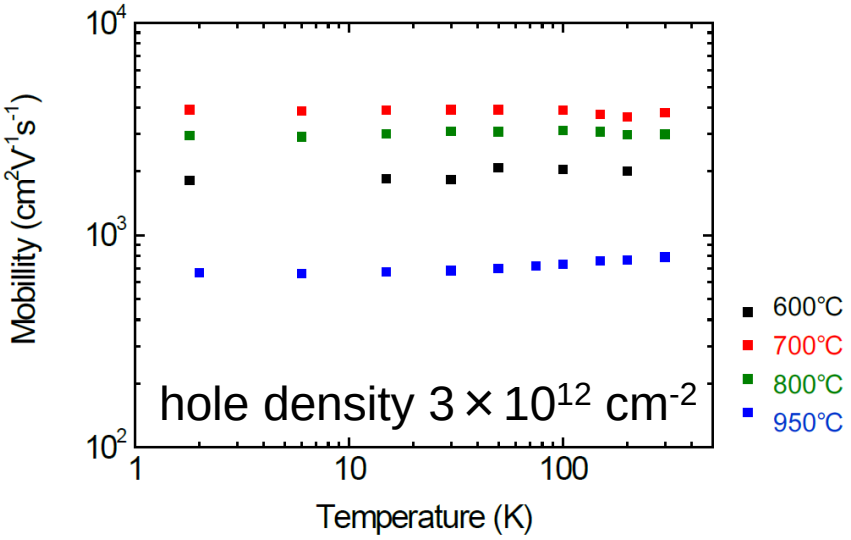
C. Riedl, C. Coletti, T. Iwasaki, A. A. Zakharov, and U. Starke, Phys. Rev. Lett. **103**, 246804 (2009)



Carrier mobility of QFMLG: less temperature dependence
less interaction between QFMLG and SiC substrate

However, mobility of QFMLG (-3000 $cm^2V^{-1}s^{-1}$) is lower than exfoliated graphene on SiO_2 or free standing graphene.

F. Speck, J.Jobst, F. Fromm, M. Ostler, D. Waldmann, M. Hundhausen, H. B. Weber, and Th. Seyller, Appl. Phys. Lett. **99**, 122106 (2011)



S. Tanabe, M. Takamura, Y. Harada, H. Kageshima, and H. Hibino, Jpn. J. Appl. Phys. **53**, 04EN01 (2014).

- QFMLG mobility depends on T_H

  T_H: temperature of substrate during H intercalation

- highest mobility by T_H = 700ºC

Purpose :
relationship between the morphology and transport property of QFMLG formed at different T_H

Experiment

sample: 4H or 6H-SiC(0001)

cleaning anneal at 1500ºC for 5 min in H_2 of 33 mbar

buffer layer growth

anneal at 1650ºC for 5 min in Ar of 800 mbar

H intercalation

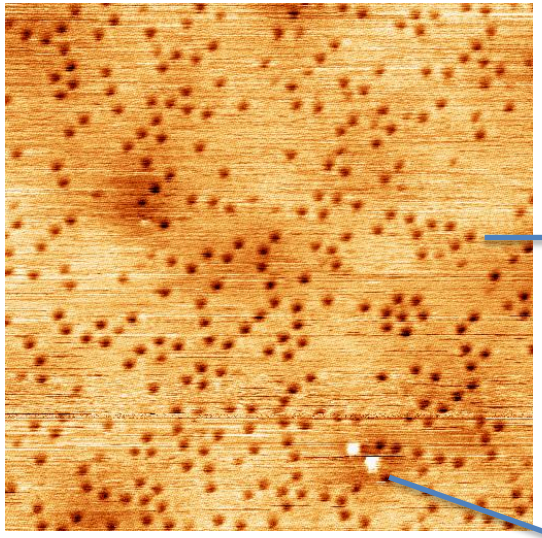
anneal at **600 - 1200ºC** for 1 hour in H_2 of 1013 mbar

