Si/Ge self-assembled quantum dots

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Why Si/Ge QD?

<u>Advantages:</u>

Low cost nanoelectronics: SemiC NW, CNT, etc.

 But how to integrate to mainstream silicon technology?

Ability to form ideal contact with metals (SC-SemiC appl.)

Potential for long spin coherence time (Spintronics)

Strong spin-orbit (SO) coupling for p-type

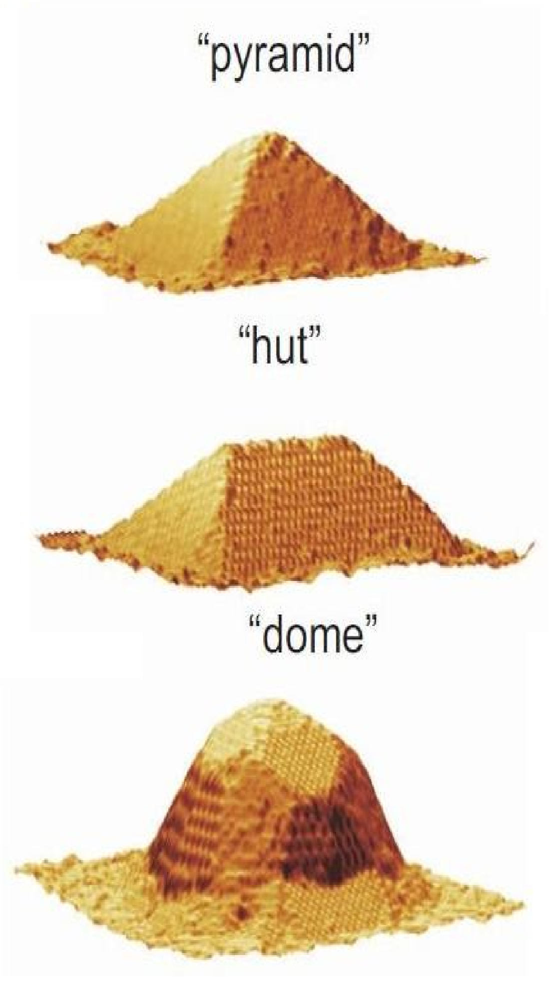
 Large modulations, anisotropies in *g*-factor (electronically controlled spin precession)

2D qubit architecture (contrary to Ge/Si core/shell NW)

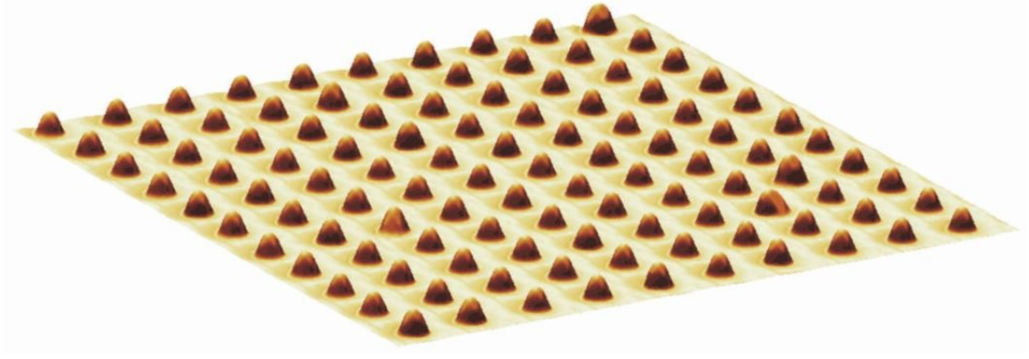
Fabrication

Silicon-on-insulator (SOI) substrate (gate control):
40 nm undoped Si
65 nm SiO2
Degenerately doped Si substrate

Stranski-Krastanow growth by MBE:
HF etching
100 nm Si buffer @620°C, 0.1 nm/s
5s interruption
7 monolayer Ge @620°C 0.04 layer/s
2 nm Si cap @300°C



