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LARGE-AREA EPITAXIAL GRAPHENE LAYER

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OBJECTIVES

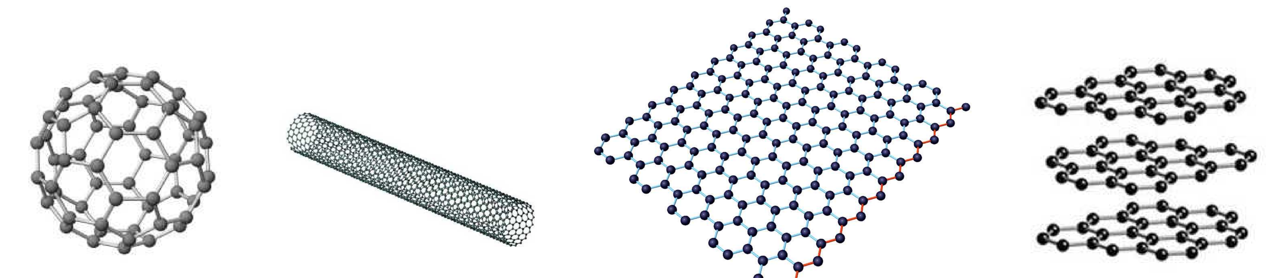
Create scientific understanding for graphene-based electronics

Graphene is a new type of electronic material based on sp^2-bonding, unlike conventional semiconductors: Si, GaAs, etc. Our goals are

- to develop scientific basis for new synthesis and processing approaches suitable to this new 2D material, and
- to create novel electronic and MEMS devices exploiting its unique electronic properties.

What is Graphene?

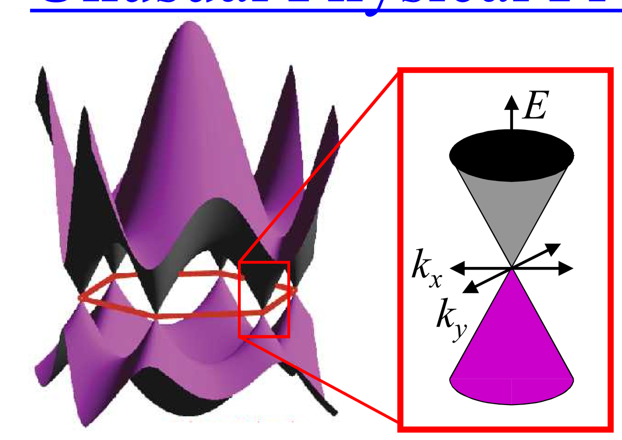
Carbon-Based Nanomaterials



C_{60} (0-D) CNT (1-D) **graphene (2D): sp^2-bonding** graphite (3-D)

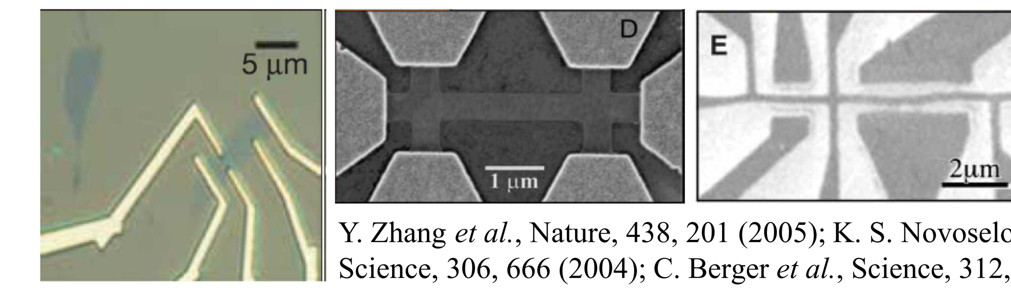
Why Graphene?

Unusual Physical Properties



Linear electronic dispersion yields unique properties including relativistic Dirac fermion.

