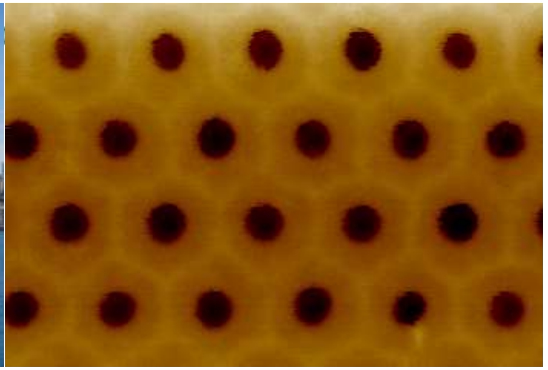
Artificial electrostatic crystals: a new platform for electronic quantum matter



Daisy Q. Wang†, Zeb Krix†, Oleg P. Sushkov†,
Chong Chen¶, Ian Farrer¶, David A. Ritchie¶,
Alexander R. Hamilton†, and **Oleh Klochan**†
† **UNSW** & ¶University of Cambridge

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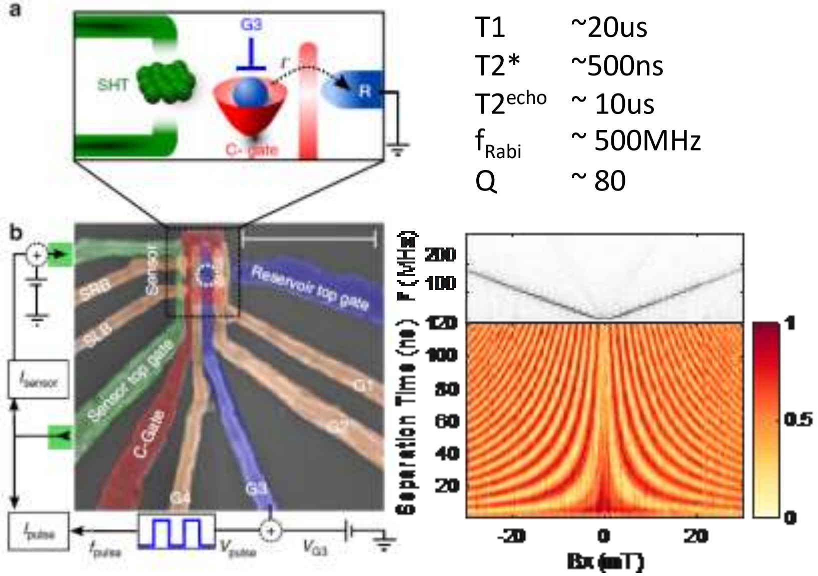
FLEET
ARC CENTRE OF EXCELLENCE IN FUTURE LOW-ENERGY ELECTRONICS TECHNOLOGIES

Australian Government
Australian Research Council

QED Group Research Projects

Fast Si *hole* spin qubits (imec, Diraq)

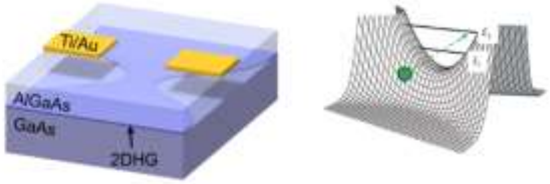


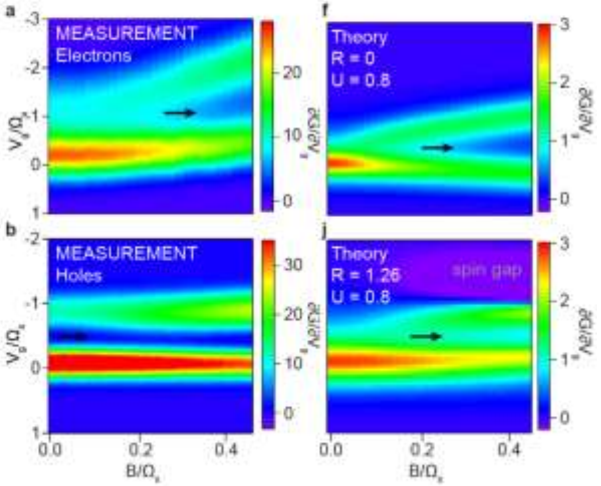
T1	~20us
T2*	~500ns
$T2^{echo}$	~ 10us
f_{Rabi}	~ 500MHz
Q	~ 80

- **Scott Liles**
  A singlet-triplet hole-spin qubit in MOS silicon, arXiv:2310.09722 (2023).
  Electrical control of the g-tensor of the first hole in a silicon MOS quantum dot, Phys. Rev. B 104, 235303 (2022).

- **Ik Kyeong Jin**
  Combining n-MOS Charge Sensing with p-MOS Silicon Hole Double Quantum Dots in a CMOS platform

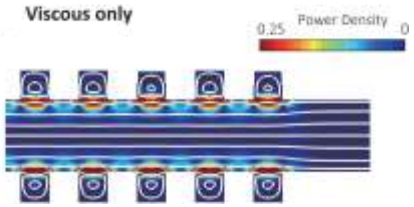
Chiral spin-gap in hole quantum wires





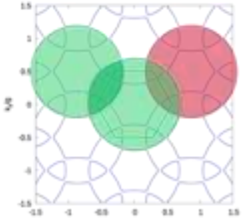

Karina Hudson, Krittika Kumar
New signatures of the spin gap in quantum point contacts,
Nature Comms
12, 5 (2021).

Hydrodynamic current flow




Daisy Wang & Aydin Keser
Geometric control of universal hydrodynamic flow in a 2D electron fluid, Phys. Rev. X, 11, 031030 (2021).

Artificial Quantum Matter

Daisy Wang & Oleh Klochan

Alex Hamilton

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May 2024

Outline and acknowledgments

OUTLINE

- Superlattices & Moiré physics
- New approach to making bands
- **Precursor to band-structure:** Creating a new Fermi surface in a triangular lattice
- **Creating a new band-structure**
  - Opening a band-gap in the artificial lattice
  - Turning electrons into holes
  - Turning massive electrons into massless Dirac particles
- **Flat bands & non-trivial insulator**

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Alex Hamilton

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Zeb Krix
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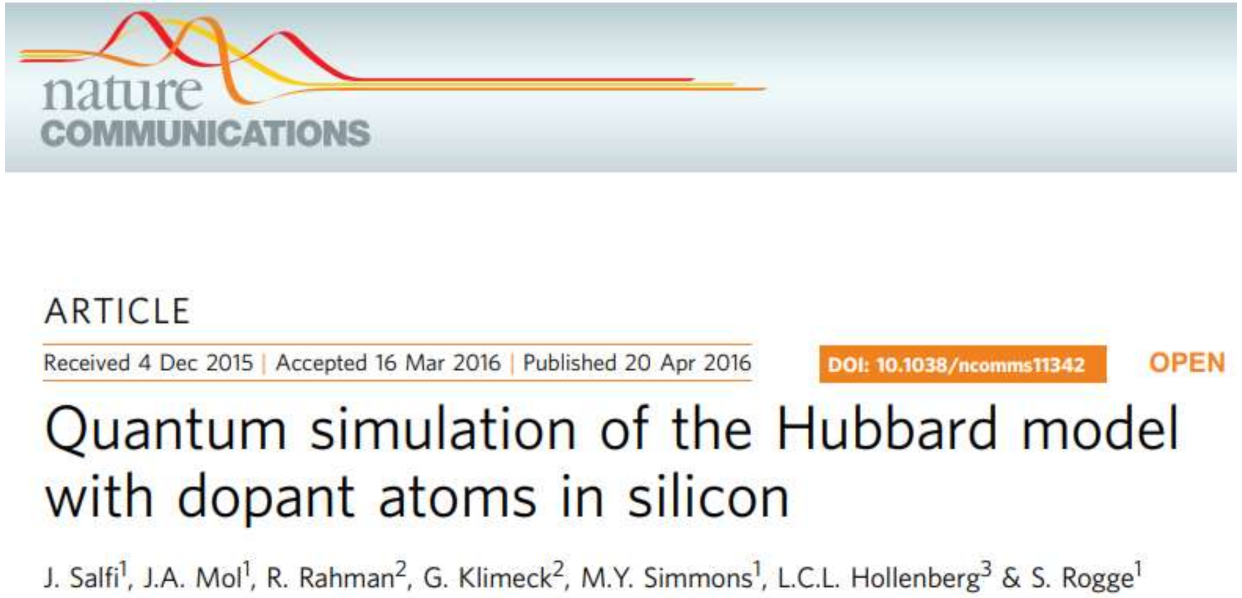
O. Tkachenko

Wafers
David Ritchie
Andreas Wieck
Werner Wegscheider

Motivation: Quantum Simulation



nature COMMUNICATIONS

ARTICLE

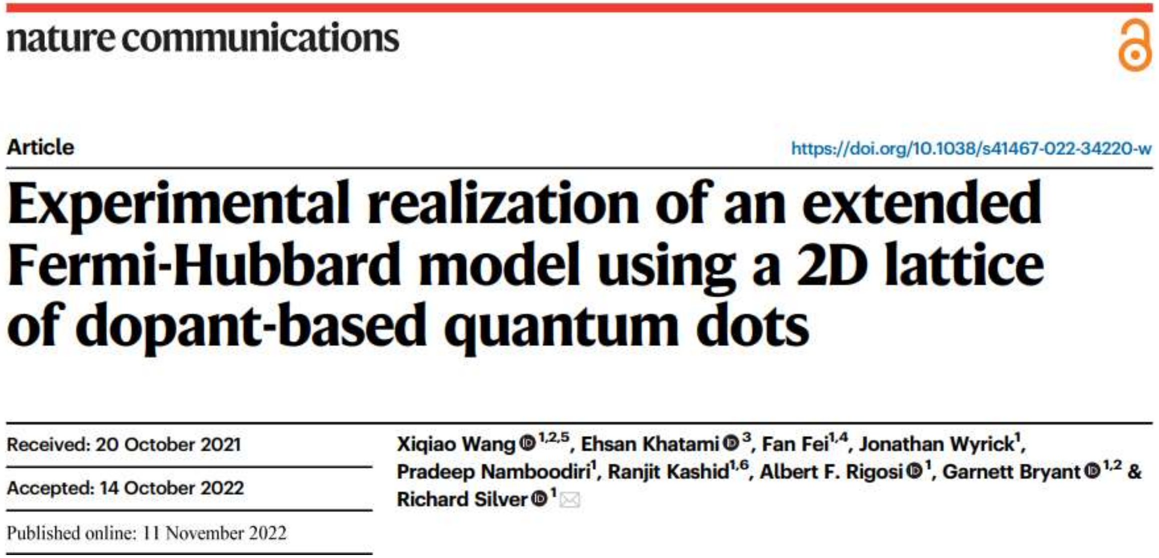
Received 4 Dec 2015 | Accepted 16 Mar 2016 | Published 20 Apr 2016

DOI: 10.1038/ncomms11342

OPEN

Quantum simulation of the Hubbard model with dopant atoms in silicon

J. Salfi[1], J.A. Mol[1], R. Rahman[2], G. Klimeck[2], M.Y. Simmons[1], L.C.L. Hollenberg[3] & S. Rogge[1]



nature communications

Article

https://doi.org/10.1038/s41467-022-34220-w

Experimental realization of an extended Fermi-Hubbard model using a 2D lattice of dopant-based quantum dots

Received: 20 October 2021

Accepted: 14 October 2022

Published online: 11 November 2022

Xiqiao Wang[1,2,5], Ehsan Khatami[3], Fan Fei[1,4], Jonathan Wyrick[1], Pradeep Namboodiri[1], Ranjit Kashid[1,6], Albert F. Rigosi[1], Garnett Bryant[1,2] & Richard Silver[1]

nature

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Article | Open Access | Published: 22 June 2022

Engineering topological states in atom-based semiconductor quantum dots

M. Kiczynski, S. K. Gorman, H. Geng, M. B. Donnelly, Y. Chung, Y. He, J. G. Keizer & M. Y. Simmons

Nature **606**, 694–699 (2022) | Cite this article

arXiv > quant-ph > arXiv:2208.11505

Quantum Physics

[Submitted on 24 Aug 2022]

Probing resonating valence bonds on a programmable germanium quantum simulator

Chien-An Wang, Corentin Déprez, Hanifa Tidjani, William I. L. Lawrie, Nico W. Hendrickx, Amir Sammak, Giordano Scappucci, Menno Veldhorst

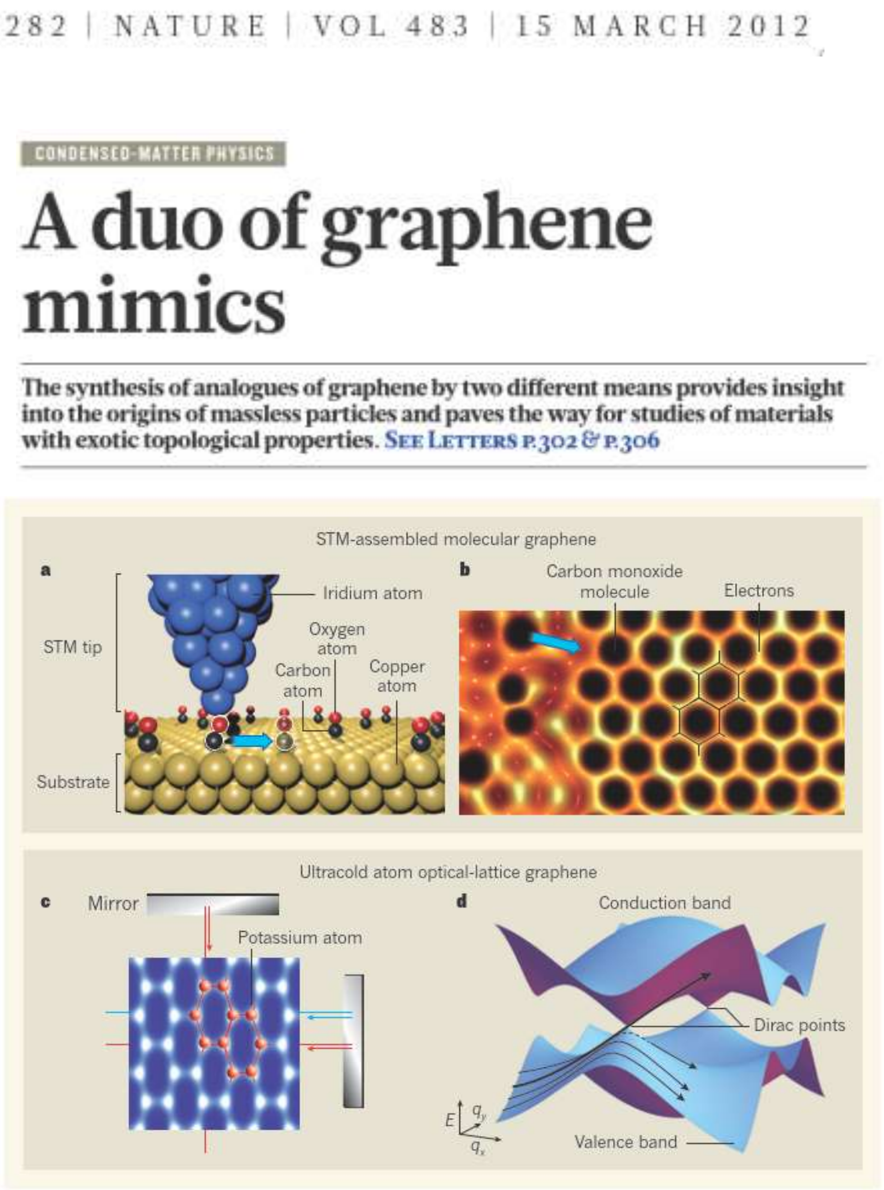
LETTER

doi:10.1038/nature23022

Quantum simulation of a Fermi–Hubbard model using a semiconductor quantum dot array

T. Hensgens[1], T. Fujita[1], L. Janssen[1], Xiao Li[2], C. J. Van Diepen[1], C. Reichl[3], W. Wegscheider[3], S. Das Sarma[2] & L. M. K. Vandersypen[1]

Motivation: Artificial quantum matter



282 | NATURE | VOL 483 | 15 MARCH 2012

CONDENSED-MATTER PHYSICS

A duo of graphene mimics

The synthesis of analogues of graphene by two different means provides insight into the origins of massless particles and paves the way for studies of materials with exotic topological properties. SEE LETTERS P.302 & P.306

nature nanotechnology

REVIEW ARTICLE

PUBLISHED ONLINE: 4 SEPTEMBER 2013 | DOI: 10.1038/NNANO.2013.161

Artificial honeycomb lattices for electrons, atoms and photons

Marco Polini[1*], Francisco Guinea[2], Maciej Lewenstein[3,4], Hari C. Manoharan[5,6] and Vittorio Pellegrini[1,7]

$V_0 \approx 10$ K
$d \approx 20$–100 nm
$N \approx 10$–10^7
$U \approx 10$ K
$V \approx 1$ K
$t \approx 1$–10 K
$T_F \approx 0.1$–100 K

≈ 10 mK
500 nm

$\Delta n \approx 10^{-3}$
$d \approx 10$ μm–10 mm

Requirements:

- Lattice constant $a \sim 100$nm
- Mean free path >> a
- Low disorder - regular artificial lattice
- Strong modulation: $\Delta U >> E_F$

Alex Hamilton

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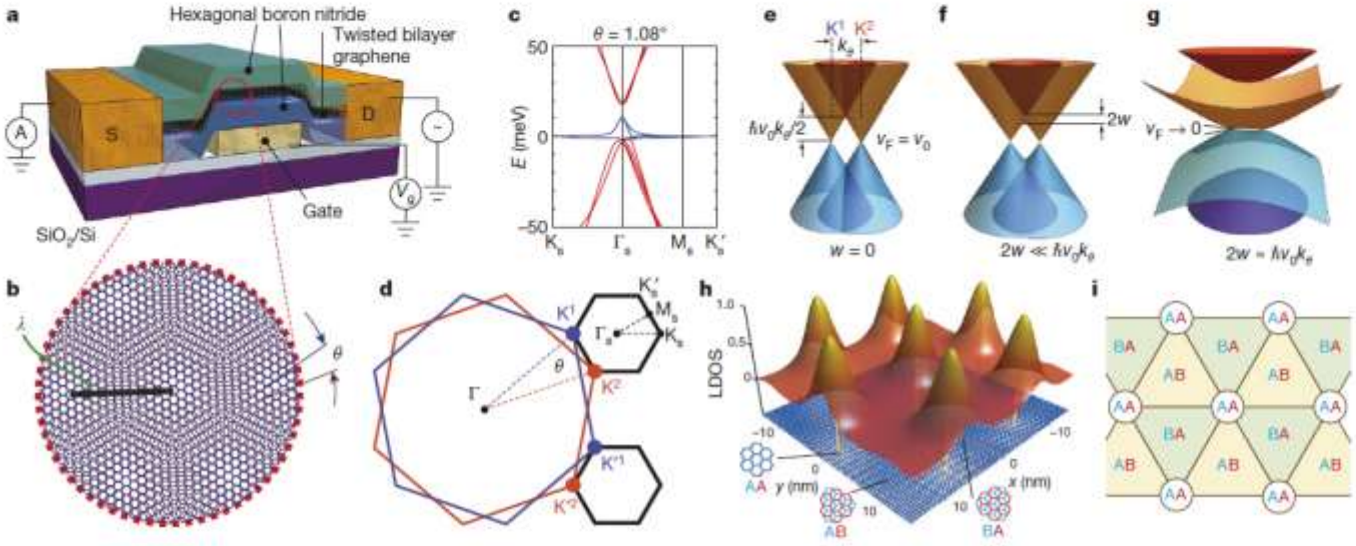
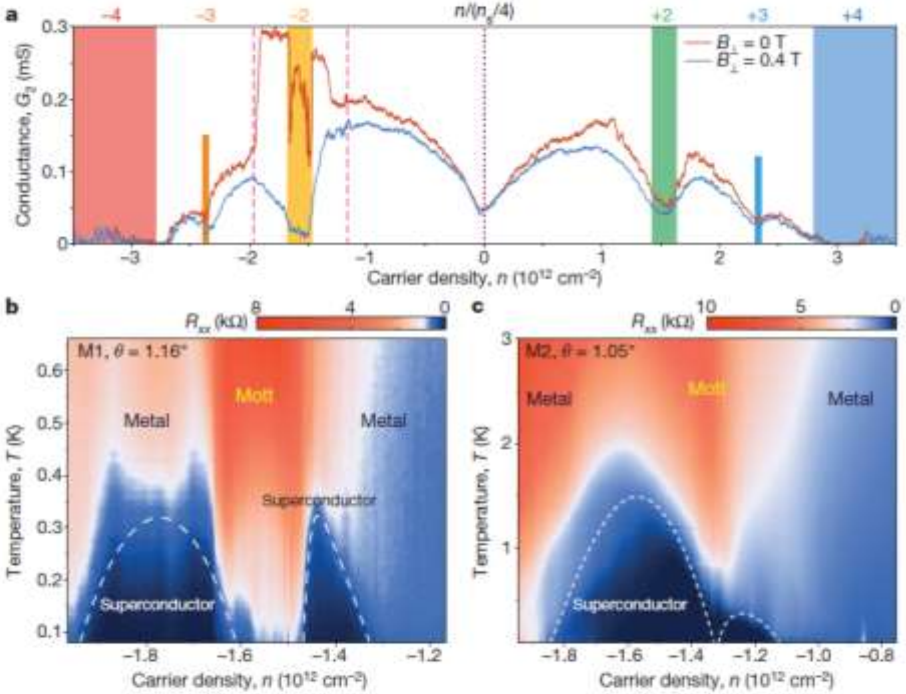
Background – Periodic lattice in MATBG

Moire superlattice due to twisted graphene layers produces a flat band

⇒ strong correlations and superconductivity



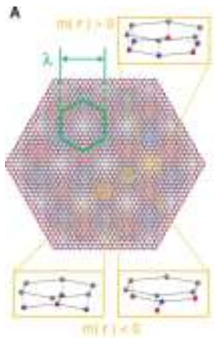


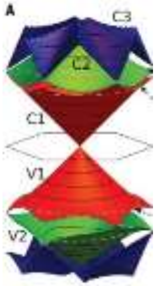
Opportunities:

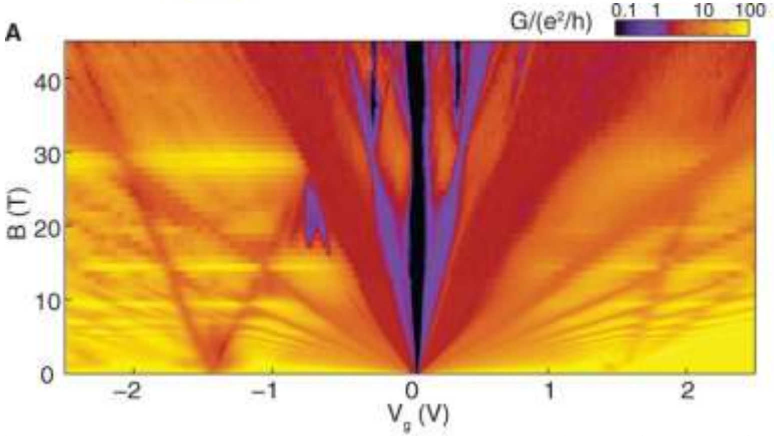
- Angle control, deformation, uniformity, domains…
- Improve control of superlattice potential – two graphene sheets interact via VdW forces
- Fixed symmetry – triangular lattice

Y. Cao doi.org/10.1038/nature26154
Y. Cao doi:10.1038/nature26160

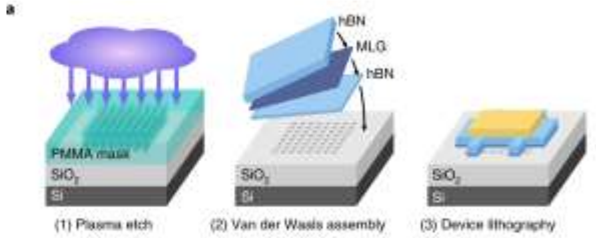
2D superlattices in Graphene

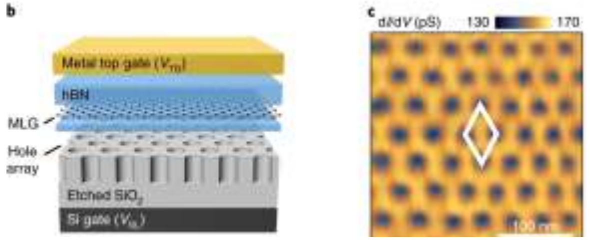


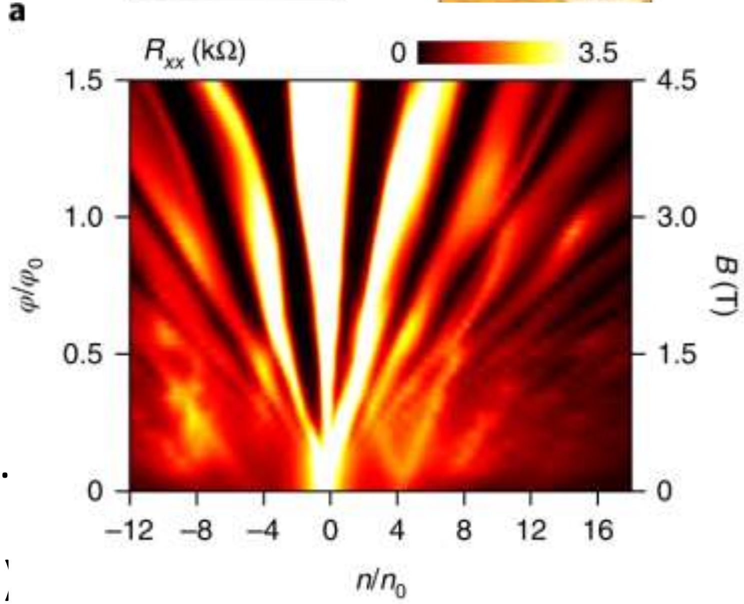




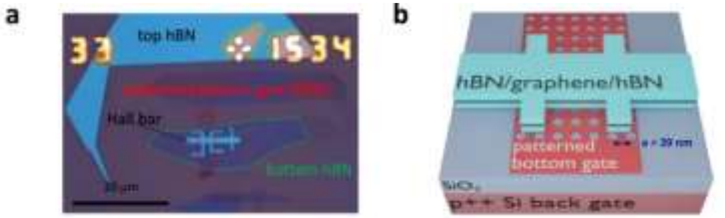
Ponomarenko … Geim," Nature (2013).
Hunt … Ashoori, Nature (2013)
Dean…Kim, Nature (2013)
Lee. …Goldhaber-Gordon, Science (2016).
Forsythe…Dean, Nat. Nano (2018)
Wang … Schönenberger, Nano Lett.(2019
Jessen … Bøggild., Nat. Nano (2019)
Huber…Weiss, Eroms Nat Comms (2022)

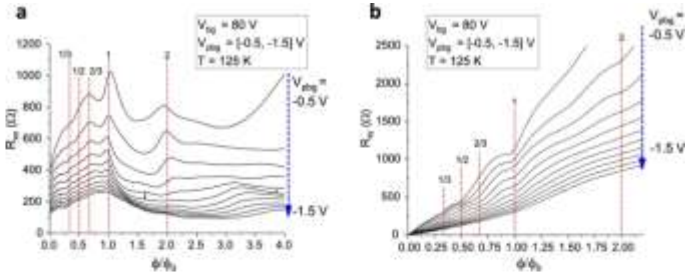


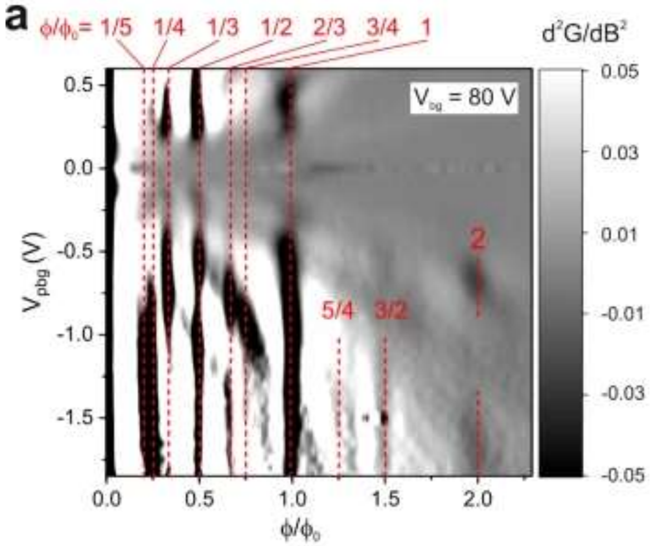




Forsythe…Dean,
Nat. Nano (2018).







