Quantum Coherence Lab
Zumbühl Group

Interferometry and coherent single-electron transport through hybrid superconductor-semiconductor Coulomb islands

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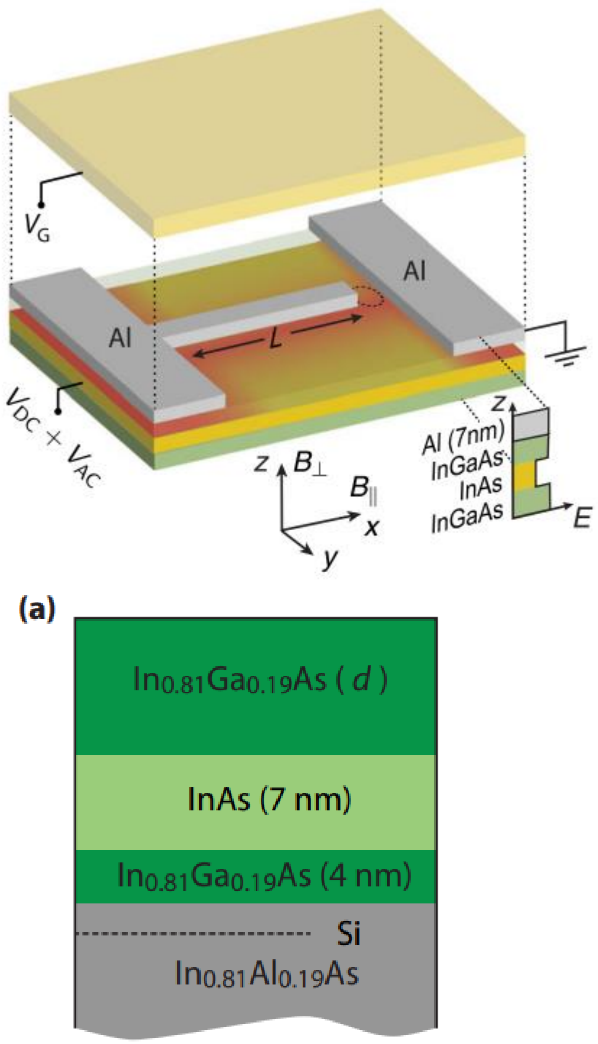
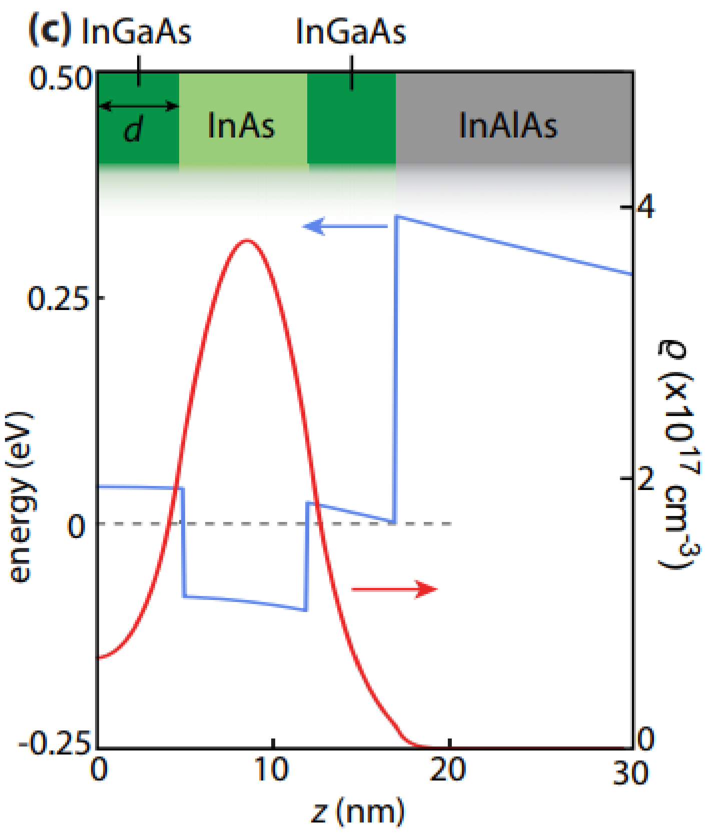
Outline

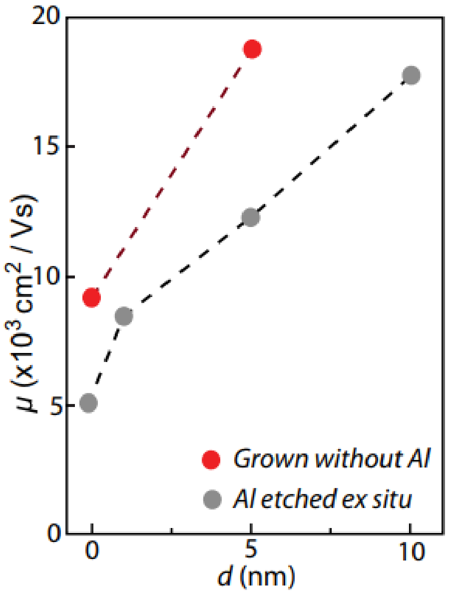
- The System
- The Physics and the Data… Maybe Majoranas
- Conclusion and Outlook

