Clean ballistic quantum point contact in $SrTiO_3$

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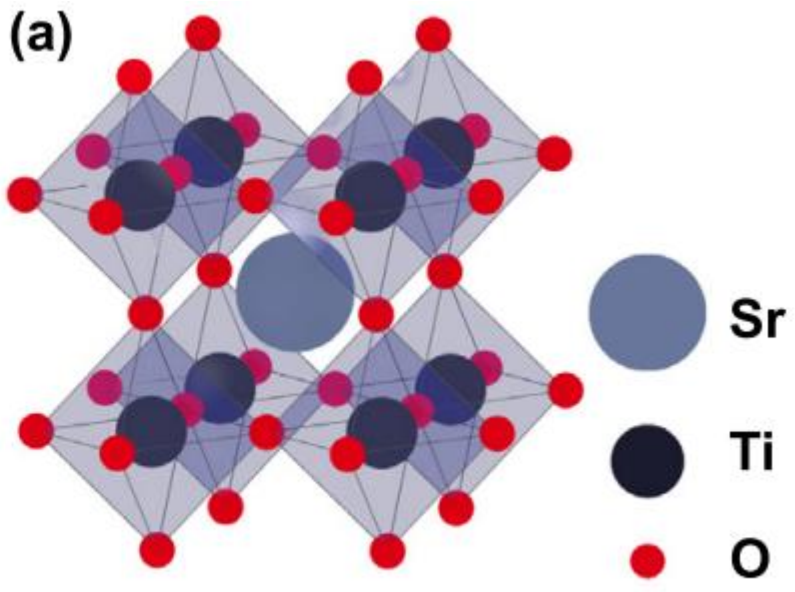
Outline

- Why you should care about $SrTiO_3$
- Device design
- Data, results
- Conclusion/discussion

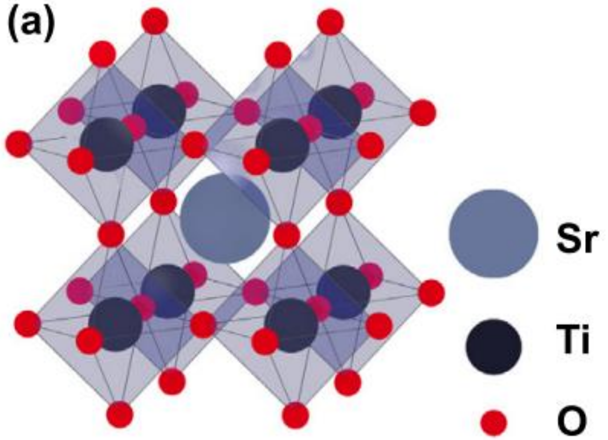
Strontium Titanate

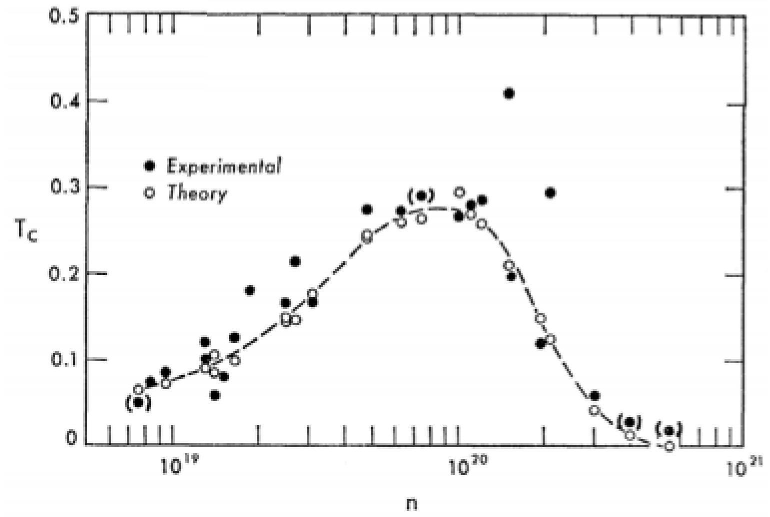


- Centrosymmetric (has inversion center)
- no DSOI
- piezoelectric effect (all centrosymmetric materials)
- Paraelectric
- Indirect band gap 3.25 eV
- Direct band gap 3.75 eV
- $\varepsilon_r \sim 300$ at room temp.
- Insulator-to-metal transition in $LaAlO_3/SrTiO_3$ interfaces

Pai et al., Rep. Prog. Phys. **81** (2018)

Low Temp





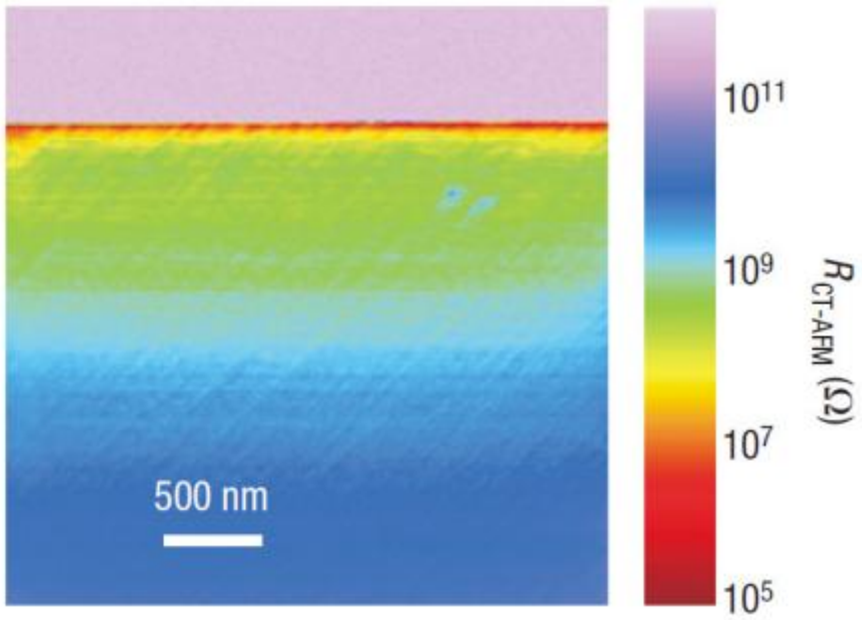
- Dielectric constant increases as temp drops
  → saturates around 4 K near ε_r = 10^5
- Density dependent superconductivity below 450 mK
- Approaches ferroelectric phase transition but remains paraelectric due to quantum fluctuations
- Jahn-Teller effect manifests at low temp
  → molecules distort geometrically to remove degenerate ground-state, thus lowering overall energy