Huber…Weiss, Eroms
Nat Comms (2022).

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TRANSPORT IN SEMICONDUCTOR ARTIFICIAL LATTICES

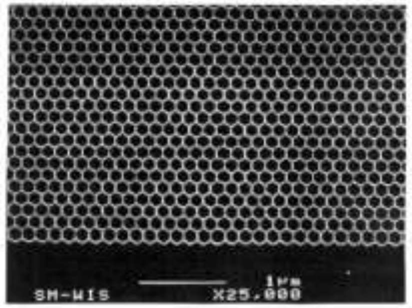
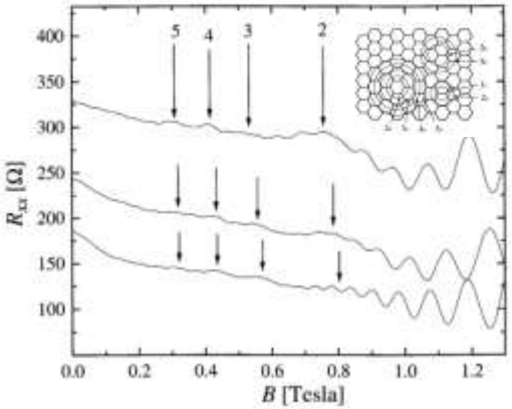
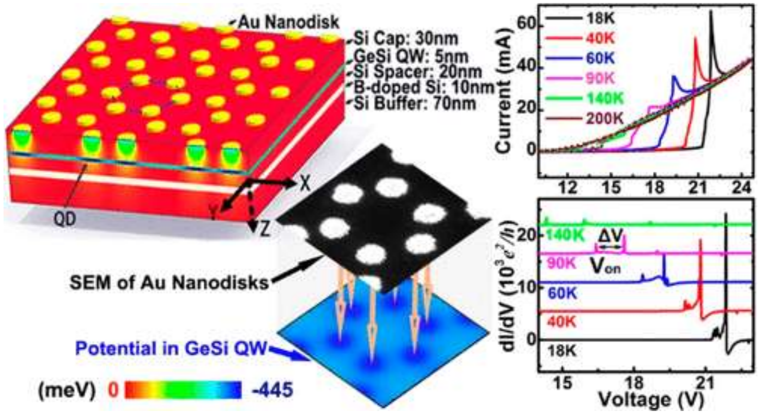


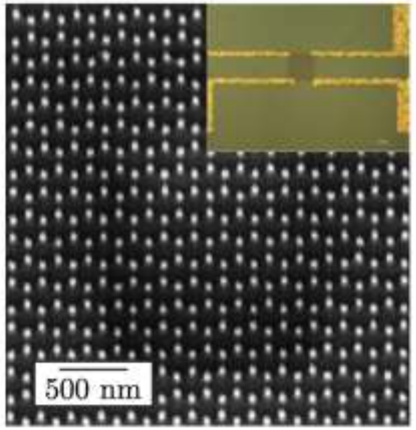
Figure 1. Scanning electron micrographs of one of our samples, showing the honeycomb gate pattern of 150 nm pitch, namely 87 nm distance between adjacent vertices. The PdAu gates (brighter areas) are patterned on the GaAs surface by electron beam lithography and lift-off.



Soibel *Semi. Sci. Tech.* (1996)



Chen et al *ACS Nano* **15**, 13703(2021)
Patterned lattice on Si/SiGe

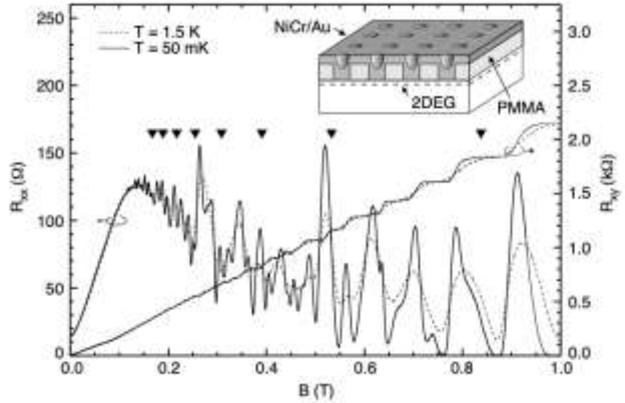


Singha et al *Science* **332**, 1176 (2011)
Etched modulation doped GaAs/AlGaAs dot array

Previous studies

- Weak modulation:
  Classical commensurability oscillations

- **Strong modulation:**
  Disorder prevents experiments



Albrecht et al *PRL* **83**, 2234(1999)
Patterned modulation doped GaAs/AlGaAs with PMMA

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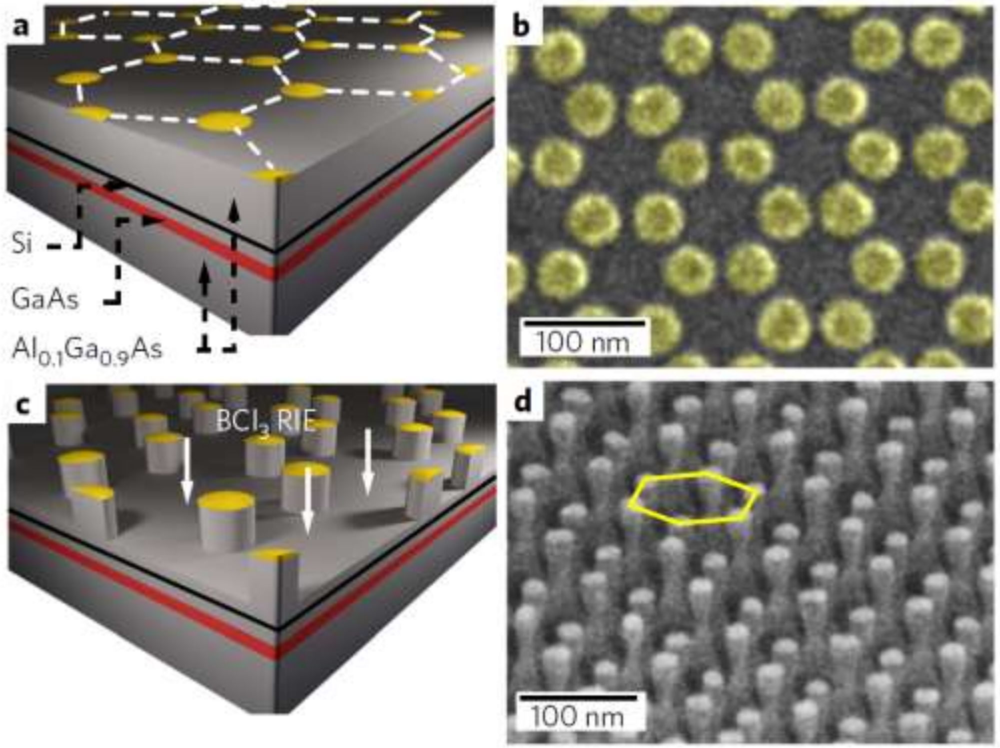
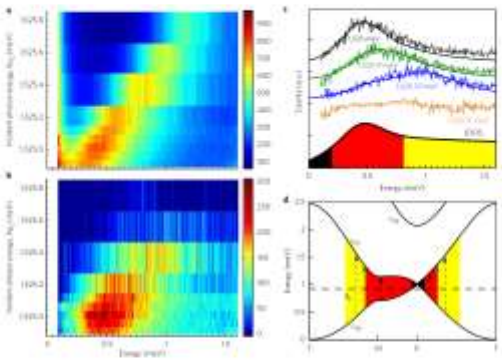
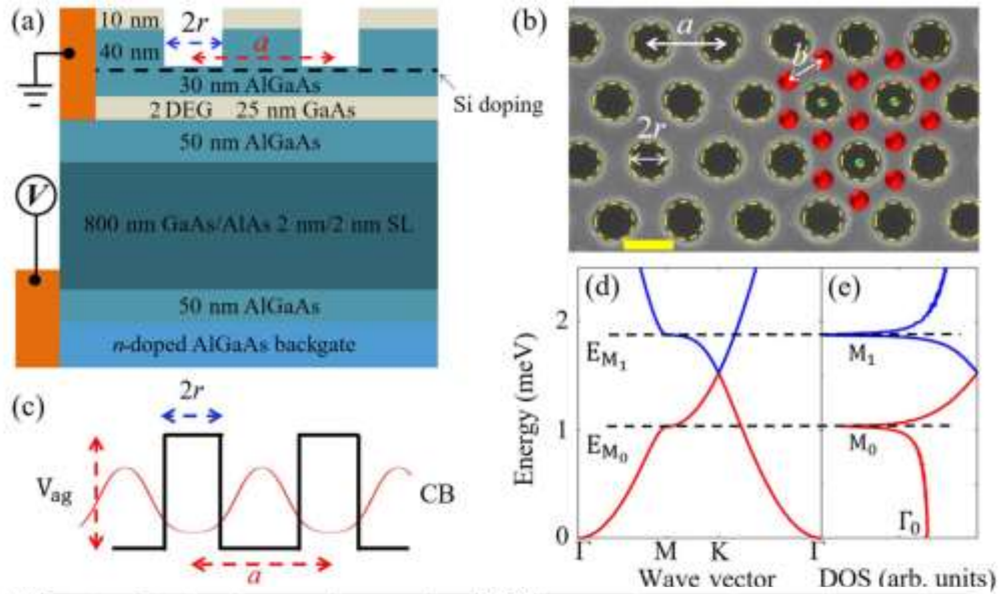
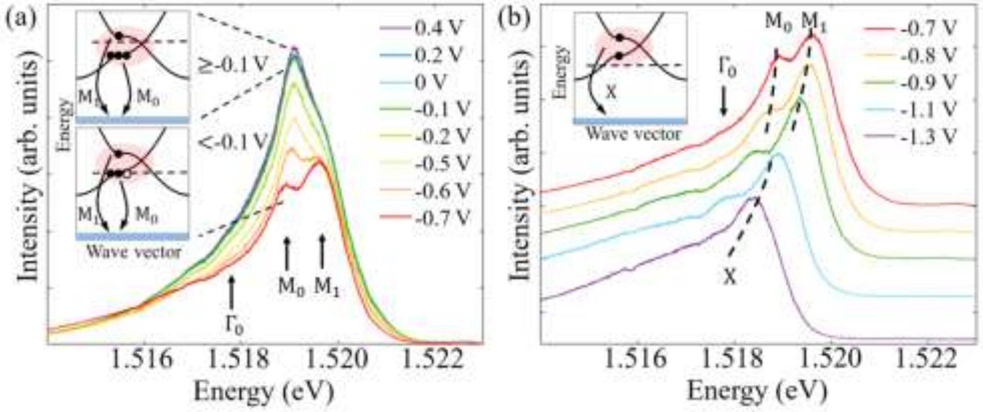
Optical studies





S. Wang et al., *Observation of **Dirac bands** in artificial graphene in small-period nanopatterned GaAs quantum wells*,
Nature Nano. 13, 29 (2018).





L. Du et al, *Observation of Flat Bands in Gated Semiconductor Artificial Graphene*,
Phys. Rev. Lett. 126, 106402 (2021).

Etched samples ⇒ Stronger modulation, but modulation cannot be tuned

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OUTLINE

- Superlattices & Moiré physics
- New approach to making bands
- **Precursor to band-structure:** Creating a new Fermi surface in a triangular lattice
- **Creating a new band-structure**
  - Opening a band-gap in the artificial lattice
  - Turning electrons into holes
  - Turning massive electrons into massless Dirac particles
- **Flat bands & non-trivial insulator**

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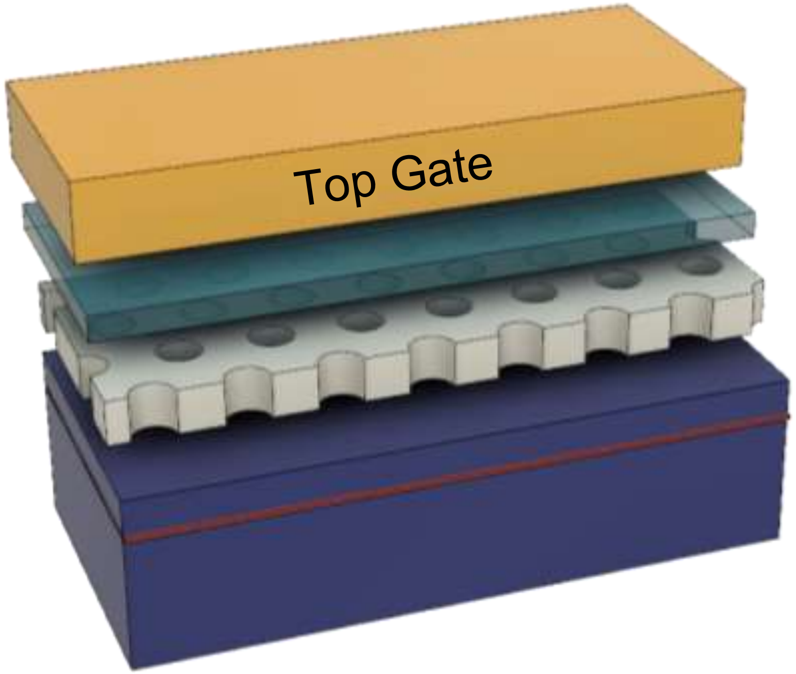
Our approach – Lateral Superlattice on GaAs 2DEG

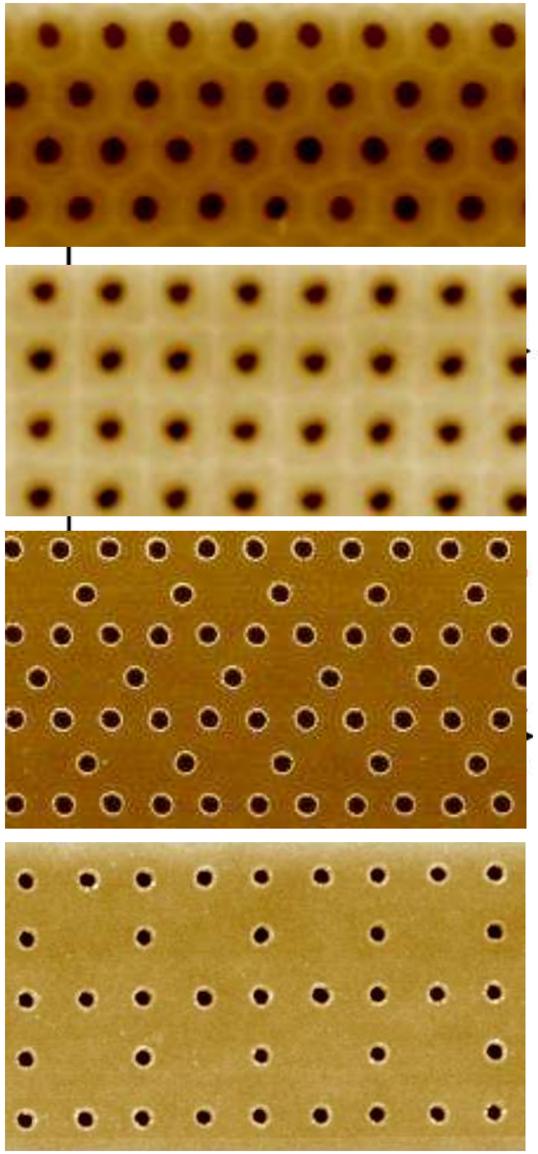


Metal Top-gate: TG controls modulation strength **ΔU**

Thin dielectric

Patterned gate:
PG controls 2DEG density ***n***

2D electron gas (2DEG) in GaAs heterostructure



Requirements:

- Lattice constant *a* ~ 100nm
- Mean free path >> *a* (*mfp* ~10 µm)
- Low disorder - regular artificial lattice (EBL)
- Strong modulation: $\Delta U \gg E_F$

Applied Physics Letters ARTICLE scitation.org/journal/apl

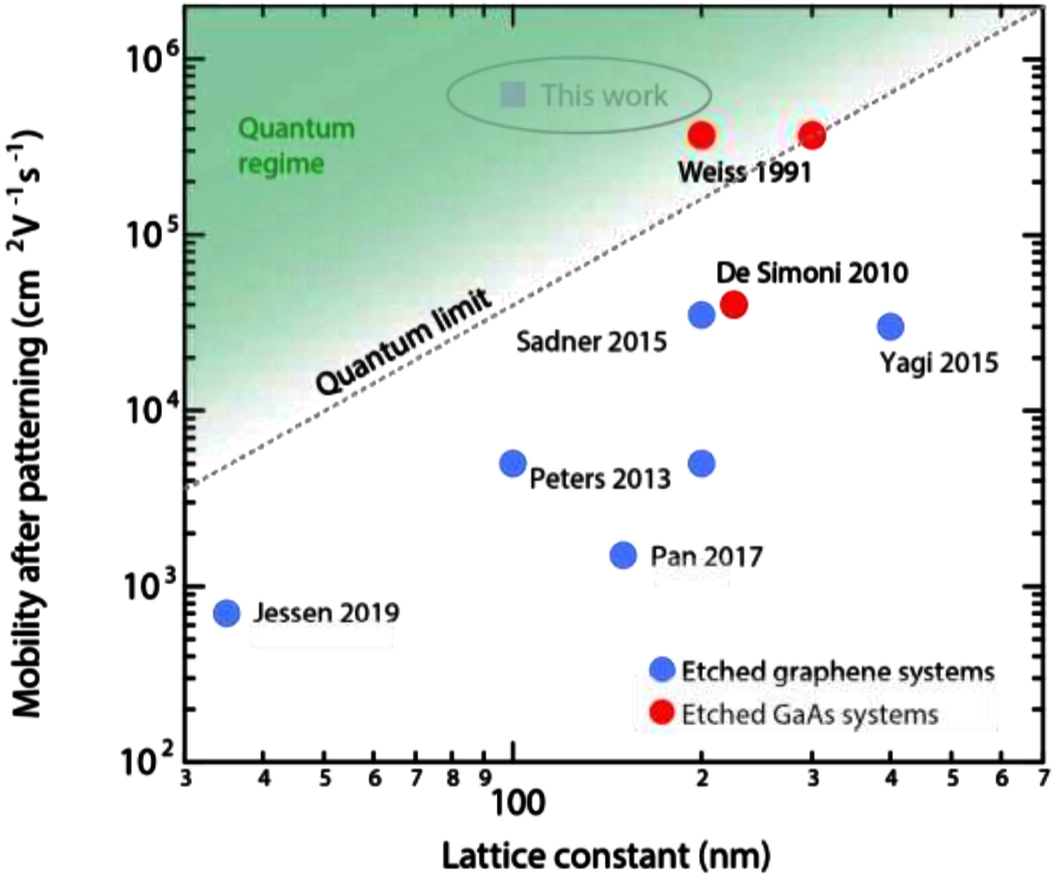
Two-dimensional lateral surface superlattices in GaAs heterostructures with independent control of carrier density and modulation potential

Cite as: Appl. Phys. Lett. **117**, 032102 (2020); doi: 10.1063/5.0009462
Submitted: 31 March 2020 · Accepted: 8 July 2020 ·
Published Online: 20 July 2020

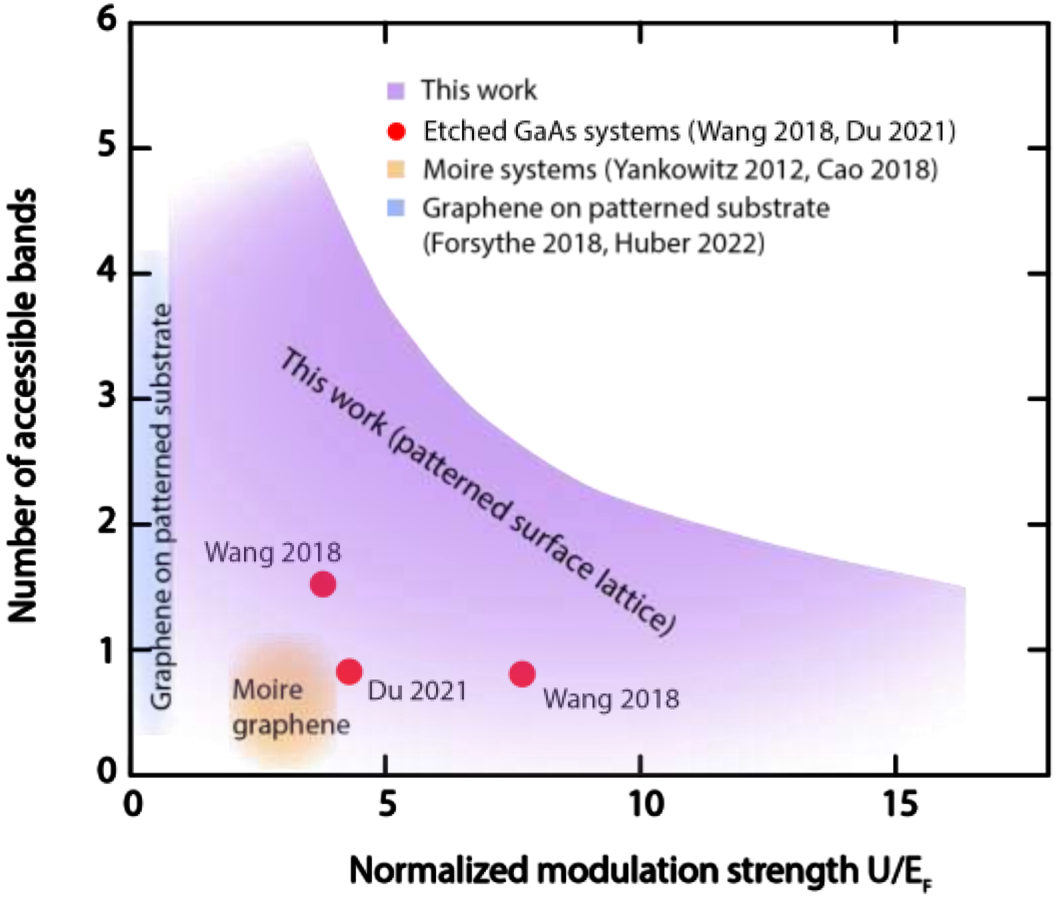
D. Q. Wang,[1,2,a] D. Reuter,[3,b] A. D. Wieck,[3] A. R. Hamilton,[1,2] and O. Klochan[1,2,4]

