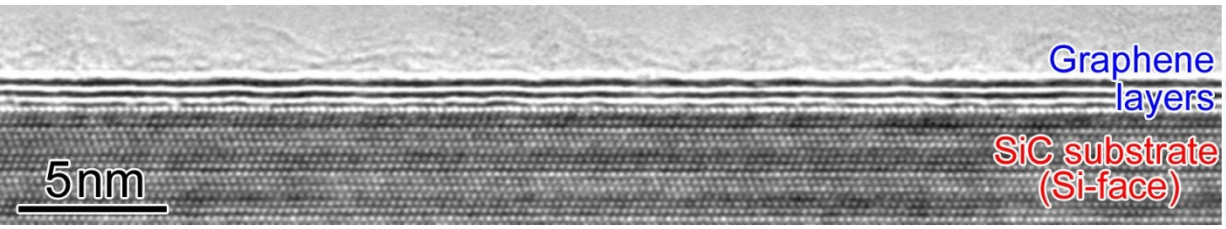
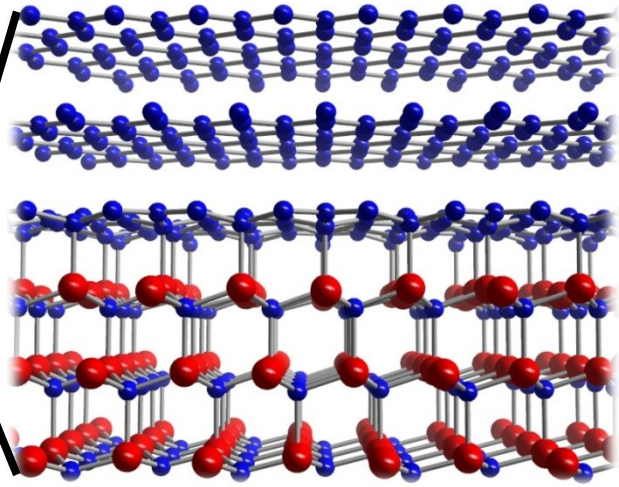
新学術領域研究「原子層科学」
合成班ミニ講演会　名古屋大学　2014.2.19

SATL 原子層科学 Science of Atomic Layers

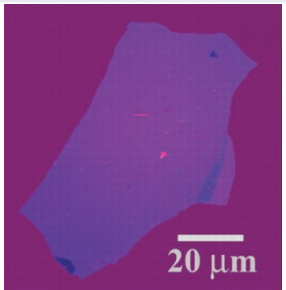
SiC表面上グラフェンの合成と評価

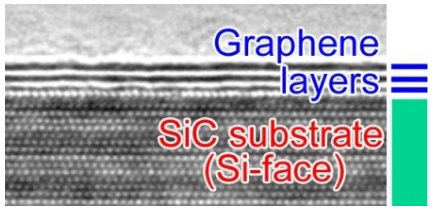


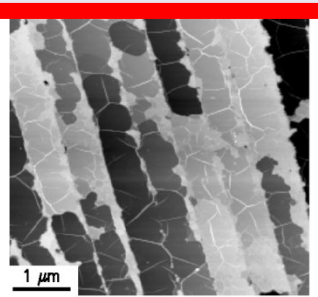


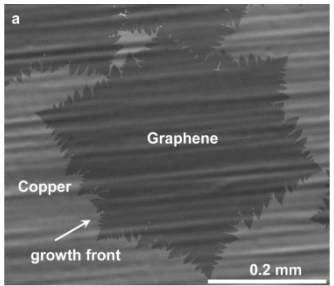
グラフェン合成法

	Mechanical exfoliation of graphite	Thermal decomposition of SiC, Si-face	Thermal decomposition of SiC, C-face	CVD on metal substrates
Quality	◎ μ=500,000cm^2/Vs	○ μ=2,000cm^2/Vs	△ μ=30,000cm^2/Vs	△ μ=1,000cm^2/Vs
Size, yield	× ~100μm	○ ~wafer Scale	○ ~wafer Scale	◎ ~wafer scale
Thickness control	× Depend on luck	○ 1~few layer	△ Rotated multilayer	○ 1~few layer
Substrate	○ SiO_2, BN, …	○ Semi-insulating SiC	○ Semi-insulating SiC	× Metal (Ni, Co, Cu)
Cost	○ Good for lab	△ Depend on SiC	△ Depend on SiC	○ Good for industry
Suitable for …	Lab experiment	Transistor electronics	Transistor electronics	Transparent conductor