Ordering: 2D array of holes by EBL and CHF_3/O_2 plasma

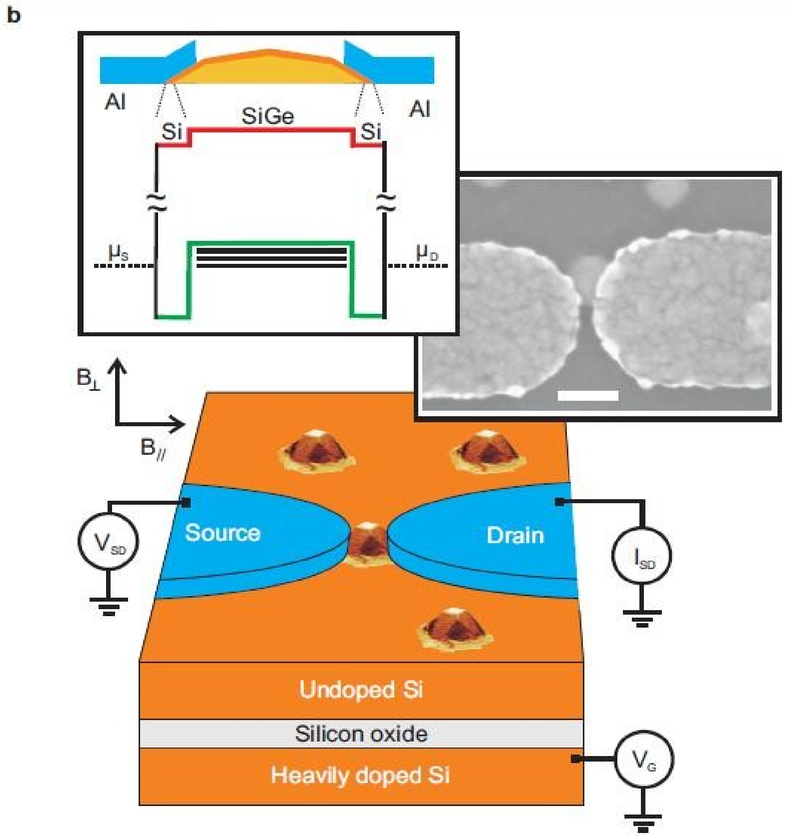


Fabrication, Basic parameters

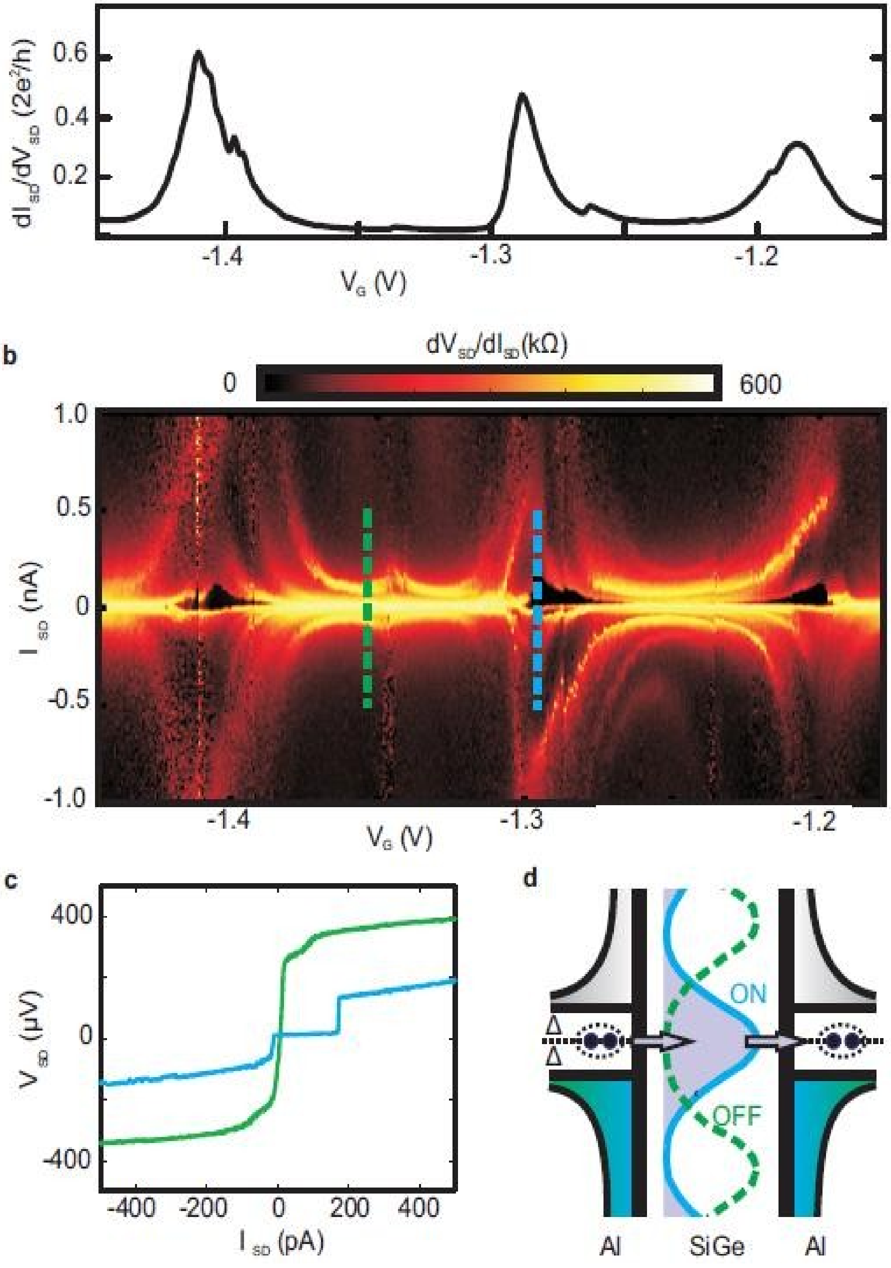
Contacting:
4 step of EBL, e-beam evap. … (Ti/Au pads)
20 nm Al electrode pairs, 10-50 nm gap

Typical devices:
Monocrystallin, dome-shaped
Height: 22±0.8 nm
Base diameter: AFM: 96±2 nm
SEM: 80 nm
P-type (holes)
Resistance: 10^4-10^5 Ohm (lowest: ~25.8 kOhm)

Measurements: @15mK



Single-hole supercurrent transistor



Normal Coulomb-peaks:
Wide peaks, finite valley conductance

→ strong coupling to the electrodes

→ Coopair-tunneling @SC phase

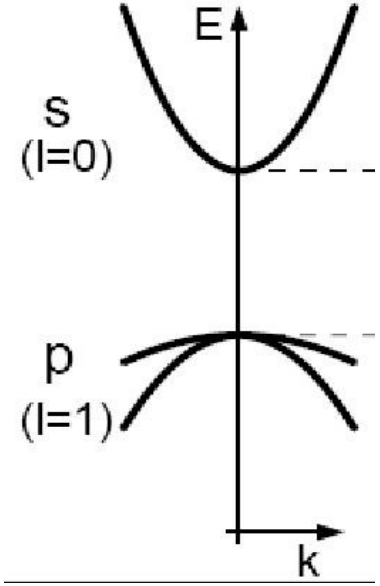
Black region: zero voltage drop on the QD
Blue line: switching form Josephson current to dissipative current

