Better Standards, Better Life

Probing Electronic Properties of Two-Dimensional Materials with a Planar Tunnel Junction

2017. 11. 15

Suyong Jung

Quantum Technology Institute

KRISS 한국표준과학연구원

KRISS 현황

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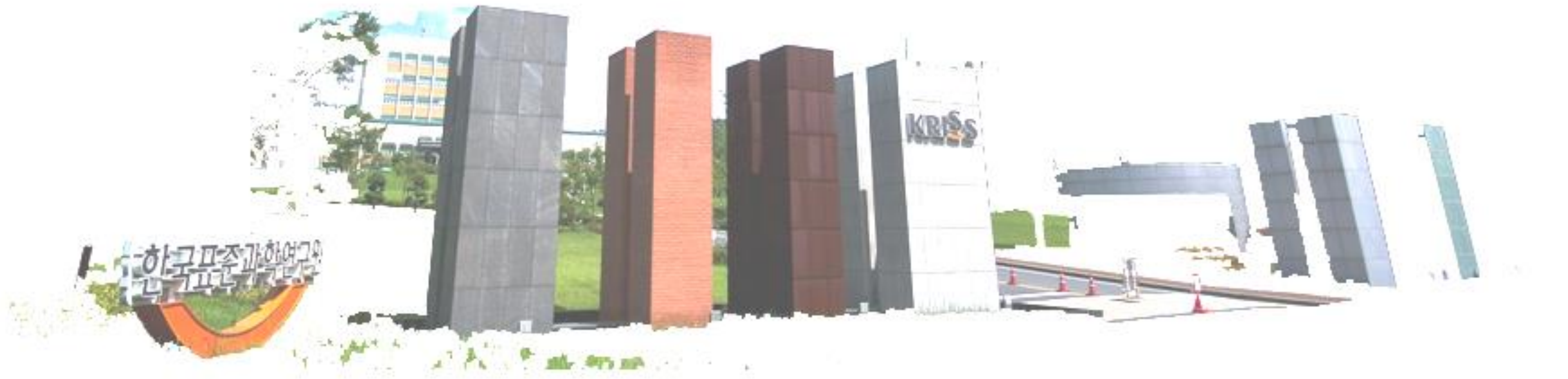

한국표준과학연구원

설립 근거

헌 법

제127조 제2항

"국가는 국가표준제도를 확립한다"

국가표준 기본법

제13조 (국가 측정표준 대표기관)

"한국표준과학연구원을 국가측정표준 대표기관으로 한다"

임무와 기능

국가 측정표준 확립및 유지향상

"편리하고 안전한 사회를 위한 기준, 국가측정표준 확립"

- 국가측정표준 원기 및 국제 소급성 유지
- 측정표준 유지 및 확대

세계 측정표준 선도기관

측정과학 기술 연구개발

"국가 산업경쟁력을 선도하는 측정기술 연구"

- 새로운 측정표준 연구개발
- 미래산업 선도 측정기술 연구개발

측정과학 기술적시 공급

측정표준 측정과학기술 보급 및 서비스

"산업체의 측정능력 향상을 뒷받침하는 믿을 수 있는 지원자"

- 교정/시험/인증표준물질(CRM) 개발 및 보급
- 산업체 측정 전문인력 교육

산업협력 지원중심 기관

연혁(KRISS 42년)

1975.12 국가표준기관으로
한국표준연구소 설립

1978.3 대덕연구단지
내 현 위치 입주

1991.10 "한국표준과학연구원"으로
기관명칭 변경 (천문대 및
기초과학지원연구센터 통합)

1999. 2 "국가표준기본법"에
국가측정표준
대표기관으로 명문화

2004.10 과학기술부
공공기술연구회
소관기관으로 변경

2014. 6
미래창조과학부
국가과학기술연구회
소관기관으로 변경

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2017. 7
과학기술정보통신부
국가과학기술연구회
소관기관으로 변경

과학기술정보통신부
Ministry of Science and ICT

nst 국가과학기술연구회
National Research Council of Science & Technology

(25 개 정부출연연구기관)

KRISS
한국표준과학연구원
Korea Research Institute of Standards and Science

KIST 한국과학기술연구원

한국물리연구원 ?

KIMM 한국기계연구원

한국천문연구원
Korea Astronomy & Space Science Institute

KFRI
한국식품연구원

KRICT
한국화학연구원

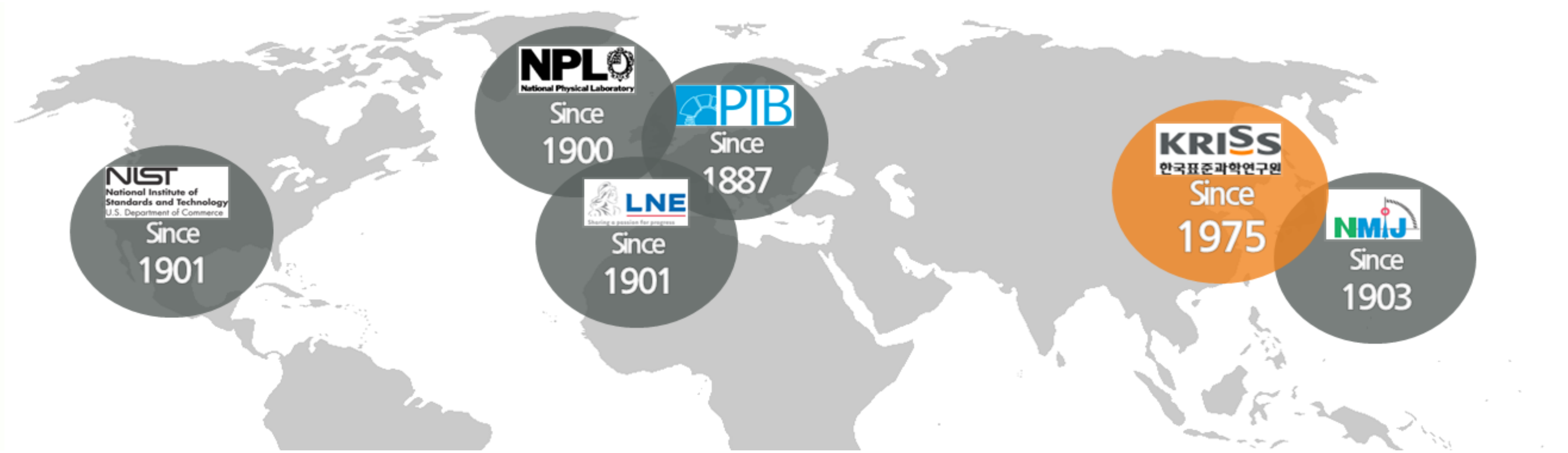
한국한의학연구원
KOREA INSTITUTE OF ORIENTAL MEDICINE

KBSI 한국기초과학지원연구원
KOREA BASIC SCIENCE INSTITUTE

KICT 한국건설기술연구원

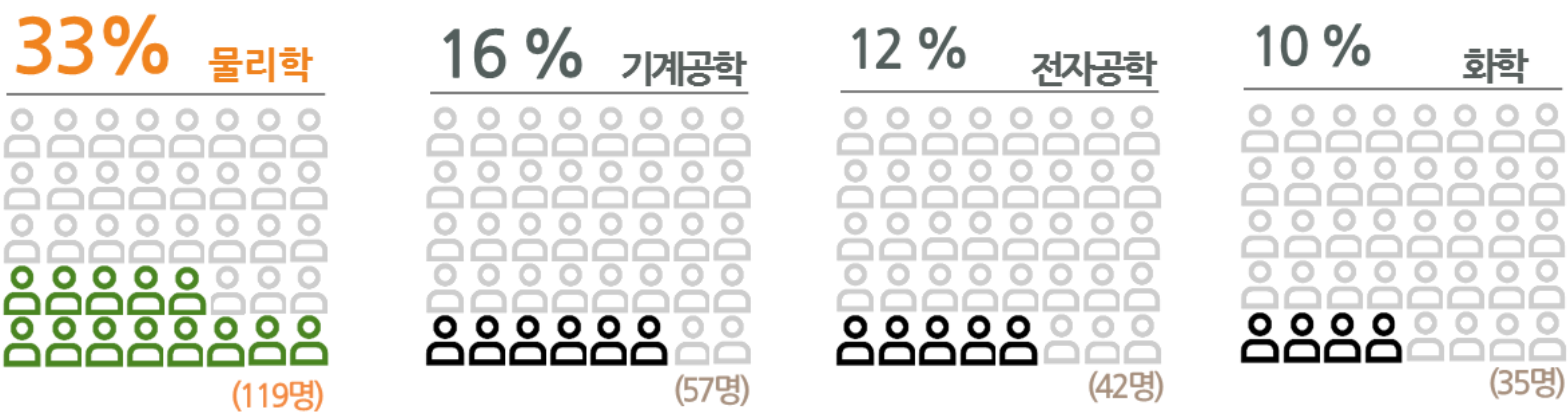
한국에너지기술연구원
KOREA INSTITUTE OF ENERGY RESEARCH

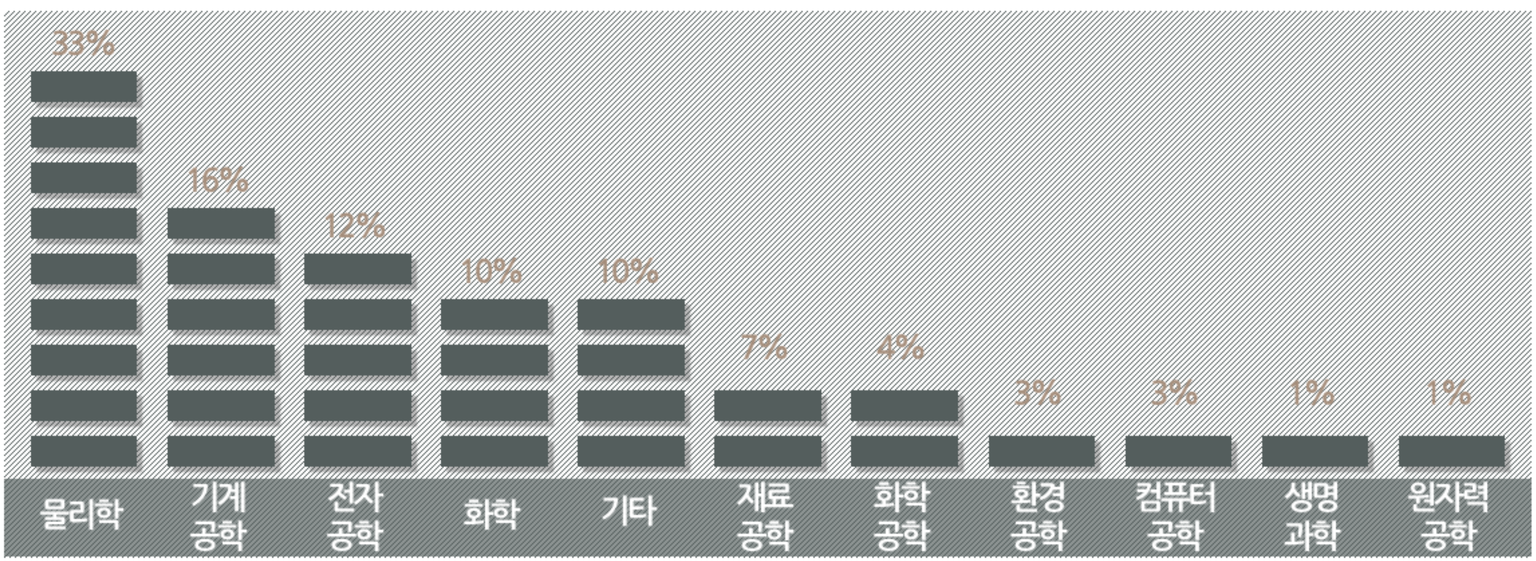
National Metrology Institute (NMI)



- (미국) National Institute of Standards and Technology (NIST) : four Nobel physics prizes
- (영국) National Physical Laboratory (NPL)
- (독일) Physikalisch-Technische Bundesanstalt (PTB)
- (프랑스) Laboratoire national de métrologie et d'essais (LNE)
- (일본) National Metrology Institute of Japan (NMIJ)

정규직원 전공별 분포 (연구·기술직)





(2015.11.기준)

KRISS 캠퍼스

KRISS 고유 임무와 기능

- **국가측정표준 확립 및 유지 향상**

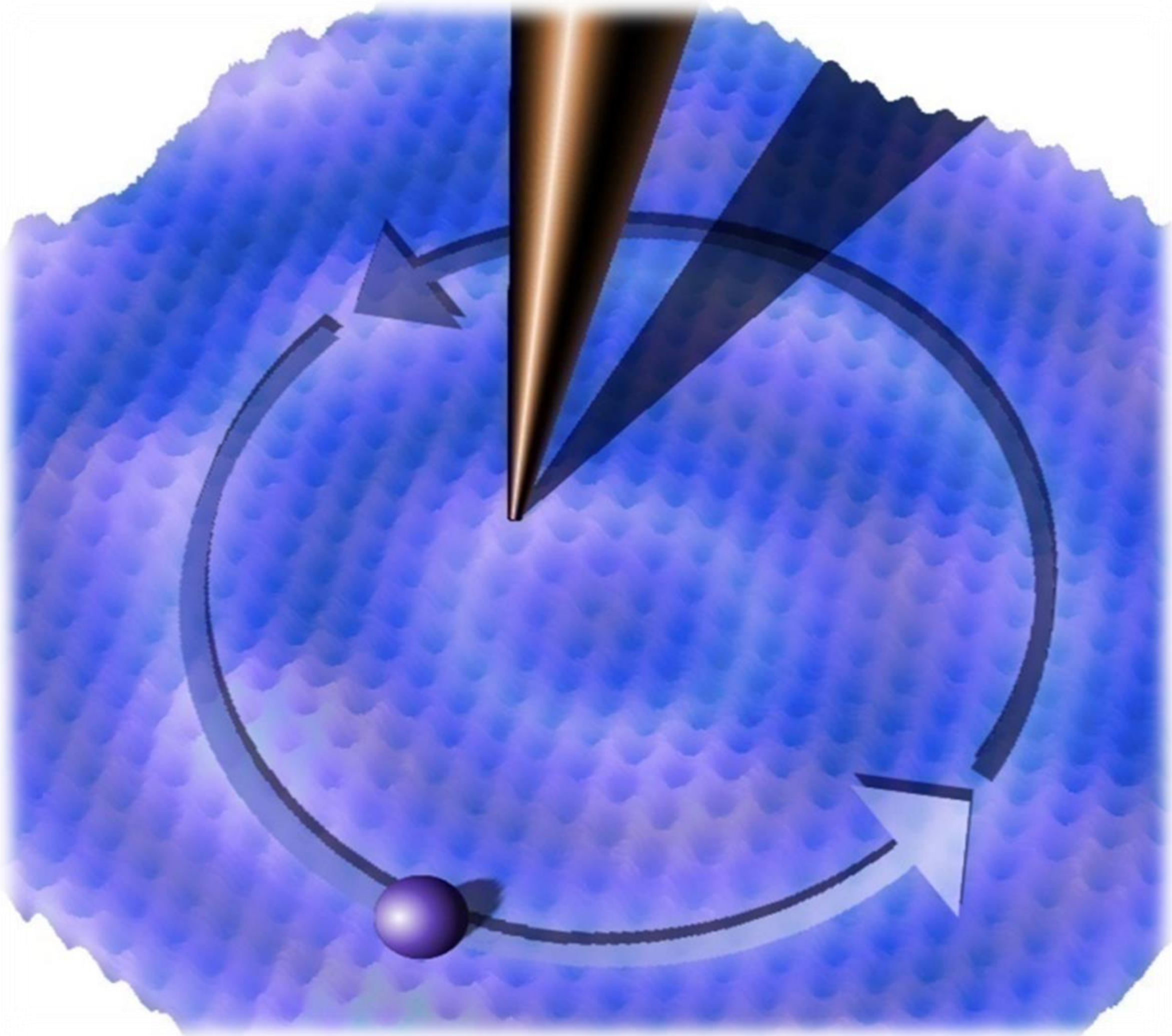
  : 국가 측정표준 대표기관, 세계 측정표준 선도기관

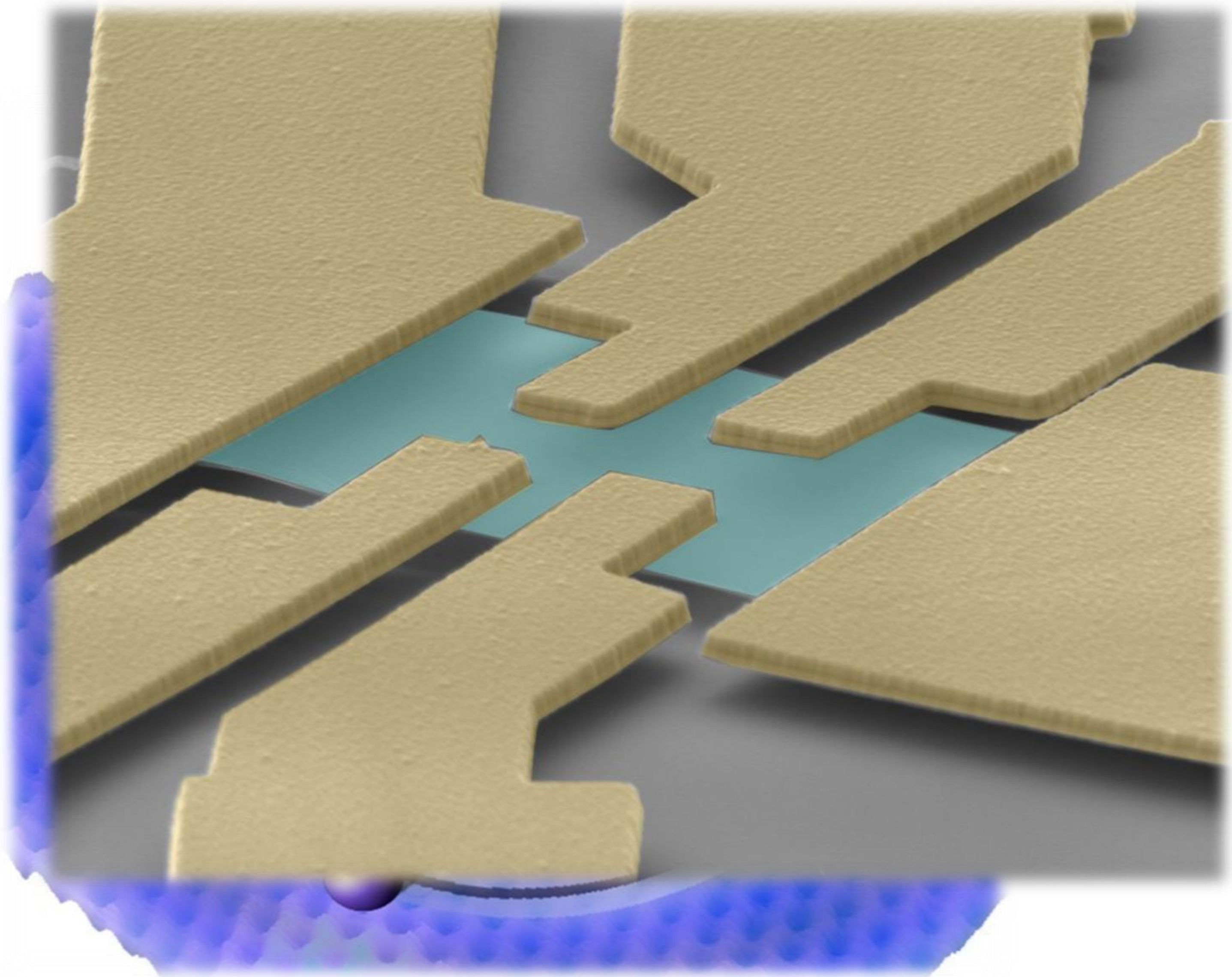
- **측정과학기술 연구개발**

  : 측정과학기술 연구기관, 측정과학 기술적시 공급

- **측정표준·측정과학기술 보급 및 서비스**

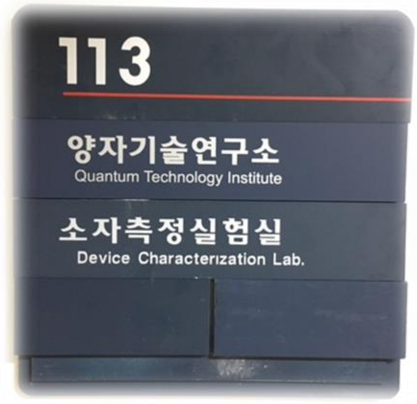
  : 측정표준보급 정점기관, 산업협력 지원중심 기관



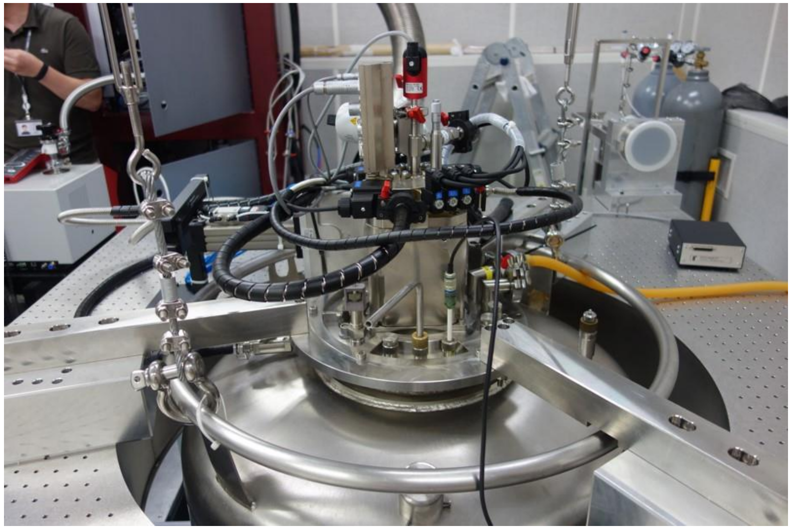


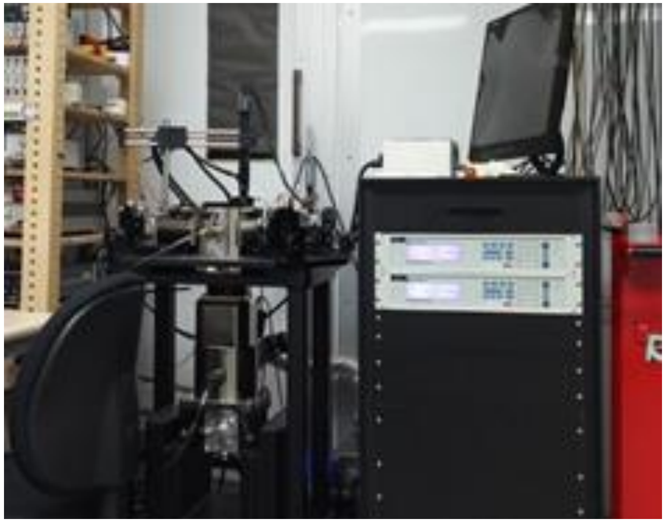
나노 소자 기반 양자물성 정밀측정법 개발

KRISS 소자측정실험실



- Dilution Refrigerator (DR, 희석식 냉장고) (4)
  : Wet DRs (3), Cryogen-free DR (1)
- Cryogen-free Probe Station (무냉매 프로브스테이션)
- Adiabatic Demagnetization Refrigerators (ADR, 단열소자냉동기) (2)
- Pits for Liquid He Dewar (3)
- Tube Furnace (3), Wire bonders (2)





KRISS 나노팹

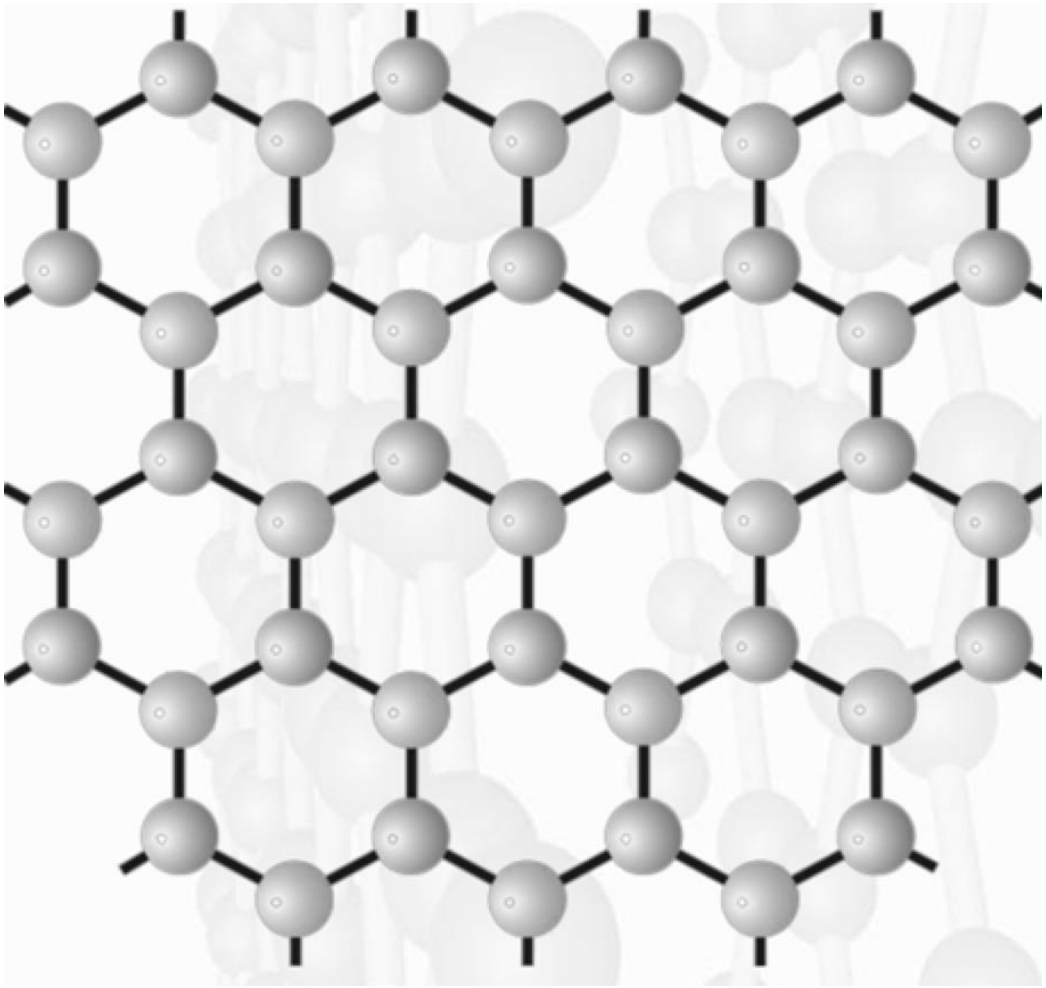
- SEM / E-beam lithography (2) : FEI Sirion 400 , Raith Voyager
- Photolithography (2) : SUS Microtech MA6
- E-beam evaporators (5), Sputtering systems (2)
- Reactive Ion Etching (RIE, 2), Ion Milling
- Critical point dryer, Surface profiler, Plasma asher
- Wet stations (solvent, acid and base bays), spin coaters, hot plates

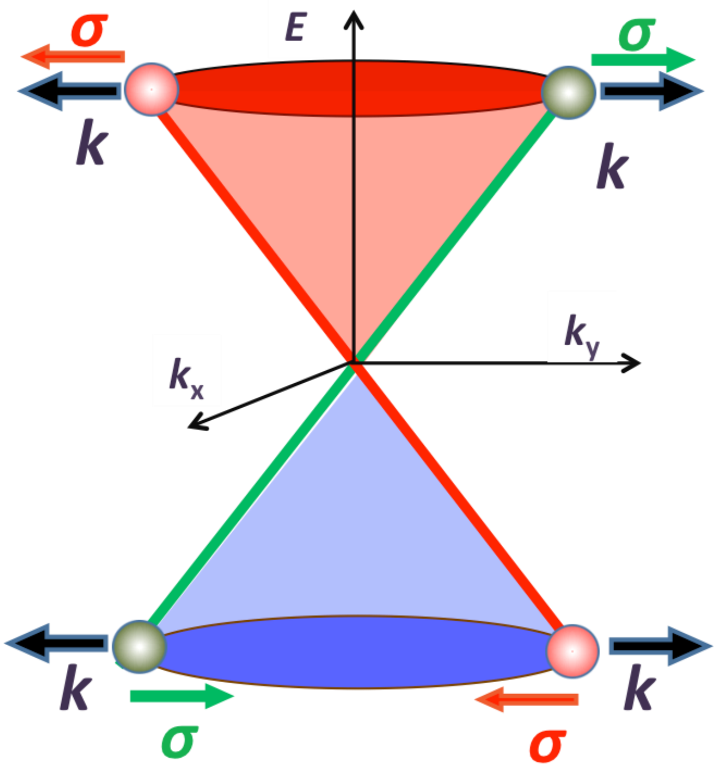
Energy gaps in graphene
on *h*-BN substrate