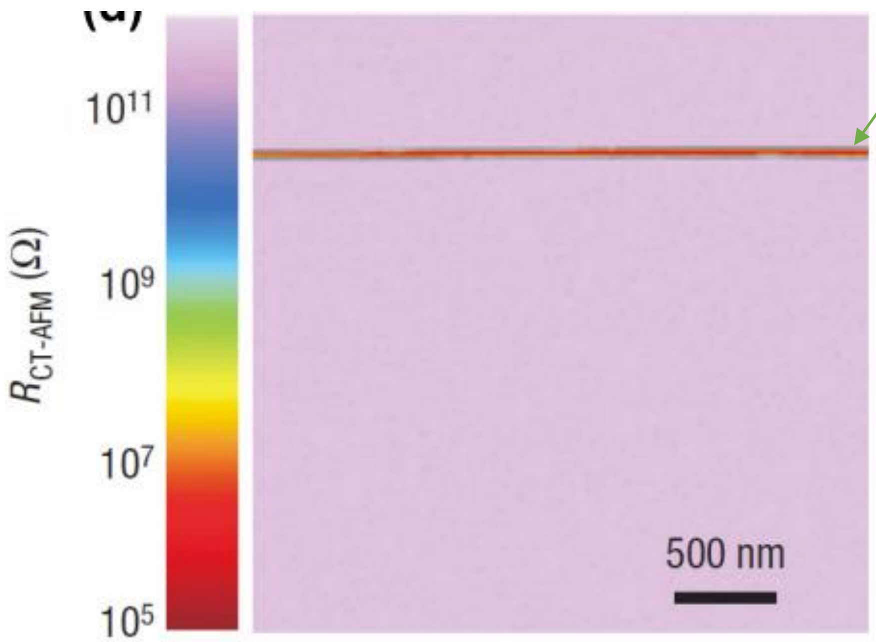
Pai et al., Rep. Prog. Phys. **81** (2018)

Will Anneal for 2DEGs

Take bulk, standard stock sample, anneal in high oxygen partial pressure
(here $LaAlO_3/SrTiO_3$)