(Critical current: $\sim 10^2$ pA)

Green line: No non dissipative current

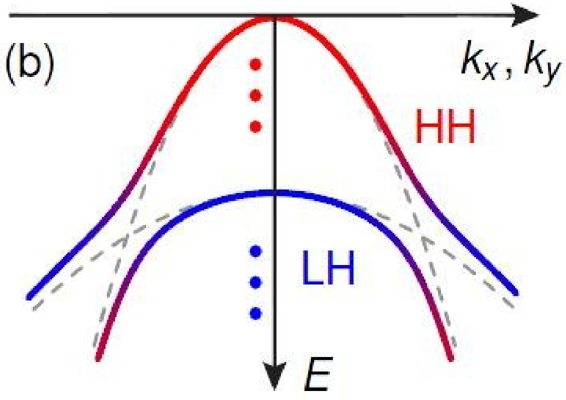
→ Switch the device On/Off by gate voltage

G-factor in Si_xGe_{1-x} materials



Bulk: 4-fold degenarcy (LH, HH) @$\underline{k}=0$
QD: deg. lifted by strain or confinement
In selfassembled nanocrystals: compressing strain,
HH has lower energy

HH g-factor: $g_{per}=6\kappa$, $g_{par}\approx 0$
LH g-factor: $g_{par}=4\kappa$, $g_{per}=2\kappa$
K: Luttinger valence-band parameter (Si: $\kappa=0.42$,
Ge $\kappa=-3.37$)
Alloys: κ has intermediate values
60-80% Ge: -0.308 - -1.153
40% Ge: 0.019
20% Ge: 0.131
(these samples: 50-75% Ge)



In QD: confinement → mixing of HH and LH states

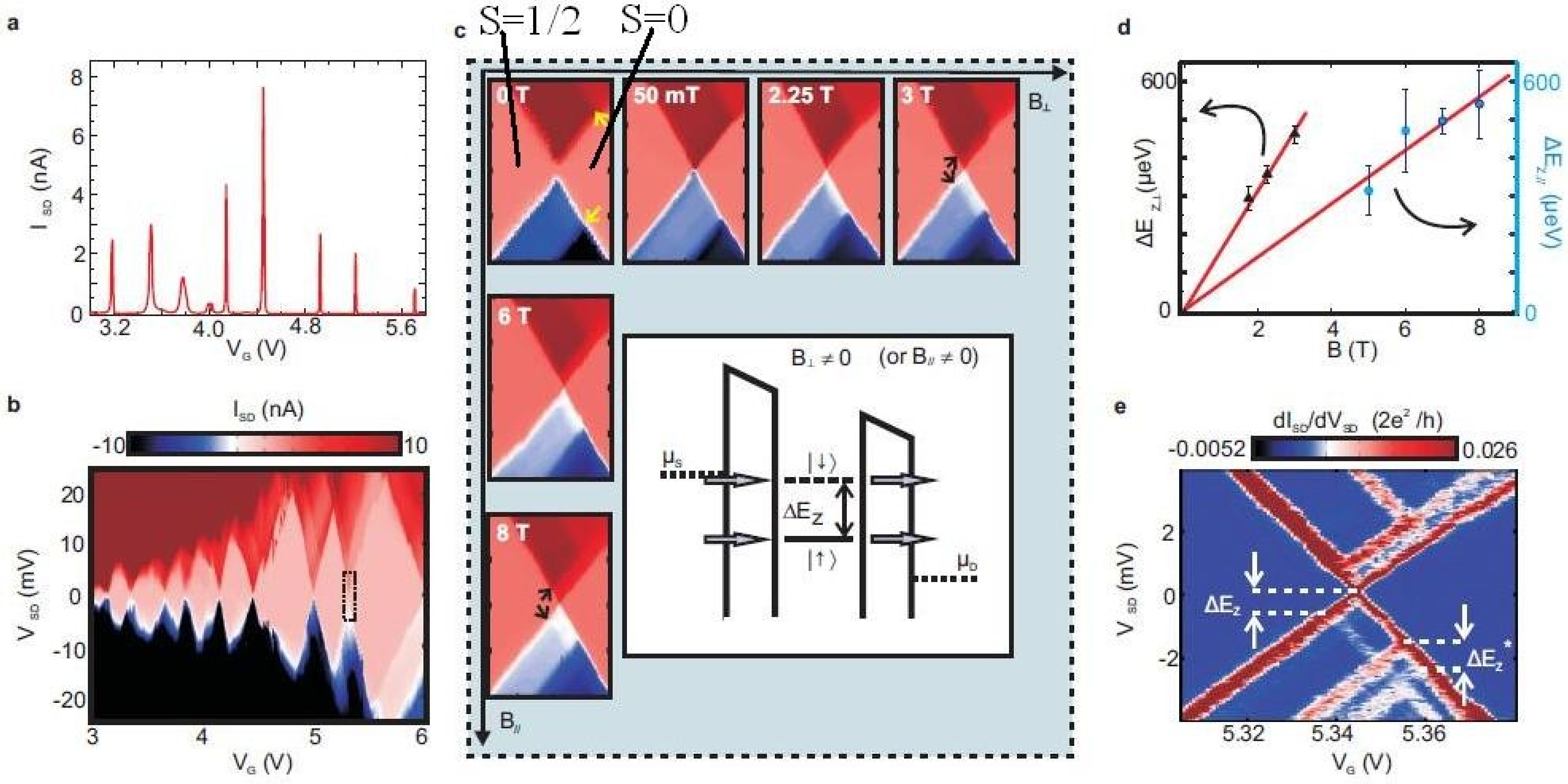
Anisotropy of g-factor I

Weak coupling to leads, high resistance

Increasing charge energy (by V_G) → decrease in coupling

<u>Rightmost diamond:</u> in magnetic field → anisotrop g-factor: g_{per}=1.21, g_{par}=2.71