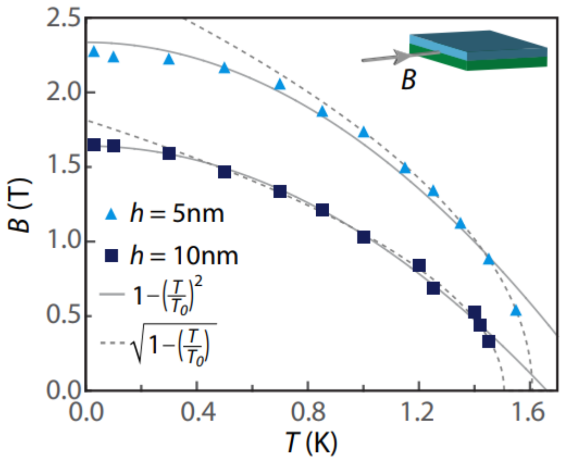
Background





Calculated charge distribution for d = 5 nm

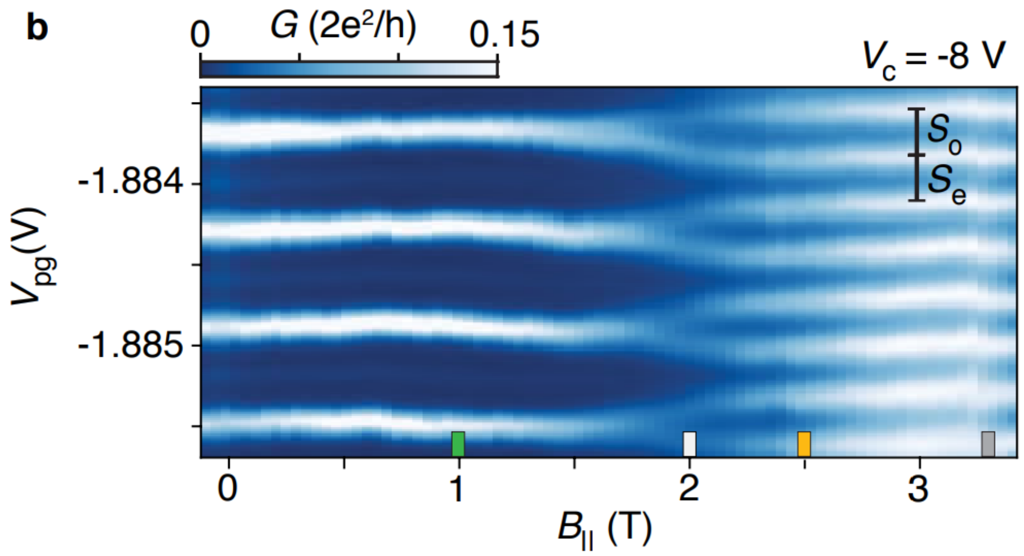




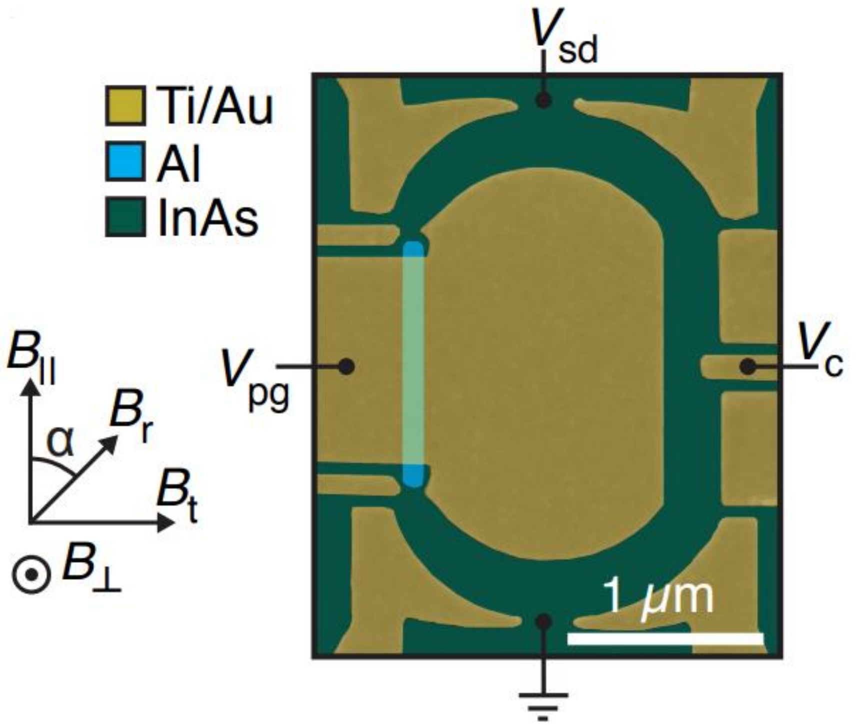
H.J. Suominen et al., PRL **119,** 176805 (2017)
J. Shabani et al., PRB **93,** 155402 (2016)

System

- V_{PG} defines the Coulomb island and the interferometer center, as well as controlling the electron occupancy (tunes the chemical potential)
- V_C controls the reference arm resistance, opening or closing the AB loop
- Vector magnet capable of out-of-plane field $B_\perp$ and in-plane field B_r, which can rotate about the angle α (tuning between fields parallel and transverse to the wire)