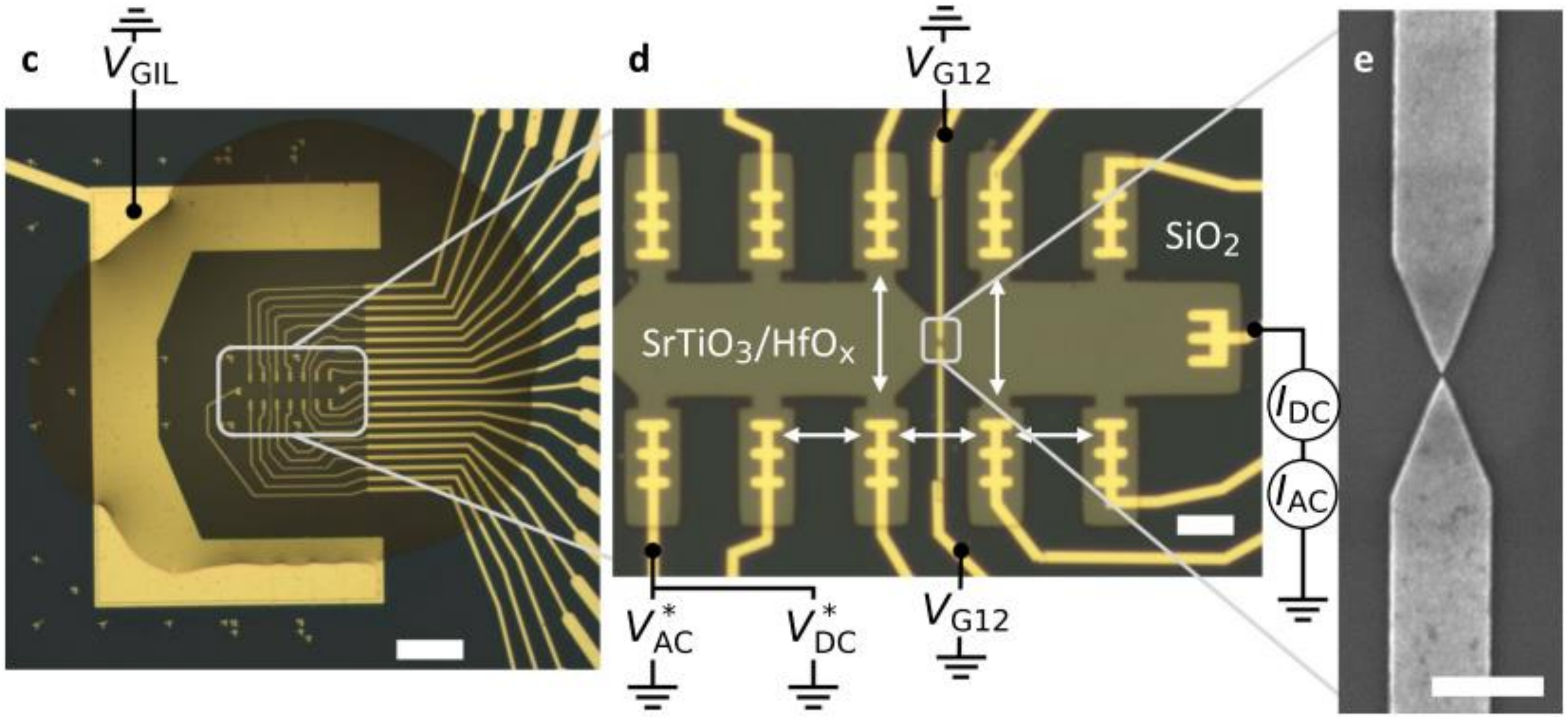
Confined
~ 7 nm

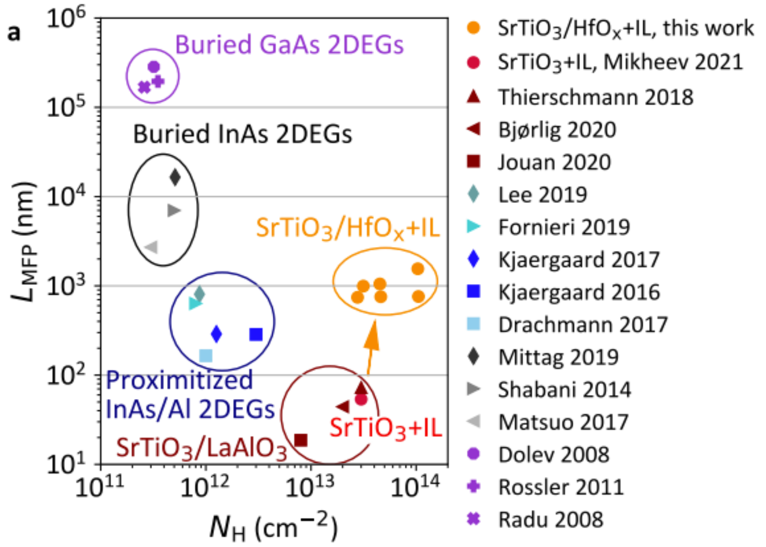




unannealed *(conductive-tip AFM probing electron profile)* annealed

Device

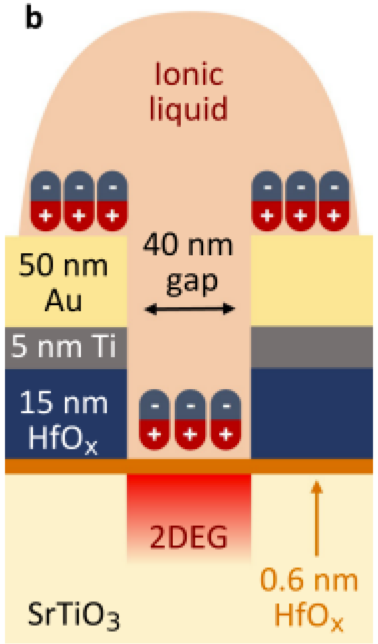




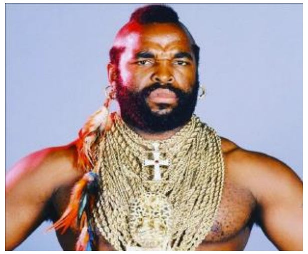
Scale bars:
c: 100 um | d: 10 um | e: 1 um

Fabrication

Fabricated on commercial (001) $SrTiO_3$ single crystal substrates



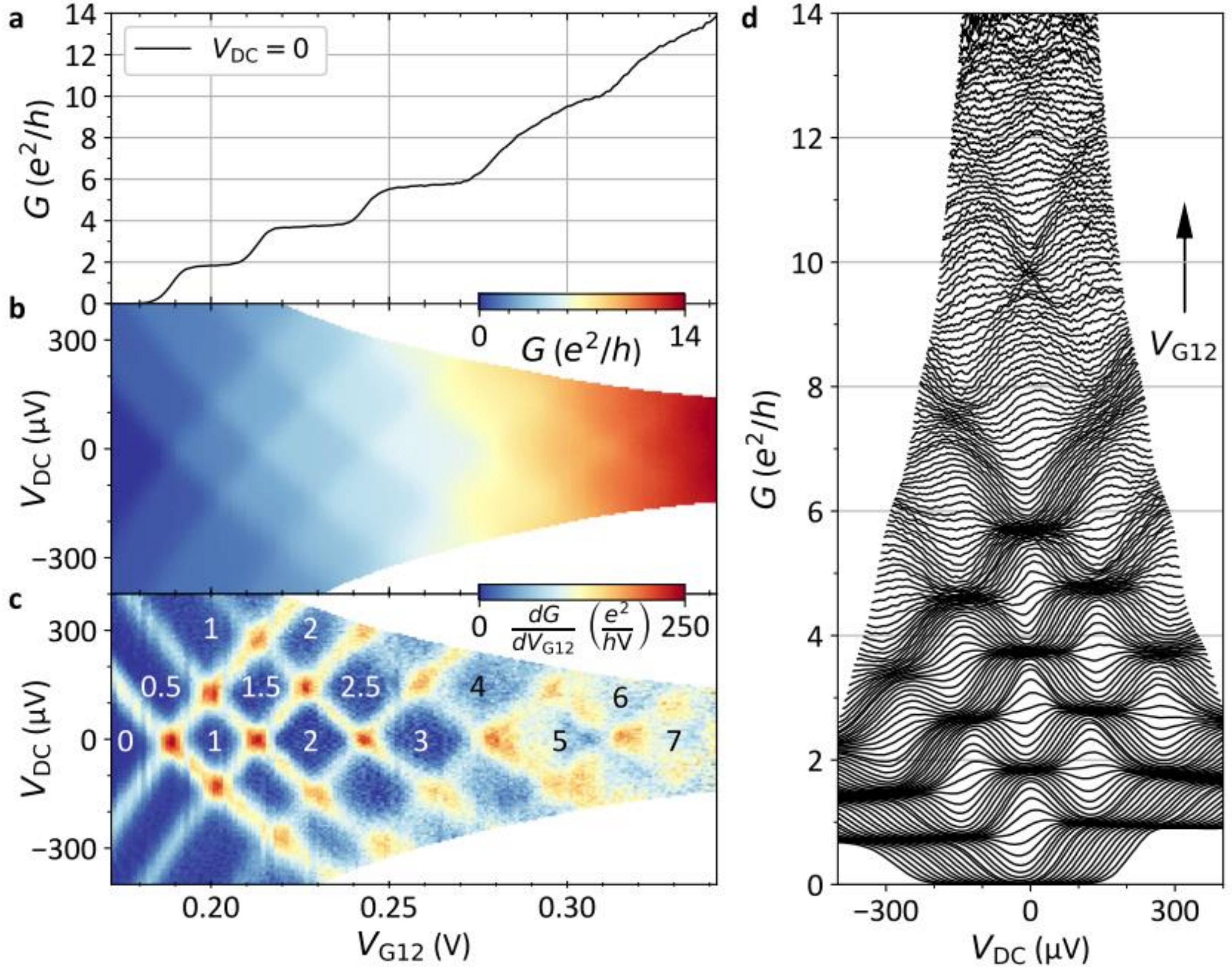
- Soak in DI water for 20 min, then annealed at 1000 C for 2 hours in Ar/O2
- HfOx (4 layers) deposited (85 C)
- (a) Selective patterning for HfOx (15 nm) and Ti/Au (5/50 nm) for QPC tip
- (b) Ebeam + Ti/Au (40/100) for remaining patterning
- (c) Ebeam, Ar milling, Ti/Au (10/80)
- (d) Ebeam + sputtering of 80 nm SiO2
- (e) ionic liquid (IL) drop (DEME-TFSI)
- Use IL to tune density before cooling below its freezing point (200 C) and doing measurements