Lowering VG → stronger coupling → larger QD level broadening → uncertainty



Anisotropy of g-factor II

Inelastic cotunneling spectroscopy:

Anisotropy in critical field: (paralel: 650 mT, perpendicular: 50 mT)

Angle depencence @3T:

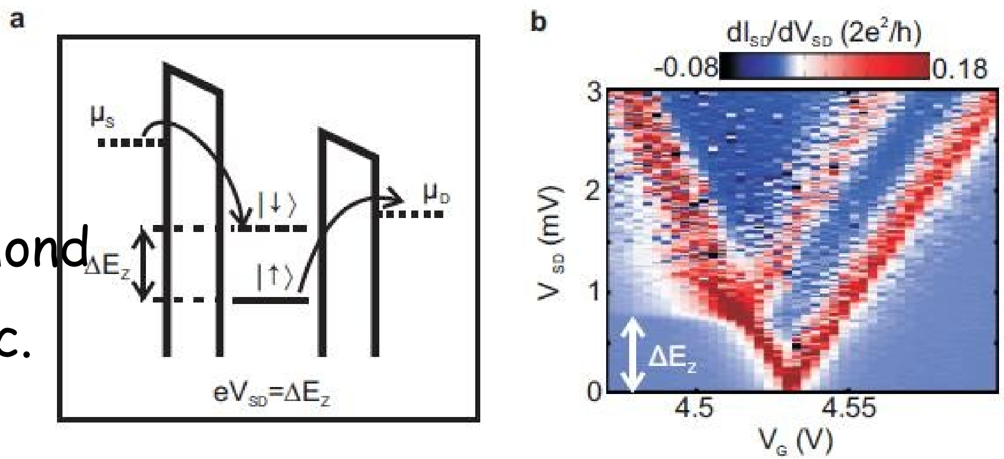
- Minimum not @15-20°
- Almost identical offset in diamonds
- Other device with min @0°
- Asymemetric overlap with the leads

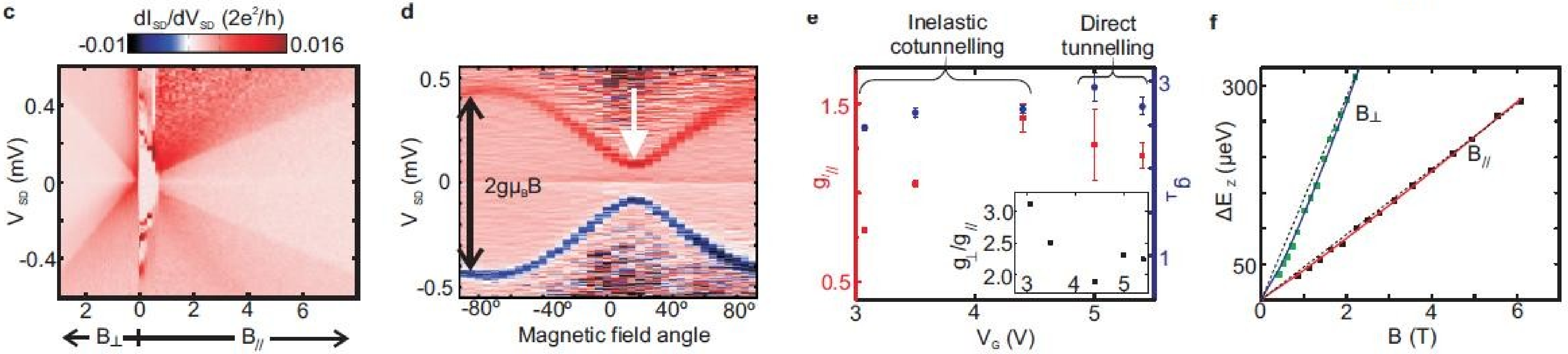
More holes → more extended wave-function (to Si-rich base) → lower g

Weaker dependence on V_G, than on diamond

- G-factor linked to the orb. wavefunc.

