Conductance through a helical state in an InSb nanowire

J. Kammhuber, M. C. Cassidy, F. Pei, M. P. Nowak, A. Vuik, D. Car, S.R. Plissard,
E. P. A. M. Bakkers, M. Wimmer and L. P. Kouwenhoven

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Why are Helical States interesting?

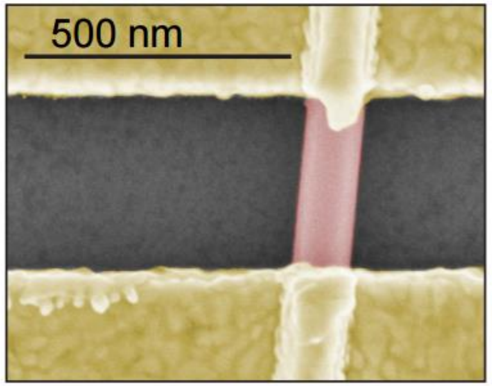
- Various applications
  - Spin filtering — *Physical review letters* 105.22 (2010): 226401.
  - Cooper pair splitter — *Physical review letters* 116.21 (2016): 217001.
  - Ingredient for topologically protected quantum computing — *Physical review letters* 105.7 (2010): 077001. *Physical review letters* 105.17 (2010): 177002.

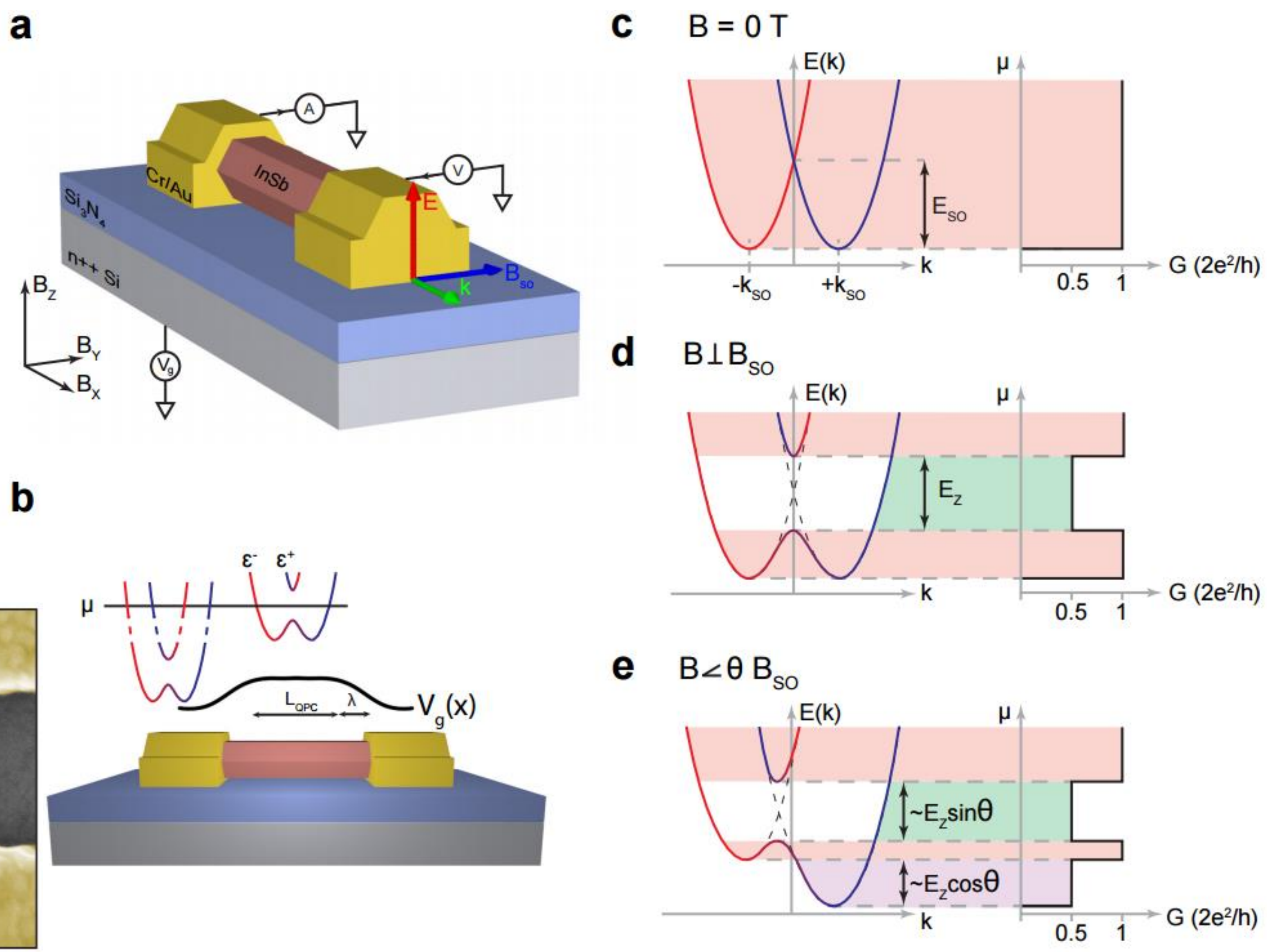
- Helical states emerge in
  - Edge modes of 2D quantum spin hall topological insulators — *Science* 318.5851 (2007): 766-770. *Nature materials* 12.9 (2013): 787-791.
  - Quantum wires created in GaAs cleaved edge overgrowth samples — *Nature Physics* 6.5 (2010): 336-339.