??

Textbook* quantized conduction

4pt measurements, no series resistance subtracted

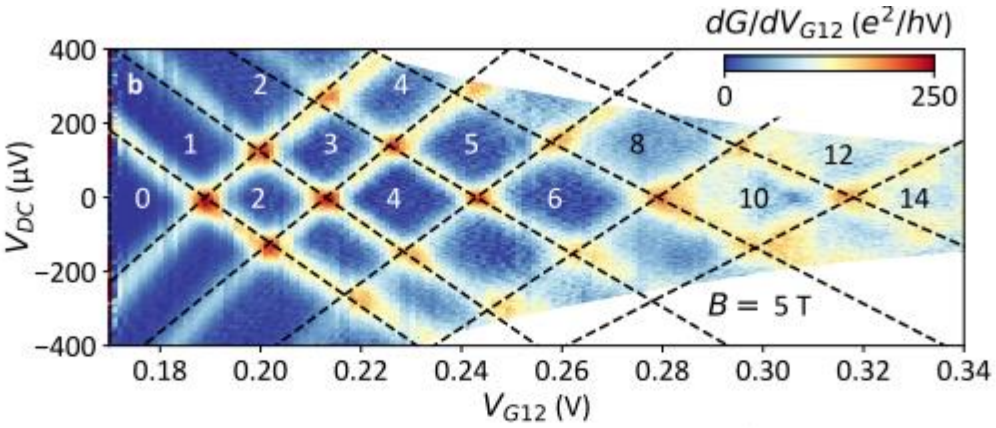


32 mK ***B = 5 T (!!)**

- Doubly degenerate subbands
- Some plateaus skipped

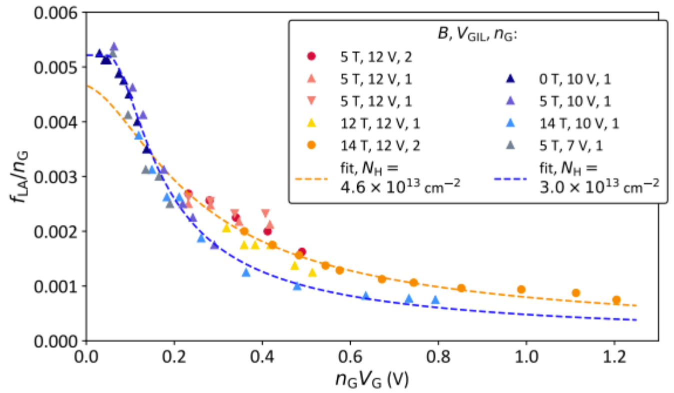
Lever Arm Non-Uniformity

$f_{\mathrm{LA}} = dV_{\mathrm{DC}}/2dV_{\mathrm{G}}$ at dG/dV_{G} peaks

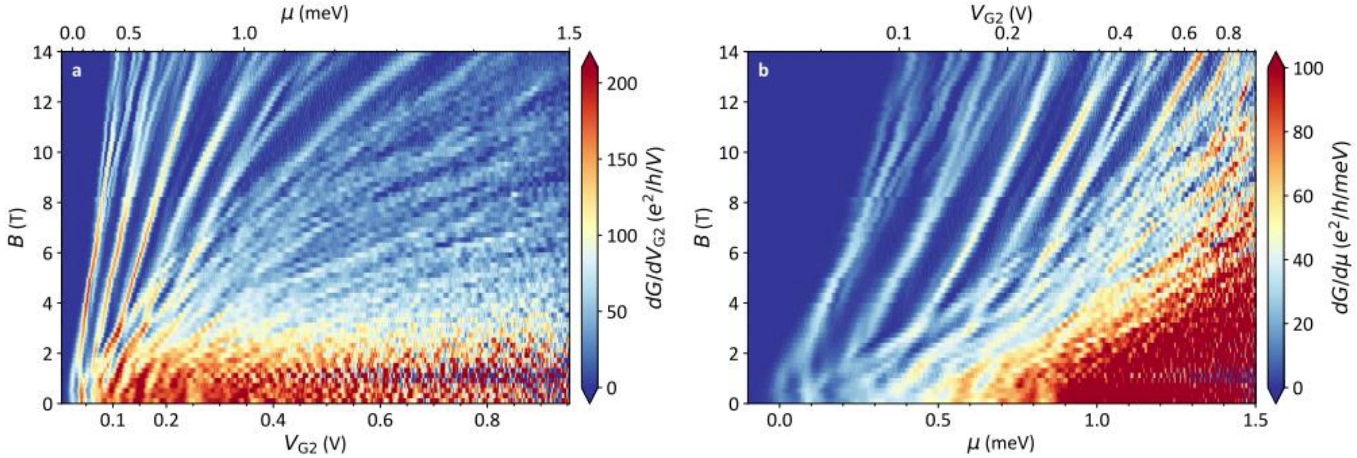


$$f_{\mathrm{LA}}(V_{\mathrm{G}}) = \frac{f_{\mathrm{LA}}(0) \cdot V_{\mathrm{NL}}}{\sqrt{V_{\mathrm{NL}}^2 + (V_{\mathrm{G}} - V_{\mathrm{G0}})^2}}.$$