Small nonlinearity is Zeeman-energy





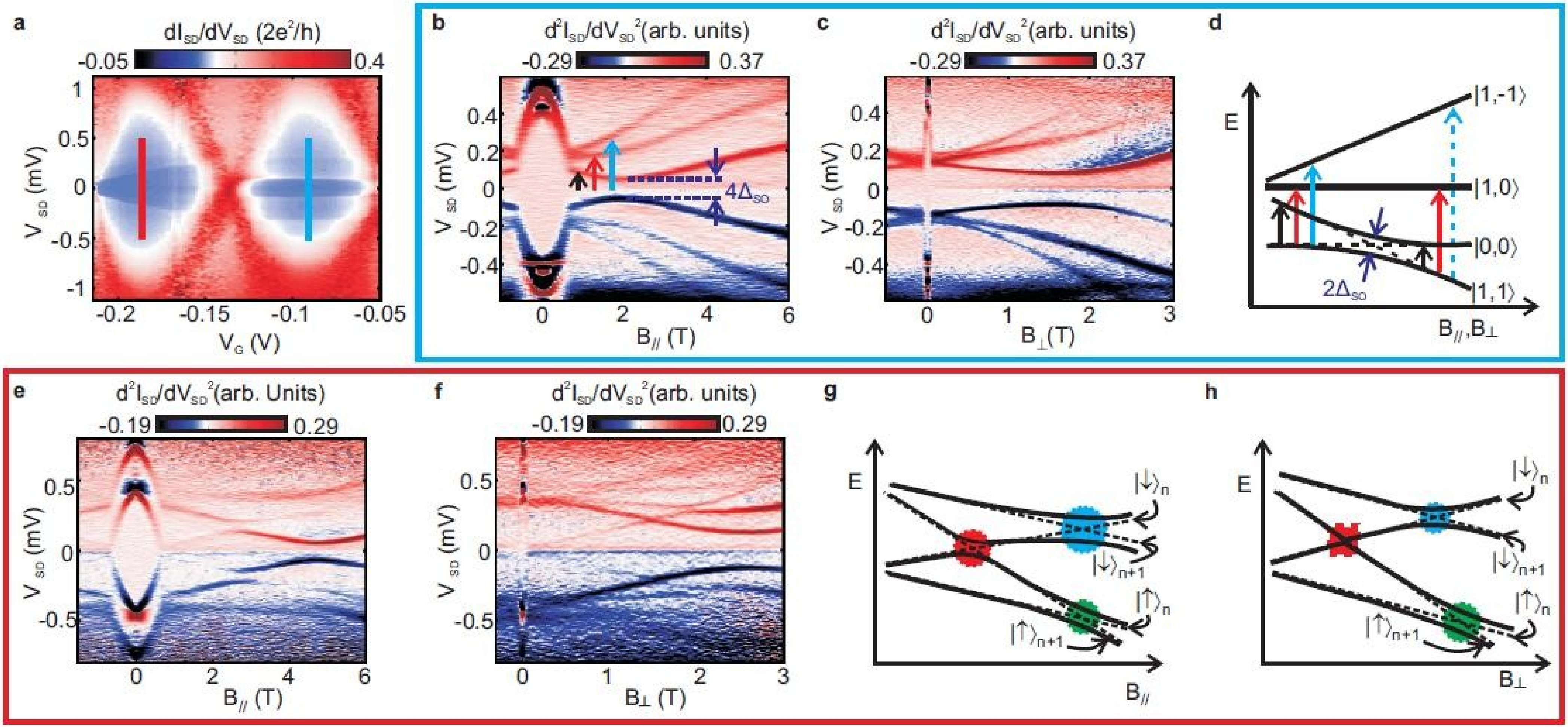
Spin-orbit interaction

Indirect evidences:

- G-factor deviation from free-particle value
- Nonlinearities is Zeeman-effect

Measurement: device with small level spacing, strong tunnel coupling

- Inelastic cotunneling spectroscopy



Spin-orbit interaction

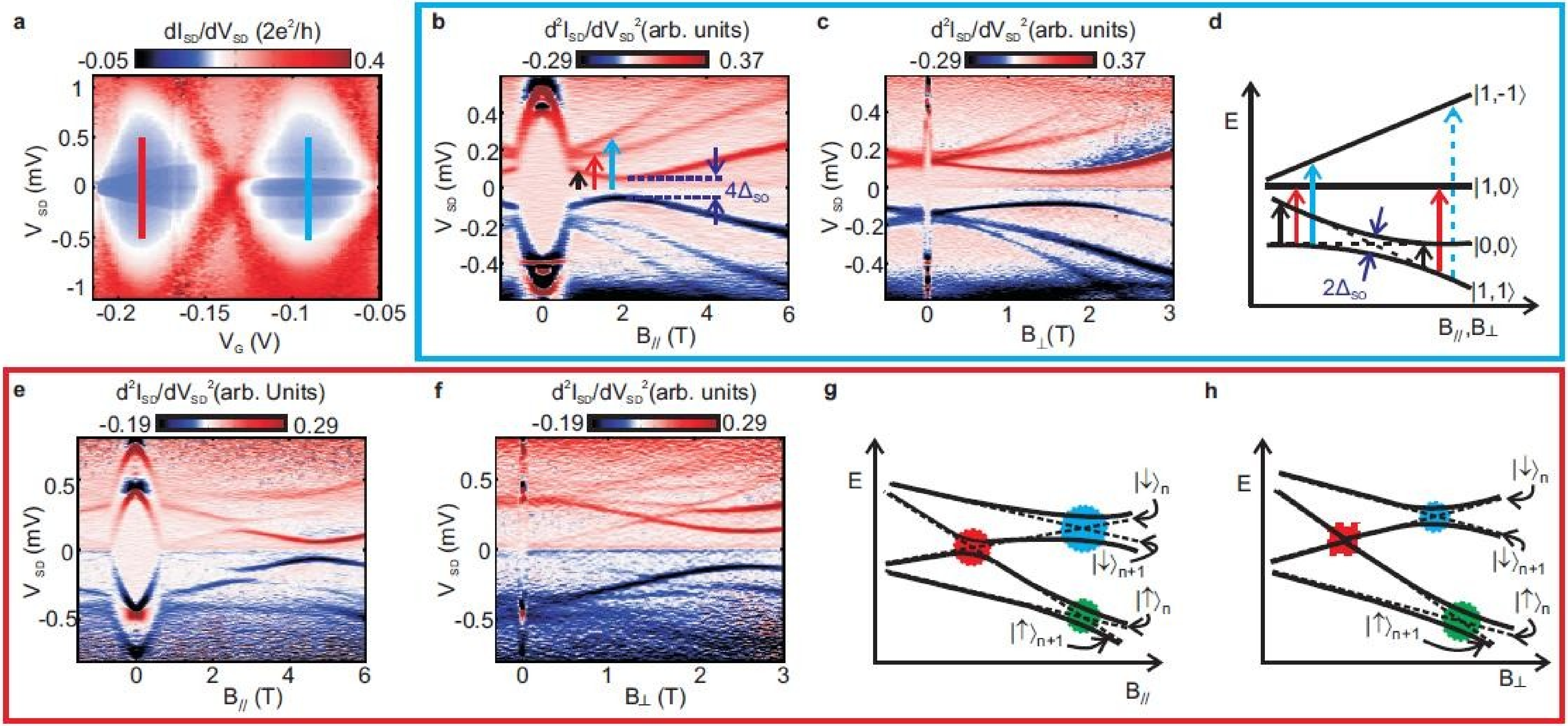
Blue: ground state: singlet, 3 lines: triplet excitations (even # of holes)