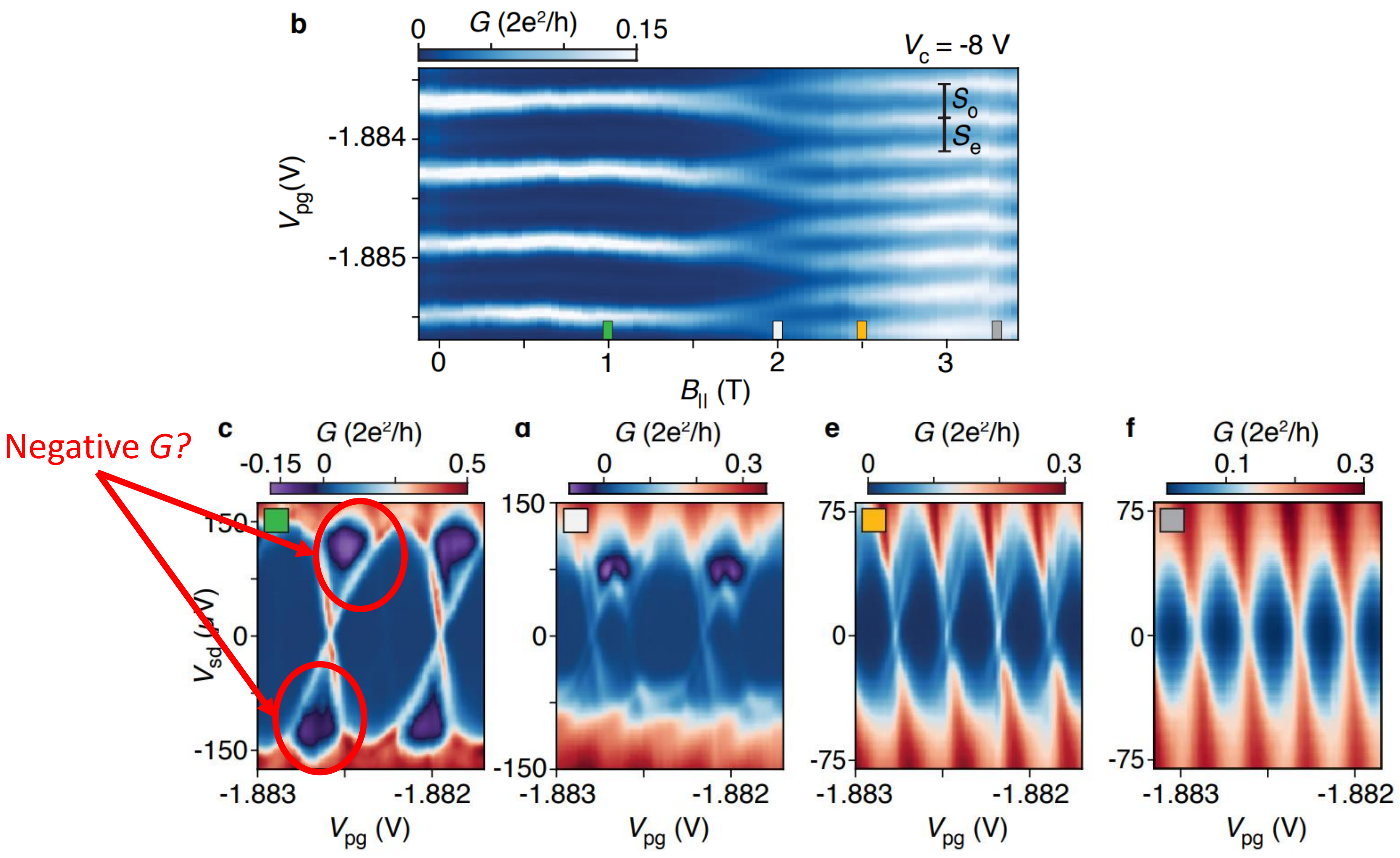
Zero bias differential conduction

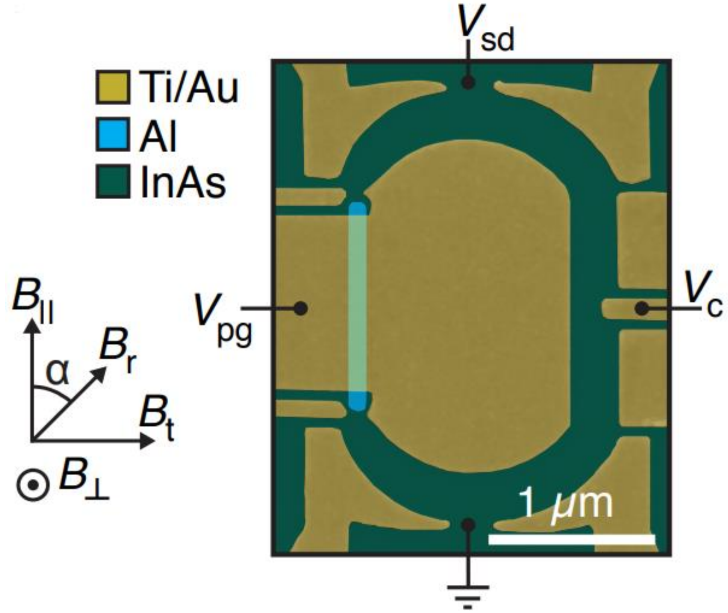


F. Nichele et al., arXiv:1902.07085 (2019)

Coulomb Island

(AB interferometer closed)