Comparison with other solid state approaches

Strong lattice modulation by etching



Low disorder approaches: tuneability



To be in quantum regime where bands exist need:
Large energy scales $\Rightarrow$ small lattice constant
Low disorder $\Rightarrow$ high mobility

To see new bandstructure need:
Form new bands $\Rightarrow$ large potential modulation
Sweep E_F through multiple bands

Alex Hamilton

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- Forming an artificial Dirac point for massive electrons
- Opening a band-gap in the artificial lattice
- Honeycomb to Kagome lattice
- Non-trivial insulator

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Alex
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Massive Dirac Fermions in a triangular lattice

Free electrons *E* vs *k*

Apply potential U(r)

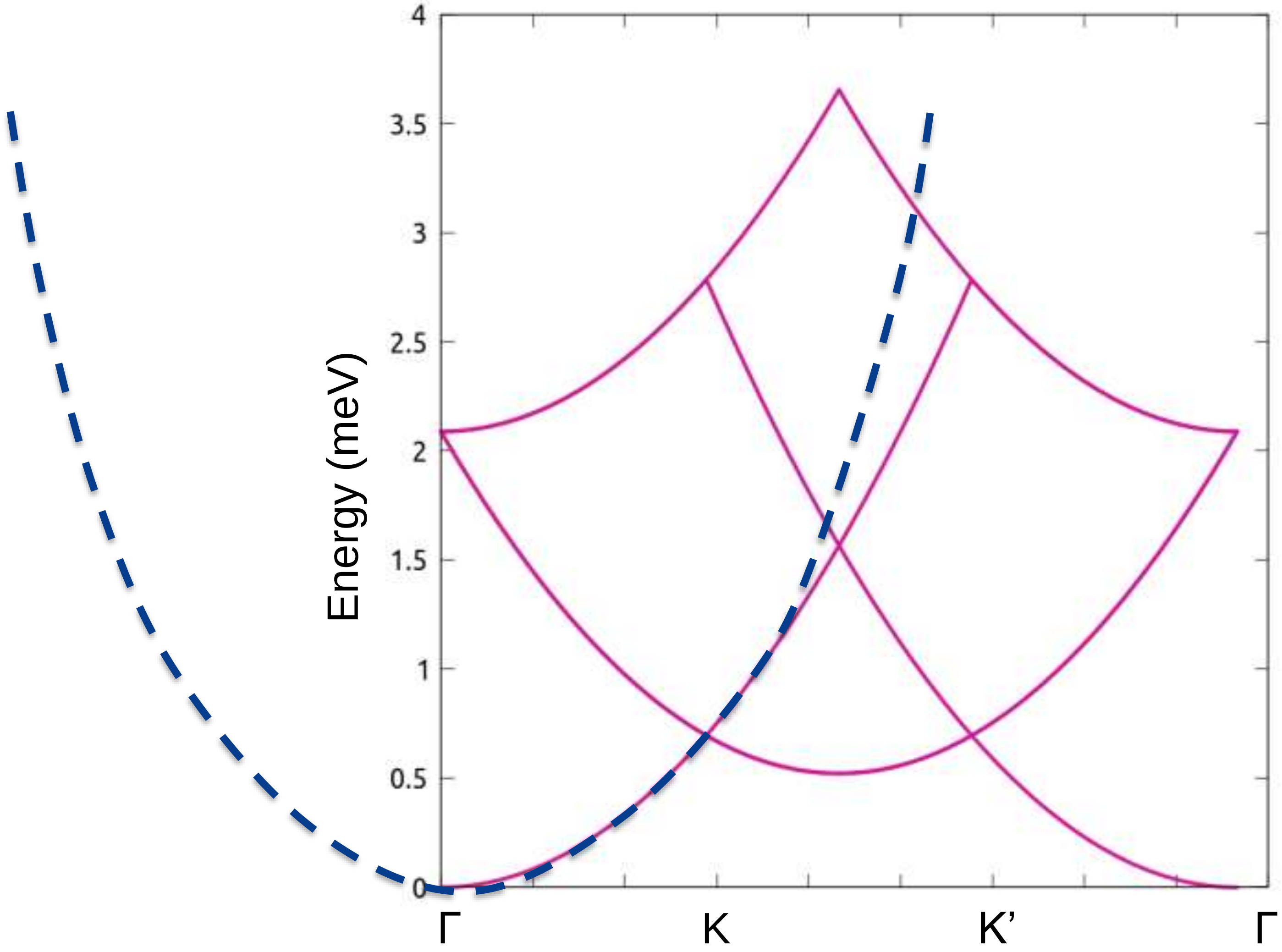
$$U(\boldsymbol{r}) = 2W \sum_{i=1}^{3} \cos(\boldsymbol{g}_i \cdot \boldsymbol{r}),$$

$$\boldsymbol{g}_1 = \frac{4\pi}{\sqrt{3}a}(0, 1),$$

$$\boldsymbol{g}_2 = \frac{4\pi}{\sqrt{3}a}(1/2, \sqrt{3}/2),$$

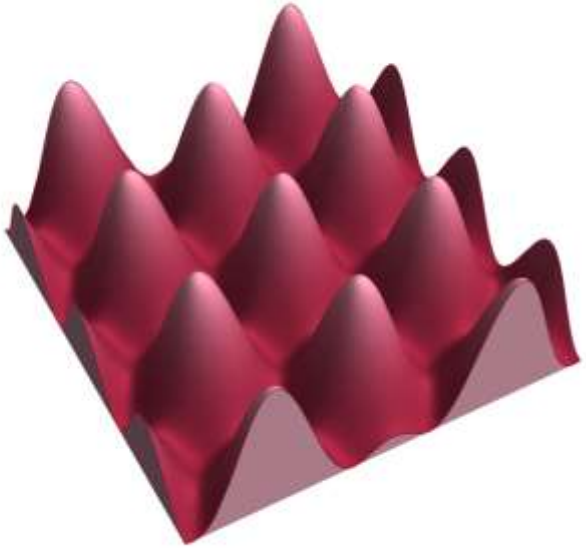
Peak-to-peak amplitude $U_{\text{p-p}} = 9W$

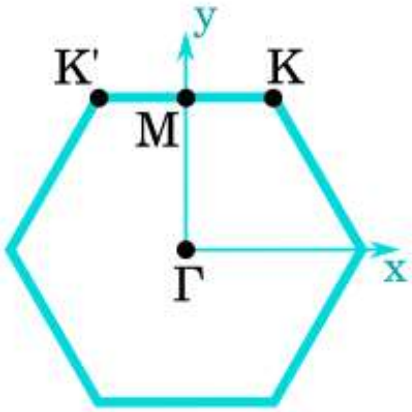
Start $U_{\text{p-p}} = 0$



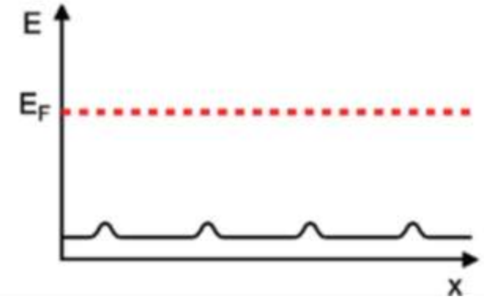
Massive Dirac Fermions in a triangular lattice

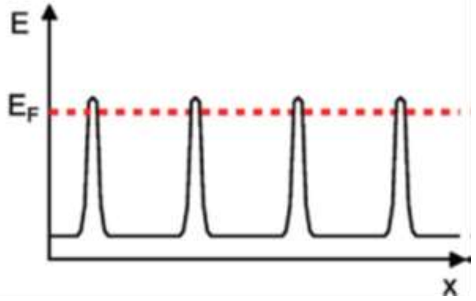
- Increase potential: $U_{\text{p-p}}$**=0.9 meV**

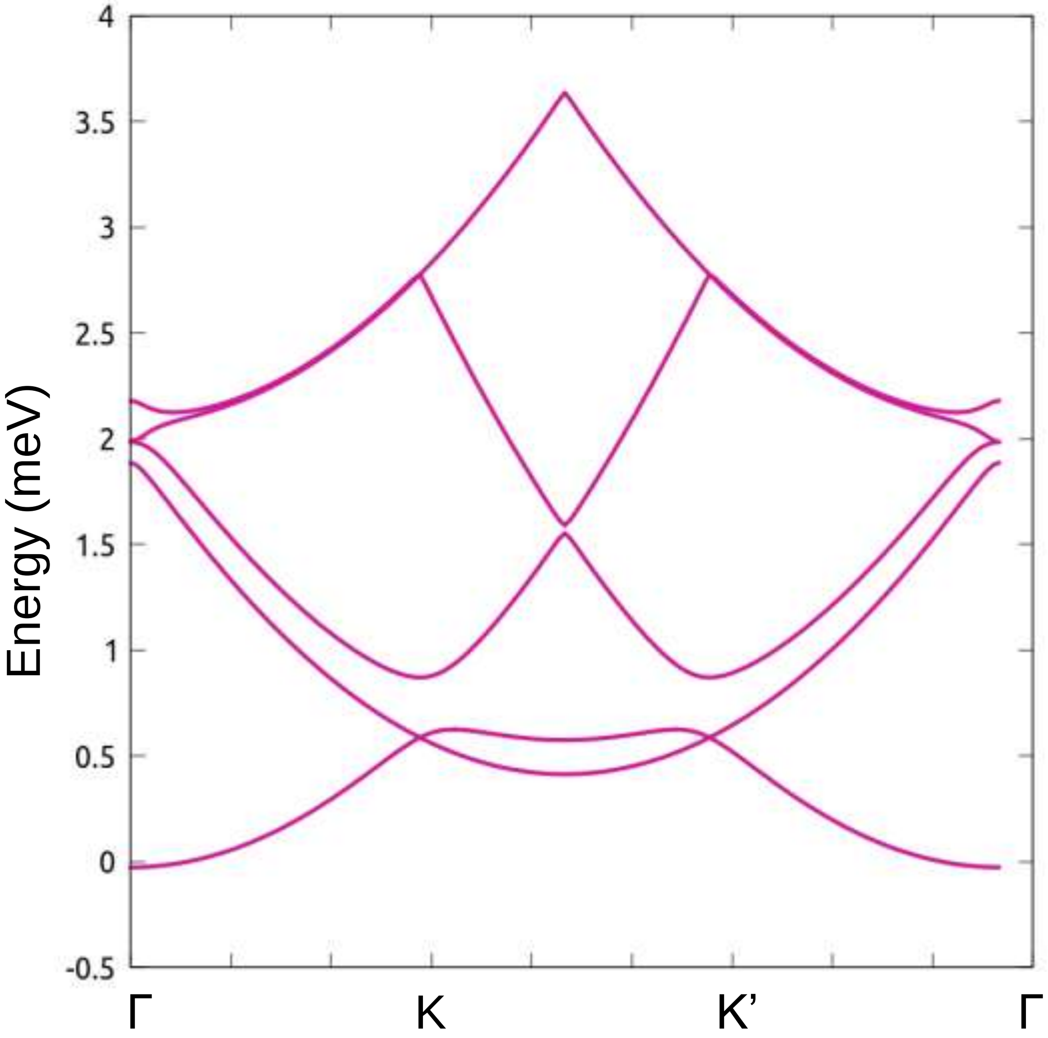




Triangular Anti-dot Lattice BZ

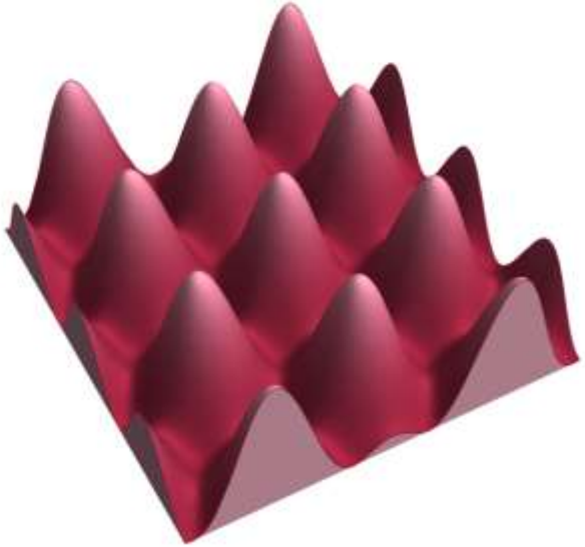




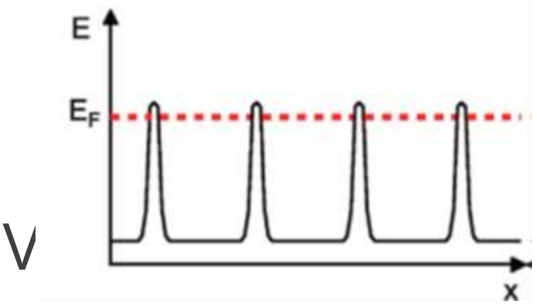


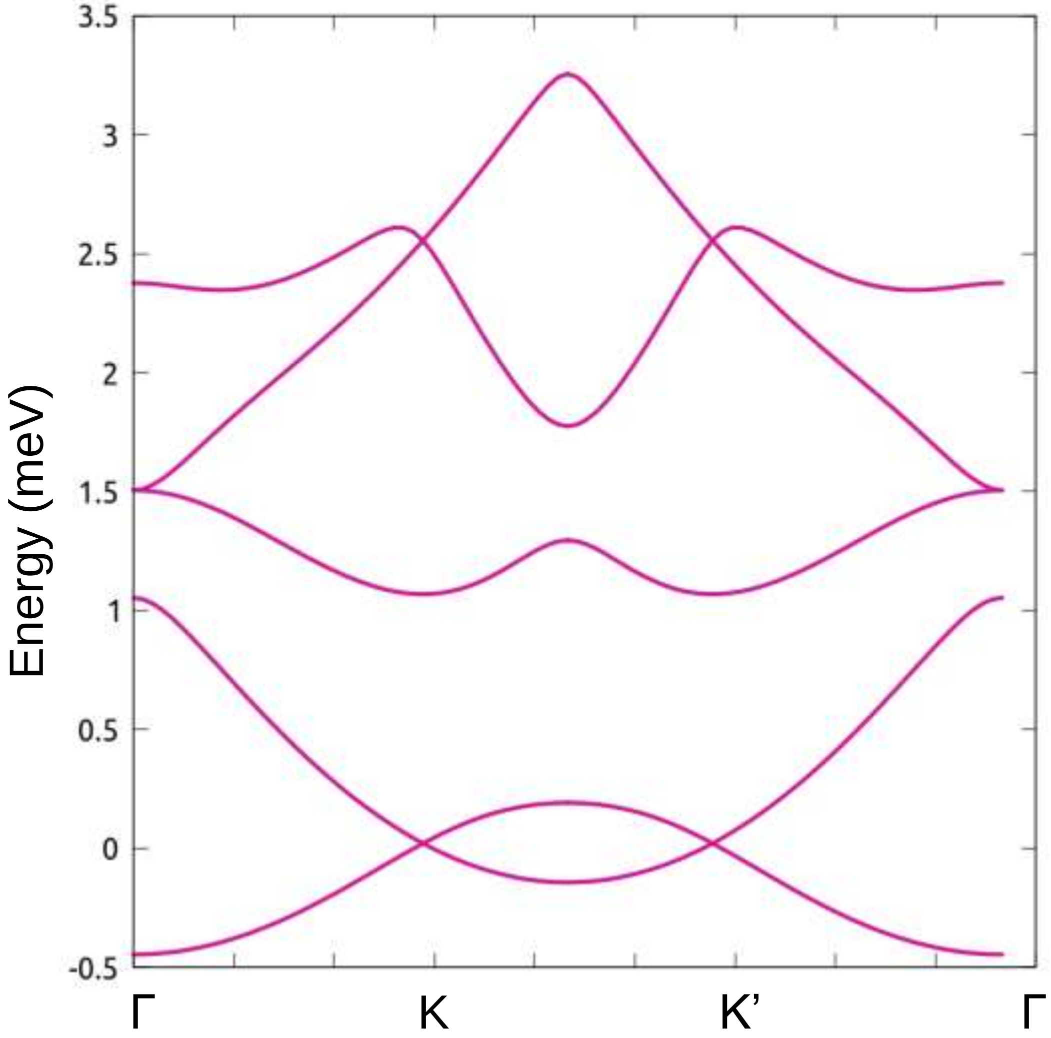
Massive Dirac Fermions in a triangular lattice

- Increase potential: $U_{\text{p-p}}$ **= 4.5 meV**



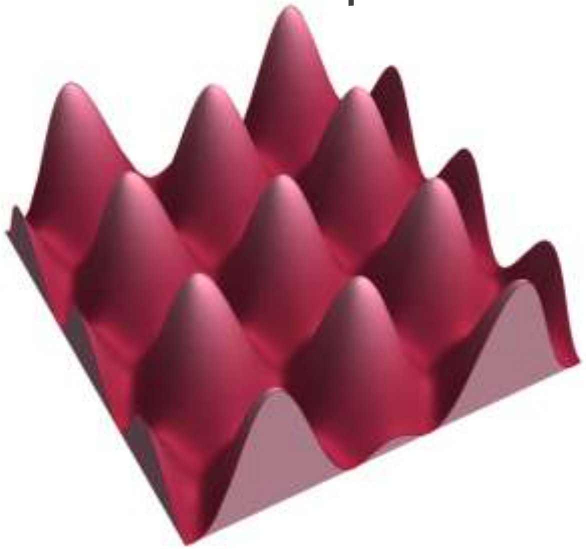
- Peak-to-peak comparable to typical E_F ~ 3meV





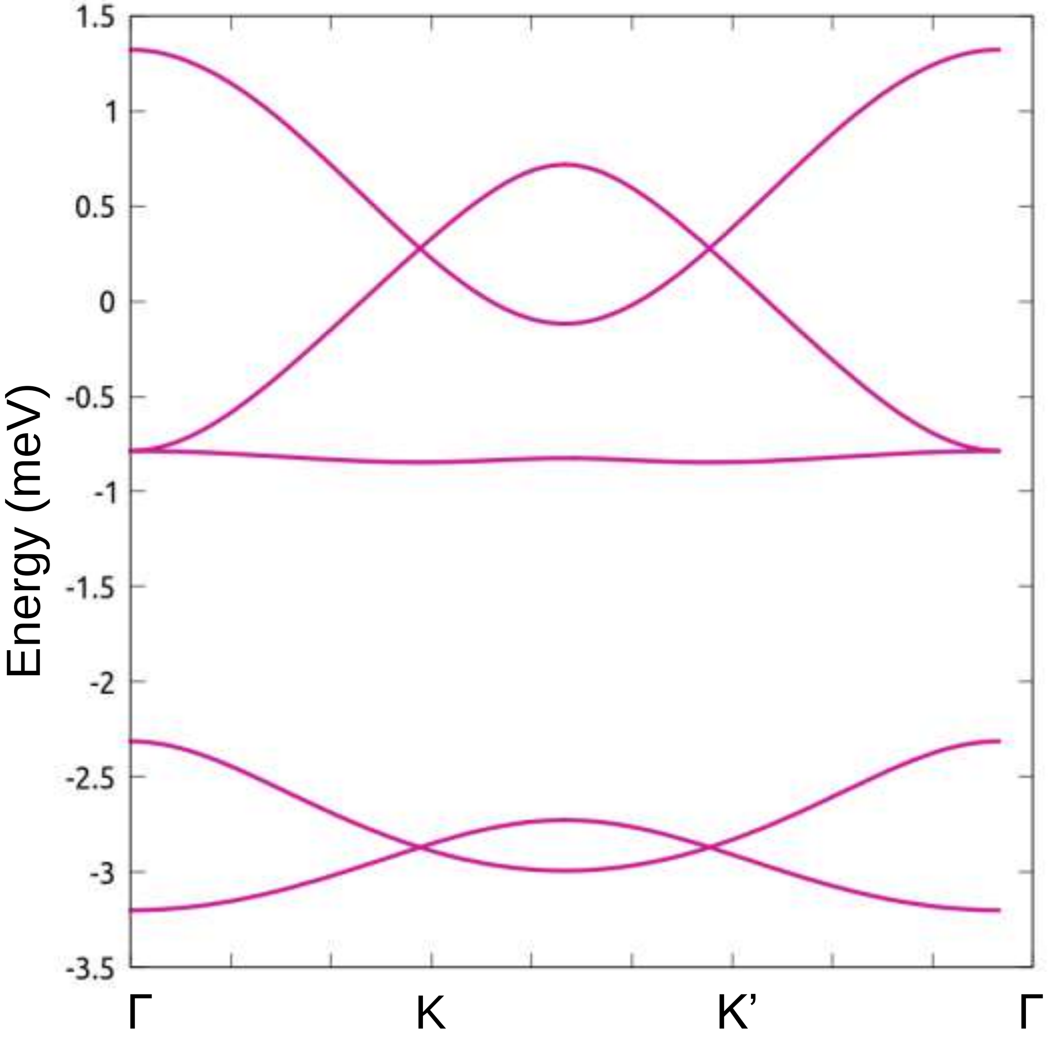
Massive Dirac Fermions in a triangular lattice

- Increase potential: **$U_{p\text{-}p}$= 18 meV**

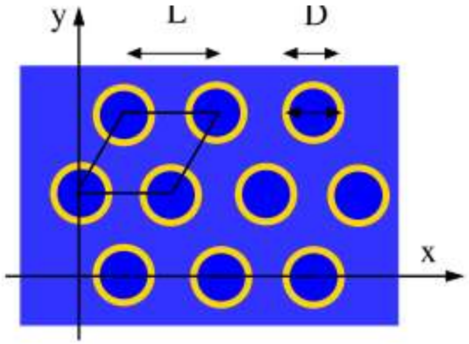


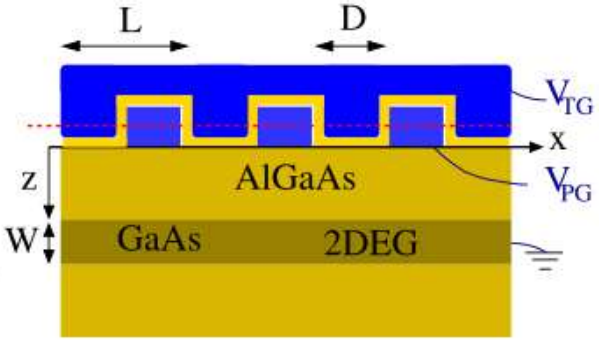
Peak-to-peak
$U_{p\text{-}p} >> E_F$

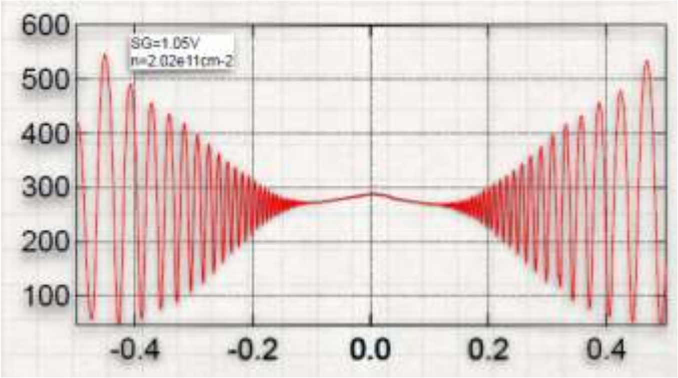
But getting strong, uniform modulation in a 2DEG is not easy.