characterization

- STM at RT and 6K in ultra-high vacuum (1×10^{-10} mbar)
- AFM
- TEM

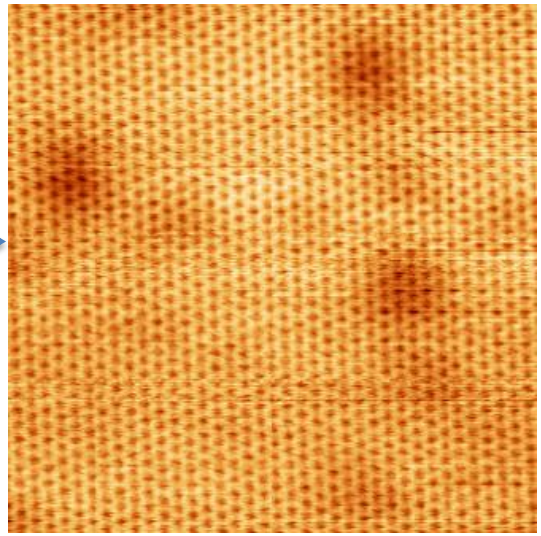
STM on QFMLG at RT

T_H = 800ºC sample



50 nm

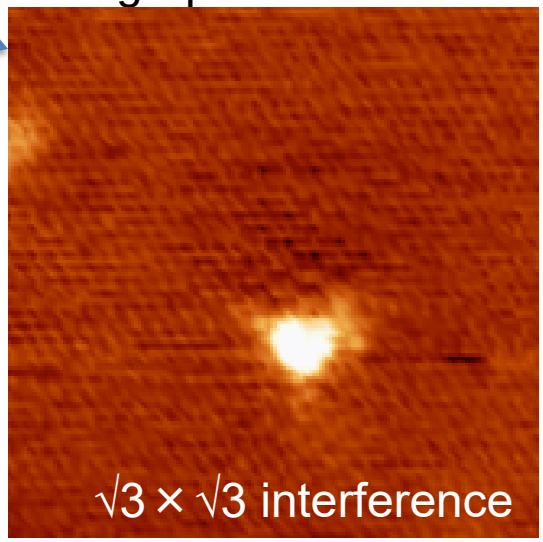
- dark site



width: 1.5 nm
depth: 20 pm

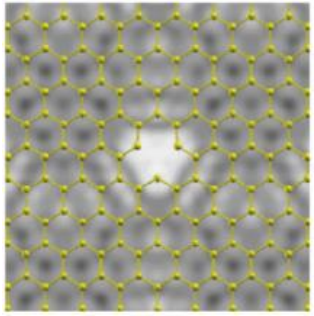
8 nm

- graphene defect



8 nm

simulated STM of defect



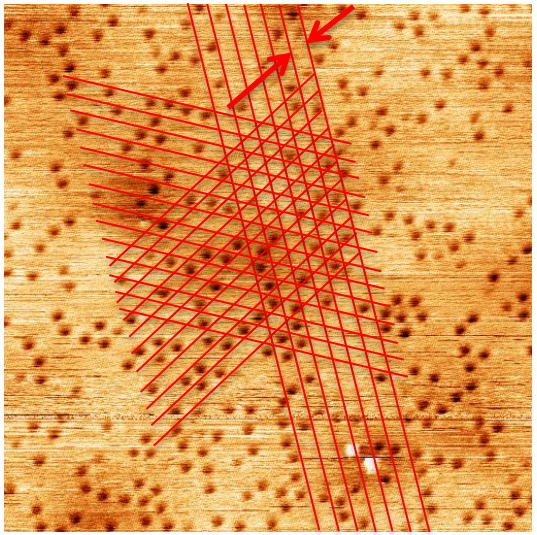
Rhim, Appl. Phys. Lett. **100**, 233119 (2012)

Murata, Appl. Phys. Lett. 105, 221604 (2014)

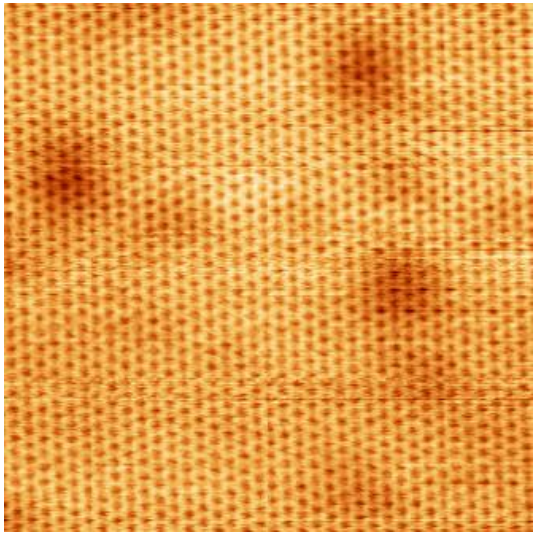
Si dangling bonds

<11$\bar{2}$0> directions
1.8 nm spacing

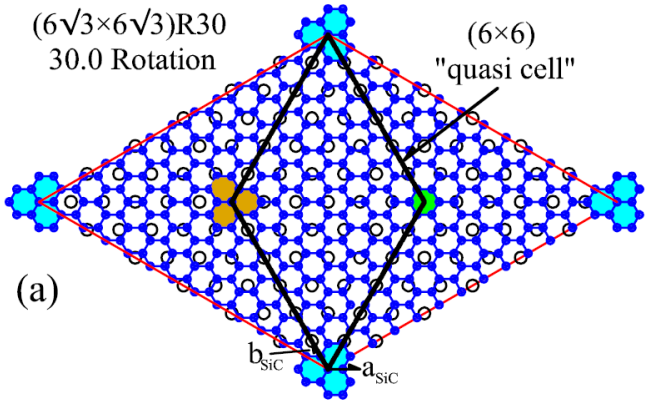
~ SiC 6 × 6 cell ~ moiré periodicity



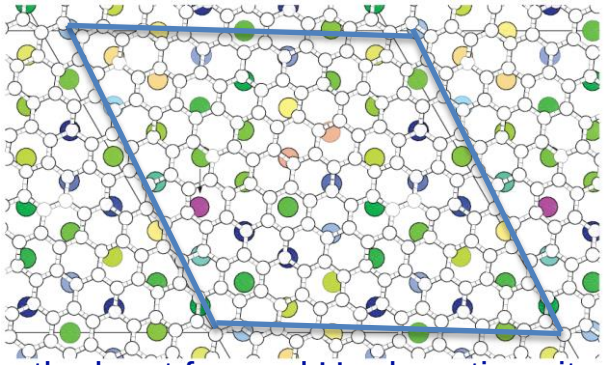
50 nm



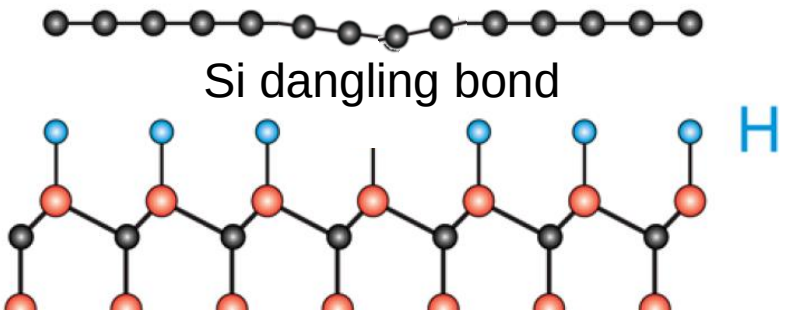
8 nm



spatial distribution of hydrogenation energy (4√3 × 4√3 model)