Sharpness

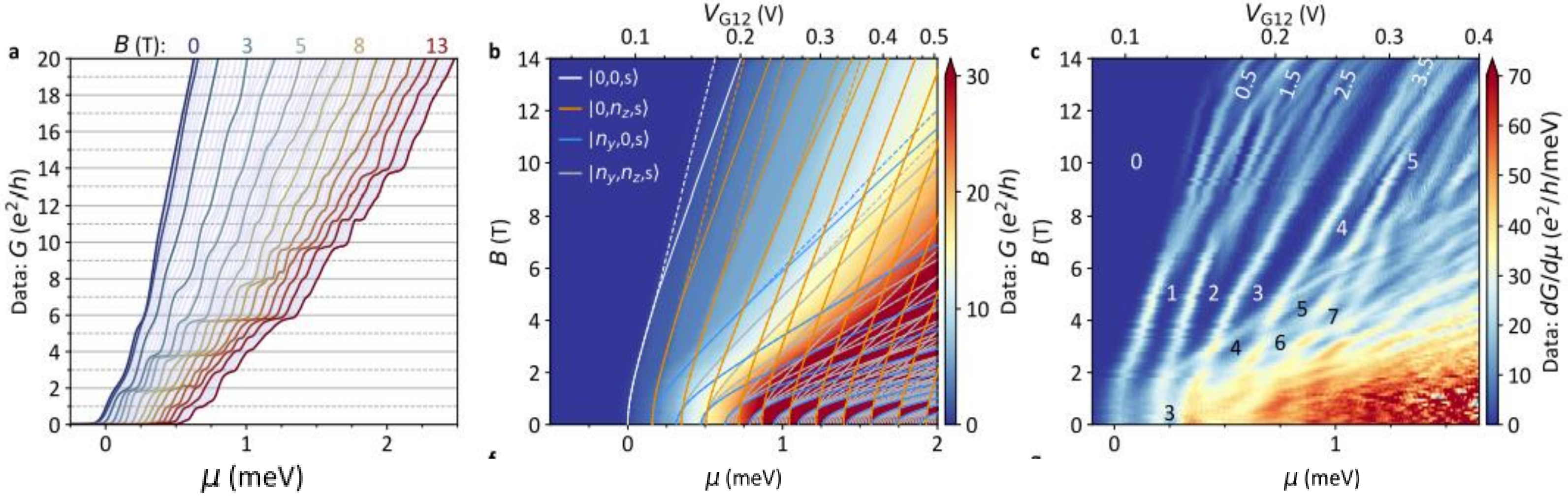


$$\mu(V_{\mathrm{G}}) = \int_{V_{\mathrm{G0}}}^{V_{\mathrm{G}}} f_{\mathrm{LA}}(V_{\mathrm{G}}) \cdot (V_{\mathrm{G}} - V_{\mathrm{G0}}) dV_{\mathrm{G}} = f_{\mathrm{LA}}(0) \cdot V_{\mathrm{NL}} \arctan\left(\frac{V_{\mathrm{G}} - V_{\mathrm{G0}}}{\sqrt{V_{\mathrm{NL}}^2 + (V_{\mathrm{G}} - V_{\mathrm{G0}})^2}}\right)$$



Subband Evolution

- 2-fold degeneracy persists til ~ 7 T
- Fast and slow moving subbands
  - Cross resulting in intermittent 4-fold degeneracies



3D QPC Saddle Potential

- Extend classic 2D model to 3D
- Quadratic in x, y, z with polarity $P_x = -1, P_{y,z} = 1$

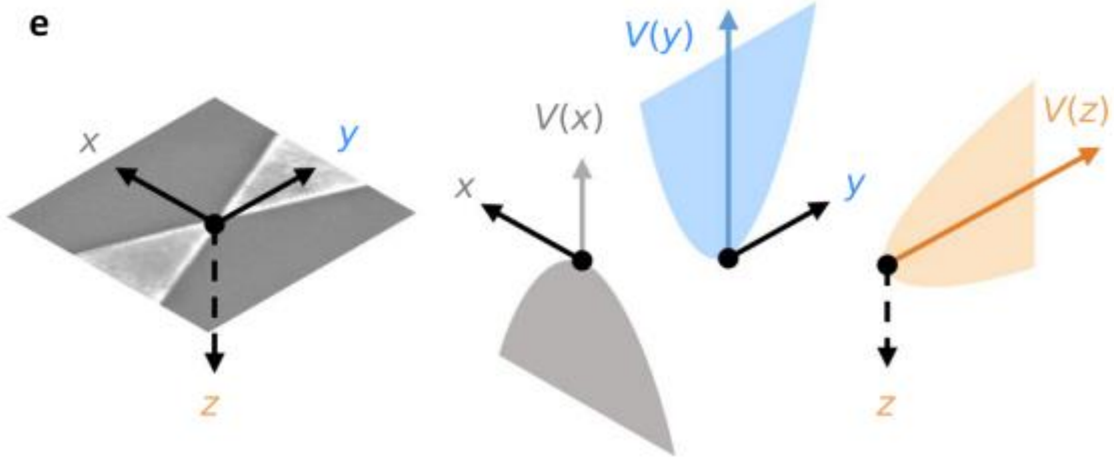
$$\mathcal{H} = \sum_{u=x,y,z} \left(-\frac{\hbar^2}{2m_u^*} \cdot \frac{\partial^2}{\partial u^2} + P_u \frac{m_u^* \epsilon_u^2 u^2}{2\hbar^2} \right) + E_Z \sigma_z$$

