Zero Field Splitting of Heavy-Hole States in Quantum Dots

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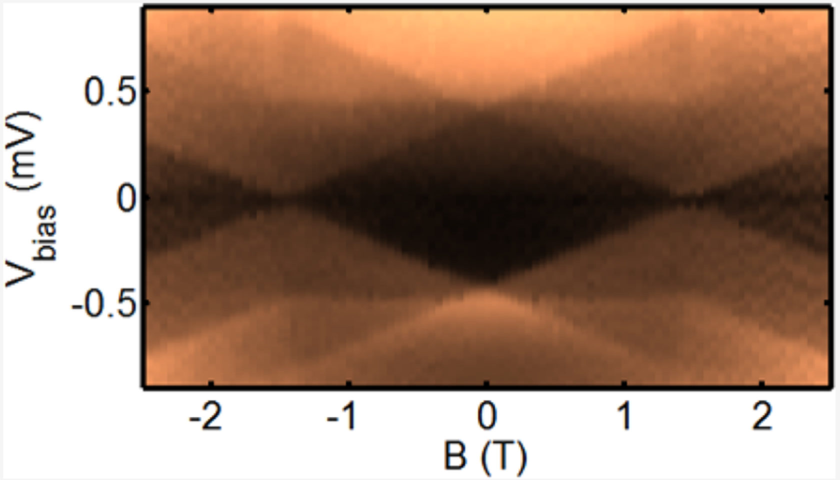
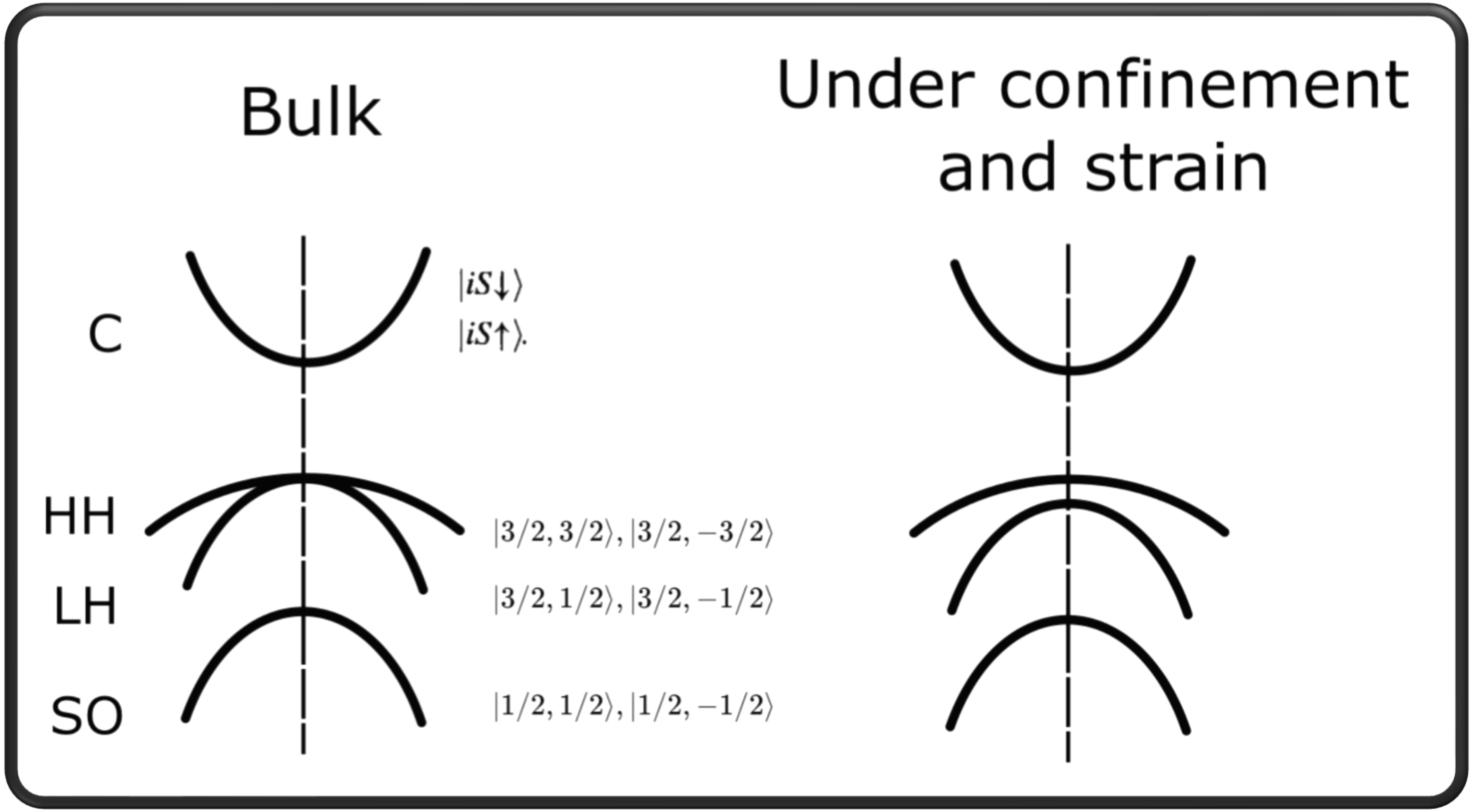
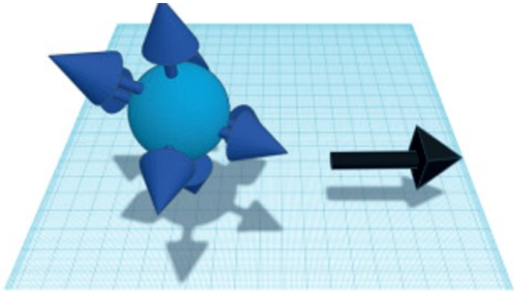
ABSTRACT: Using inelastic cotunneling spectroscopy we observe a zero field splitting within the spin triplet manifold of Ge hut wire quantum dots. The states with spin ±1 in the confinement direction are energetically favored by up to 55 μeV compared to the spin 0 triplet state because of the strong spin–orbit coupling. The reported effect should be observable in a broad class of strongly confined hole quantum-dot systems and might need to be considered when operating hole spin qubits.