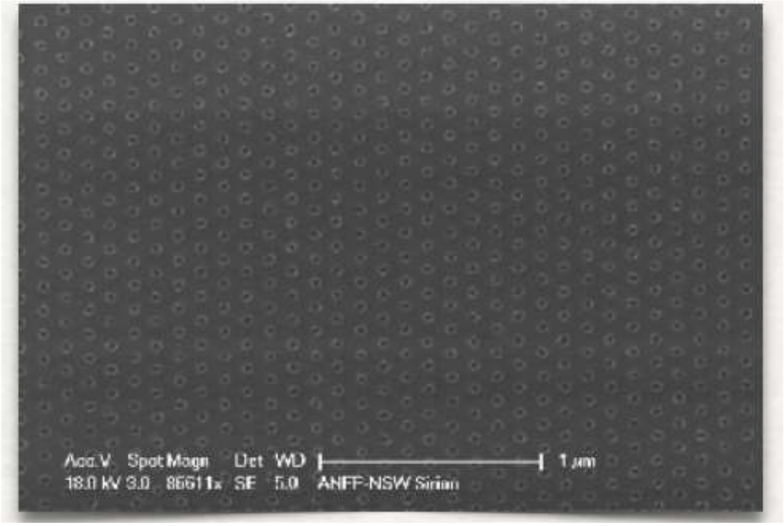


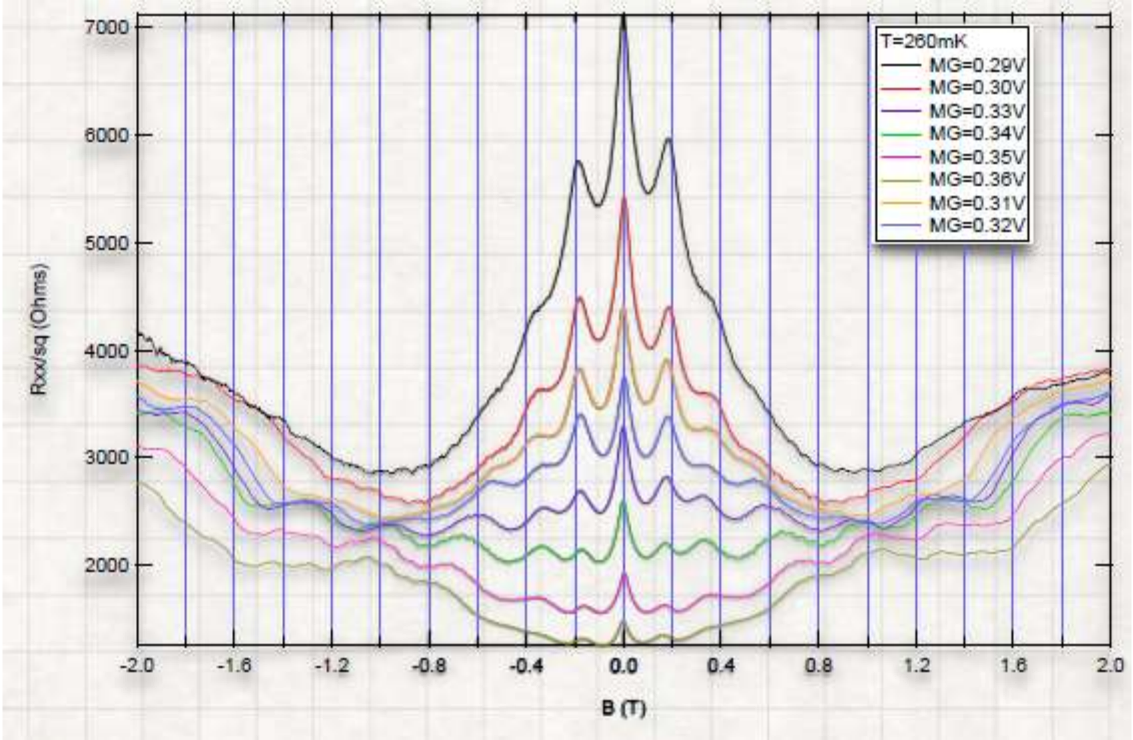
FIRST ARTIFICIAL GRAPHENE ATTEMPT











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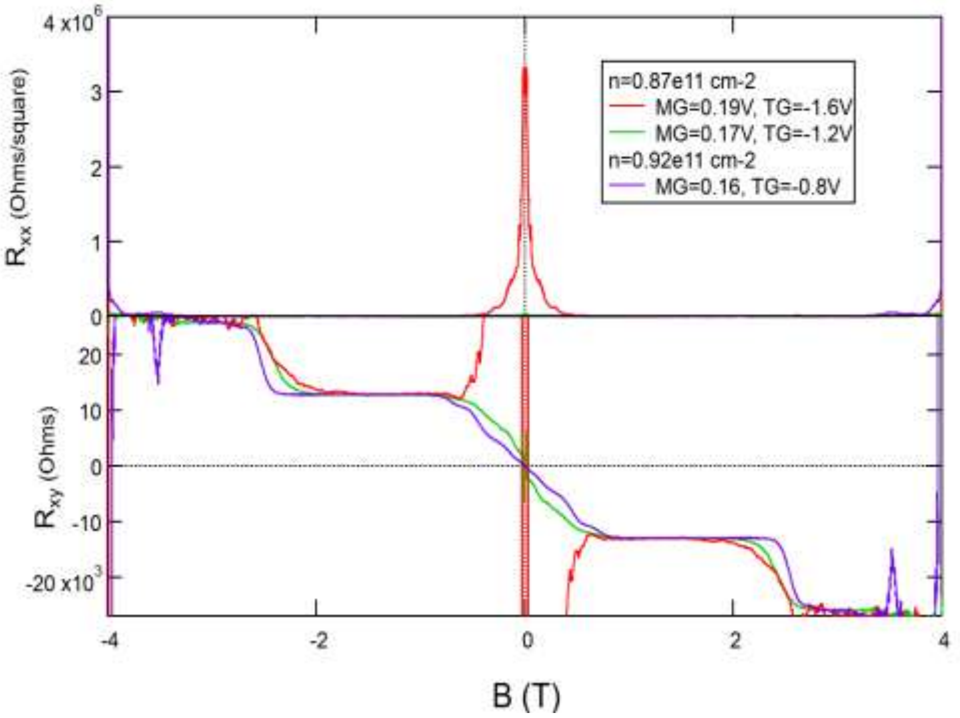
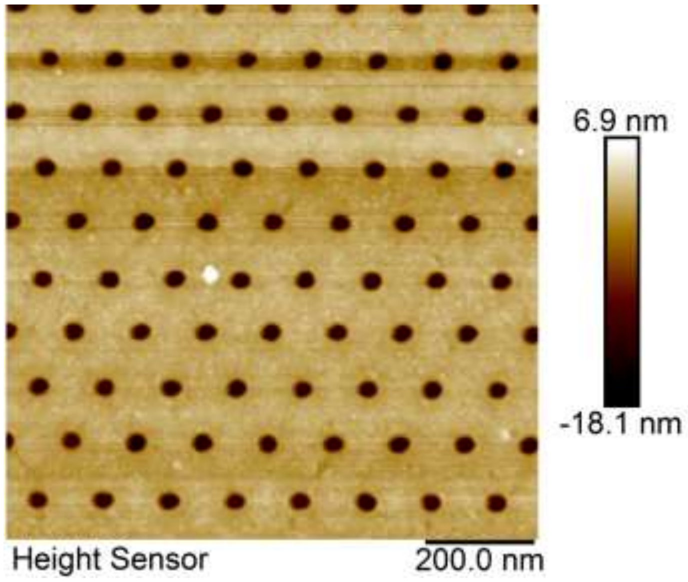
SECOND GENERATION DEVICES

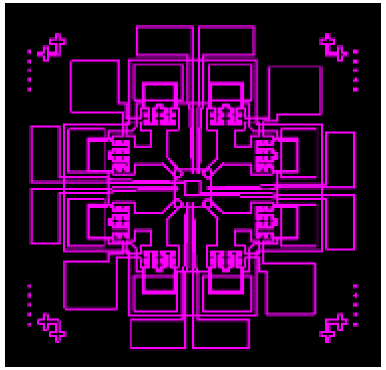
More complex devices, better lithography

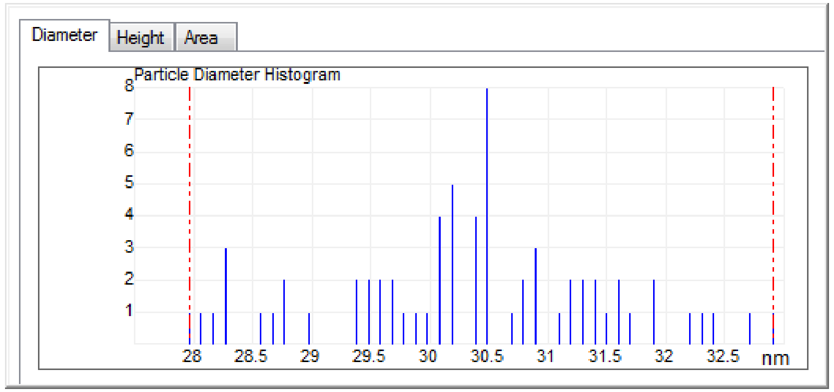
Uniformity better than 10%

Strange insulating behaviour









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NEED LOWER DISORDER: 3rd GENERATION

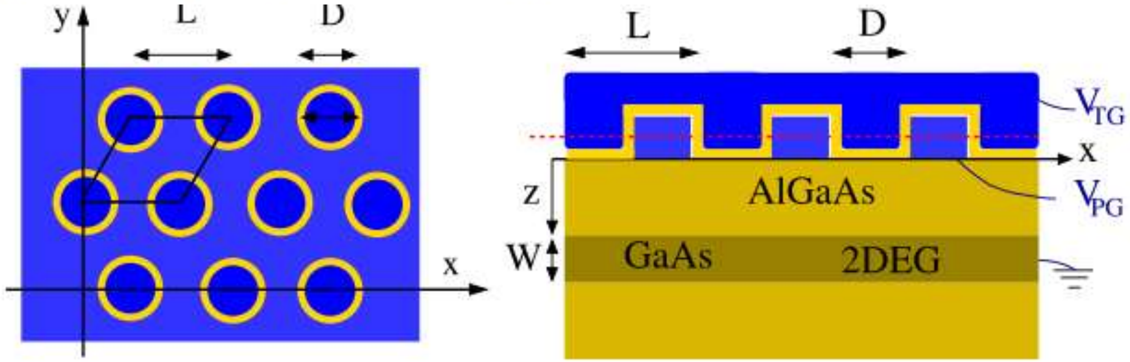
Screening and inhomogeneities matter

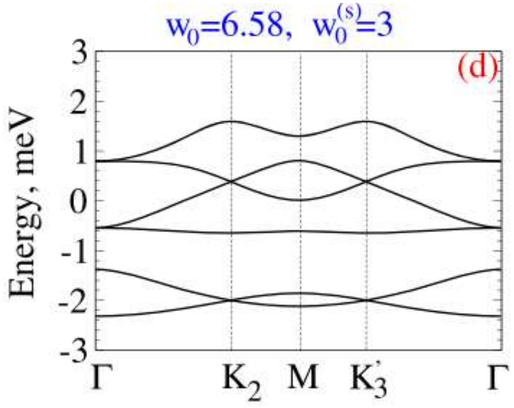
2D Materials

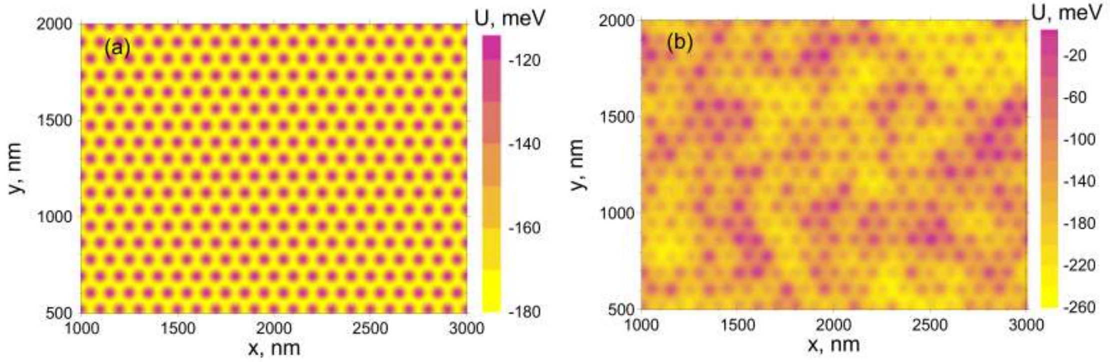
PAPER

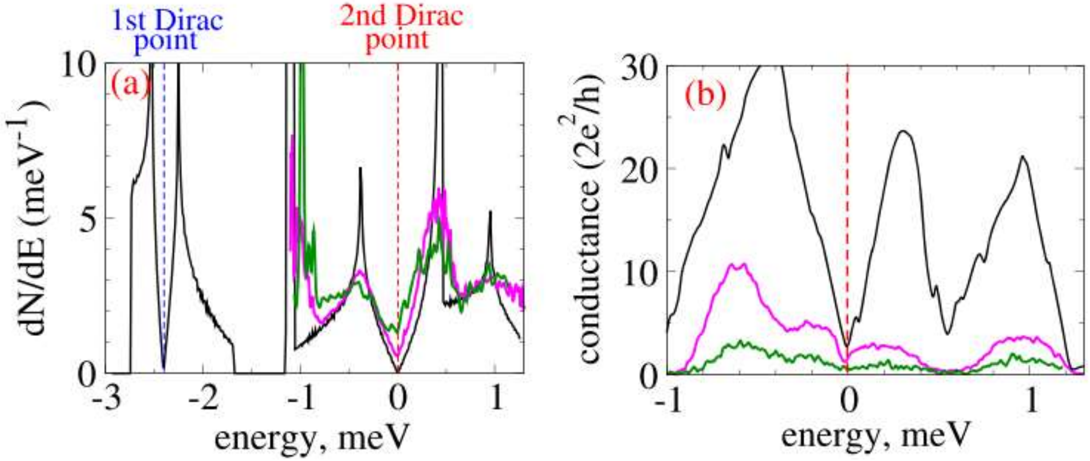
Effects of Coulomb screening and disorder on an artificial graphene based on nanopatterned semiconductor

O A Tkachenko[1], V A Tkachenko[1,2], I S Terekhov[3] and O P Sushkov[3,4]









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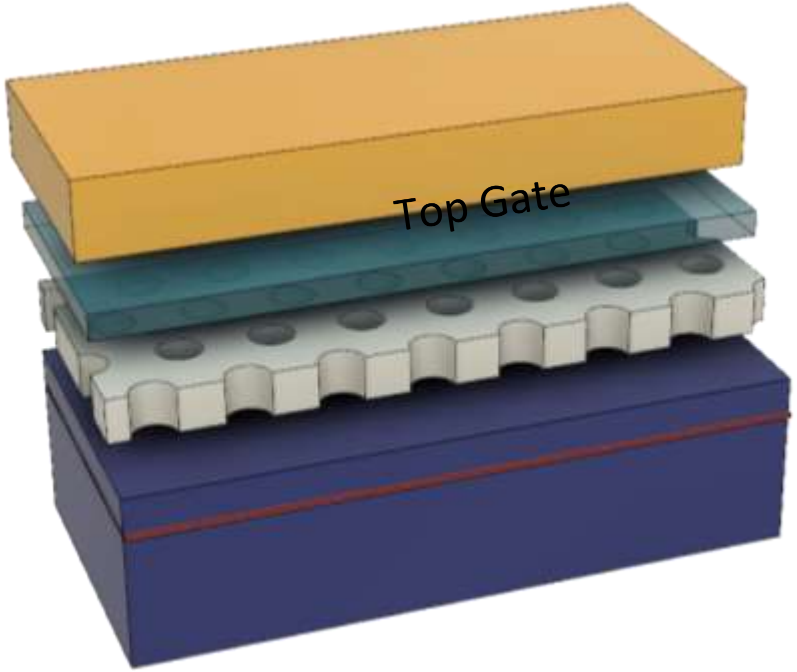
NEED STRONG MODULATION: 3rd GENERATION



Metal Top-gate
TG controls modulation ΔU

Thin dielectric

Patterned gate
PG controls 2DEG density *n*

2D electron gas (2DEG)
in GaAs heterostructure

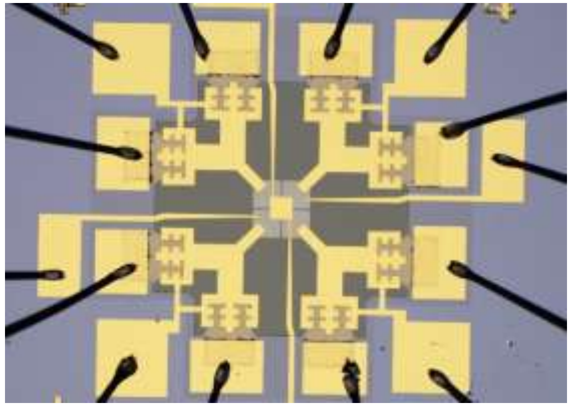
Applied Physics Letters ARTICLE scitation.org/journal/apl

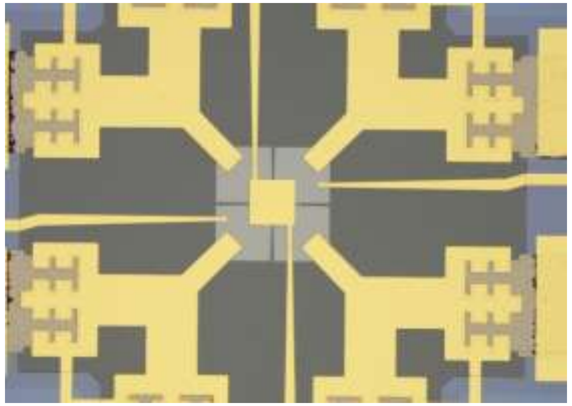
Two-dimensional lateral surface superlattices in GaAs heterostructures with independent control of carrier density and modulation potential

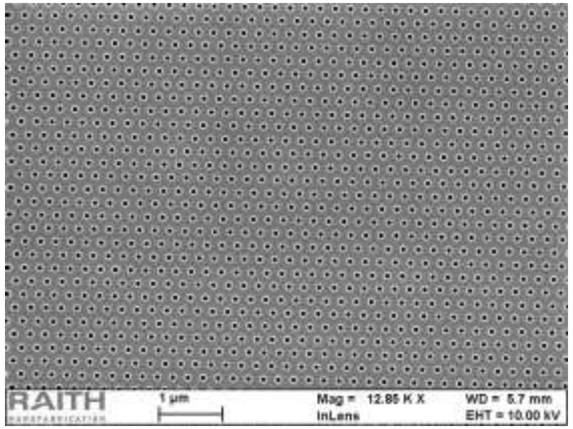
Cite as: Appl. Phys. Lett. **117**, 032102 (2020); doi: 10.1063/5.0009462
Submitted: 31 March 2020 · Accepted: 8 July 2020 ·
Published Online: 20 July 2020

D. Q. Wang,[1,2,a)] D. Reuter,[3,b)] A. D. Wieck,[3] A. R. Hamilton,[1,2] and O. Klochan[1,2,4]

Parameters:
- 2DEG depth: 37nm - 25nm
- a=120nm – 100nm







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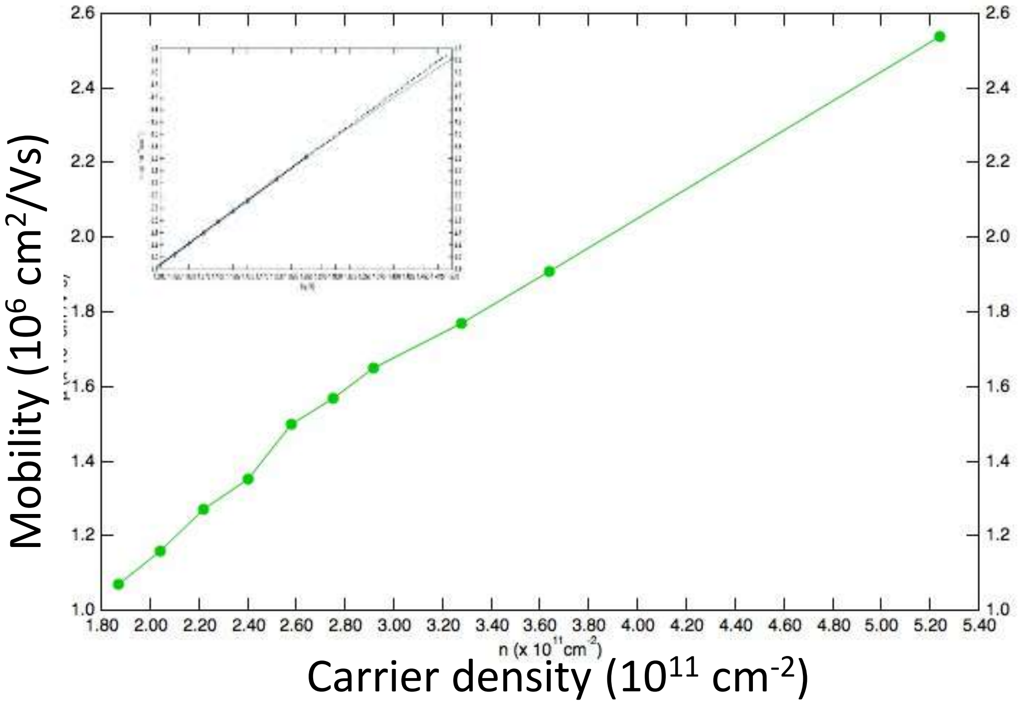
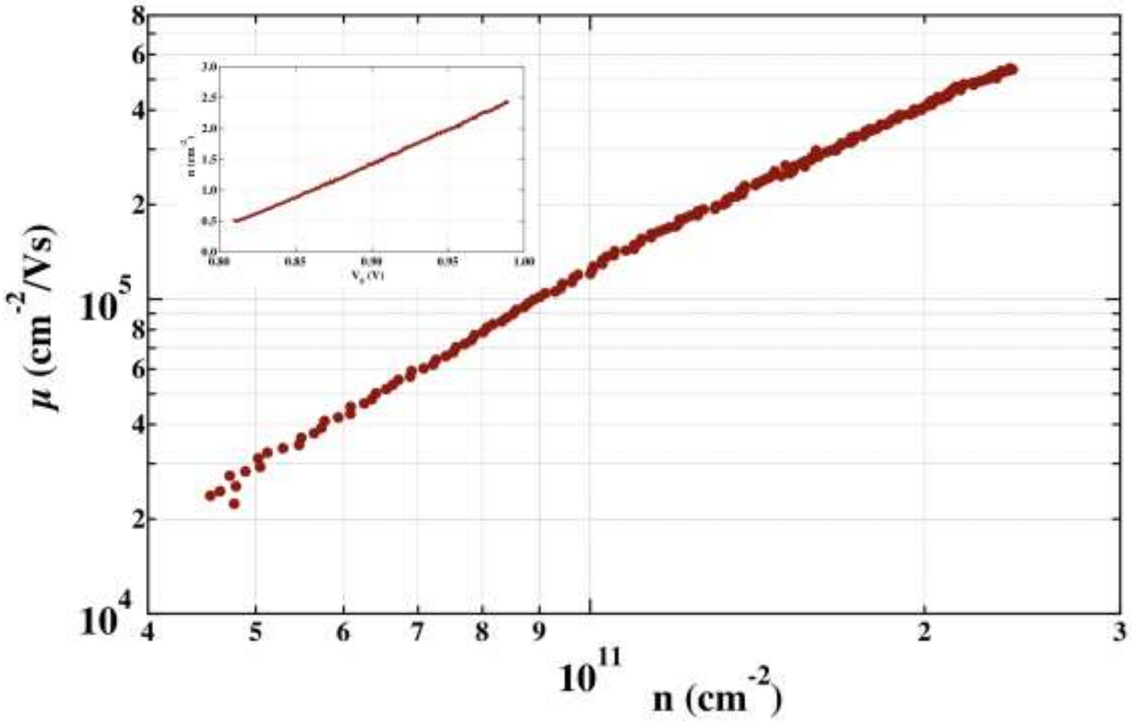
Modulation potential decays exponentially with 2DEG depth

Extremely shallow 2DEGs: Sacrifice mobility for depth





2DEG depth d=37nm

n up to 5.4x10^{11} cm^{-2+}

μ up to 2.5 million cm^2/Vs

limited by surface charge

2DEG depth d=25nm

n up to 2.4x10^{11} cm^{-2+}

μ up to 0.8 million cm^2/Vs

limited by surface charge

OUTLINE

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  - Turning massive electrons into massless Dirac particles
- **Flat bands & non-trivial insulator**

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O. Tkachenko

Wafers

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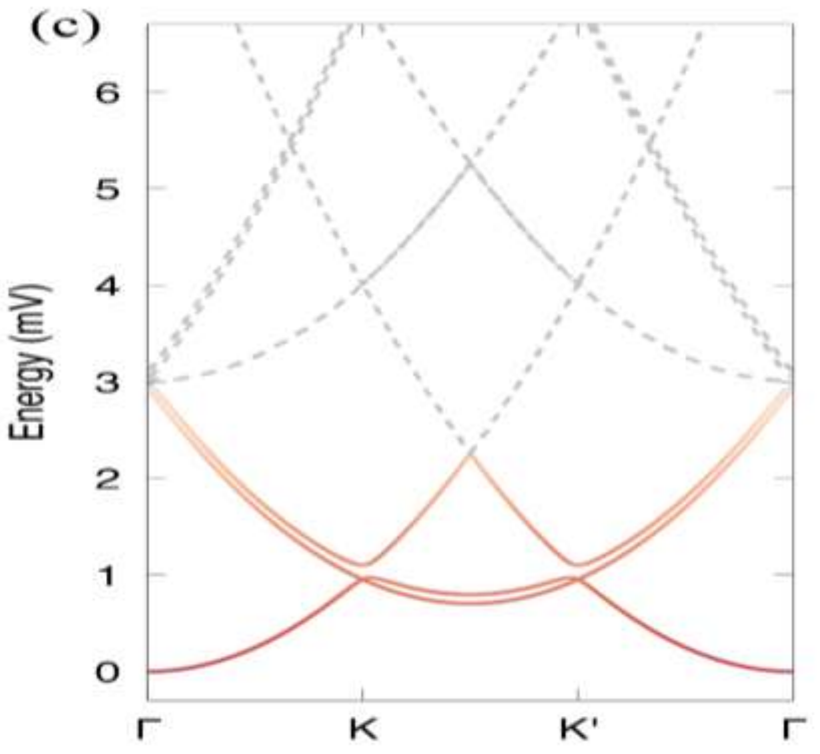
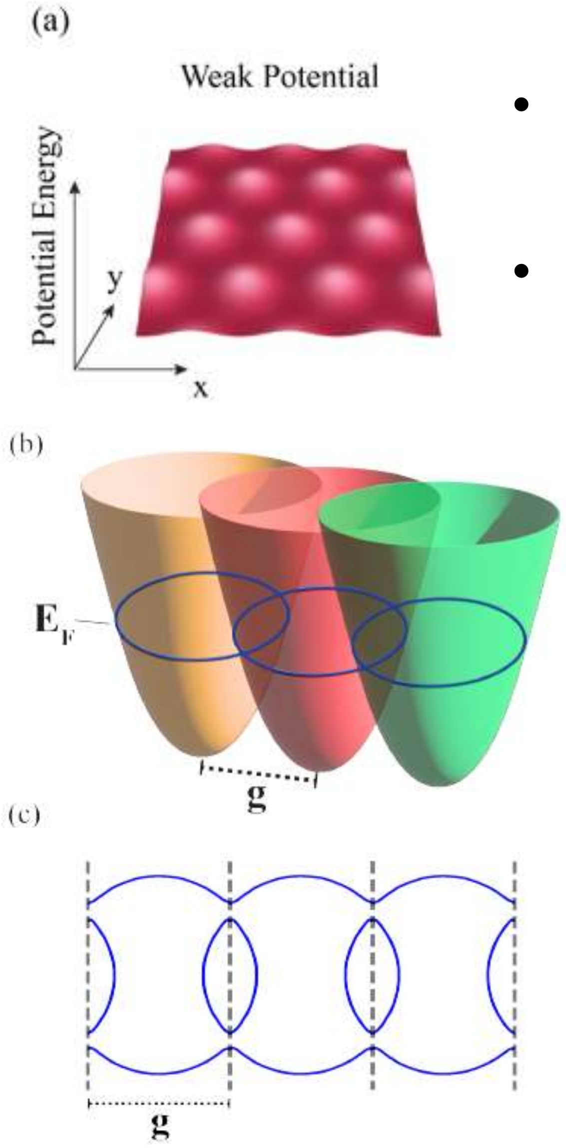
Werner Wegscheider

Starting with “weak” modulation

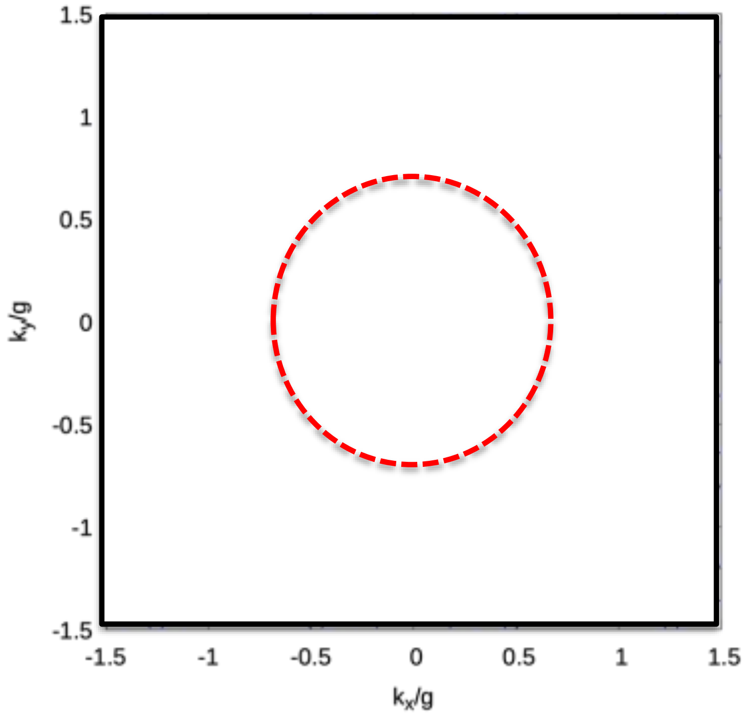
- What would we see with “weak” modulation?
  (weak ≡ quite strong by many standards)



Daisy Q. Wang et al, Nano Lett 23, 1705 (2023).