- At B = 0, $\epsilon_u(B = 0) = \frac{\hbar^2}{(m_u^* l_u^2)}$
- At B $\neq 0$, cyclotron frequency renormalizes x-y plane confinement:

  $\epsilon_x = \hbar\omega_x/\left(1 + \omega_c^2/\omega_y^2\right)^{1/2}, \epsilon_y = \hbar\left(\omega_y^2 + \omega_c^2\right)^{1/2},$

  ϵ_z unaffected

- Can separate Hamiltonian to y-z subbands discretized as $|n_y, n_z, s\rangle$ + x component which broadens them



Results

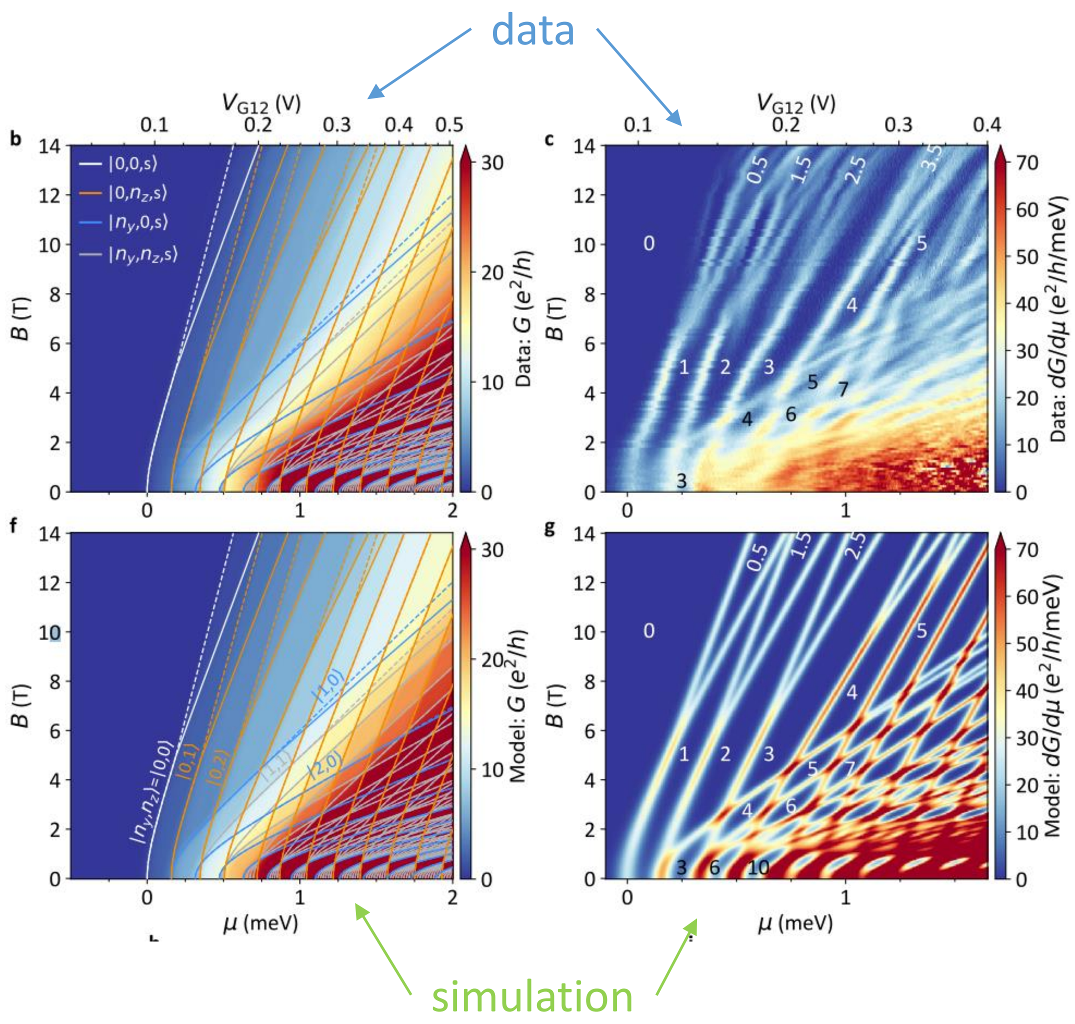
- Integers $n_{x,y} \geq 0$ and $s = \pm 1/2$ yield subband spectrum:

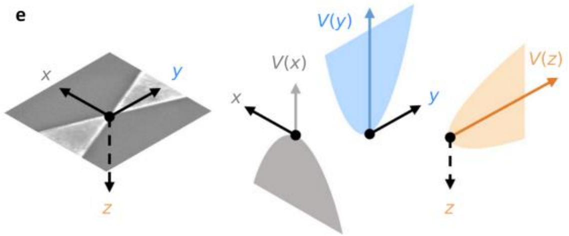
$$\epsilon_{yz} = \epsilon_y \left(n_y + \frac{1}{2} \right) + \epsilon_z \left(n_z + \frac{1}{2} \right) + E_Z(B, s)$$

- Empirically modify
  $E_Z(B,s) = g\mu_B s(B - B_P)$ when $B \geq B_P$,
  $E_Z(B,s) = 0$ when $B < B_P$