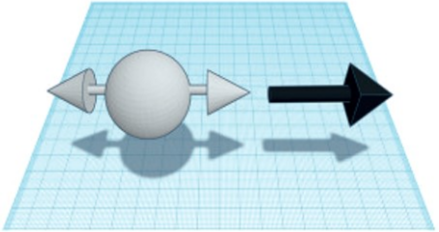
Heavy hole states



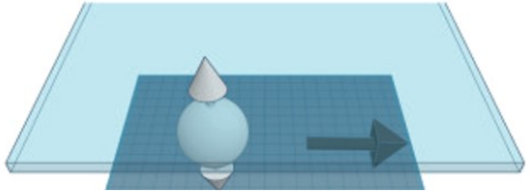
Electrons in conduction band



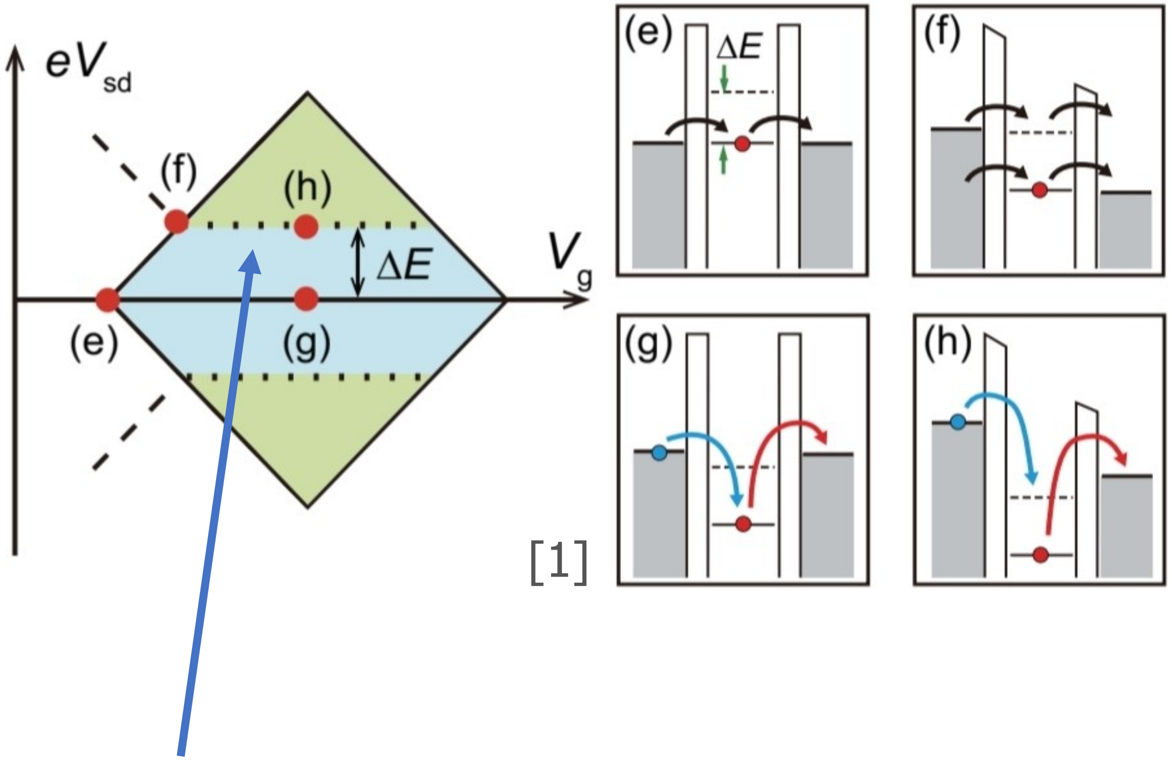
HHs in Bulk



HHs in confinement



Elastic/Inelastic Cotunneling



Onset of inelastic cotunneling

No VG dependence

First order tunneling Processes

(e), and (f) Sequential tunneling transport