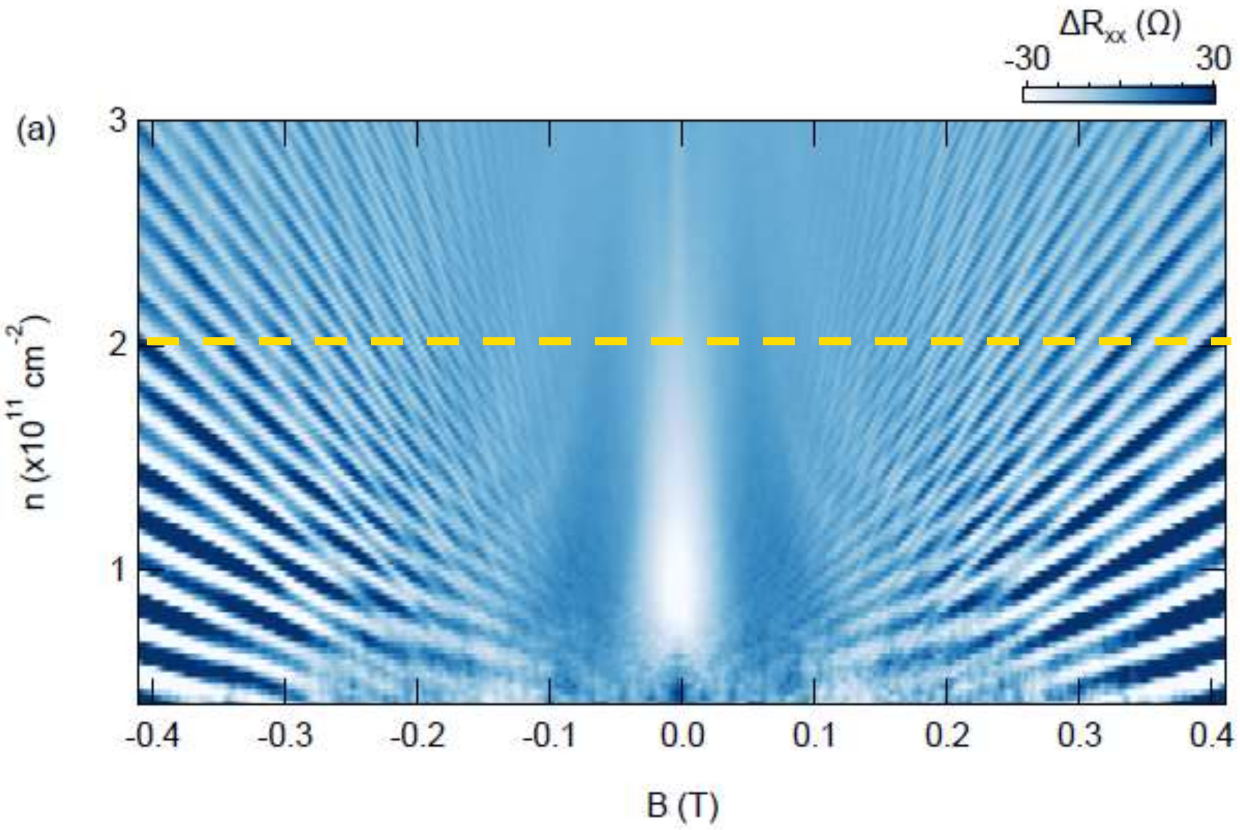


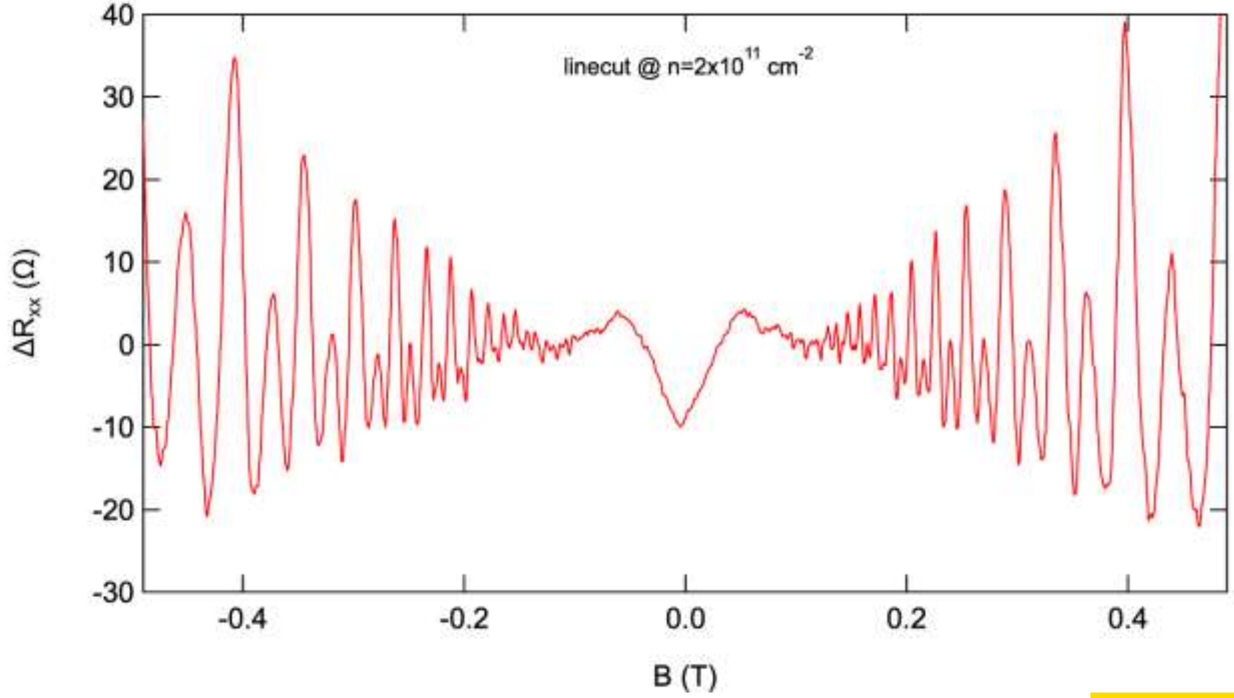
- Free electrons – single circular Fermi surface
- Electrons in periodic potential – many Fermi surfaces.



Weak modulation I

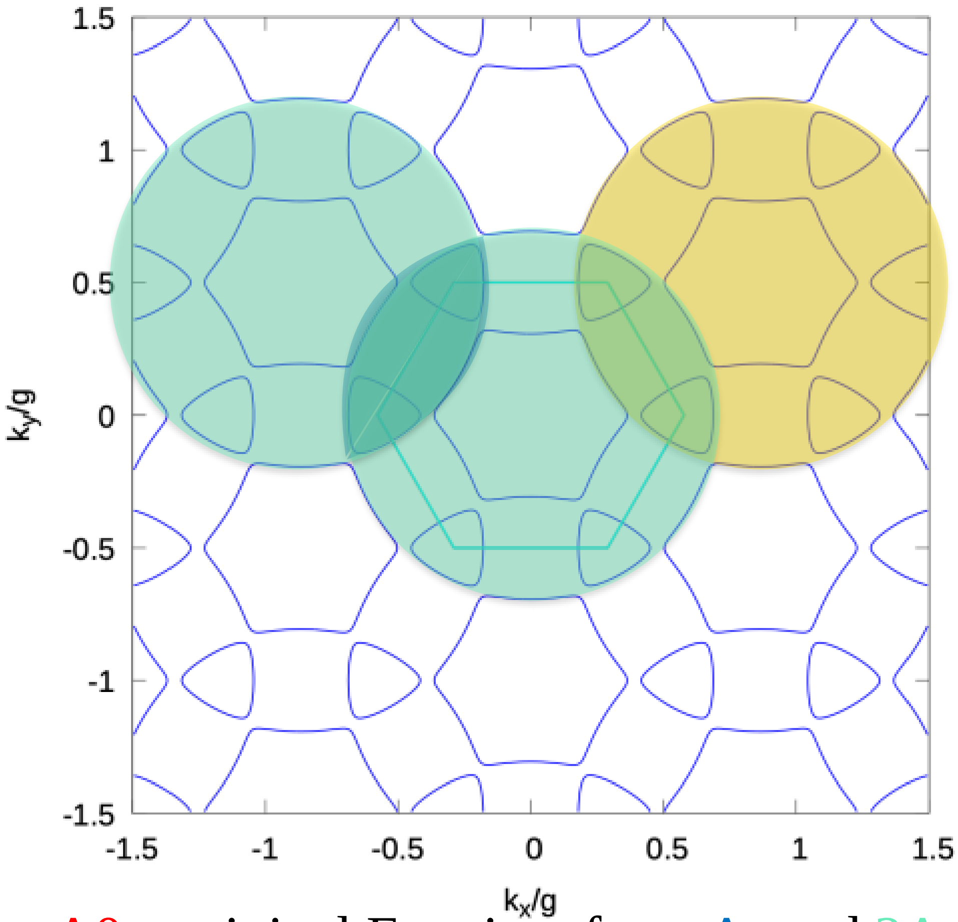
- Wafer W916, z =37 nm, a=80 nm. V_{PG}= +0.5V. T=20mK
- Multiple oscillation frequencies

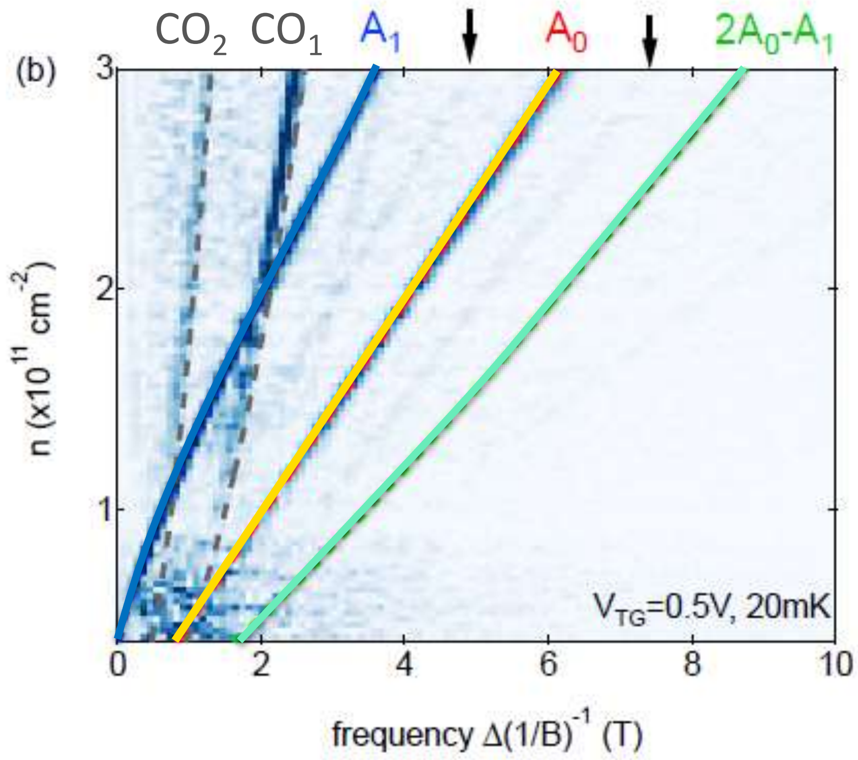




Daisy Q. Wang et al, Nano Lett 23, 1705 (2023).

Weak modulation II





A0 – original Fermi surface; A_1 and $2A_0$-A_1 – reconstructed Fermi surfaces,
CO_1 and CO_2 are classical commensurability oscillations

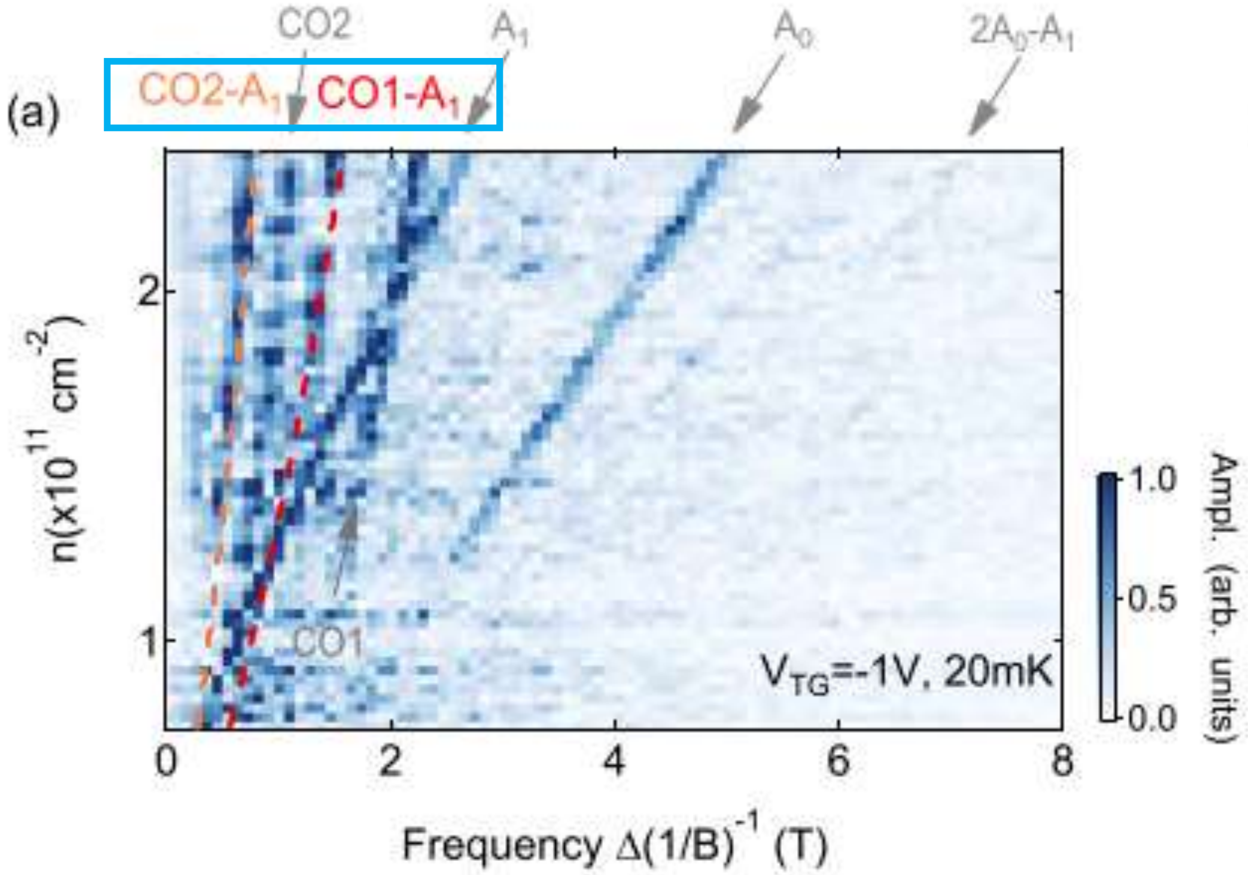
Quantum Interference in Artificial Band Structures

R. A. Deutschmann, W. Wegscheider, M. Rother, M. Bichler, G. Abstreiter, C. Albrecht, and J. H. Smet
Phys. Rev. Lett. **86**, 1857 – Published 26 February 2001

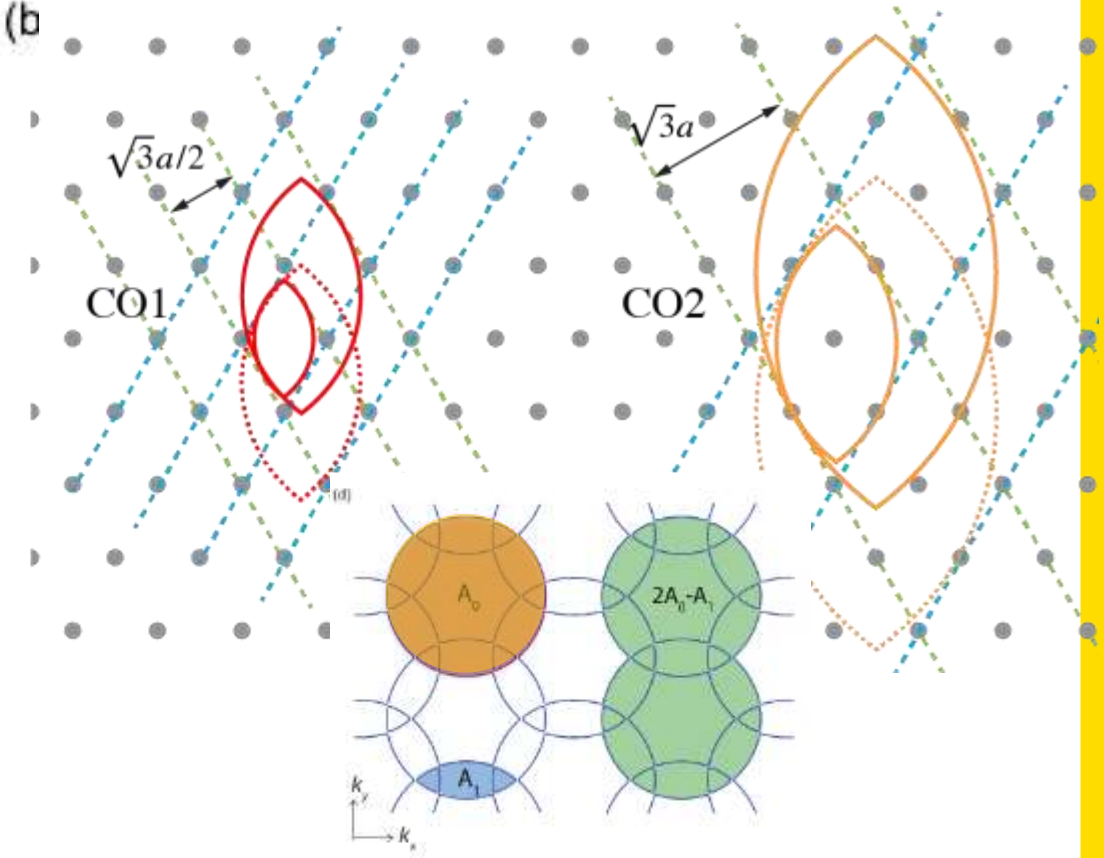
Daisy Q. Wang et al, Nano Lett 23, 1705 (2023).

Weak modulation IV – slightly stronger modulation, 20mK

- Increased modulation strength V_{TG}= -1V



Wang, Nano Lett 23, 1705 (2023).



Take home:

- 2 extra lines are classical commensurability oscillations of new Fermi surface A_1.