- Helical states are predicted in
  - Carbon nanotubes — *Physical review letters* 106.15 (2011): 156809.
  - Graphene nanoribbons — *Physical review X* 3.1 (2013): 011008.
  - RKKY systems — *Physical review letters* 111.18 (2013): 186805.
  - InAs and InSb nanowires — *Physical review letters* 105.17 (2010): 177002.

Helical Gap in a 1D Nanowire Device

- InSb nanowire (zincblende [111]) on 20 nm SiN dielectric
- Contacts define length of QPC $L_{QPC} \sim 245$ nm and the onset potential $\lambda \sim 80$ nm (influence described in Ref [1])
- Electric field generated by backgate and substrate induces Rashba type spin orbit interaction
  - Shift in k: $k_{SO} = m^{*}\alpha/\hbar^{2}$
  - Energy: $E_{SO} = \hbar^{2}k_{SO}^{2}/2m^{*}$
- Magnetic field B opens gap at $k = 0$
  - Helical gap: $E_Z = g\mu_B B$
- If B-field not perpendicular to B_{SO} -> shift in energy

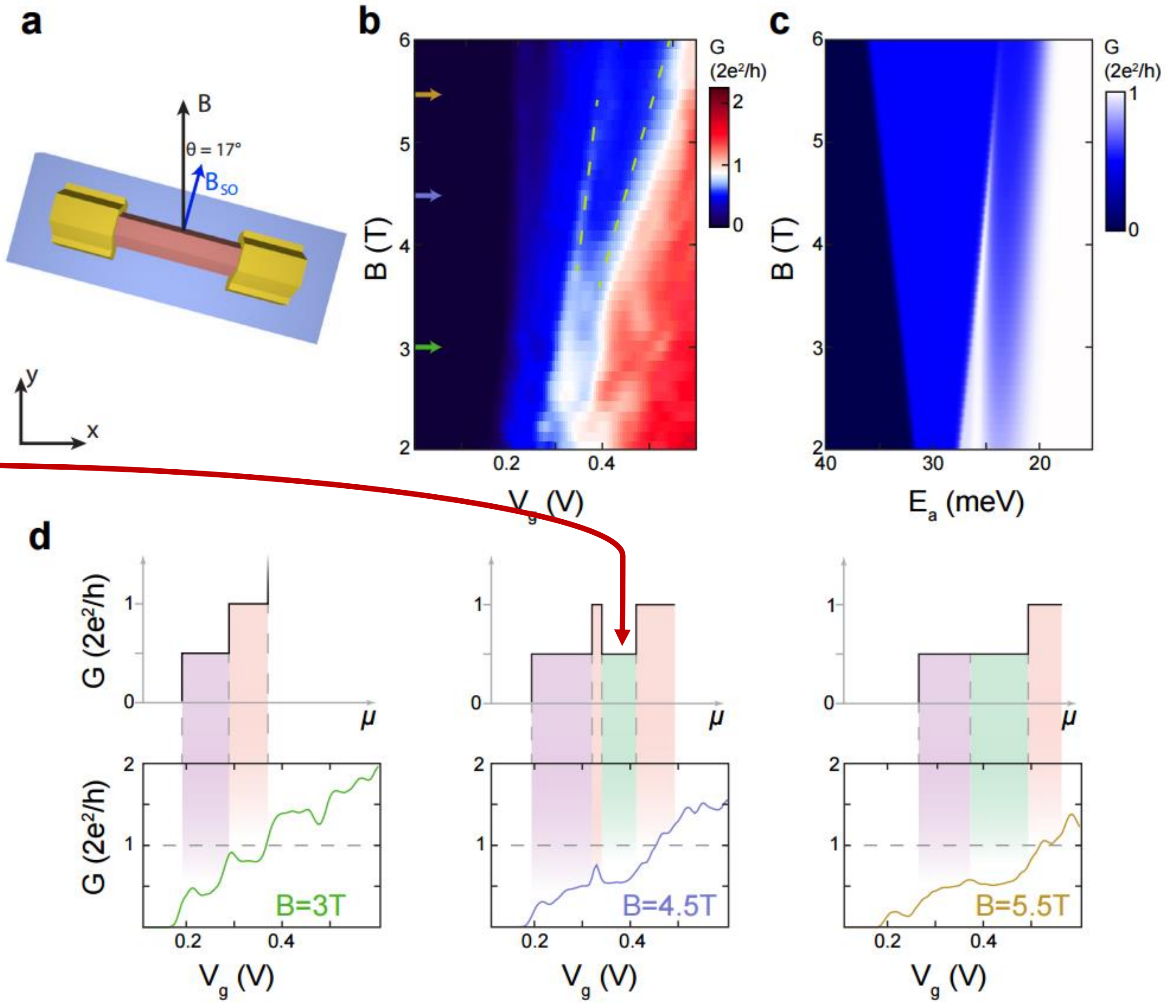




Magnetic Field Dependece of the Helical Gap

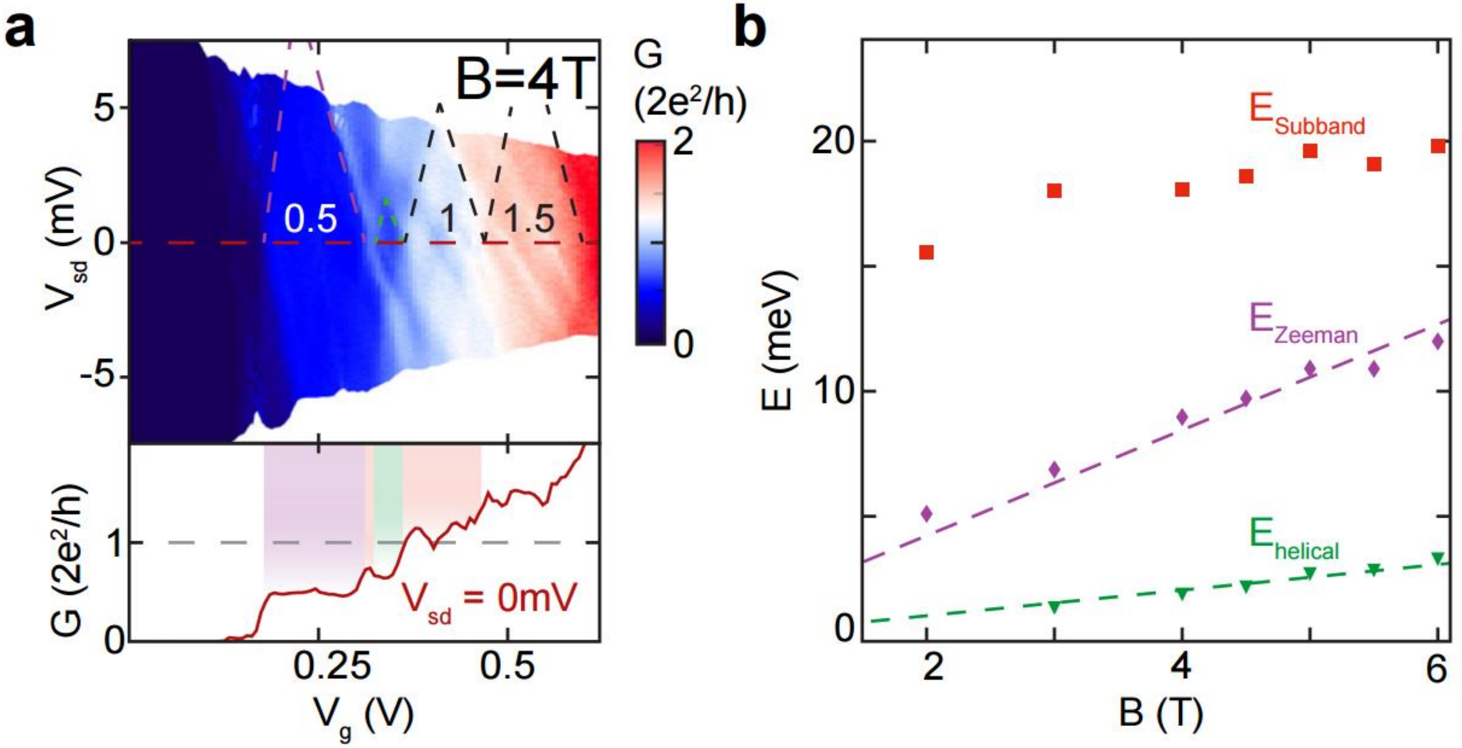
- B-Field not perpendicular, but at an angle $\theta = 17°$
  - Reasons are unknown
- Results in a different sequence of conductance at certain B-Field strengths
  - ➢ $0.5 \rightarrow 1 \rightarrow 0.5 \rightarrow 1\, G_0\ (2e^2/h)$
- B-Field dependence
  - $B < 3$ T: Steps in 0.5 G_0
  - 3 T $< B <$ 5.5 T: Drop in the 1 G_0 Plateau
  - 5.5 T $< B$: fully envelopped 1 G_0 Plateau
- Using the g-factor ($g = 38$): $E_{SO} = 5.5$ meV
  - In WAL measurements: $E_{SO} = 0.25 - 1$ meV
  - Quantum dot: $E_{SO} = 40$ μeV
  - Claim: WAL and quantum dot measurements do not probe the SOI with only one mode transmitting
  - Elephant in the room: more than one mode in the experiment