Blocked inside the diamond

Higher order tunneling processes

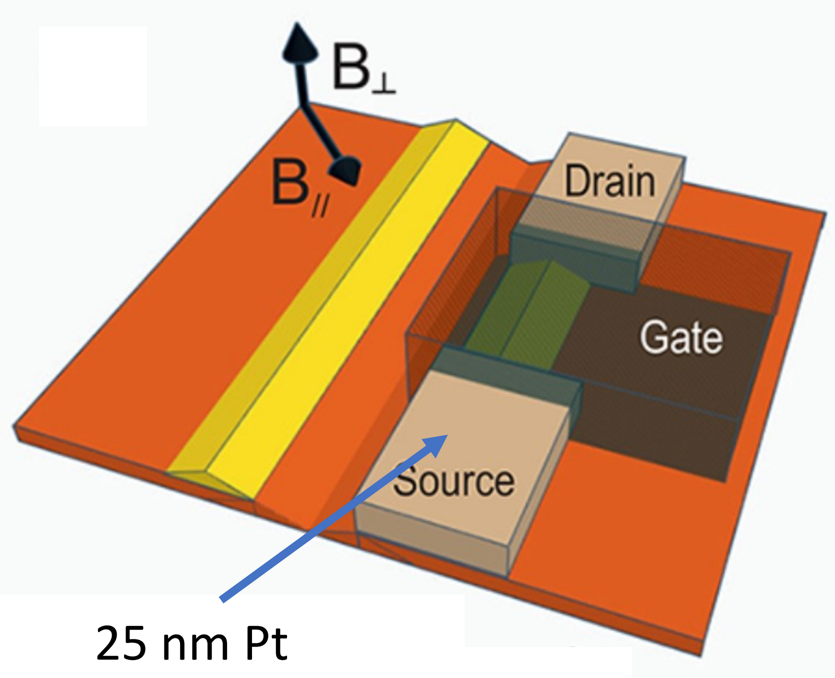
(g) Elastic Cotunneling

(h) Inelastic Cotunneling $eV_{sd} \geq \Delta E$

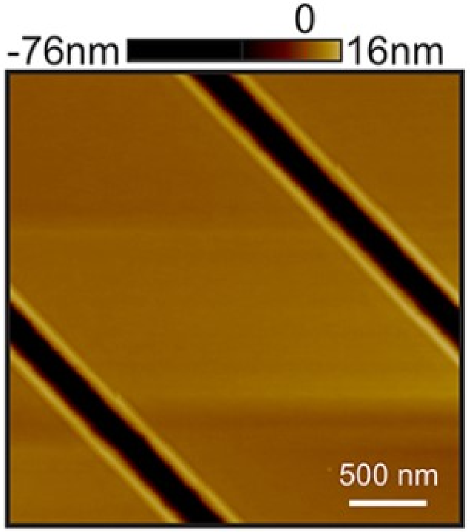
[1] Phys. Rev. B **87**, 041302

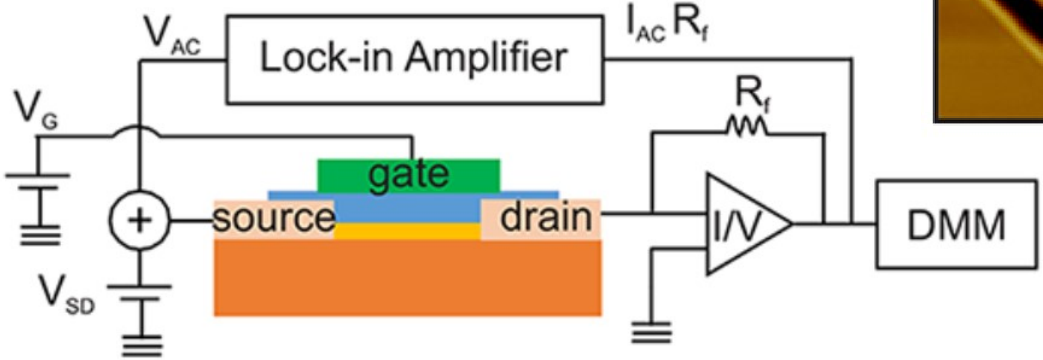
Setup and device

Distance btw Source and drain=50 nm
Height of the Ge HW=3.8 nm
Width of the HW= 38 nm

