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CONTROL OF HOLE SPIN IN LATERAL GATED QUANTUM DOT DEVICES

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OUTLINE

1. Motivation: Photon - to - spin interface

2. Holes in semiconductors: a brief reminder

3. Heavy-hole single-subband regime:
   Anisotropic g factor, spin-orbit interactions

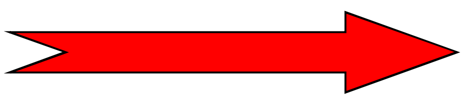
4. Single hole in a gated double dot:
   Coherent spin-flip tunneling – theory and experiment

5. Two holes in a double dot: Lifting of Pauli blockade,
   strong g-factor anisotropy

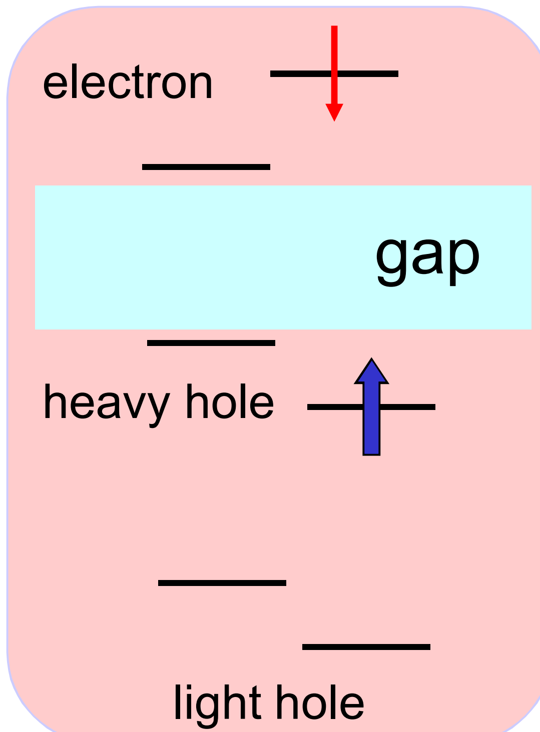
MOTIVATION

Photon – to – spin interface

Photon

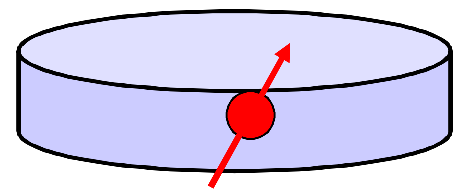


$$|\Psi\rangle = \alpha|\sigma^{+}\rangle + \beta|\sigma^{-}\rangle$$



Intermediate
e-h pair state

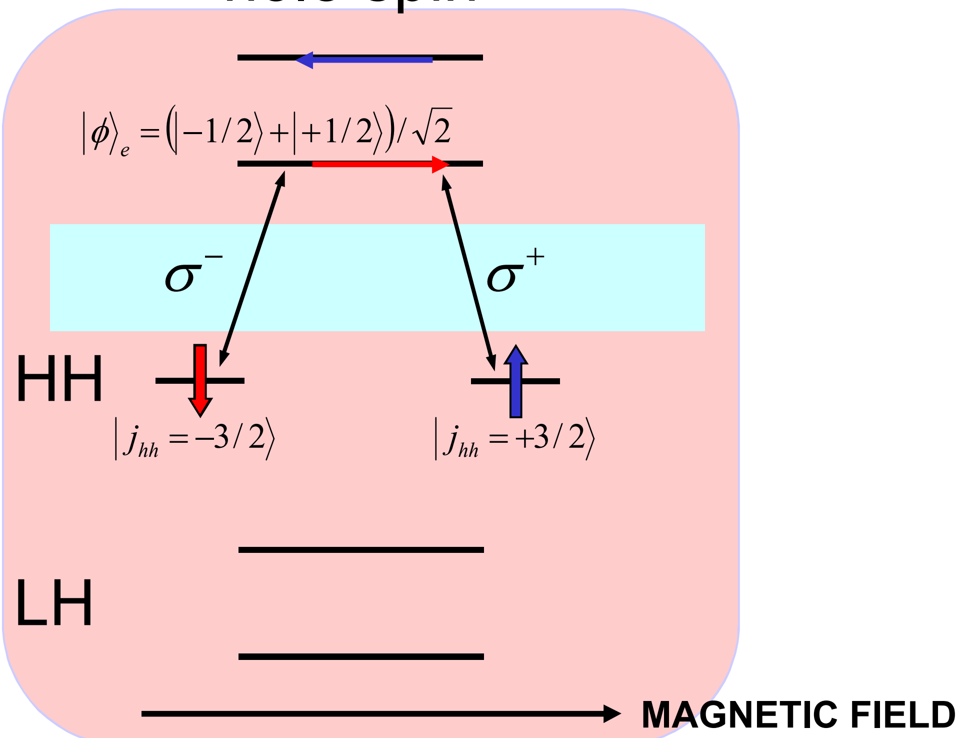
Confined
carrier



$$|\Psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$$

PHOTON-TO-SPIN PROCESS

Transfer to hole spin



$$|\Psi\rangle = \alpha|\sigma^+\rangle + \beta|\sigma^-\rangle$$

Optical selection rules

$$|\Psi\rangle = |\phi\rangle_e \otimes \left(\alpha|\Uparrow\rangle_{HH} + \beta|\Downarrow\rangle_{HH}\right)$$

Electron ejected

Superposition e-h state built on **one electron orbital**

Finite electron g-factor, but zero hole g-factor

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CONDITIONS FOR P-S INTERFACE

1. Direct bandgap of the material -
   we focus on GaAs devices

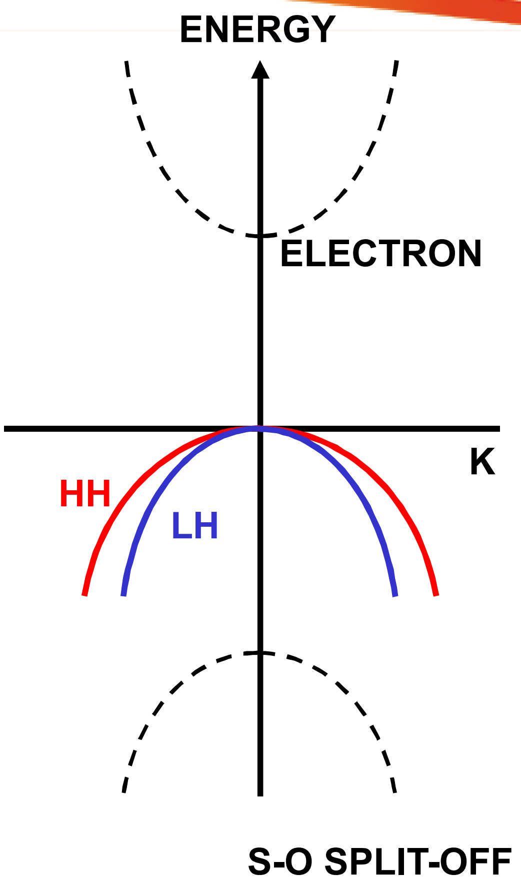
2. Fast, possibly electrostatic control of spin