Potential graphene-based devices



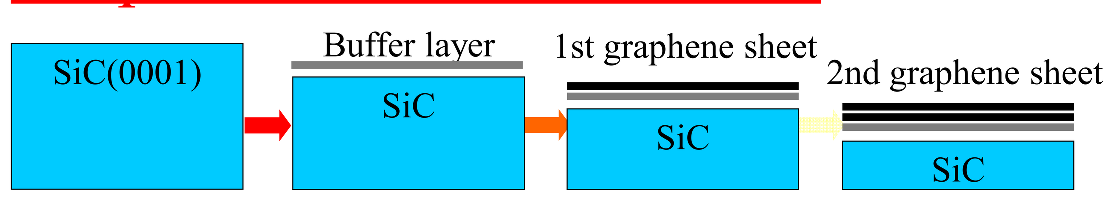
Y. Zhang *et al.*, Nature, 438, 201 (2005); K. S. Novoselov *et al.*, Science, 306, 666 (2004); C. Berger *et al.*, Science, 312, 1191 (2006)

Technological advantages: high carrier mobility (~200,000 cm^2/Vsec), ballistic transport (coherent length > 1µm), high heat conductance, outstanding mechanical properties.

Potential applications: high-speed and high-power electronics, THz devices, sensors.

SYNTHESIS

Graphene Formation on SiC

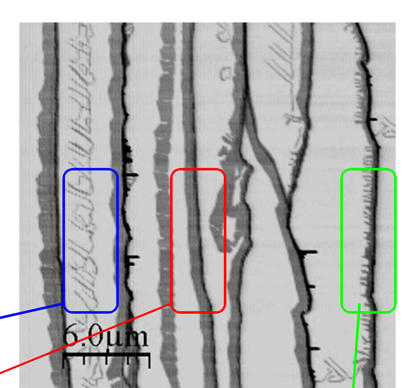


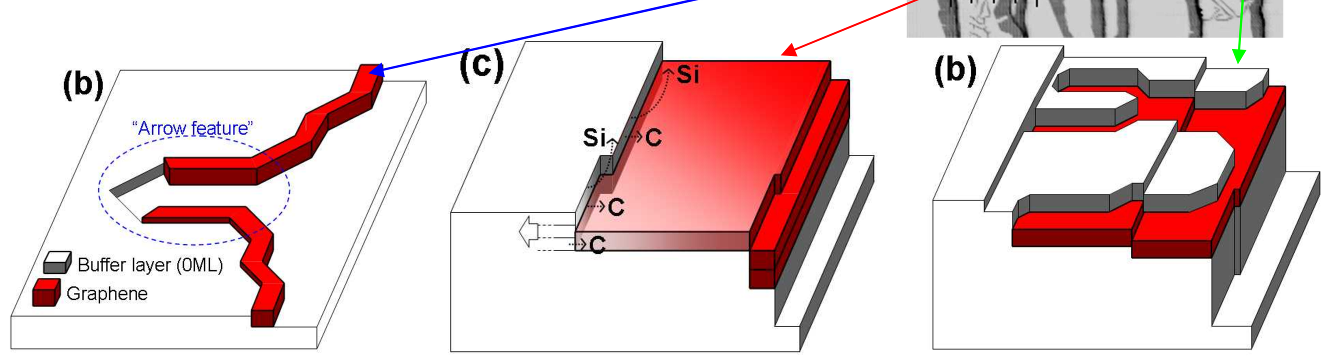
Graphene can be readily formed on SiC substrates. By annealing (~1100 C), sublimation of silicon modifies SiC(0001) surface terminated by an interface carbon layer (buffer layer). Further Si sublimation at higher temperature or carbon deposition creates a high concentration of surface carbon atoms, which assemble ("graphitize") into graphene layers, and form a new buffer layer underneath.

Characteristic Growth Fronts

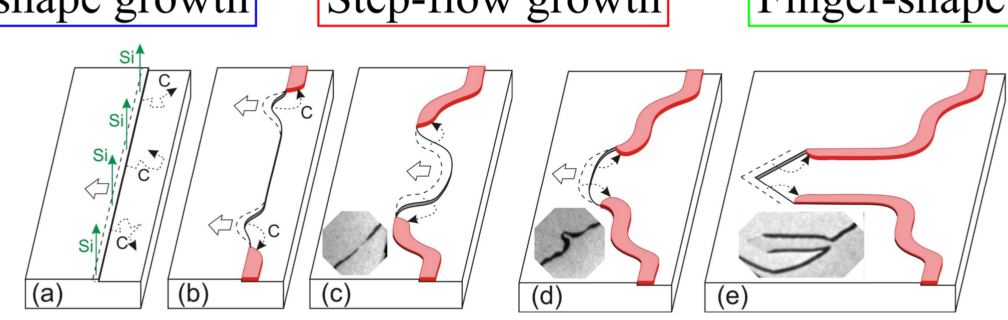
Influences of the substrate step structure and the surface diffusion of carbon atoms