**tunneling spectroscopy
with *h*-BN as a tunnel insulator**

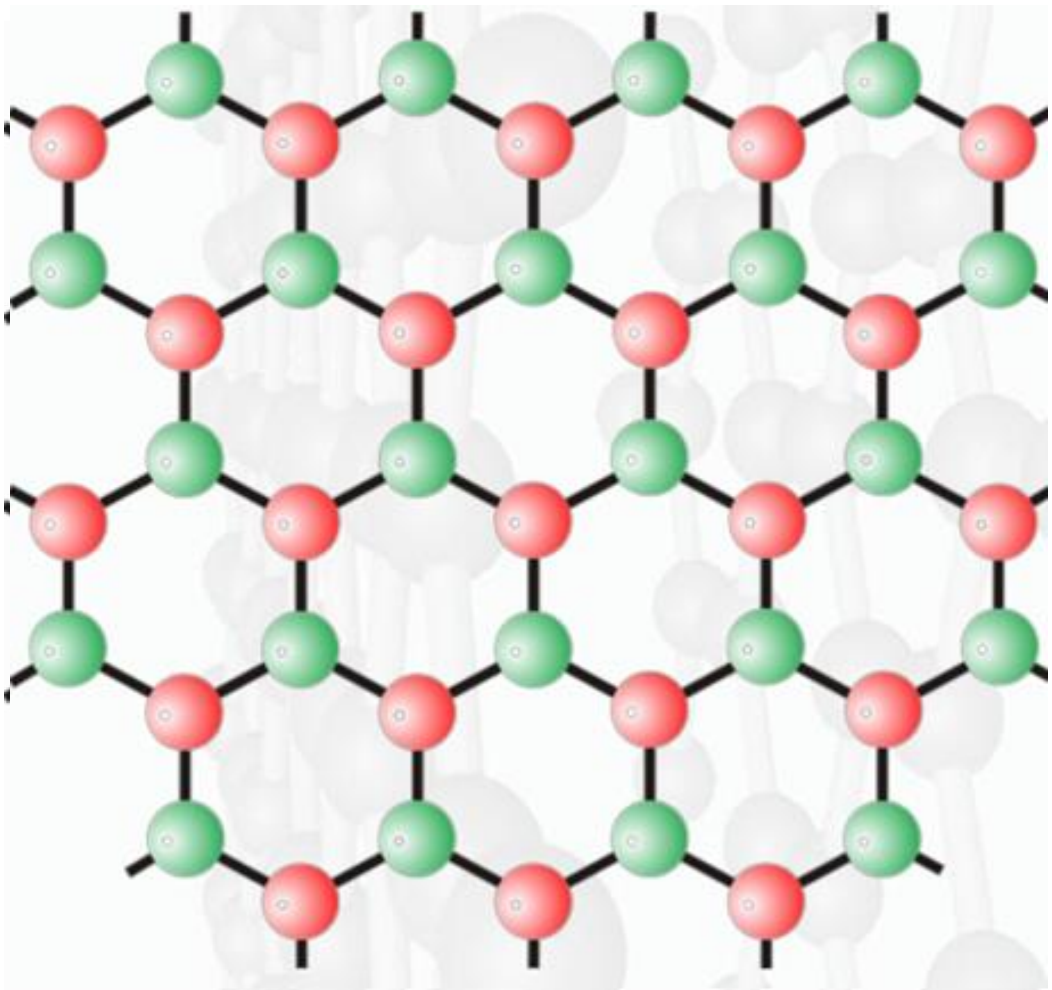
and others

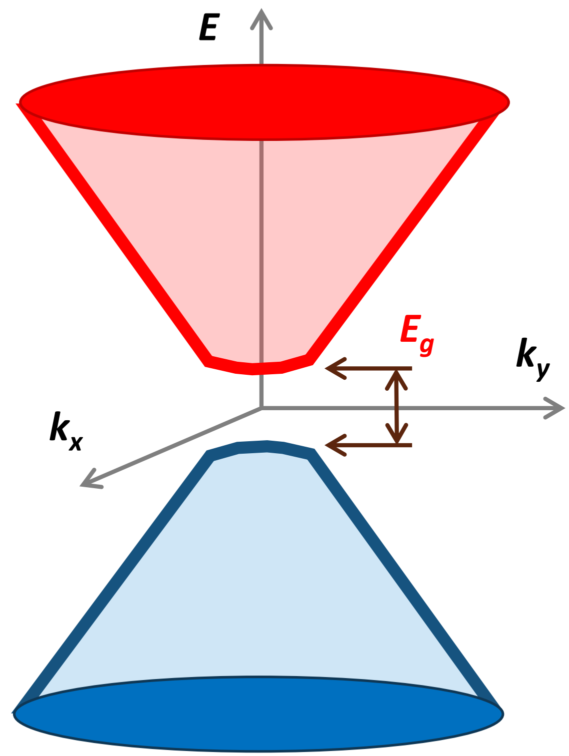
Sublattice Symmetry of Graphene / Energy Gap



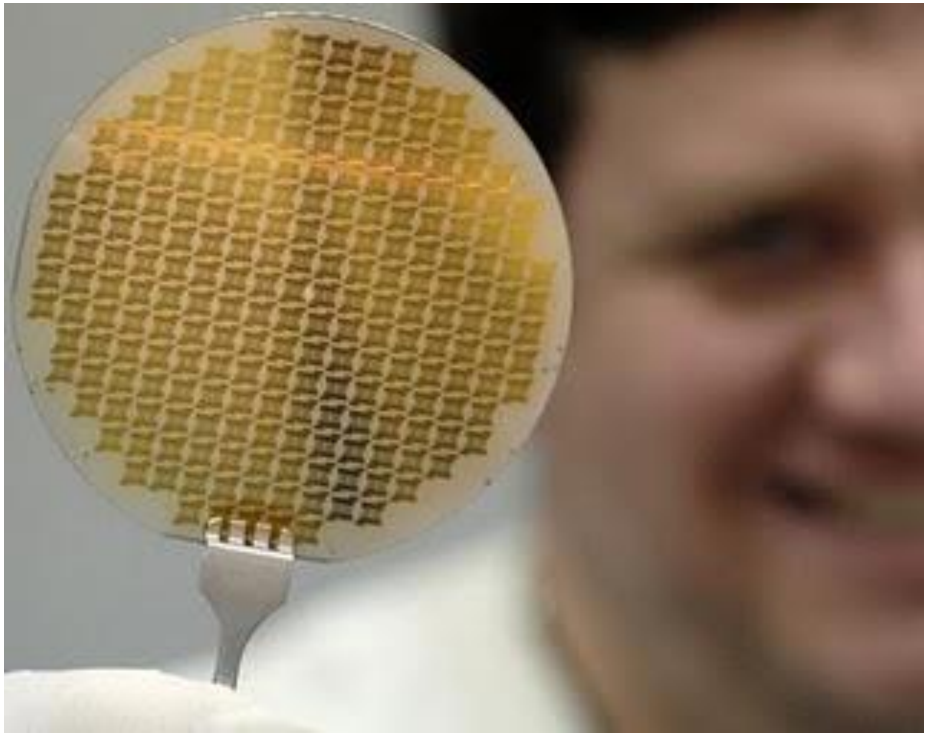


Sublattice Symmetry of Graphene / Energy Gap



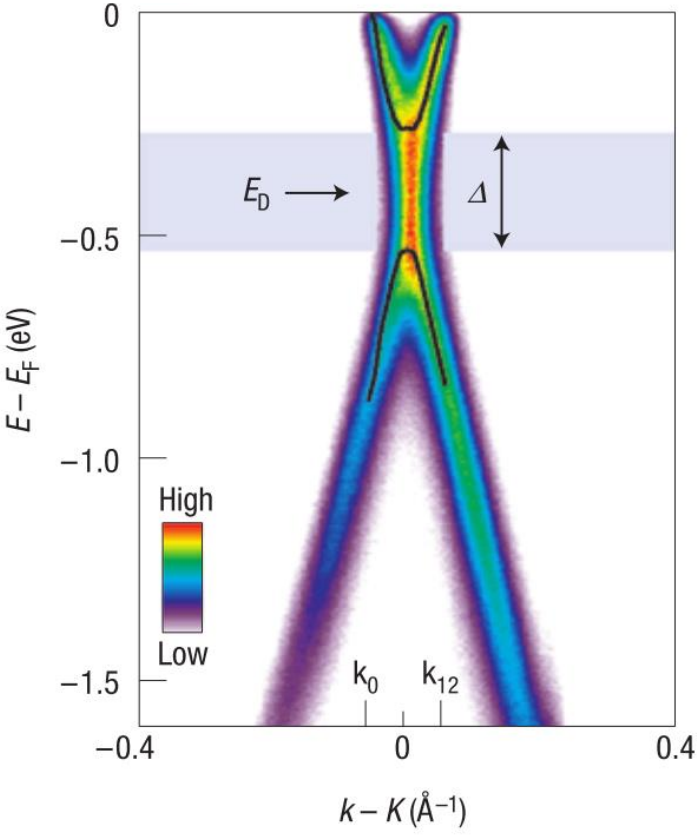


Experimental Evidence for Graphene Energy Gap



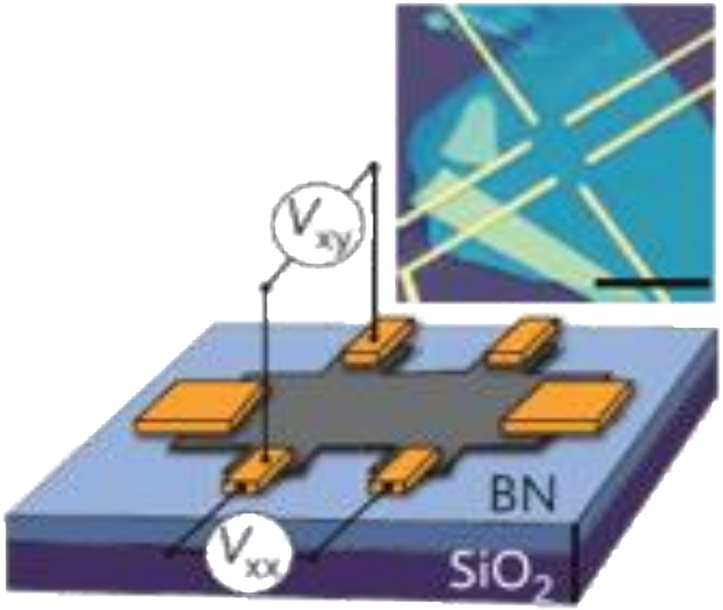
Courtesy of
Electro-Optics Center (EOC) Materials Division at Penn State

Graphene on SiC
(ARPES)



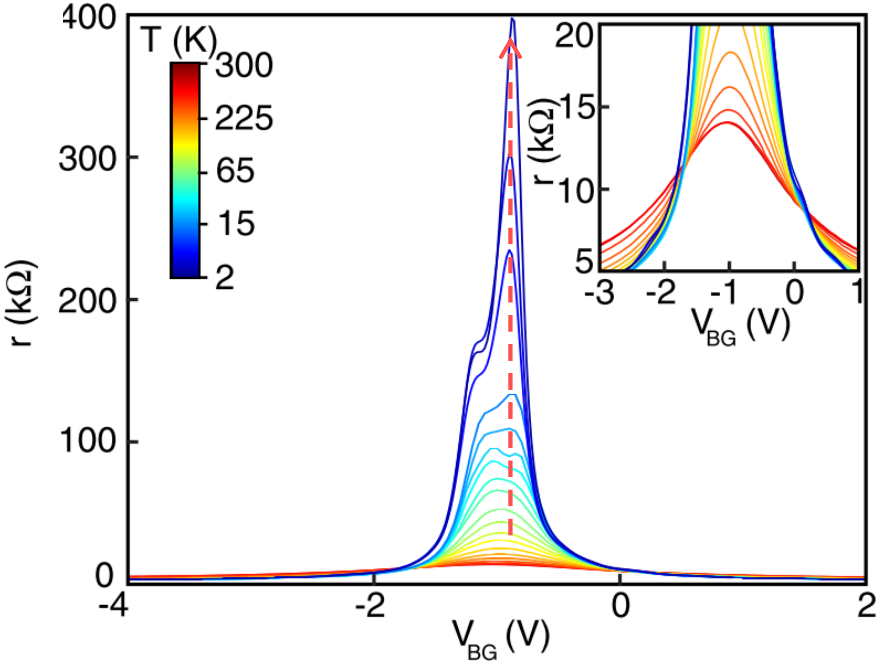
S. Zhou *et al*. Nat. Mater. **6**, 770 (2007)

Experimental Evidence for Graphene Energy Gap



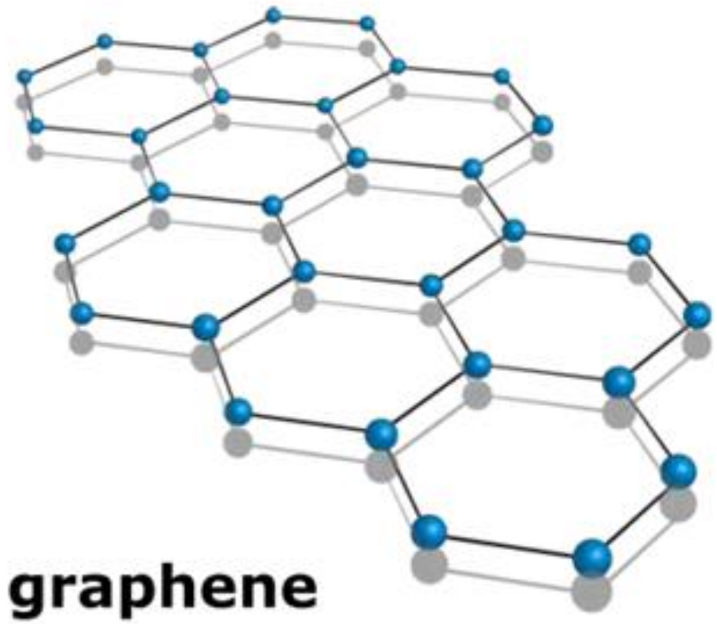
C. R. Dean *et al*. Nature Physics **7**, 693 (2011)

Graphene on *h*-BN
(multi-probe transport measurement)



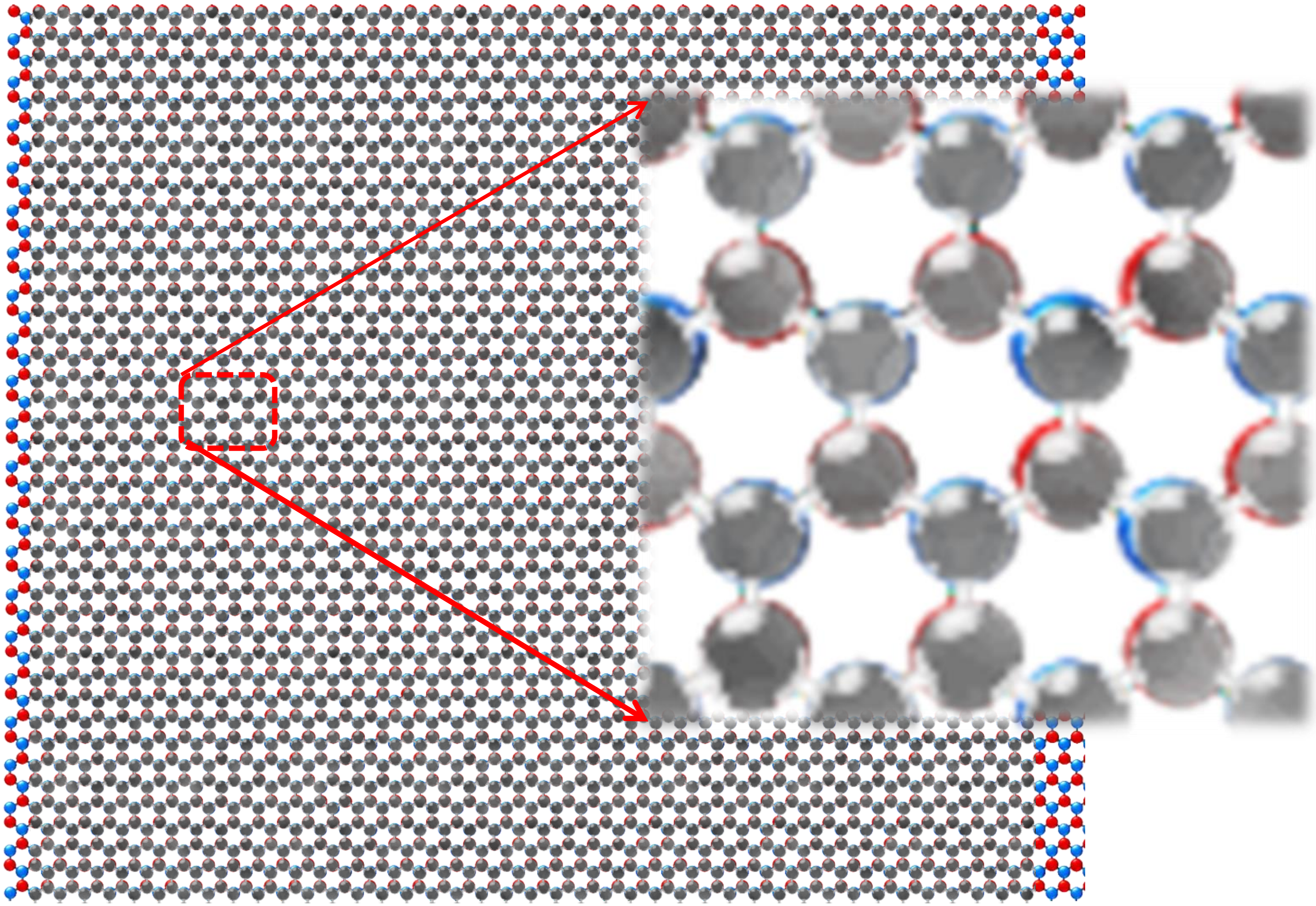
F. Amet *et al.* Phy. Rev. Lett. **110**, 216601 (2013)

Graphene *vs.* hexagonal Boron Nitride

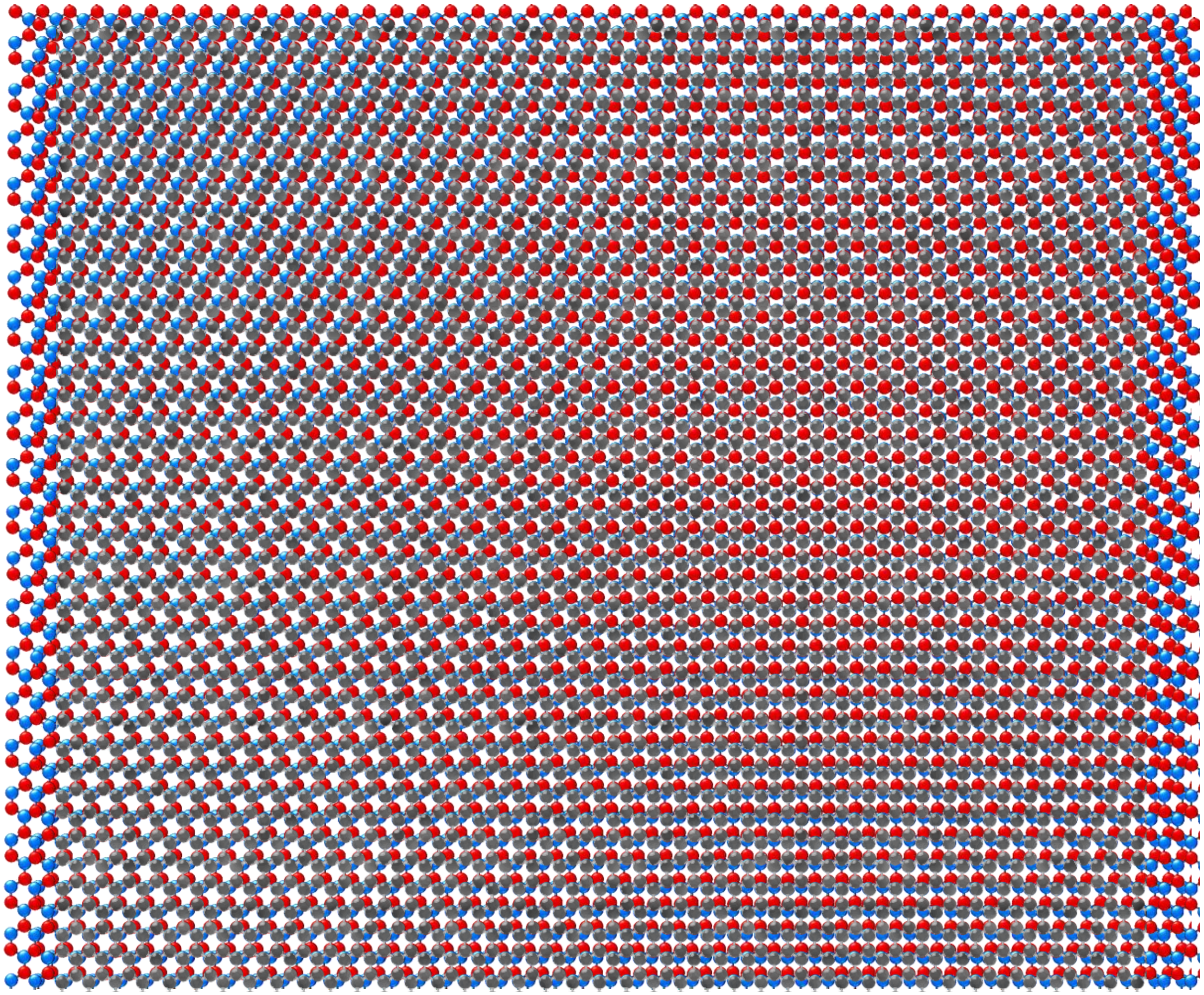


Adapted from Dr. Philip Kim's presentation in Graphene School 2010

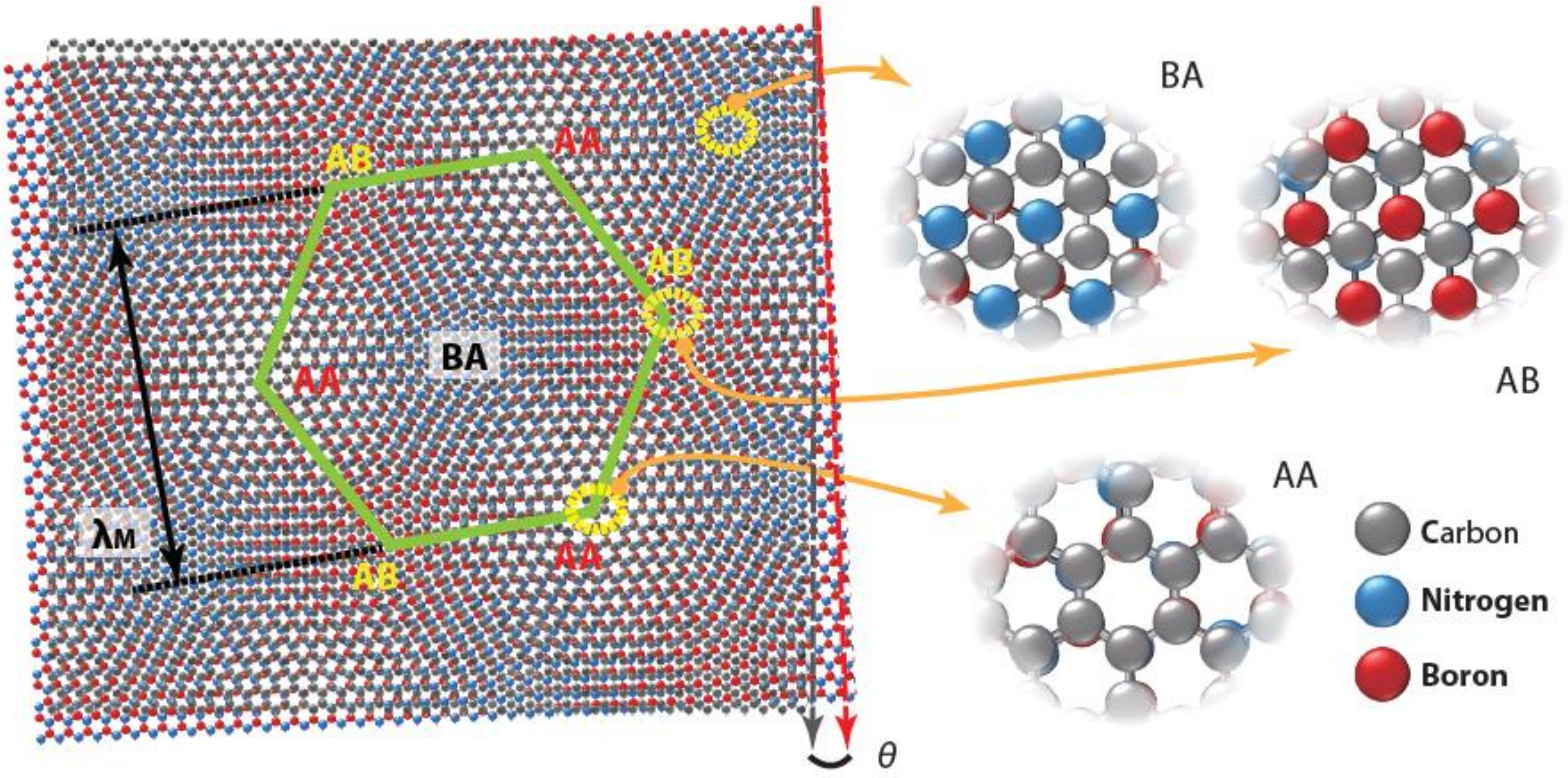
Graphene Superlattices on hexagonal boron nitride



