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Carbon-Based Materials for Flexible Electronics

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Sep 10, 2015

BAO RESEARCH

Flexible Electronics in Life

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Display

Skin-Attached Sensor

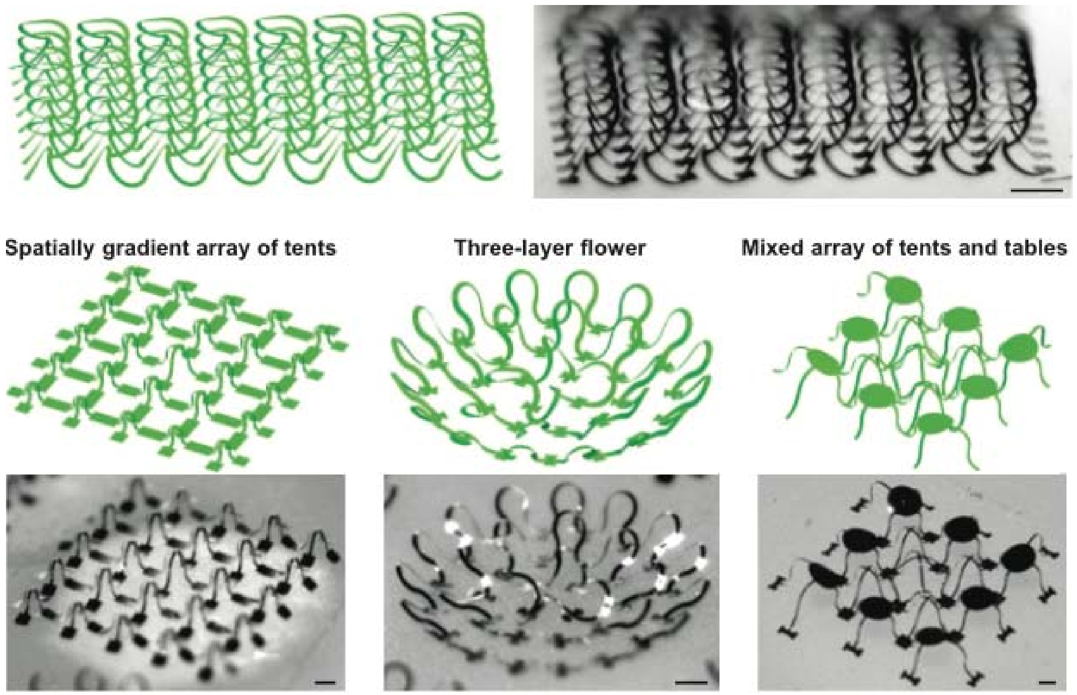
MP3 Player
Embedded Jacket

Solar Cell on Bags

Sensor for Meat Freshness

Approach to Flexible Electronics

With conventional materials/processes



→ Etched thin silicon with conventional device fabrication process
→ **Expensive** for the process
→ Limitations for wearables due to its **own stiffness**

John A. Rogers Group
University of Illinois at Urbana-Champaign

Rogers et al, Science, 2015, 347, 6218

Our Approach to Flexible Electronics

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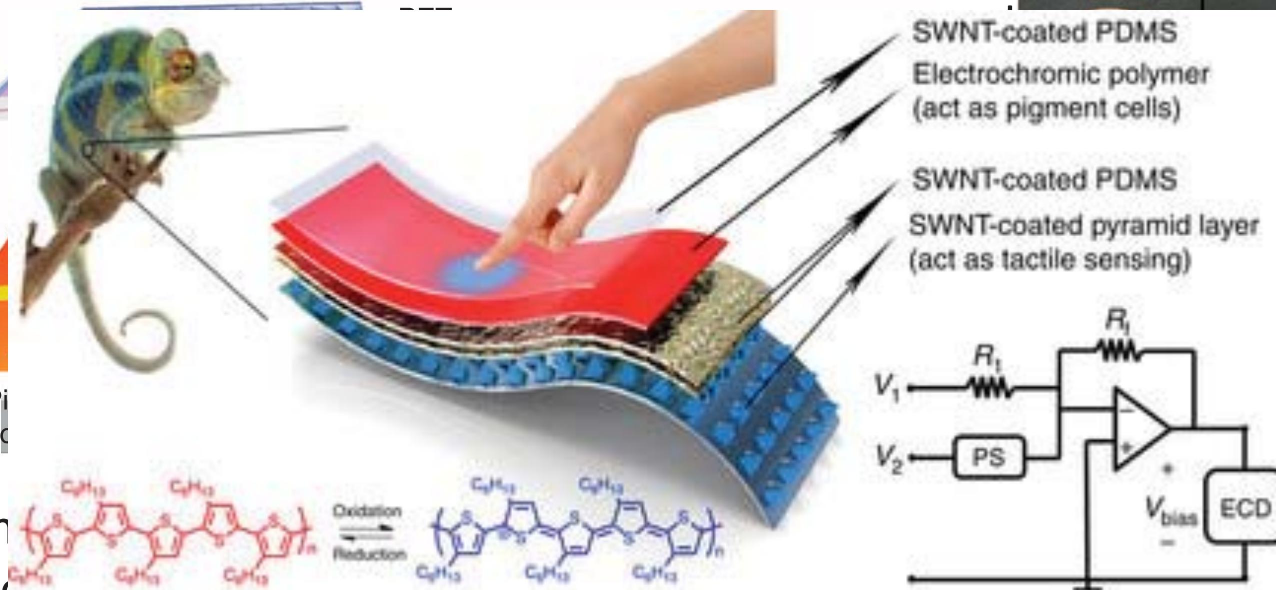
1 New structure: microstructured PDMS (polydimethylsiloxane)

2. New material: organic materials (polyisoindigobithiophene-siloxane, PiI2T-Si)
(poly(3-hexylthiophene-2,5-diyl), P3HT)

Inte… sensor



Pi…
po…

40 50

In… er transistor, we have
ac… an pulse monitor.

…2010, 9, 860

G Schwartz, Z Bao, Nature Comm 2013,4:1859

Ho-Hsiu, Chou, Z Bao, Nature Comm 2015,6:8011

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Carbon-Based Materials: CNTs

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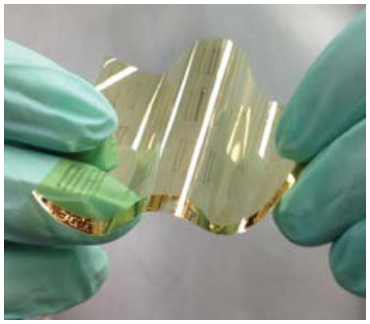
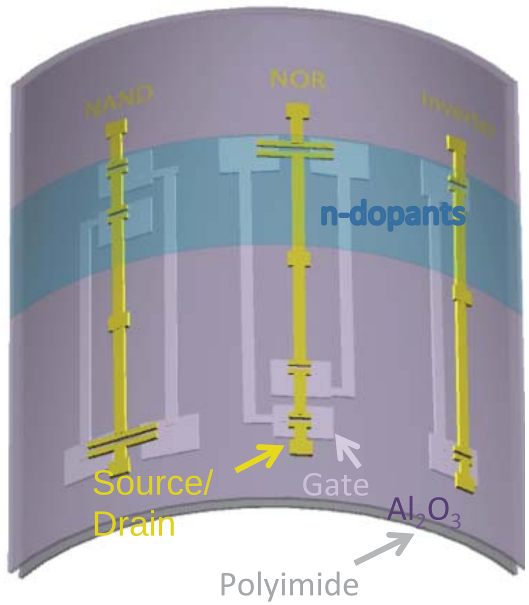
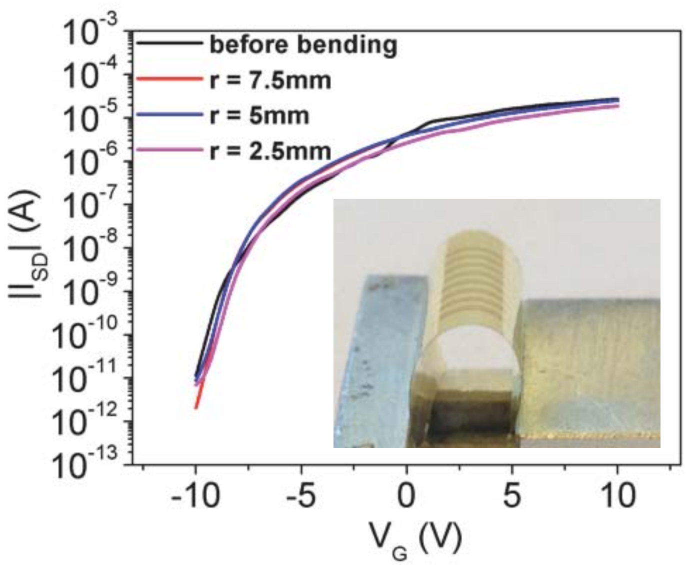
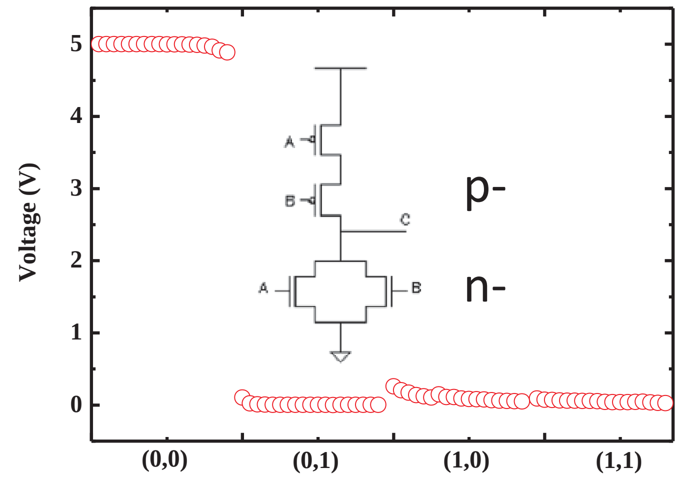






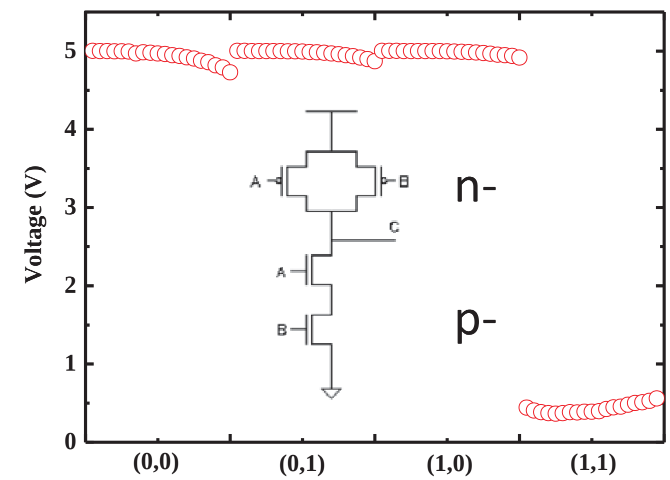
NOR logic gate

INPUT		OUTPUT
A	B	
0	0	1
0	1	0
1	0	0
1	1	0



NAND Gate

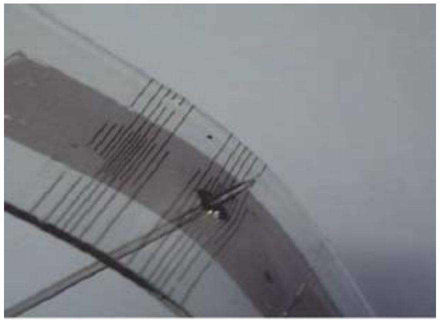
INPUT		OUTPUT
A	B	
0	0	1
0	1	1
1	0	1
1	1	0