- Slow moving subbands have $|n_y = 0, n_z, s = \pm 1/2\rangle$

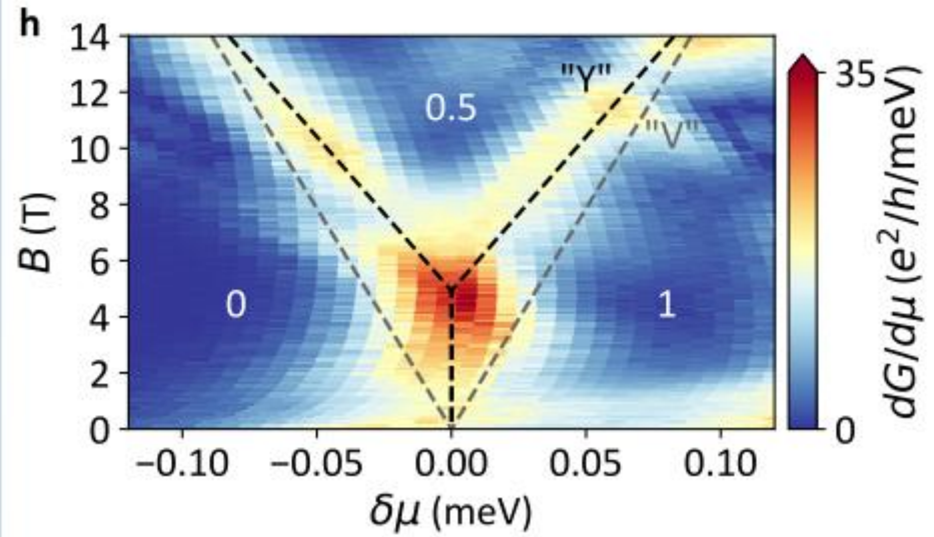
- Fast subbands have $n_y > 0$, due to renormalization of ϵ_y by cyclotron frequency

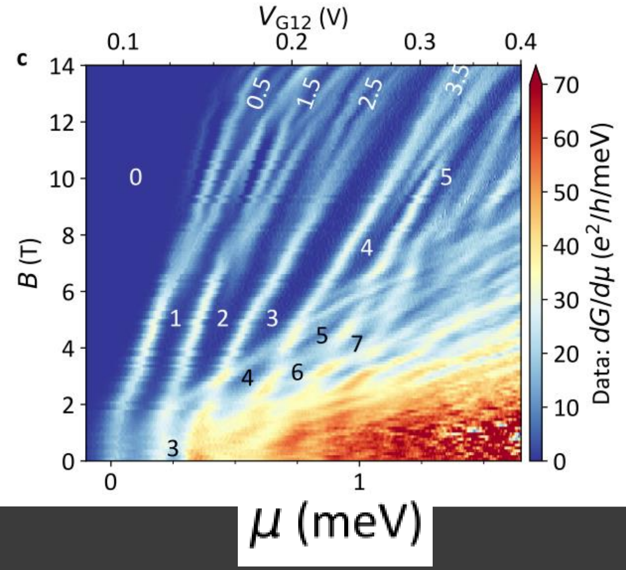


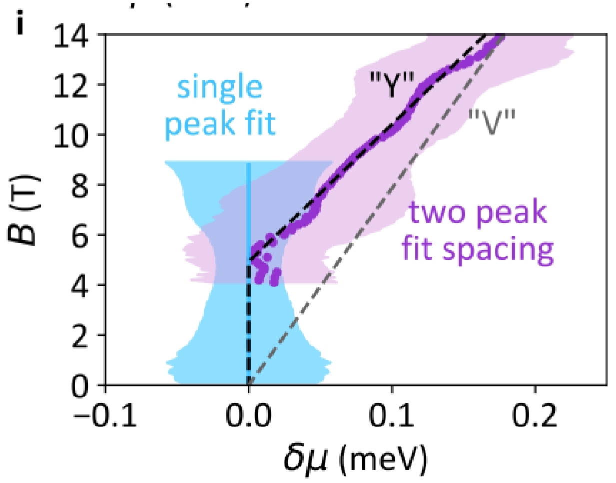


Unusual Spin-Splitting

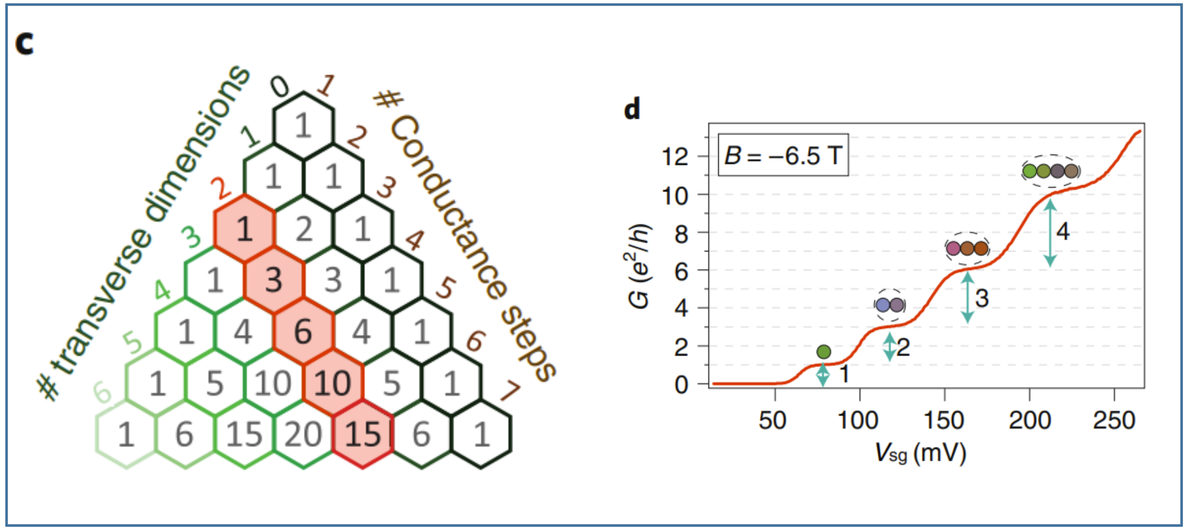
- Modified E_Z results in subband splitting into ‘Y’ shape
  - → Y: $B_P = 4.9$ T, $g = 0.32$
  - → V: $B_P = 0$ T, $g = 0.22$
- Appears to not be due to subband broadening
- Possible explanation: attractive “negative-U” interaction between e^-
  - Then: B_P is field when pairing interaction (singlets) balances with E_Z (alignment of spins)
  - Critical field/temp higher than plausible global SC state in 2DEG
  - Pre-formed pairs condensing at low T?
  - Pairing locally enhanced at ferroelastic domain walls?
  - Valence-skipping defects?