Zero-field singlet-triplett splitting: 130 μeV

@2T: anticrossing between: |0,0> and |1,1> → SO coupling:

Parallel field: Δ_{SO}=34 μeV (one order smaller than in InAs or InSb)

Perpendicular field: Δ_{SO}=42 μeV



Spin-orbit interaction

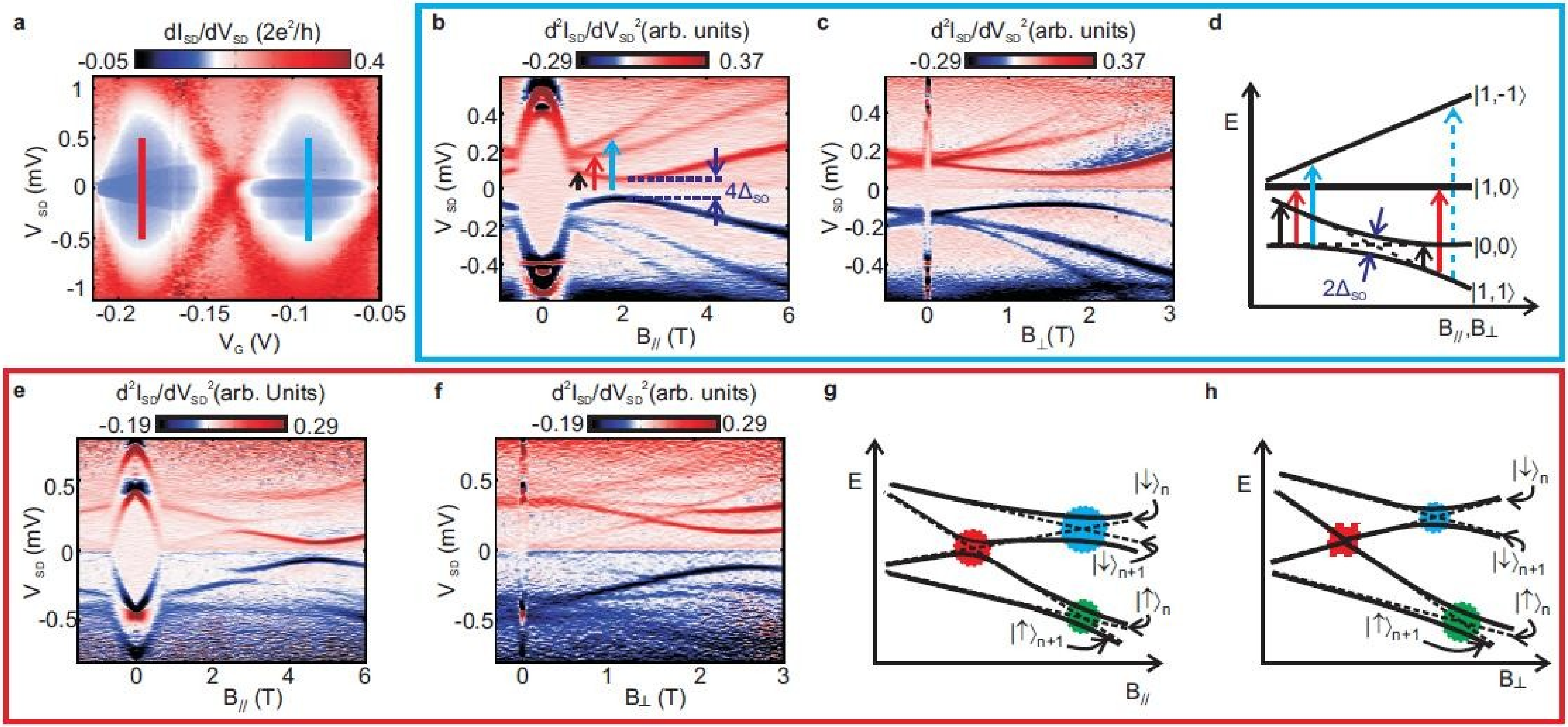
Red: (odd # of holes) two subsequent orbital (zf energy diff: 300 μeV)

Field-induced decrease in orb. splitting, diff. g-factor for diff. orb.