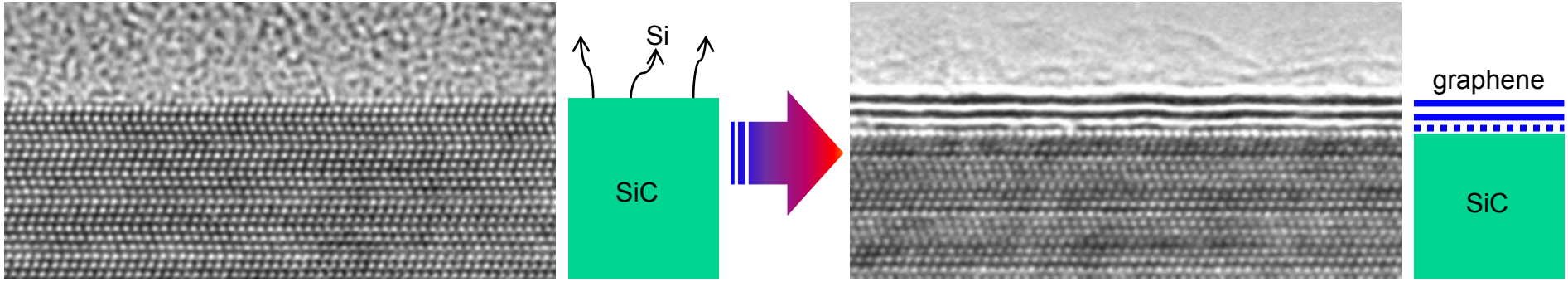






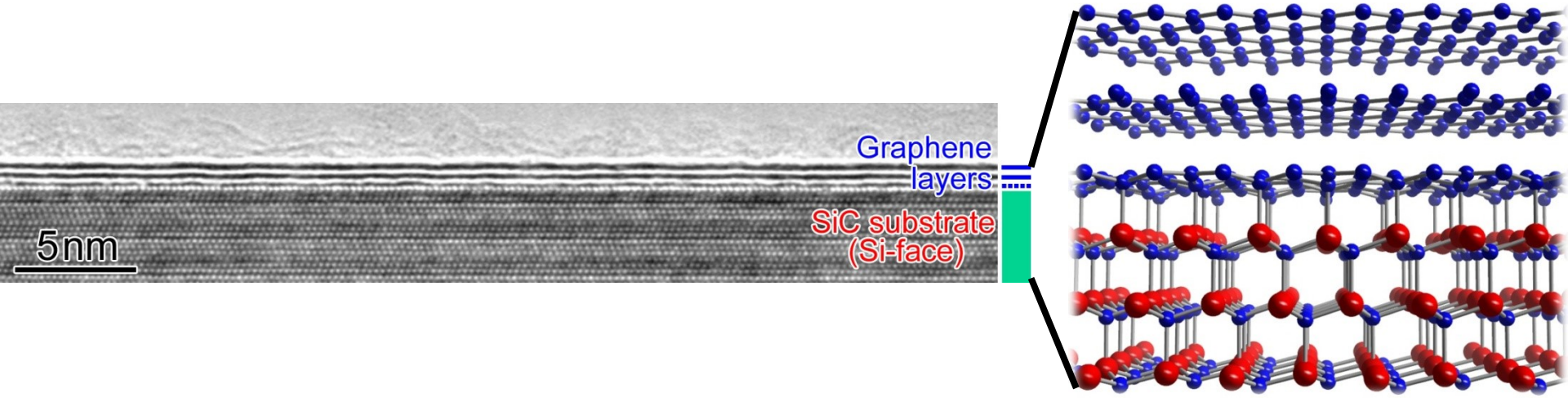


Epitaxial Graphene on SiC



~1200℃

1300℃~ in vac or 1600℃~ in Ar



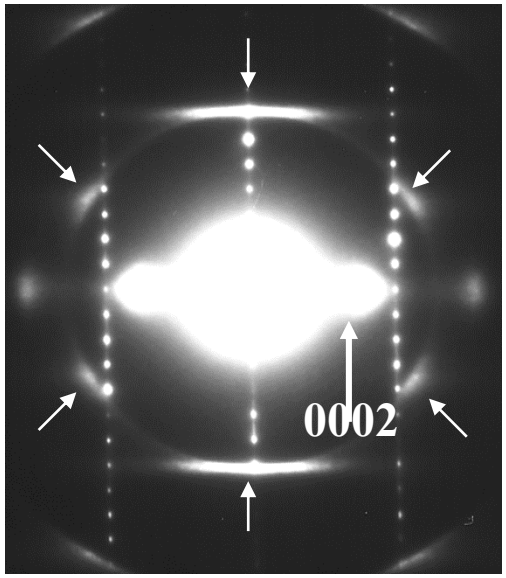
SiCを真空中or Ar中で加熱すると、表面からSi原子のみが除去され、
残存したC原子が自発的にグラフェンを形成

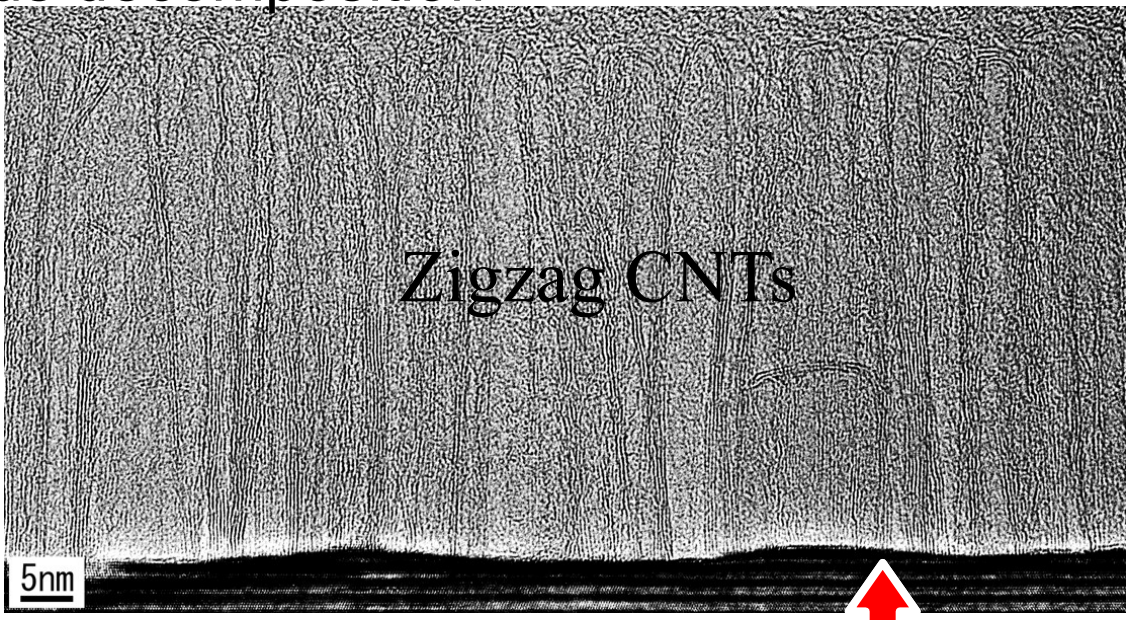
Red:Si
Blue:C

Ref.) W. Norimatsu and M. Kusunoki, *Chem. Phys. Lett.*, 468, 52 (2009), *J. Nanosci. Nanotech*, 10, 3884 (2010)., *Physica E* 42, 691 (2010)., *Phys. Rev. B* 81, 161410 (2010), *Phys. Rev. B* 84, 035424 (2011)., PCT/JP2009/004200.