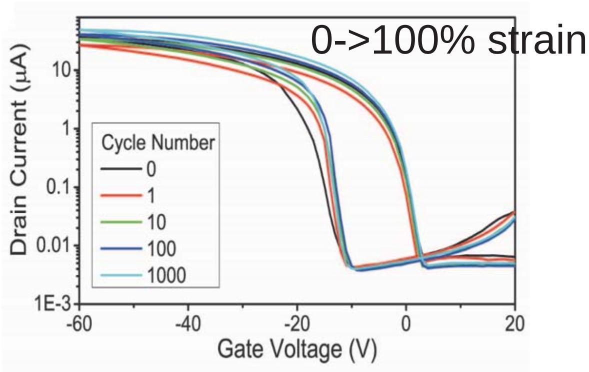


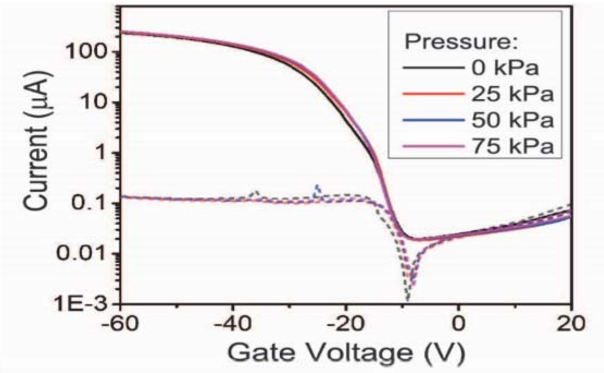
BAO RESEARCH

H. Wang, Z. Bao et al. ***PNAS****, 2014, 111(13), 4776-4781*

Highly Robust All-CNT Stretchable Transistors





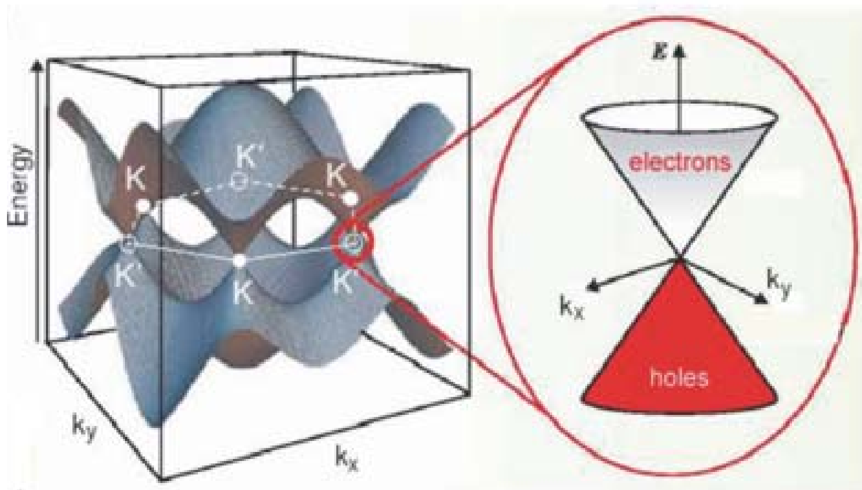


Chortos, Bao et al. Adv. Mater. 2015

Carbon-Based Materials: Graphene

1. The electrons in graphene behave as massless Dirac Fermions

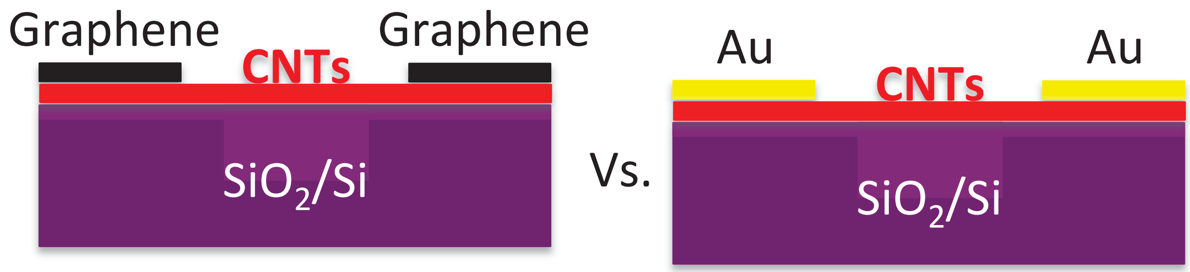
- High electron mobility (15,000 cm^2/Vs in Experiment; 200,000 cm^2/Vs in Theory);
- Resistivity $10^{-6}\Omega m$ lower than silver

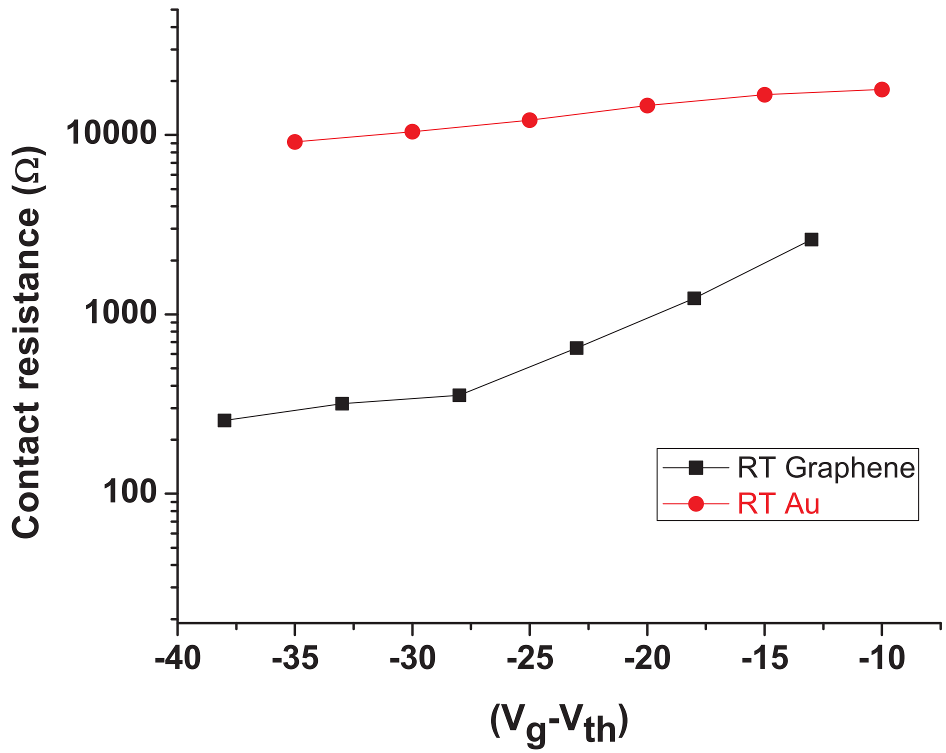


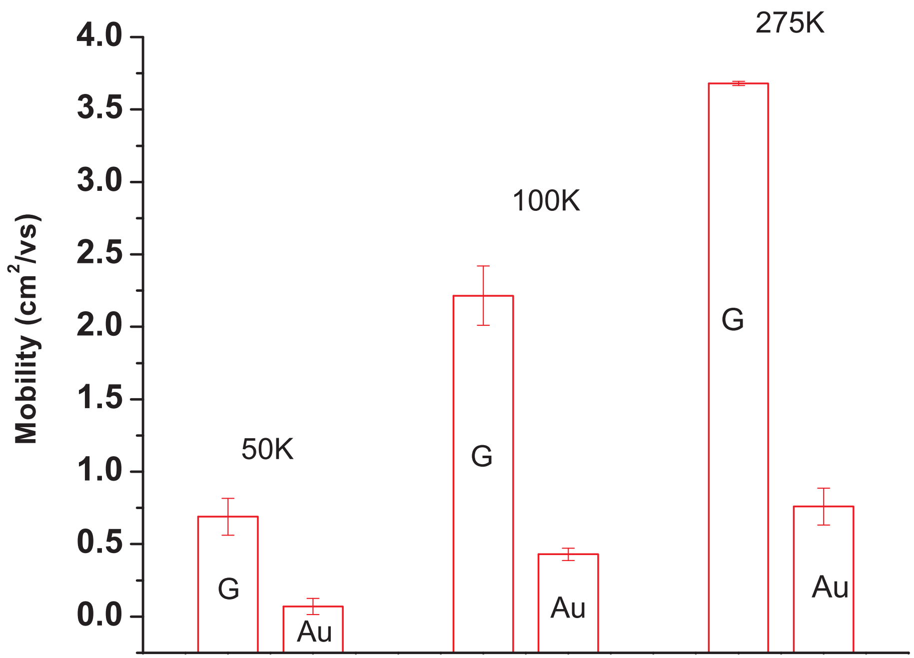
S Sarma, Review of Modern Physics, 2011, 83, 407

2. It is flexible, transparent and biocompatible

Better Interaction between Carbon-Based Materials







Graphene-CNT Stretchable Transistors

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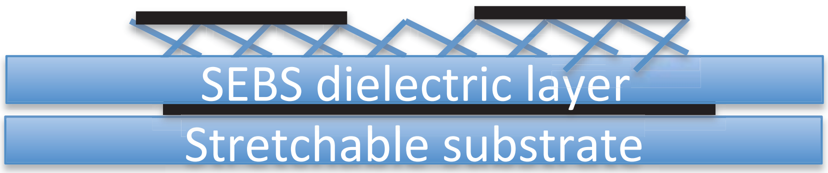
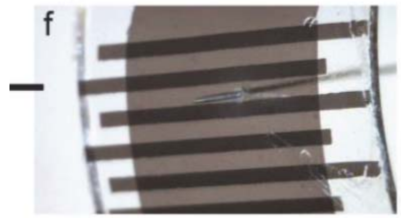
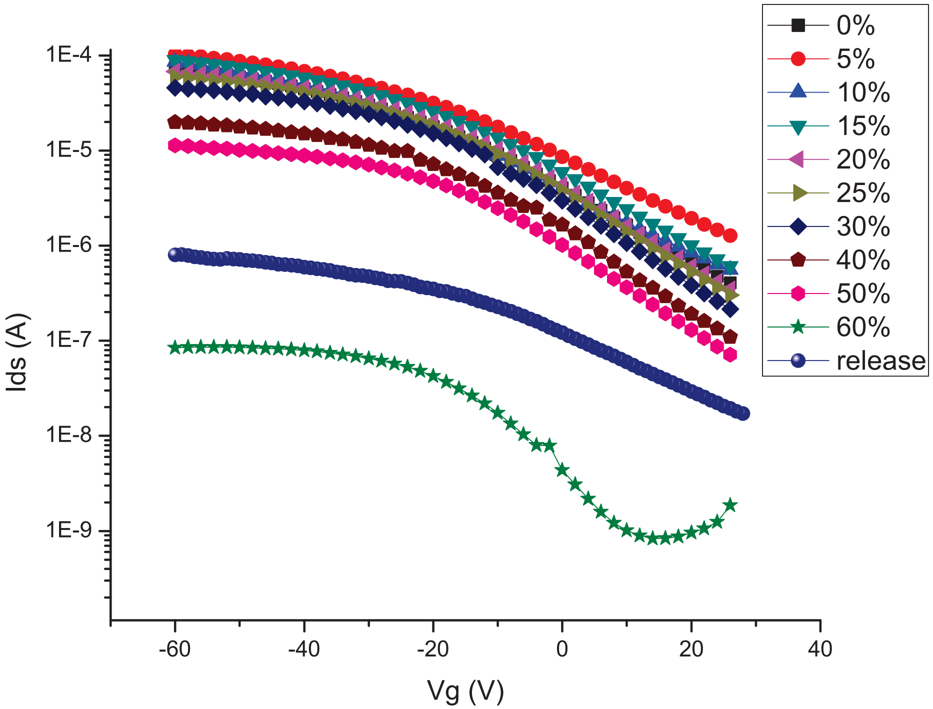
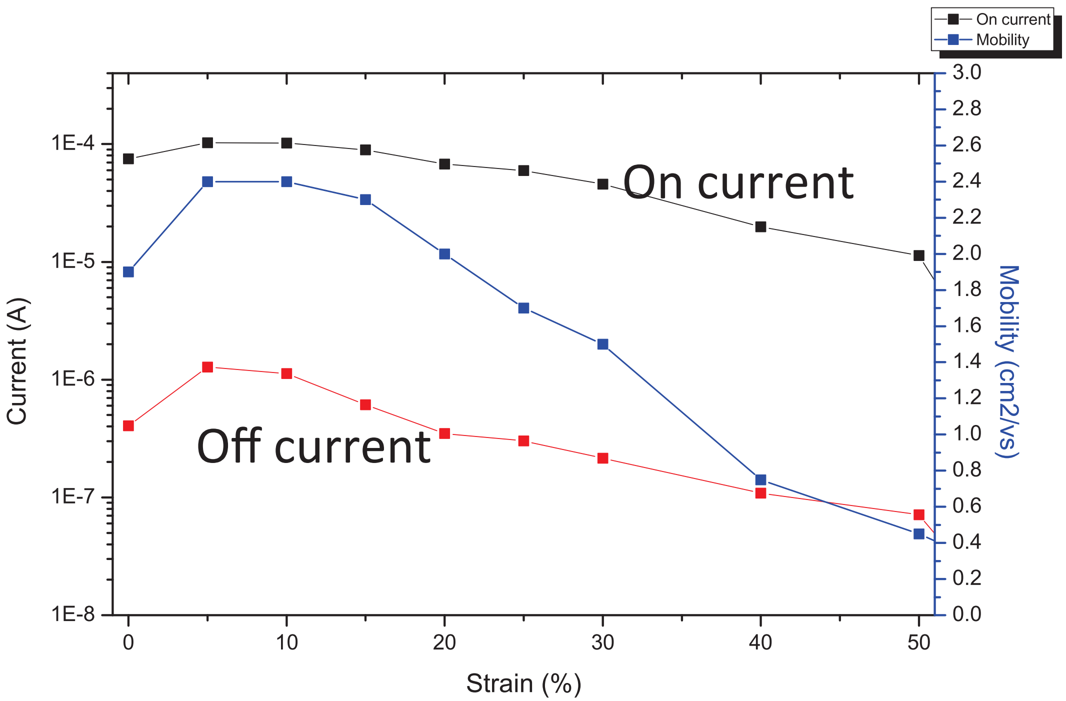
Our goal is to fabricate ultra-transparent and stretchable Graphene-based transistors.





vs

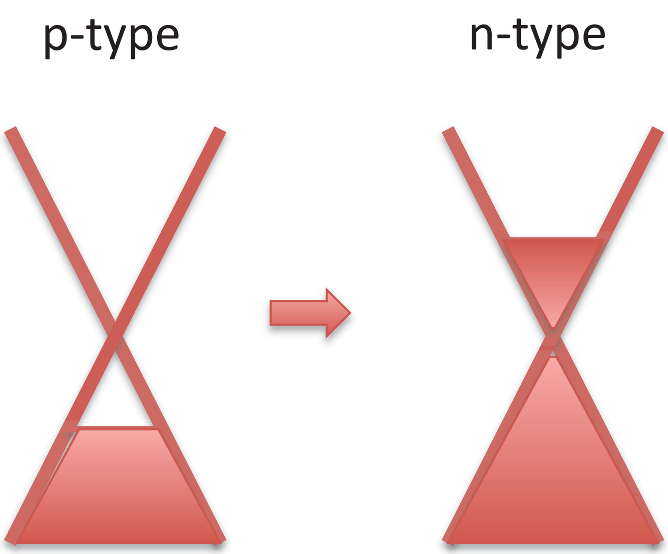




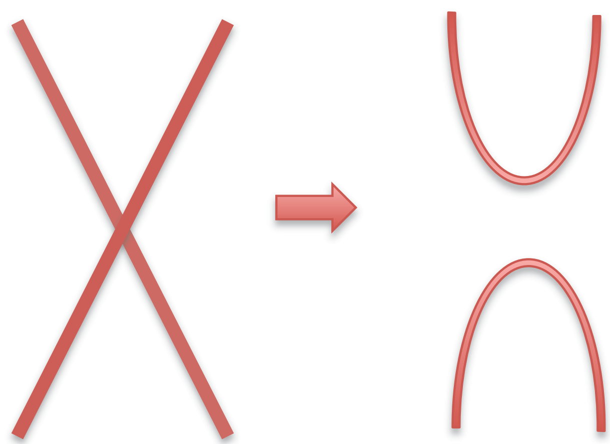
Graphene toward Ideal Electronic Materials