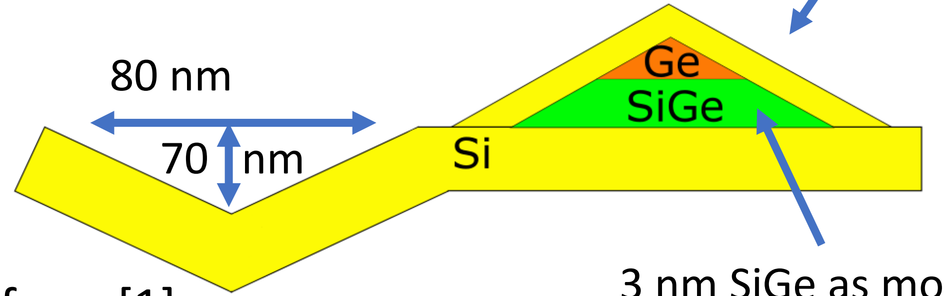


25 nm Pt





5 nm thick Si cap

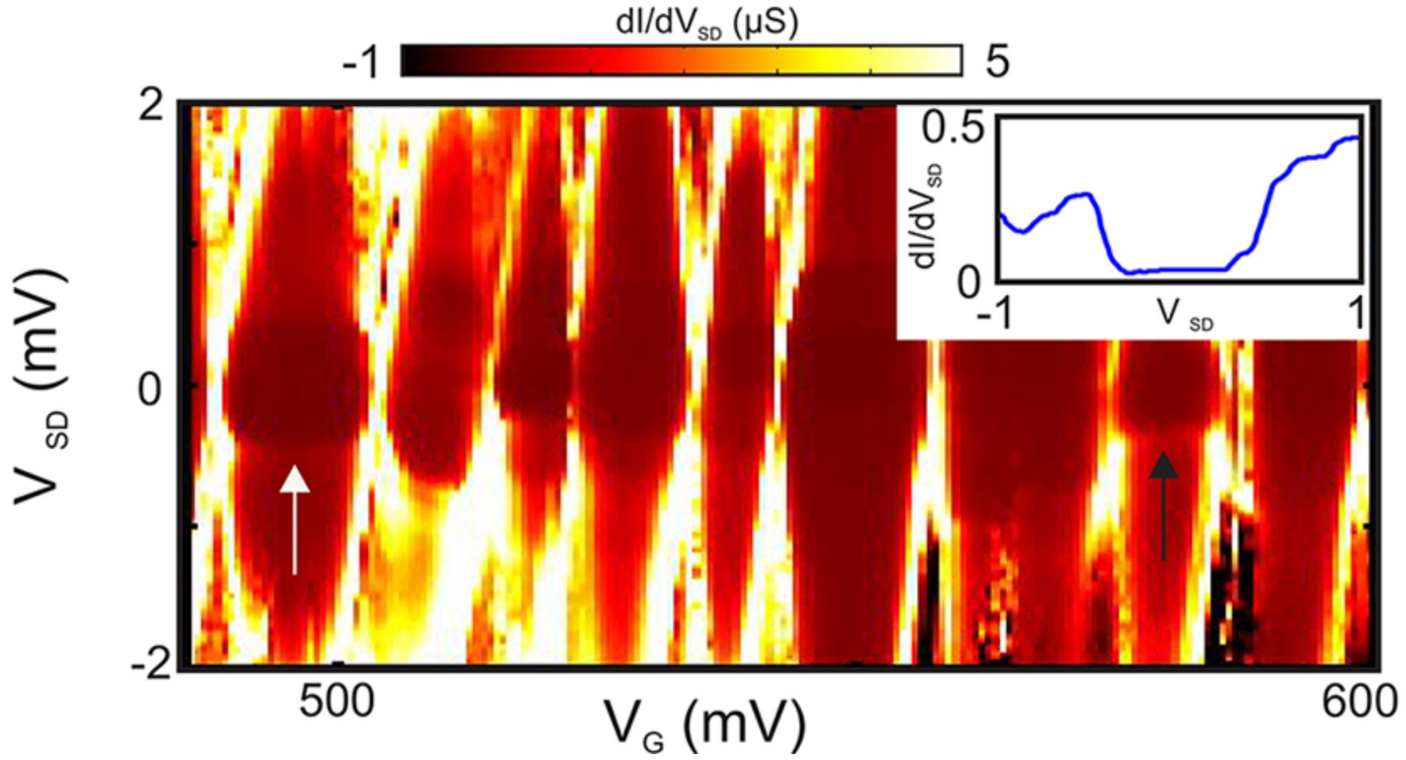


3 nm SiGe as mound

Info from [1]

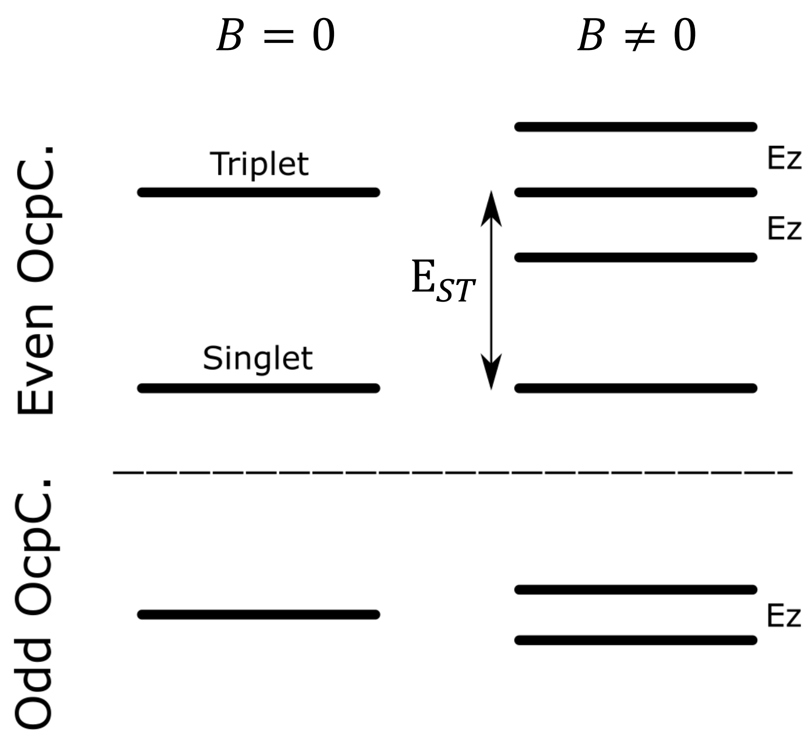
[1] F. Gao, et al. *Advanced Materials* 32.16 (2020): 1906523

Stability diagram



Effective electron temperature of 100 mK

Odd/even occupancy



By comparing E_{ST} and E_{ORB}, one can obtain information about the strength of hole-hole interactions