➢ **We have made artificial Fermi surface & scattered it off 2D lattice**

OUTLINE

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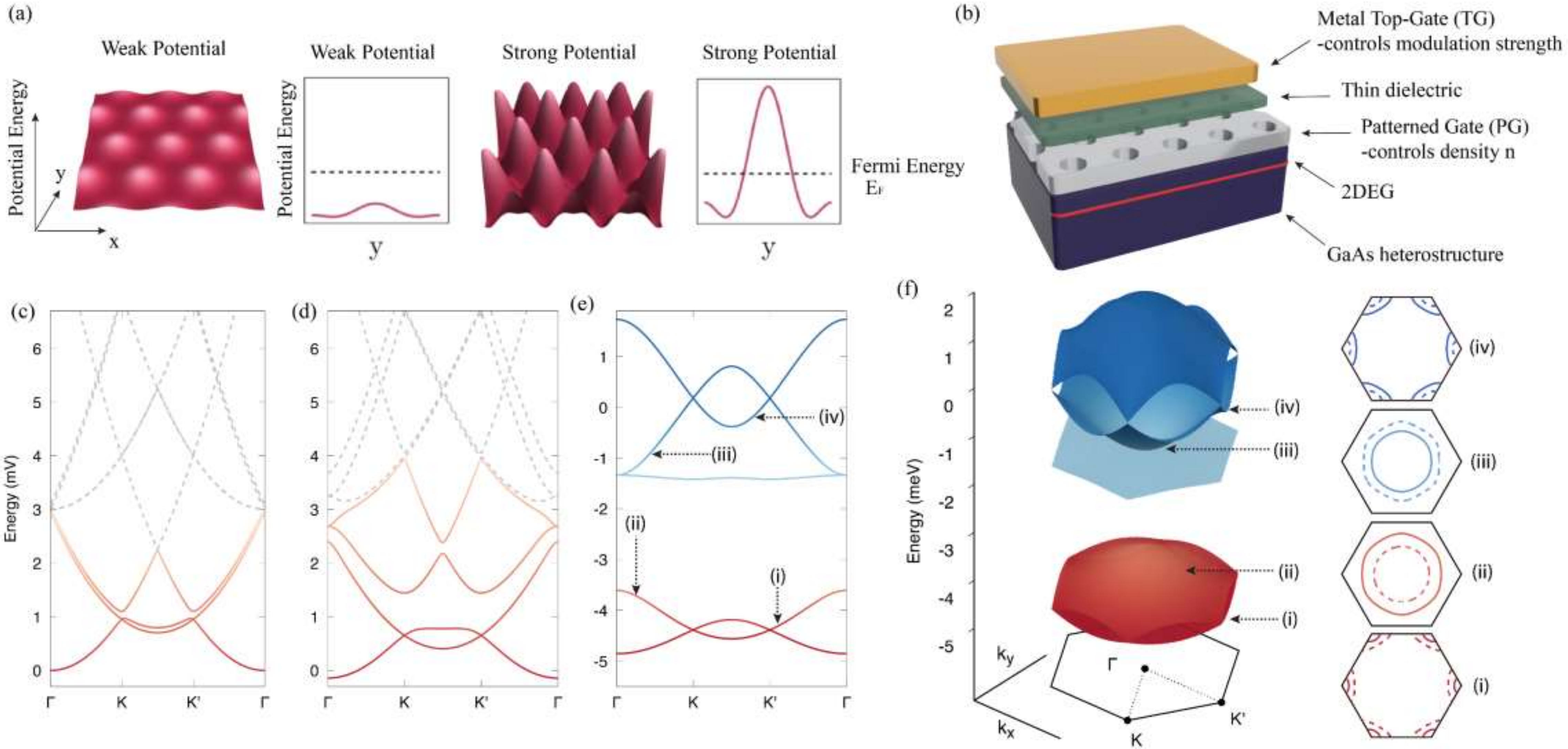
Moving to higher modulation strength



Band-gaps open

- Should see electrons and holes in the minibands
- Should see change of sign of Hall slope

D.Q. Wang…ARH, arXiv:2403.07273 (2024)

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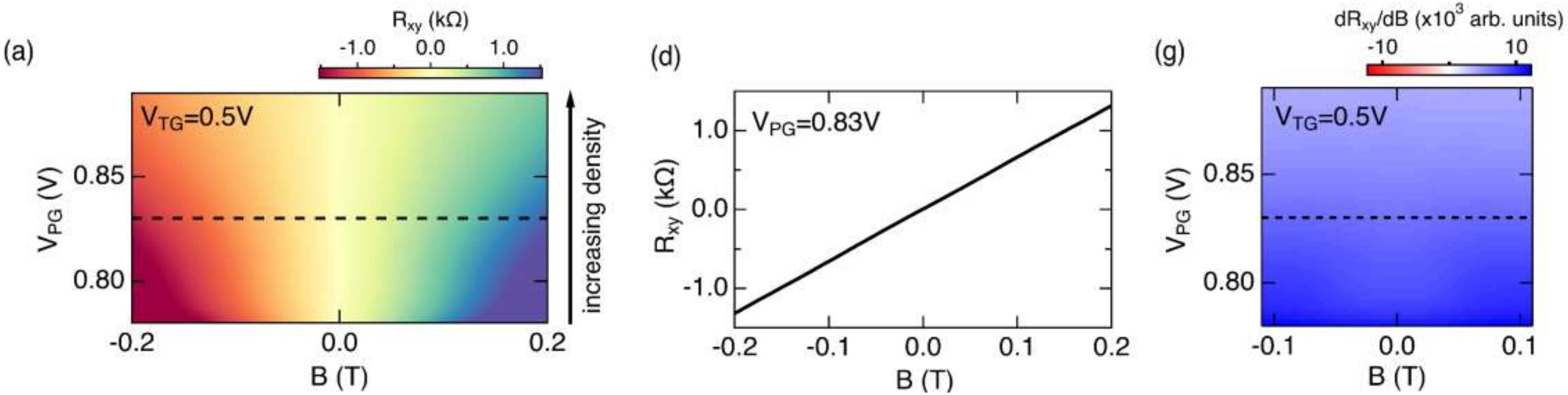
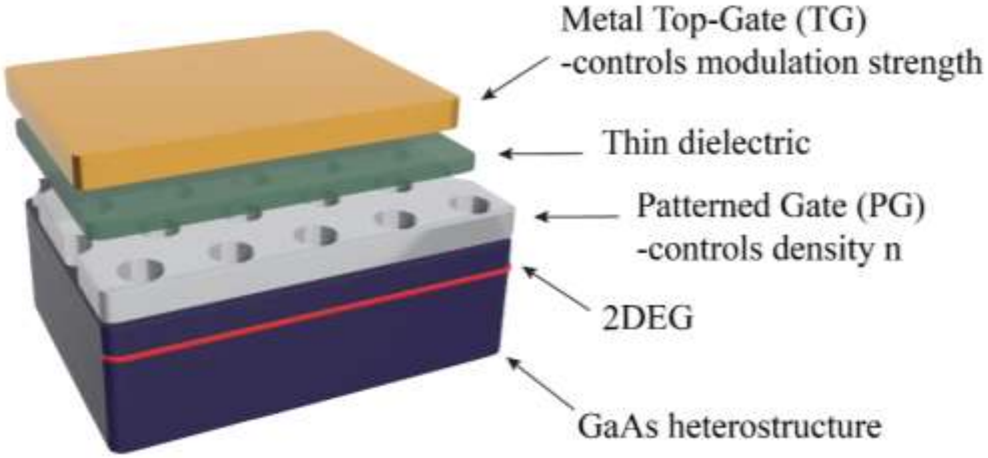
Turning electrons into holes



Hall effect with modulation off (positive V_{TG})

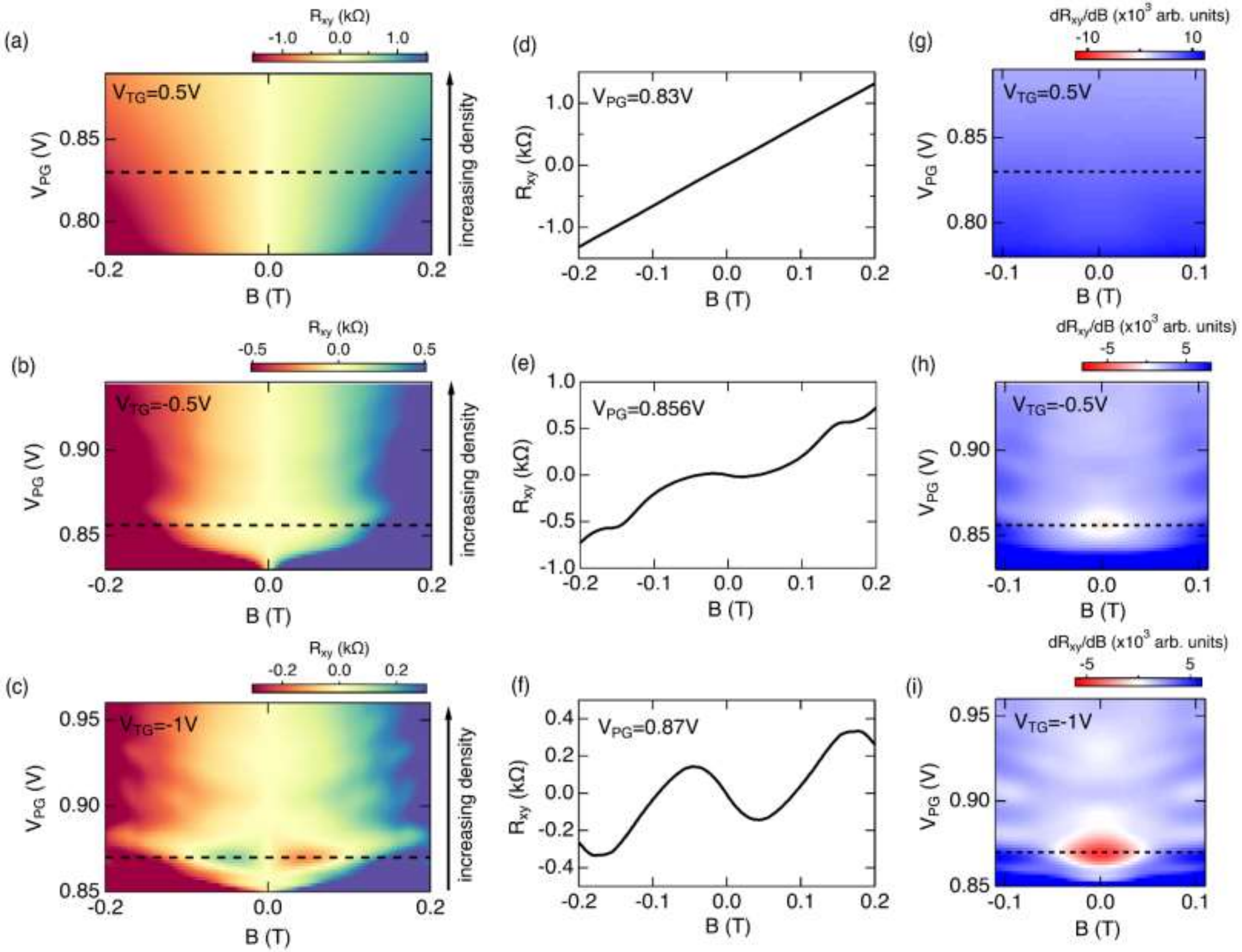
- Linear in B,
- Positive slope
- $dR_{xy}/dB>0$ => electrons (blue)

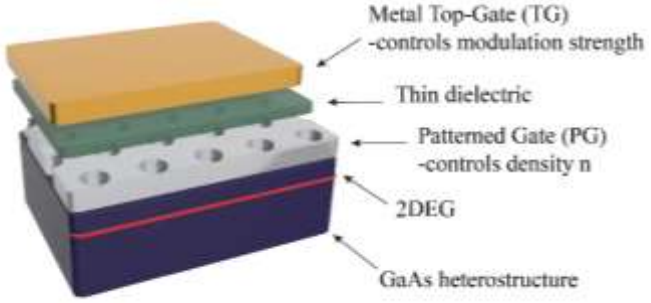


Wafer W916, z =37 nm, a=120 nm. T = 1.5 K

D.Q. Wang…ARH, arXiv:2403.07273 (2024)

Turning electrons into holes





Hall effect with increasing potential modulation (V_{TG} → -1V)

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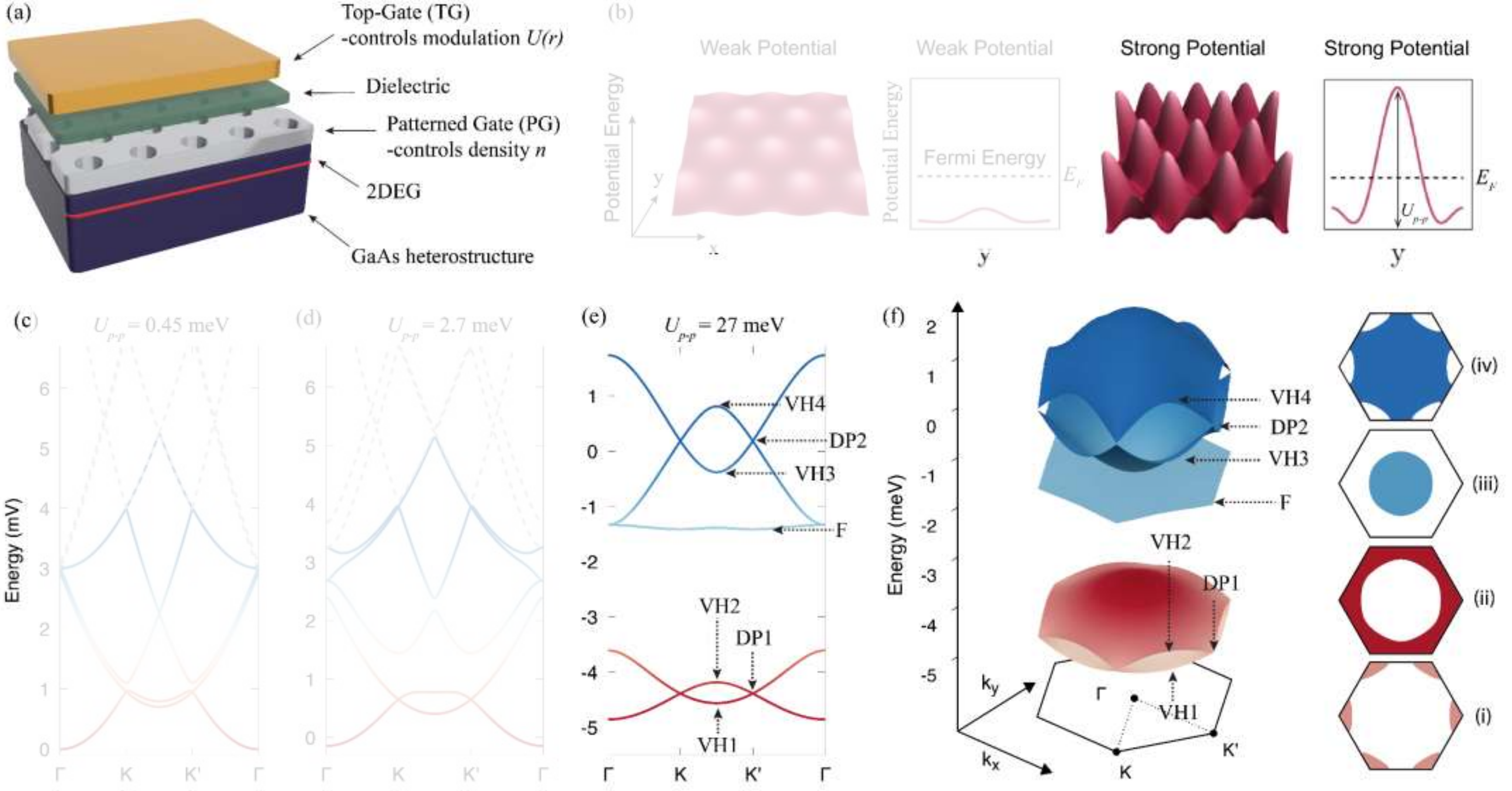
Even stronger modulation: miniband identification



Challenge:
Relate measurements to calculated bandstructure

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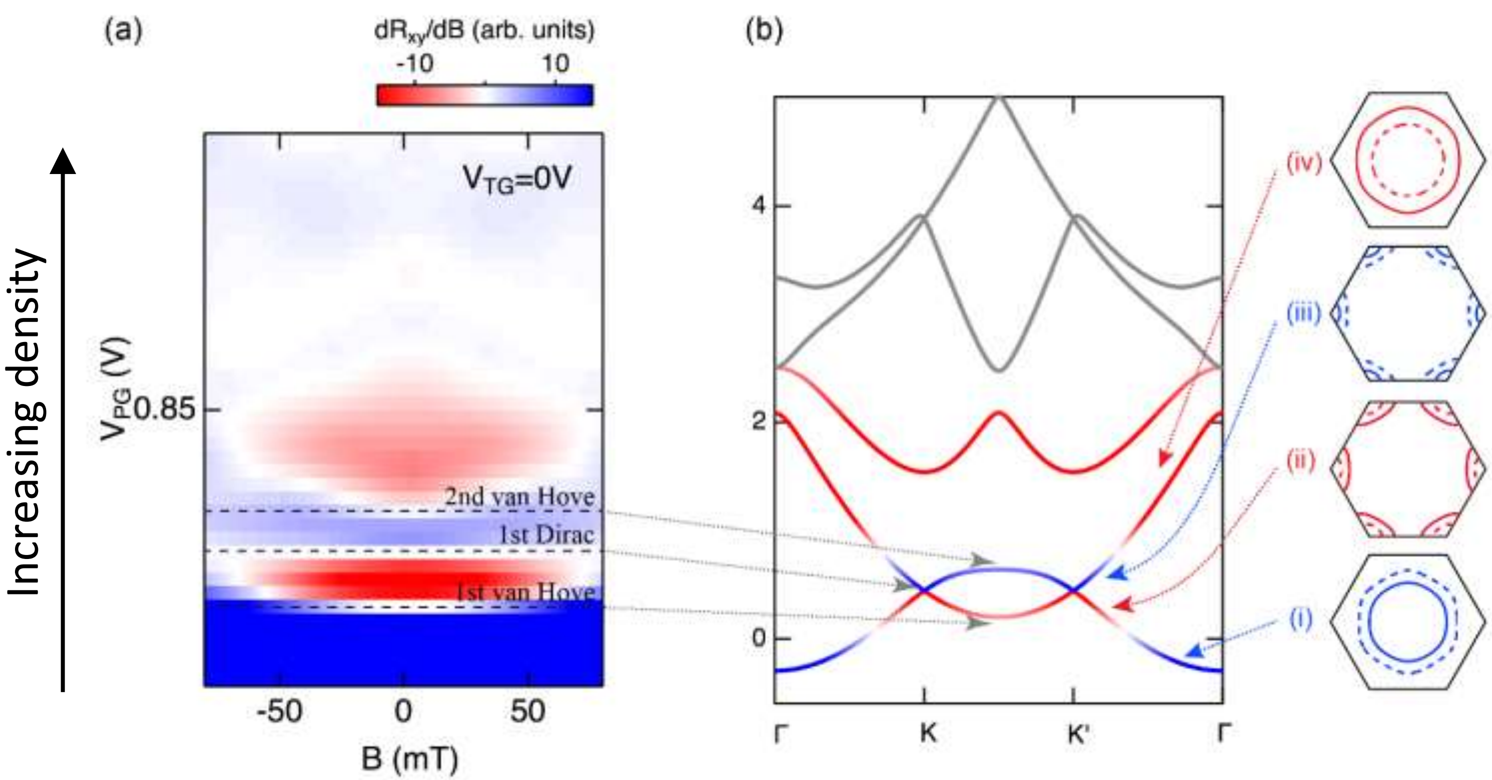
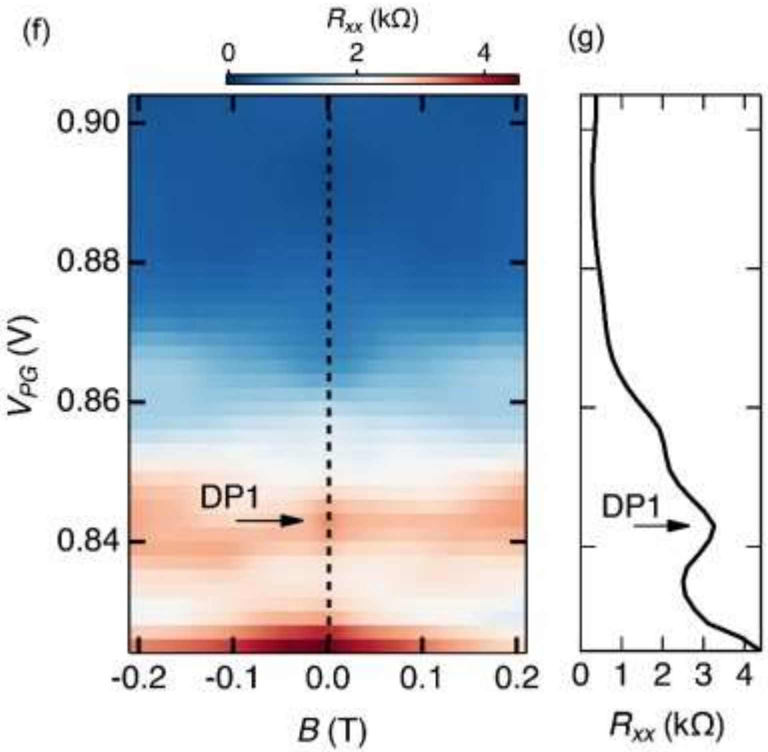
Strong modulation: Honeycomb lattice





Reduce a to 100nm.

Band-gaps open

- Count changes of Hall sign: Blue=electrons, red=holes.
- Identify band filling
- Calculations with $U_{\text{p-p}}$= 4.05meV
- Charge distribution at E_F = 1.5 meV, for states below E_F
- Peak in resistance at Dirac Point – cf graphene
- Band disorder ~ 0.2 meV

$$U(\boldsymbol{r}) = 2W \sum_{i=1}^{3} \cos(\boldsymbol{g}_i \cdot \boldsymbol{r}),$$

$$\boldsymbol{g}_1 = \frac{4\pi}{\sqrt{3}a}(0, 1),$$

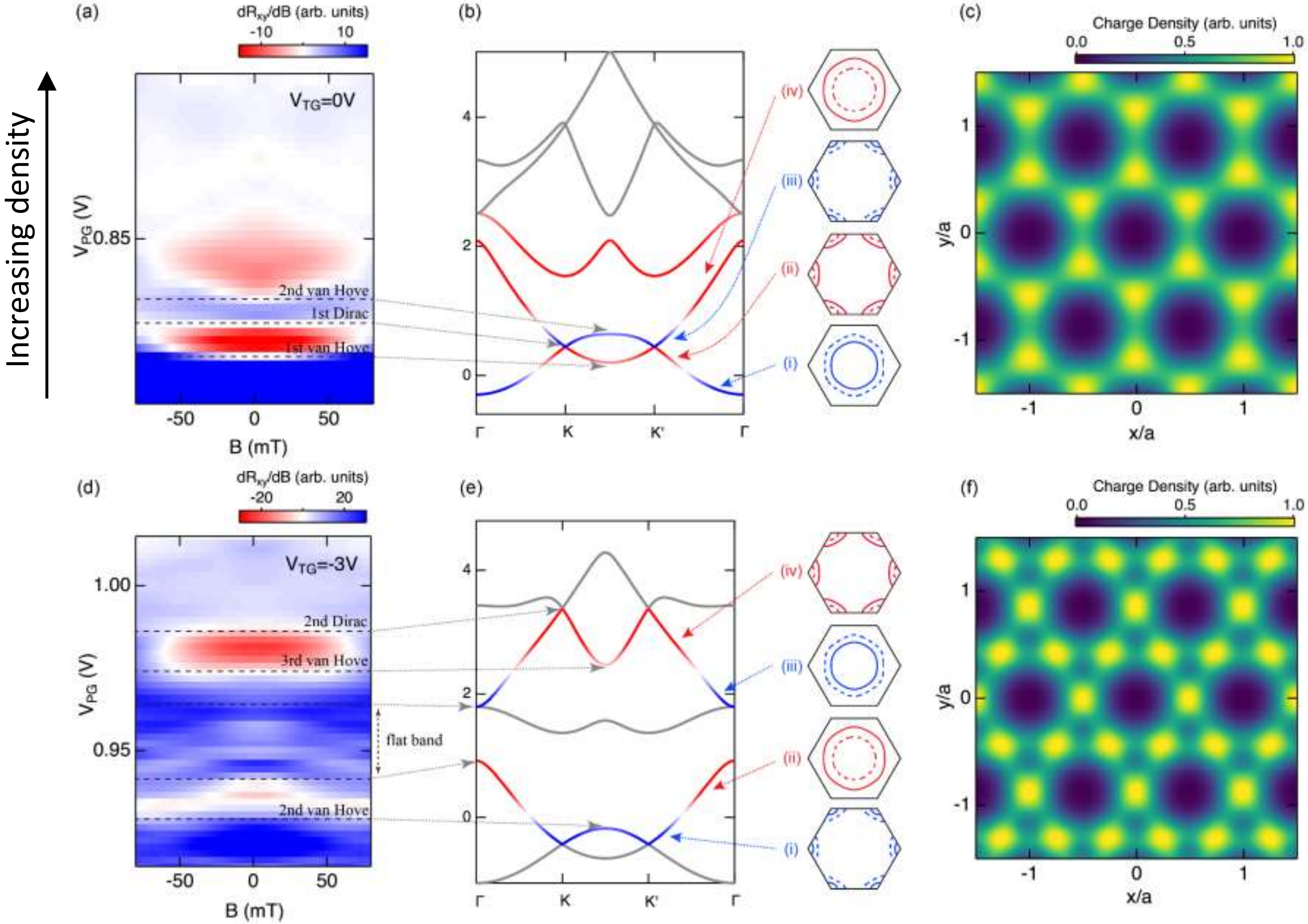
$$\boldsymbol{g}_2 = \frac{4\pi}{\sqrt{3}a}(1/2, \sqrt{3}/2),$$

D.Q. Wang…ARH, arXiv:2403.07273 (2024)

Strongest potential modulation: $U_{p\text{-}p}$=9meV

Blue=electrons

red=holes



Stronger modulation
V_{TG}=-3V

- $U_{p\text{-}p}$=9 meV
- Charge distribution at E_F = 3.4 meV, for bands 3 & 4 only
- **Kagome charge distribution**

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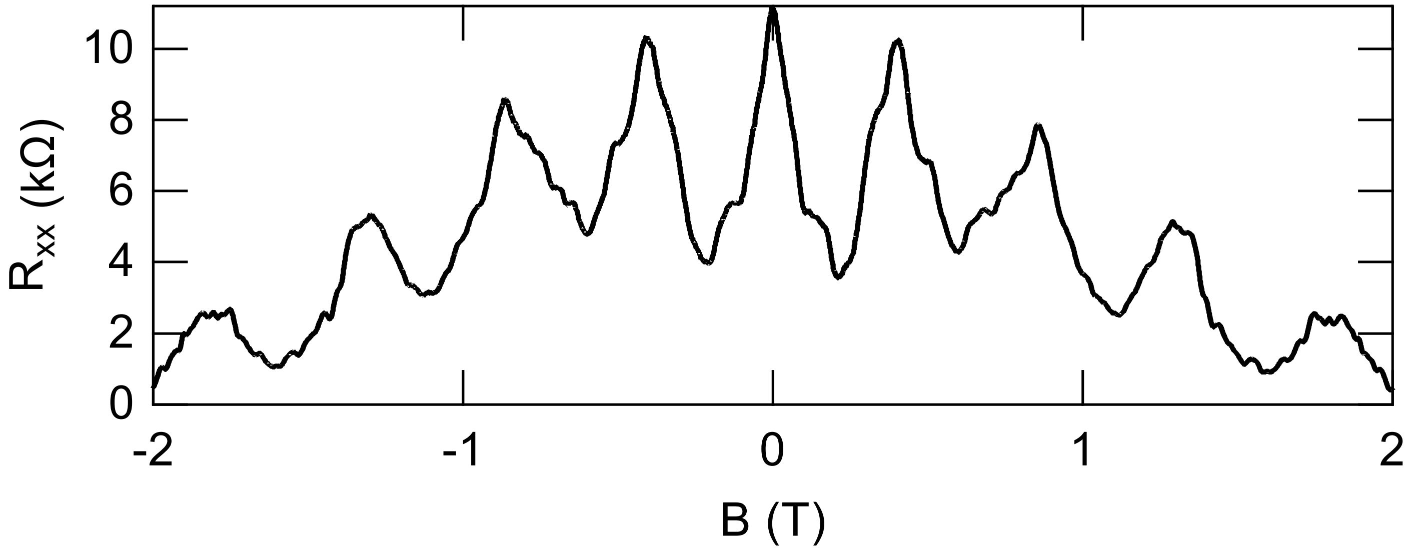
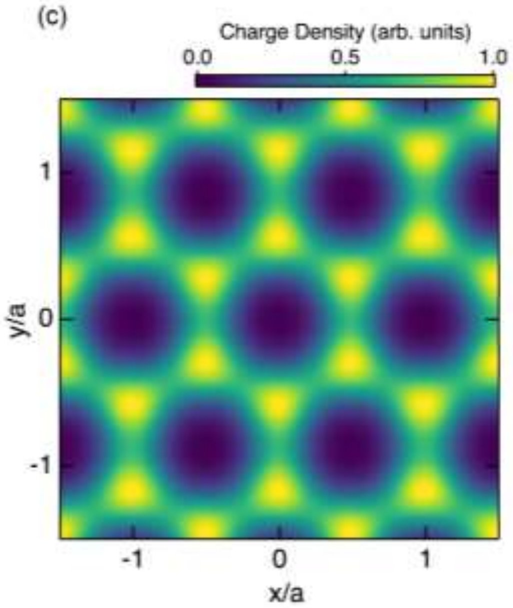
Magnetoresistance oscillations: evidence for artificial lattice