CNT? or Graphene? on SiC

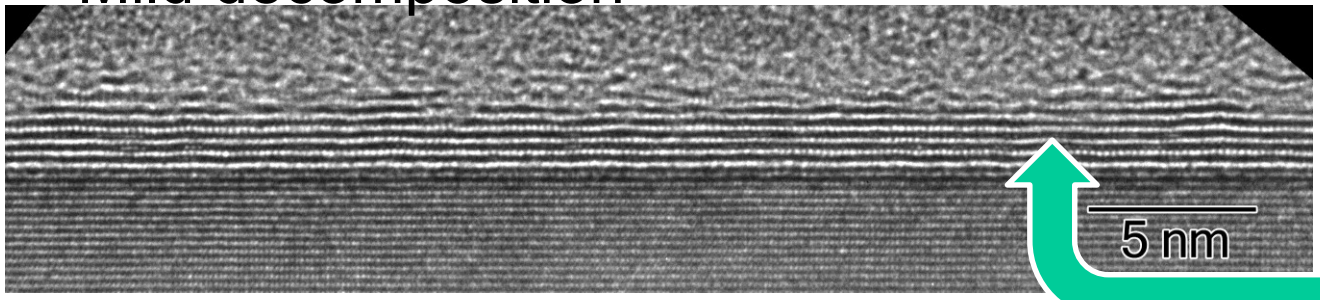
Furious decomposition

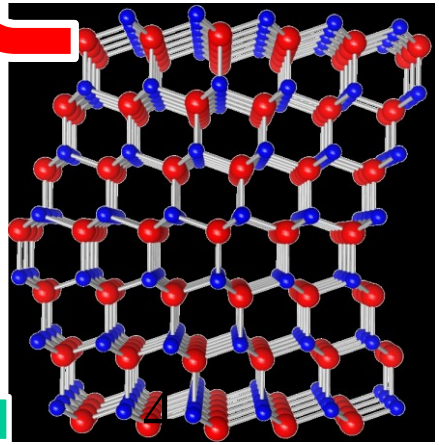




Mild decomposition

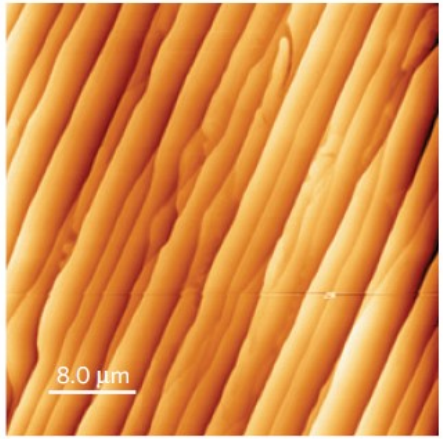
Graphene growth

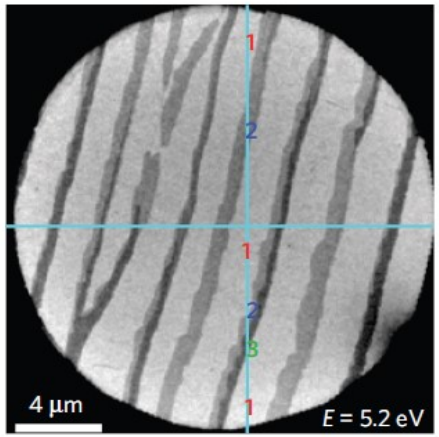




Epitaxial Graphene on SiC

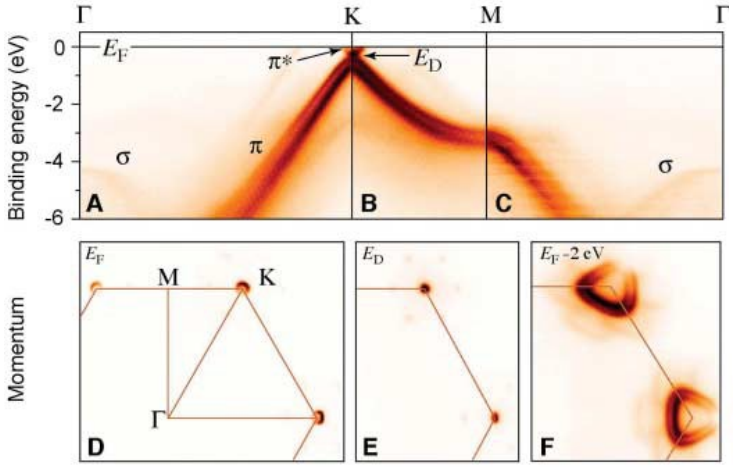
Ar中加熱による
均一グラフェン作製

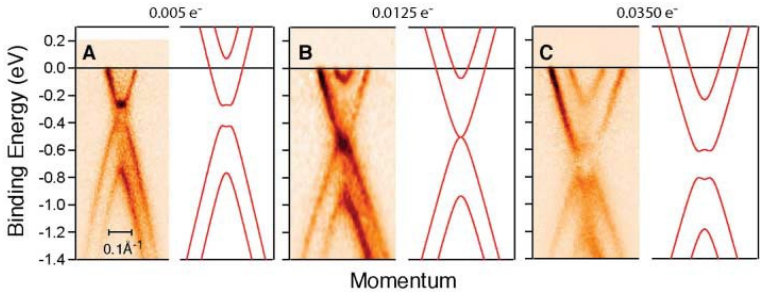




Ref.) K. V. Emtsev, et al., *Nature Mat.*, 8, 203 (2009).

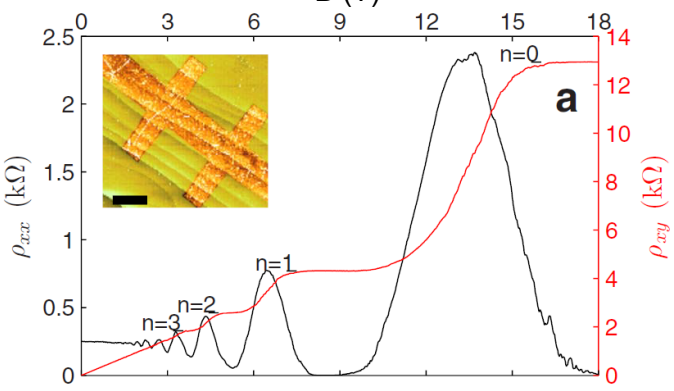
角度分解光電子分光(ARPES)に
よるバンド構造測定





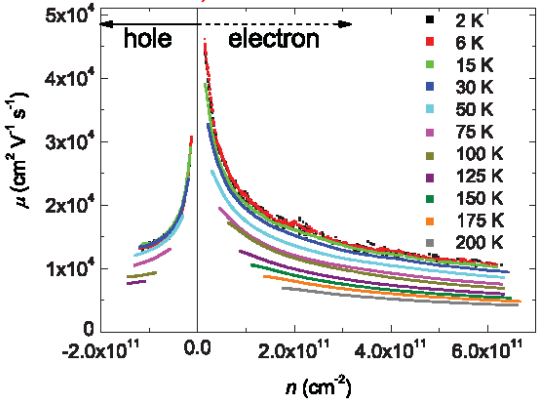
Ref.) T. Ohta, et al., *Science*, 313, 951 (2006).

量子ホール効果



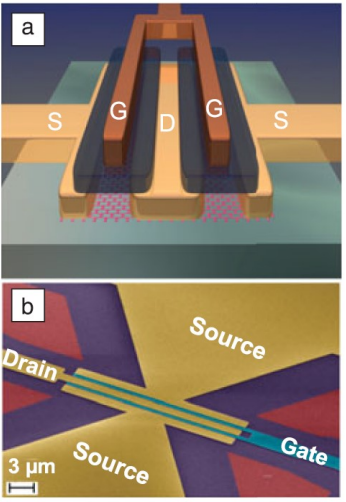
Ref.) X. Wu, et al., *Appl. Phys. Lett.*, 95, 223108 (2009).