F. Nichele et al., arXiv:1902.07085 (2019)

Negative Differential Conduction

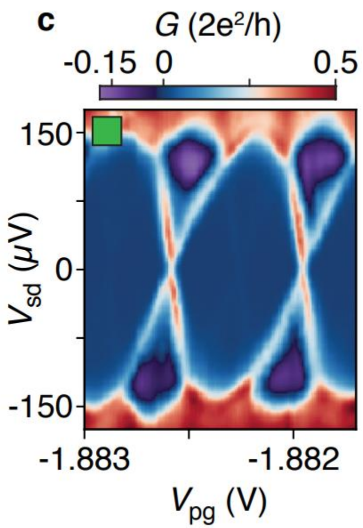
- At resonance in a superconducting island the current is proportional to the bias. This holds while e^- can only travel in pairs.

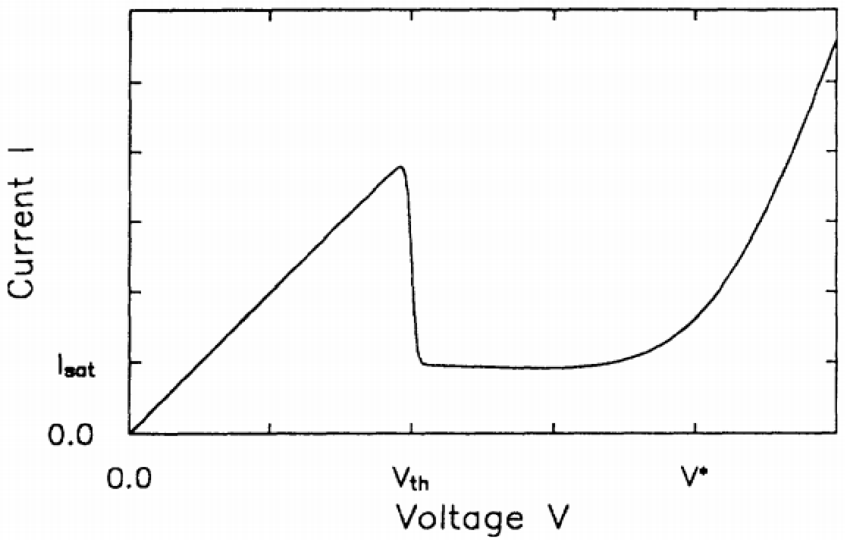
- At larger bias (above V_{th}) where quasiparticle tunneling is possible, there is an abrupt drop off in current.

- A single e^- can tunnel into the SC island, but the escape rate of the particle is different!

- ***Any*** e^- with $E > E_{th}$ in the normal lead can tunnel in, but ***only one*** unpaired e^- can tunnel out.

- The tunnel escape rate is determined by the tunnel width of a discrete energy level available to the “odd” e^-.