dark blue: the least favored H adsorption site

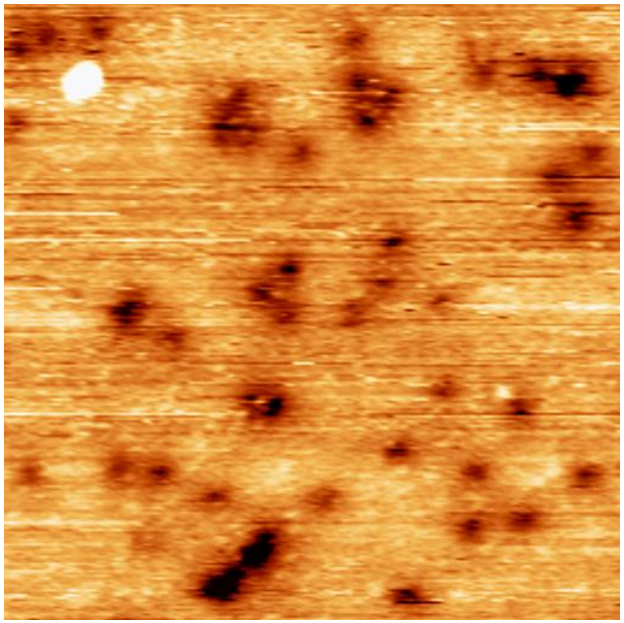


Murata, Appl. Phys. Lett. 105, 221604 (2014)

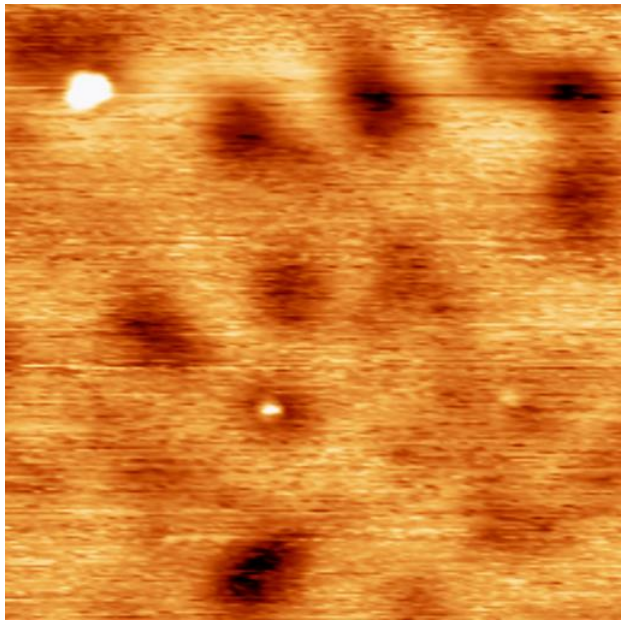
G. Sclauzero, A. Pasquarelo, Appl. Surf. Sci. 291, 64 (2014).