For artificial lattice

- Properties must be gauge invariant to 1 flux / lattice site (Zak Phys. Rev. 1964)
  (Magnetic breakdown of crystal structure)
- c.f. Hofstadter butterfly: fractional filling 1 flux / *m* lattice sites (PRB 1974)
- 2T here is equivalent to 320,000T in graphene; over 100T in MATBG

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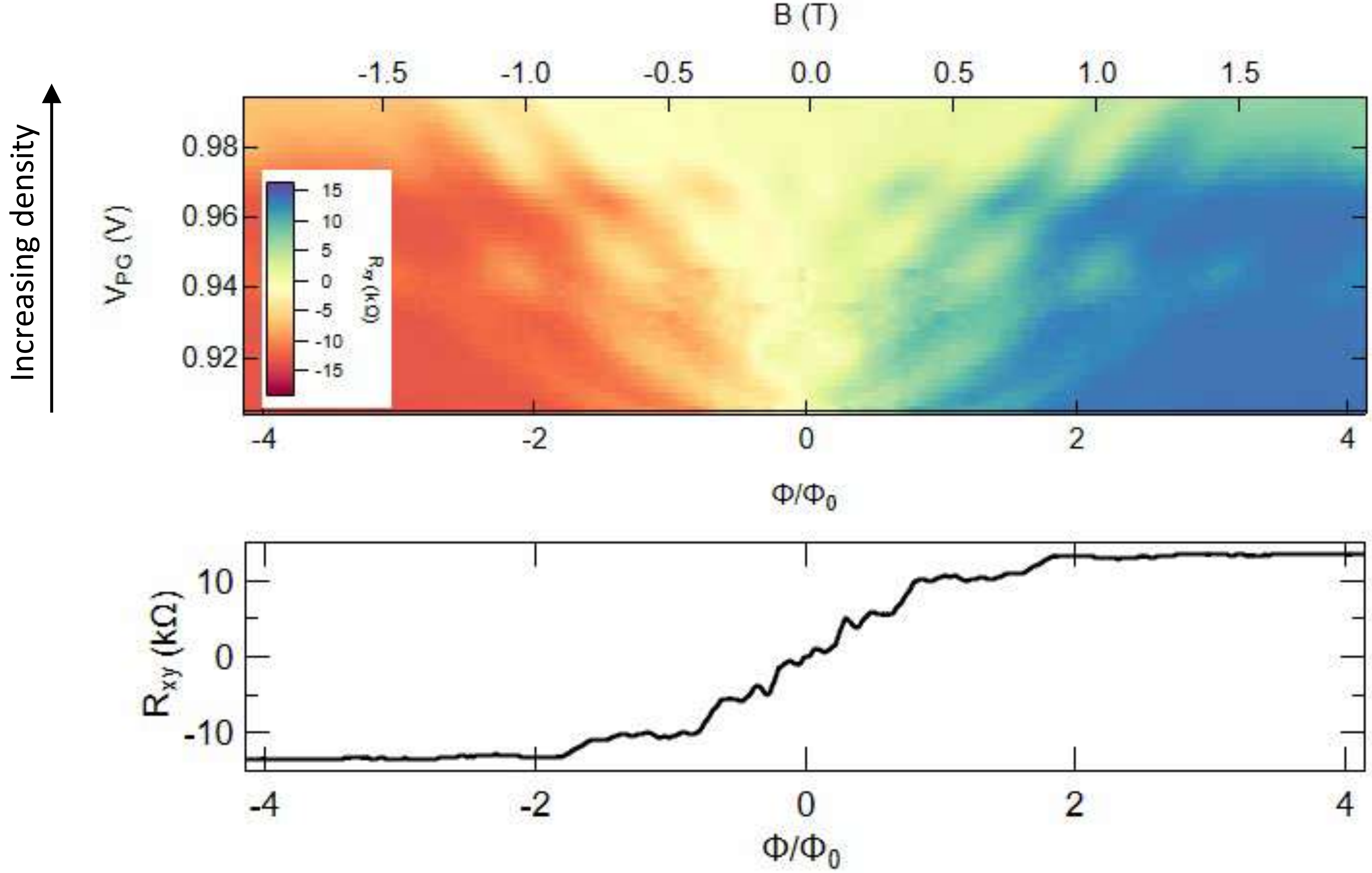
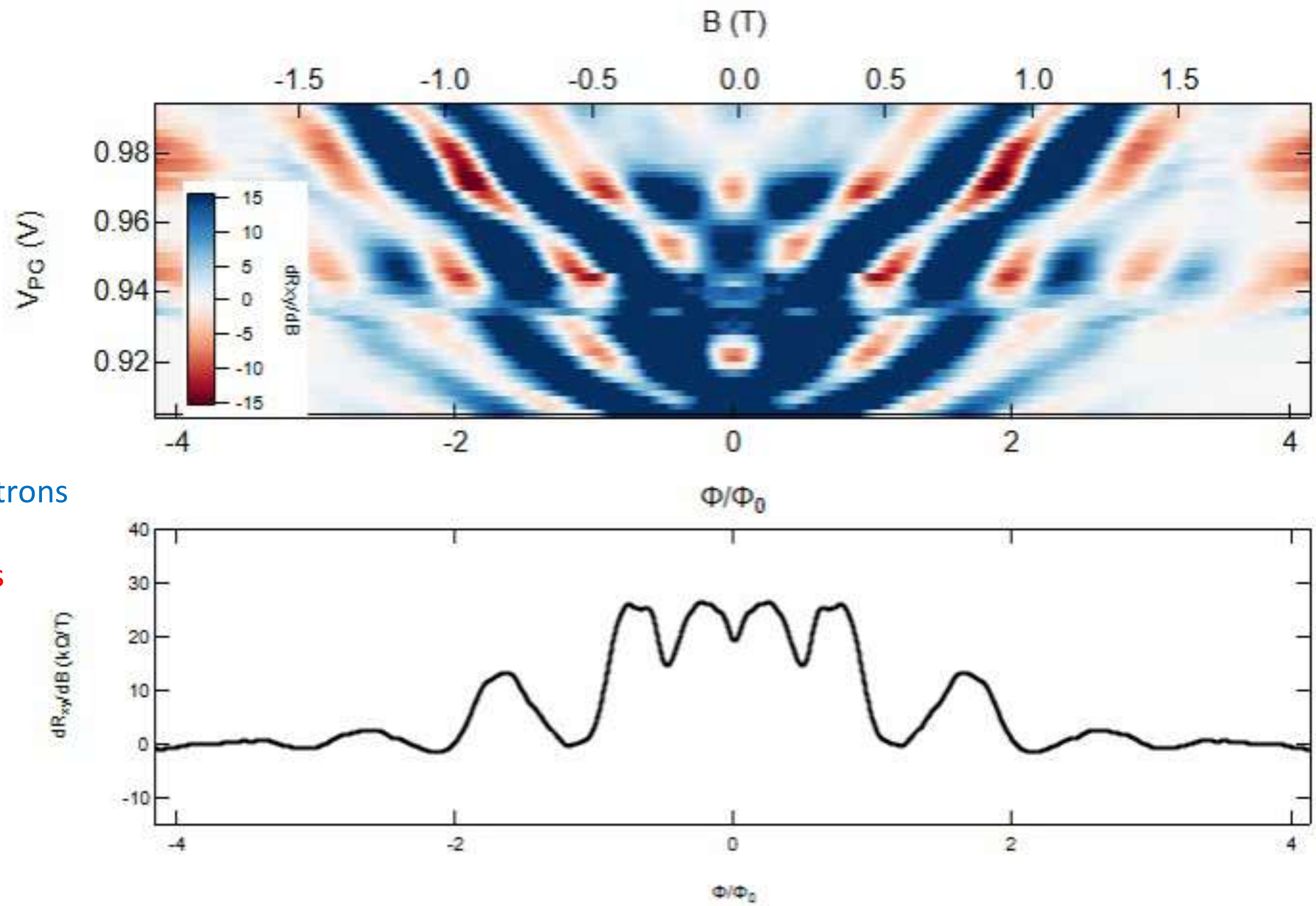
Zak oscillations in R_{xy}



Increasing density

Zak oscillations in dR_{xy}/dB

Increasing density



Blue=electrons

Red=holes

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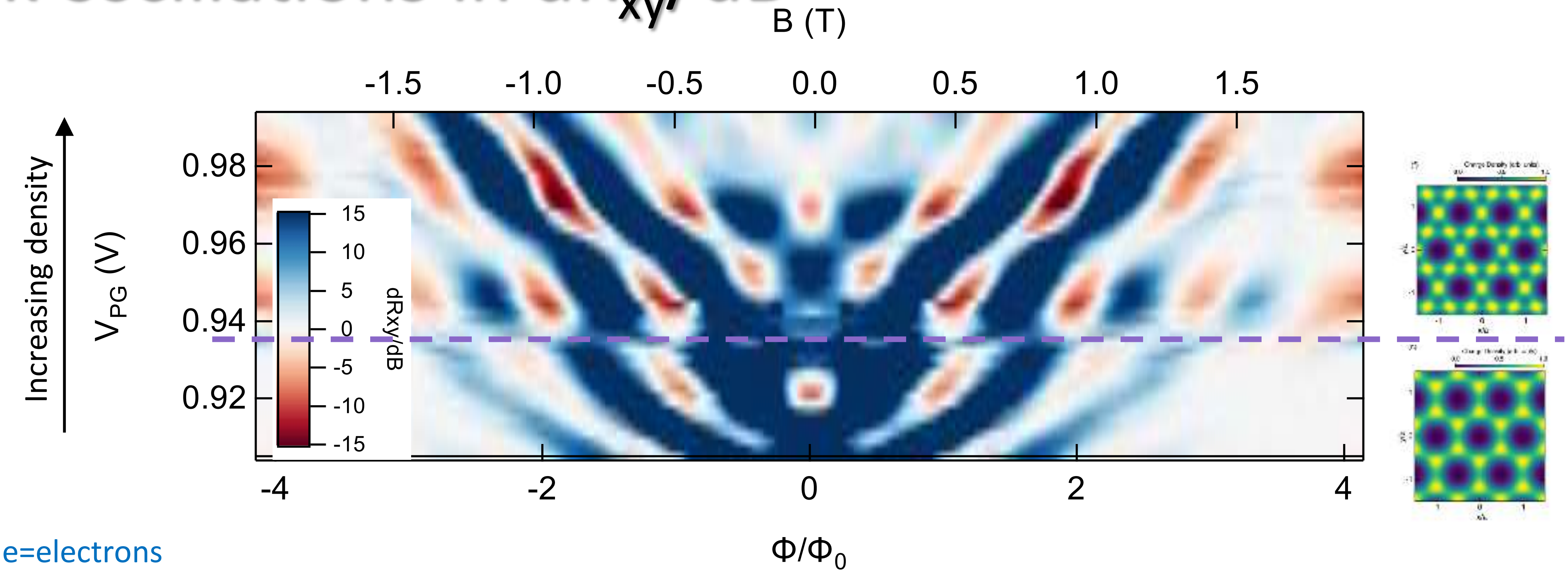
Zak oscillations in dR_{xy}/dB



Blue=electrons

Red=holes

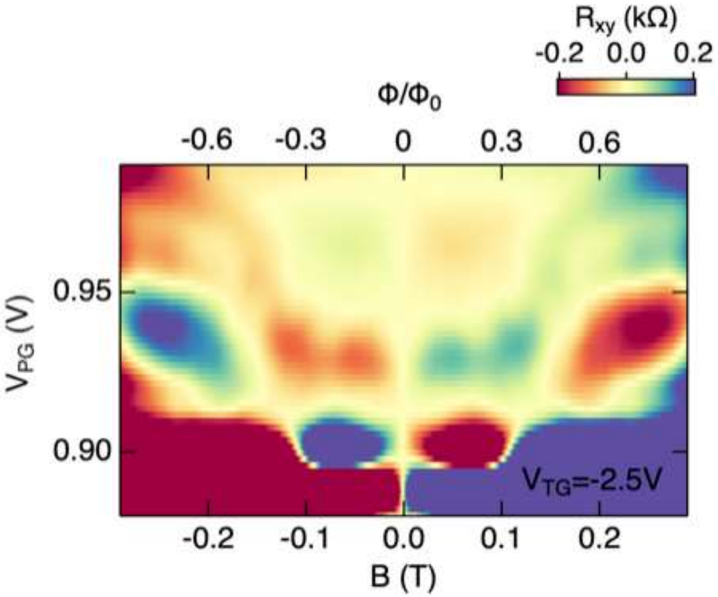
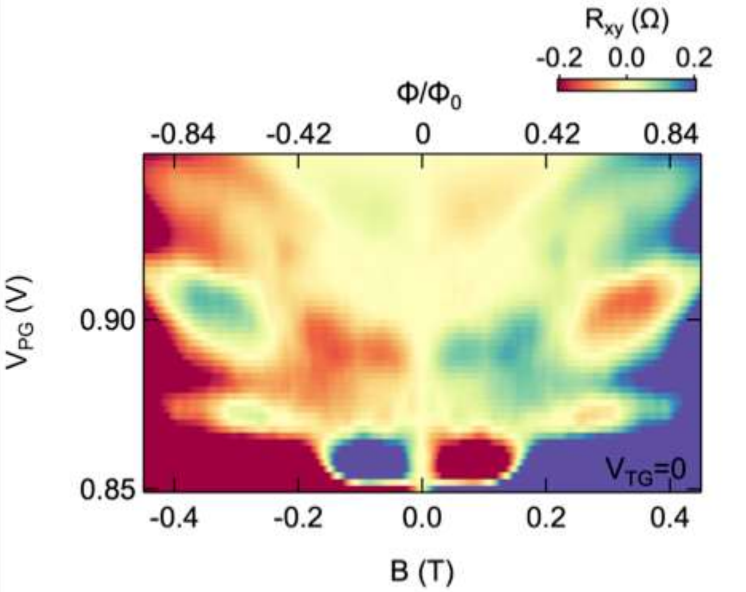
This provides absolute calibration of gate voltage to band filling

X periodicity: # electrons / band

Y periodicity: # flux / lattice

Phase shift: change in band topology ?

Reproducibility: 2 devices on different wafers with 2 different lattice periods

W916	**W1740**
30nm AlGaAs(0.6) + 7nm GaAs	22nm AlGaAs(0.6) + 3nm GaAs
Electron mobility ~600,000 cm^2/Vs @ 1e11 cm^-2	Electron mobility ~150,000 cm^2/Vs @ 1e11 cm^-2
AG device: 120nm lattice, 10um area	AG device: 100nm lattice, 5um area
AG: sign change of Hall slope at **TG=-2.5V** (1.5K)  	AG: sign change of Hall slope at **TG=0V** (1.5K) 

- Wafer W916, **z =25 nm**, a=100 nm. T = 1.5 K. TG = 0 V now very similar to TG=-2.5V before.

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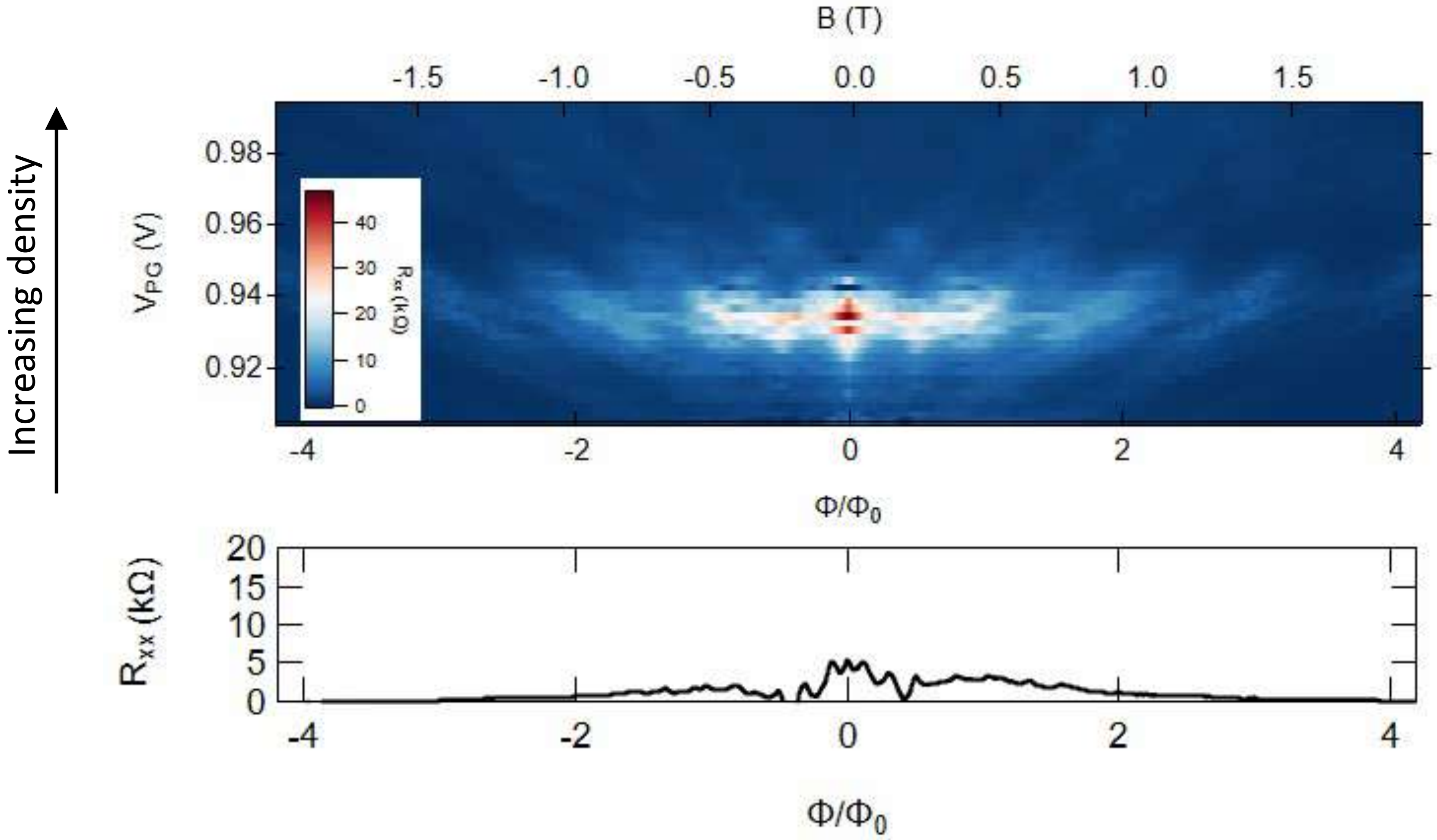
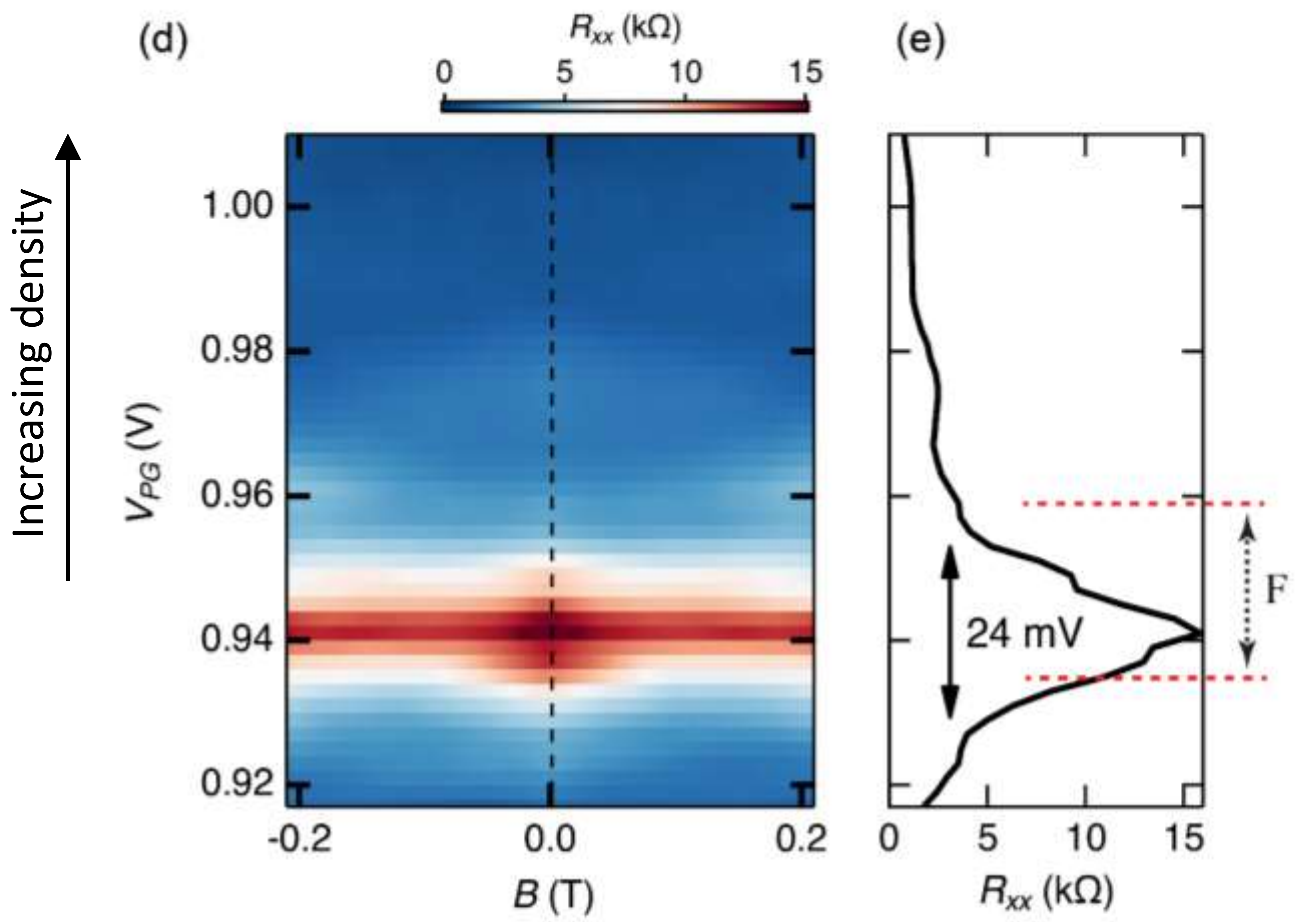
Longitudinal resistance: Insulator after Dirac bands filled



Not disorder:

- Same flux periodicity as lattice
- Killed with increasing *and* decreasing density

Longitudinal resistance: Insulator after Dirac bands filled



Not disorder:

- Same flux periodicity as lattice
- Killed with increasing *and* decreasing density