Graphene Superlattices on hexagonal boron nitride



Graphene Superlattices on hexagonal boron nitride



Graphene Superlattices on hexagonal boron nitride

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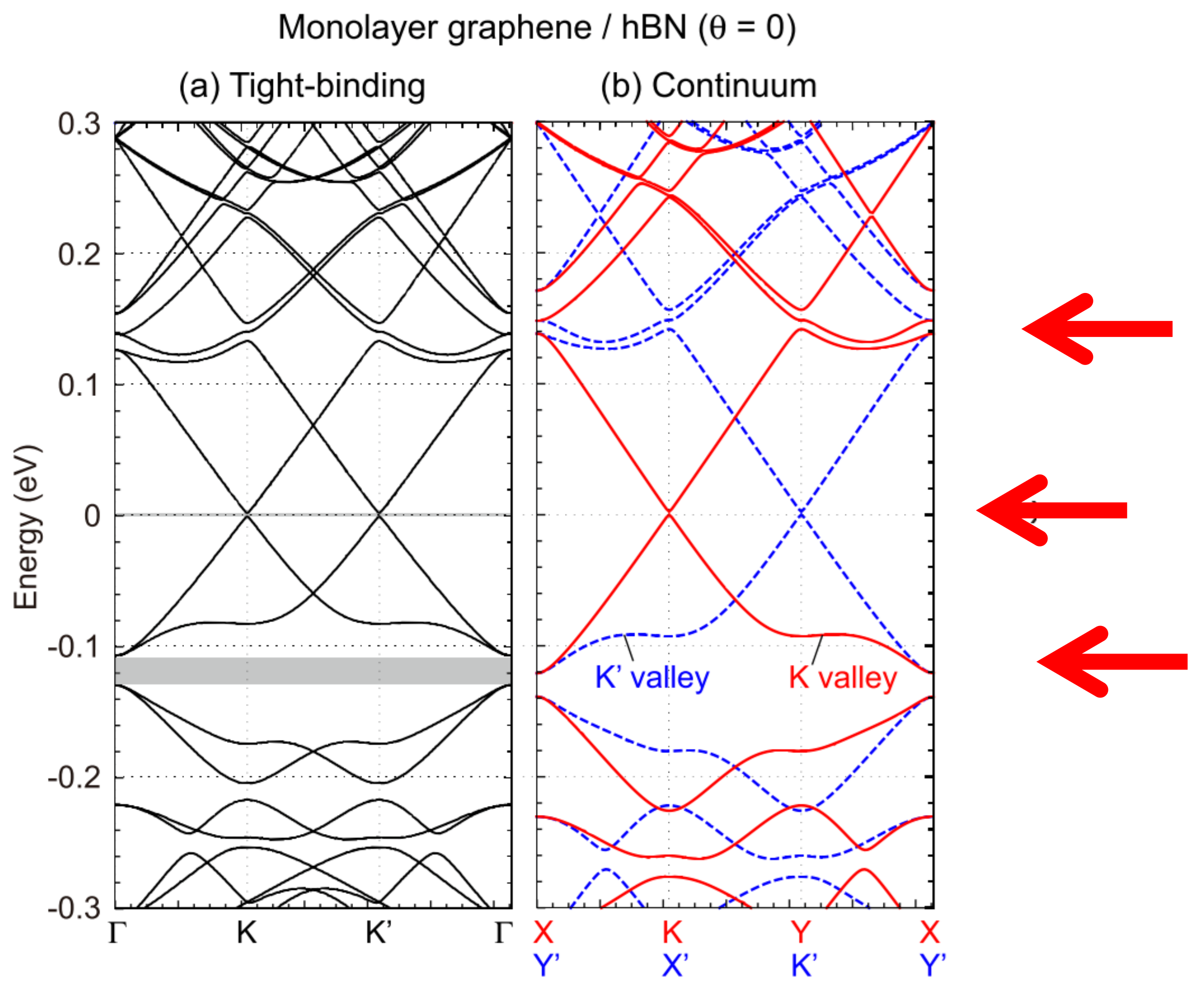
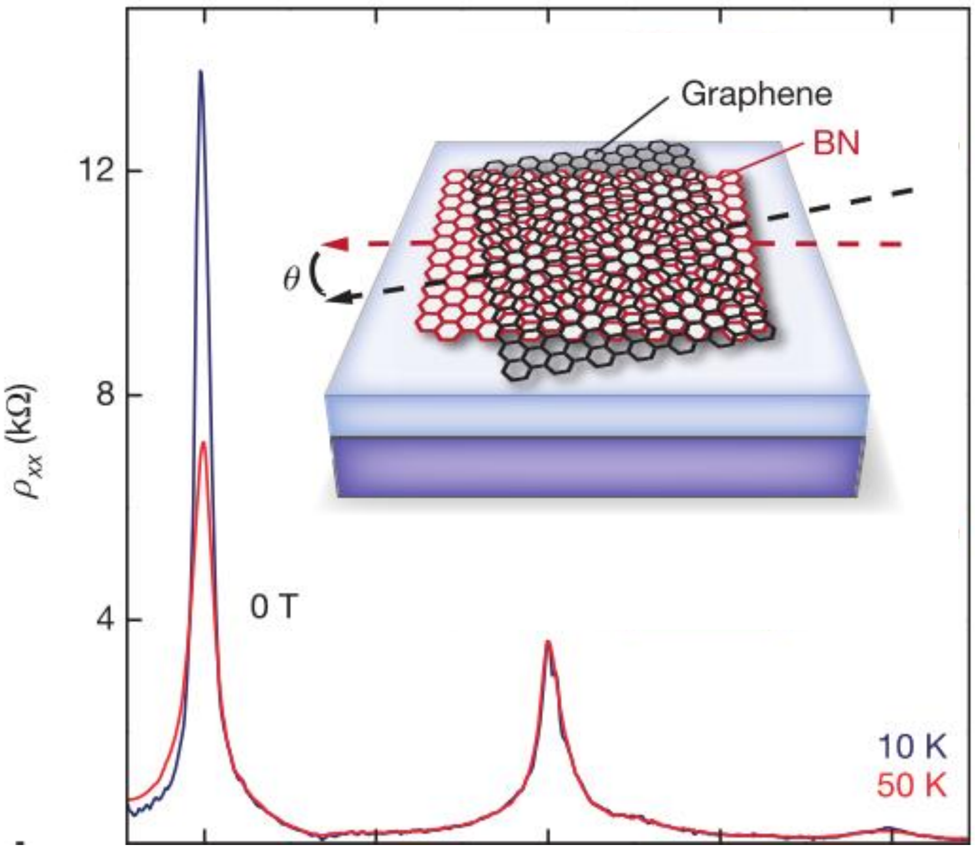
Band Structure of Graphene Superlattice

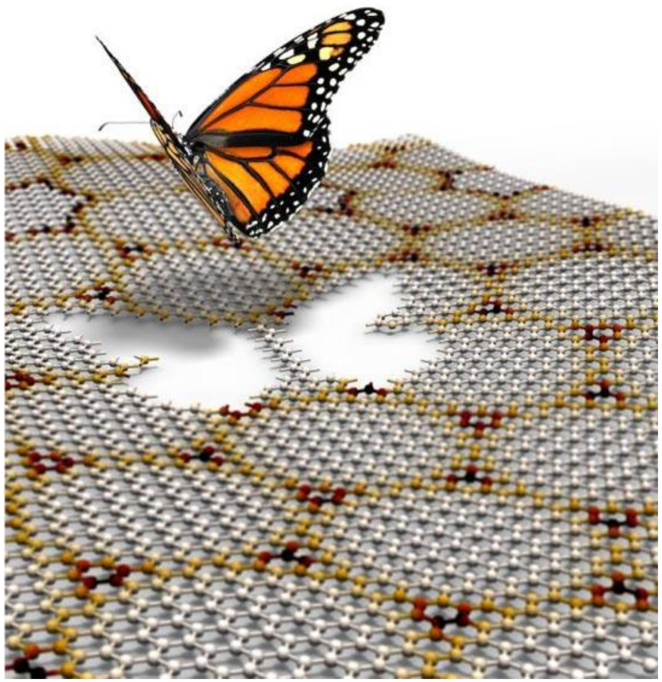


P. Moon *et al.* Phy. Rev. B **90**, 155406 (2014)

Graphene Superlattices on *h*-BN

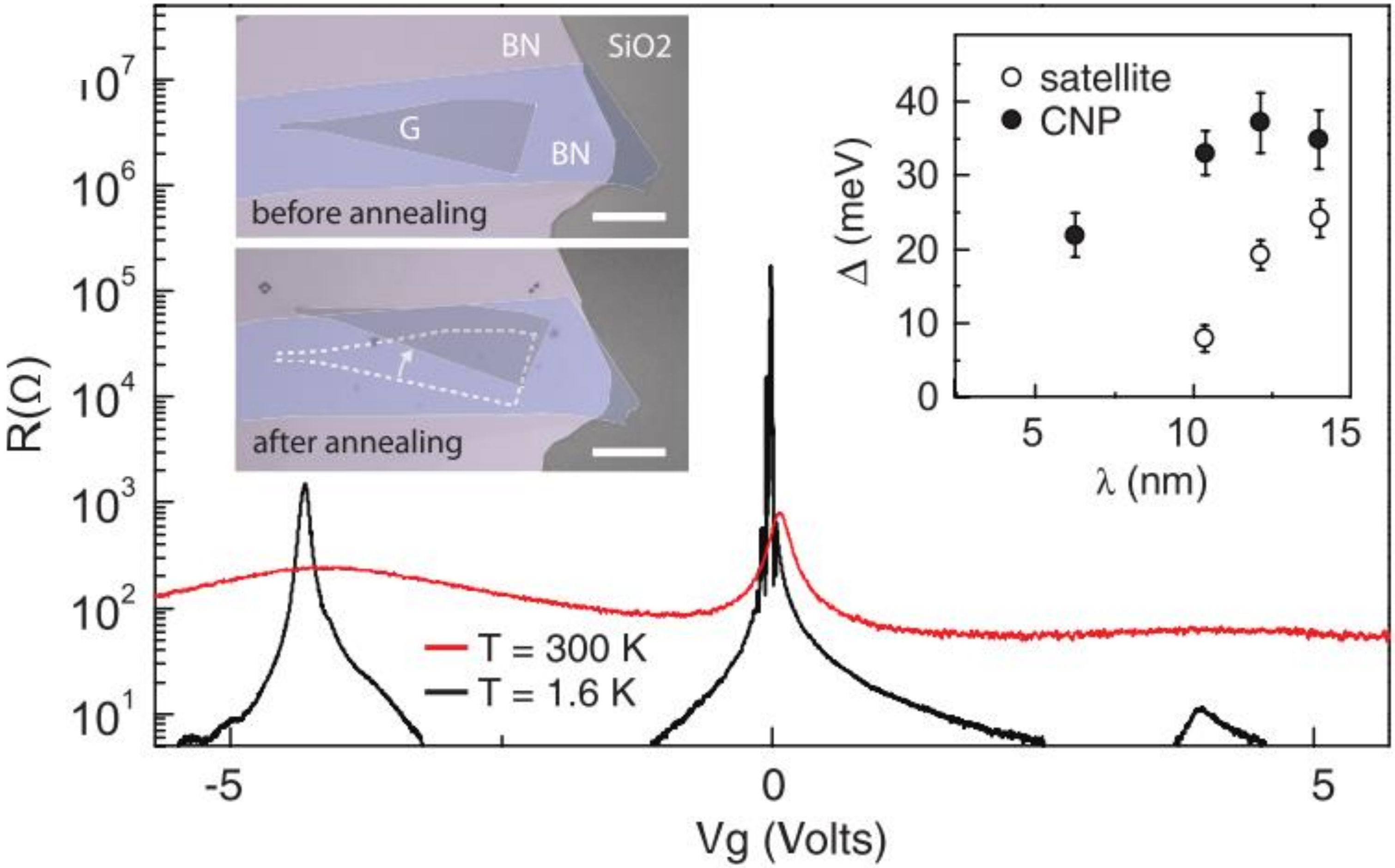
Experimental evidence for the 2nd Dirac points in graphene superlattice





C. R. Dean *et al*. Nature (2013) - ***bilayer***
L.A. Ponomarenko *et al.* Nature (2013) – ***single layer***
B. Hunt *et al.* Science (2013) – ***single layer***

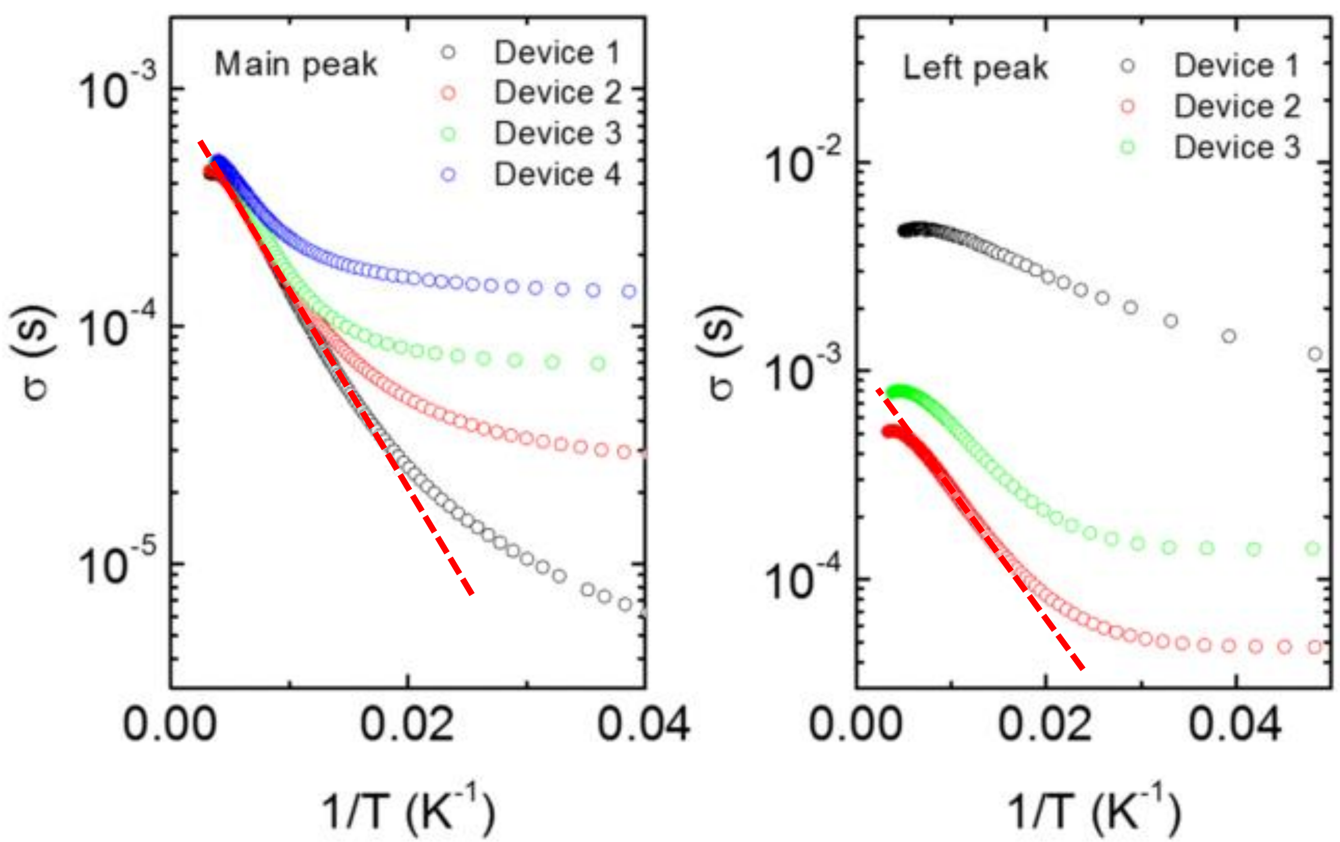
Quantitative Analysis for the Energy Gaps



L. Wang *et al.* Science **350**, 1231-1234 (2015)

Quantitative Analysis for the Energy Gaps

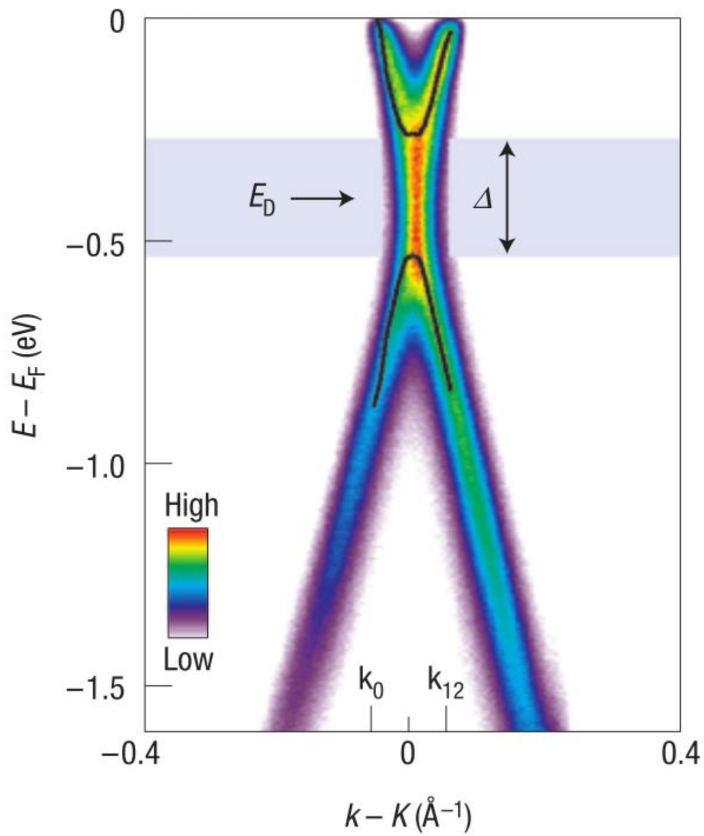
Extracting the energy gaps from Arrhenius plot of the peak conductivities



L. Wang *et al.* Science **350**, 1231-1234 (2015)

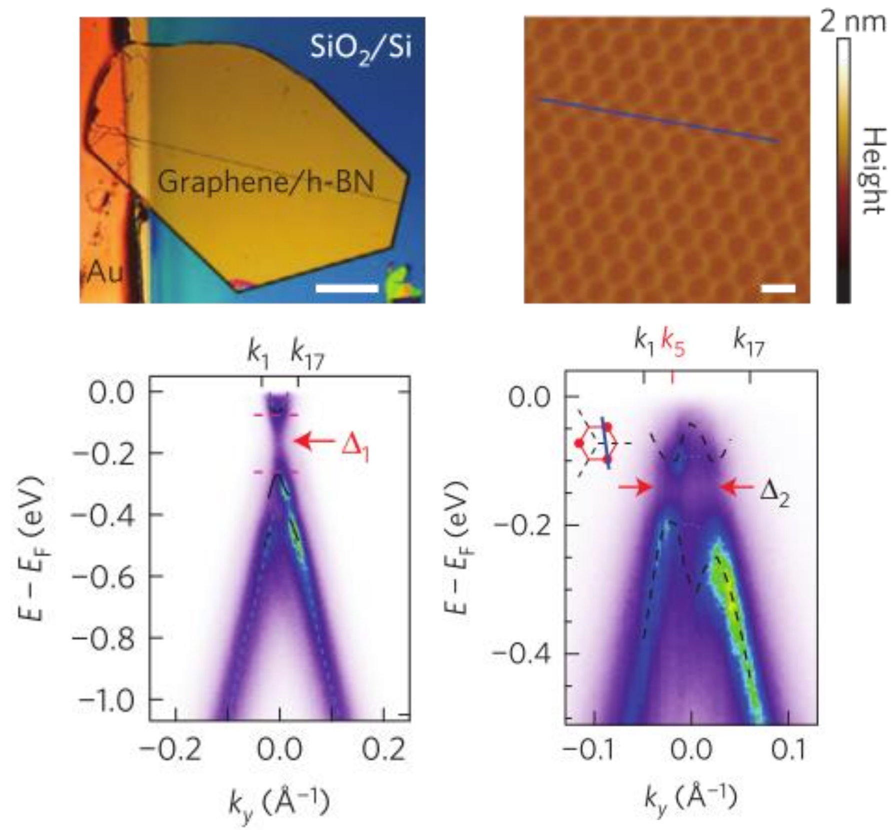
Alternative Method for Probing the Energy Gaps

Graphene on SiC
(ARPES)



S. Zhou *et al*. Nat. Mater. **6**, 770 (2007)

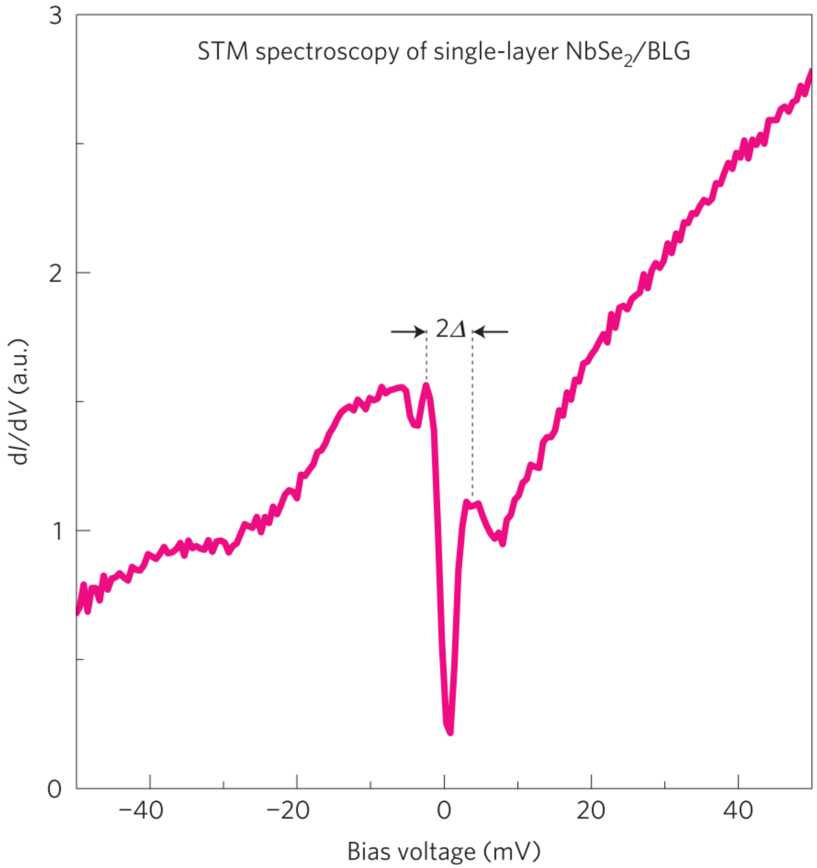
Graphene on *h*-BN
(ARPES)



E. Wang *et al*. Nat. Phys. **12**, 1111 (2016)

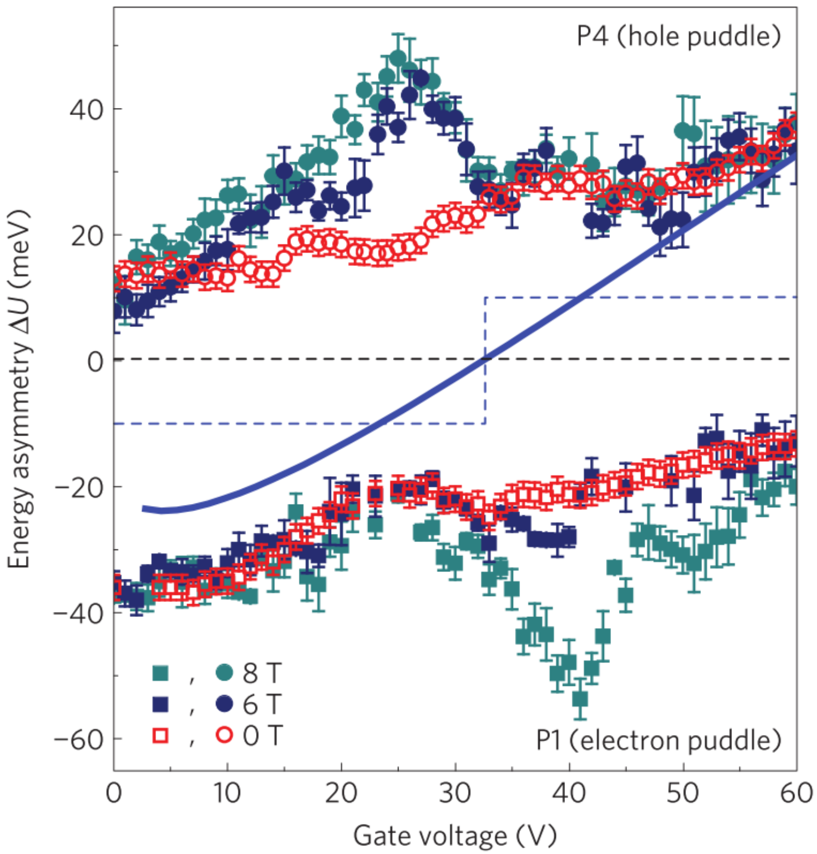
Tunneling Spectroscopy for Probing Energy Gaps

Gap from Charge-Density Wave in $NbSe_2$ (STM)



M. Ugeda *et al.* Nat. Phys. **12**, 92-97 (2016)

Energy Gap in Bilayer Graphene (STM)



G. Rutter *et al.* Nat. Phys. **7**, 649-655 (2011)

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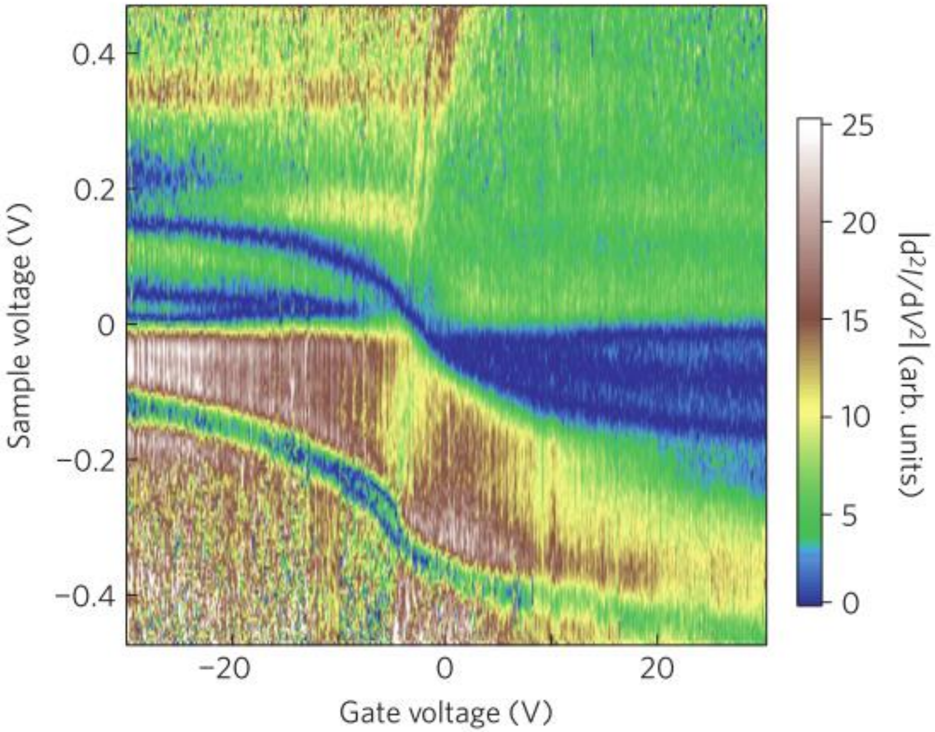
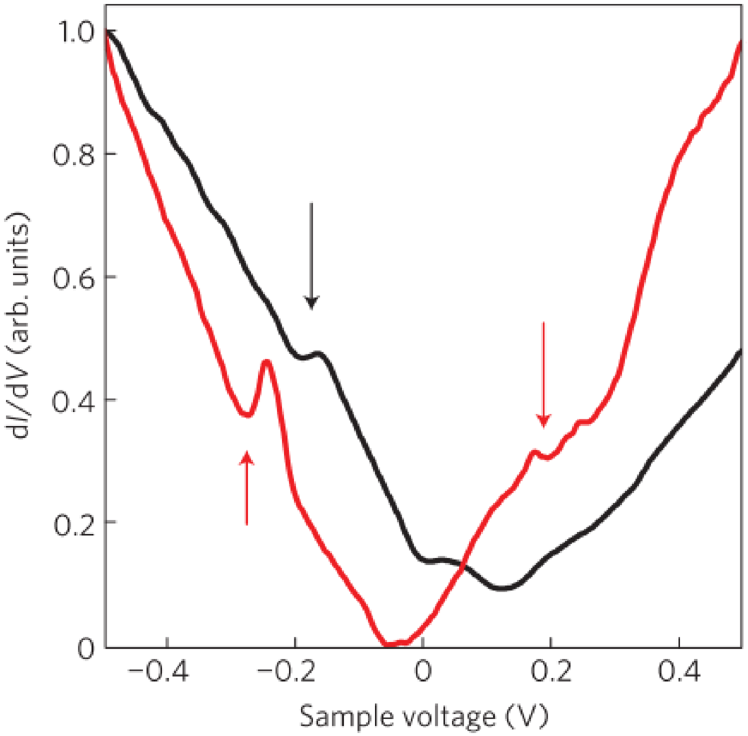
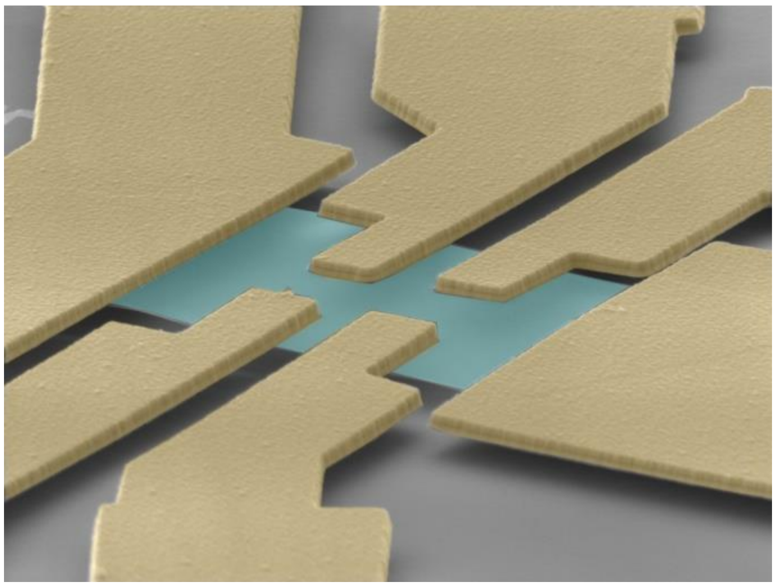
STM / STS Measurement