Si dangling bonds

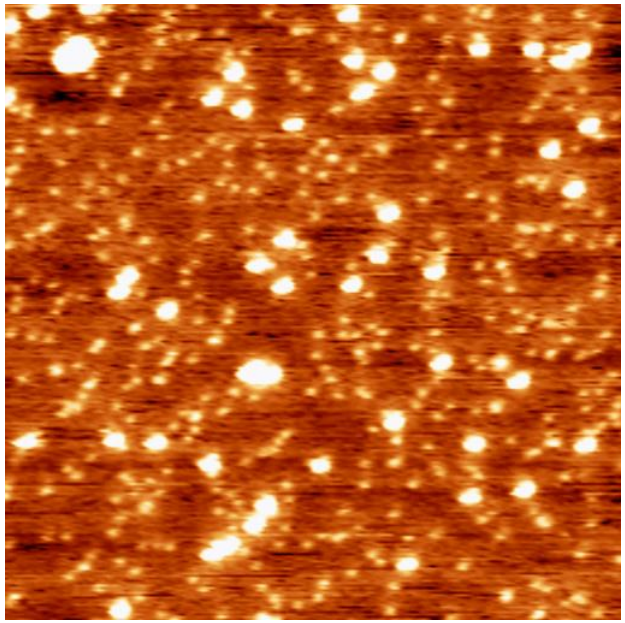
Vs = -1.5V 0.1nA



-0.1V



1.5V

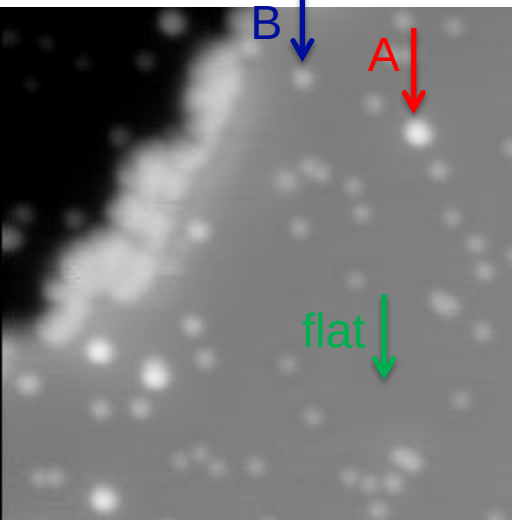


50nm

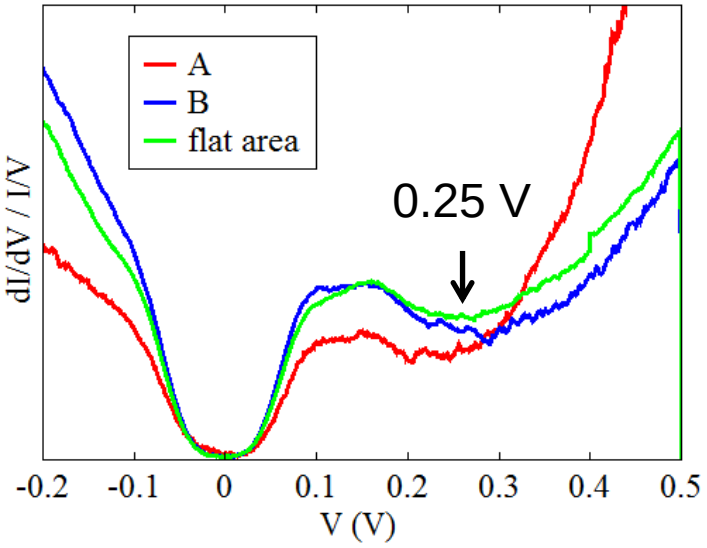
- contrast changes with Vs – electronic effect
- 2 different contrasts at 1.5V

Si dangling bonds

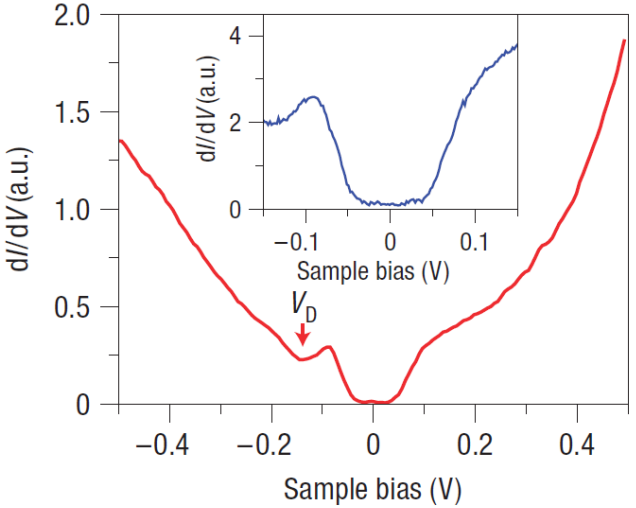
STM and STS at 6K



1.8V, 0.01nA, 20 nm



STS on G/SiO_2



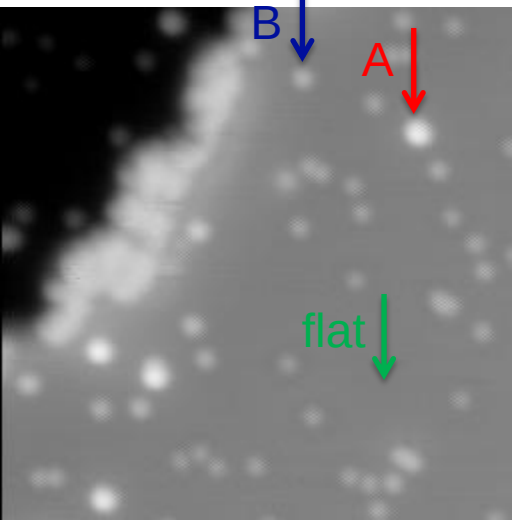
Y. Zhang, V. W. Brar, F. Wang, C. Girit, Y. Yayon, M. Panlasigui, A. Zettl, and M. F. Crommie, Nat. Phys. 4, 627 (2008).

- p doping of graphene with shift of Dirac point by 0.25 V
- consistent with other measurements on QFMLG (ARPES, STS, Hall)
- spontaneous polarization of polar surface on SiC substrate

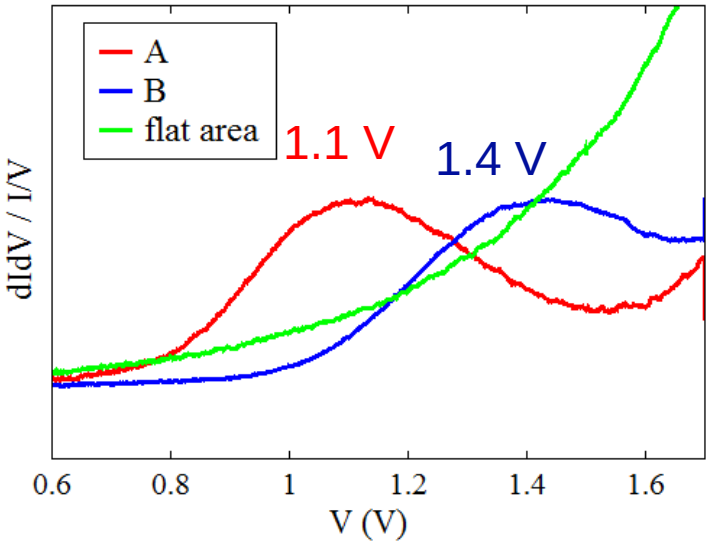
Ristein, Mammadov, Seyller, PRL, 108, 246104 (2012)