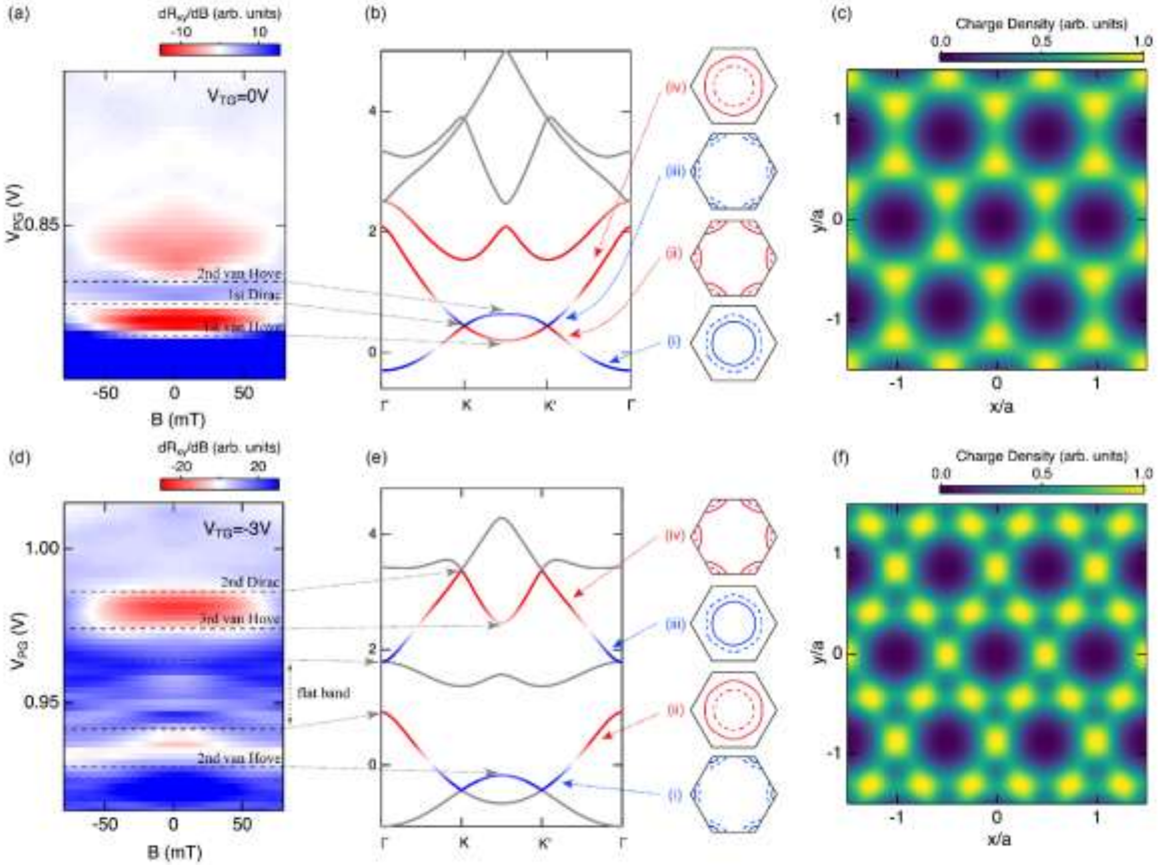
- Width of insulator in gate bias = one full band $\Rightarrow$ from flat band, not bandgap
- Theory: $\mathcal{U}_{\text{onsite}}/t \sim 50 \Rightarrow$ strong correlations

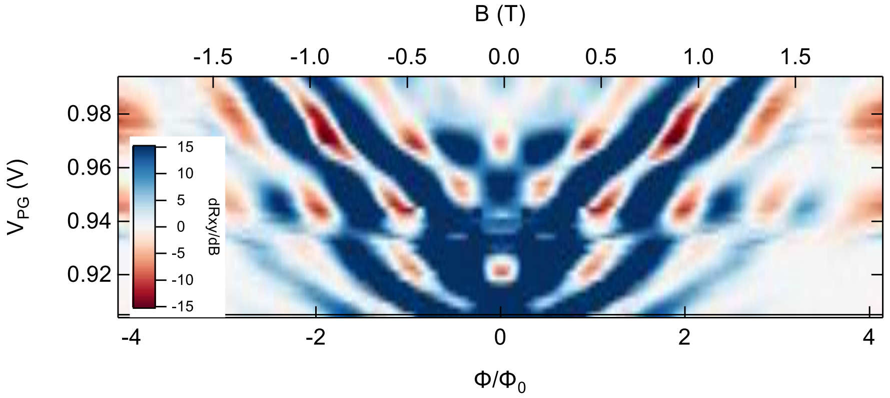
Summary

- Artificial bandstructure
- Tune E_F and U over many bands
- Turn electrons into holes
- Band filling: Dirac bands
- Transition Dirac – Kagome lattice
- Created band gap
- Non-trivial insulator

Future:

- Ultra-low disorder (ask)
- Add band topology ***L•S***





D.Q. Wang…ARH, arXiv:2403.07273 (2024)

Alex Hamilton

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Outline and acknowledgments

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- Superlattices & Moiré physics
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- Forming an artificial Dirac point for massive electrons
- Opening a band-gap in the artificial lattice
- Honeycomb to Kagome lattice
- Non-trivial insulator

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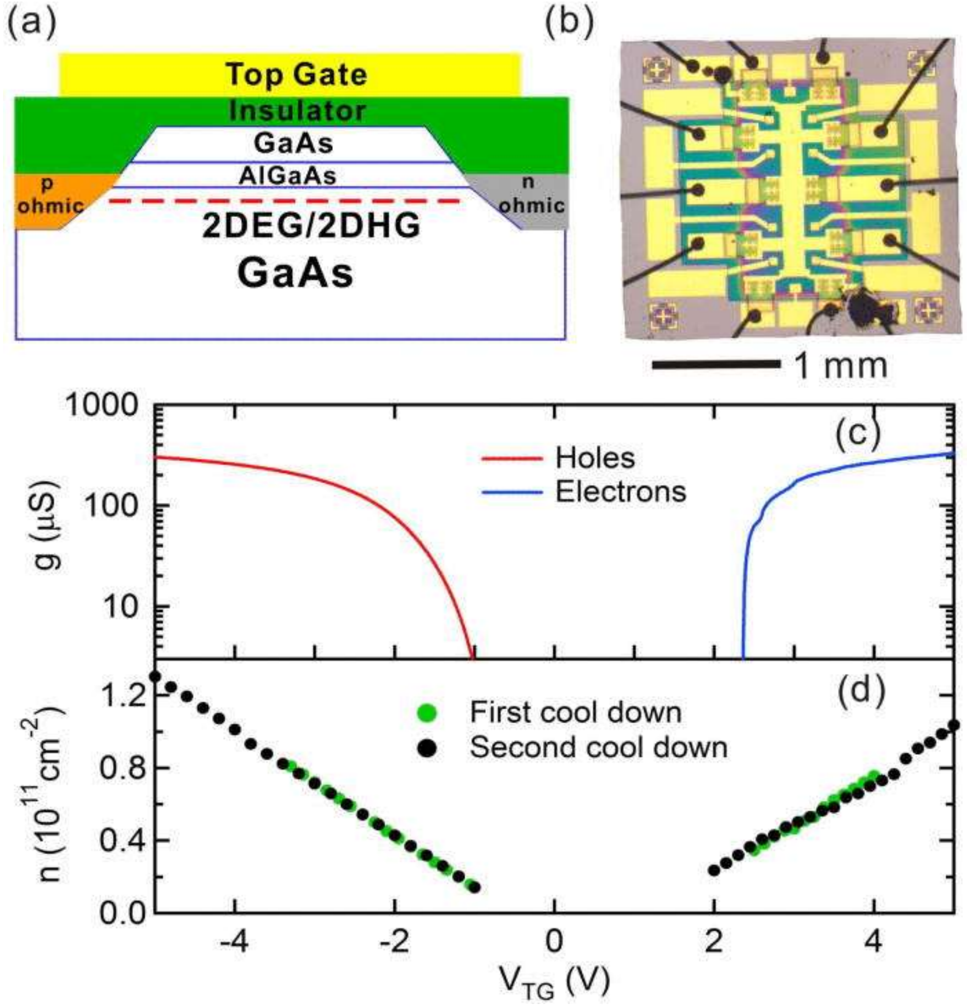
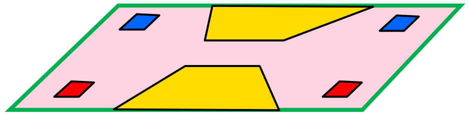
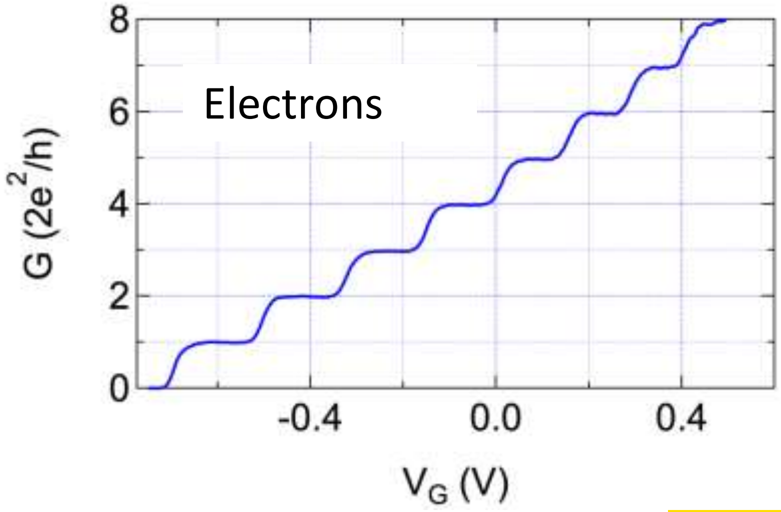
Ambipolar accumulation mode GaAs nanowires / QPCs

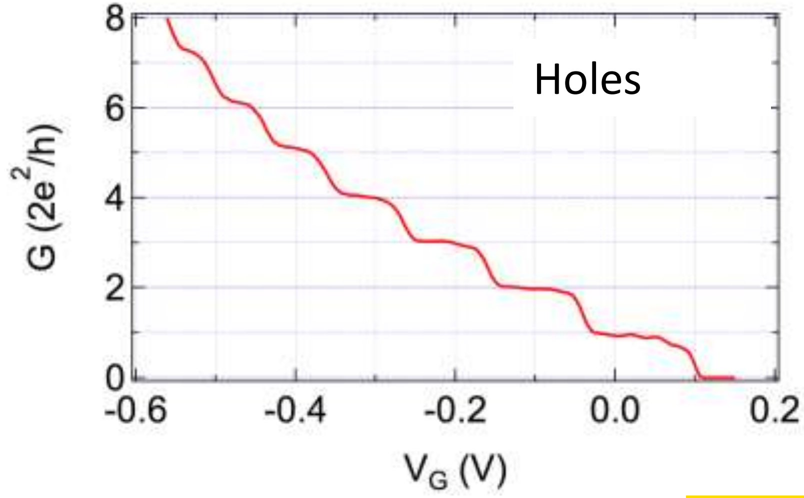




μ_e = 5,000,000 cm^2/Vs

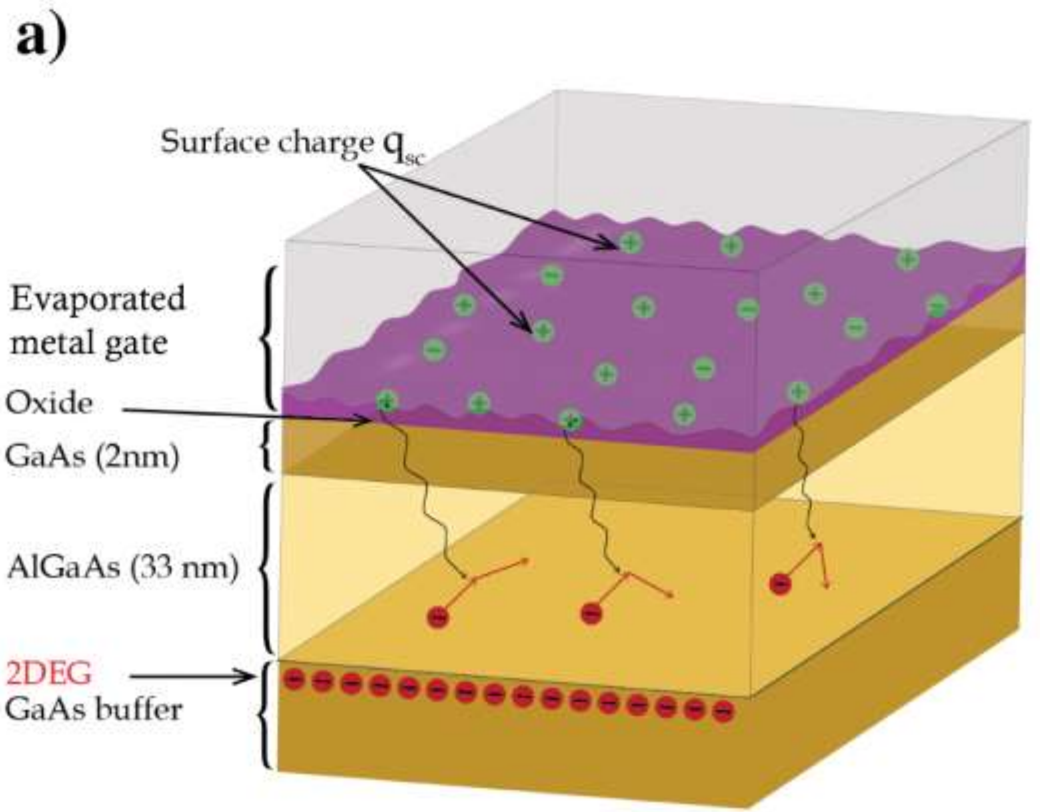
μ_h = 800,000 cm^2/Vs

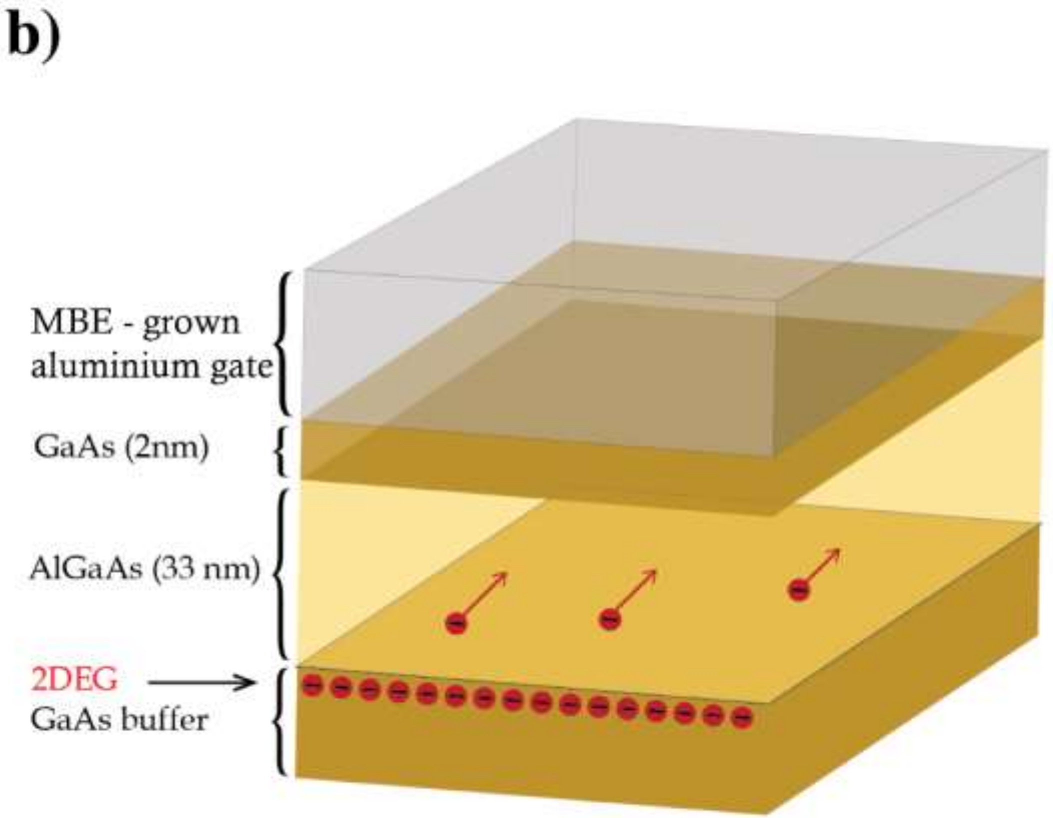




J.C.H Chen..ARH. APL 2012 & APL 2015.

Reducing disorder and noise





- **Problem:** Small quantum devices, Large transconductance
  => channel close to gate
- Surface of semiconductor exposed to air
  => oxidation, adsorbates
  => surface charge
  => scattering of electrons in channel
- Issue for Ge, III-V's, II-VI's, etc

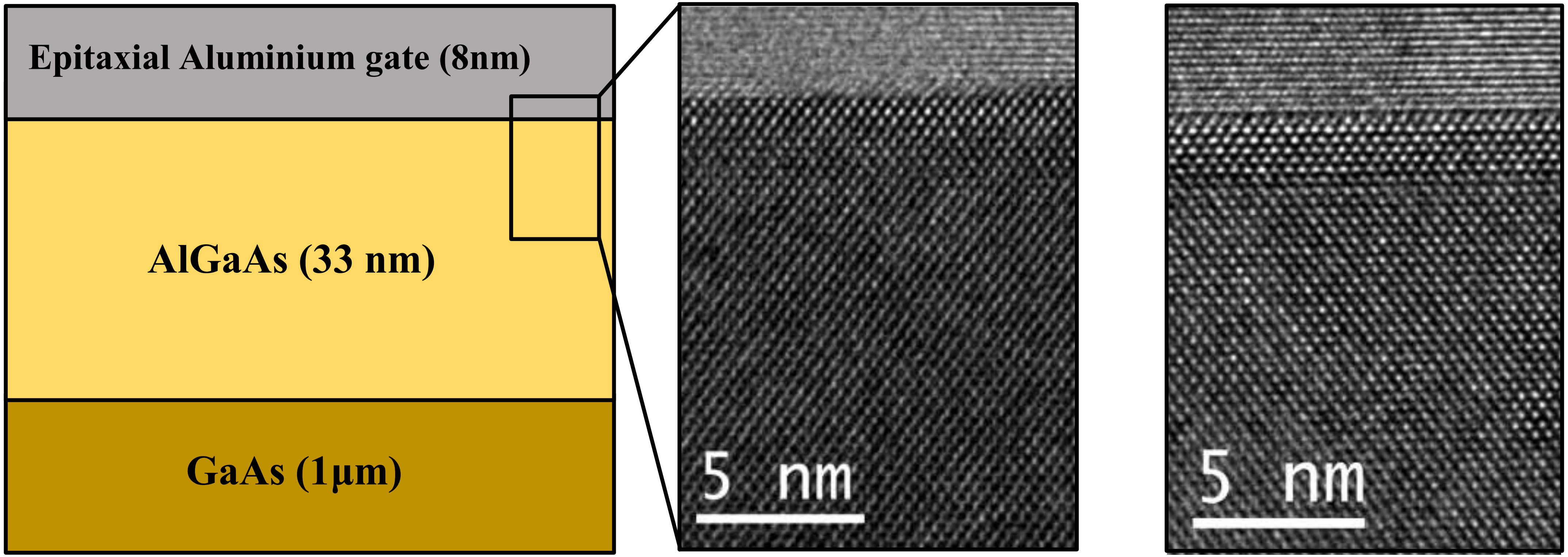
- **Solution:** Grow gate as part of the heterostructure
- Semiconductor surface never sees air
- Eliminates unwanted surface charge, surface contaminants

Perfect metal-semiconductor interface

DEVICE STRUCTURE

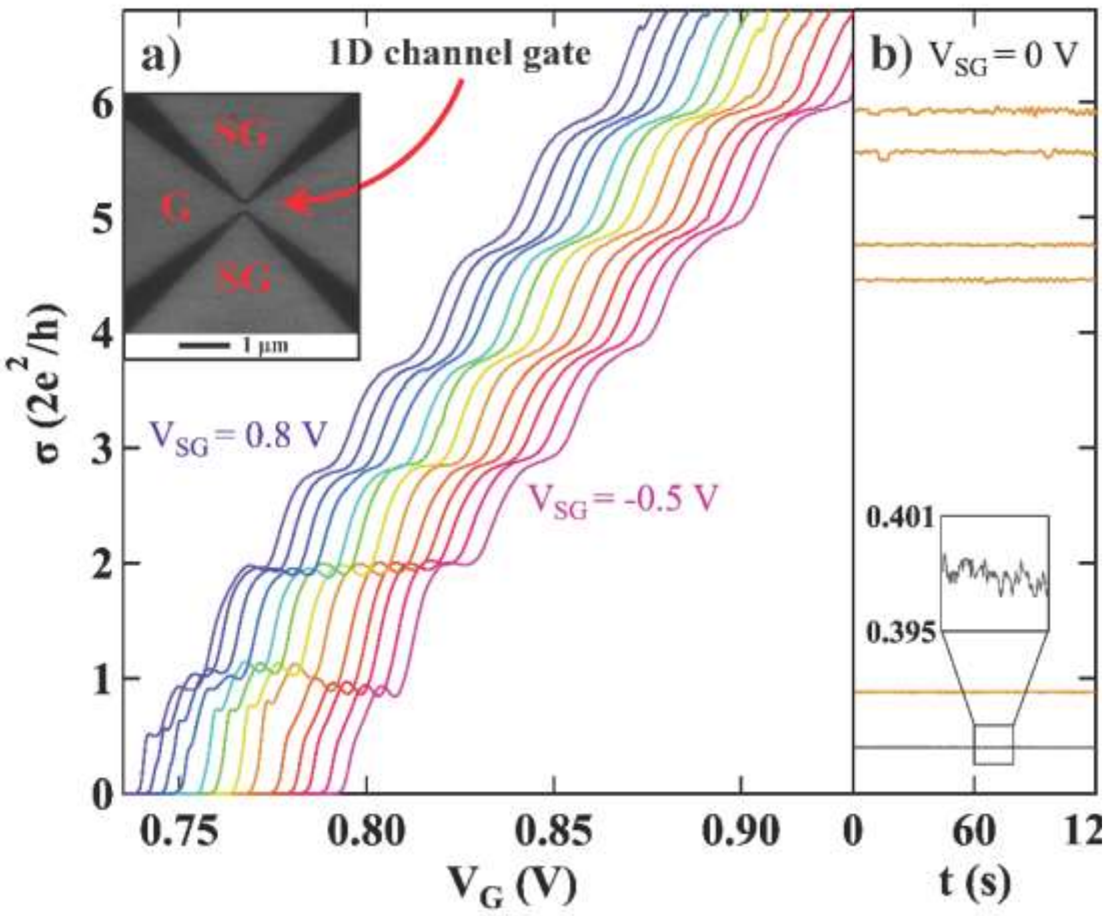
Before anneal

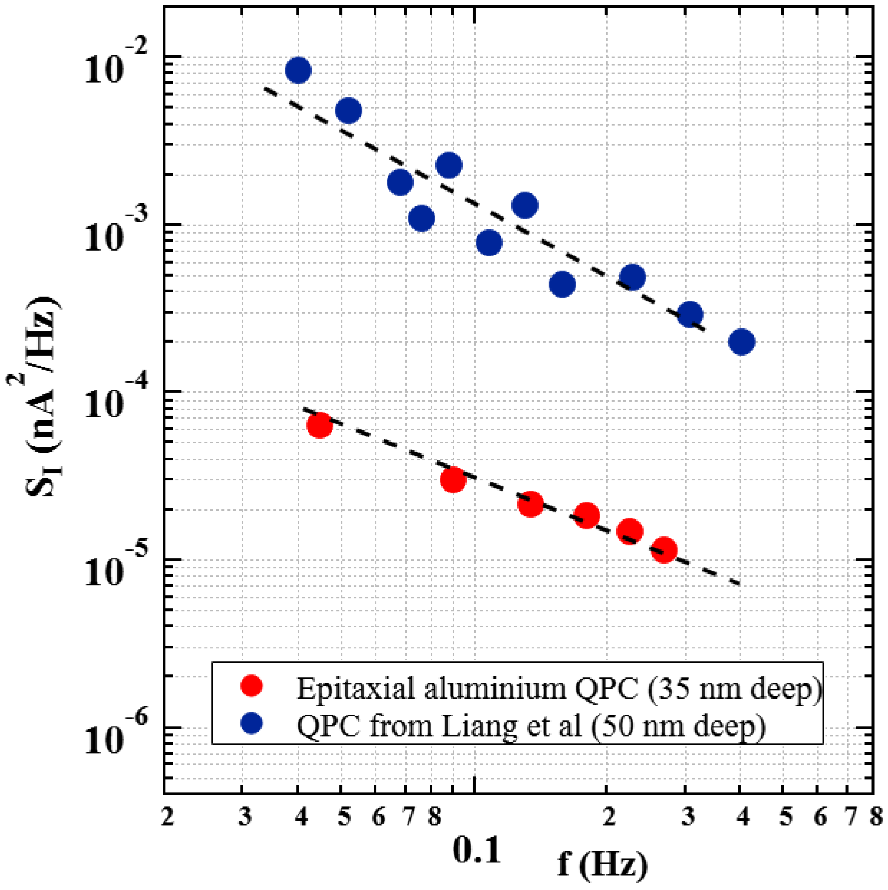
After anneal



Y. Ashlea Alava, D.Q. Wang, C. Chen, D.A. Ritchie, A. Ludwig, J. Ritzmann,
A.D. Wieck, O. Klochan, and A.R. Hamilton,
Ultra-shallow all-epitaxial aluminium gate GaAs/AlGaAs transistors with high electron mobility, Advanced Functional Materials (2021)

Ultra low noise quantum point contacts





- Etch Aluminium to define quantum point contact => Clear conductance steps
- Hold gate V_G on steep “risers” & monitor I(t) => See 1/f noise
- **Noise 20x lower than non-epitaxial gates**

Y. Ashlea Alava, D. Q. Wang, C. Chen, D. A. Ritchie, O. Klochan, and A. R. Hamilton, *High electron mobility and low noise quantum point contacts in an ultra-shallow all-epitaxial metal gate GaAs/Al$_x$Ga$_{1-x}$As heterostructure*, Appl. Phys. Lett. 119, 063105 (2021).