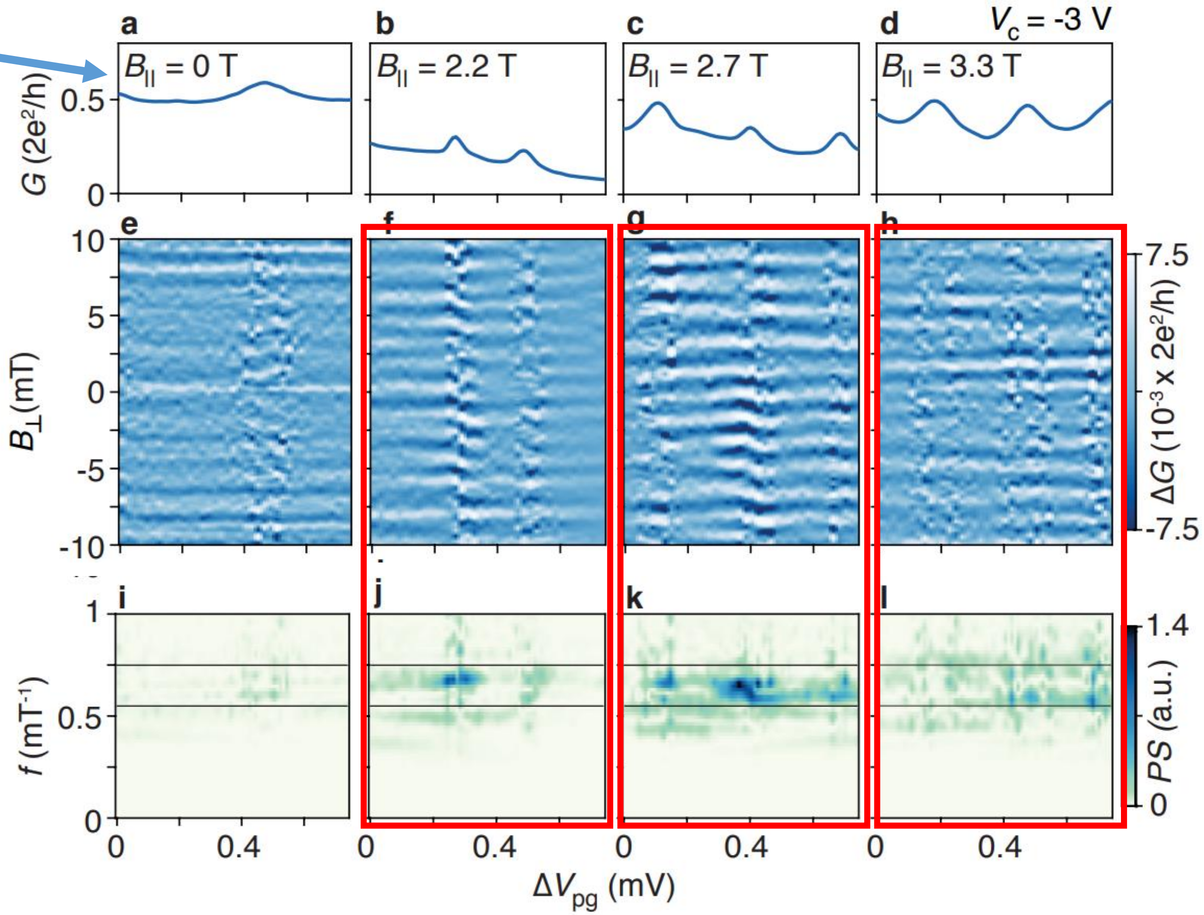


F. W. J. Hekking et al., PRL **70,** 4138 (1993)
F. Nichele et al., arXiv:1902.07085 (2019)

Reference Arm Connected

- e-h show conductance with smooth background subtracted
- At $B_{\parallel} = 2.2\ T$ (with even-odd spacing) have moderate oscillation amp and period of $\triangle B_{\perp} = 1.5\ mT$, PS signal peaked $\sim f = 0.65\ mT^{-1}$, consistent with single flux quantum $^{h}/_{e}$ → consistent with coherent transport of single electron
- At higher $B_{\parallel} = 2.7\ T$ (single e spacing) gives maximal oscillation amp. Largest at CB peaks
- For $B_{\parallel} > 3\ T$ (SC driven normal), oscillations reduced comparable to at low parallel field