3. Zero g factor easily achievable

4. Long spin coherence times

HEAVY HOLES IN BULK

$$H_{LK} = \left[\begin{array}{cc|cc} P_+ & 0 & S & R \\ 0 & P_+ & R & -S \\ \hline S^* & R^* & P_- & 0 \\ R^* & -S^* & 0 & P_- \end{array}\right] \begin{array}{l} |HH, \Downarrow (-3/2)\rangle \\ |HH, \Uparrow (+3/2)\rangle \\ |LH, \downarrow (-1/2)\rangle \\ |LH, \uparrow (+1/2)\rangle \end{array}$$



P_+ : HEAVY-HOLE KINETIC ENERGY

P_- : LIGHT-HOLE KINETIC ENERGY

HHs not coupled directly

HEAVY HOLES IN BULK

Heavy hole spin "up" is **not** coupled directly to heavy hole spin "down"

- Not by kinetic tensor elements
- Not by the Dresselhaus or Rashba spin-orbit interaction
- Not by the Zeeman term, even for the in-plane magnetic field

Any heavy-hole spin flip has to be mediated by the light-hole subband

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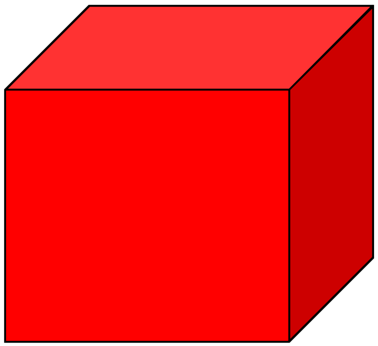
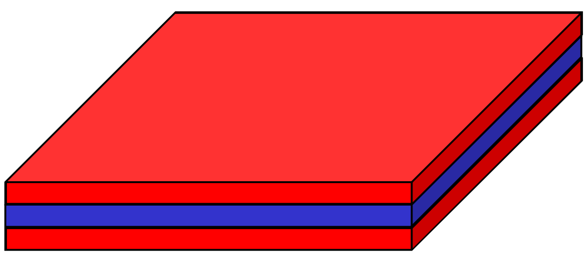
HEAVY HOLES IN QUANTUM WELLS

In bulk: HH and LH close in energy



$$H = \left[\begin{array}{cc|cc} P_+ & 0 & S & R \\ 0 & P_+ & R & -S \\ \hline S^* & R^* & P_- & 0 \\ R^* & -S^* & 0 & P_- \end{array}\right]$$

In quantum wells:
HH and LH separated by a gap



$$H = \left[\begin{array}{cc|cc} P_+ & 0 & S & R \\ 0 & P_+ & R & -S \\ \hline S^* & R^* & \Delta E_{HL} + P_- & 0 \\ R^* & -S^* & 0 & \Delta E_{HL} + P_- \end{array}\right]$$

HEAVY HOLES IN QUANTUM WELLS

Large heavy–light hole gap
(quantum wells, flat quantum dots)
- perturbative regime

$$\left|HH,\Downarrow\right\rangle$$

$$\left|HH,\Uparrow\right\rangle$$

$$H=\begin{bmatrix}\frac{1}{2m_{HH}^{*}}\hat{P}^{2}+V(x,y)-\frac{1}{2}g^{*}\mu_{B}B_{z} & 0\\ 0 & \frac{1}{2m_{HH}^{*}}\hat{P}^{2}+V(x,y)+\frac{1}{2}g^{*}\mu_{B}B_{z}\end{bmatrix}$$

$$+\frac{3\gamma_{23}}{\Delta_{hl}}\frac{\hbar^{2}\left\langle k_{z}^{2}\right\rangle}{2m_{0}}\beta\begin{bmatrix}0 & K_{+}K_{-}K_{+}\\ K_{-}K_{+}K_{-} & 0\end{bmatrix}\qquad -i\frac{3\gamma_{23}}{\Delta_{hl}}\frac{\hbar^{2}E_{z}}{2m_{0}}\alpha_{R}\begin{bmatrix}0 & -(K_{+})^{3}\\ (K_{-})^{3} & 0\end{bmatrix}$$

D. LOSS ET AL., Phys. Rev. Lett. **95,** 076805 (2005)
F. PEETERS ET AL., Phys. Rev. Lett. **109,** 107201 (2012)

HEAVY HOLES IN QUANTUM WELLS

Large heavy–light hole gap
(quantum wells, flat quantum dots)
- perturbative regime

Extreme anisotropy of the heavy-hole g-factor:
- zero for the magnetic field in-plane
- nonzero for the field in the growth direction

Spin-orbit interactions cause heavy-hole spin flips
Matrix element ~ K^3 (spin rotation as HH moves)