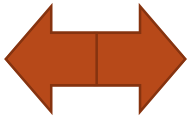


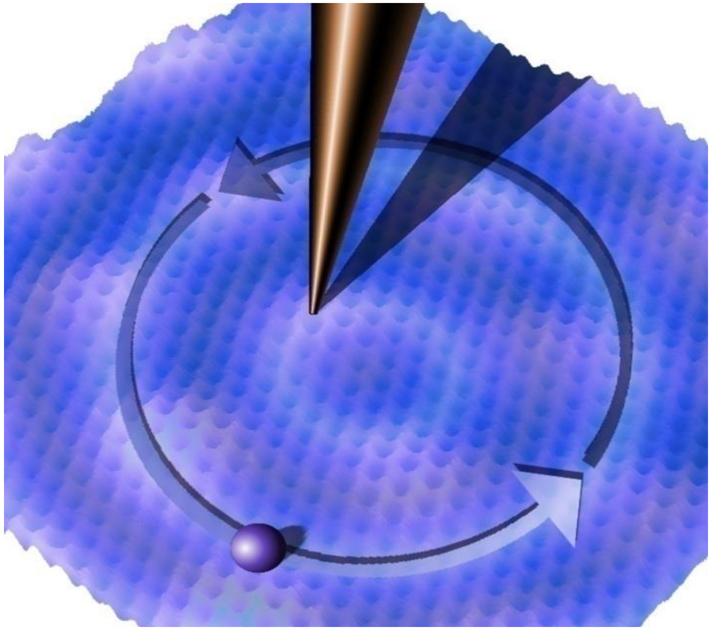


M. Yankowitz *et al.* Nat. Phys. **8**, 382-386 (2012)

Tunneling Spectroscopy for Probing Energy Gap







Tunneling Spectroscopy with h-BN as Insulator

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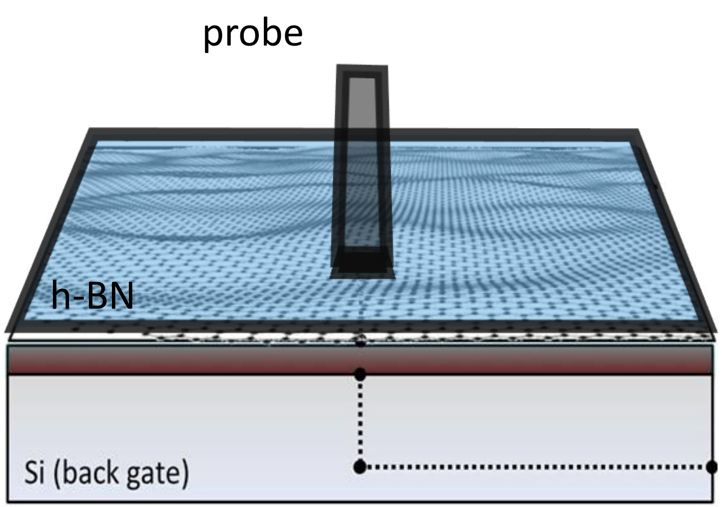
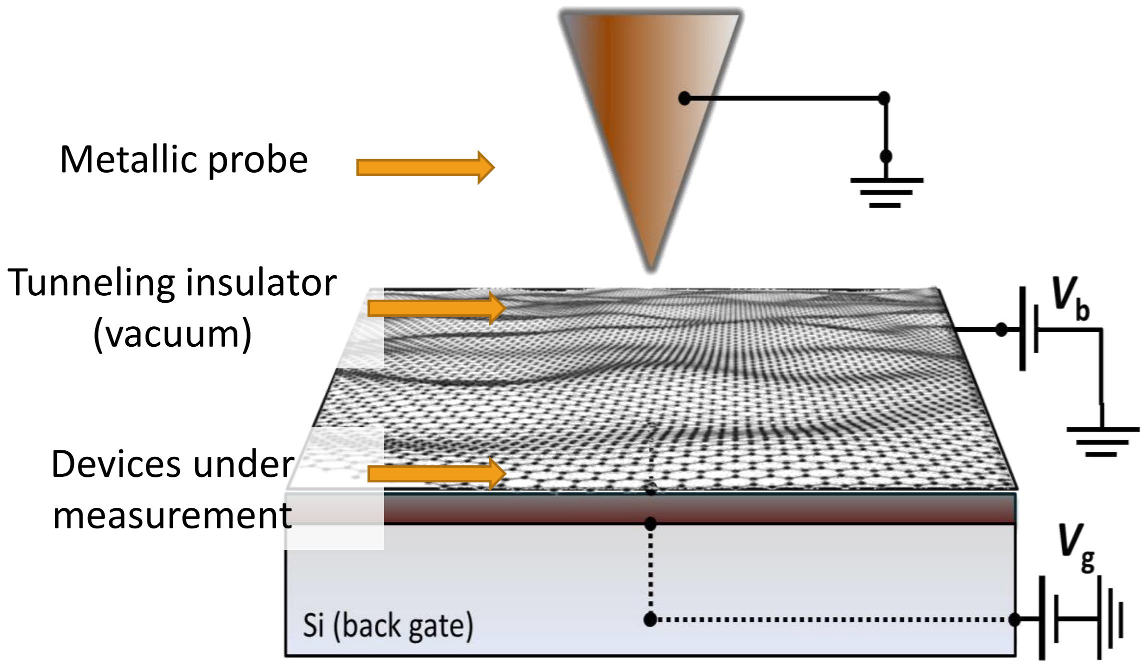
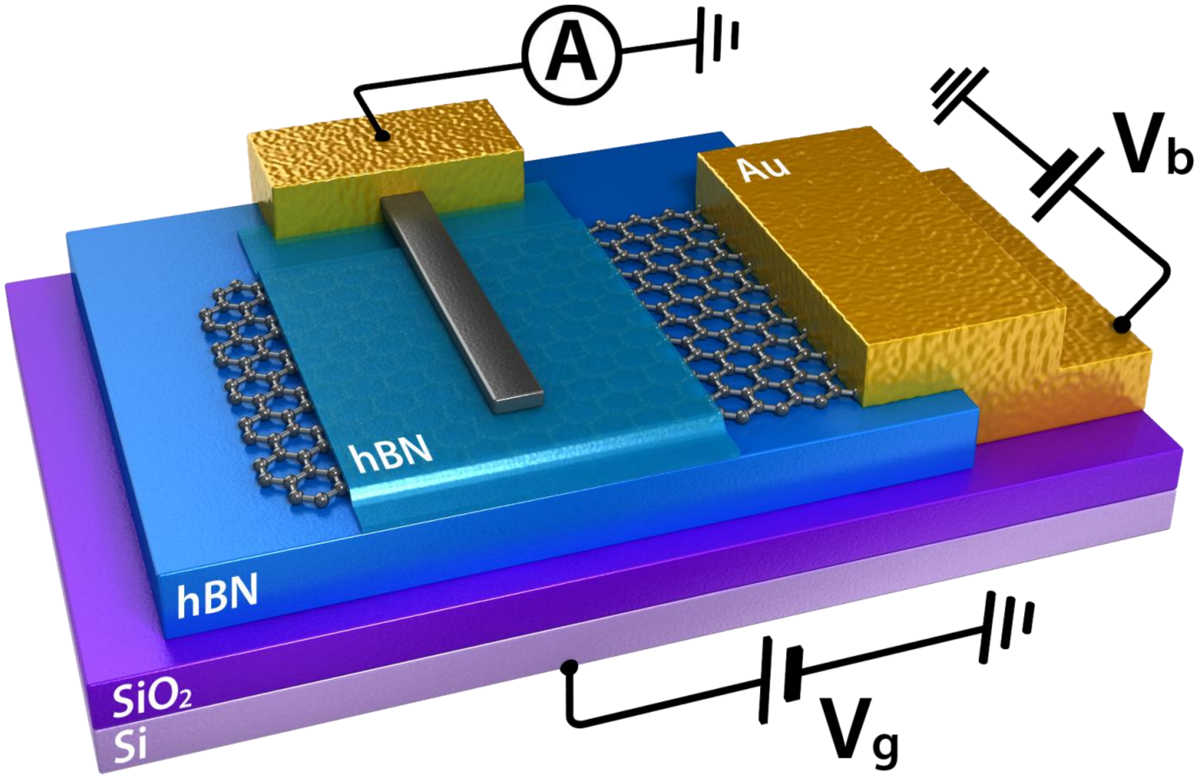




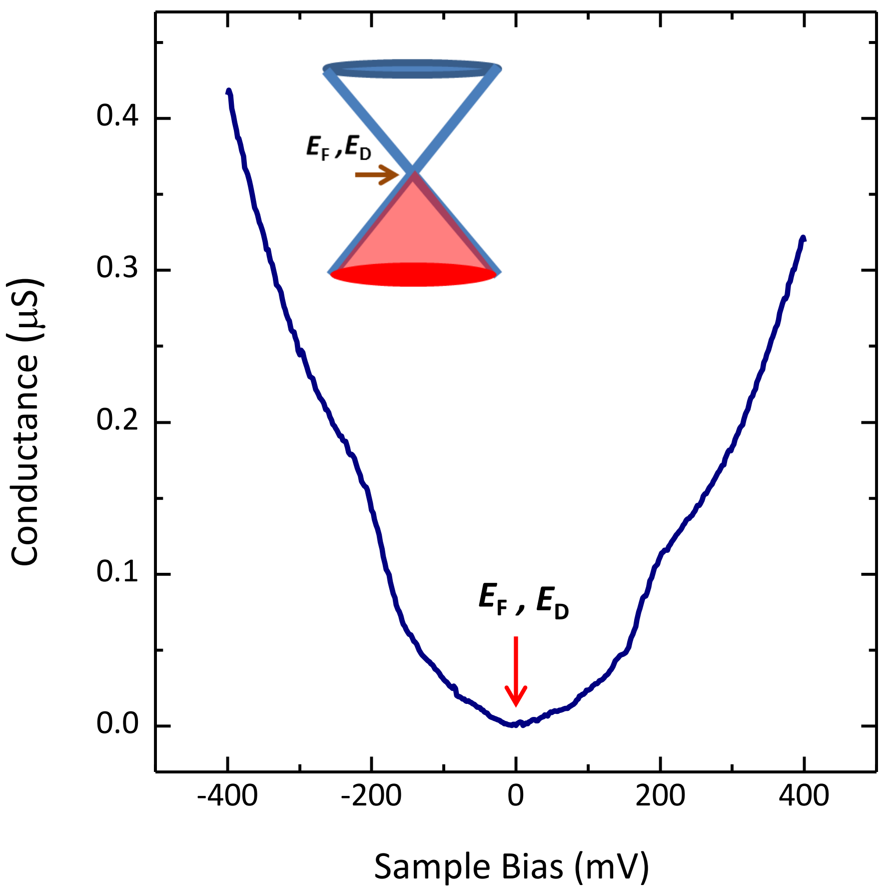
Tunneling Spectroscopy with *h*-BN



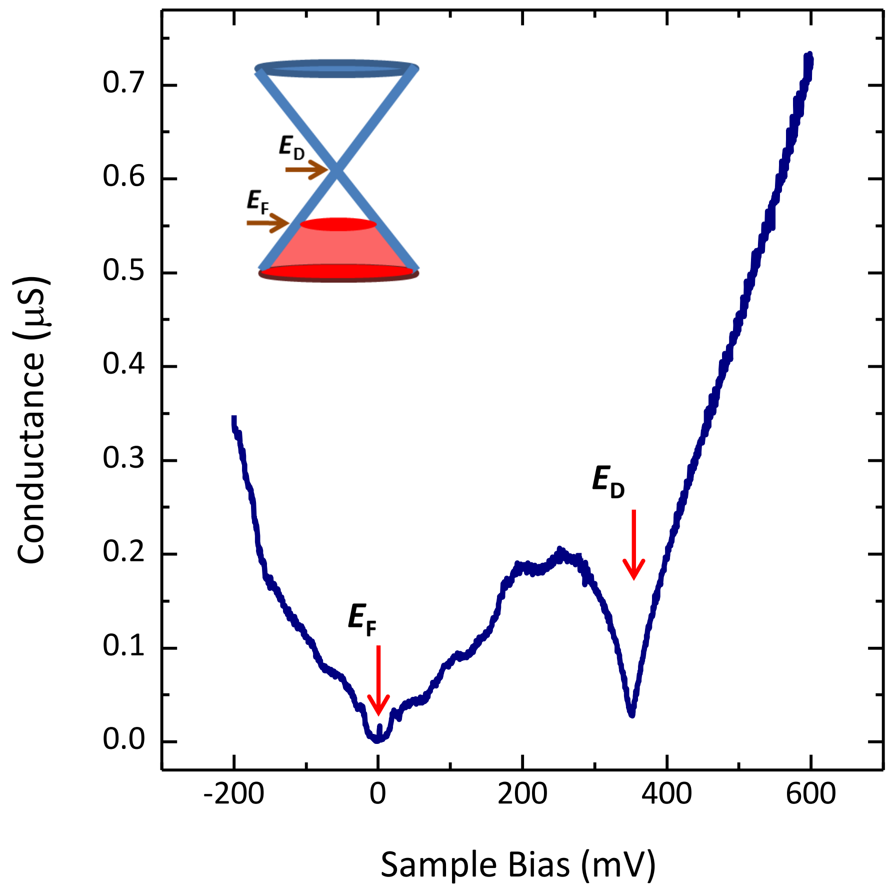
S. Jung *et al. Sci. Rep.*. **5**, 16642 (2015)
S. Jung *et al.* Nano Lett. **17**, 206-213 (2017)

Tunneling Spectroscopy of Single Layer Graphene

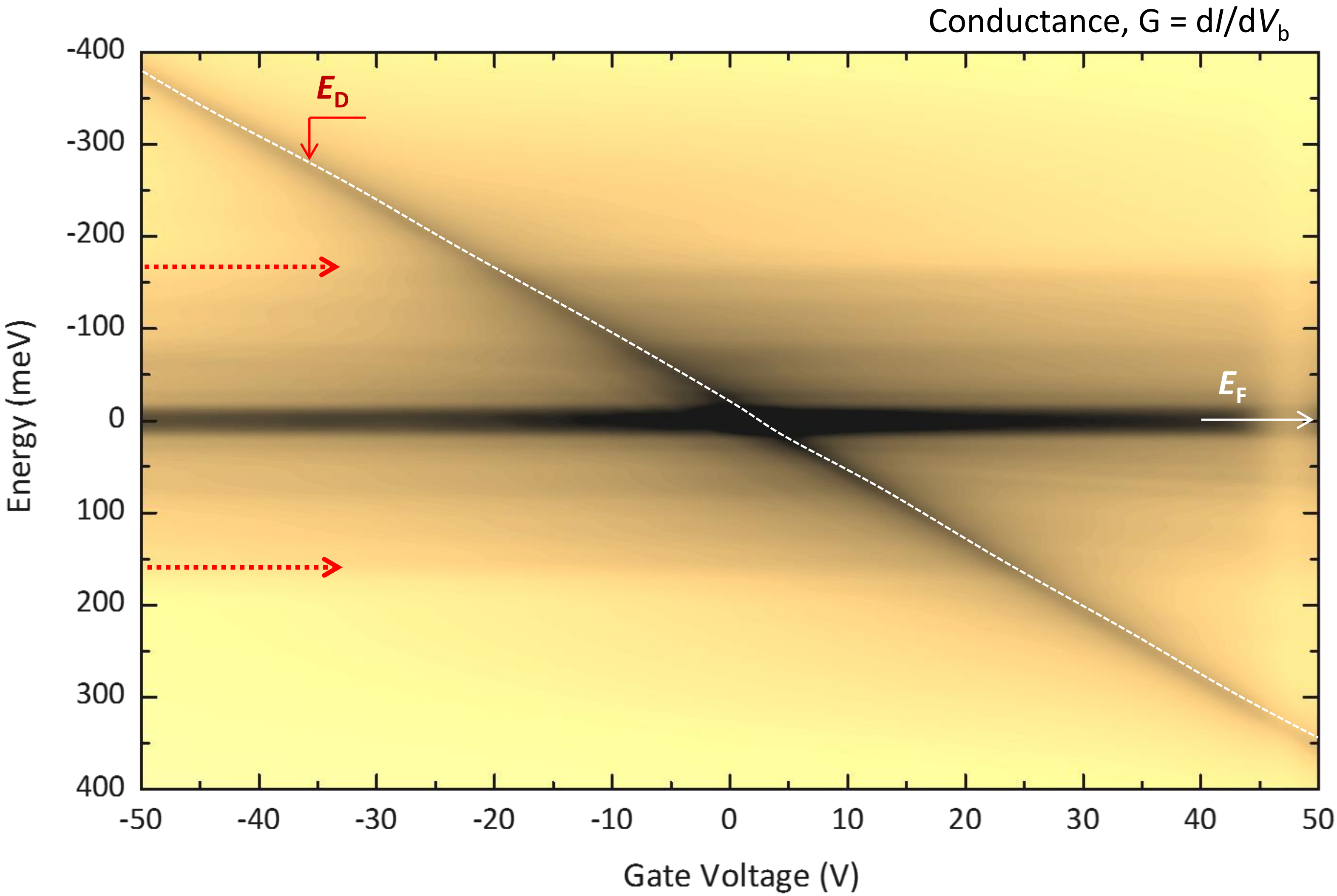
@ charge neutrality point (V_g = 0 V)



@ hole doping region (V_g = - 50 V)



Gate Mapping of Single-Layer Graphene



Inelastic Tunneling Spectroscopy (Phonons)

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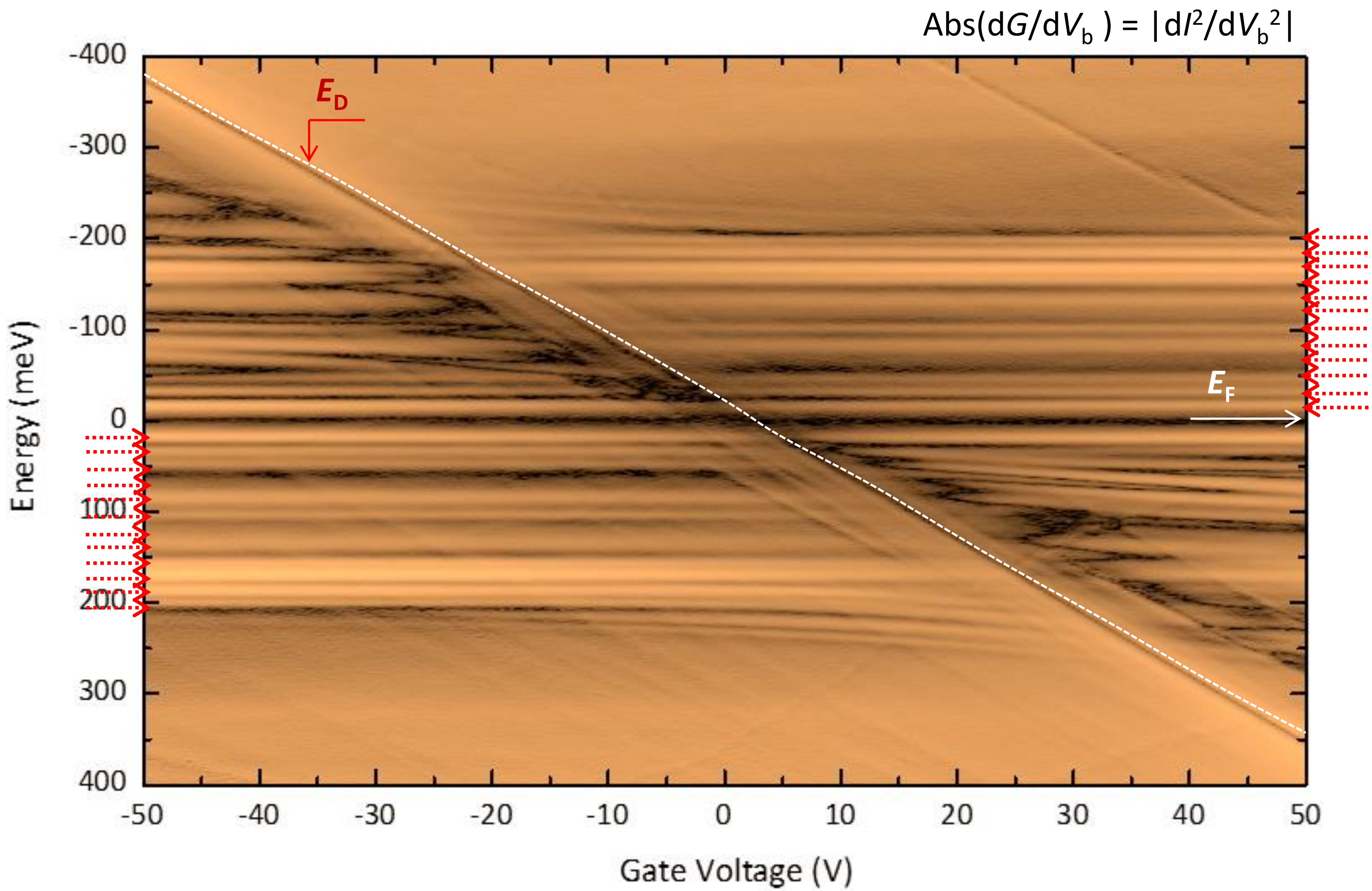
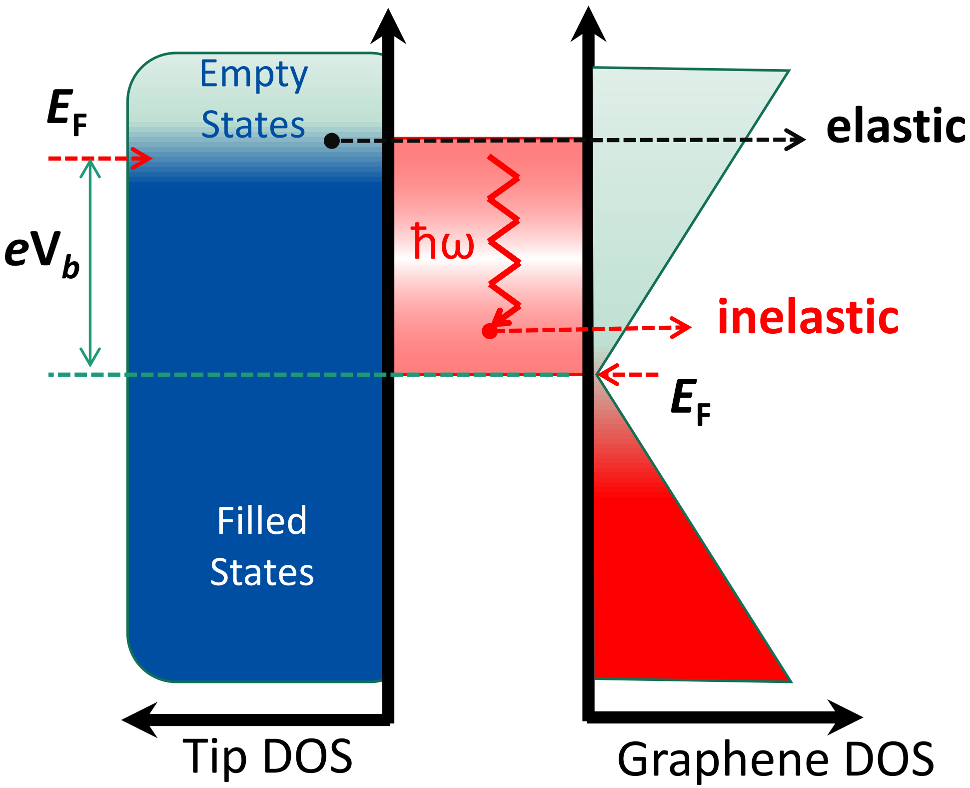
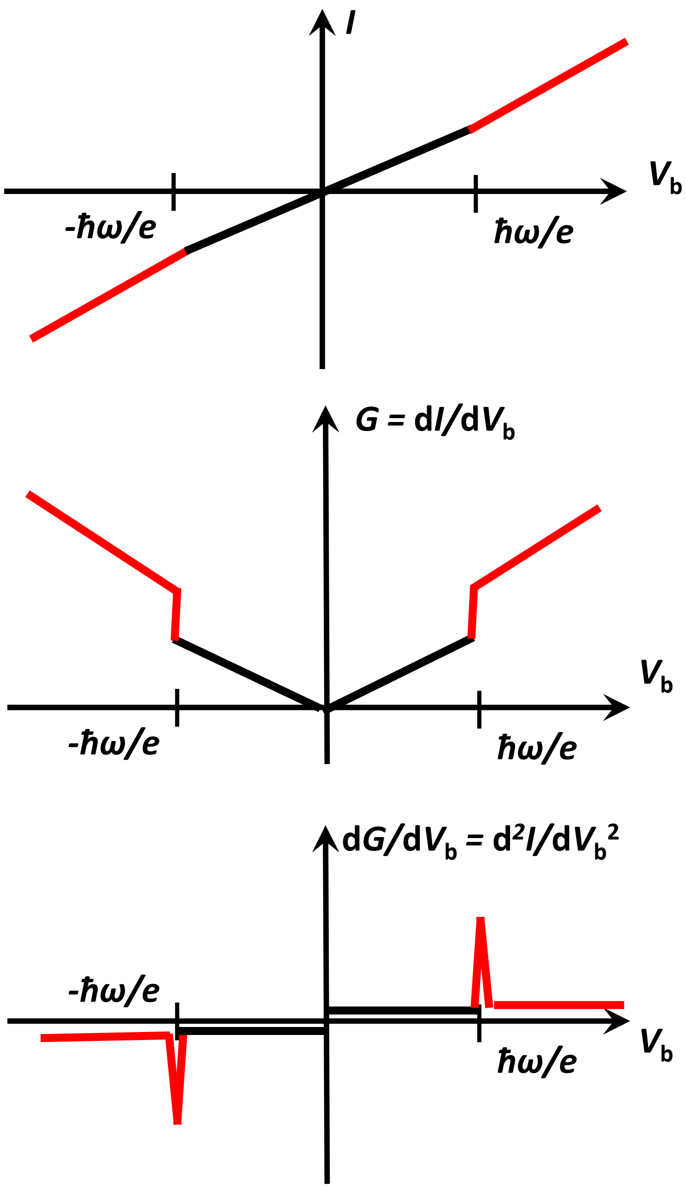


Inelastic Electron Tunneling Spectroscopy (Phonons)