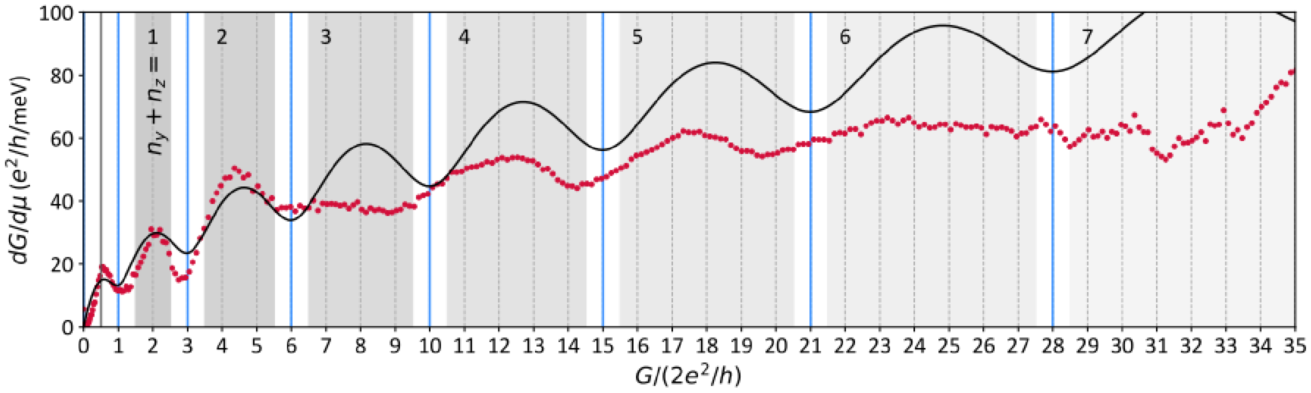




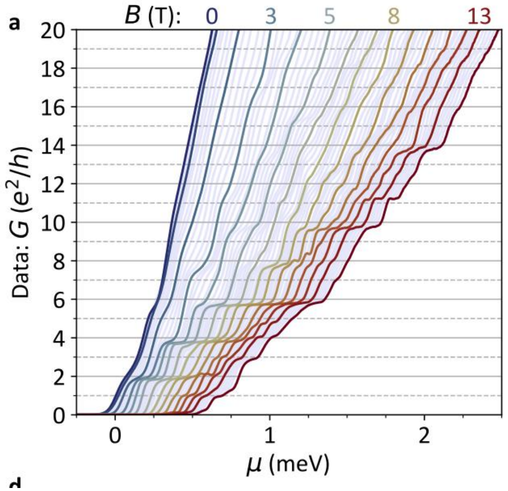


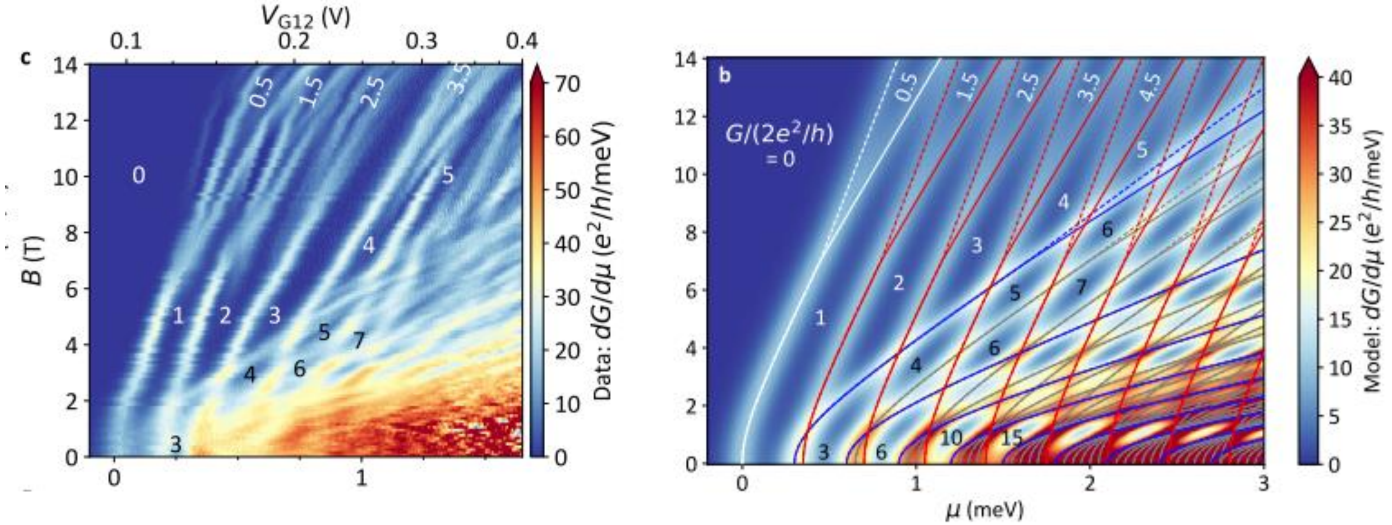
Pascal Conductance with $2e^2/h$ Steps?





$$\epsilon_{yz} = \epsilon_y \left(n_y + \frac{1}{2}\right) + \epsilon_z \left(n_z + \frac{1}{2}\right) + E_Z(B, s)$$





Briggeman, et al., Science **367**, (2020)

That’s It

- Interesting material and device architecture
- Unconventional quantized conductance
- Strange attractive e-e effects without global superconductivity

Thanks for listening!!