Anticrossing: $@B_{||}=2.6$ T between $|\downarrow>_n$ and $|\uparrow>_{n+1} \rightarrow \Delta_{SO}=37$ μeV

$@B_{per}=1.5$T it vanishes → longer spin relaxation time

Blue and green anticrossing: could anticross in the absence of SOI too



Spin selective tunneling

Coulomb blockade regime → Second order cotunneling

Different tunnel rates for Zeeman levels: $\Gamma=\pi\nu|t|^2$

QD w/o SOI w/ FM electrodes:

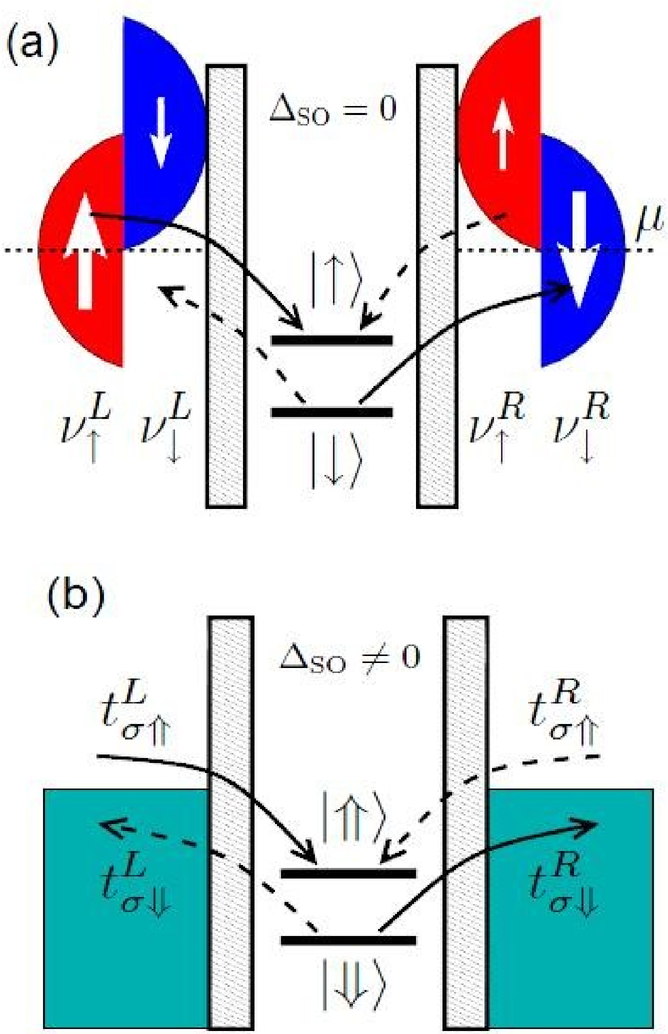
  Origin: DOS (ν) in the leads

QD w/ SOI w/ N electrodes:

  Γ is spin dependent in B field → $\Gamma^L_\uparrow\Gamma^R_\downarrow \neq \Gamma^R_\uparrow\Gamma^L_\downarrow$

  G(V) is expected to be asymmetric

  w/o B → no spin selectivity expected



Measurement

Odd # of holes, finite G @V=0 → spin-1/2 Kondo

In B field: Kondo peaks splits up

  Perpendicular B: asymmetric G(V) for $|eV|>E_{Zeeman}$

Rotating 3T field:

  Angle dependent g-factor

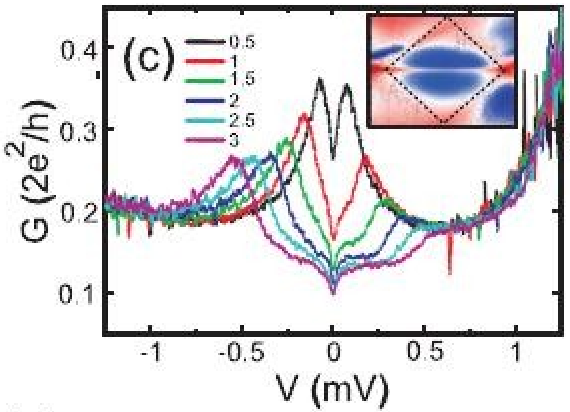
Asymmetry parameter:

$$A=\left|\frac{G_{-}-G_{+}}{G_{-}+G_{+}}\right| \quad ahol \quad G_{\pm}=G(\pm E_Z/e)$$