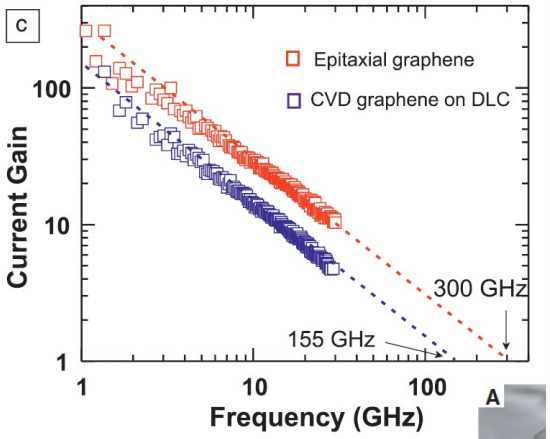
低キャリア密度領域での移動度
40,000cm^2/Vs以上



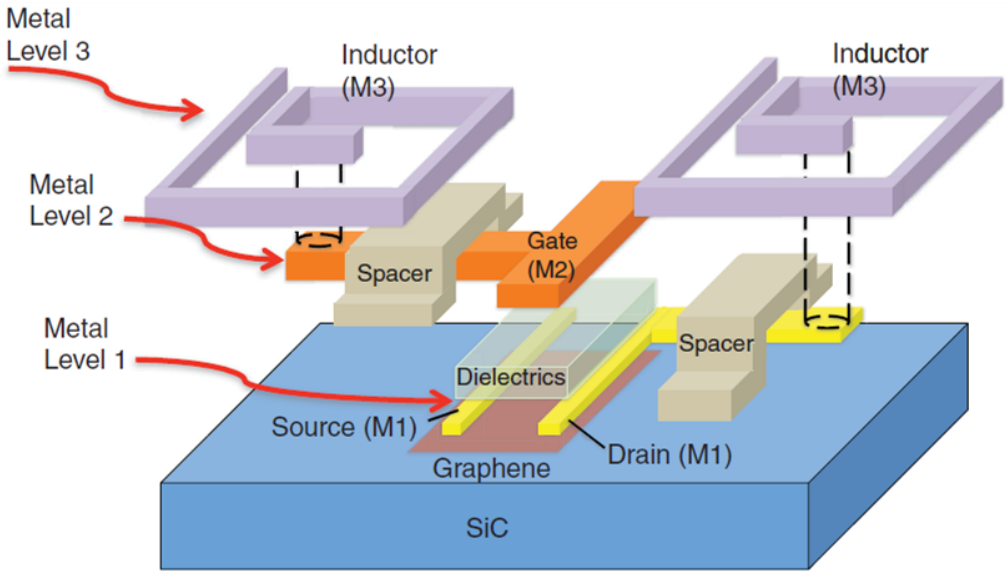
Ref.) S. Tanabe, et al., *Phys. Rev. B*, 84, 115458 (2011).

SiC表面上グラフェンのトランジスタ応用

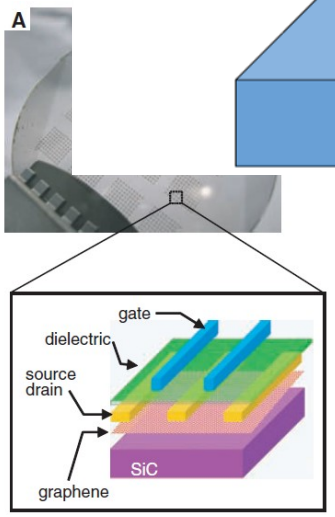




Ref.) Ph. Avouris and F. Xia, *MRS Bulletin*, 37, 1225 (2012).



Ref.) Y. M. Lin, et al., *Science*, 332, 1294 (2011).



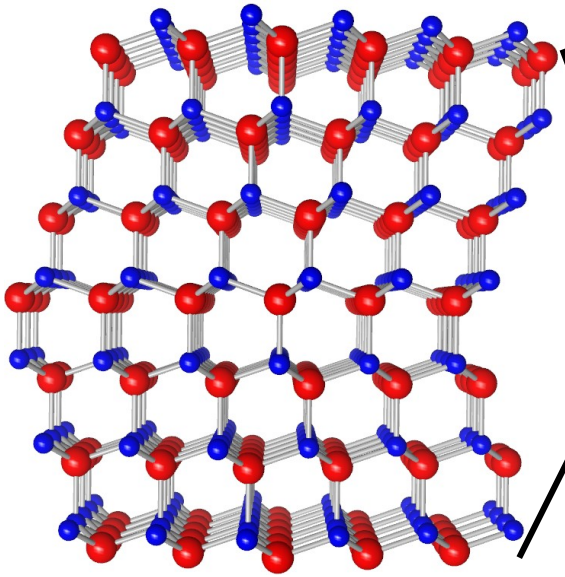
高周波トランジスタ応用(IBM)
遮断周波数f_T：～300GHz
（40GHz is limit in Si-device）