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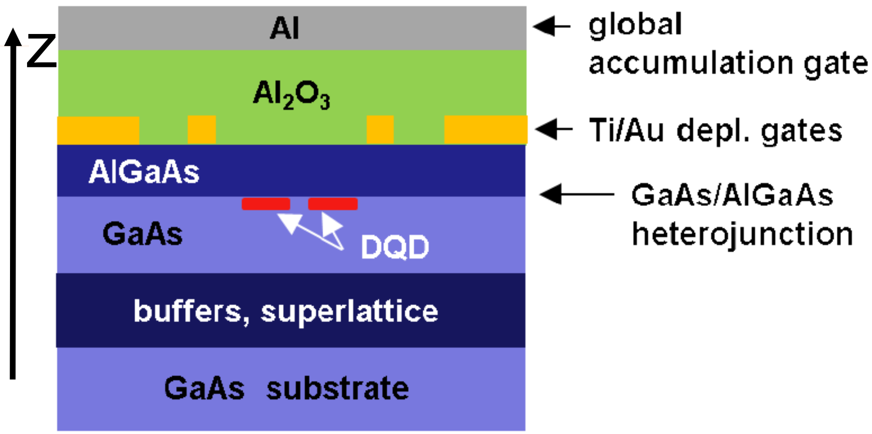
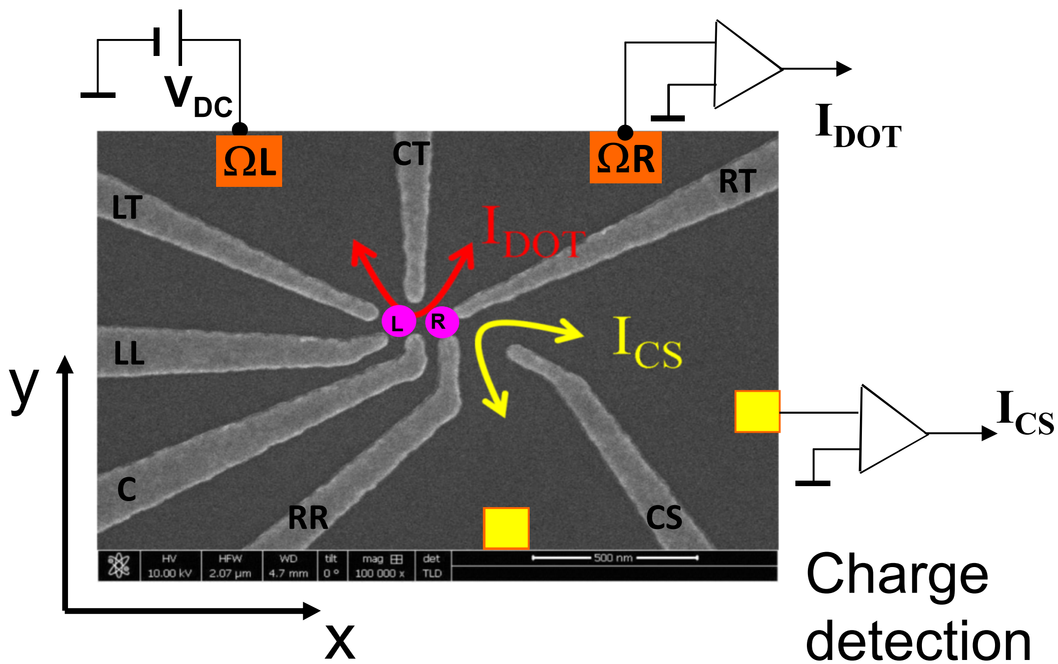
GATED LATERAL DOUBLE QDOT



Transport measurement



Charge detection

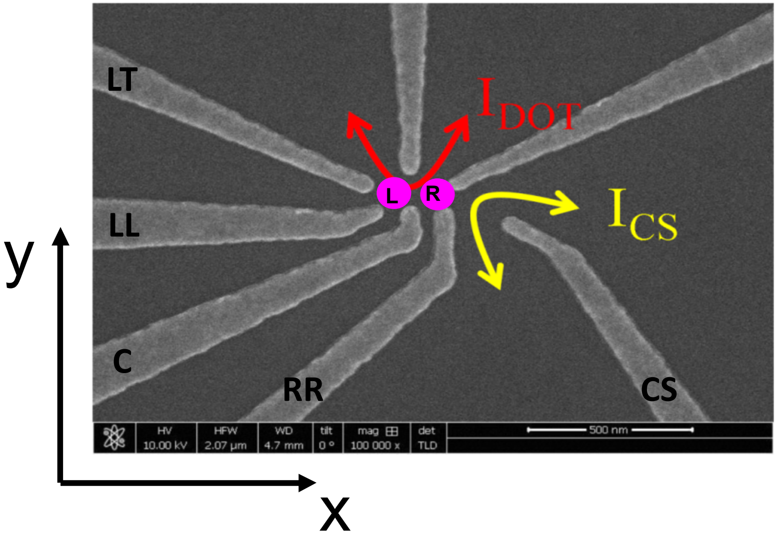
Strong confinement in the z direction

Defines heavy-hole spin quantization axis

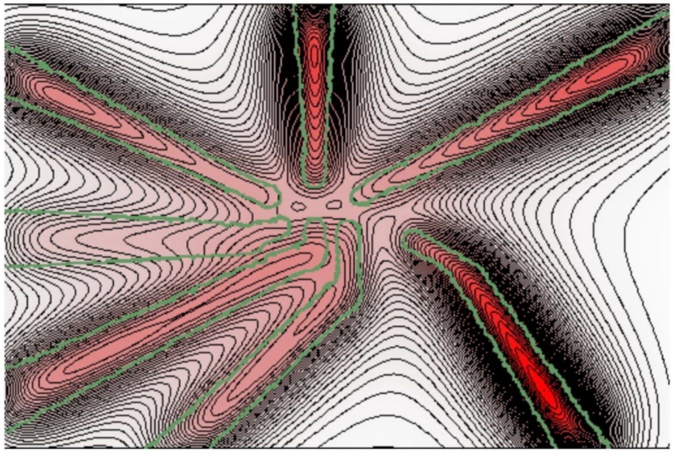
L. A. Tracy et al., Appl. Phys. Lett. **104,** 123101 (2014)

GATED LATERAL DOUBLE QDOT

Gate layout



Calculated potential



Simulations:

Only heavy holes are confined laterally

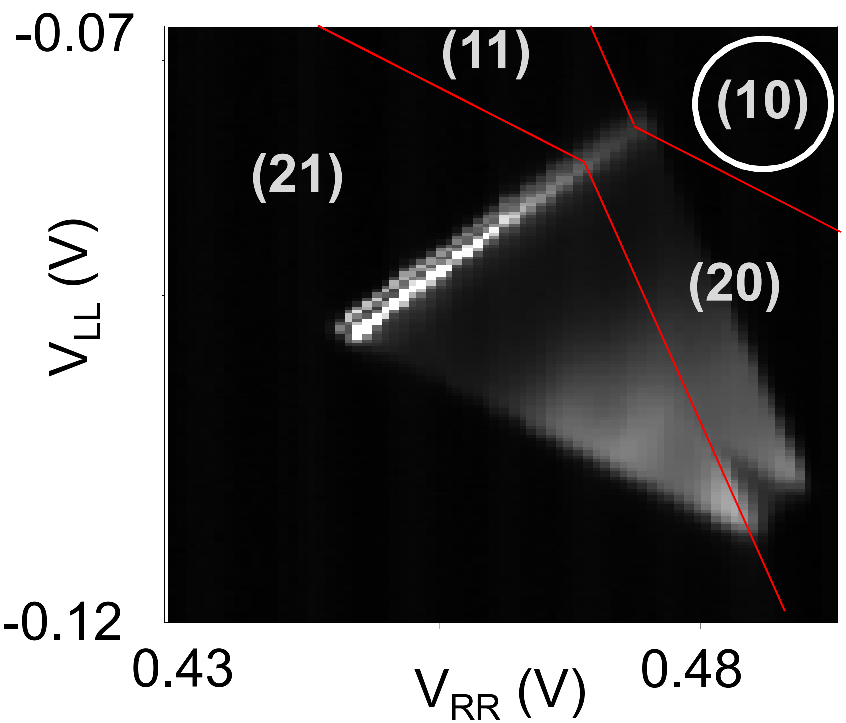
Light hole states are not confined in dots