Odd no. of holes → splitting of the doublet

Even no. of holes → splitting of the triplet

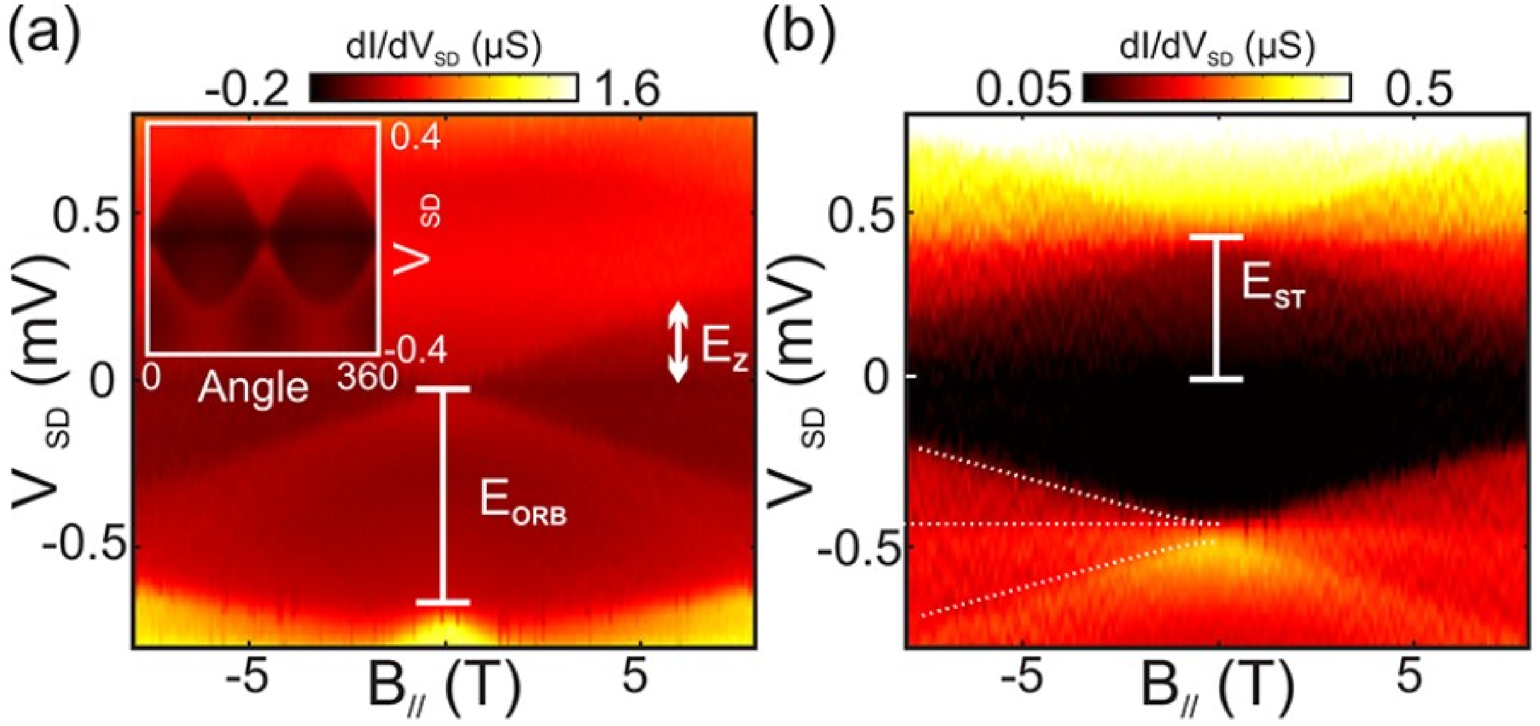
(a) doublet, VG= 510.5 mV

Inset: B = 1 T,

→ **g-factor anisotropy of about 7.5**

(g|| = 0.56 ± 0.06 and g⊥ = 4.17 ± 0.22)

- This anisotropy is due to the HH character of the confined states [1]



E_{ORB} = 690 μeV

E_{ST} is 415 μeV

b) singlet VG = 528.3 mV

→g|| = 0.57 ± 0.01 and g⊥ =4.56 ± 0.16

- **triplets are nonequally spaced**
- **ZFS of 55 μeV**

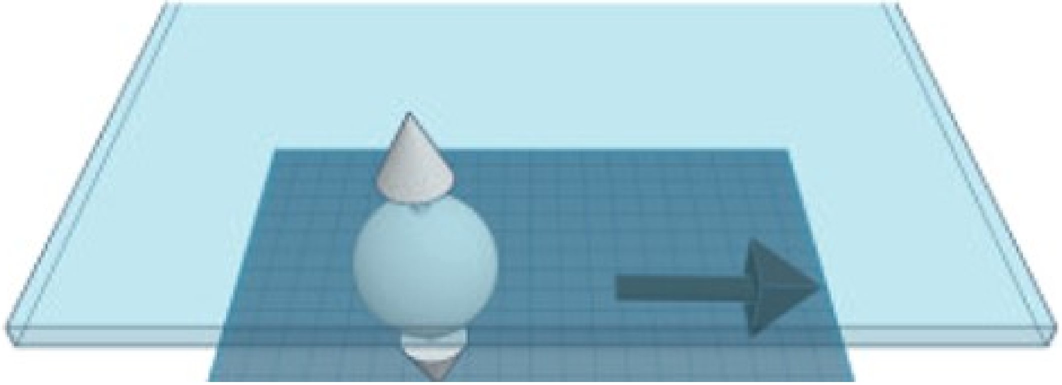
$E_{ORB} - E_{ST}$ = 275 μeV

Coulomb interaction energy

[1] Watzinger et al., Nano Lett. 16, 6879 (2016)

Model

Ge is known to have a very strong valence band SOC which leads to the HH spin pointing in the perpendicular direction.
Assuming the triplet state as being made up of two such HH spins.