To control graphene electronic properties via graphene-organic interface

a) To control Fermi level



b) To open up band gap



Importance of Controlled Fermi Level

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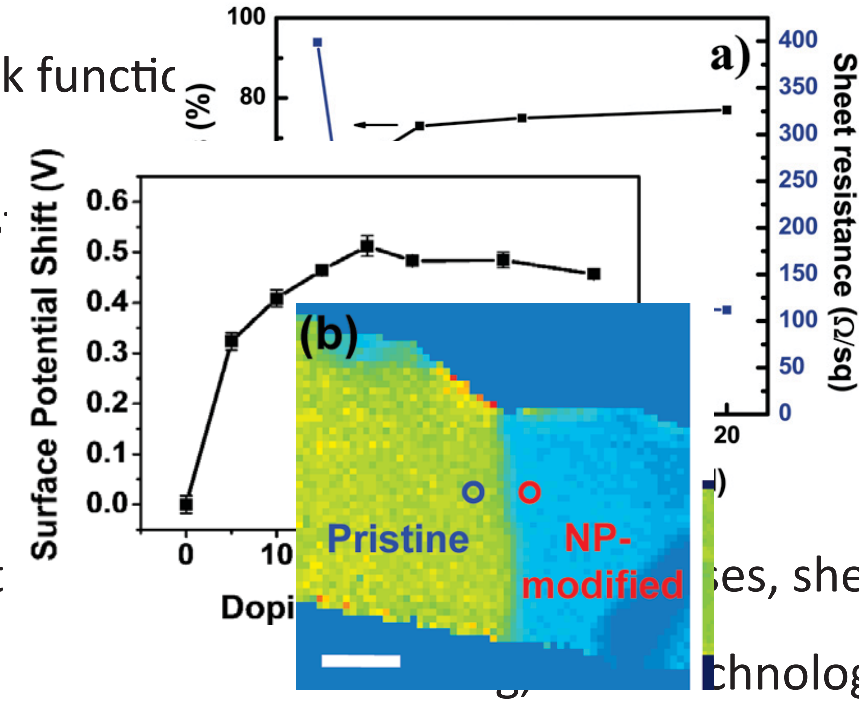
1) Tuning conductivity

2) Modulating work functic

3) Creating heteros



As t ses, sheet resistance decreases

chnology, 2010, 21, 285205

By changing the doping time, the surface potential of graphene is modulated to make efficient contact to different materials

By having complementary doping, p-n junctions can be created.

Y Chen, ACS Nano, 2011, 3, 26051

J Kong, ACS Nano, 2010, 5, 2689

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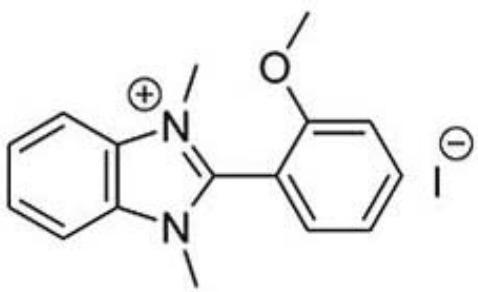
Design New n-type Dopant

2-(2-Methoxyphenyl)-1,3-dimethyl-1H-benzoimidazol-3-ium Iodide



o-MeO-DMBI-I

P Wei, Z Bao, J. Am. Chem. Soc. 2012, 134, 3999
P Wei, Z Bao, J. Am. Chem. Soc. 2010, 132, 8852

- *o*-MeO-DMBI is air-stable and can be stored and handled in air for extended periods without degradation
- Solution process or vacuum deposition

Process of Doping Graphene

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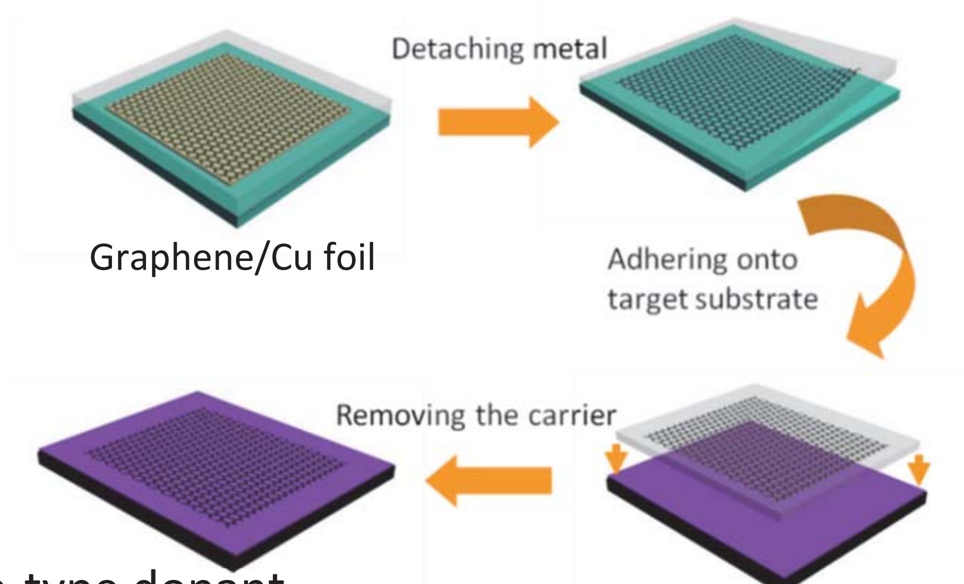
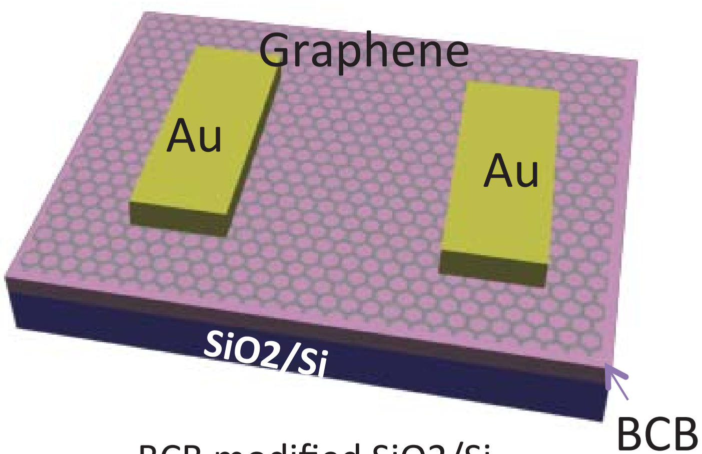
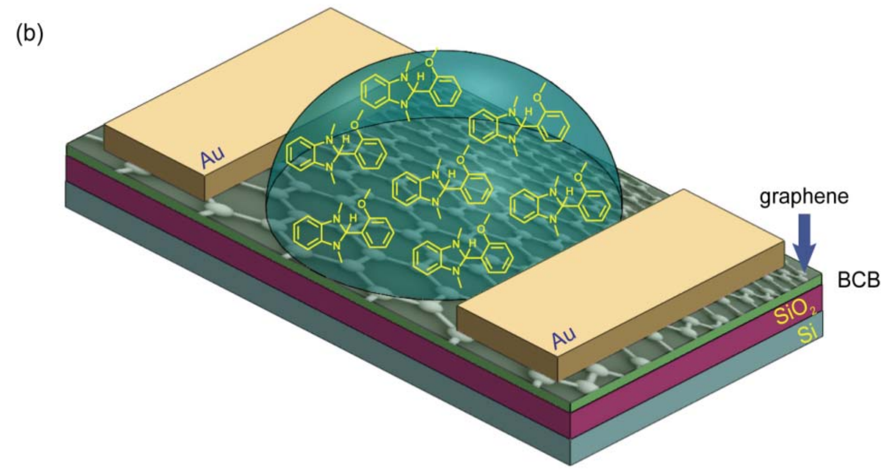
1. Transfer graphene and fabricate graphene devices



2. Spin-coating of n-type dopant



BCB modified SiO2/Si



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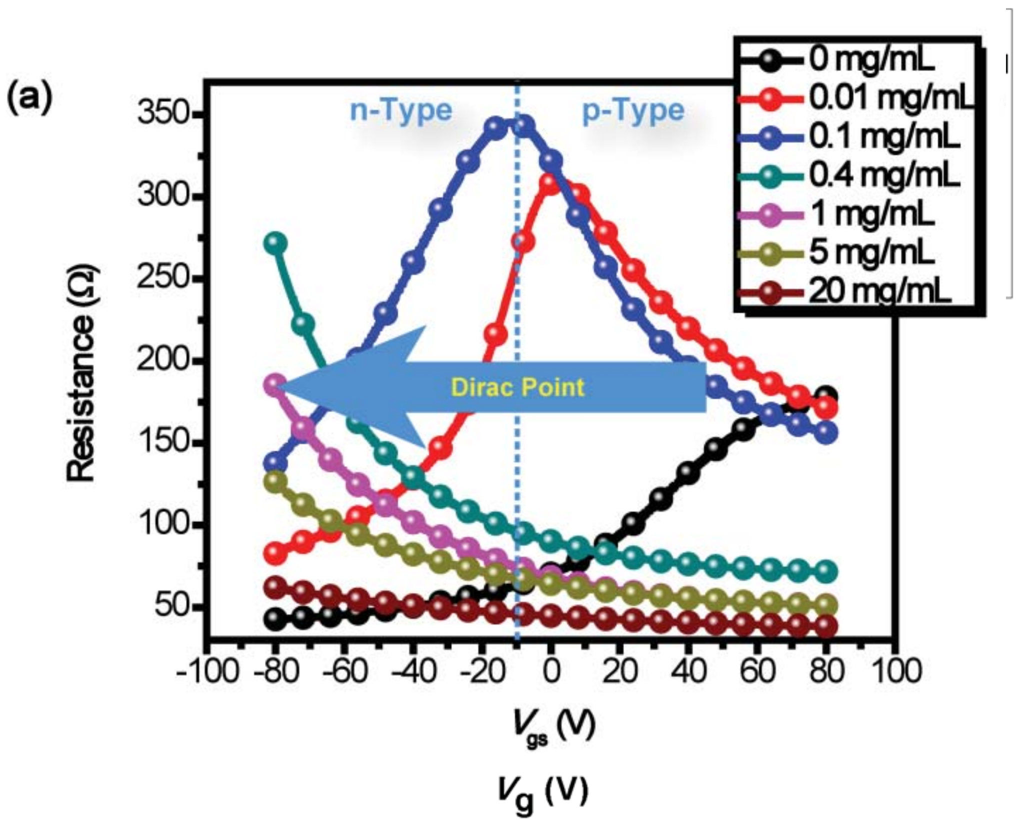
Peng Wei†; Nan Liu†; Z Bao, Nano Lett. 2013, 13, 1890

Transport Behavior Before and After n-doping



Transfer curves: charge neutrality points (CNPs) shift downwards.

Indicating: p-type to ambipolar to n-type

Peng Wei†; Nan Liu†; Z Bao, Nano Lett. 2013, 13, 1890

UPS Study Before and After n-doping

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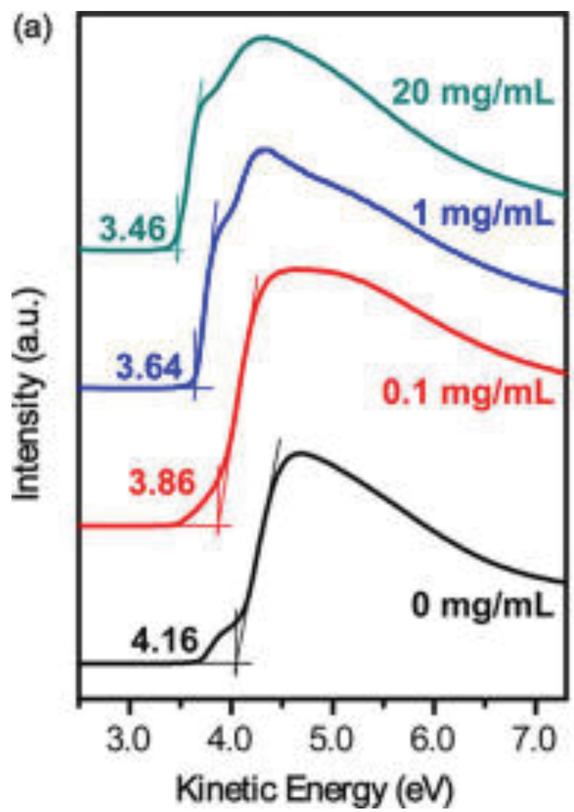
Ultraviolet photoelectron spectroscopy (UPS):



- 0.5eV shift of work function by n-type doping
- This indicates an interfacial charge transfer from the n-type dopant to the underlying graphene

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Peng Wei†; Nan Liu†; Z Bao, Nano Lett. 2013, 13, 1890