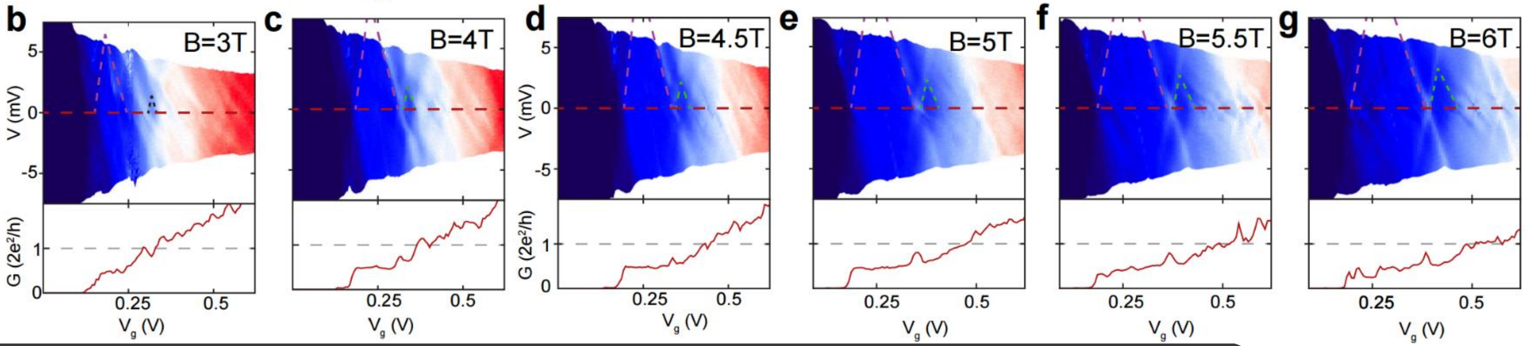
Reentrant conductance feature (RCF)