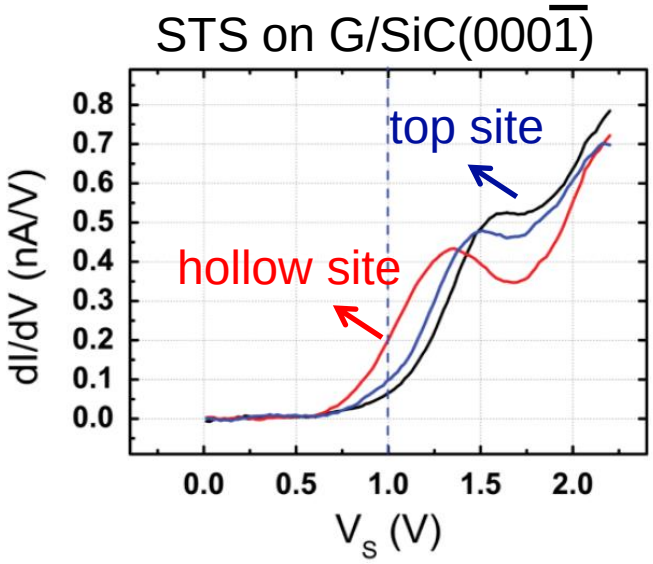
Si dangling bonds

STM and STS at 6K



1.8V, 0.01nA, 20 nm

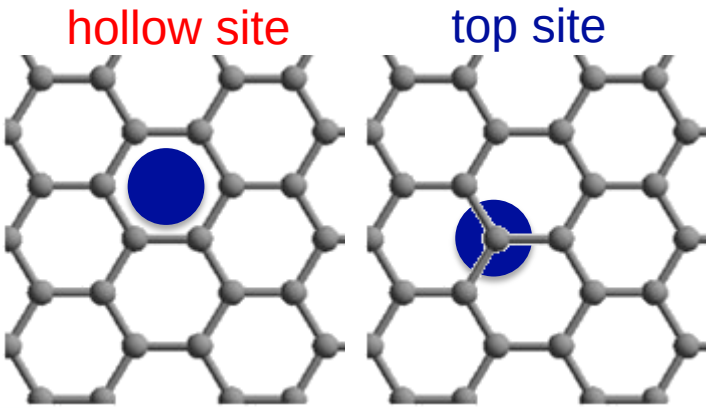




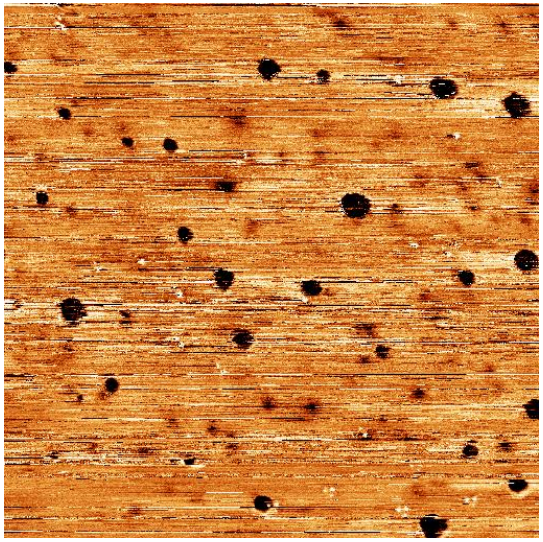
F. Hiebel, P. Mallet, J.-Y. Veuillen, and L. Magaud, Phys. Rev. B 86, 205421 (2012).

- 2 types of Si dangling bonds at different graphene / Si stacking configurations

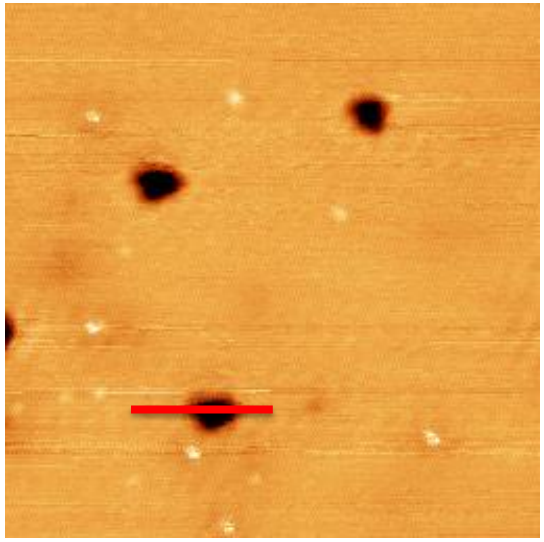
>>> DFT calculation of the electronic states in progress