Application 1: Inverter

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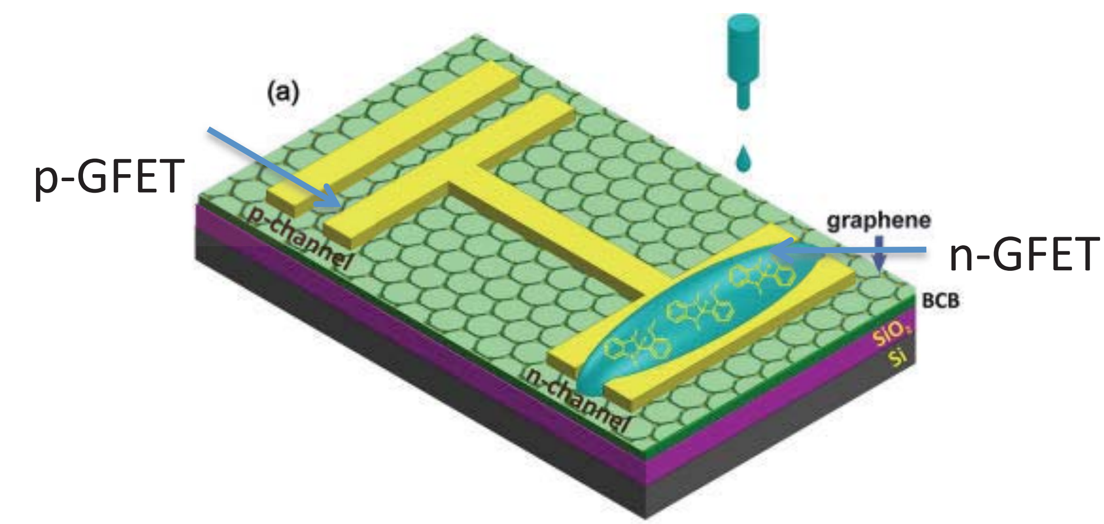
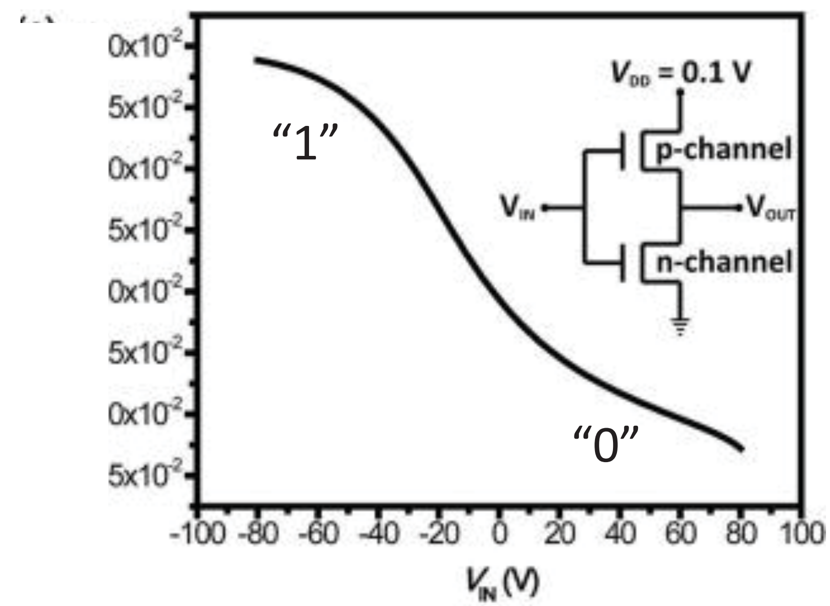
A complementary inverter, that integrates both p- and n- type graphene transistors





An inverter behavior: output level at low; input level at high

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Peng Wei†; Nan Liu†; Z Bao, Nano Lett. 2013, 13, 1890

Application 2: p-n Junction

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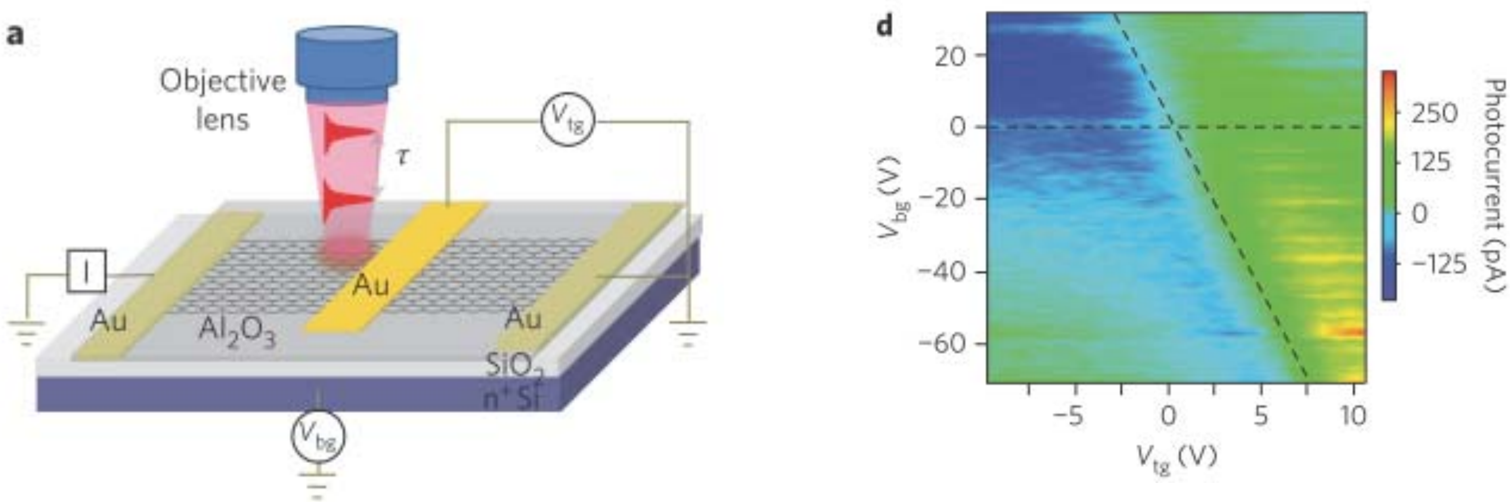
Using dual gates to fabricate graphene p-n junction as a photosensing device



- It requires 4 terminals to operate the device, which complicates both fabrication and the operation of the photodetector.
- Metal top gates prevent creation of flexible, all-transparent photodetectors

Can we use chemical doping to create p-n junctions to address these challenges?

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X Xu, Nature Nanotechnology 2012, 7, 114

Fabrication of Graphene p-n Junctions

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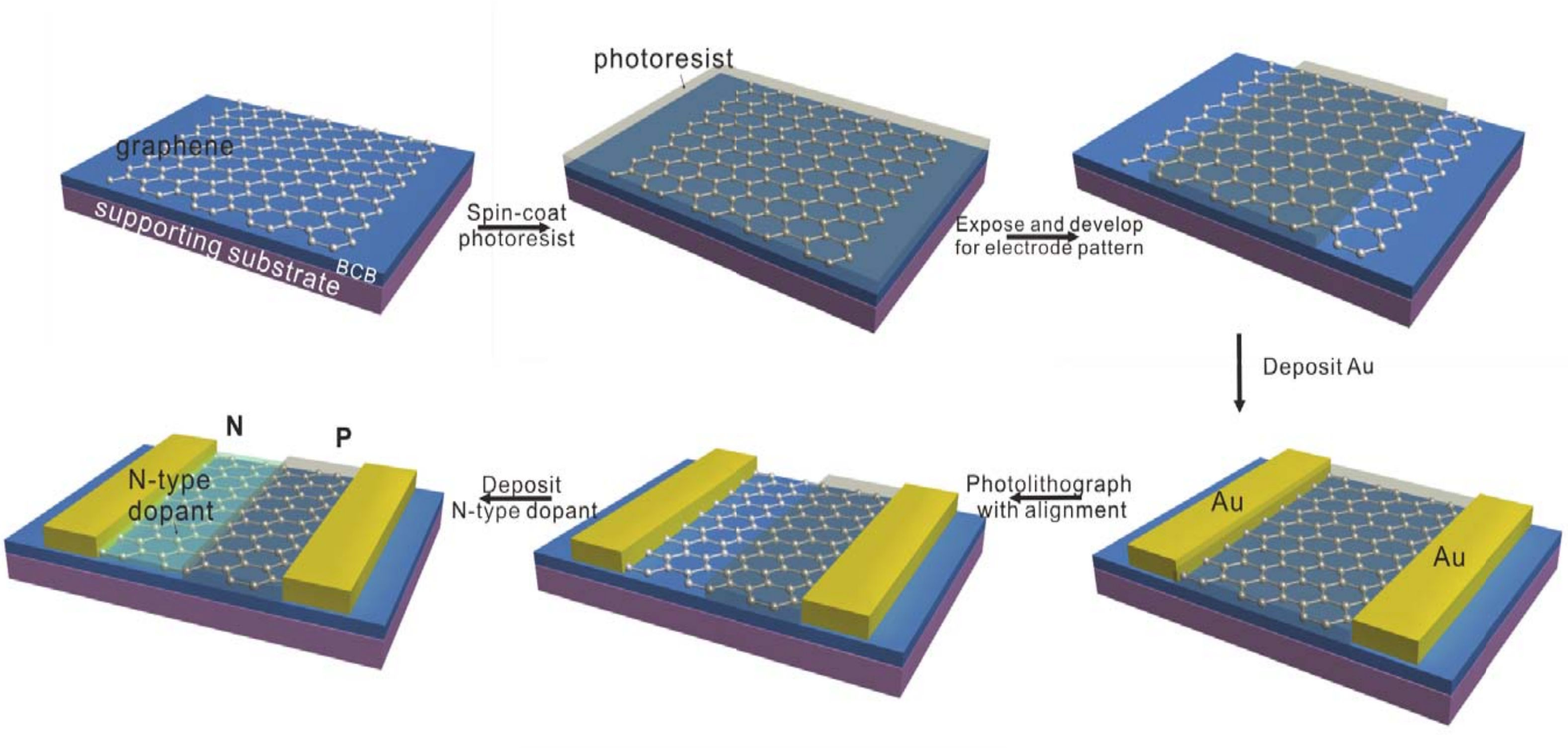

- Selectively mask part of the channel and apply n-dopant to the exposed part
- P-region: as-transferred graphene; N-region: n-type doped graphene

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Nan Liu, Z Bao, Nano Lett, 2014, 14, 3702

Formation of p-n Junctions

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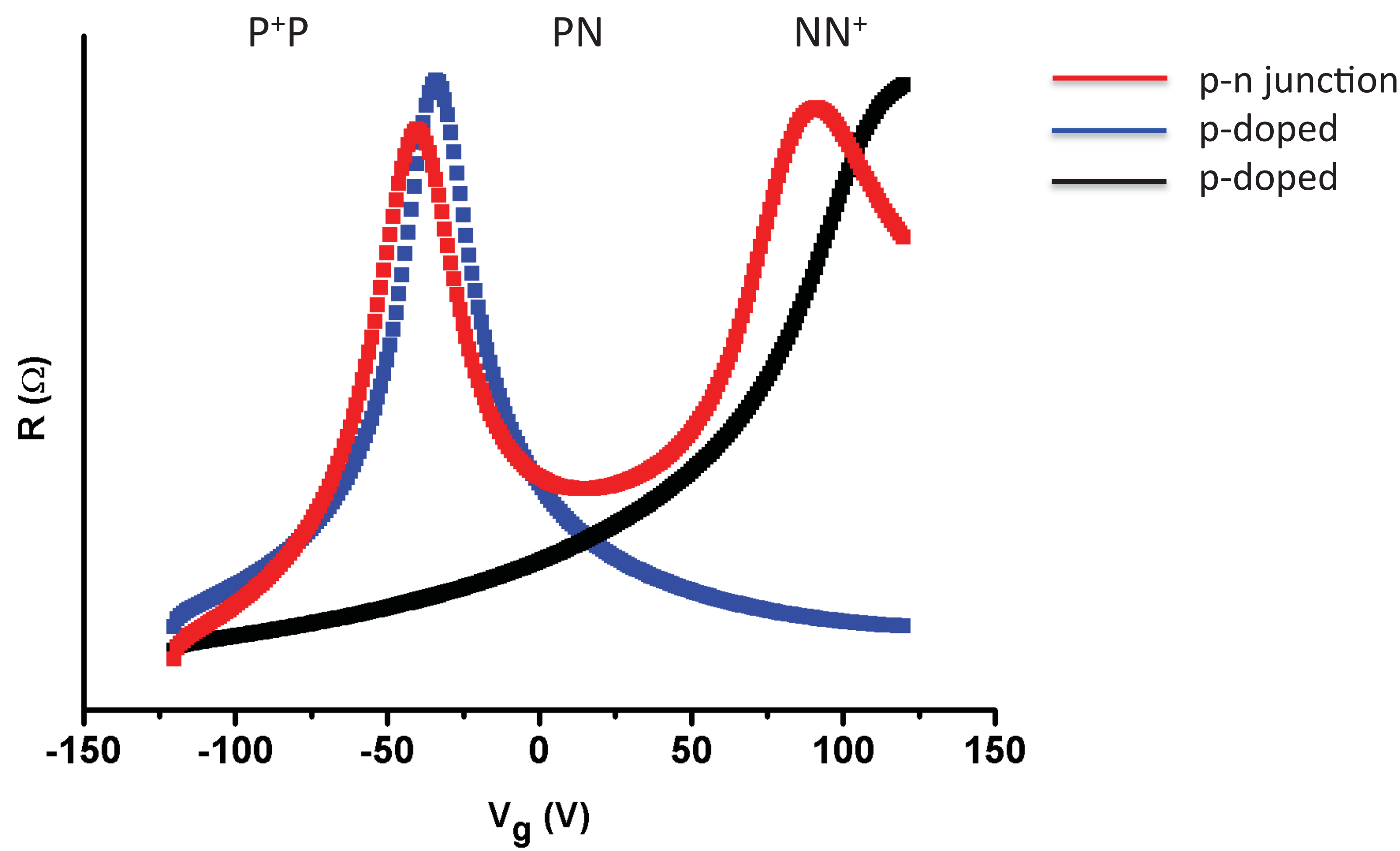

Double charge neutrality points (CNPs) confirms the formation of p-n junction.