集積回路（周波数ミキサ）の作製と130℃での安定な動作に成功

SiC表面上グラフェンはエレクトロニクス応用に適合

Graphene on SiC {0001} surfaces

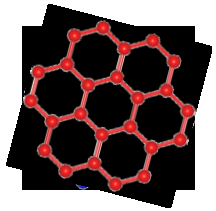
C終端(000-1)面



Si終端(0001)面

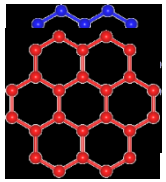
C面上グラフェン

- 多層
- 回転積層
- 低品質
- 高移動度



Si面上グラフェン

- 1、2層
- 高品質・均一
- バッファー層
- 低移動度



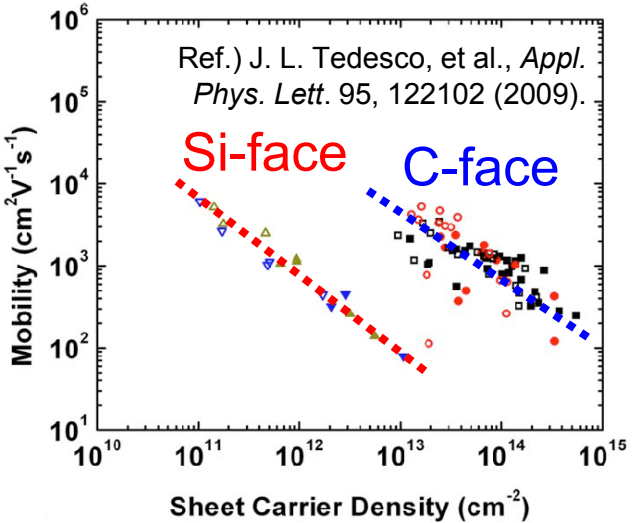