- Inelastic Electron Tunneling Spectroscopy



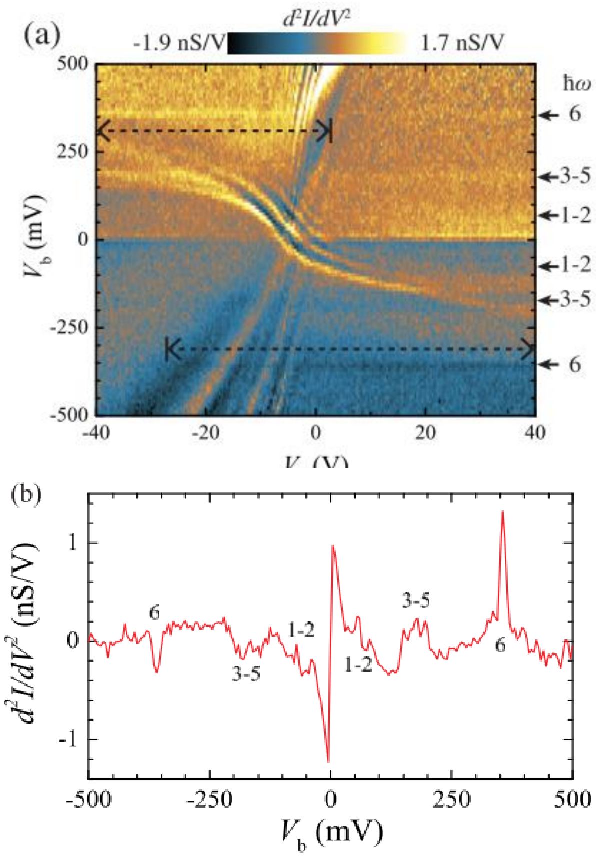


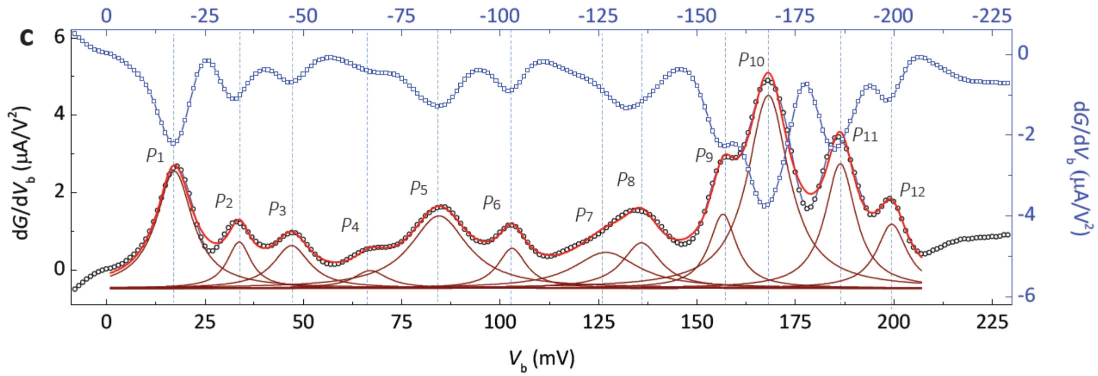
Inelastic Electron Tunneling Spectroscopy (Phonons)

STM measurement

IETS for graphene phonons

F. D. Natterer et al. Phy. Rev. Let. (2015)



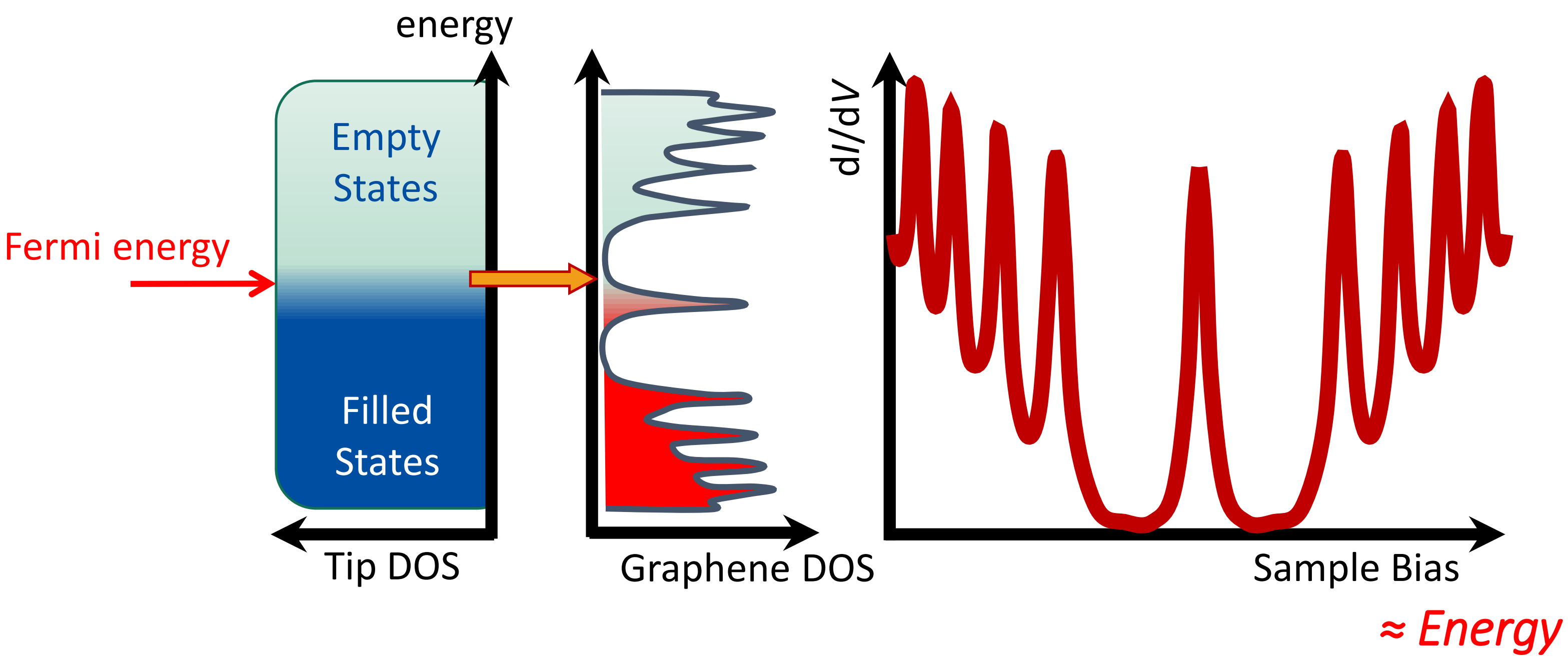


Density Functional Perturbation Theory (DFPT) Calculation

Peak No.	Position (mV)	FWHM (mV)	Phonons	DFT (meV)
1	16.7 ± 0.1	11.6 ± 0.6	Γ_{4+} (*h*-BN) / Γ_{6-}, Γ_{2-} (graphite)	11 / 14
2	33.5 ± 0.3	7.8 ± 1.0	Γ_{6-}, Γ_{2-} (graphene/*h*-BN hetero)	36
3	46.4 ± 0.4	12.6 ± 1.7	K_6 (graphene/*h*-BN hetero)	46
4	66.7 ± 1.7	7.8 ± 6.9	K_6 (graphite/graphene)	67
5	83.8 ± 0.3	18.1 ± 1.5	M_{2+} (graphene/*h*-BN hetero)	86
6	102.9 ± 0.3	9.4 ± 1.5	Γ_{3-}, Γ_{4+} (*h*-BN) / Γ_{4+} (graphite)	99 / 110
7	124.7 ± 2.4	19.7 ± 5.8	K_5 (*h*-BN) / K_2 (graphite)	129 / 124
8	134.8 ± 0.6	11.5 ± 2.5	K_5 (graphene/*h*-BN hetero)	140
9	156.4 ± 0.2	7.6 ± 0.7	$K_{1,2}$ (*h*-BN)	155
10	167.9 ± 0.1	12.6 ± 0.4	Γ_{5+} (*h*-BN)	167
11	186.3 ± 0.1	9.3 ± 0.4	LO overbending (*h*-BN)	184
12	199.2 ± 0.2	7.1 ± 0.7	Γ_{5+} / LO overbending (graphite)	198 / 202

S. Jung *et al.* Scientific Reports 5:16642 (2015)

Probing Electronic Structure with Tunneling



Tunneling Spectroscopy in High Magnetic Field

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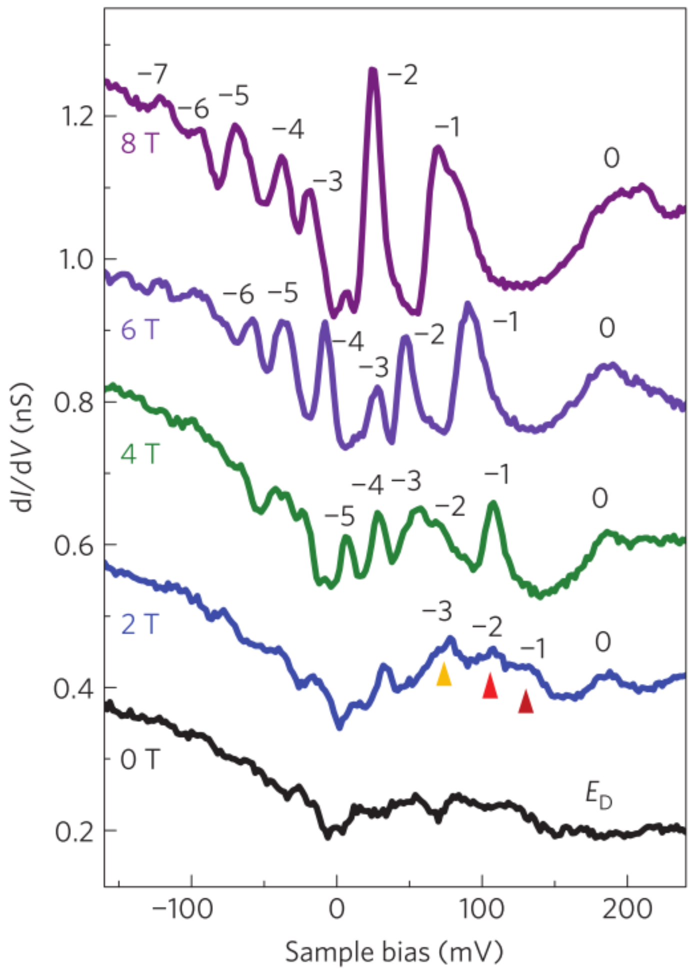
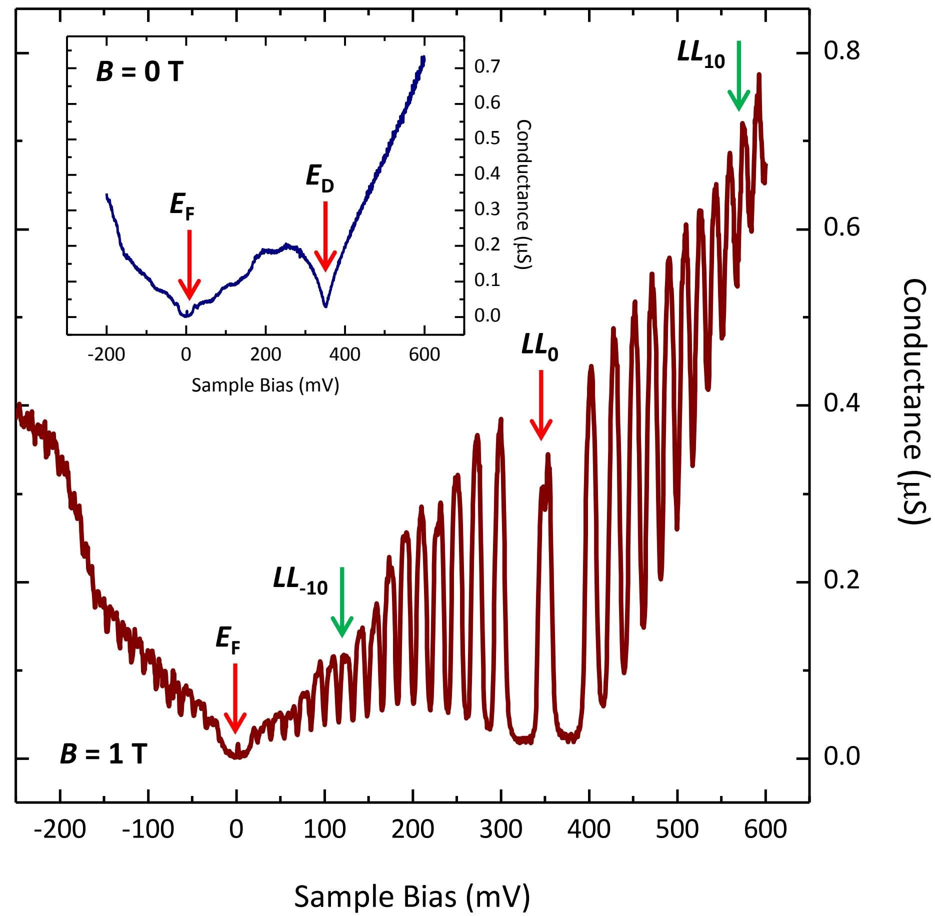
STM measurement

S. Jung et al. Nat. Phy. **7**, 245-251 (2011)

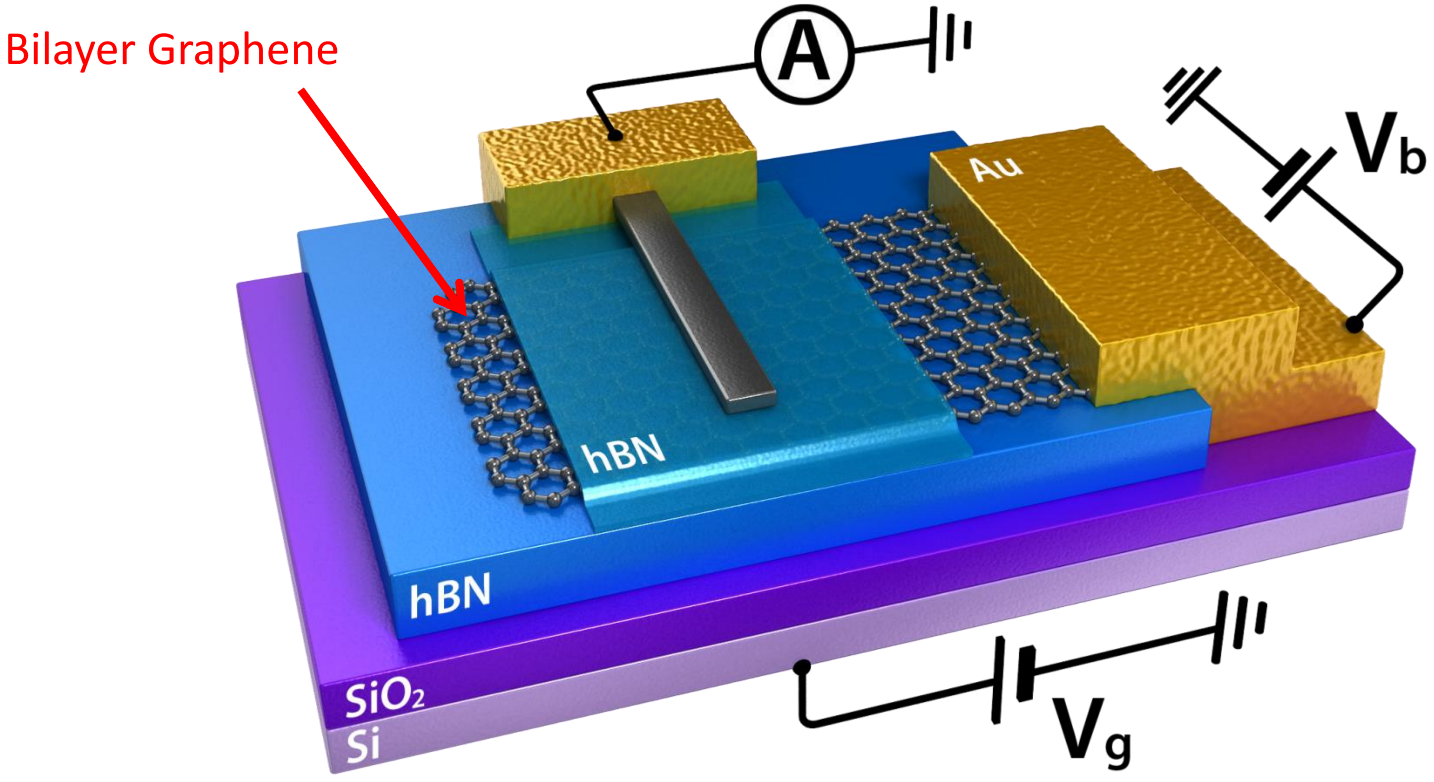


@ hole doping region (V_g = - 50 V)

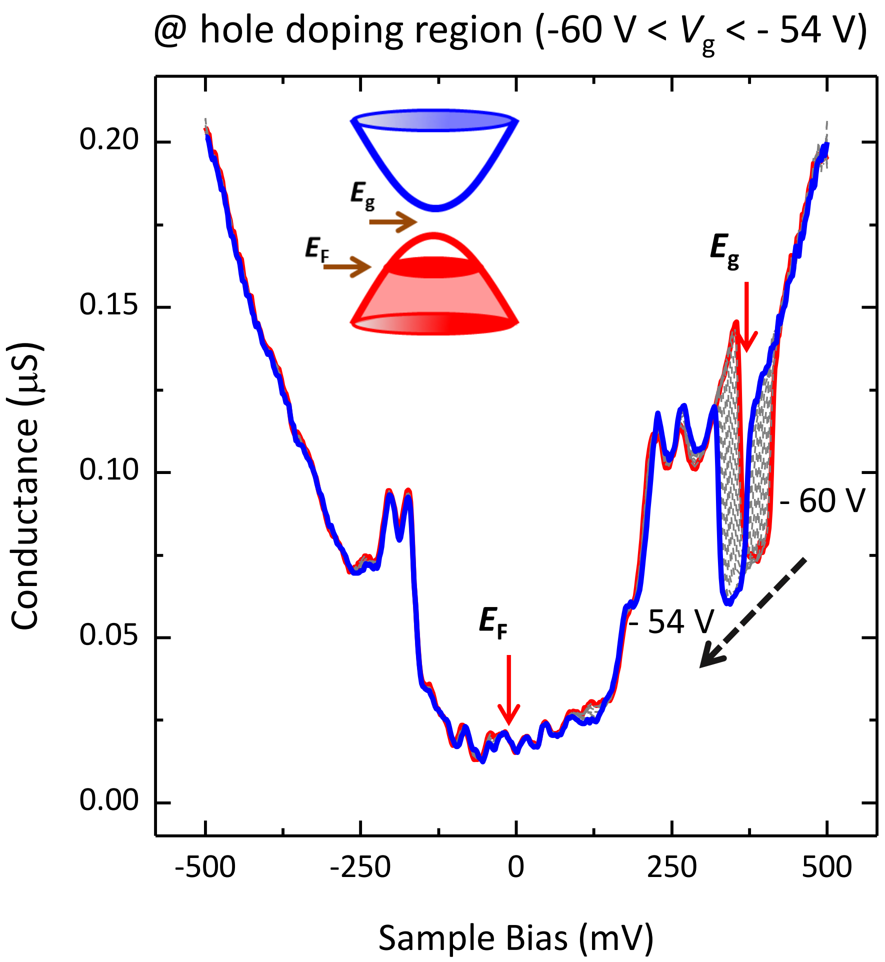


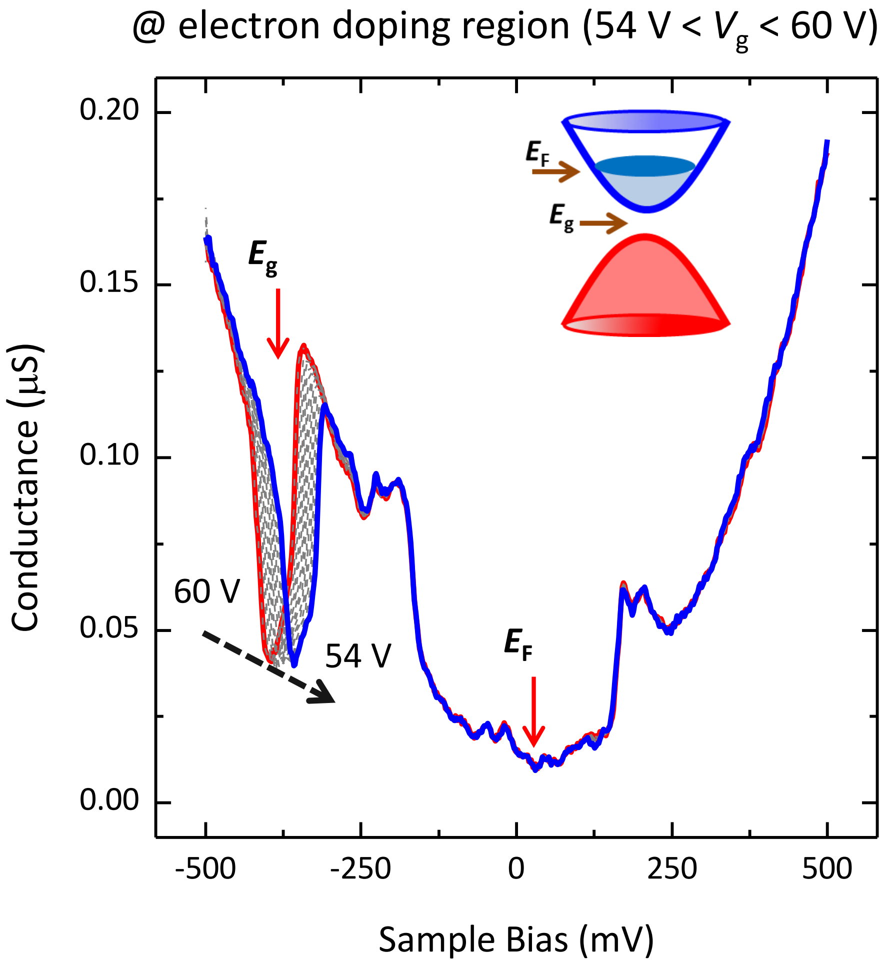
S. Jung, N. Myoung *et al.* Nano Lett. **17**, 206-213 (2017)

Tunneling Spectroscopy with h-BN as Insulator



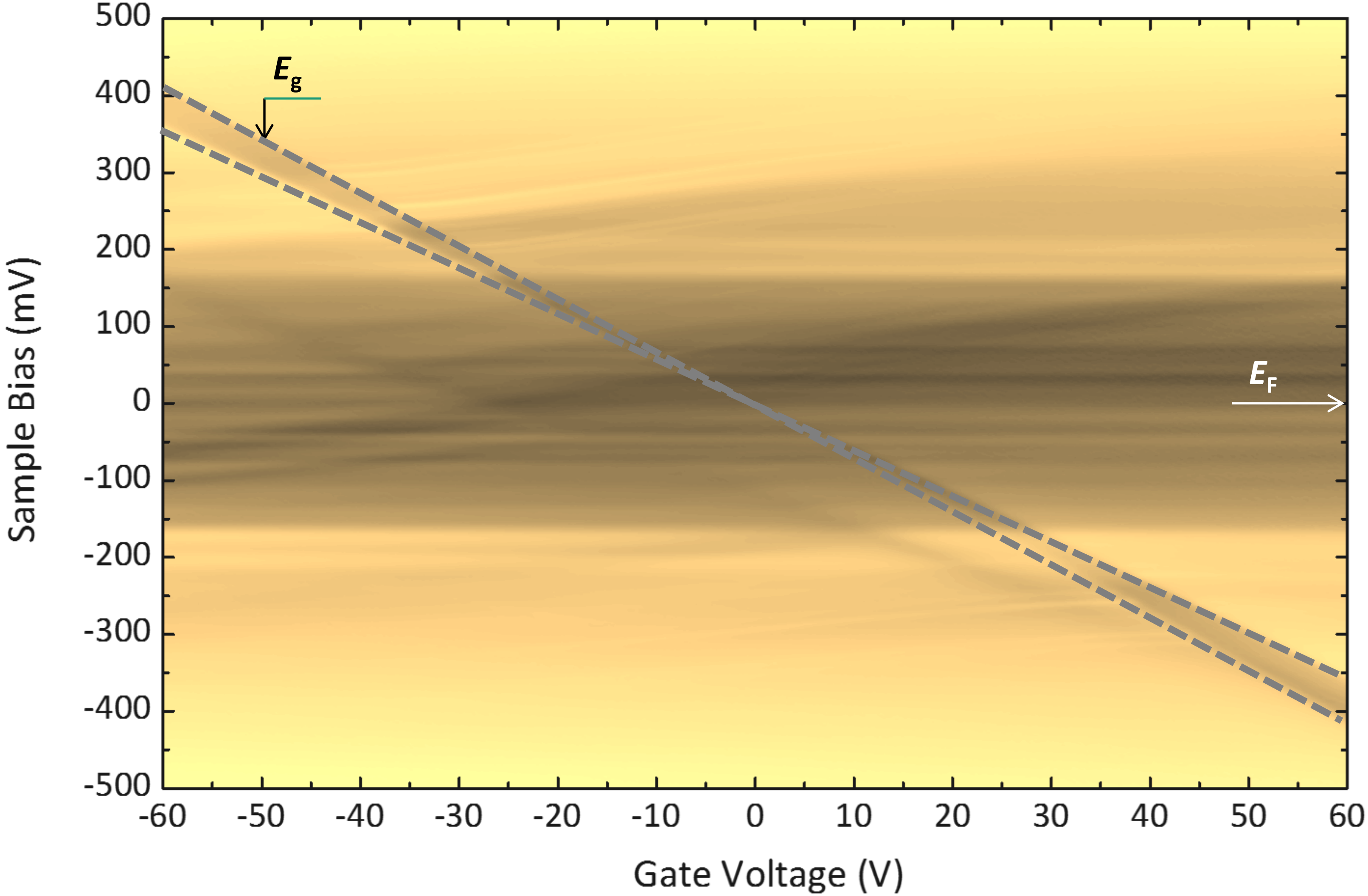
Tunneling Spectroscopy of Bilayer Graphene Device





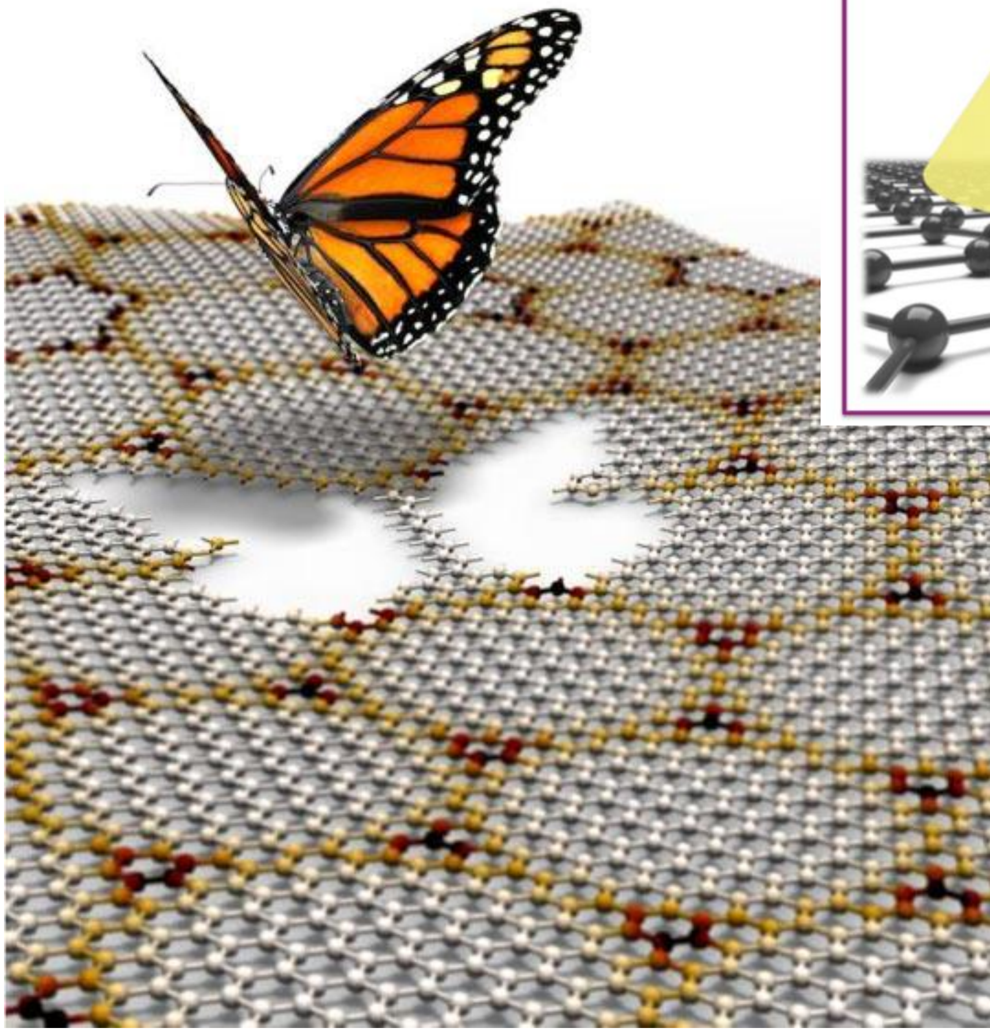
S. Jung, N. Myoung *et al.* Nano Lett. **17**, 206-213 (2017)