As a result, very weak HH-LH coupling expected in the dots

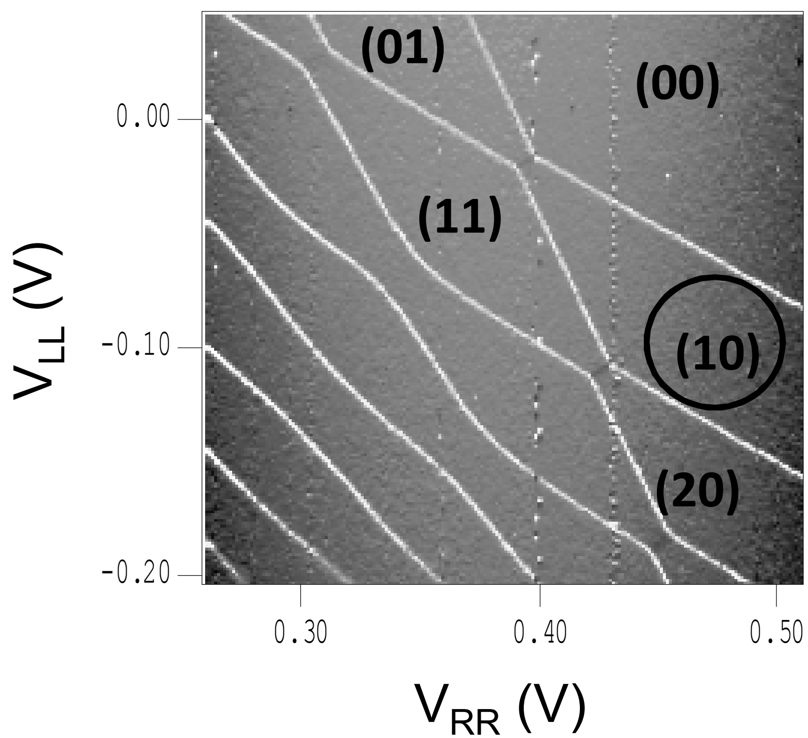
This is unlike in self-assembled dots or nanowires

CHARGING DIAGRAMS

Transport measurement (I_{DOT})



Charge measurement (dI_{CS})



We can empty the double dot and readmit exactly one hole

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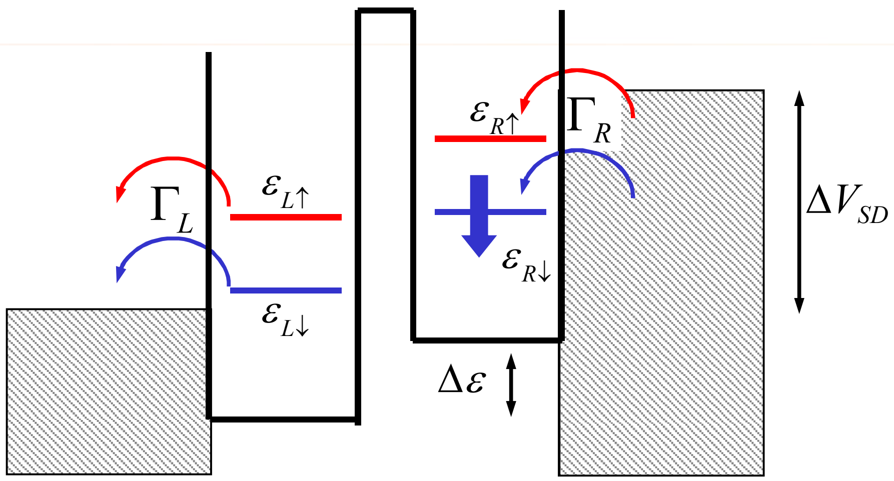
SINGLE-HOLE TRANSPORT MODEL



We control the Zeeman splitting by the magnetic field

We control detuning by gates

$$H = \begin{bmatrix} \varepsilon_{L\uparrow} & 0 & t_N & -i|t_F|e^{-i\phi} \\ & \varepsilon_{L\downarrow} & -i|t_F|e^{i\phi} & t_N \\ & & \varepsilon_{R\uparrow} & 0 \\ c.c. & & & \varepsilon_{R\downarrow} \end{bmatrix}$$