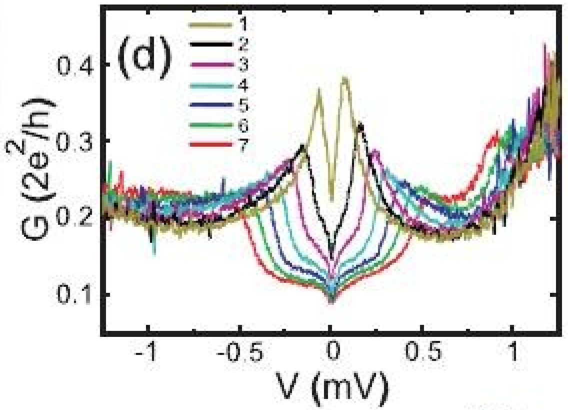
A has min @ 0,180°, max = 0.2

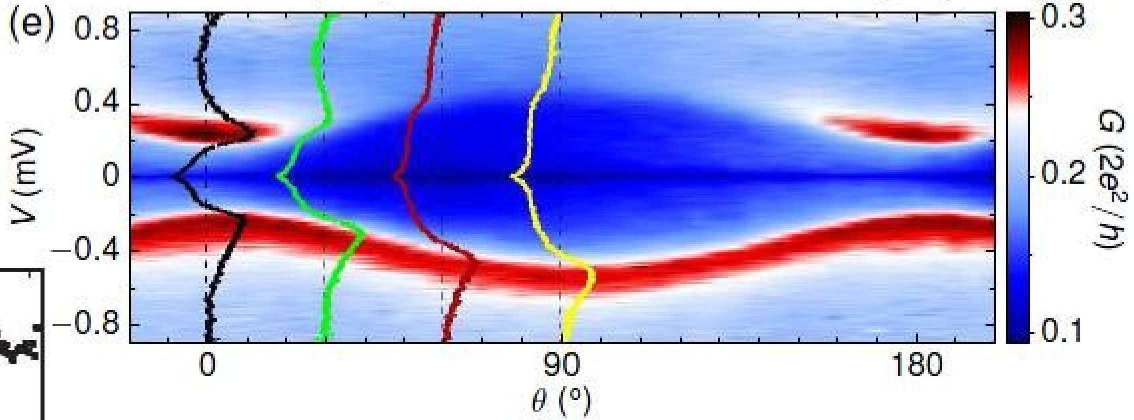
Asymmetry increases with B_z

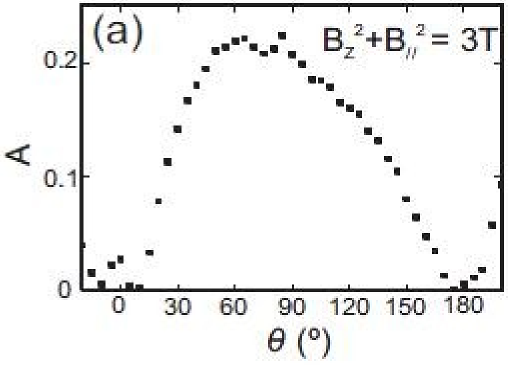
Perpendicular B

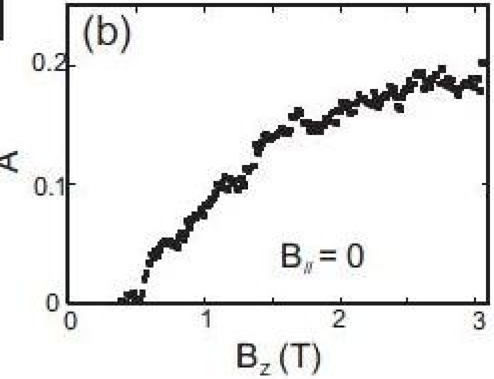


Parallel B









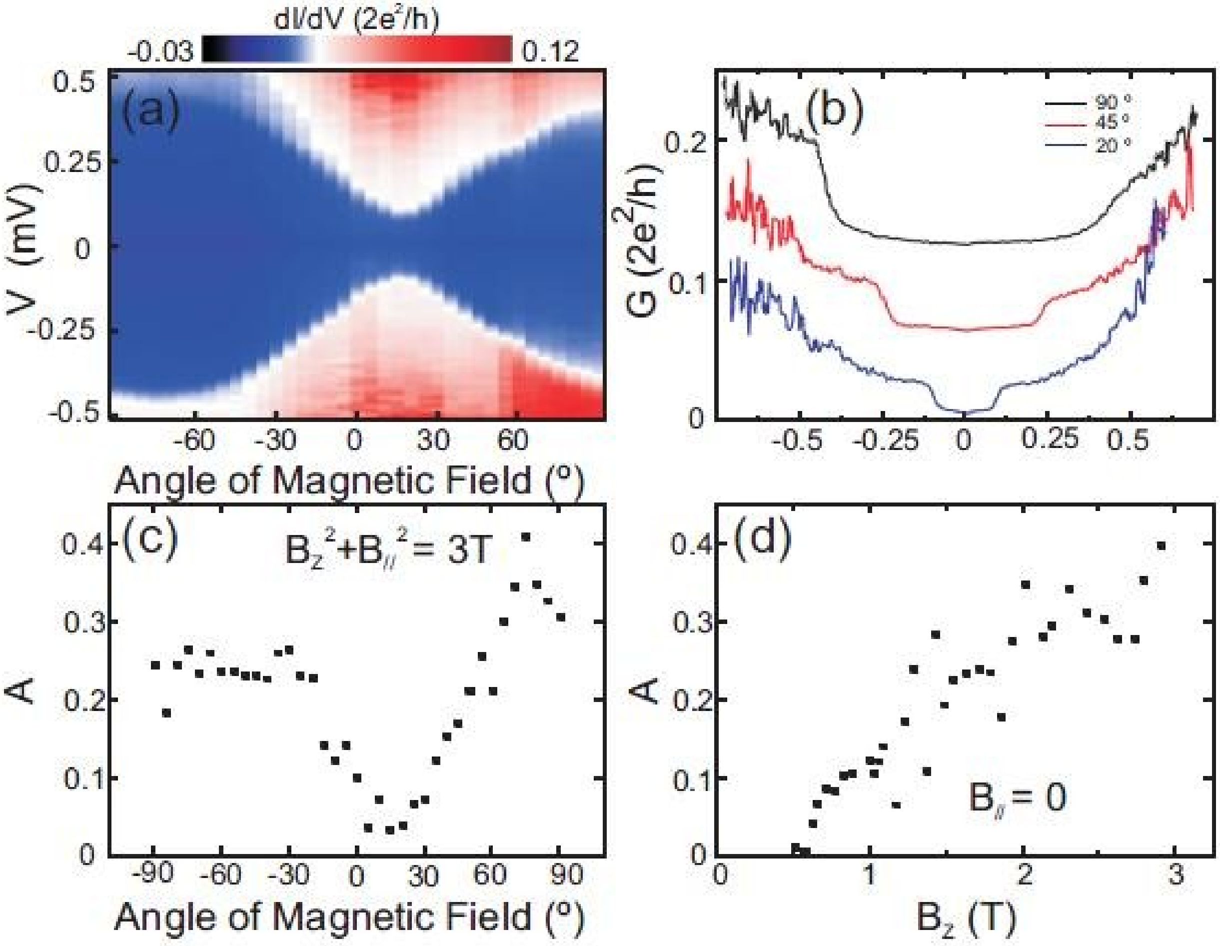
Other device

No Kondo-effect, weaker coupling to the leads

Min g-factor @15-20°, but here is no asymmetry

The plane of wavefunction may not parallel to the substrate

A has a greater maximum (0.35-0.4)



References

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