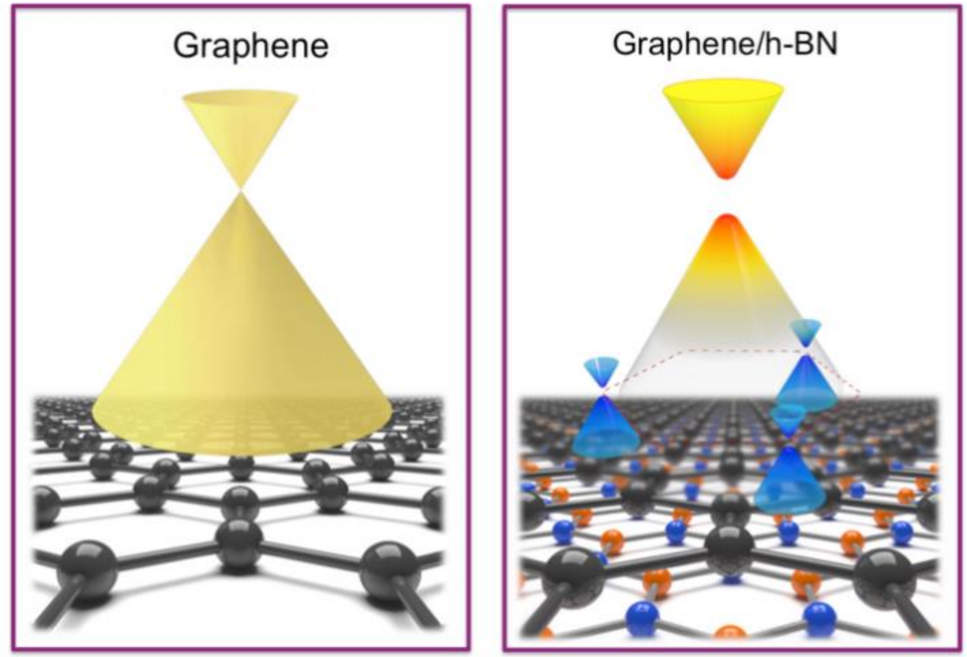
Gate Mapping of Bilayer Graphene Device

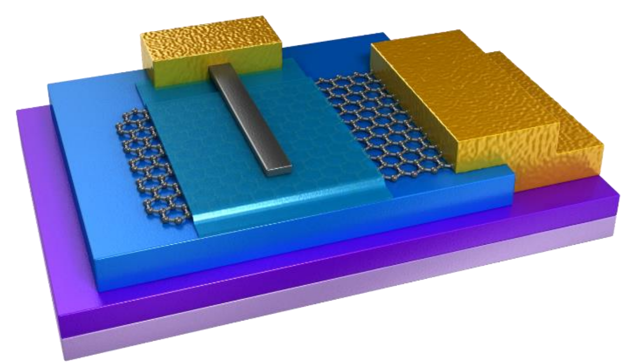


S. Jung, N. Myoung *et al.* Nano Lett. **17**, 206-213 (2017)

https://als.lbl.gov/altered-states-graphene-heterostructures/

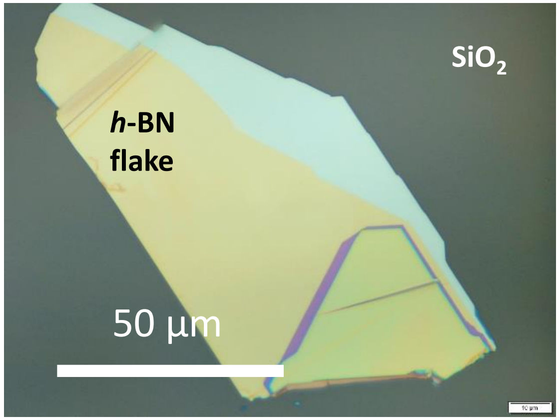






Fabricating Graphene-*h*-BN Tunneling Devices

h-BN/SiO_2



Fabricating Graphene-*h*-BN Tunneling Devices

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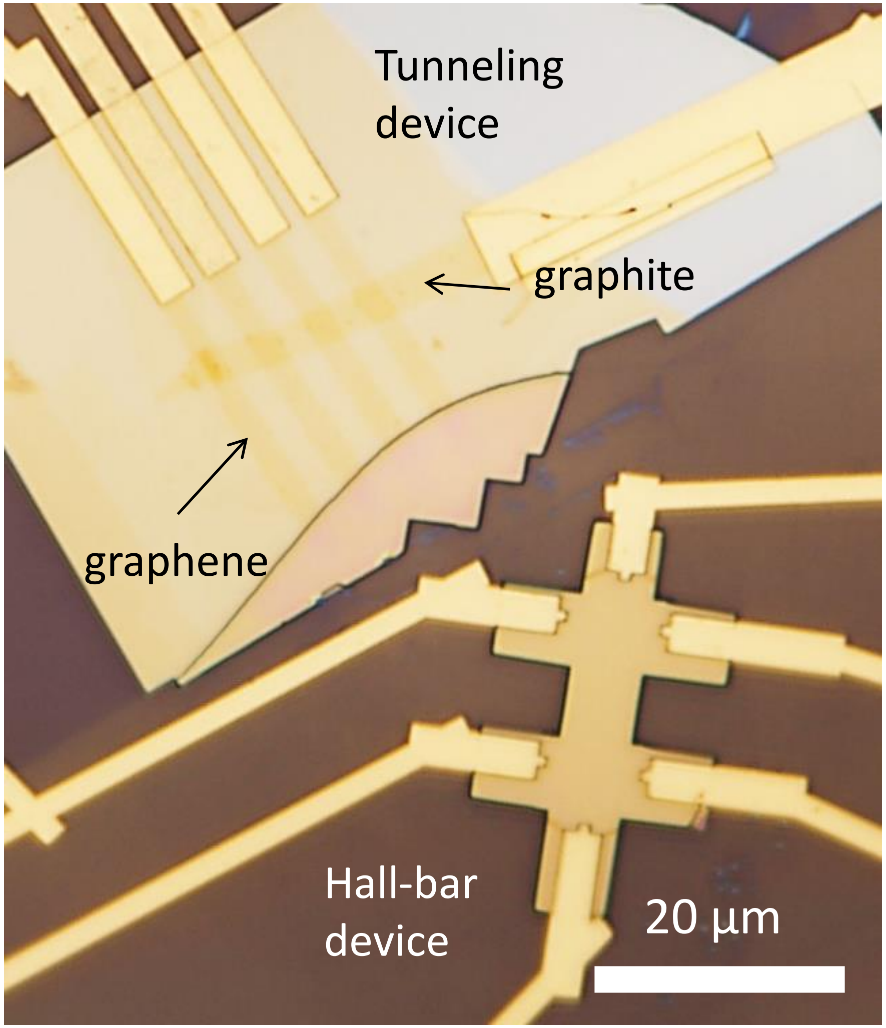
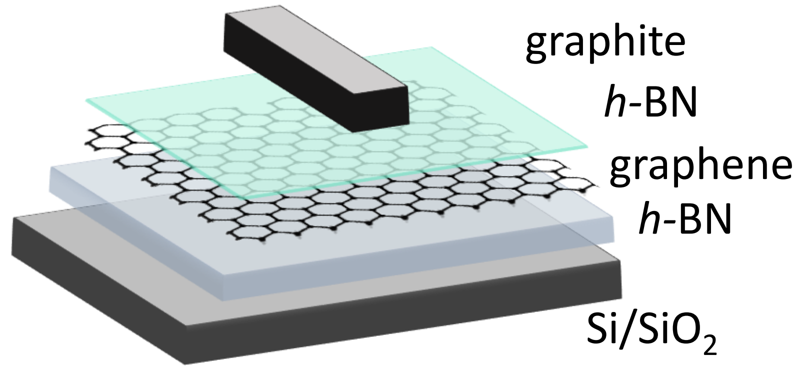
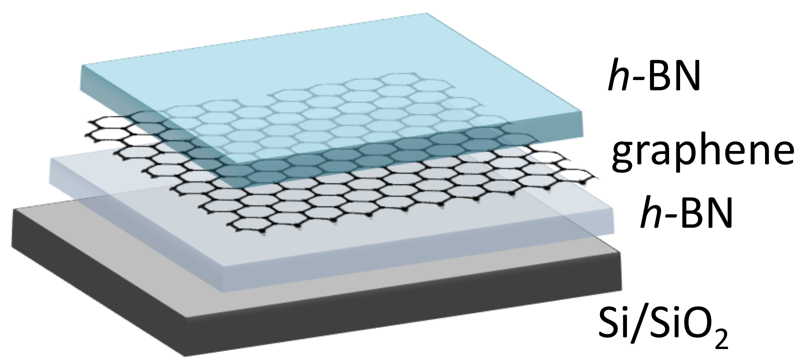


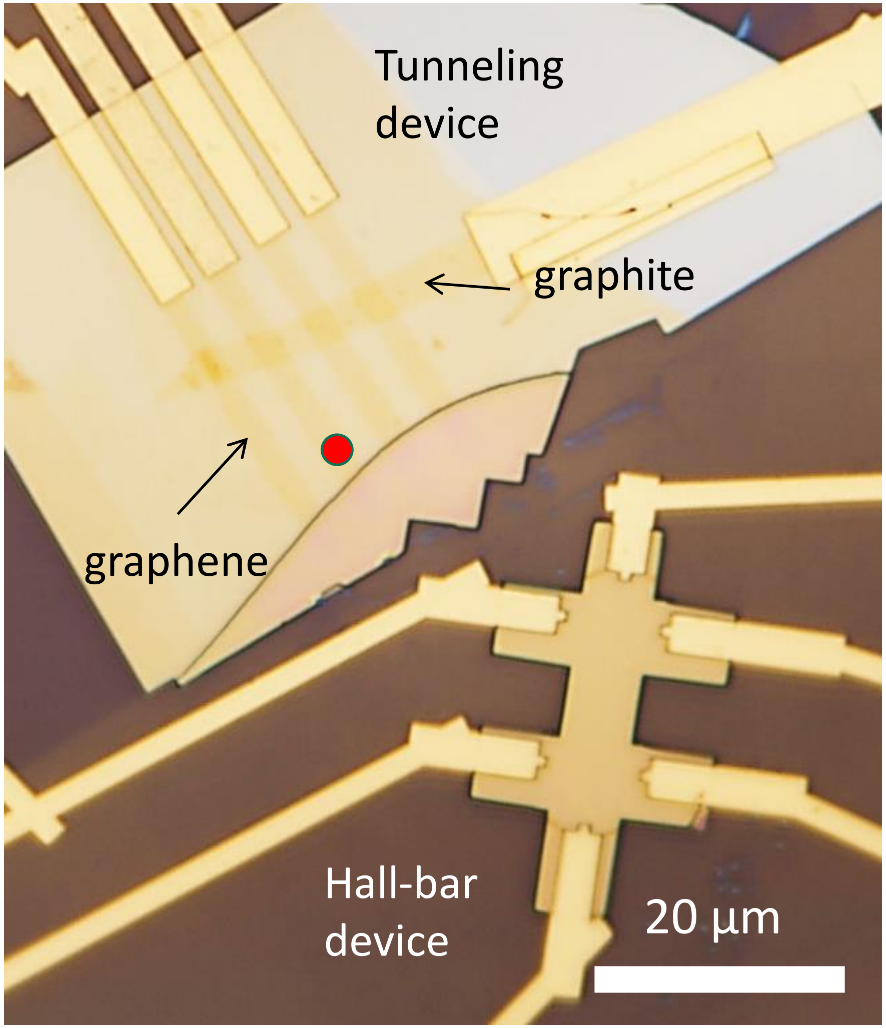
Tunneling device



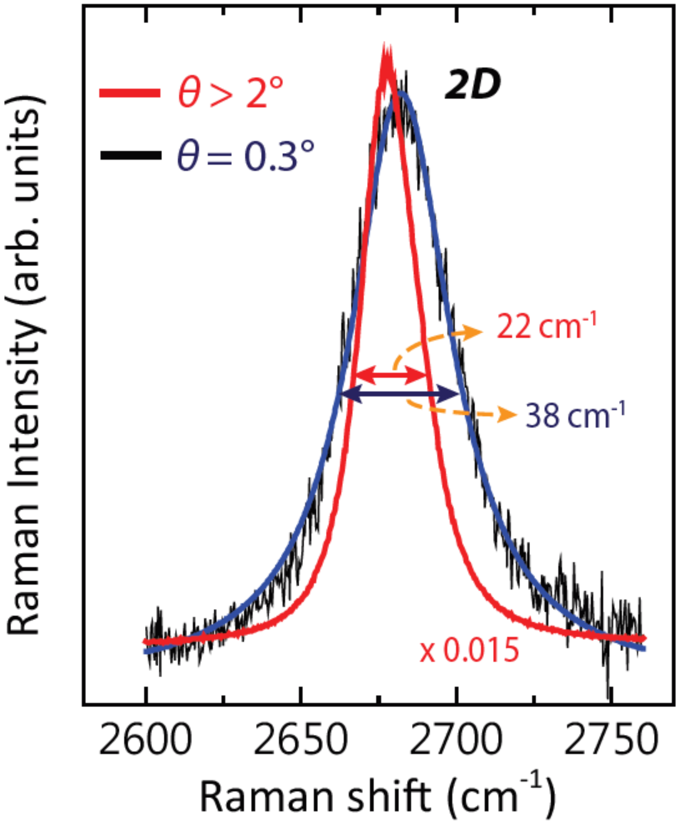
Edge-contact Hall-bar device



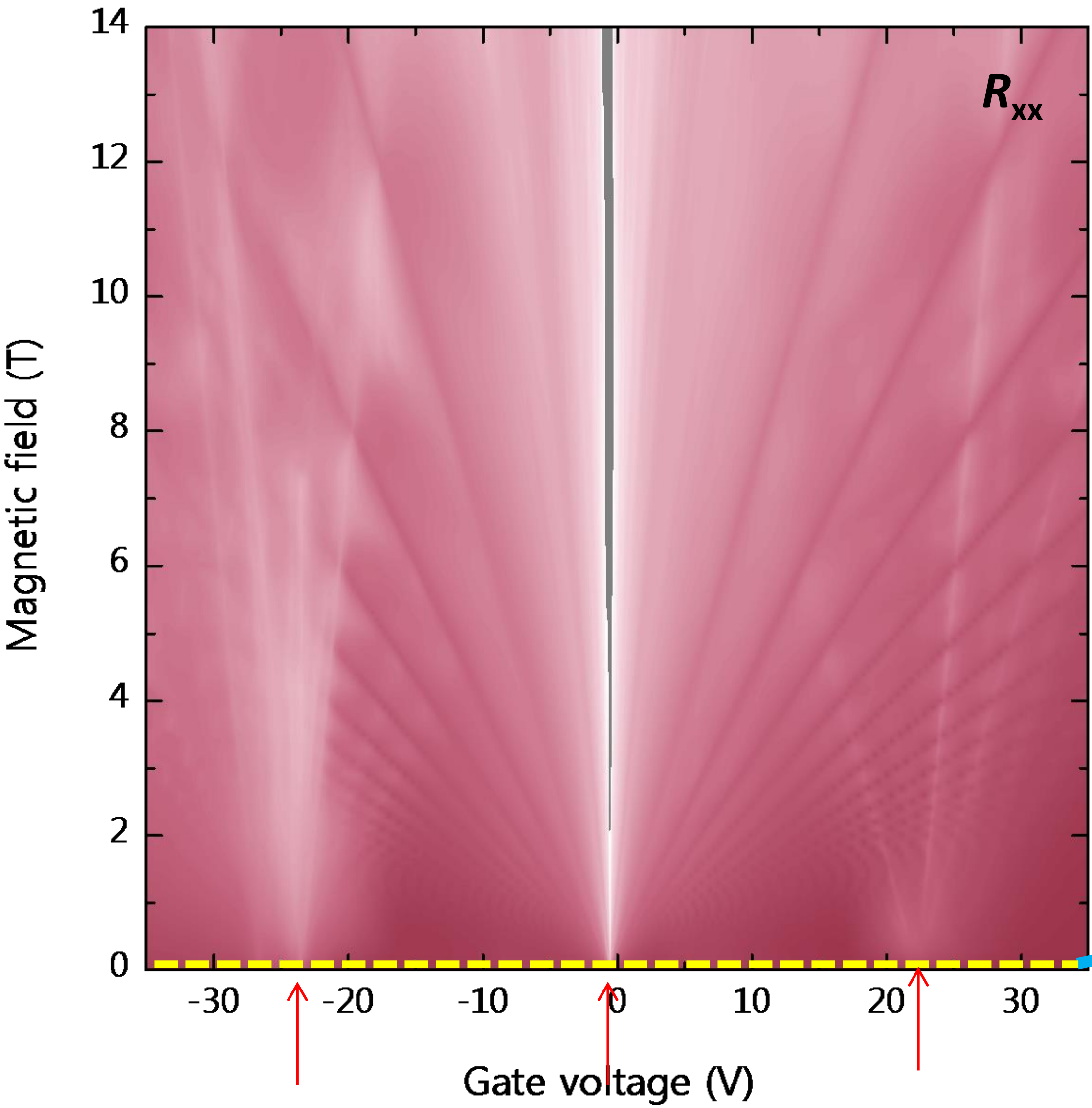
Basic Parameters for Graphene Superlattice



Twist angle (i.e. Moire superlattice length) from the FWHM width of Raman 2D



Basic Parameters for Graphene Superlattice



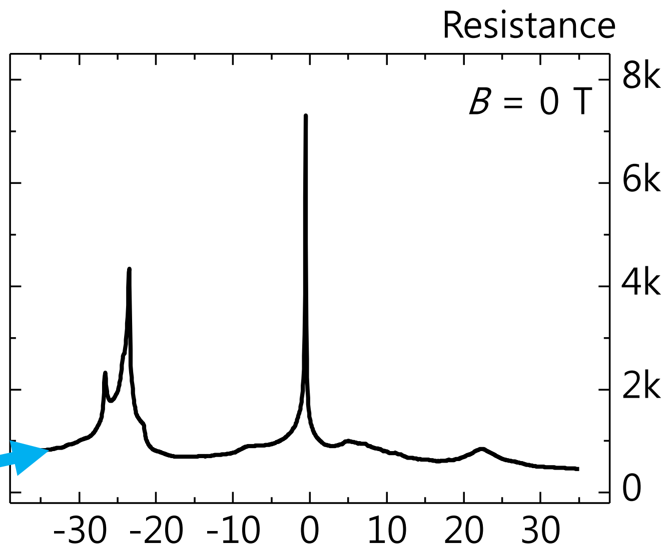
V_g (FDP) = -0.5 V , V_g (SDP) = -23.1 V

density(n) = 2.35 x 10^{12} cm^{-2}

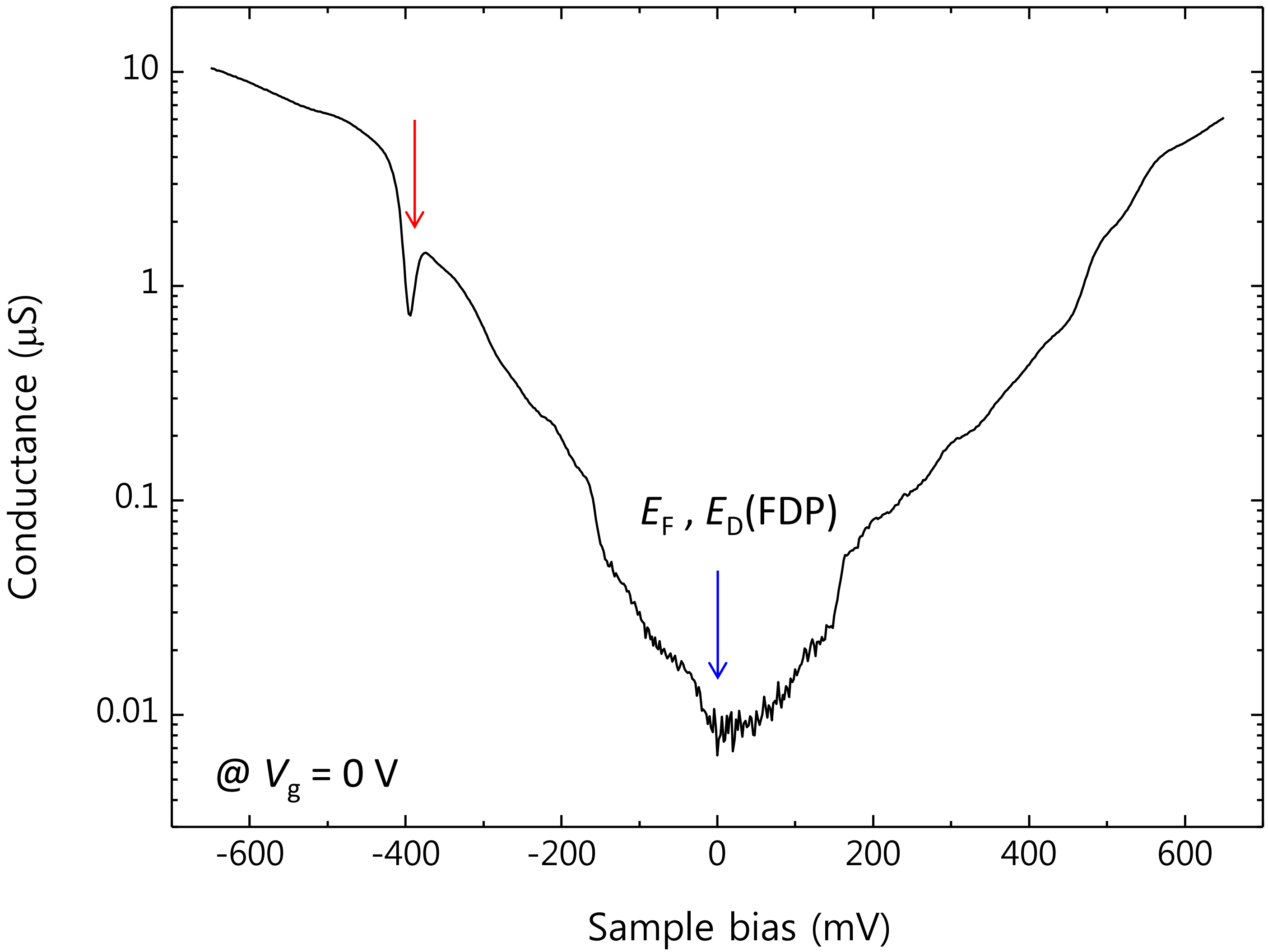
E_D @ SDP : 0.18 eV

Superlattice length: 13.4 nm

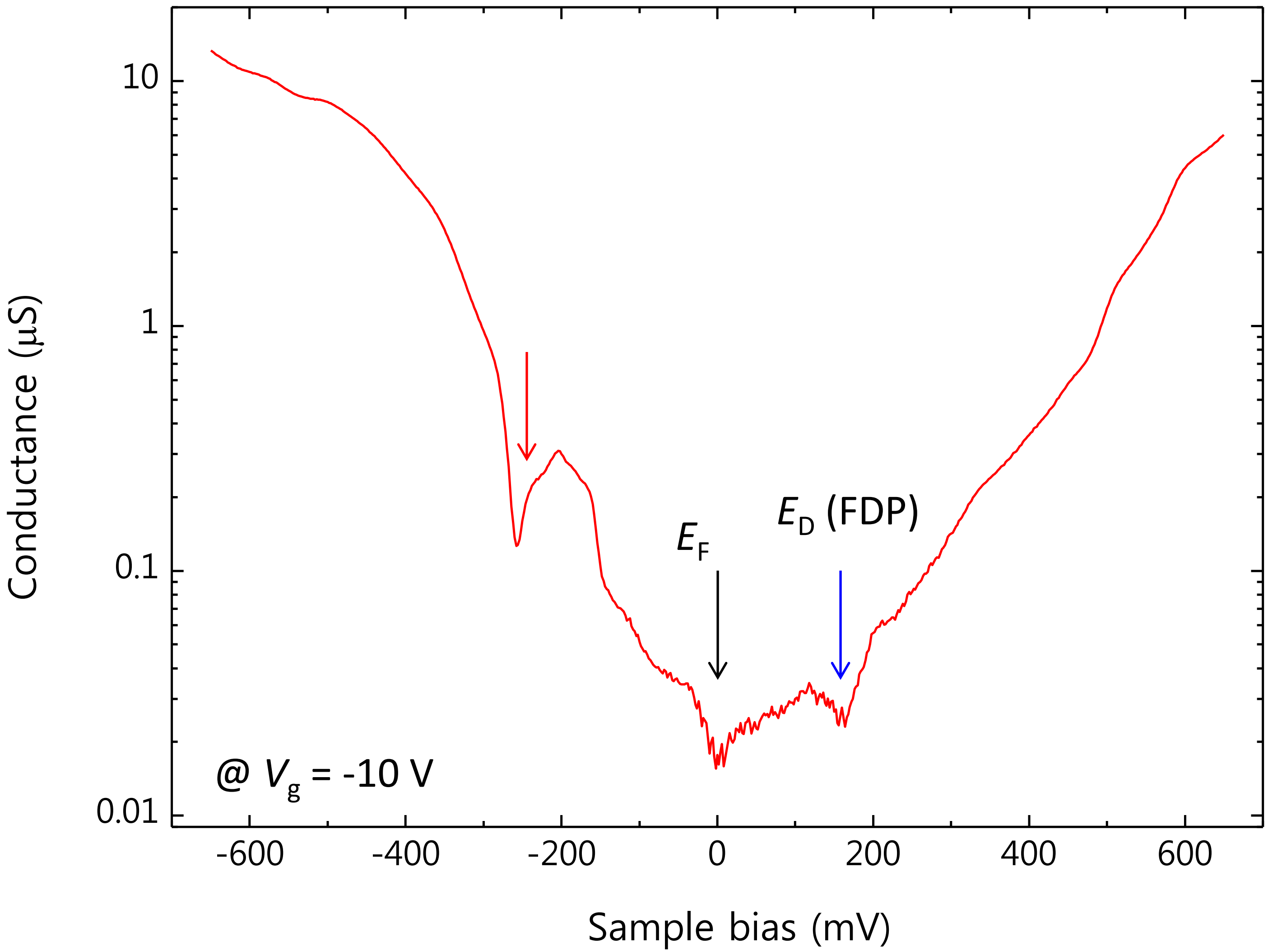
Twist angle : 0.3°



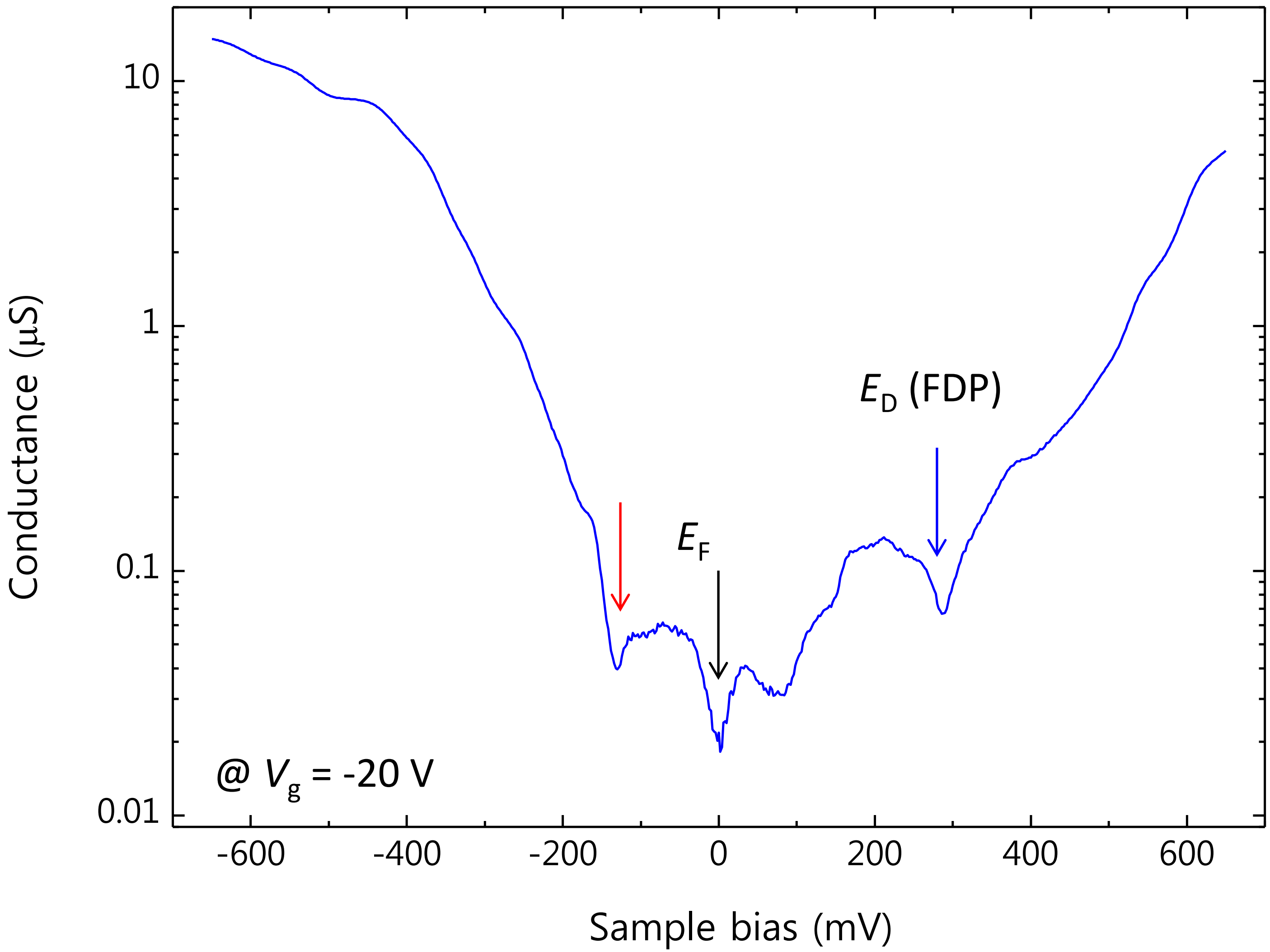
Tunneling Spectra of Graphene-*h*-BN Superlattice