- Step bunches of SiC produces high quality graphene by promoting step flow growth





Arrow-shape growth Step-flow growth Finger-shape growth

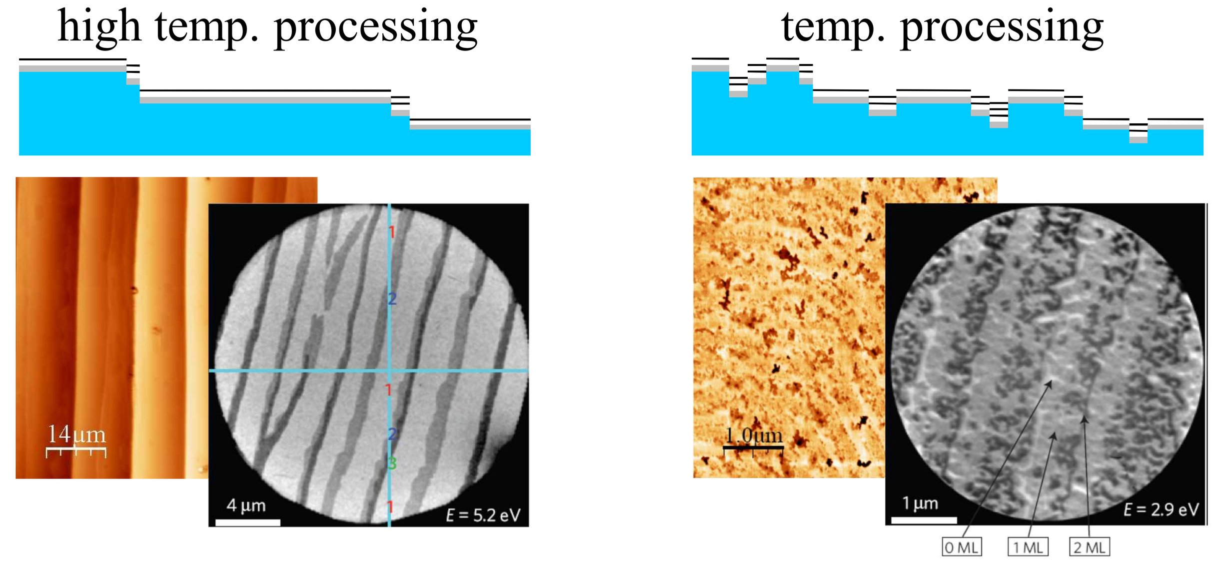


The diffusion model of a arrow feature suggest that the observed distinctive morphologies result from cooperative diffusion processes: Si sublimation rates depend on carbon adatom concentrations.

T. Ohta, N. C. Bartelt, S. Nie, K. Thürmer, G. L. Kellogg, submitted for publication (2010).

Argon-Assisted Graphene Formation

Atmospheric pressure Ar high temp. processing | Ultrahigh vacuum mid temp. processing



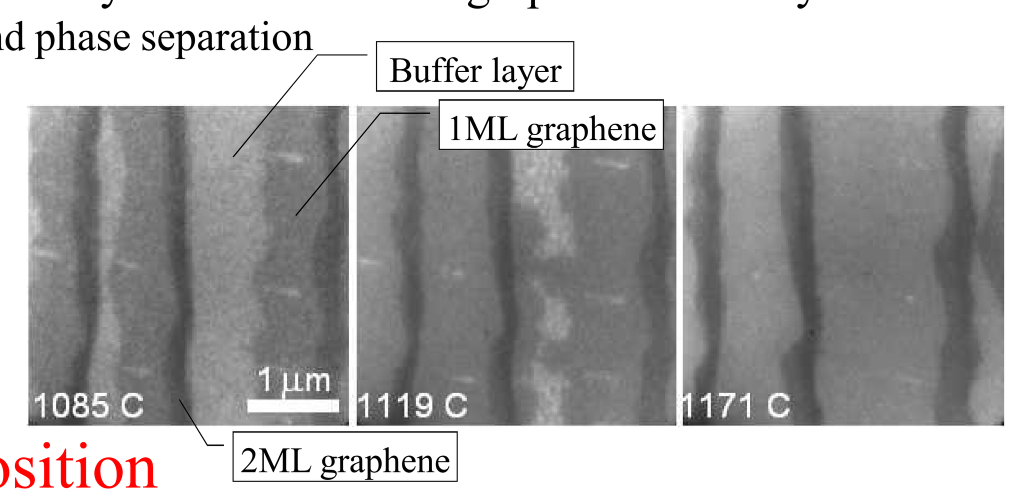
K. V. Emtsev, G. L. Kellogg, T. Ohta et al., Nature Materials 8, 203 (2009).