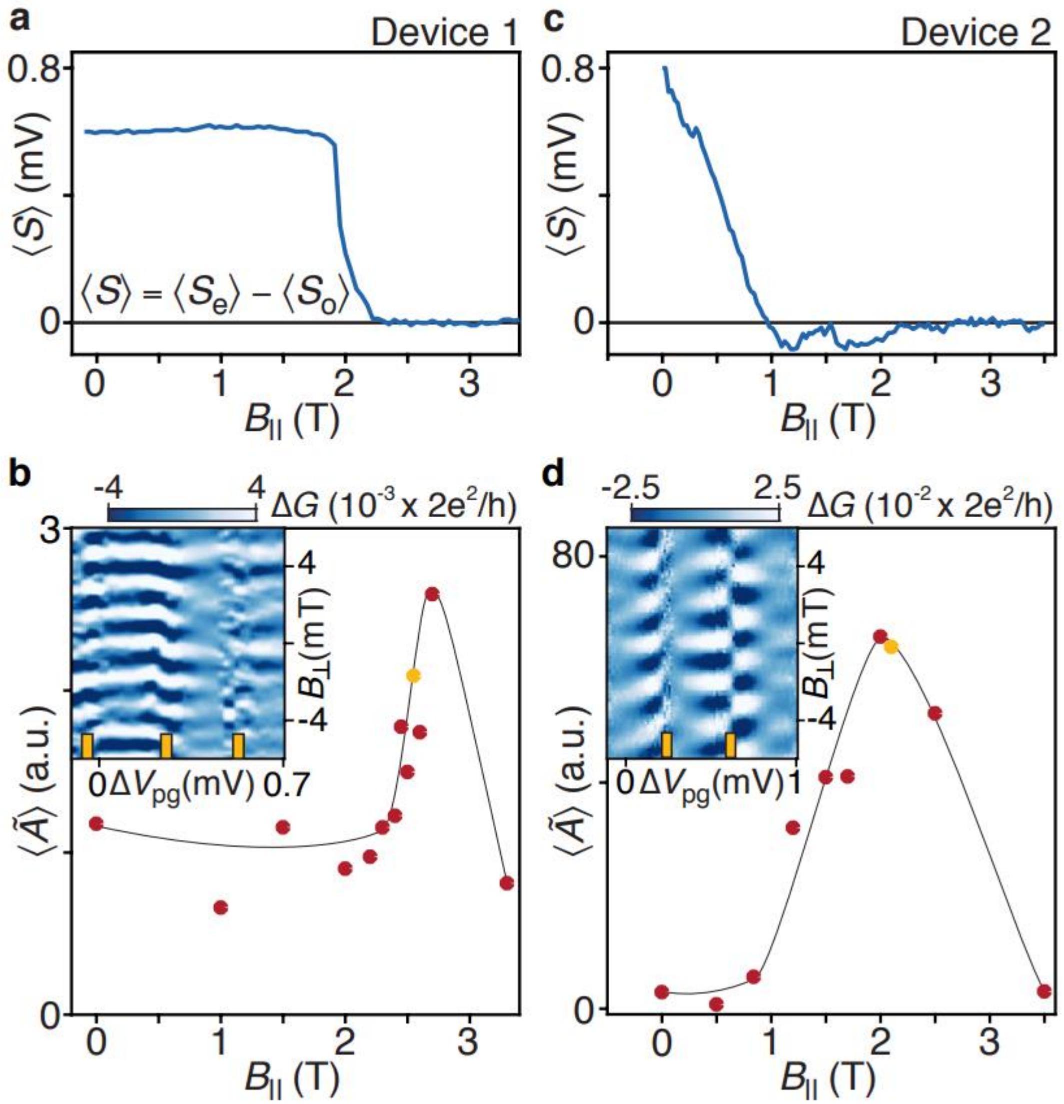
Zero bias conductance

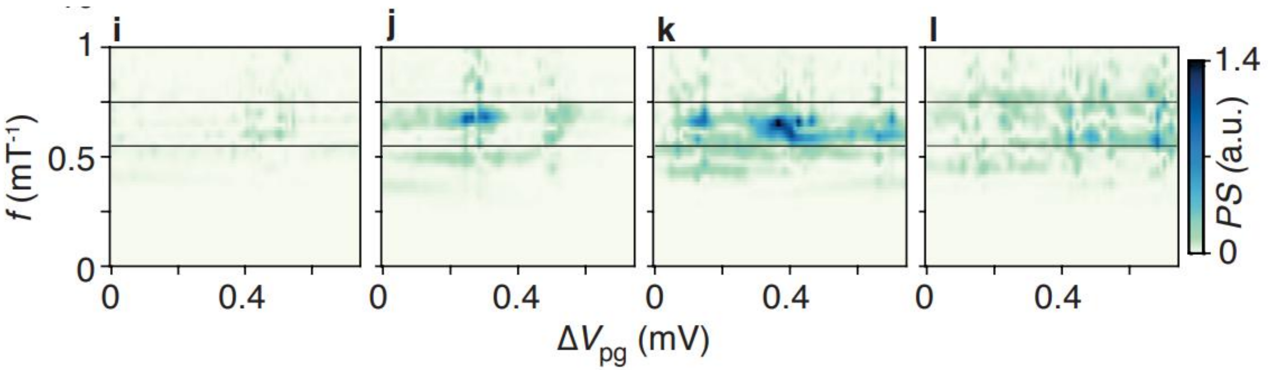


$\Delta V_{pg} = 0 \rightarrow V_{pg} = -1.896\ V$

Oscillation Amplitude (1)

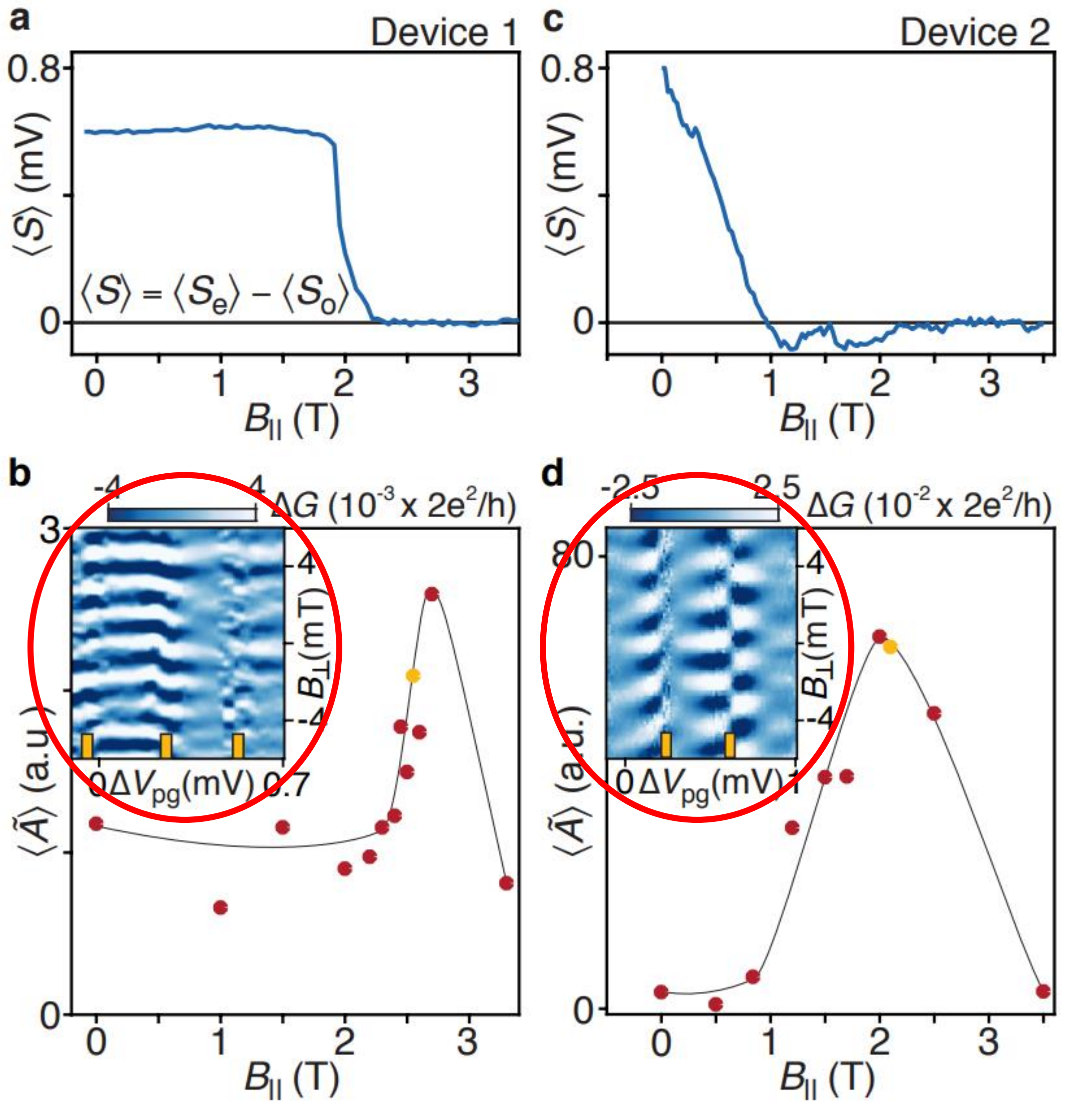
- Compare $B_{\parallel}$ dependence of AB oscillation amp to field dependence of lowest sub-gap state $E_0(B_{\parallel})$
- Sub-gap energy $\langle S \rangle = \langle S_e \rangle - \langle S_o \rangle$ found through taking difference between even and odd CB spacings, separately averaged
- Integrated power spectrum gives amplitude $\langle \tilde{A} \rangle$ of oscillations
- $\langle S \rangle$ constant ⬄ 2e transport until sub-gap state E_0 moves below E_c
    - No overshoot at 2.2 T expected for MZM in long wire