Tunneling Spectra of Graphene-*h*-BN Superlattice



Tunneling Spectra of Graphene-*h*-BN Superlattice



Tunneling Spectra of Graphene-*h*-BN Superlattice

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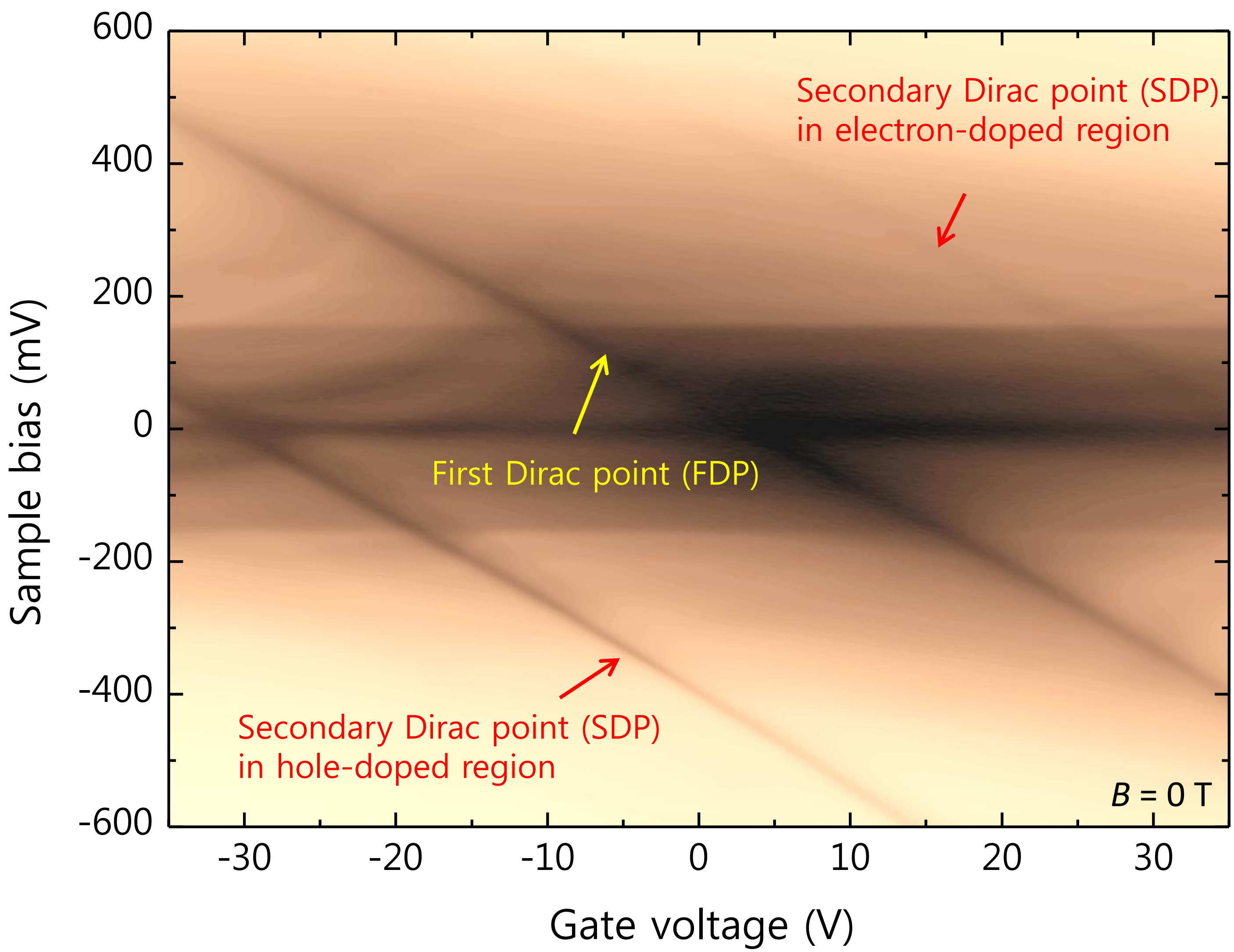
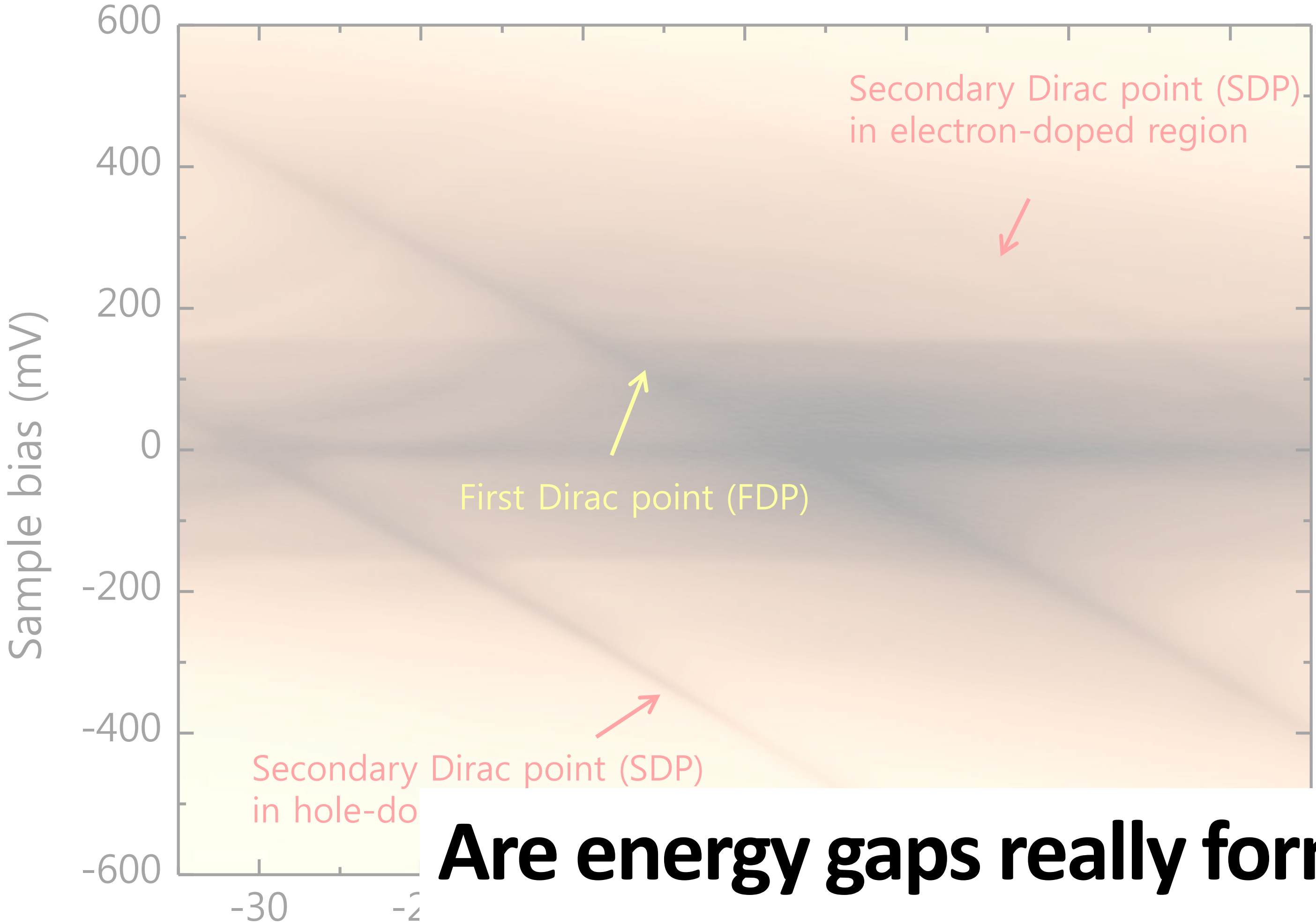


Tunneling Spectra of Graphene-*h*-BN Superlattice



Are energy gaps really formed at both the DPs ?

Landau Level Spectroscopy for Energy-gap Analysis

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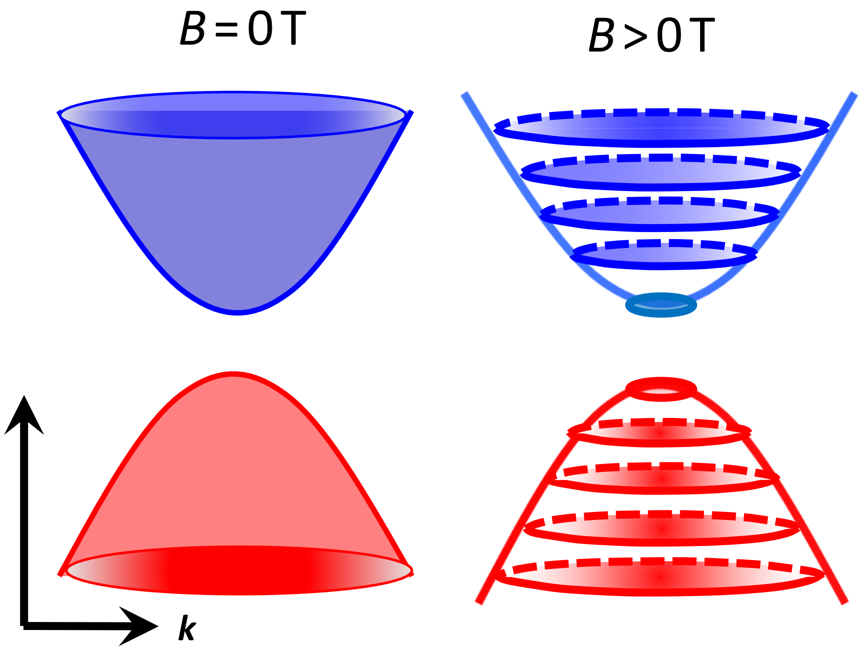
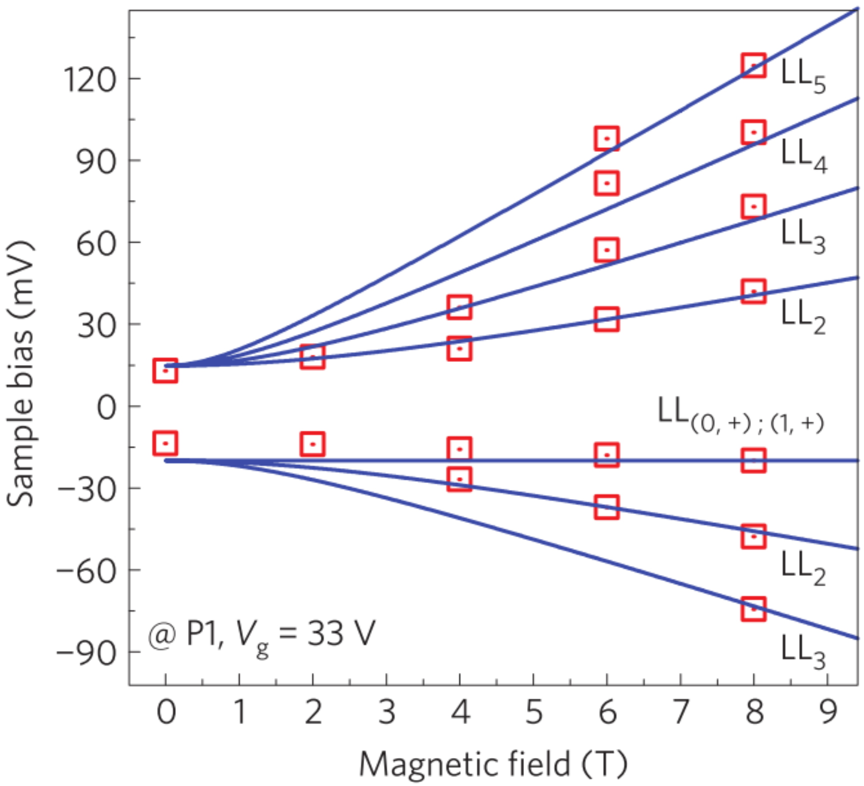
Bilayer graphene with an energy gap

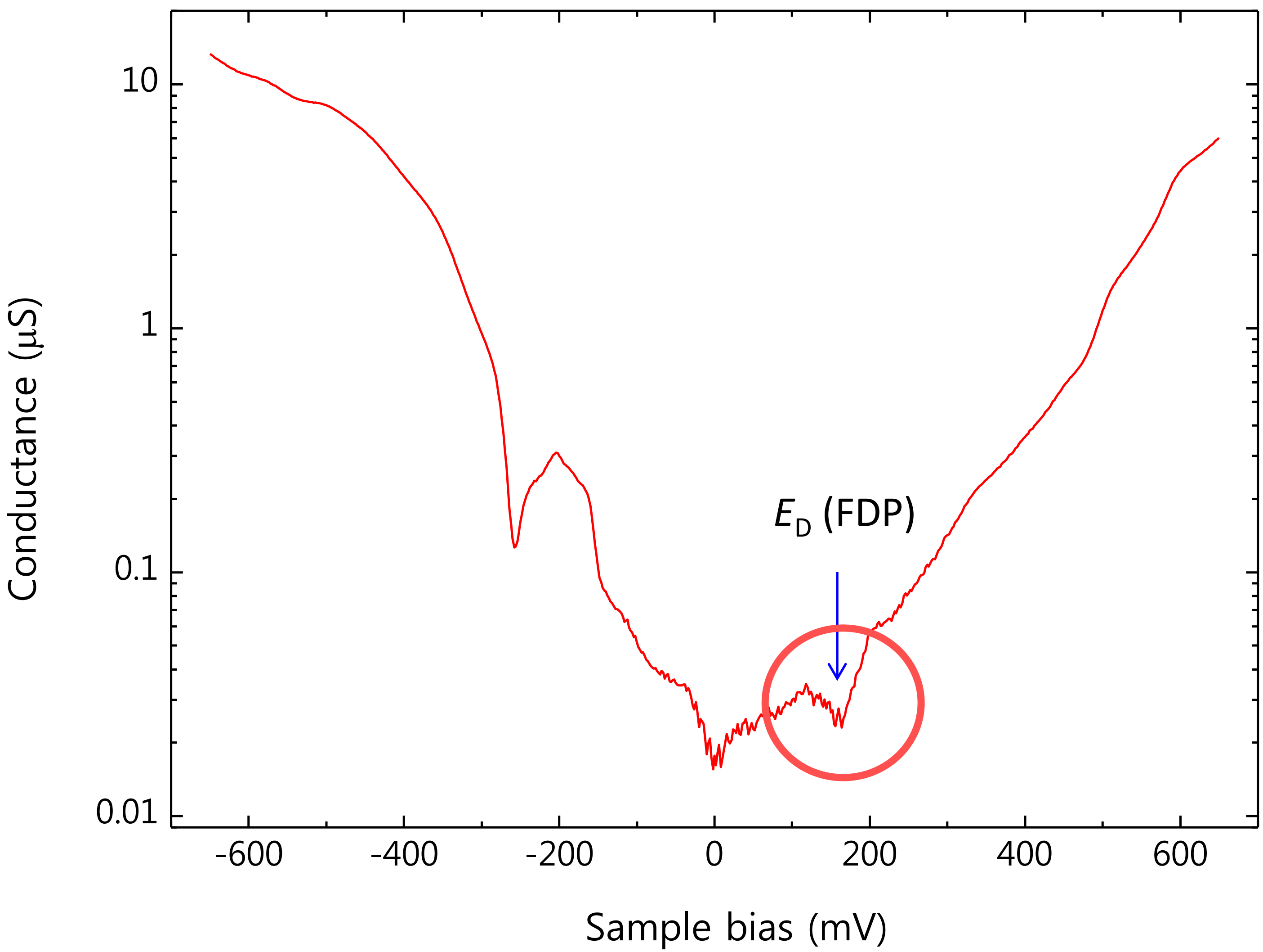


Landau-level spectroscopy



G. Rutter. S. Jung *et al.* Nat. Phys. **7**, 649-655 (2011)

Tunneling Spectra of Graphene-*h*-BN Superlattice



Tunneling Spectra of Graphene-*h*-BN Superlattice

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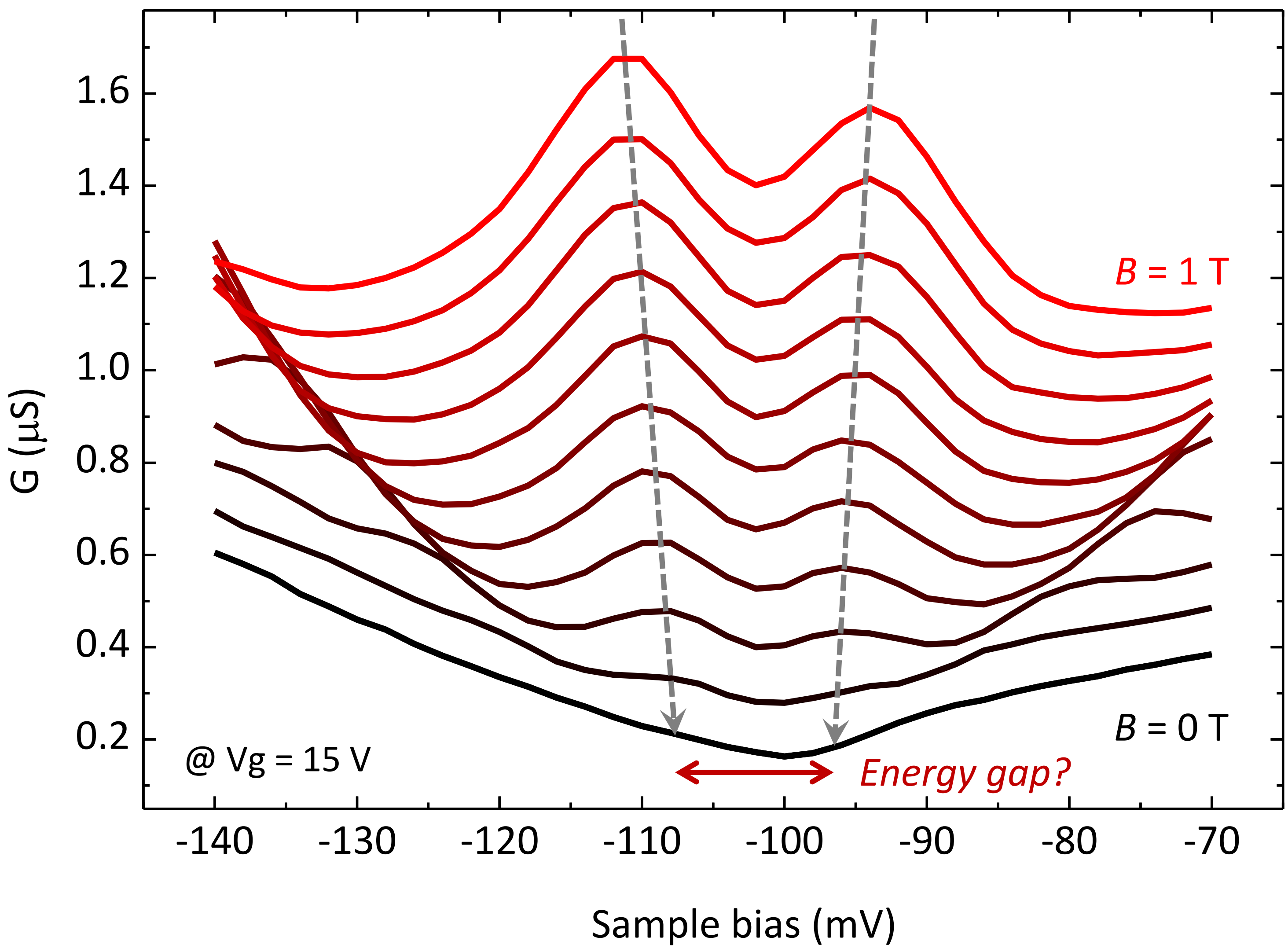
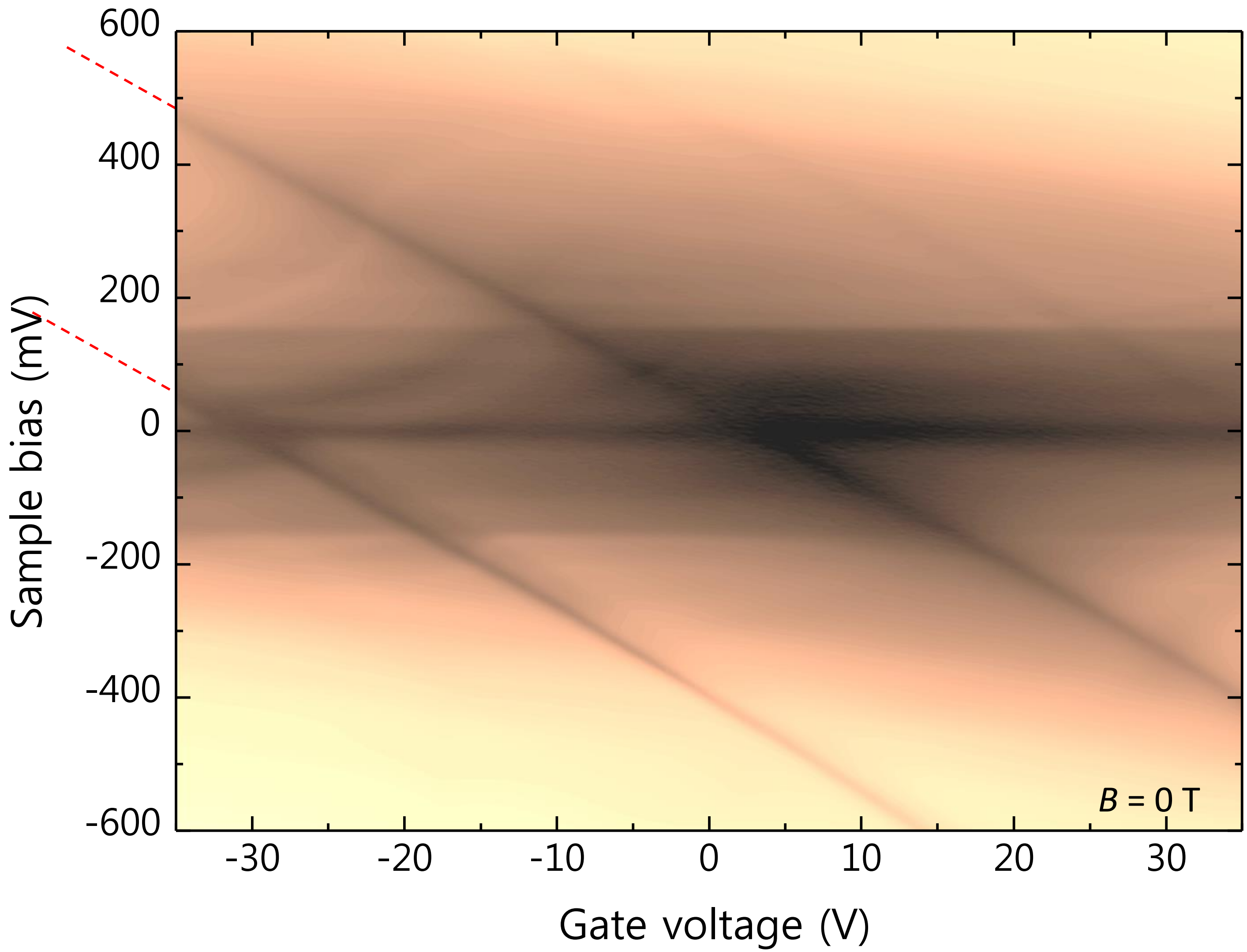
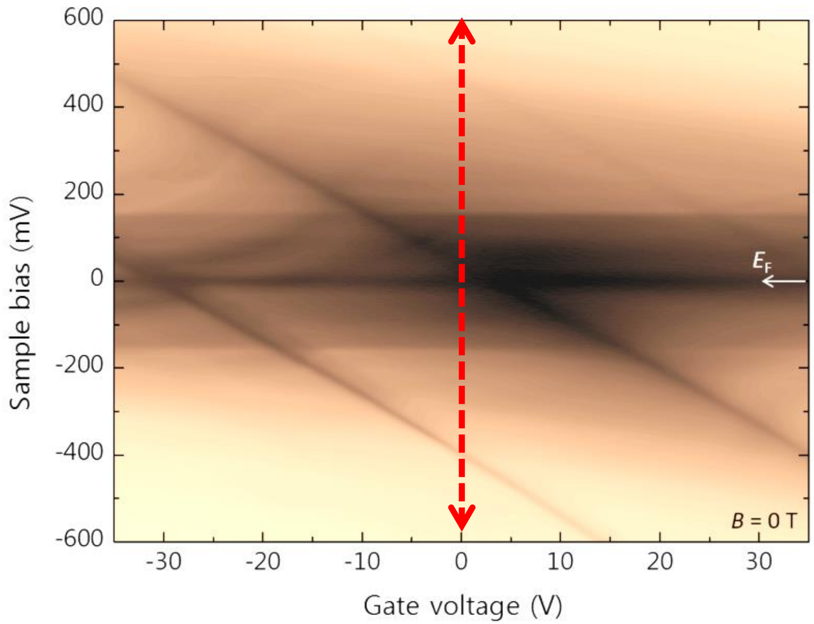