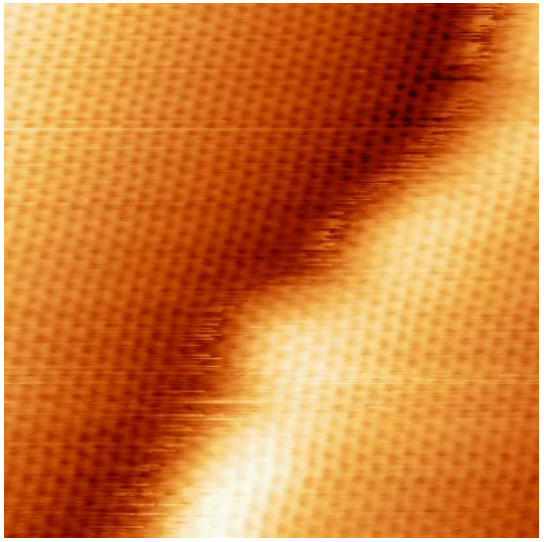
SiC holes: T_H = 1000ºC



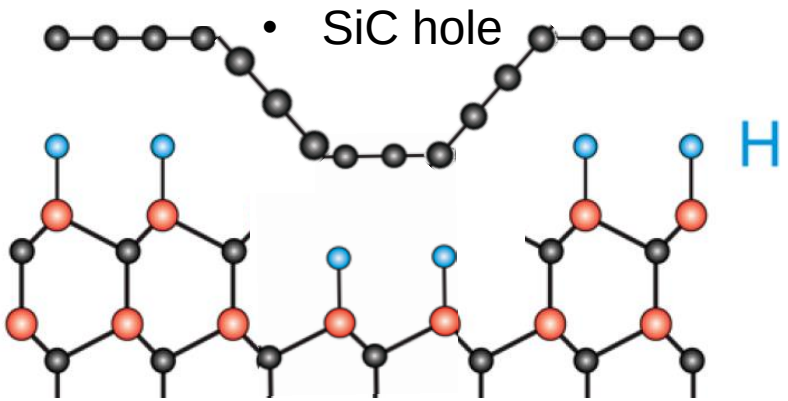
200 nm



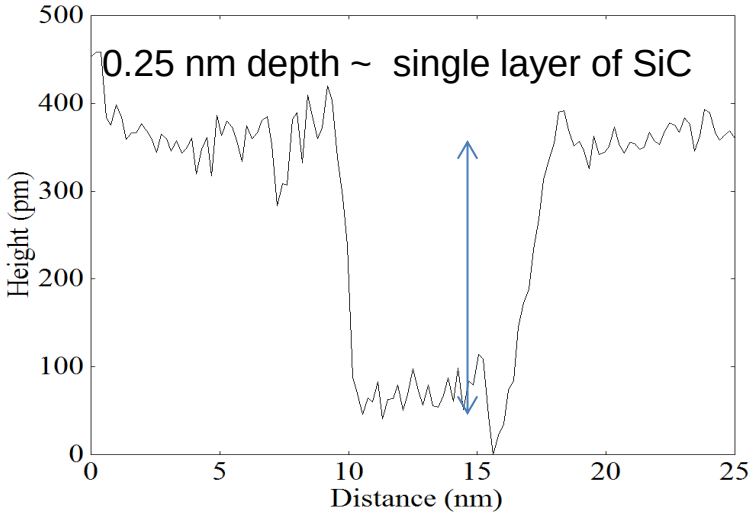
50 nm



8 nm



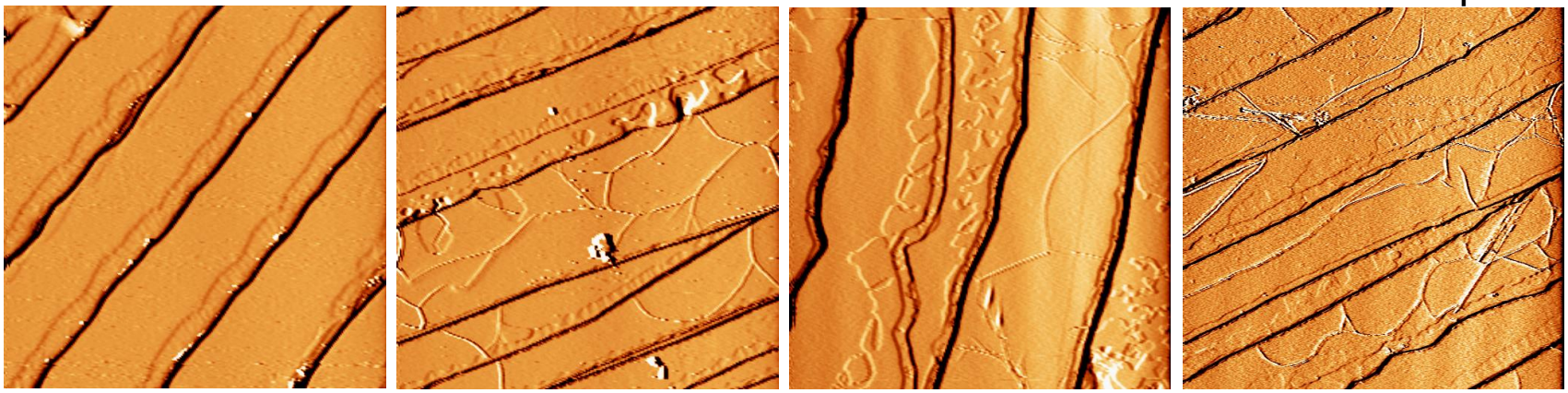
Murata, Appl. Phys. Lett. 105, 221604 (2014)