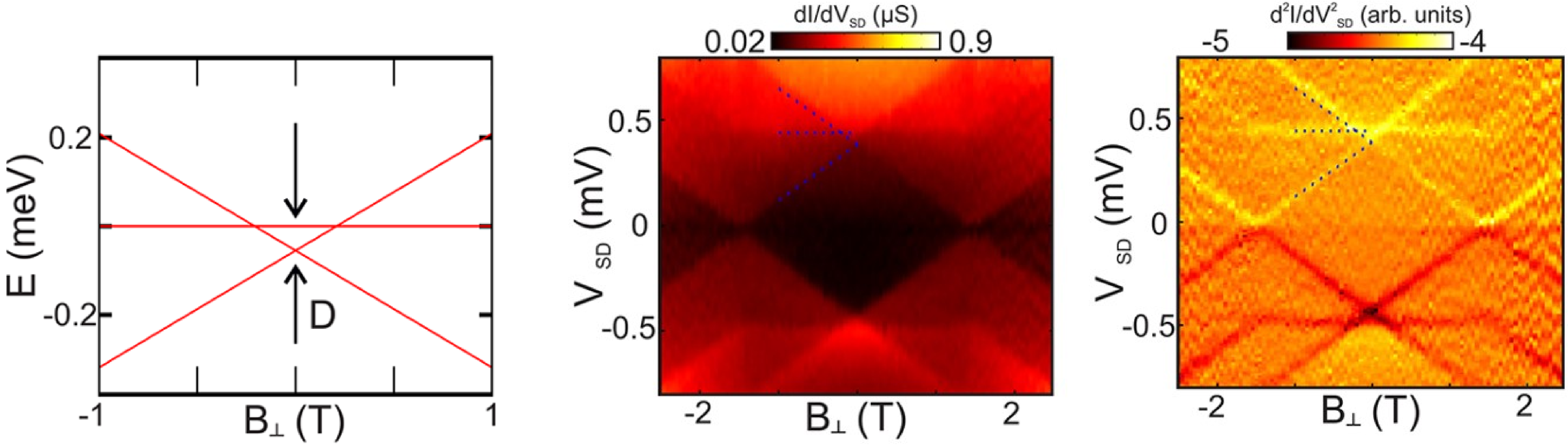
$$H = -J/2\mathbf{SS} + g_{\perp}\mu_{\mathrm{B}}S_{\perp}B_{\perp} + g_{||}\mu_{\mathrm{B}}S_{||}B_{||} - DS_{\perp}^{2}$$

Exchange term J differentiates singlet and triplet

Zeeman terms

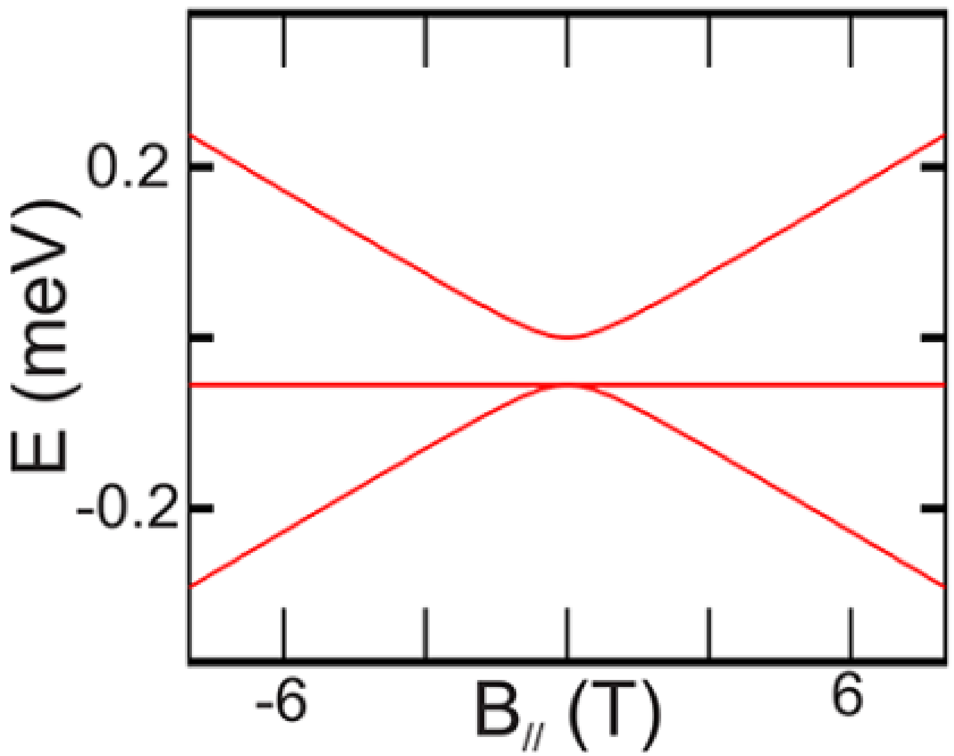
makes it preferably by an energy D to align the triplet in the ⊥-direction