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Nan Liu, Z Bao, Nano Lett, 2014, 14, 3702

Photoresponse of p-n Junctions

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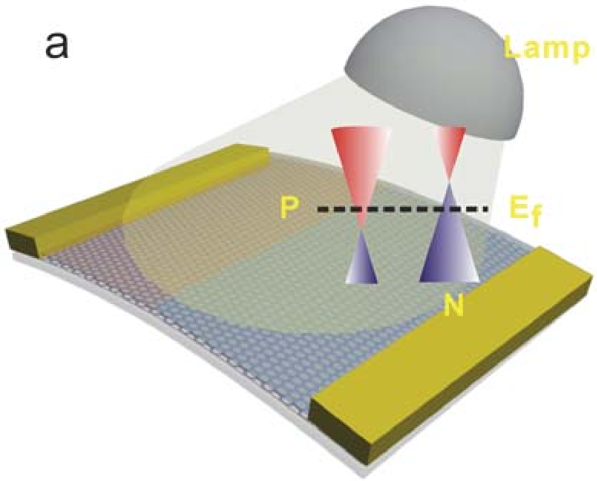
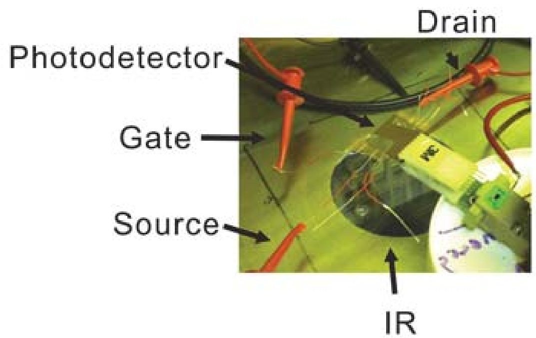
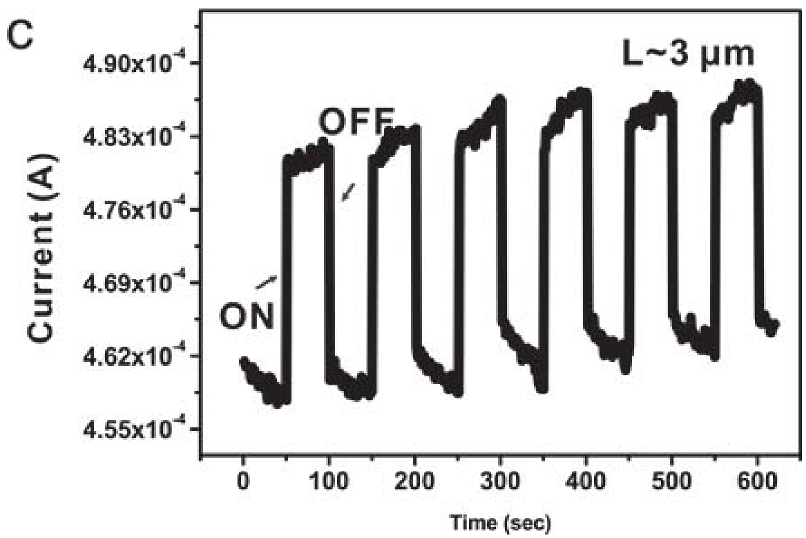
Schematic of the p-n junction photodector



Setup of the phototest





Photocurrent density (10^{-4}A/cm^2)†	Photoresponsivity (mA/W)
$(5.50\pm0.47)\times10^{4}$	(1.20 ± 0.11) $)\times10^{4}$

- Positive IR photoresponse
- Fast response speed
- High responsivity

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Nan Liu, Z Bao, Nano Lett, 2014, 14, 3702

Transparent and Flexible IR Photodetectors

Transparency

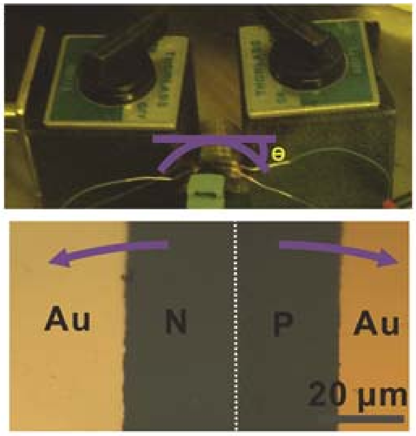
Flexibility

a

b

Bending test

c



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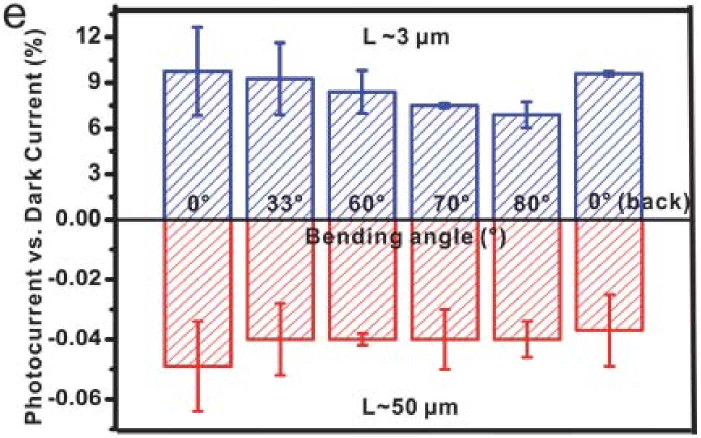

- The photocurrent is almost same at different bending angles up to 80 degrees
- The bending/releasing processes can be repeated for many times

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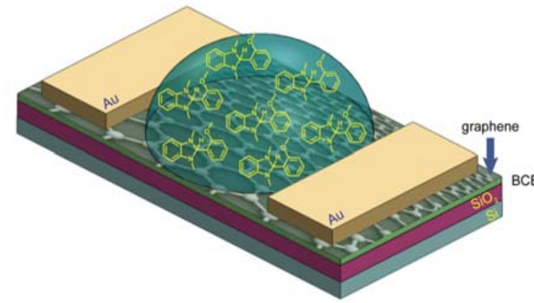
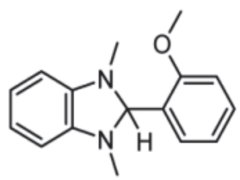
Nan Liu, Z Bao, Nano Lett, 2014, 14, 3702

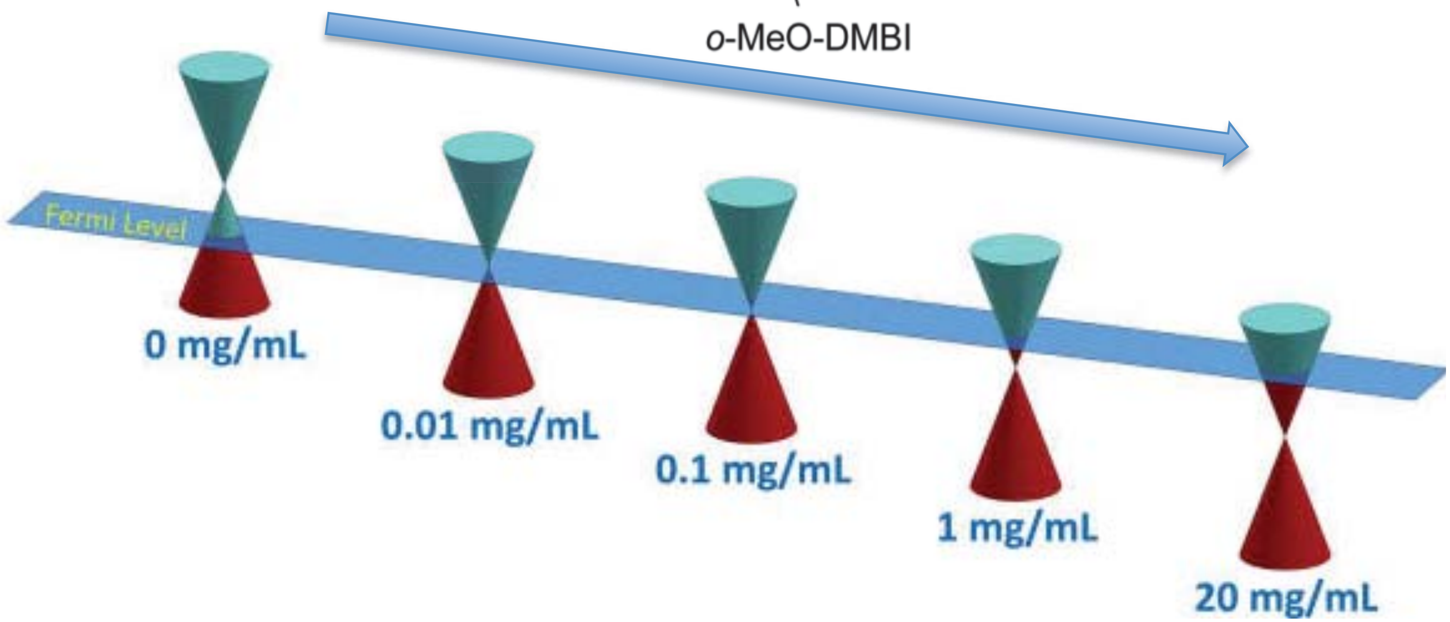
Summary I

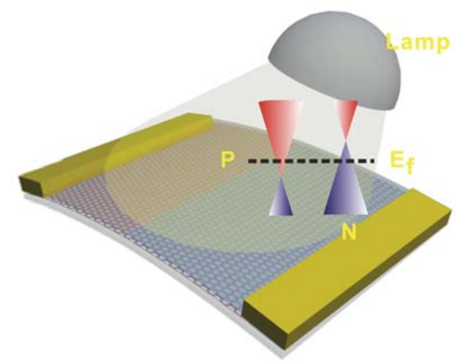
- O-MeO-DMBI is an efficient n-dopant for graphene
- New device structures (flexible and all transparent graphene photodetectors)are enabled by chemical n-doping





o-MeO-DMBI





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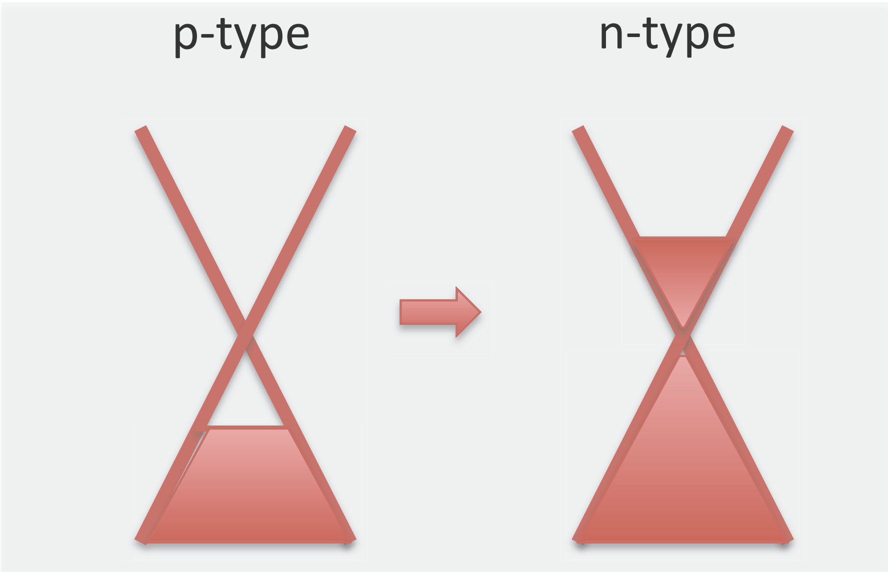
Peng Wei†; Nan Liu†; Z Bao, Nano Lett. 2013, 13, 1890
Nan Liu, Z Bao, Nano Lett, 2014, 14, 3702

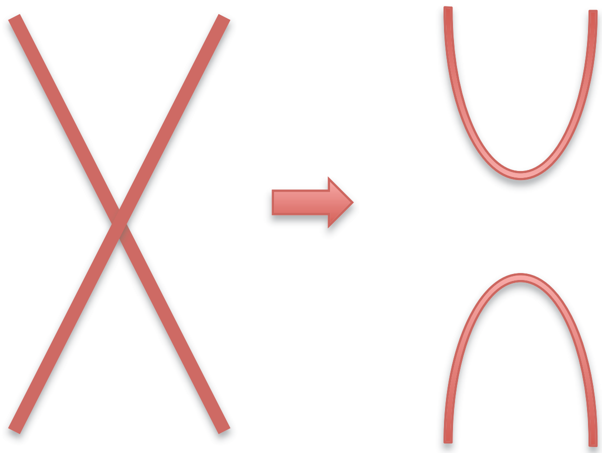
Outline

To control graphene electronic properties via graphene-organic interface

a) To control Fermi level



b) To open up band gap



Why Bandgap?