t_N spin-conserving tunneling

t_F spin-flip tunneling
Rashba+Dresselhaus

Hybrid spin-charge system

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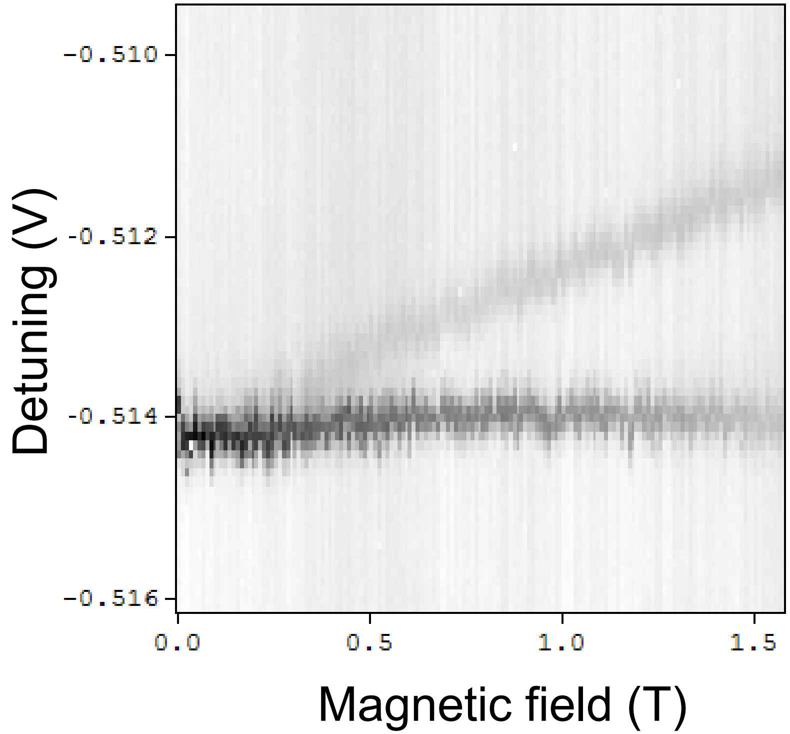
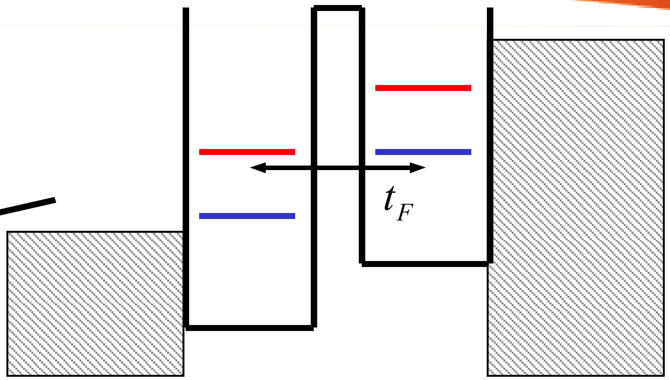
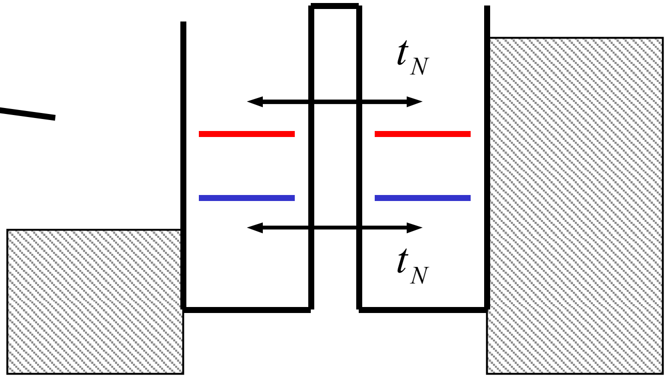
SINGLE-HOLE TRANSPORT

Measured tunneling current

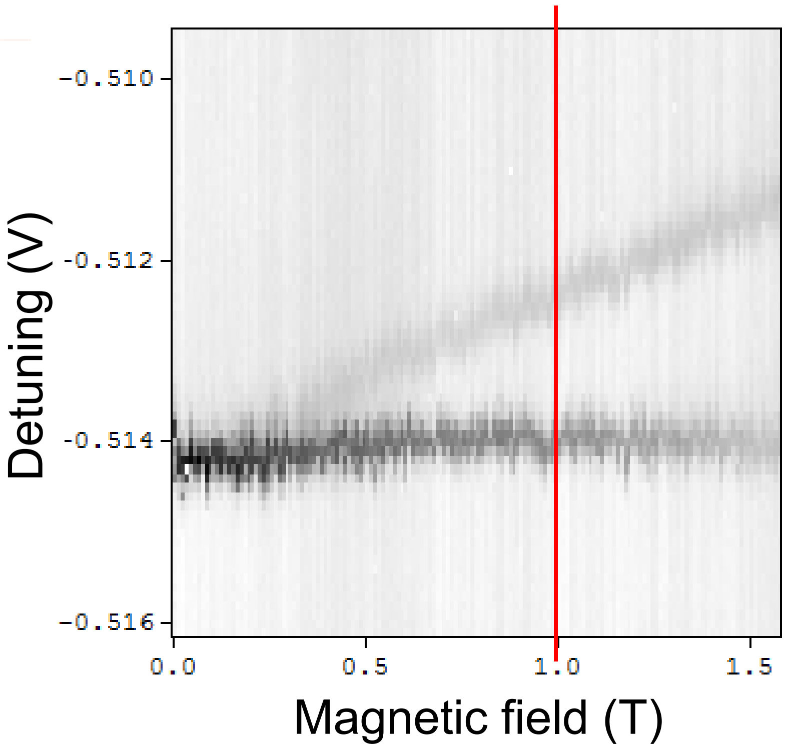




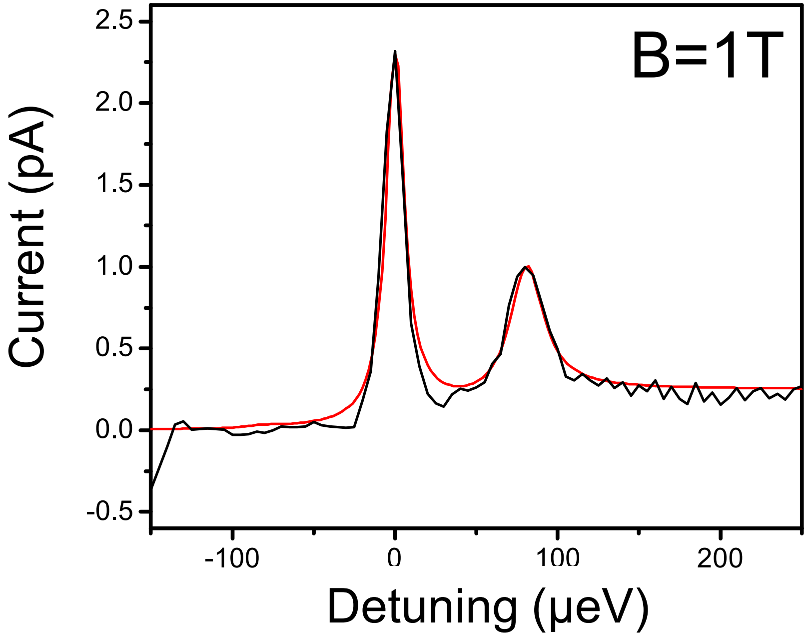


Both spin-conserving and spin-flip resonances are strong

TUNNELING MATRIX ELEMENTS



Extracted current trace



Black – measurement

Red – theoretical fit

$$\frac{d}{dt}\hat{\rho}(t) = -i\left[\hat{H}, \hat{\rho}(t)\right] + \hat{\Gamma}\hat{\rho}(t)$$