グラフェン成長機構・界面構造解明

↓

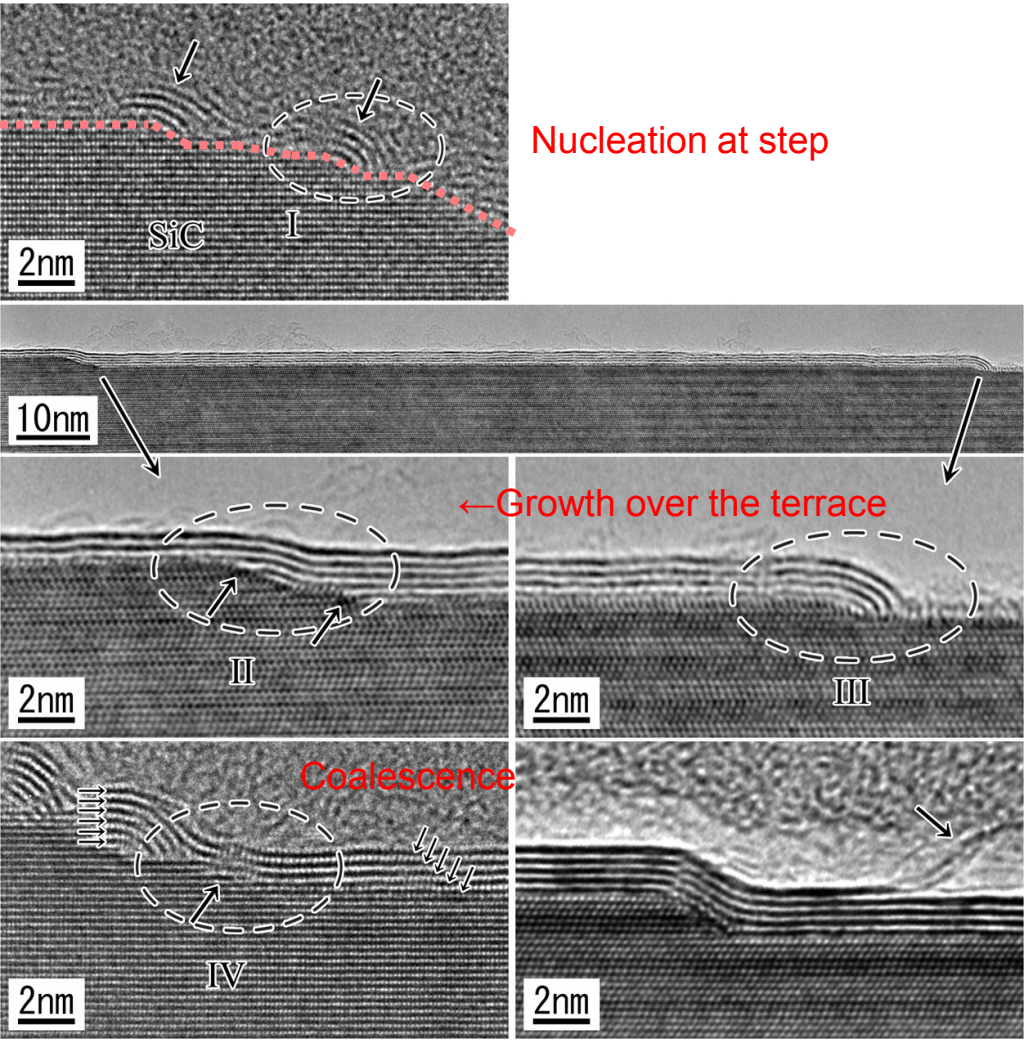
大面積・高品質グラフェン作製方法開発

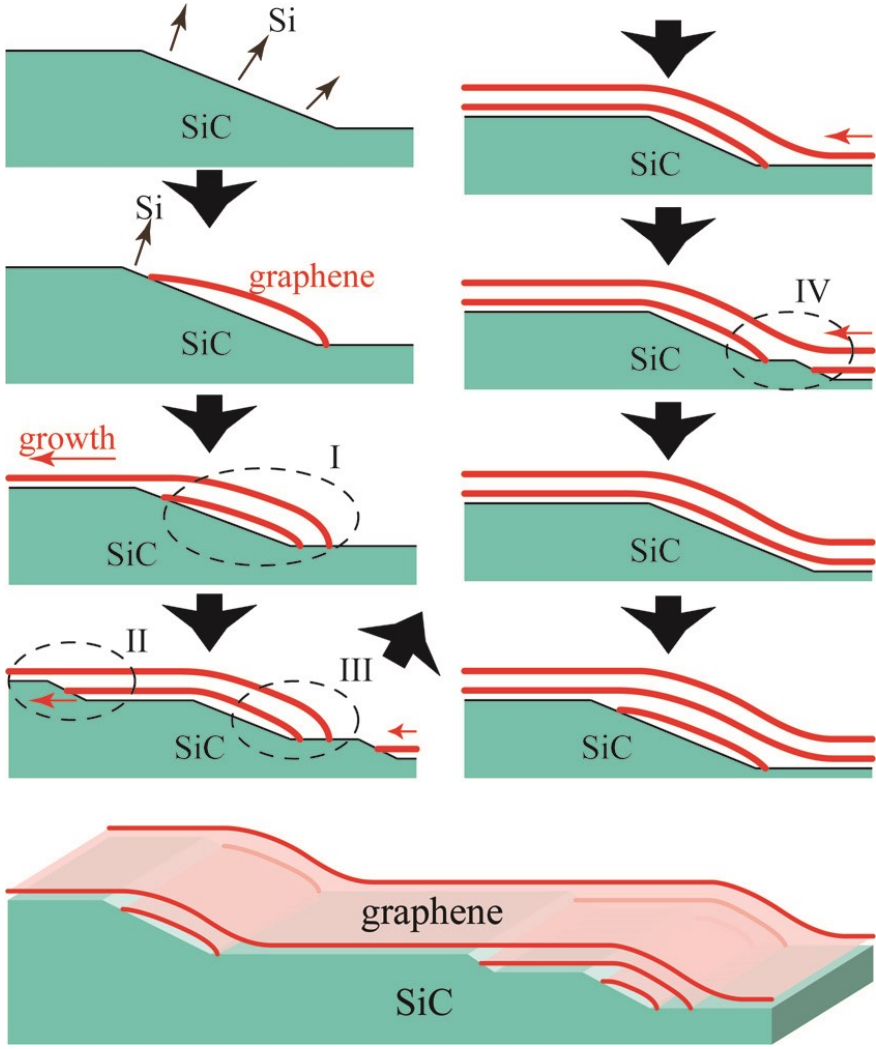
↓

高機能・高性能グラフェン素材開発



Si面上グラフェンの形成機構

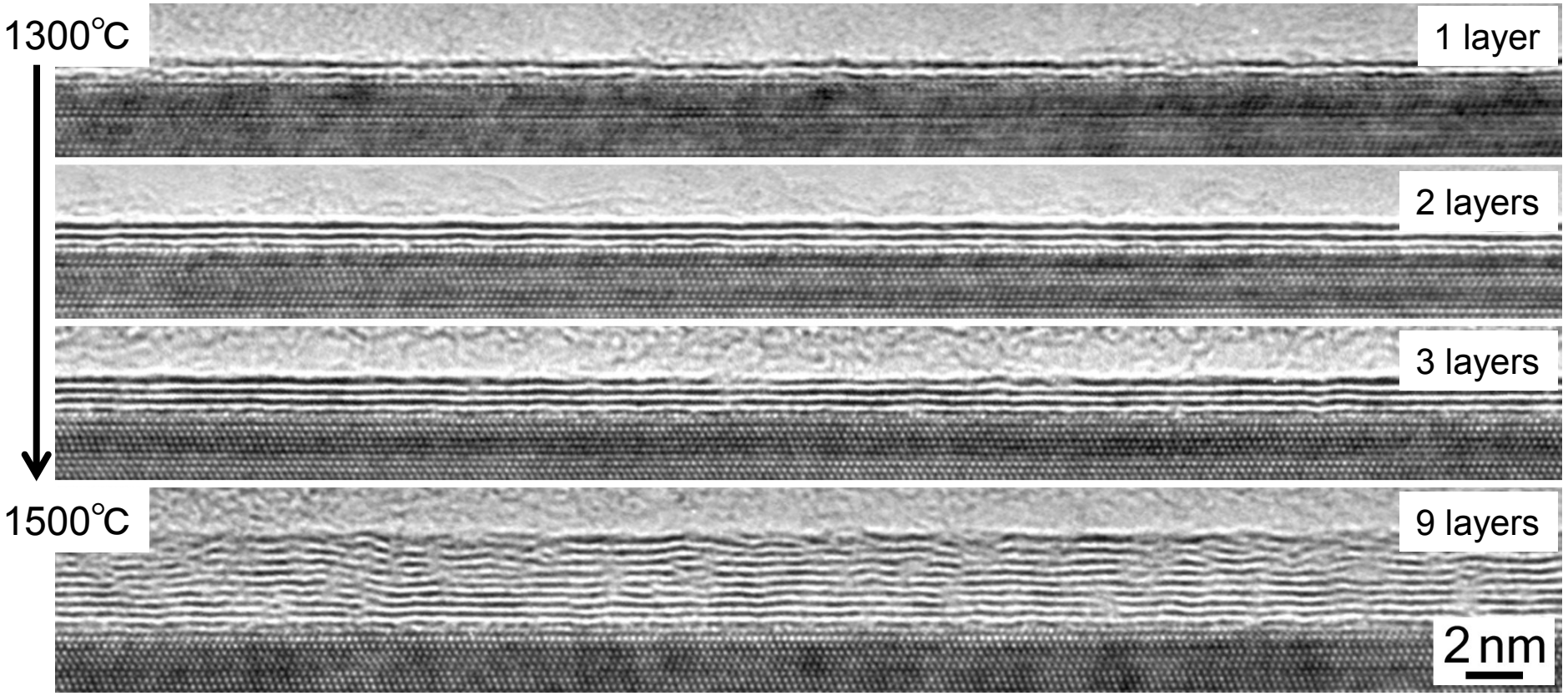




ステップで核生成→成長。　Layer-by-layer成長による均一グラフェン成長が容易。

Ref.) W. Norimatsu and M. Kusunoki, *Physica E*, 42, 691 (2010).