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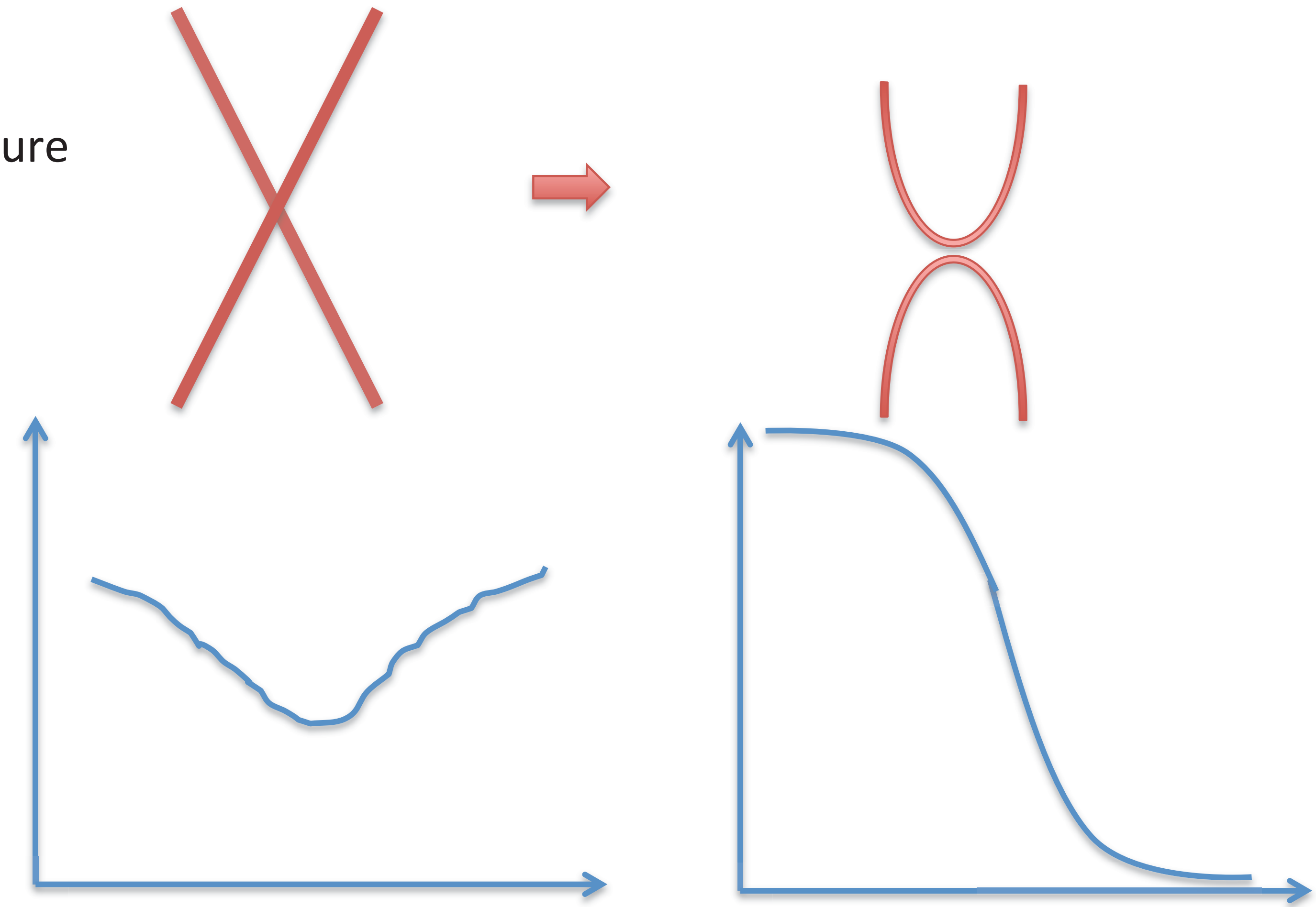
Band structure

Transport curves



- The application of graphene in digital electronics is limited by its lack of a band gap.
- No full turn-off; poor on/off ratio; large static power consumption

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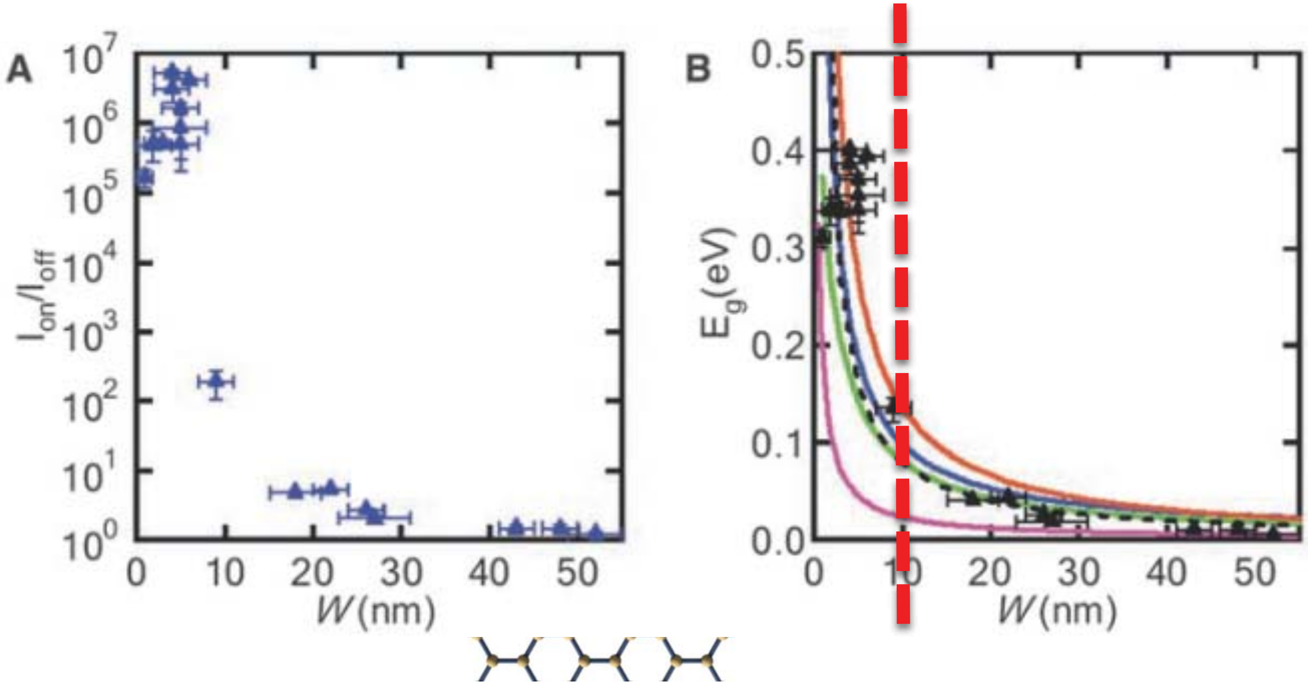
Bandgap in GNR



$$E_g(eV) = \frac{0.8}{w(nm)}$$

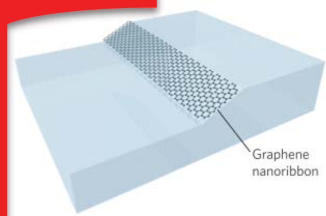
GNR below 10 nn will result in a sufficient band gap and large on/off ratio for room temperature operation.

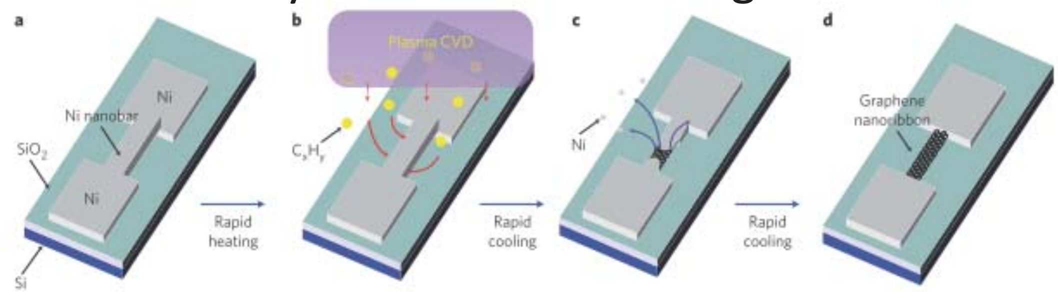
H Dai, Science 2008, 319, 1229

Synthetic Approaches to GNRs — Bottom up

1. High Temperature Growth

Lack scalability and not small enough





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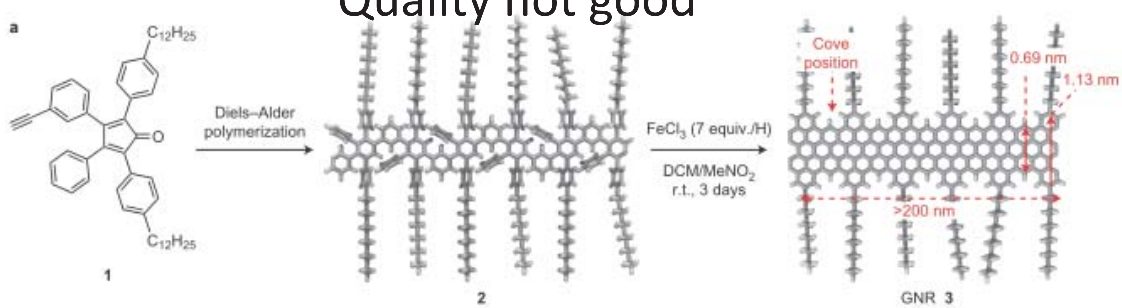
Heer*, et al. Nature Nanotechnology, 2010, 5, 729

Walt A. de Heer*, et al. Nature 2014, 506, 349

Toshiaki Kato* et al, Nature Nanotechnology, 2012, 7, 651

2. Or anic Synthesis

Quality not good



Klaus Mullen* et al, Nature Chemistry, 2014, 6, 126

DNA Bio-template to GNRs

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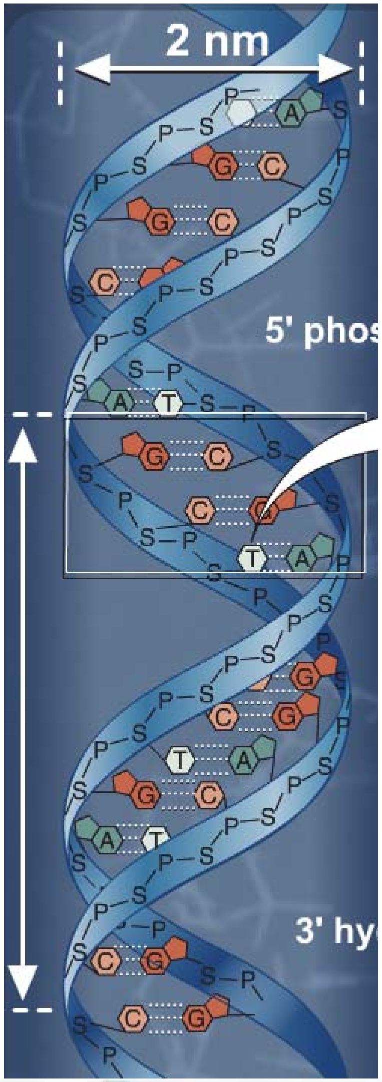
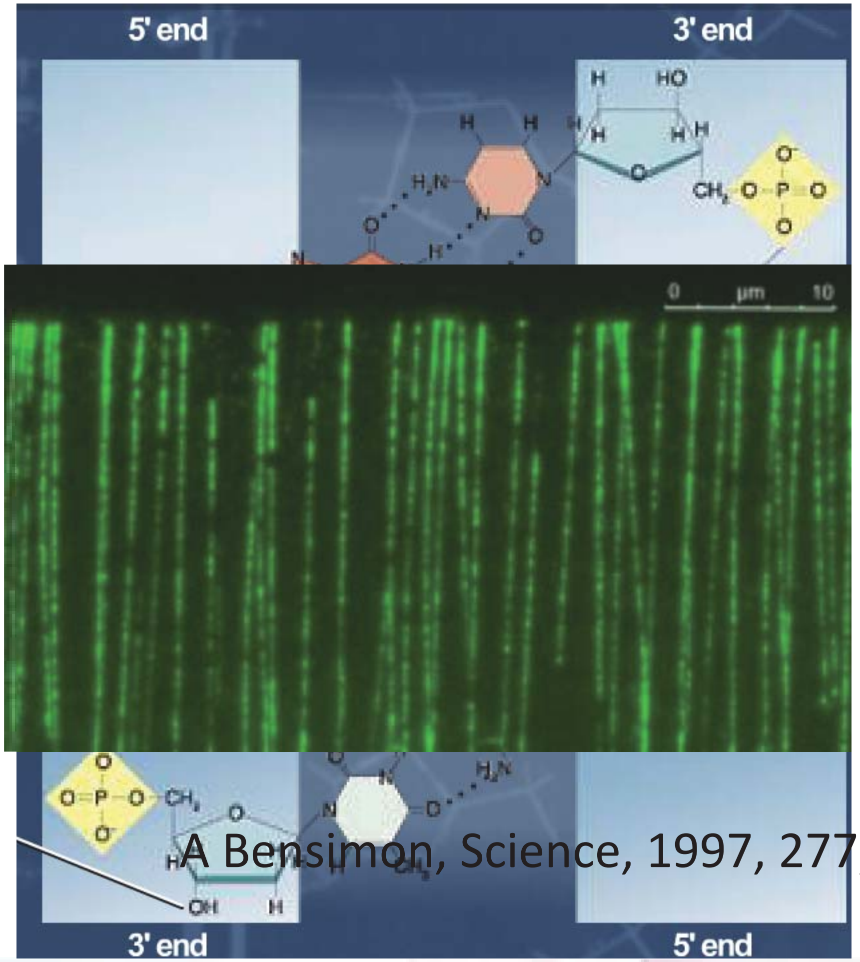
1. DNA width ~2 nm



2. Easily aligned with a molecular combing method, which can pre-pattern GNRs by DNA template for large scale circuits



A Bensimon, Science, 1997, 277, 1518

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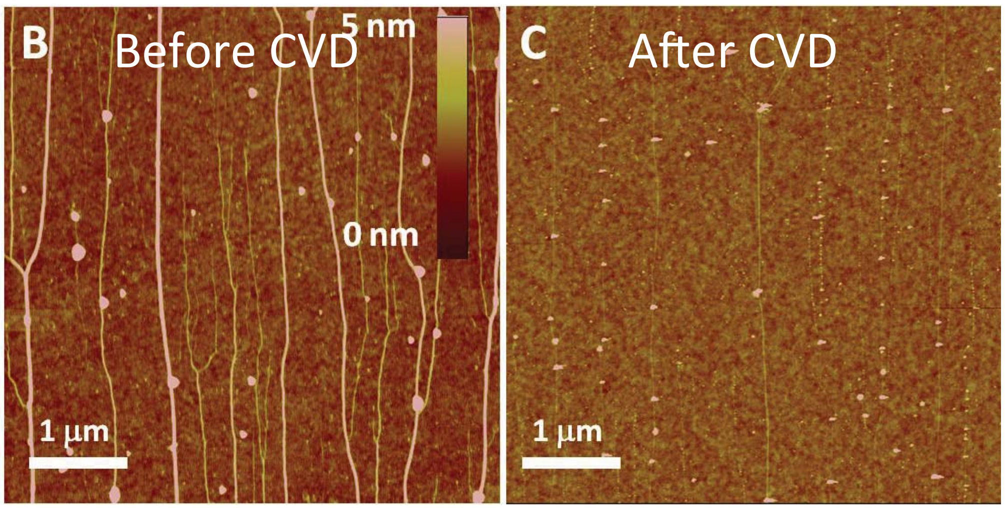
GNRs from DNA