Real-time Observation of Formation Processes using LEEM (low energy electron microscopy)

• High-Temp. silicon sublimation

Following how buffer layer is converted to graphene monolayer

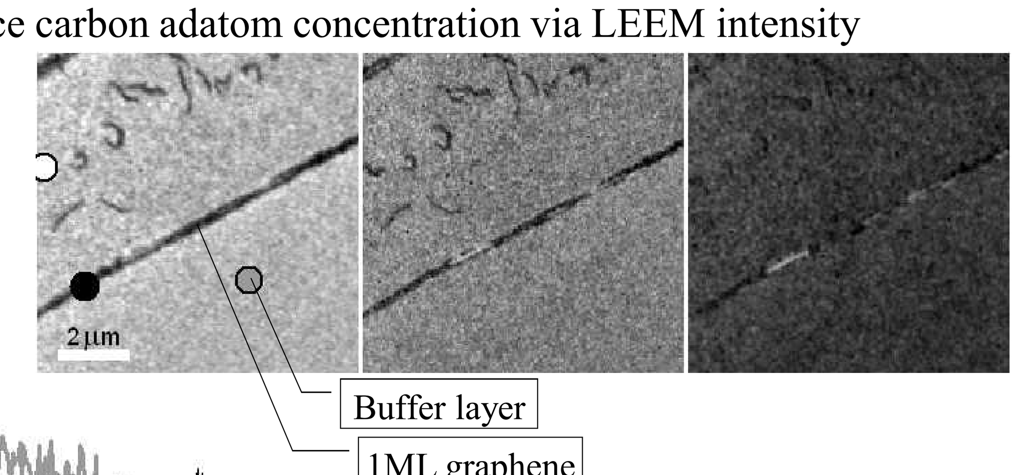
- Step-flow growth and phase separation

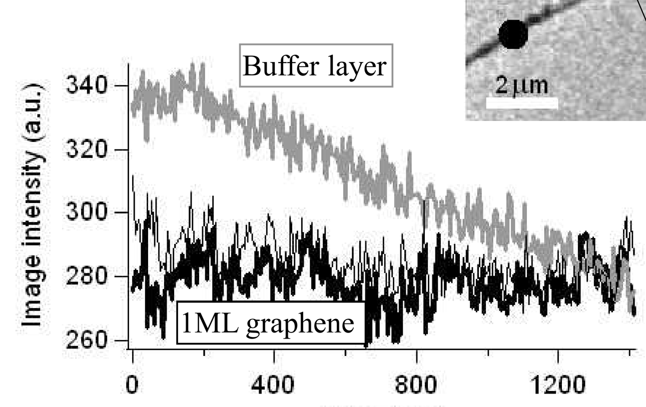


• Carbon deposition

Watching the growth of graphene layer on buffer layer

We monitor the surface carbon adatom concentration via LEEM intensity





T. Ohta, S. Nie, T. Friedmann, K. McCarty, N. C. Bartelt, G. L. Kellogg, preparing for publication.

Team & Collaborations

S. W. Howell (project lead), T. Friedmann, W. Pan, K. McCarty, K. Leung, L. Biedermann, A. J. Ross, C. Gutierrez (project manager): supported by LDRD