graphene wrinkles: T_H = 1000ºC

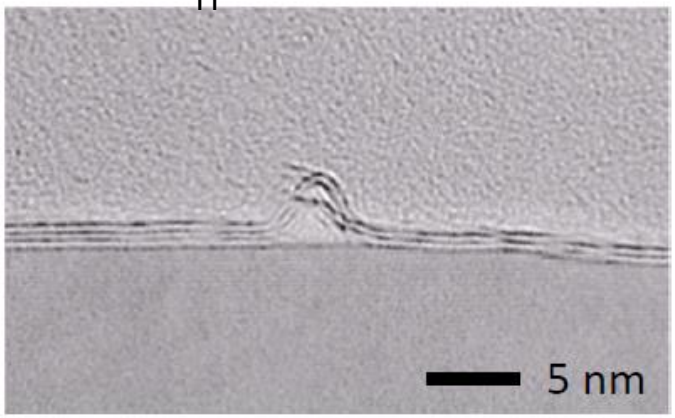
AFM

14 µm



T_H = 650ºC 800ºC 950ºC 1100ºC

TEM T_H = 1200ºC



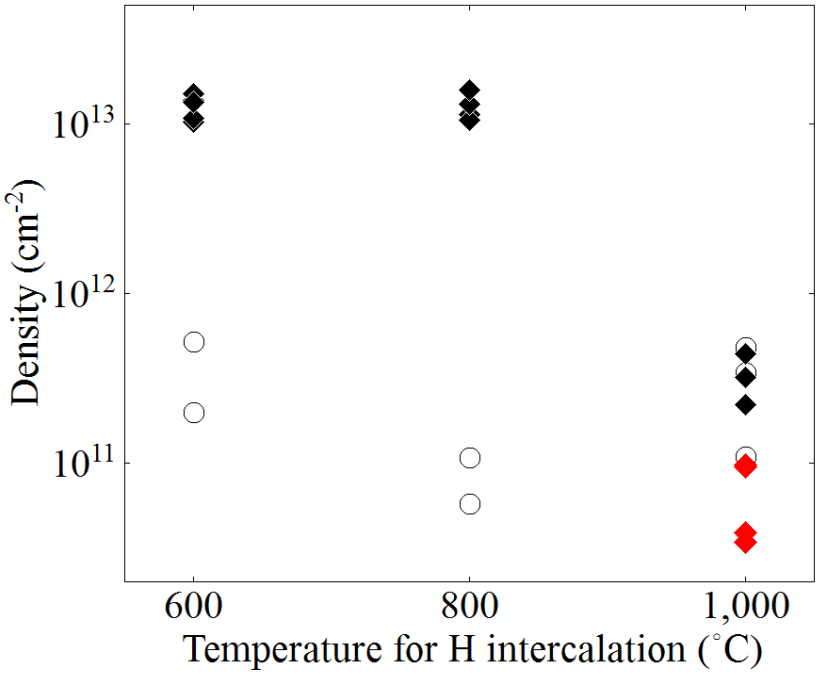
- graphene wrinkle

the difference in thermal expansion coefficients between graphene and SiC

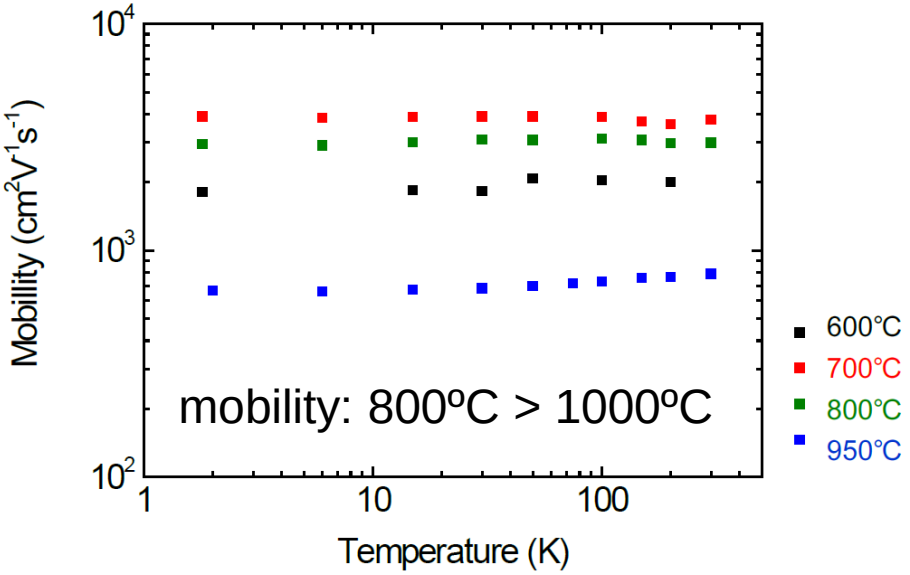
Murata, Appl. Phys. Lett. 105, 221604 (2014)

Morphology and transport

densities of features on QFMLG



mobility vs T_H



S. Tanabe, Jpn. J. Appl. Phys. **53**, 04EN01 (2014).

○ graphene defect ---------- constant with T_H • influence on mobility

◆ Si dangling bonds ---------- decrease with T_H ----- small increase

◆ SiC hole (and G wrinkle) ------- increase with T_H ----- large decrease

Murata, Appl. Phys. Lett. 105, 221604 (2014)

Conclusion

- We investigated the morphology of QFMLG formed at different temperatures for H intercalation with STM, AFM, and TEM.

- graphene defect and Si dangling bond
- additionally, SiC holes and graphene wrinkle on T_H = 1000ºC sample
- 2 Si sites with different electronic states. The difference may be attributed to different local graphene / Si stacking configurations.

- In order to obtain a high mobility QFMLG, we need to optimize H intercalation condition to intercalate more H, below the temperature at which SiC holes and graphene wrinkles appear.

Murata, Appl. Phys. Lett. 105, 221604 (2014)