Morphology of the post-growth surface duplicate that of the DNA template (1D parallel lines)

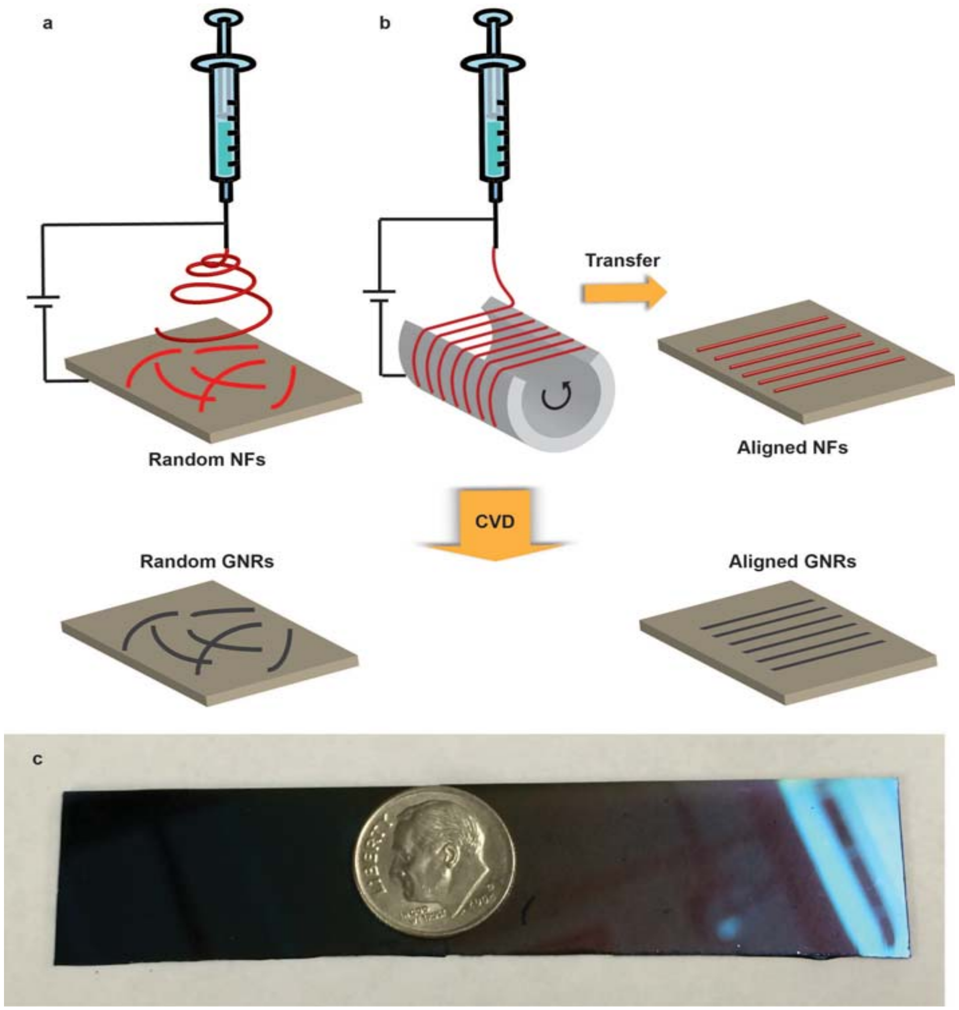
A Sokolov†, F. Yap†, N Liu, Z Bao, Nature Comm 2013,4:2402

Electrospinning

❖ Particularly interested in electrospun polymer

1. A larger variety of polymer can be electrospun, allowing us to explore the correlation between chemical structure and GNRs.
2. A powerful tool to create 1D polymer with higher scalability and lower cost.

Electrospun Polymer to GNRs



1. Methane CVD on these nanofiber templates yielded highly-graphitic GNRs with well-controlled widths.

2. These nanofibers can be aligned on a metallic rotor with a gap.

3. Scalable demonstration

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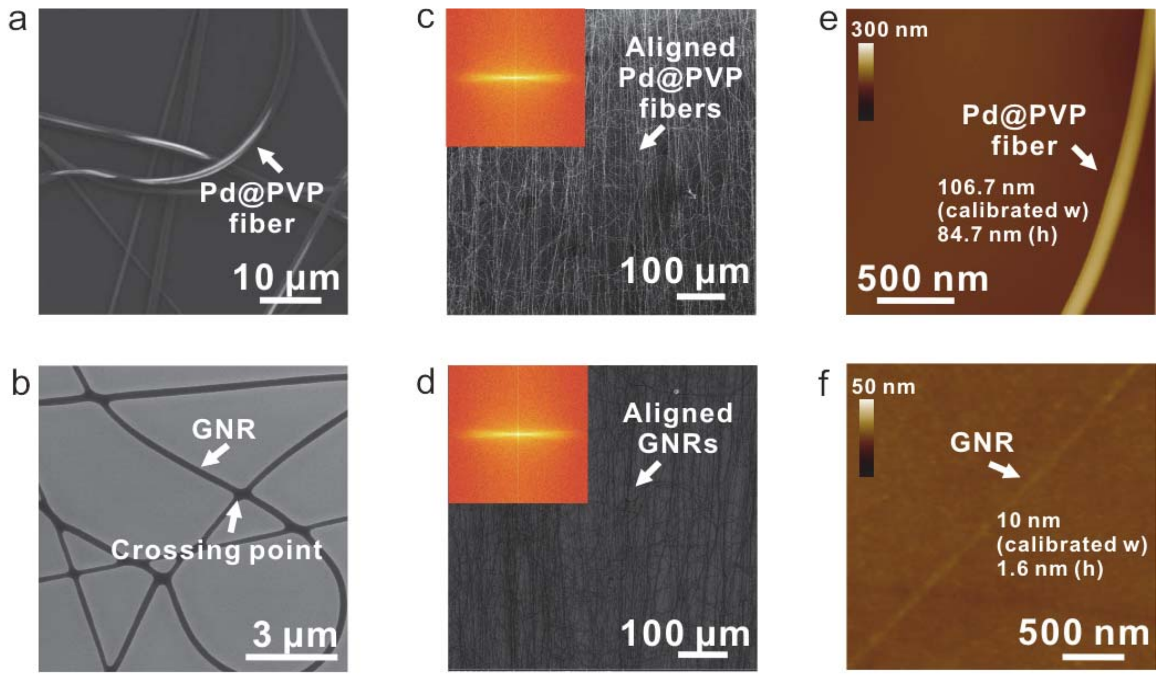
Nan Liu, Z Bao, J. Am. Chem. Soc., 2014, 136, 17284

Overview of the GNRs - Morphology



- The post-growth substrate shows a similar morphology of the polymer fibers before growth.
- The 1D structures on the post-growth substrates are extremely long.

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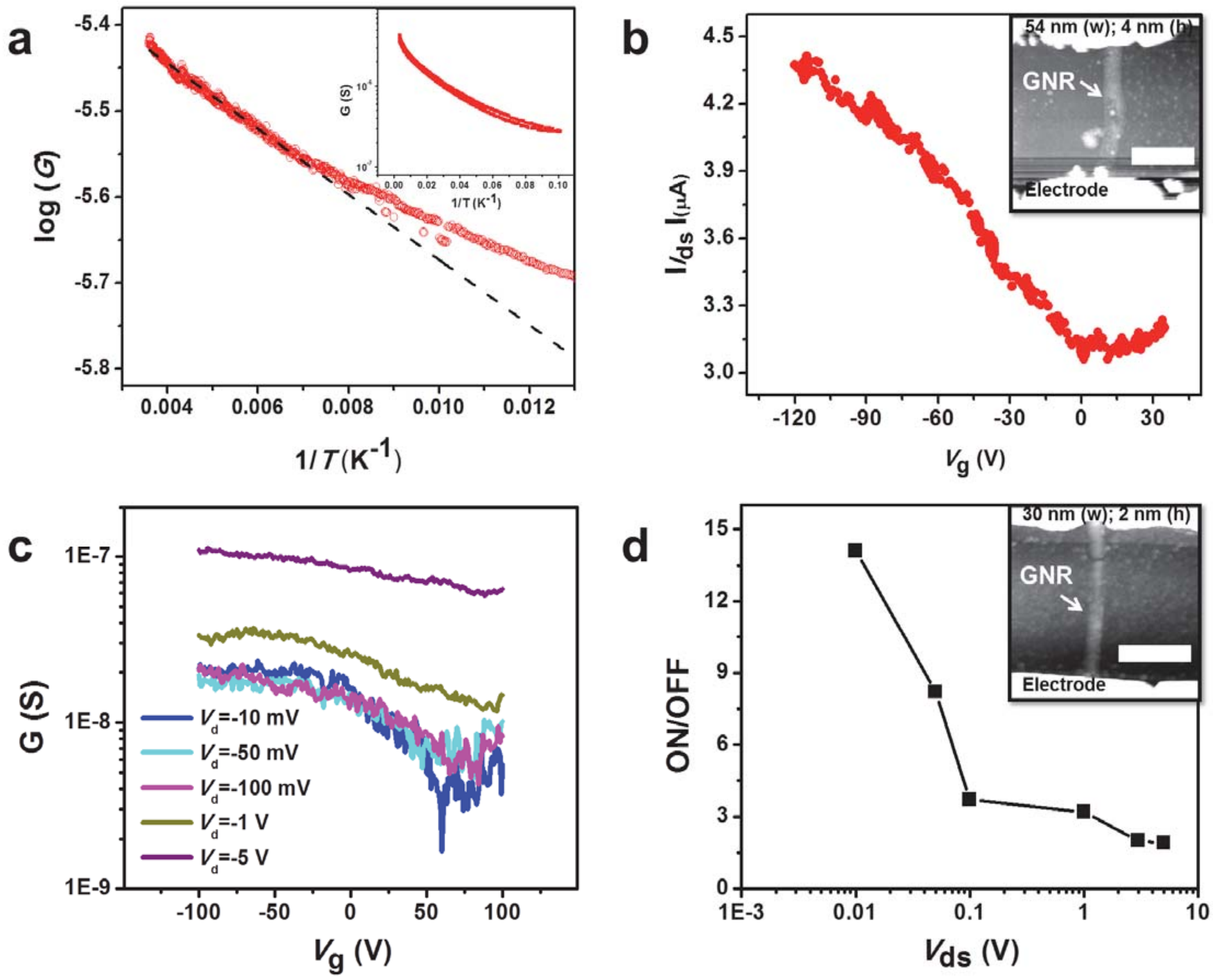
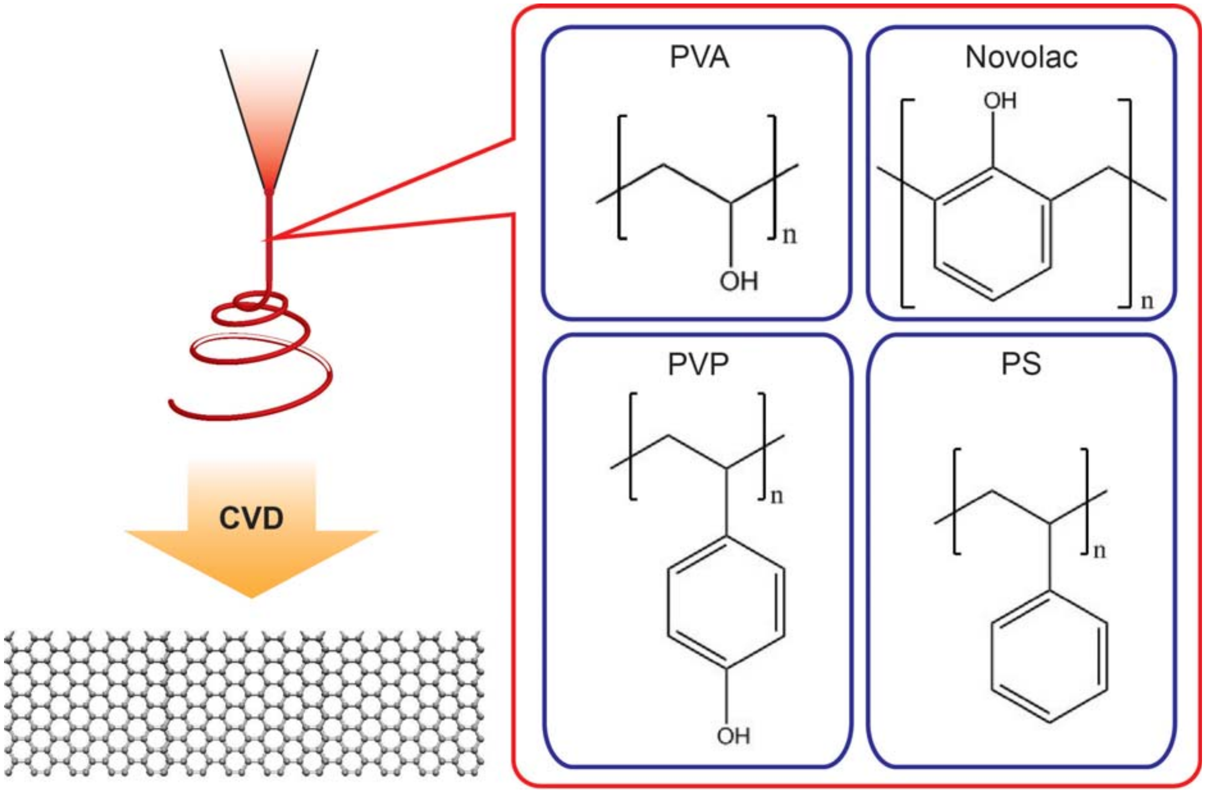
Nan Liu, Z Bao, J. Am. Chem. Soc., 2014, 136, 17284