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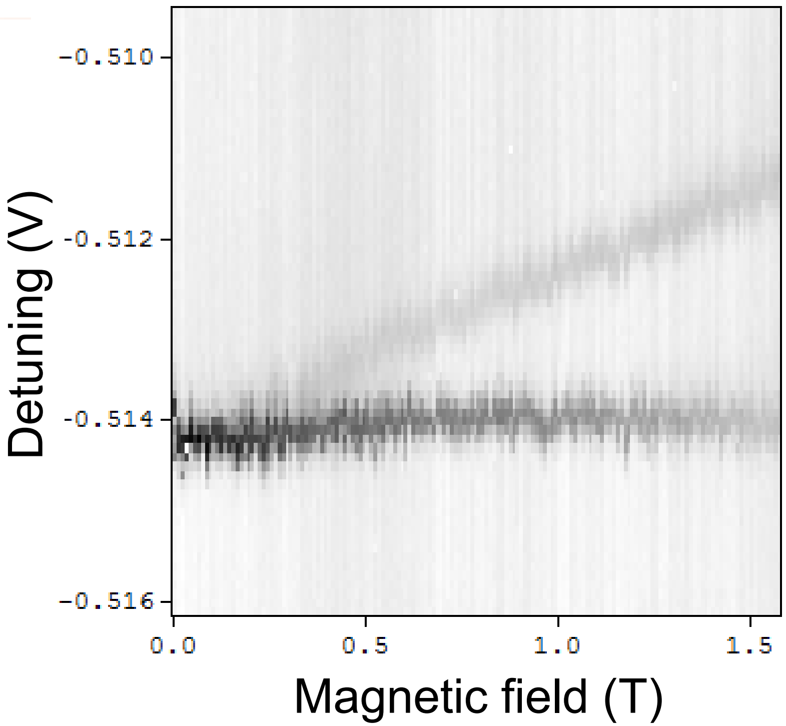
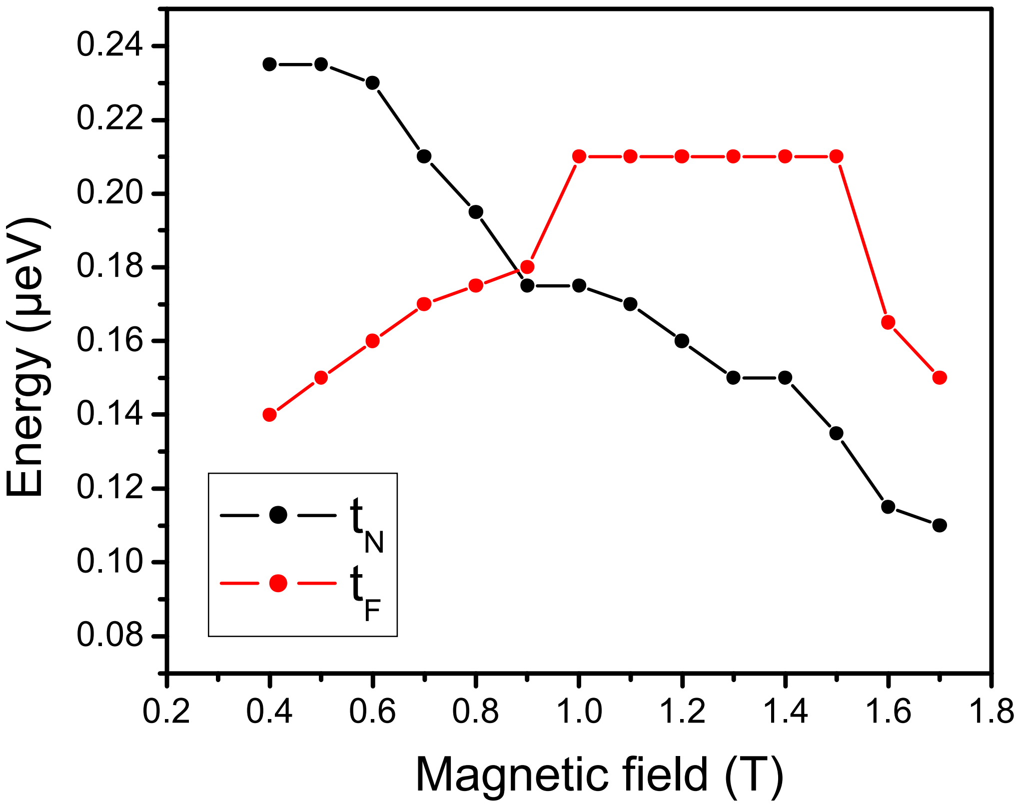
TUNNELING MATRIX ELEMENTS





t_N and t_F of similar magnitude

$$t_N \sim \langle L\downarrow | V(x,y) | R\downarrow \rangle \qquad t_F \sim \langle L\uparrow | K_x^3 | R\downarrow \rangle$$

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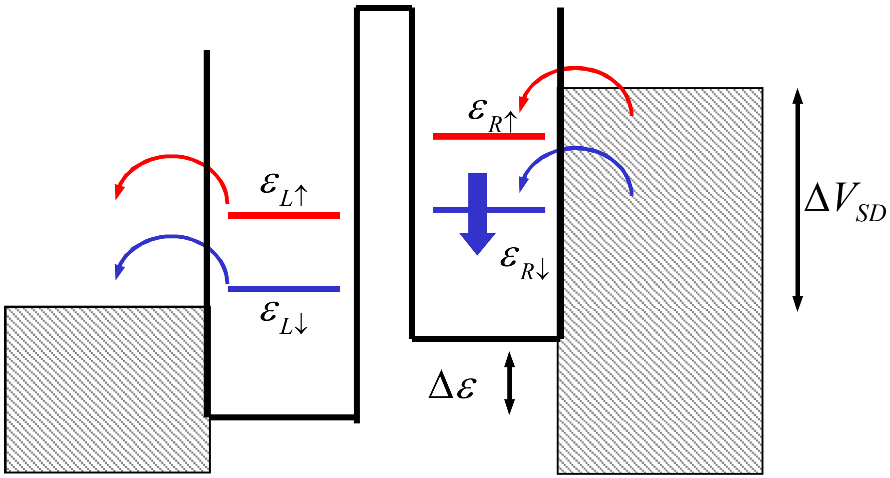
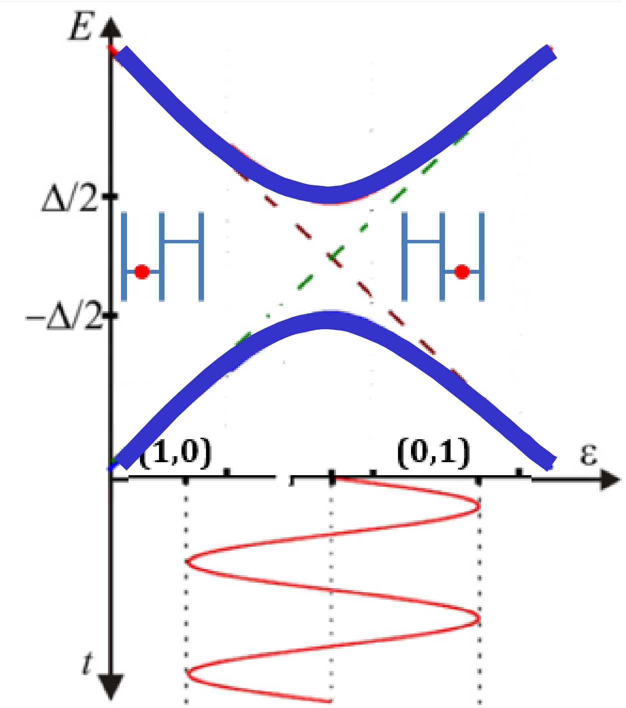
MICROWAVE MODULATION