Landau Level Spectroscopy for Gap Analysis



Landau Level Spectroscopy for Gap Analysis



Landau Level Spectroscopy for Gap Analysis

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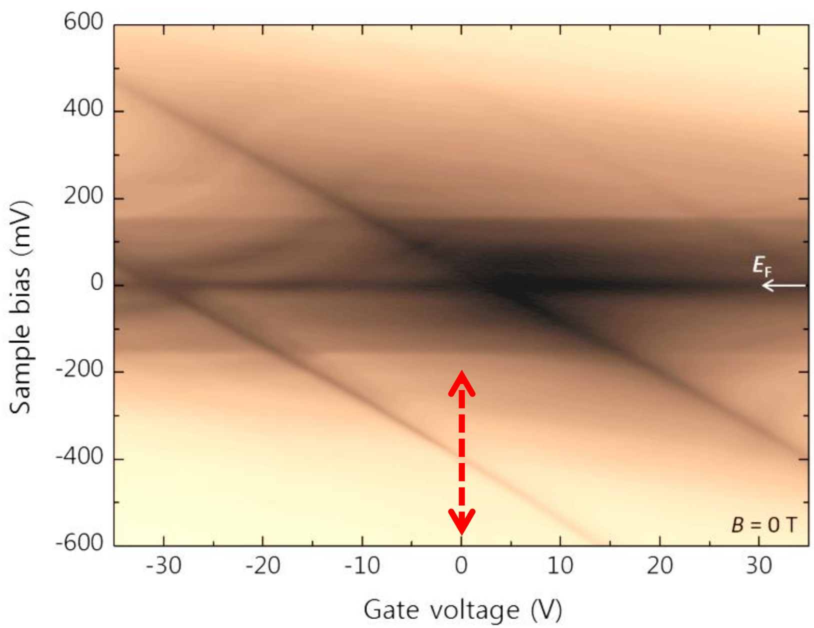
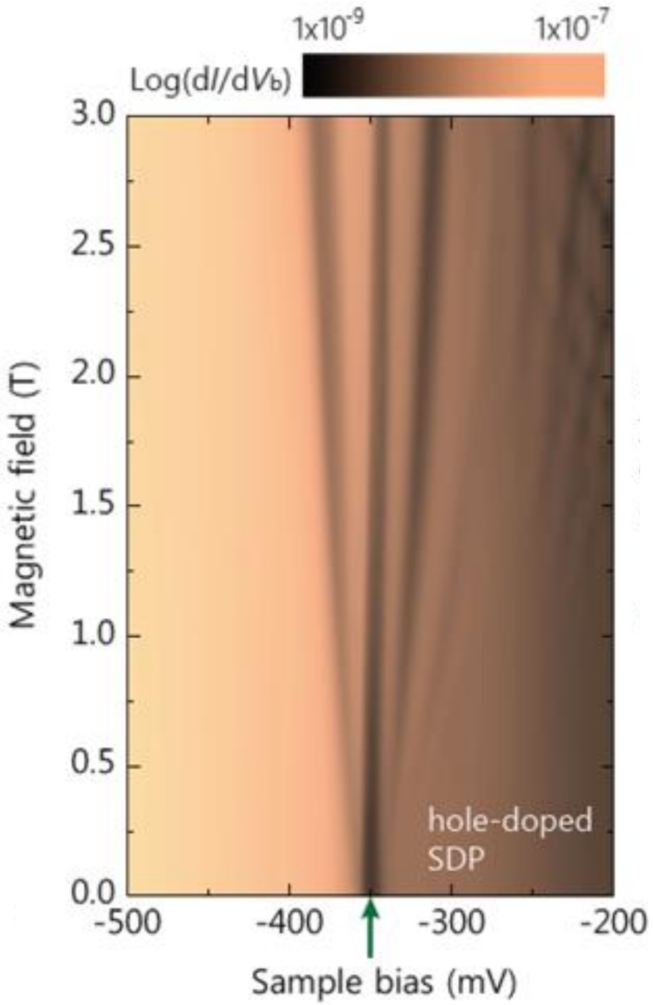
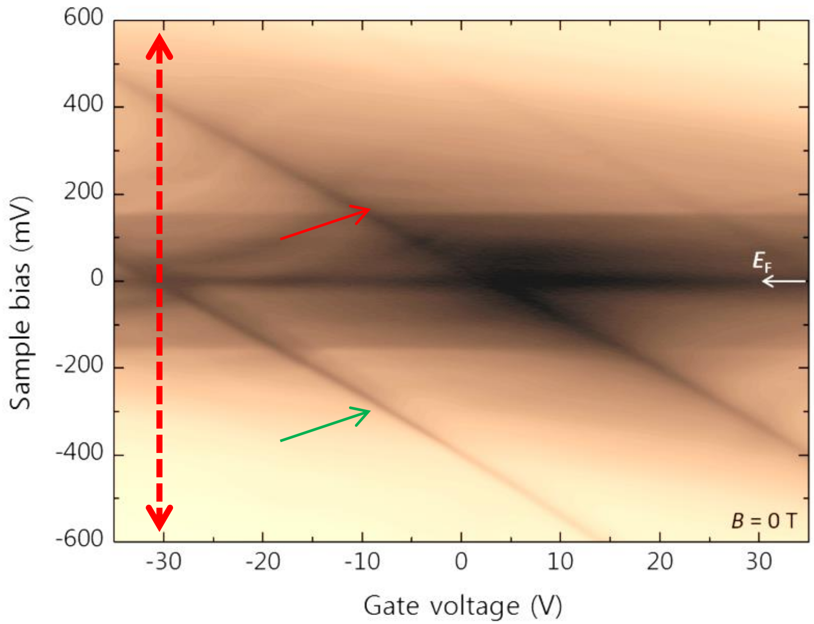
Energy gap formed at the 2nd Dirac point of graphene-*h*-BN superlattice in hole-doped region



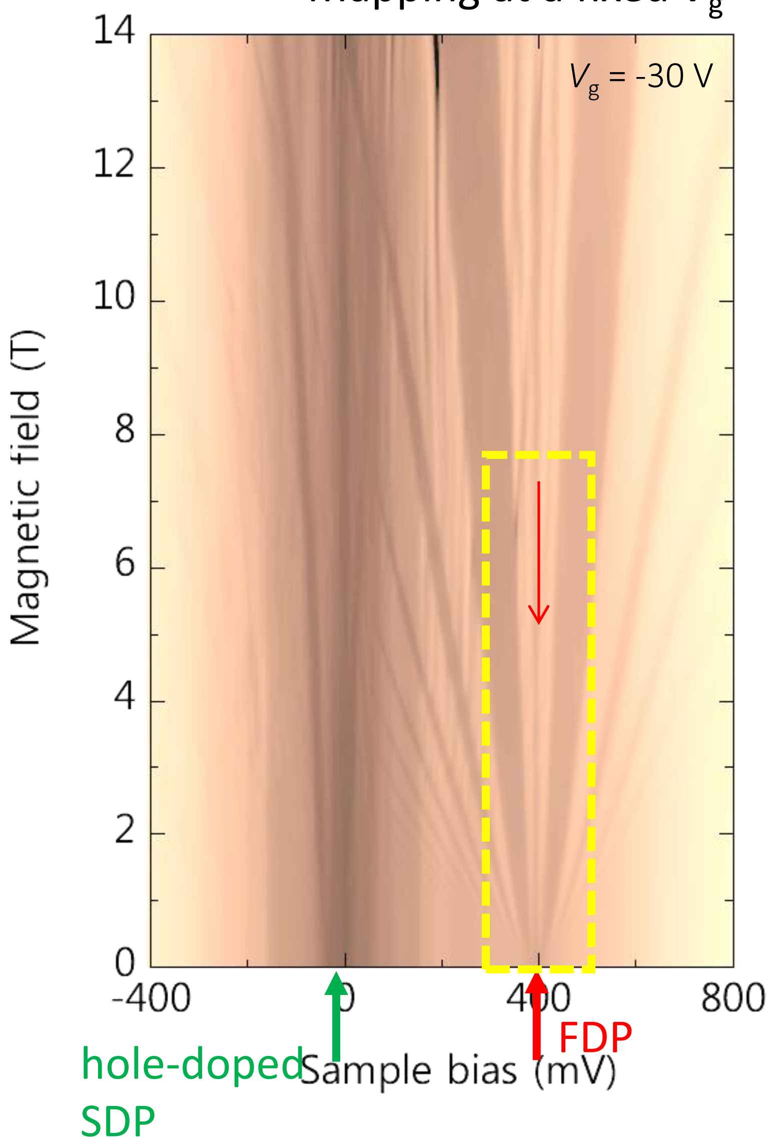


Landau Level Spectroscopy for Gap Analysis

Gate Mapping at a fixed B field



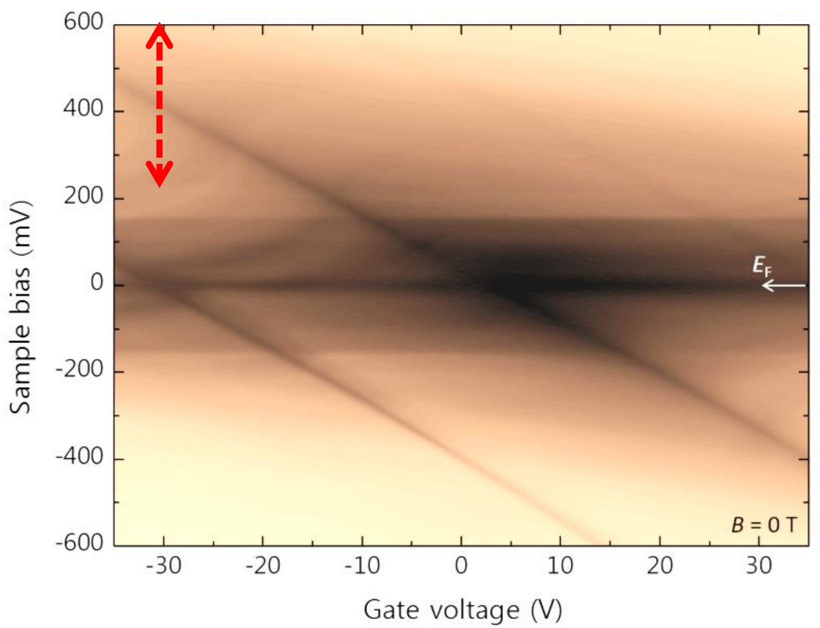
Mapping at a fixed V_g

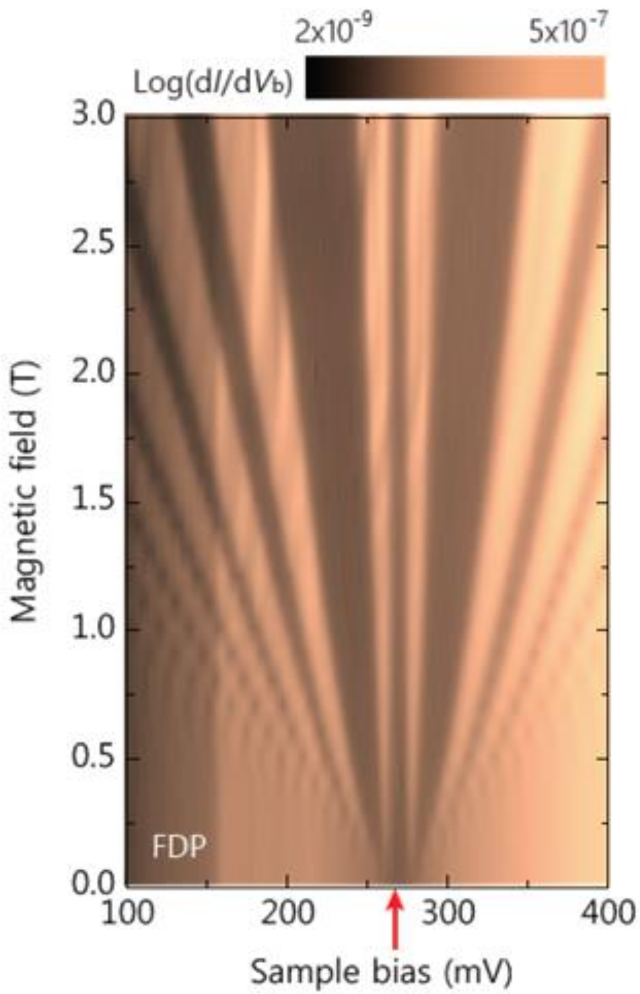


Landau Level Spectroscopy for Gap Analysis

KRISS

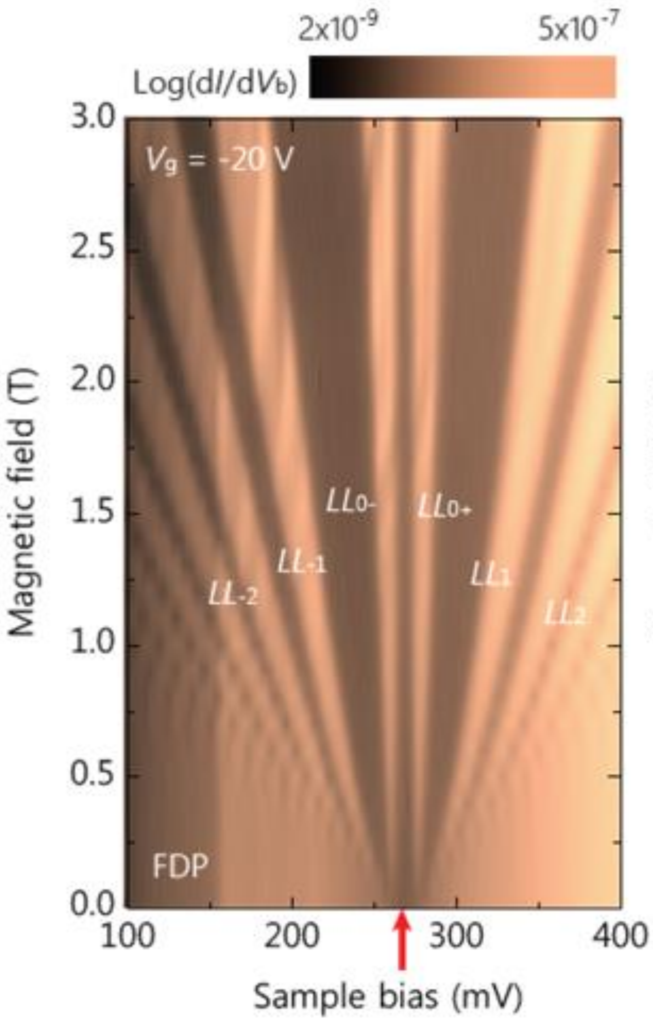
Energy gap formed at the 1st Dirac point of graphene-*h*-BN superlattice



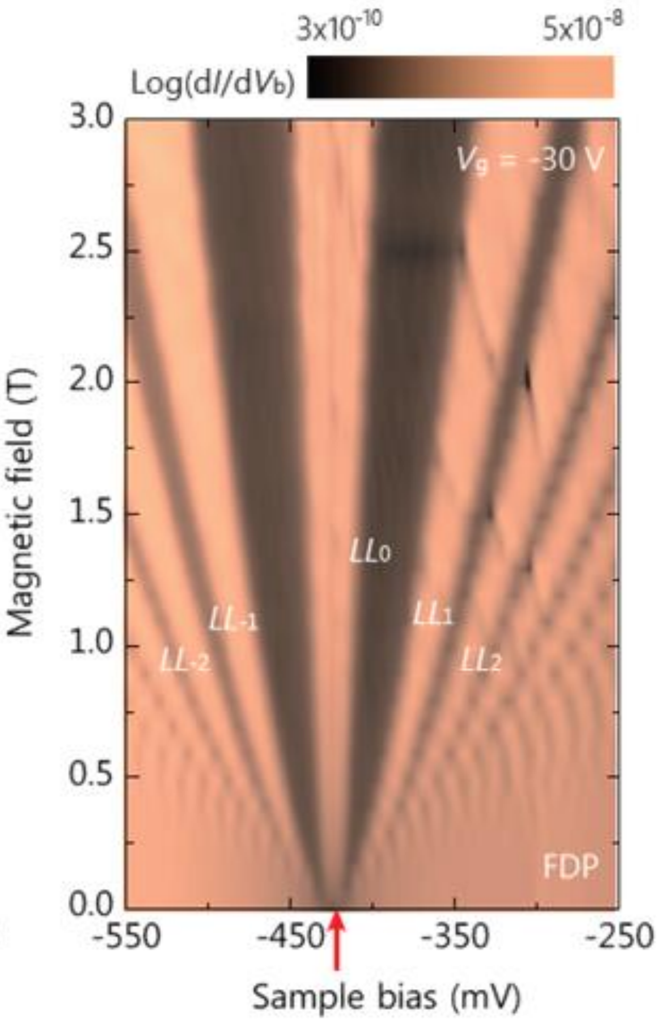


Landau Level Spectroscopy for Gap Analysis

Energy gap at the 1st Dirac point



Dirac point from misaligned graphene-*h*-BN device



Landau Level Spectroscopy for Gap Analysis

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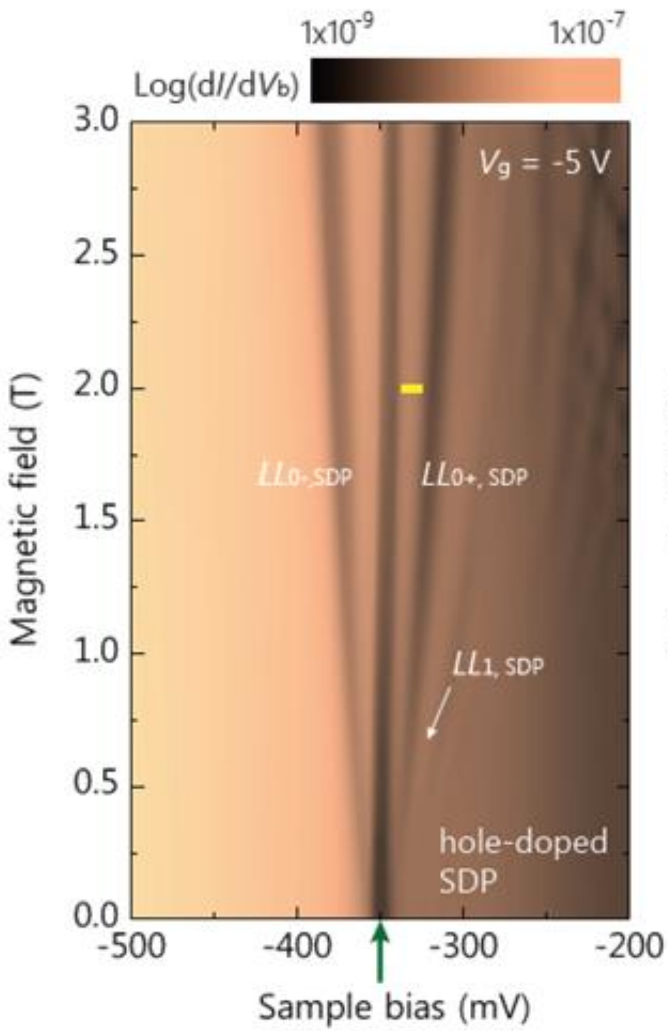
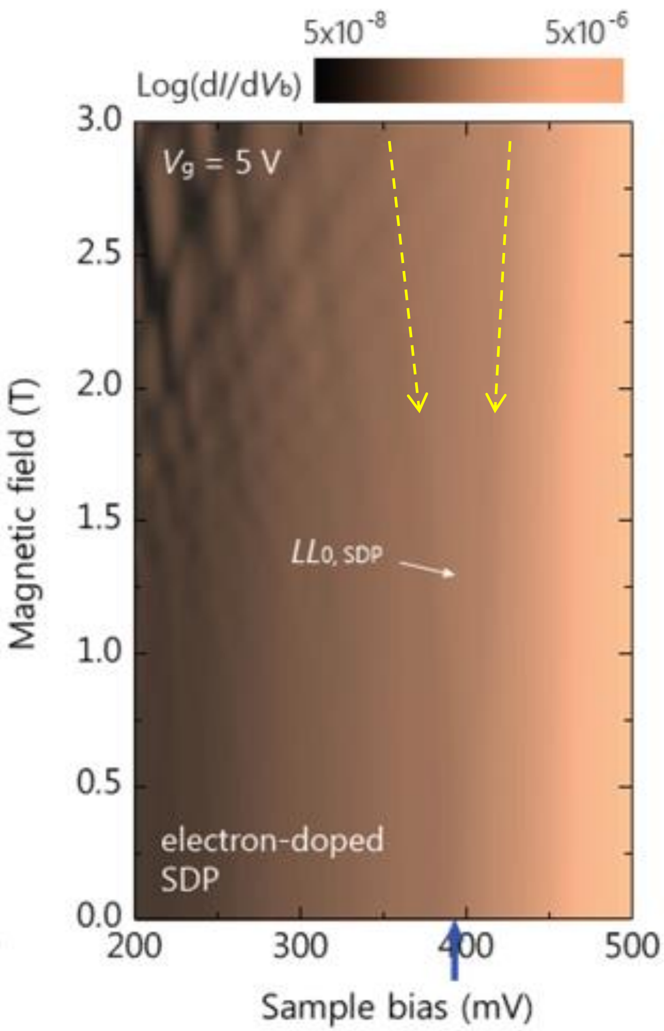
2nd Dirac point in hole-doped region

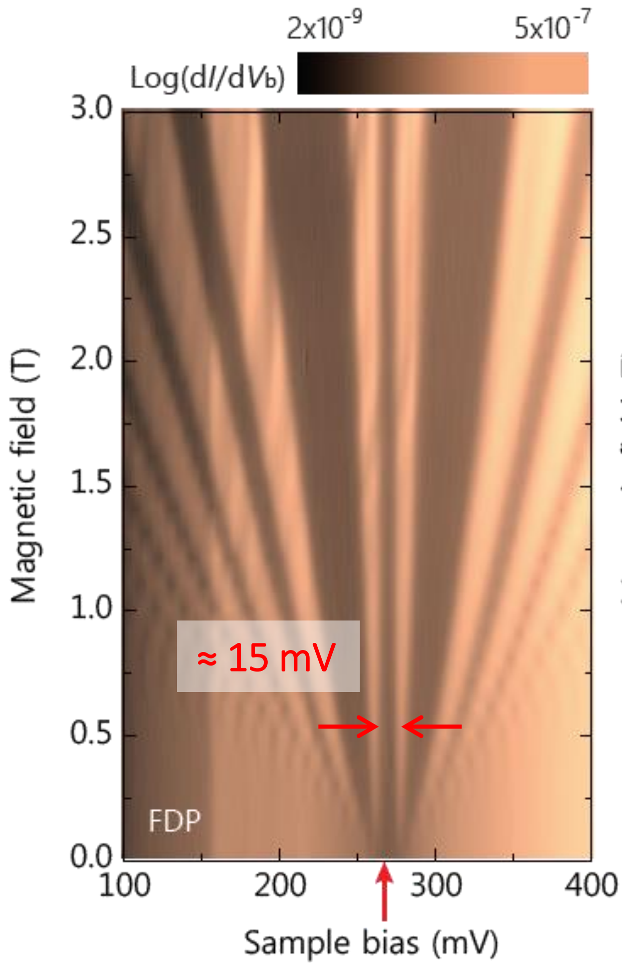


2nd Dirac point in electron-doped region

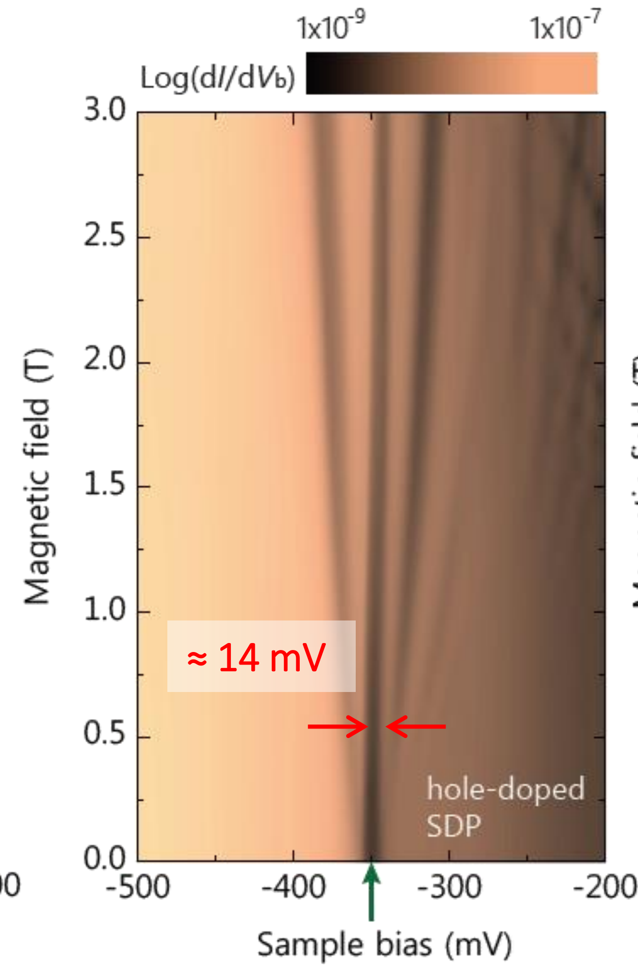


Landau Level Spectroscopy for Gap Analysis

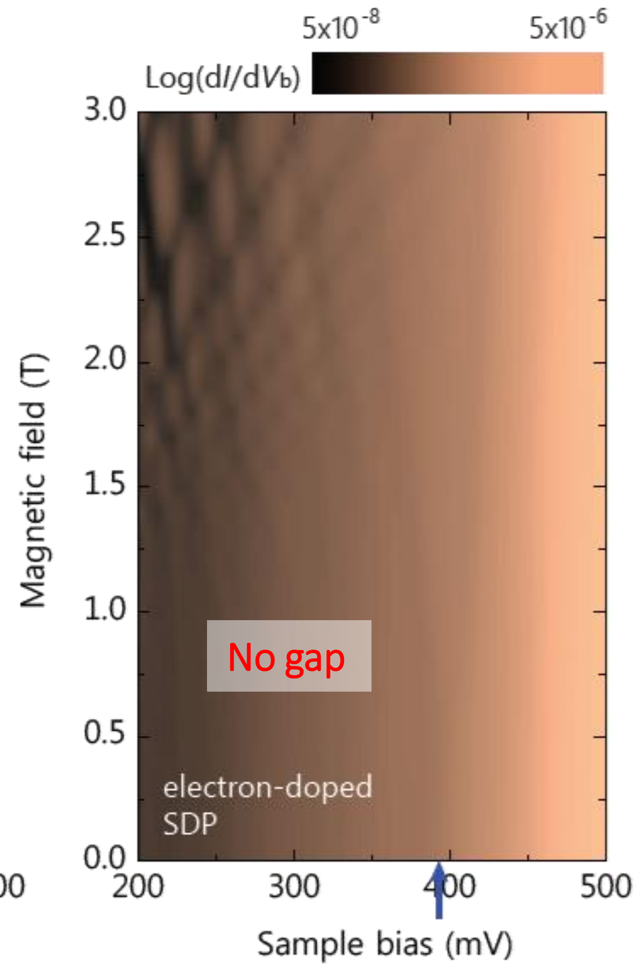
Energy gap at the 1st DP



2nd DP in hole-doped region



2nd DP in electron-doped region



H. Kim *et al.* In preparation

Graphene-*h*-BN twist angle : 0.14° , Moire wavelength : 13.8 nm

Summary / Ongoing Efforts

KRISS

Developed experimental platforms for high-quality graphene devices

: hybrid devices with h-BN, dry transfer technique

Investigate novel quantum phenomena in low-dimensional systems

Tunneling spectroscopies for low-dimensional systems under various physical conditions

: Carbon nanotubes , Transition Metal Dichalcogenide (TMDC)

: tunneling + optical, thermal, mechanical knobs varying *T*, *B*, *P* and others

- Acknowledgement

Hakseong Kim, Tae-Young Jeong, **Jaesung Park,** Donghan Ha, Chanyong Hwang, Minkyu Park, Yongsung Kim (KRISS)

M. Farooq Khan, Jonghwa Eom (Sejong U.)

Nojoon Myoung, Hee Chul Park (IBS) , Nikolas Neconte, Jeil Jung (U. Seoul)

Kenji Watanabe, Takashi Taniguchi (NIMS, Japan)

Thank you for your attention