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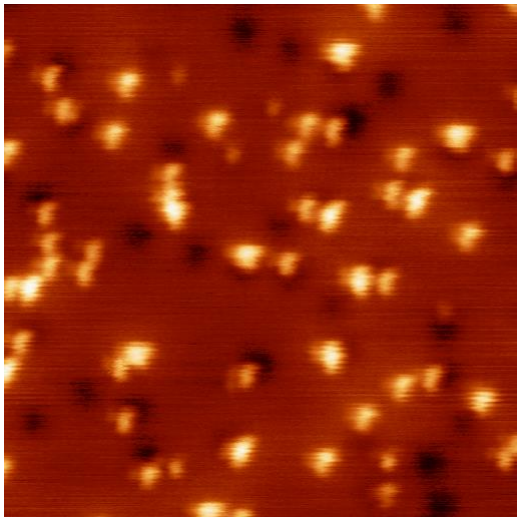
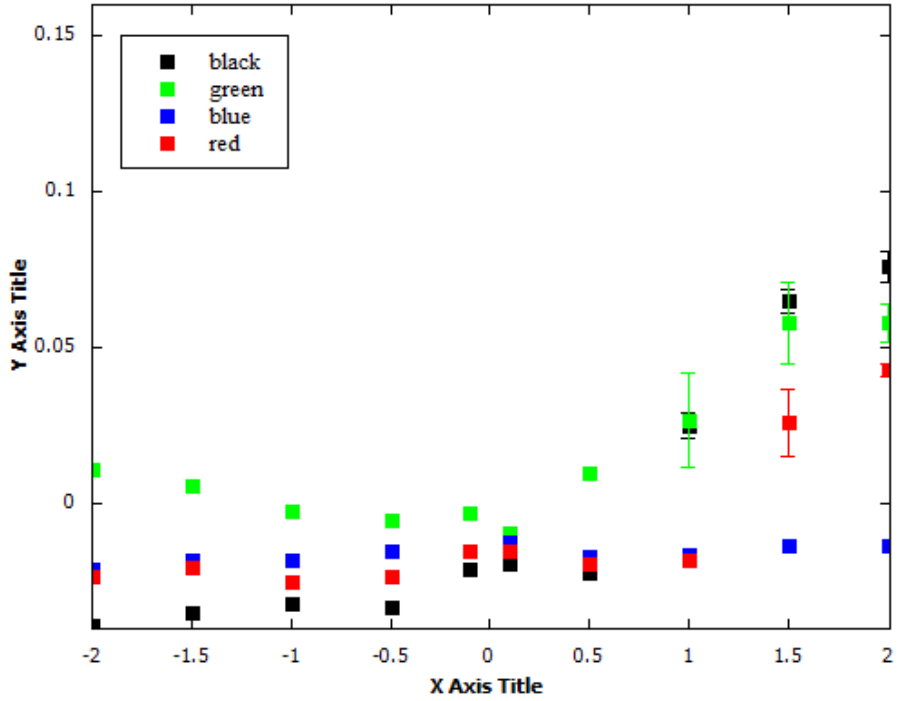
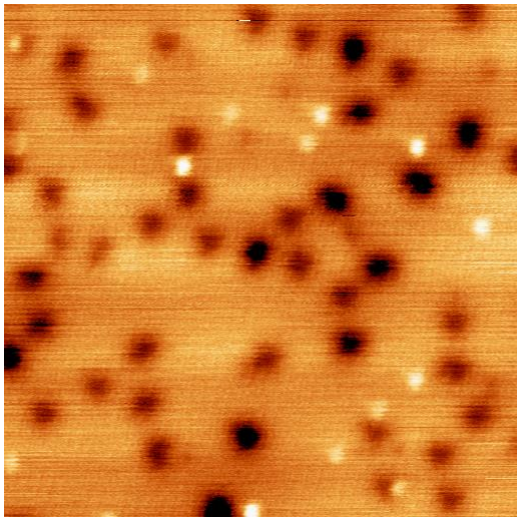
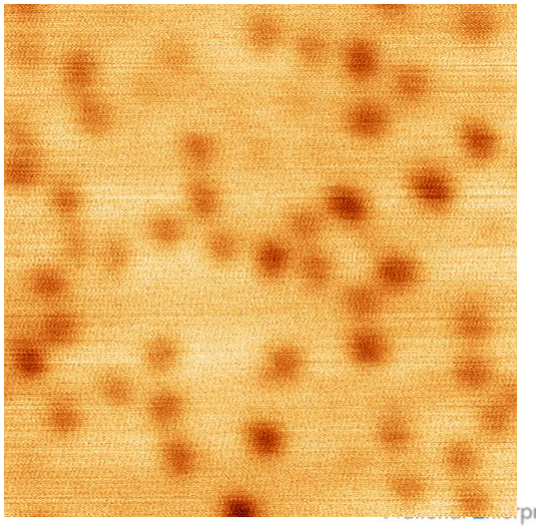


2V 0.1nA 20nm

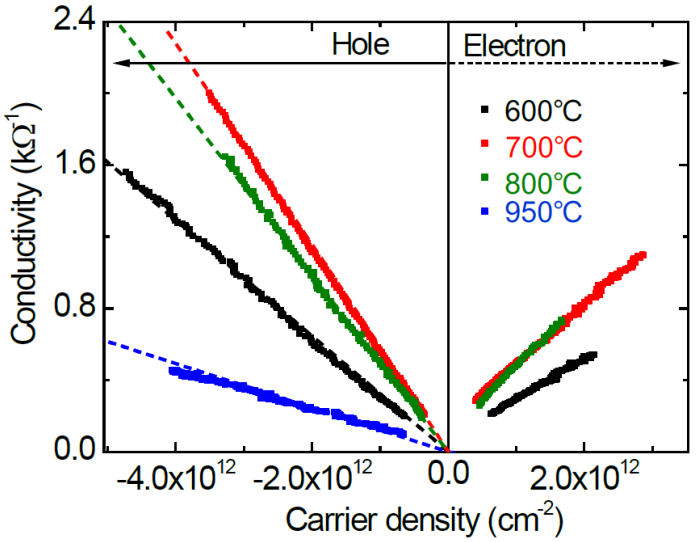




-2V 0.1nA 20nm



0.1V 0.1nA 20nm



S. Tanabe, M. Takamura, Y. Harada, H. Kageshima, and H. Hibino, Jpn. J. Appl. Phys. **53**, 04EN01 (2014).

conductivity – carrier density

- linear for T_H = 600-800ºC
  - charged impurity

- sublinear for T_H = 950ºC
  - additional scattering by defect