Probing the tunneling dynamics



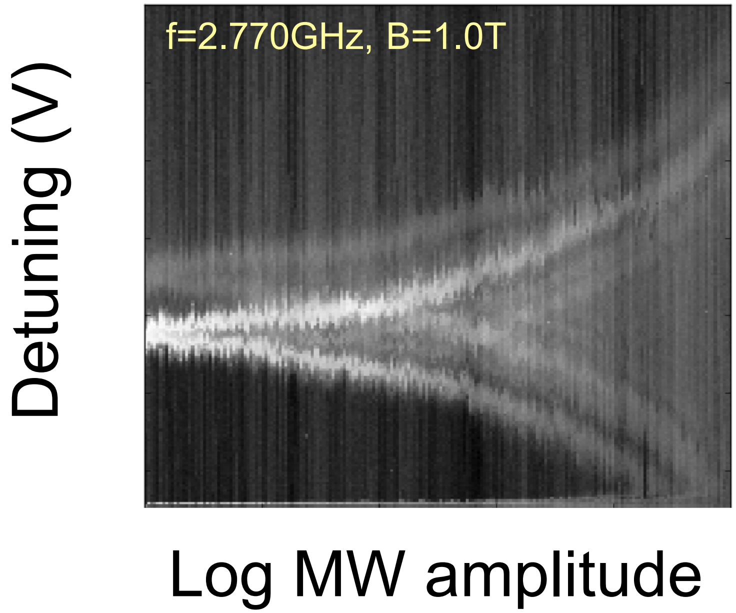


$$\Delta\varepsilon(t) = \Delta\varepsilon_0 + V\sin\omega_{MW}t$$

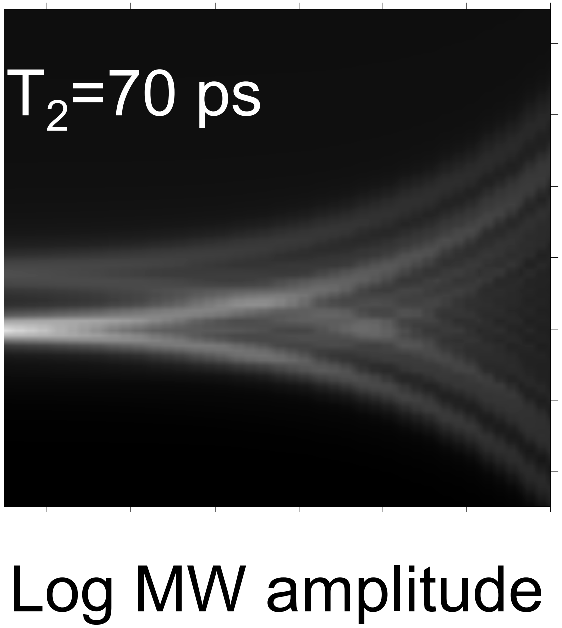
LANDAU-ZENER-STUECKELBERG OSCILLATIONS

MICROWAVE MODULATION

Measured



Calculated



Charge relaxation time: T_1 ~2.5 μs

Spin relaxation time: T_{1S} ~1 μs

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HEAVY HOLES IN QUANTUM WELLS

Now we explore the g-factor anisotropy

$$H = \begin{bmatrix} \frac{1}{2m^*_{HH}}\hat{P}^2 + V(x,y) - \boxed{\frac{1}{2}g^*\mu_B B_z} & 0 \\ 0 & \frac{1}{2m^*_{HH}}\hat{P}^2 + V(x,y) + \boxed{\frac{1}{2}g^*\mu_B B_z} \end{bmatrix}$$

$$+\frac{3\gamma_{23}}{\Delta_{hl}}\frac{\hbar^2\langle k_z^2\rangle}{2m_0}\beta\begin{bmatrix} 0 & K_+K_-K_+ \\ K_-K_+K_- & 0 \end{bmatrix} \qquad -i\frac{3\gamma_{23}}{\Delta_{hl}}\frac{\hbar^2 E_z}{2m_0}\alpha_R\begin{bmatrix} 0 & -(K_+)^3 \\ (K_-)^3 & 0 \end{bmatrix}$$

D. LOSS ET AL., Phys. Rev. Lett. **95,** 076805 (2005)
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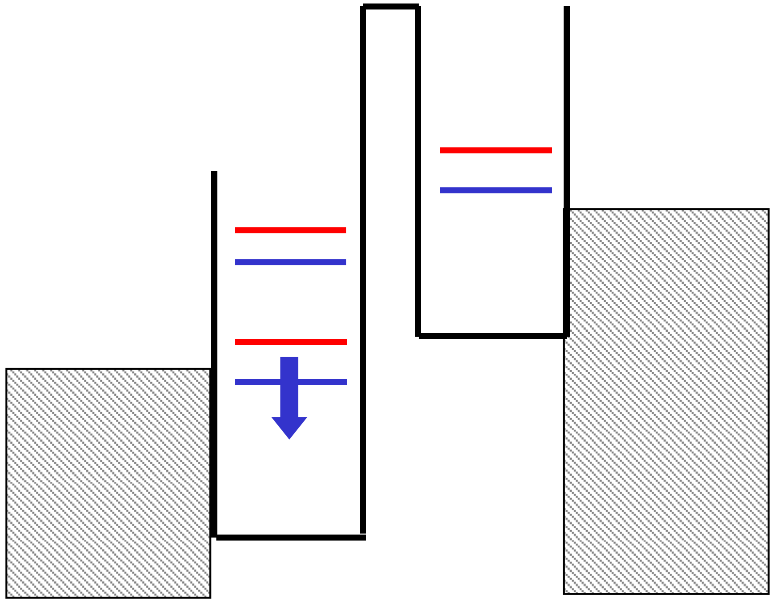
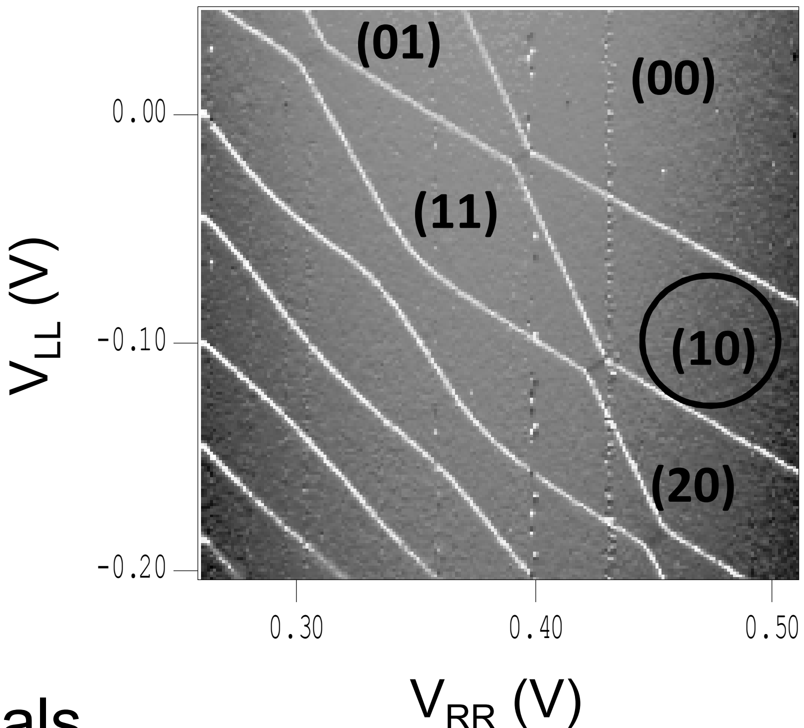
RESONANT TUNNELING SPECTRA