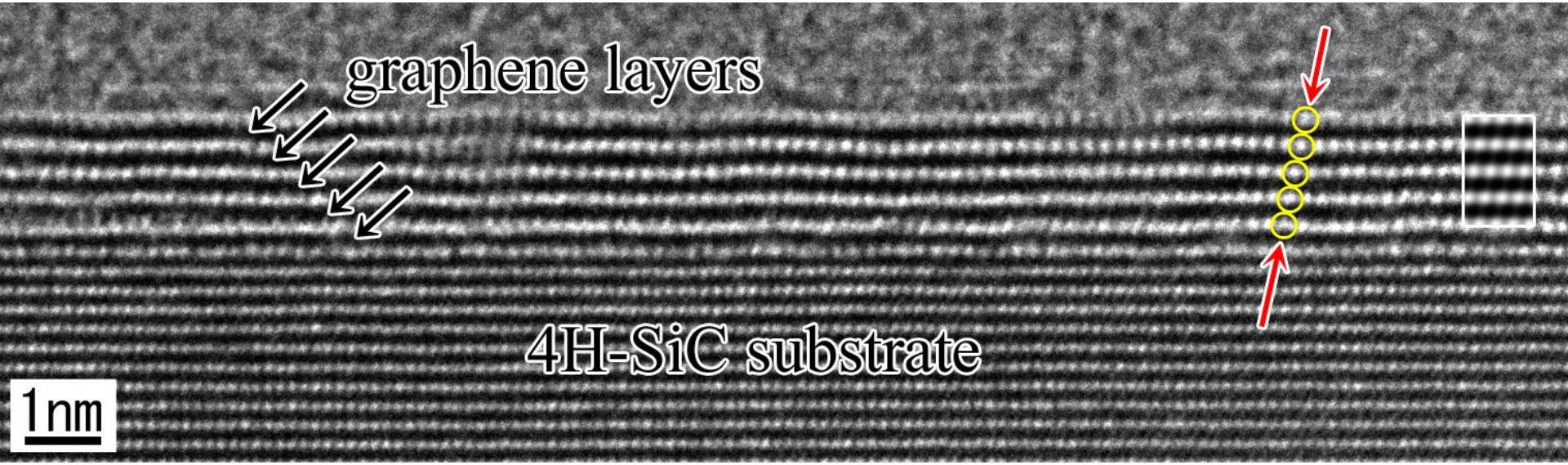
Thickness control by temperature

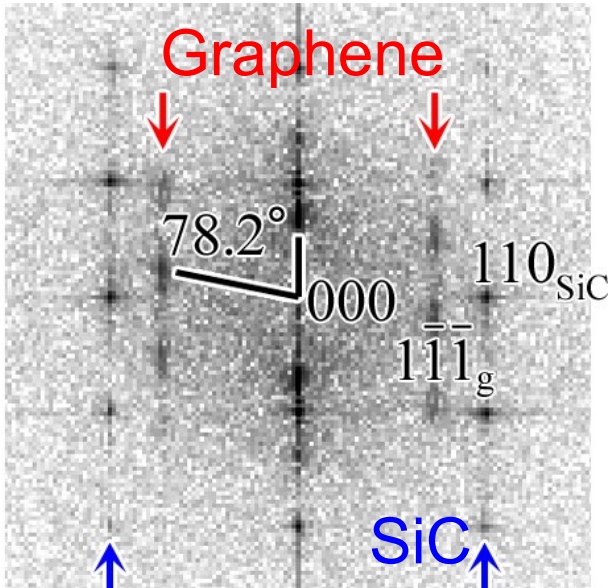


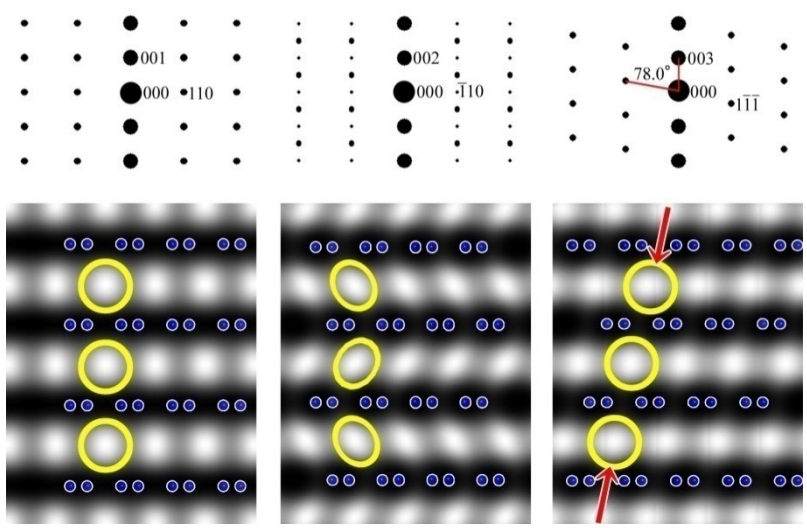
- Increasing annealing temperature→Increase in the number of layers.
- Inhomogeneous above 1500℃.

Ref.) W. Norimatsu and M. Kusunoki, *Chem. Phys. Lett.* 468, 52 (2009).

4H-SiC表面上グラフェンの積層秩序





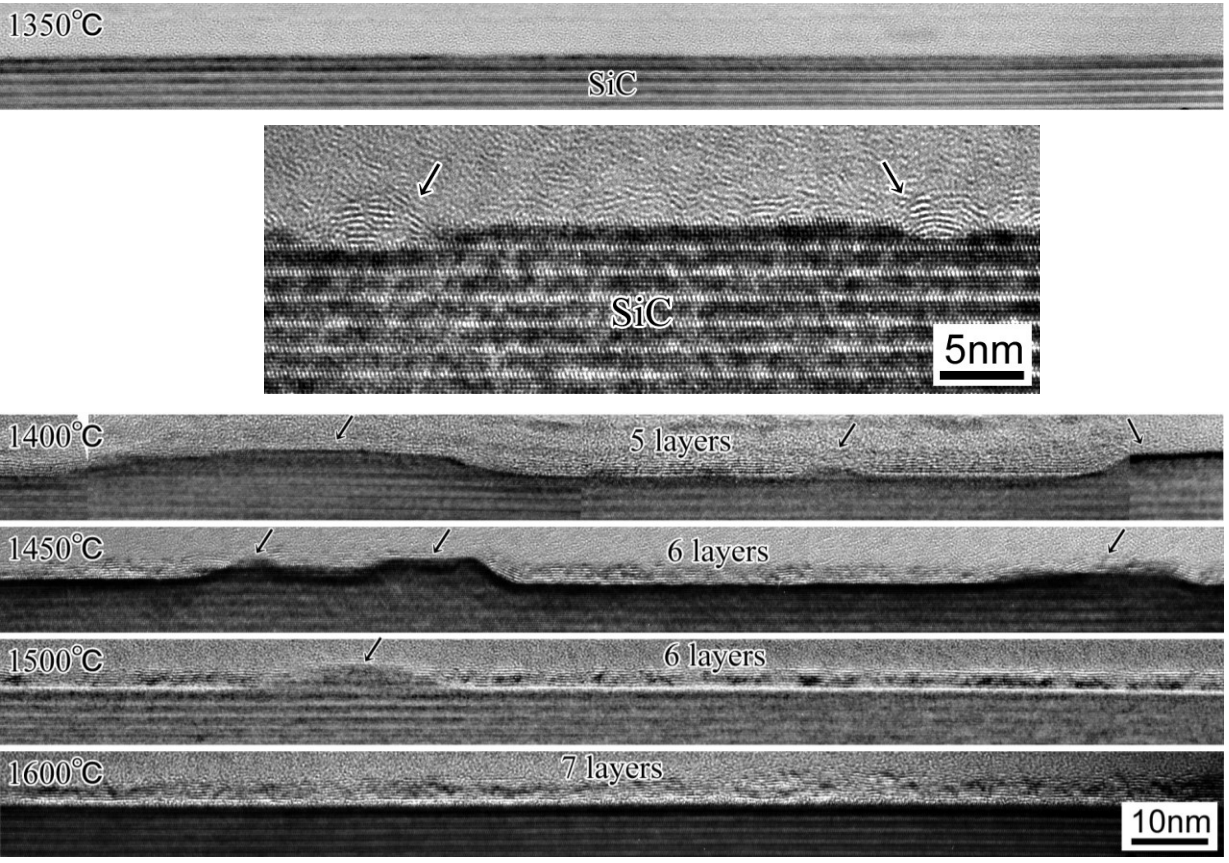


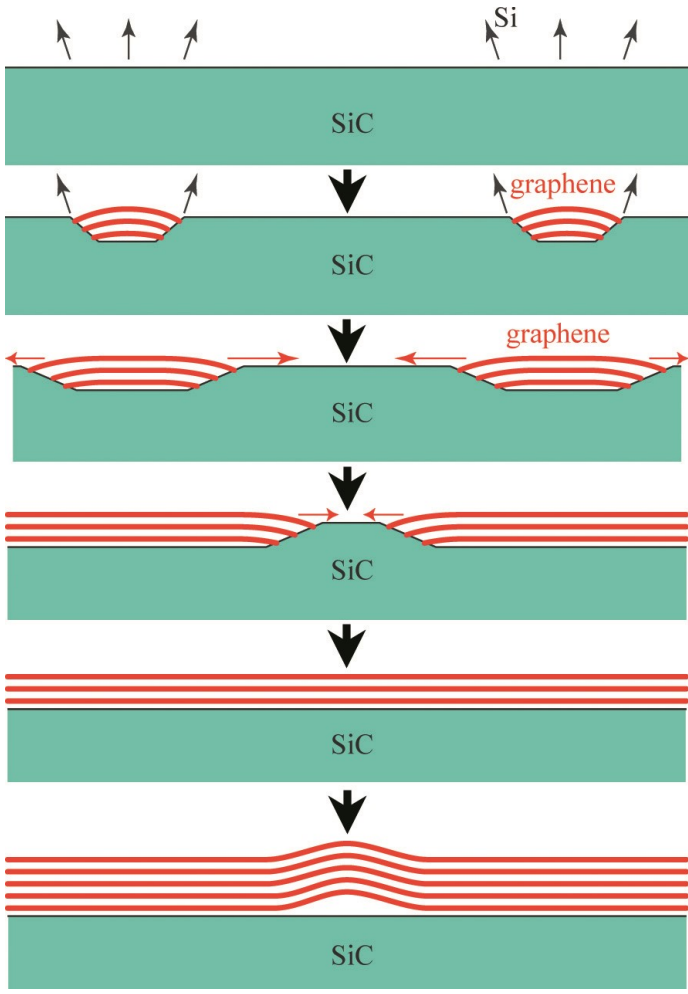
AA- AB- ABC-stacking

4H-SiC表面上グラフェンはABC積層

Ref.) W. Norimatsu and M. Kusunoki, *Phys. Rev. B* 81, 161410 (2010).