Oscillation Amplitude (2)

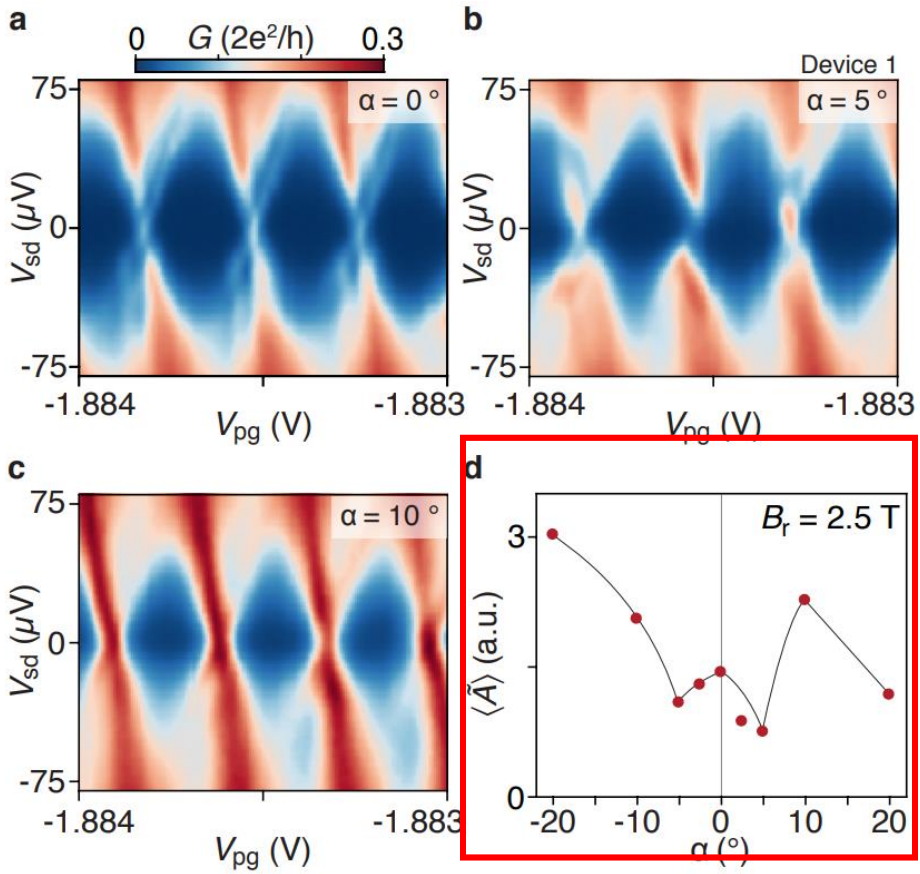
- Low fields: CB periodicity 2e → $\langle \tilde{A} \rangle$ small
- Higher fields ($B_{\parallel}$ > 2 T): $\langle S \rangle$ approaches zero → $\langle \tilde{A} \rangle$ has sharp increase coinciding with 2e to 1e transition
- $B_{\parallel}$ > 3 T: SC killed, $\langle \tilde{A} \rangle$ returns to low field regime (2e transport)
- Changing charge occupancy by 1e yields transmission phase shift of π in the 1e regime

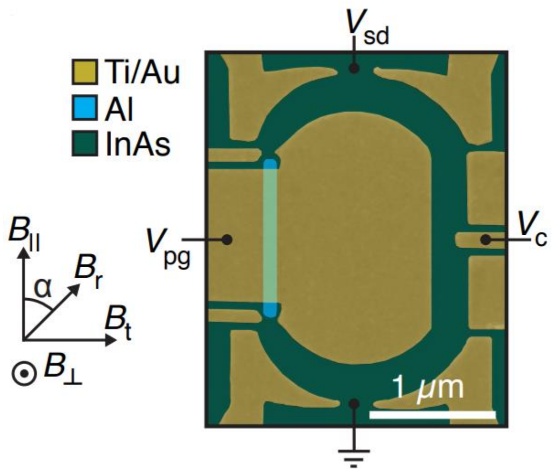


In-plane B-field Rotations

- At α = 0 discrete state at each charge degeneracy point
- At α = 5 discrete state lifted from zero energy
- At α = 10 no discrete ZBP
- Consistent with MZM, but observation of coherent transport in absence of ZBP suggests trivial quasiparticles are phase coherent across length of island