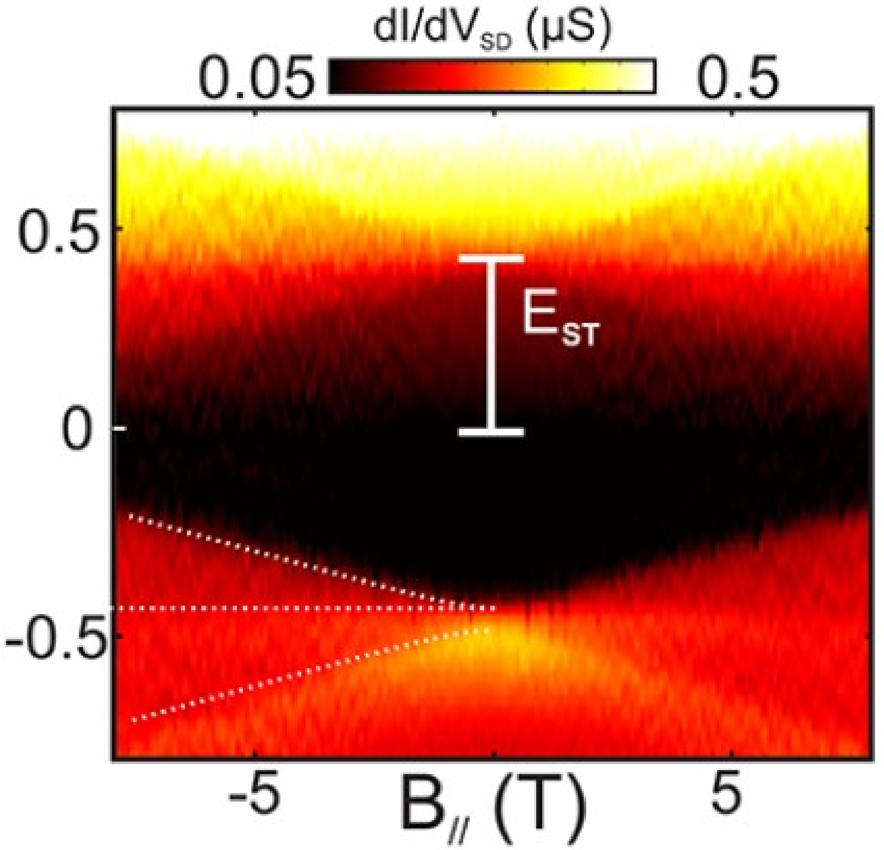
Simulation and the measurement for $B_\perp$



$g_\parallel = 0.57$, $g_\perp = 4.56$, and D = 55 μeV, as extracted from the

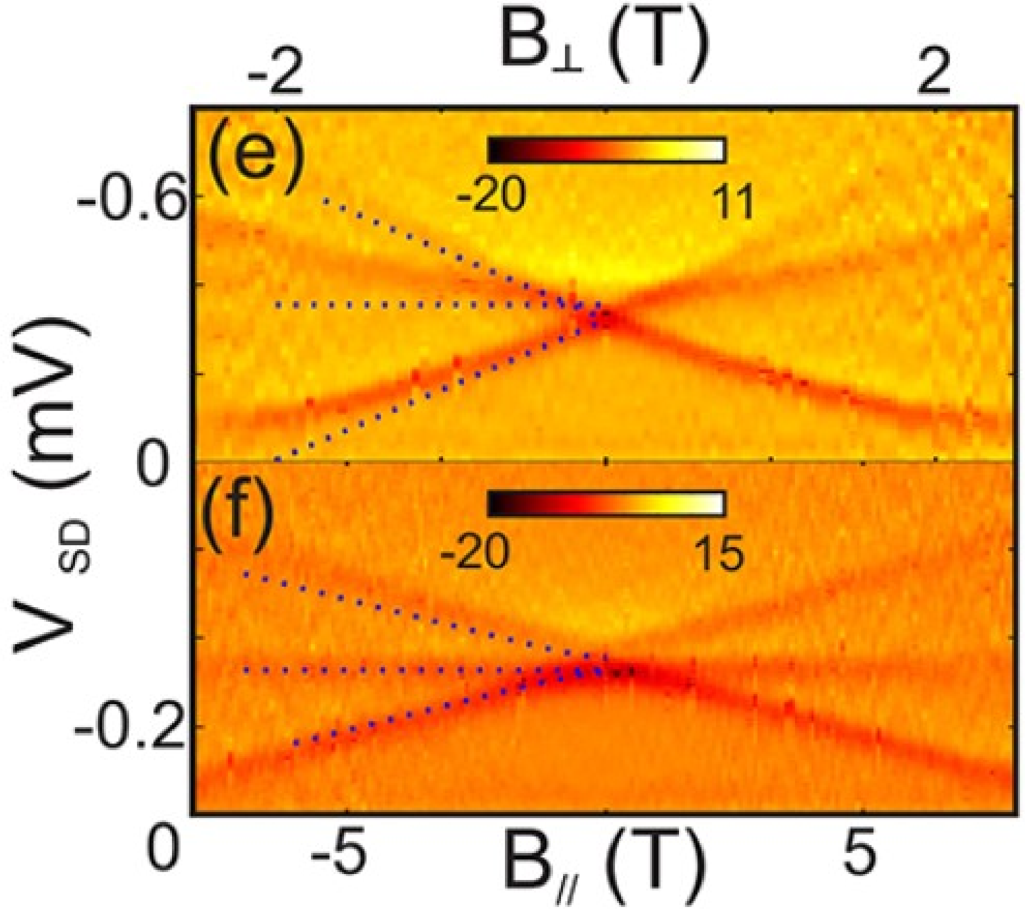
Simulation and the measurement for $B_{||}$





For large $g_{\parallel} \mu B_{\parallel} \gg D$, the usual Zeeman splitting of the triplet states into $S_{\parallel} = \pm 1, 0$ is recovered as the HH pseudo spins now reorient along $B_{\parallel}$.