C面上グラフェンの形成機構

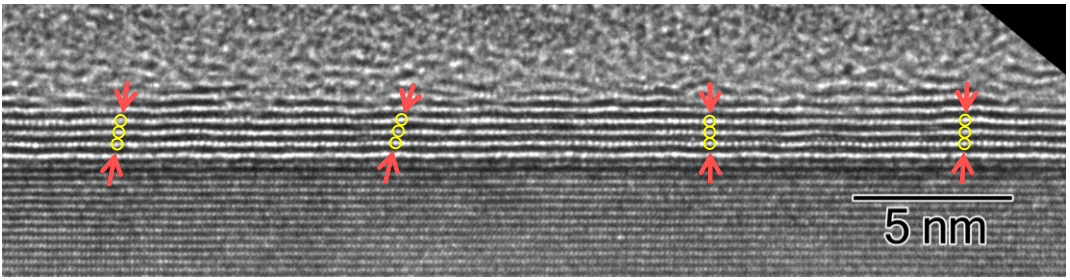


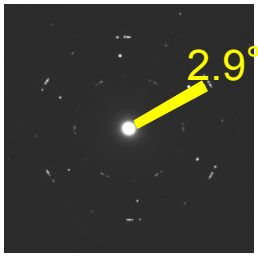


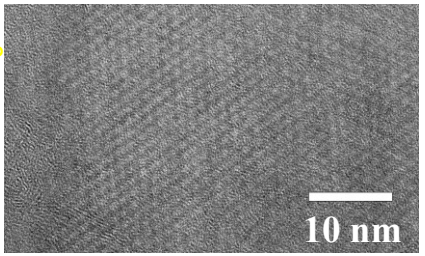
テラス上で核生成→四方に成長。　多層が同時に成長。

Ref.) W. Norimatsu and M. Kusunoki, *Phys. Rev. B* 84, 035424 (2011).

C面上グラフェンの特徴

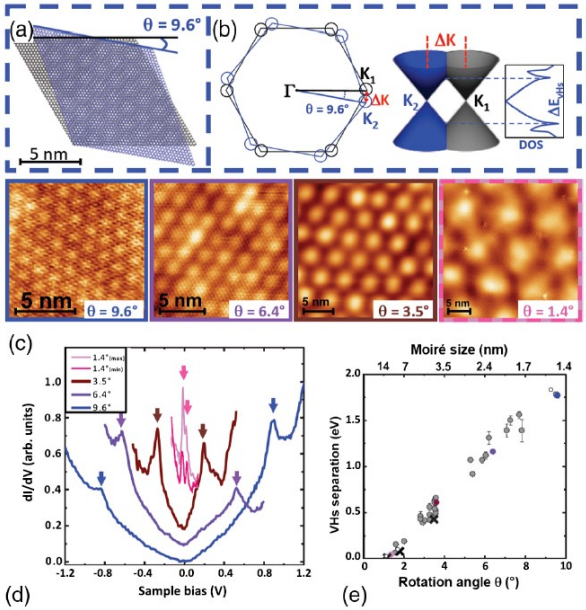


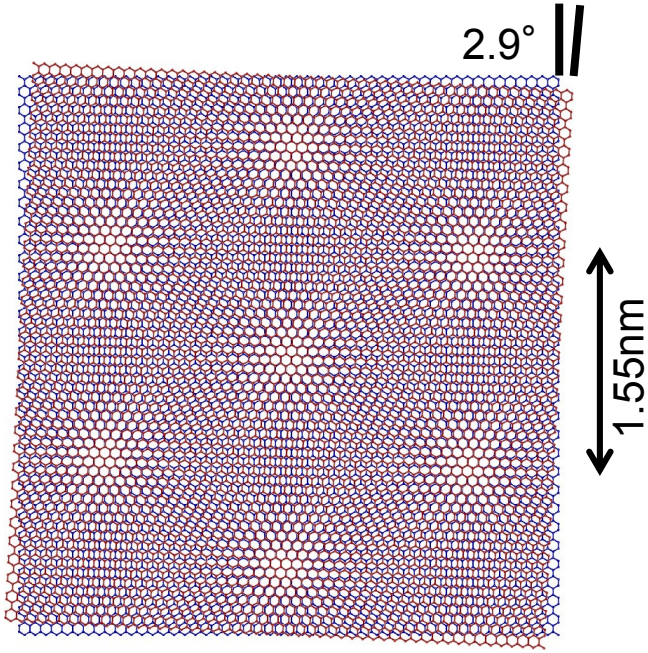




- 多層が一気に成長
- グラフェンとSiCの相互作用は弱い。
  →グラフェンは基板の影響を受けず、n型, p型が混在し、不均一ではあるものの、移動度はSi面より一桁高い。

Ref.) W. Norimatsu and M. Kusunoki, *Phys. Rev. B* 84, 035424 (2011), J. L. Tedesco, et al., *Appl. Phys. Lett*. 95, 122102 (2009).





•C面上多層グラフェンは、互いに回転して積層。回転角はランダム
（成長温度によっては準安定な回転角有り）。
→一つの試料中に、van Hove特異点間のエネルギー差が、様々な値を持つ。

Ref.) J. Kuroki, W. Norimatsu, and M. Kusunoki, *e-J. Surf. Sci. Nanotech.*, **10**, 396 (2012), I. Brihuega, et al., *Phys. Rev. Lett.*, 109, 196802 (2012).

グラフェン/TiC/SiC-C面の積層不整

TiC/SiC

0.75nm

5 nm

5 μm

Gr

20.40nm

5μm

5μm

Phys. Rev. B 87, 075431 (2013).

TiC

SiC

10 nm

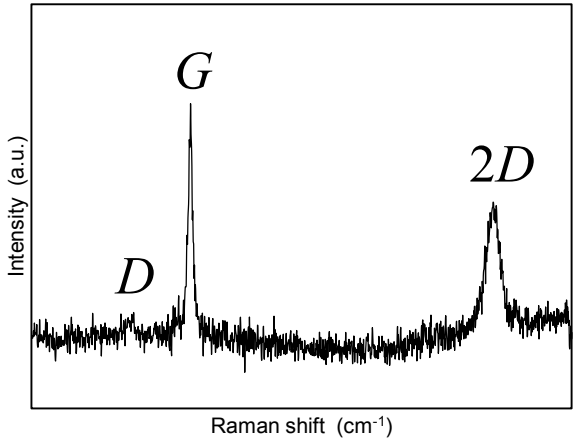
TiC

TiC

SiC

アモルファス界面

3 nm



研究室メンバー

acknowledgment