$B_{\parallel}$ = 2.5 T



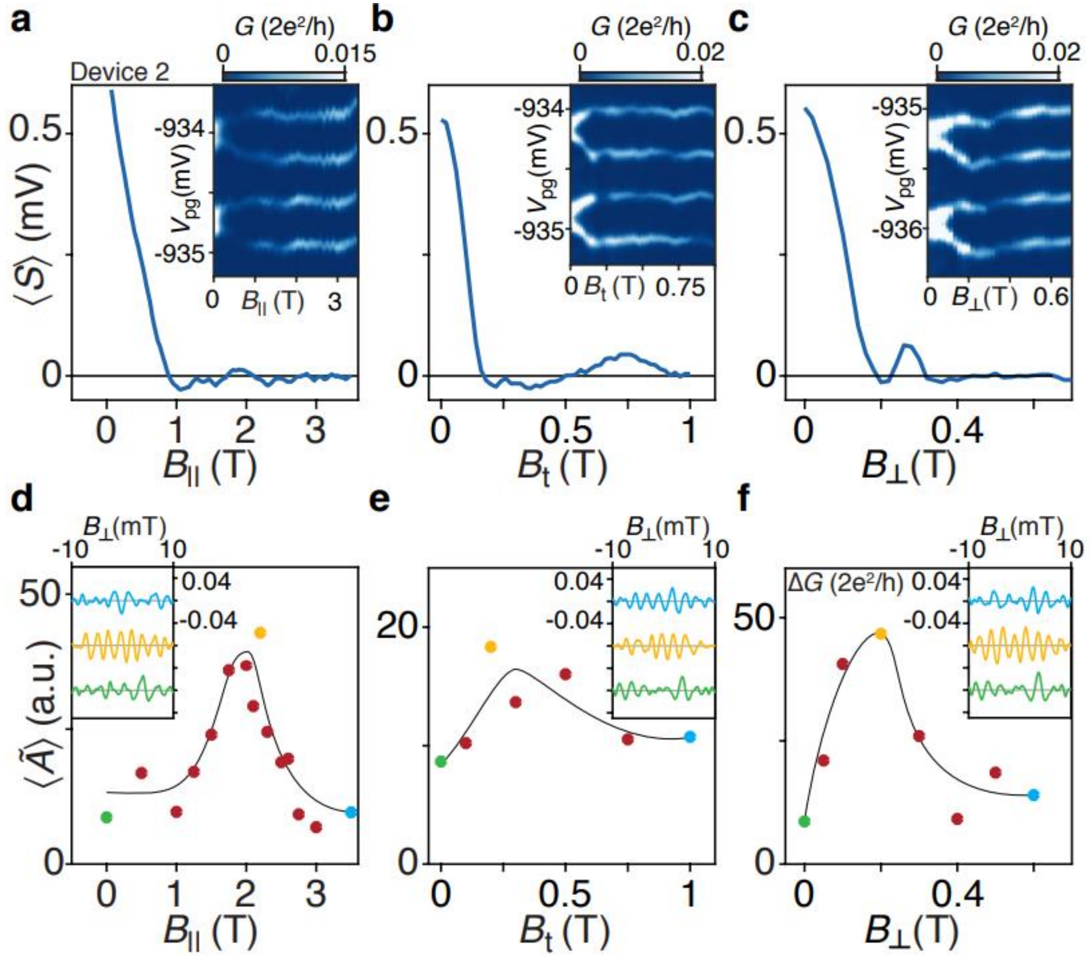


Oscillation Amplitude (3)

- Peak spacing $\langle S \rangle$ as function of field
- d-f show $\langle \tilde{A} \rangle$ for the three field directions
- Coherent transport observed for all directions
  - $\langle \tilde{A} \rangle$ increases as $\langle S \rangle$ approaches zero

    → Amplitude dictated by energy E_0 in all directions

    → Interference not unique to parallel B field



Correlating Osc. Amp. To E_0 (Summary)

- Low B field: Coulomb island favors even parity.
  - Transport occurs as two electrons sequentially tunneling on either end of the island
  - Electrons acquire condensate phase while forming a Cooper pair, suppressing single electron coherence

- Moderate field: Discrete sub-gap state brought below E_0
  - single electron transport channel opened
  - Coherent resonant tunneling through island possible

- High field: Island in normal state
  - Reduction of interference interpreted as reflection of short coherence length in the diffusive aluminum wire

- **Conclusion:** AB interference combined with stable discrete zero-energy states consistent with MZM predictions and *excludes* contribution of ABS localized at the ends of the wire

- To differentiate between trivial and topological states, stable 1e peak spacing and discrete zero-bias conduction peaks at successive charge degeneracy points must accompany AB interference!

Thanks for your attention!