G. L. Kellogg, N. Bartelt, K. Thürmer, S. Nie: supported by DOE-BES

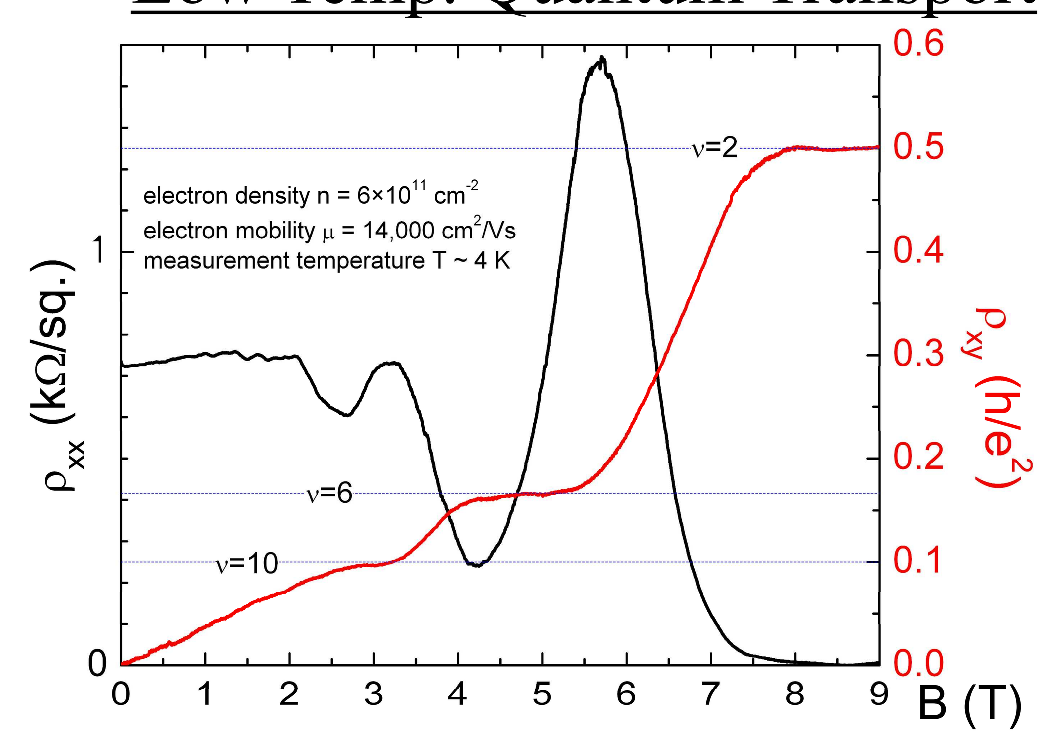
T. E. Beechem: Raman Lab

B. S. Swartzentruber: DOE CINT user facility

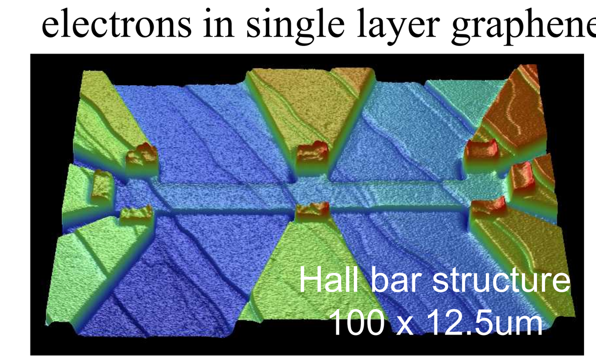
D. A. Schmidt, M. Havenith, Dept. of Physical Chemistry II, Ruhr-Universität Bochum

CHARACTERIZATION

Low Temp. Quantum Transport



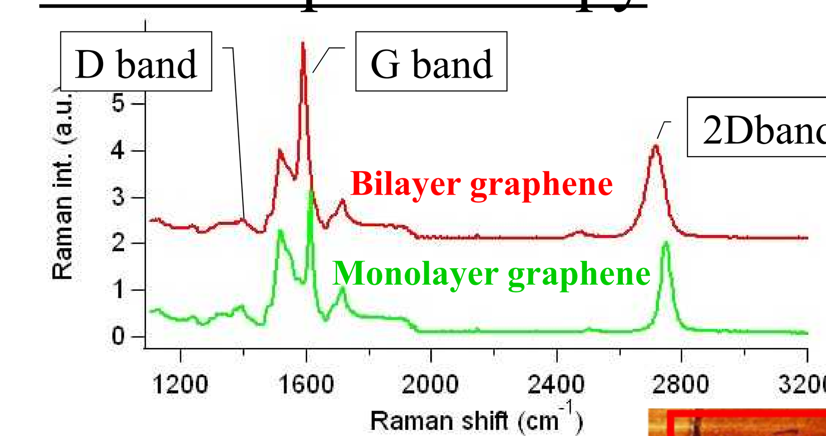
Our sample (Ar-assisted grown) displays integer-quantum Hall effect (IQHE). The unique sequence of IQHE states at ν=2, 6, 10 ($\sigma = \nu \cdot e^2/h$) is a distinguishing signature of Dirac electrons in single layer graphene. (Figure Courtesy W. Pan, S. W. Howell, A. J. Ross)