Measurements on a 2nd device

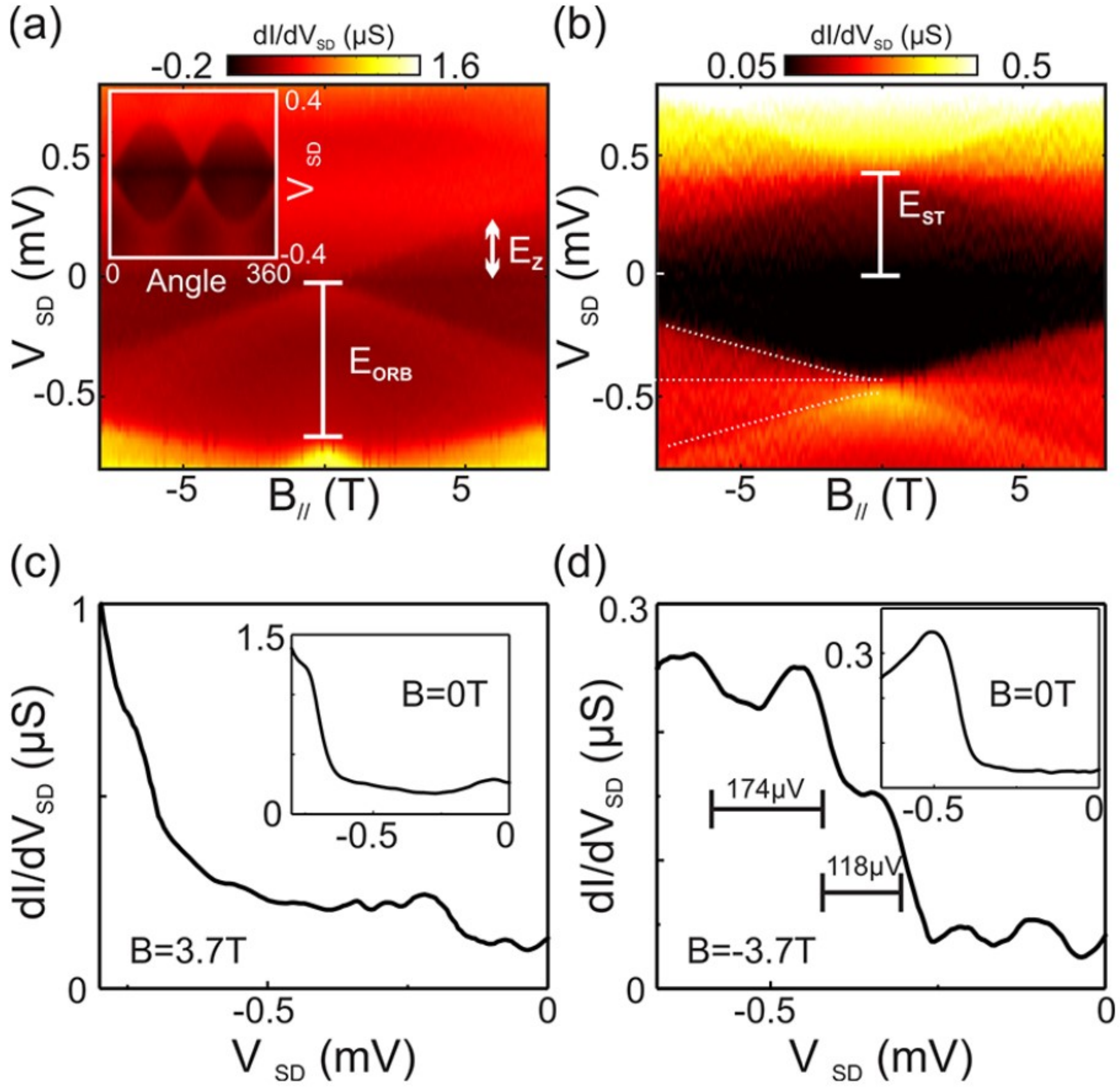


In this case **orbital effects** →slight bending of the states for B⊥
ZFS=35 μeV
g|| = 0.52 ± 0.13, g⊥ = 2.78 ± 0.06

Summary

- They investigated spin anisotropy of HH states
- They measured the ZFS for HH states in a 2D quantum dot
- They extracted the hole-hole interaction

Thanks for your attention


(a)
dI/dV_SD (μS)
-0.2
1.6
0.4
V_SD
-0.4
0
Angle
360
E_Z
E_ORB
V_SD (mV)
0.5
0
-0.5
-5
B_// (T)
5
(b)
dI/dV_SD (μS)
0.05
0.5
E_ST
V_SD (mV)
0.5
0
-0.5
-5
B_// (T)
5
(c)
1
1.5
B=0T
0
-0.5
0
B=3.7T
dI/dV_SD (μS)
0
-0.5
0
V SD (mV)
(d)
0.3
0.3
B=0T
174μV
-0.5
0
118μV
dI/dV_SD (μS)
B=-3.7T
0
-0.5
0
V SD (mV)