Overview of the GNRs – Electronic Properties



Nan Liu, Z Bao, J. Am. Chem. Soc., 2014, 136, 17284

Effect of Chemical Structure on the Graphitization Degree



- ✓ Metal-binding functional groups
- ✓ Aromatic moieties

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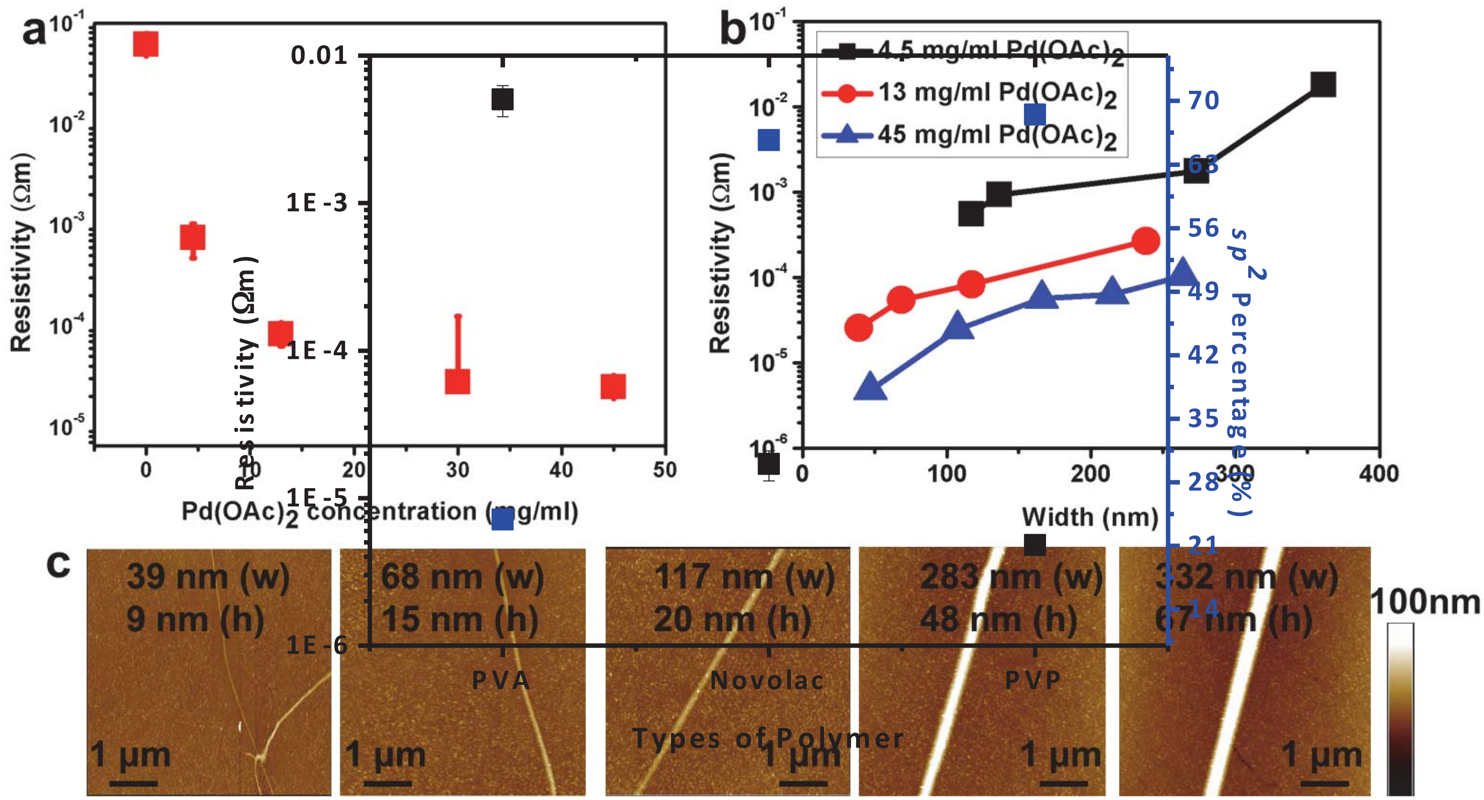
Effect of Chemical Structure on the Graphitization Degree



- Higher concentration of metal ions corresponds with lower resistivity, / Polymer with aromatic moieties leads to higher electrical conductivity,
  indicating metal-binding functional groups is crucial.

Nan Liu, Z Bao, ACS Nano, 2015, ASAP

Summary II

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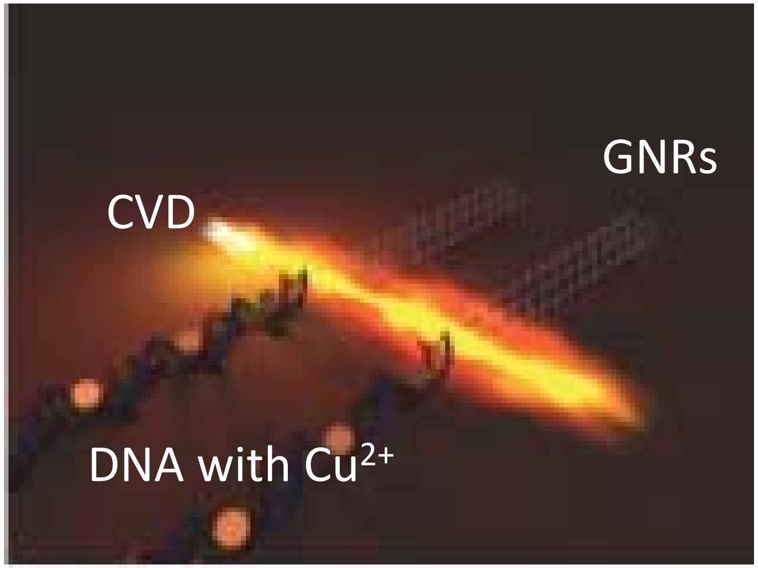
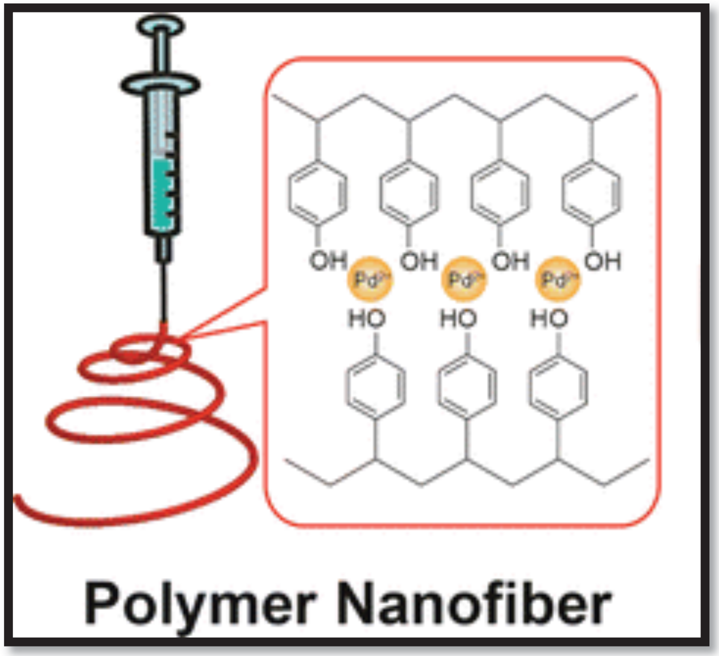
- First demonstration of large scale, polymer templated GNR growth
- Understand the effect of chemical structure on the quality of GNR





A Sokolov†, F. Yap†, N Liu, Z Bao, Nature Comm 2013,4:2402
Nan Liu, Z Bao, J. Am. Chem. Soc., 2014, 136, 17284
Nan Liu, Z Bao, ACS Nano, 2015, ASAP

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Conclusion

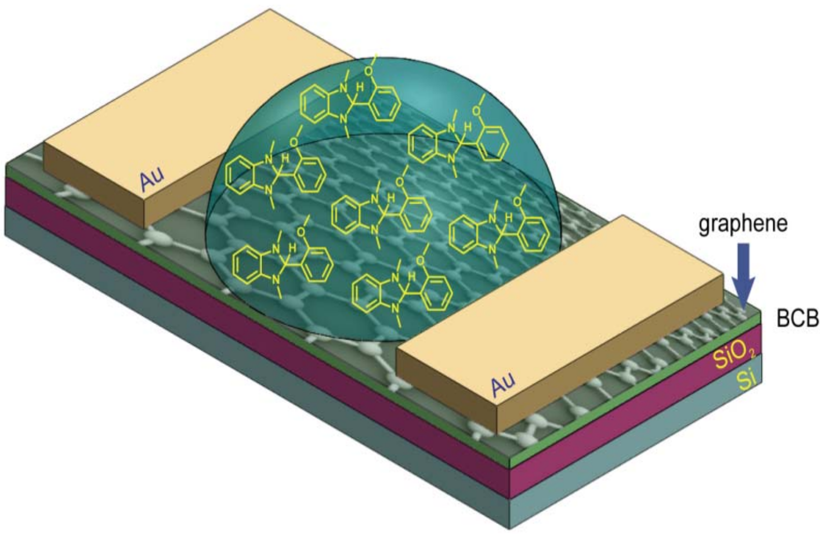
To control graphene electronic properties via graphene-organic interface

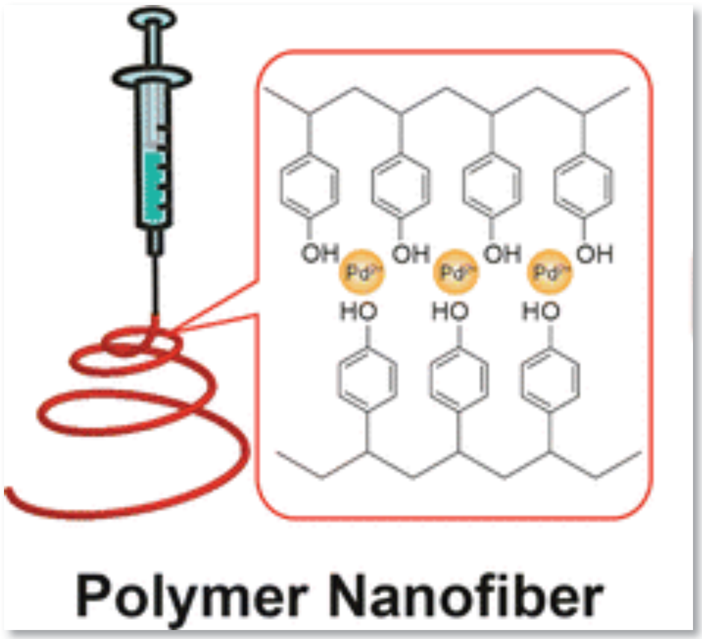
Graphene-organic molecules

Graphene-polymer

a) To control Fermi level: n-type doping

b) To open up band gap: to GNRs





To flexible electronics

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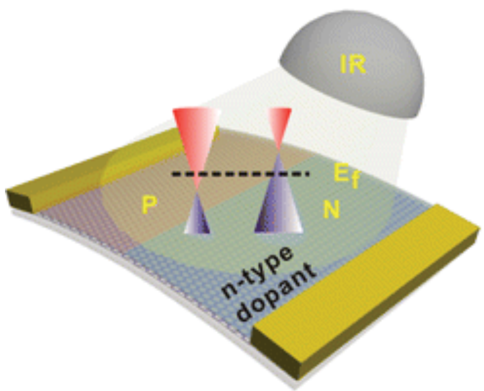
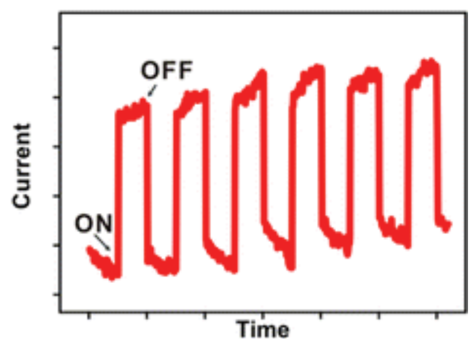
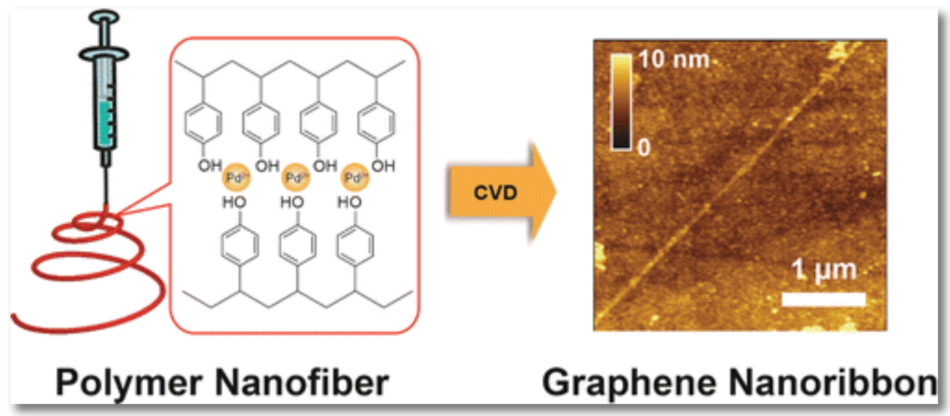
Thank you all for coming and listening!







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