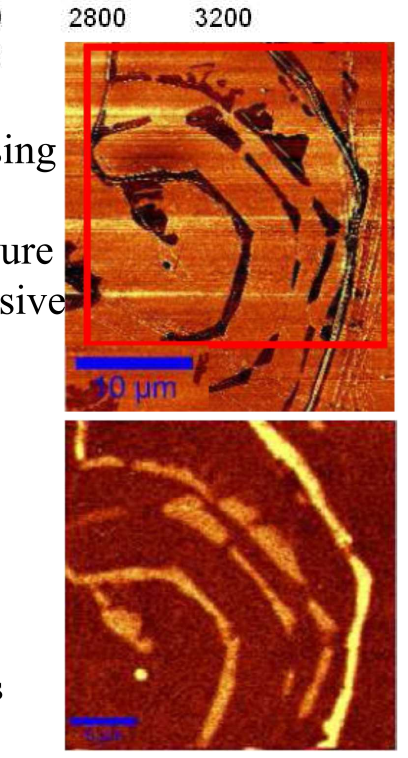
The mobility of 14,000 cm^2/Vs is by far the highest obtained from an epitaxial graphene on SiC(0001). The sheet resistances of multiple Hall bar structures across the whole specimen (12 x 6mm[2]) displays roughly uniform value (~1600 Ω/sq) at 4K, suggesting that the macroscopic steps and accompanying multilayer graphene domains may play a minor role.

W. Pan, A. J. Ross, T. Ohta, S. W. Howell, T. Friedmann, preparing for publication.

Raman Spectroscopy

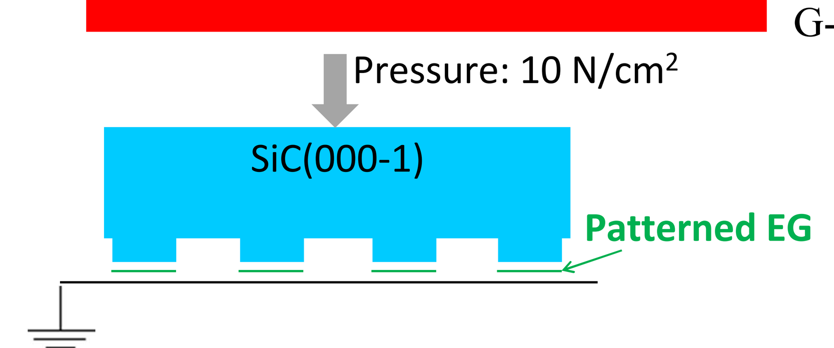


Thickness, defect, strain, and carrier concentration of graphene can be deduced using Raman spectra. Our samples (Ar-assisted grown) display a very small D band, a signature of atomic defect, as well as built–in compressive strain. (Figure Courtesy D. A. Schmidt)

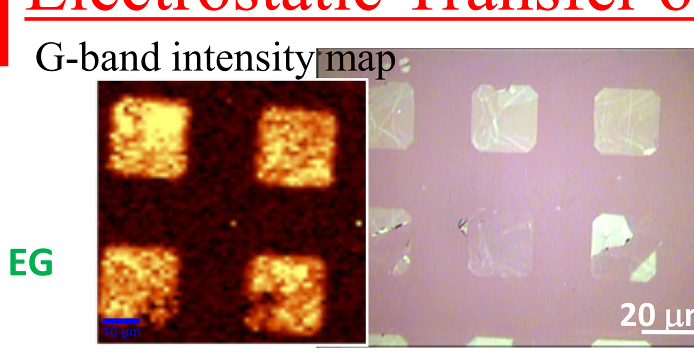


PROCESSING

Electrostatic Transfer of Epitaxial Graphene



G-band intensity map



We demonstrated that pre-structured epitaxial graphene films can be transferred to a glass substrate using electrostatic transfer method. (Figure Courtesy L. Biedermann, A. J. Ross, T. E. Beechem, S. W. Howell)

SUMMARY

- Producing large-area graphene films via Ar-assisted growth process
- Observing IQHE with high carrier mobility
- Furthering the understanding of graphene growth mechanism - Real-time LEEM observation
- Developing a transfer scheme for epitaxial graphene
- Establishing characterization capabilities for future development efforts

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Acknowledgments

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