Voltage Bias Spectroscopy

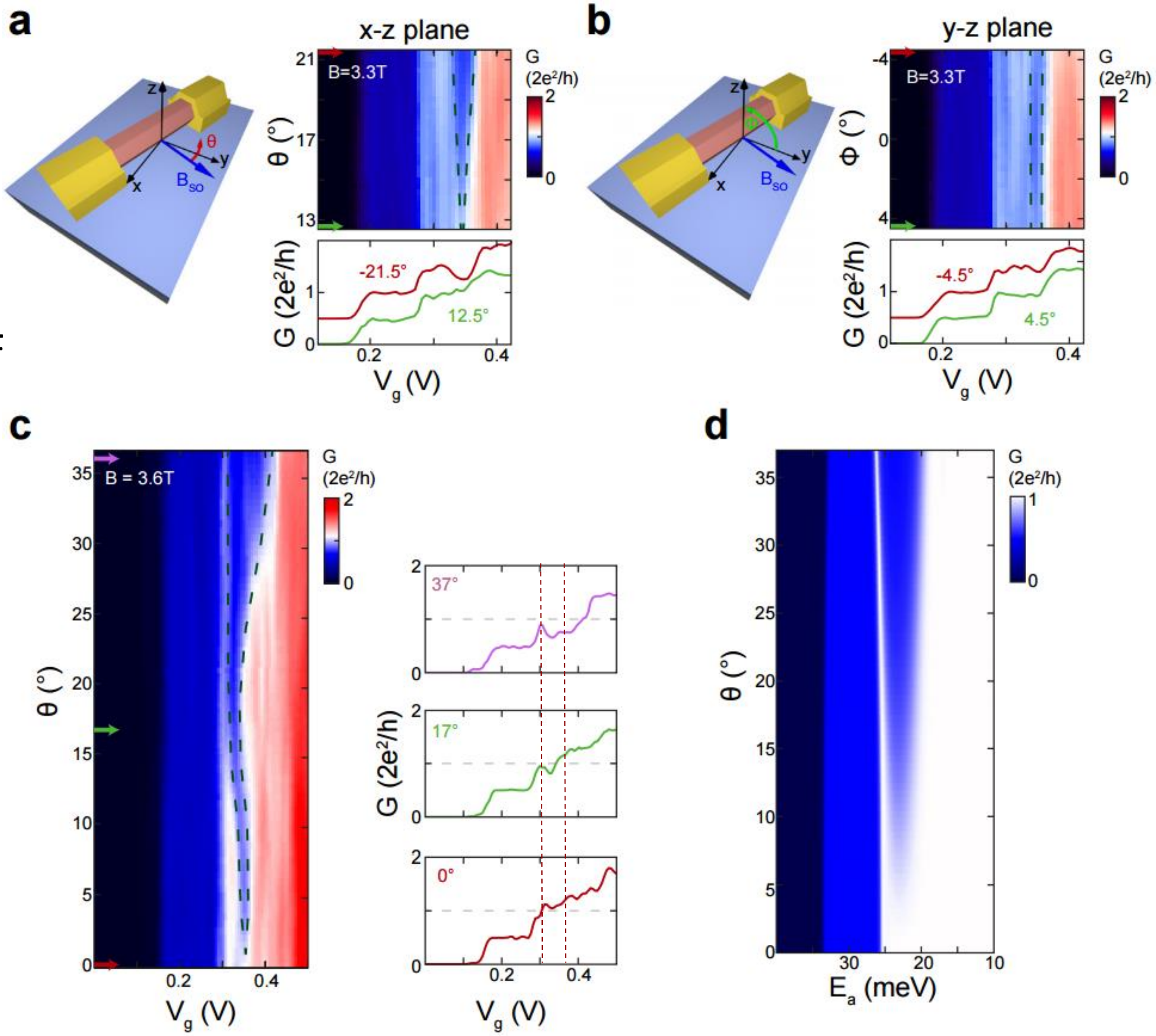
- Helical state evolves as a constant energy feature
- Measuring the width of both the first 0.5 G_0 plateau and the reentrant conductance feature
  - ➢ Incrases linearly with B-Field
- By comparing E_{Zeeman} and $E_{helical}$ the offset angle of the magnetic field can be determined: $\frac{E_{Zeeman}}{E_{helical}} \approx \tan\theta$
- Some problems:
  - $1\ G_0$ is not clearly visible
  - RCF seems linear in V_g and is not clearly visible for most B-Field strengths
  - G becomes larger than $1\ G_0$ after RCF





Angle Dependence of the Helical Gap

- Rotation of the B-Field to confirm that the RCF agrees with spin theory
  - y-z plane: no change in gap width
  - x-y plane: change in the 0.5 G_0 plateau as well as the RCF
- Claim: small difference in the angle evolution is caused by imperfect alignment of the substrate with the x-y plane
- Elefants in the room:
  - Rotation shown only from 0 to 35° (helical gap is largest for 90°)
  - rapid jump in conductance to $4e^2/h$
  - ➢ At least two modes -> clouds conclusions



- First signs of a helical gap opened in an InSb nanowire
- B-Field dependence seems consistent with theory
- Some problems:
  - Conductance features are not always clearly visible
  - Angle dependence is only shown up to 35°
  - Theoretical model only considers one mode, but experiment shows at least two modes

➢ Still a lot of work needed, but on the right track