We start with configuration (10)



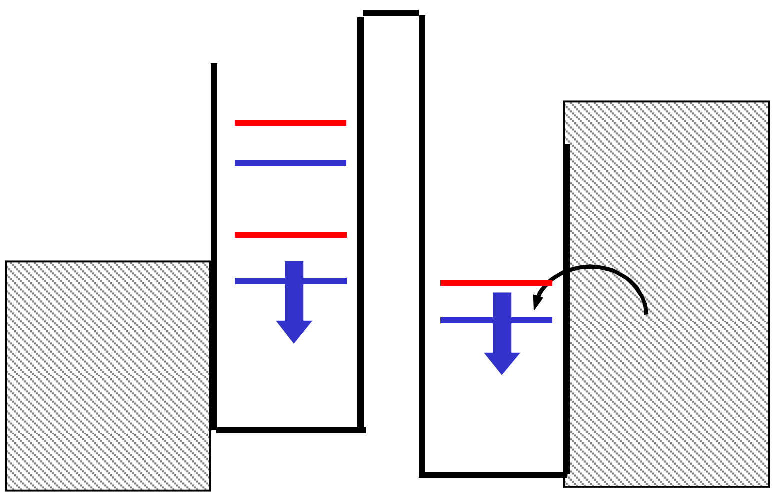


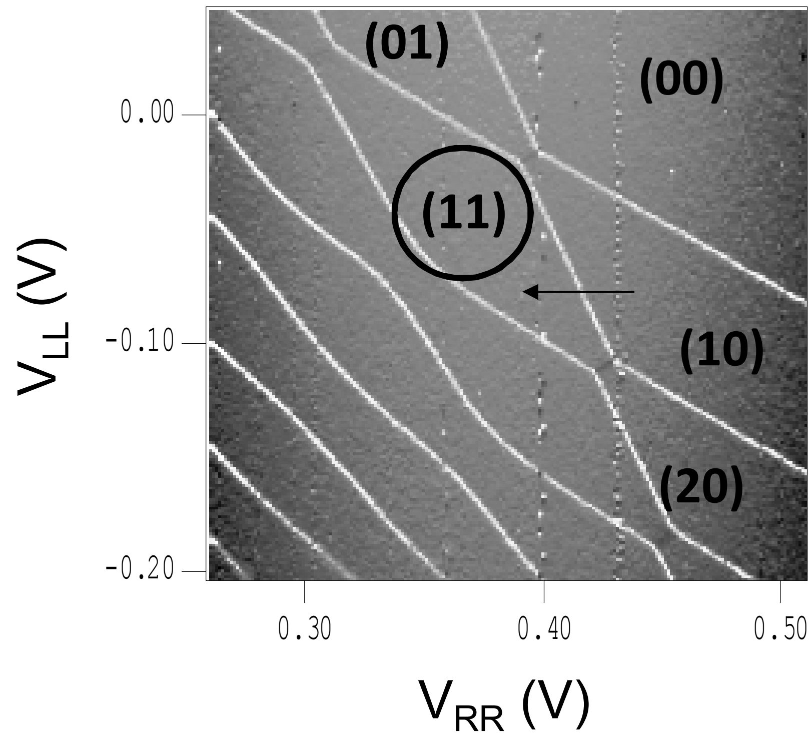
In the left-hand dot
we account for an extra pair of orbitals

Similar work (with more holes): A. Hamilton et al., Nano Lett. **16,** 7685

RESONANT TUNNELING SPECTRA

We admit one more hole creating (11)

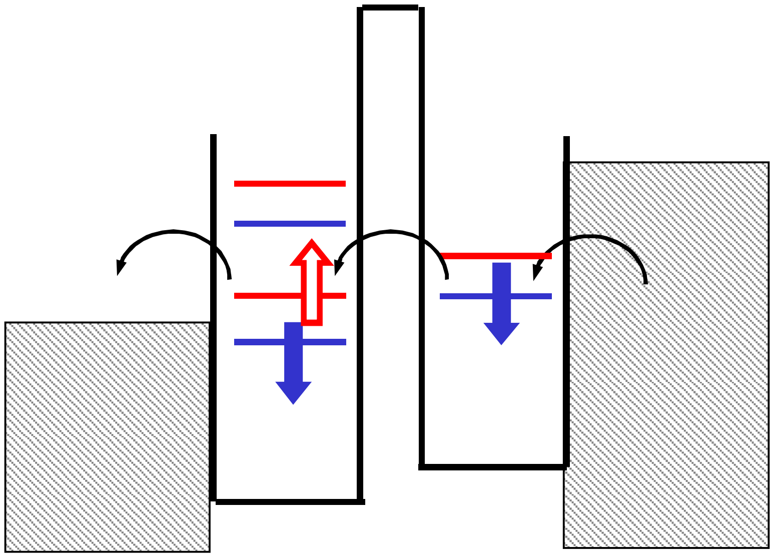


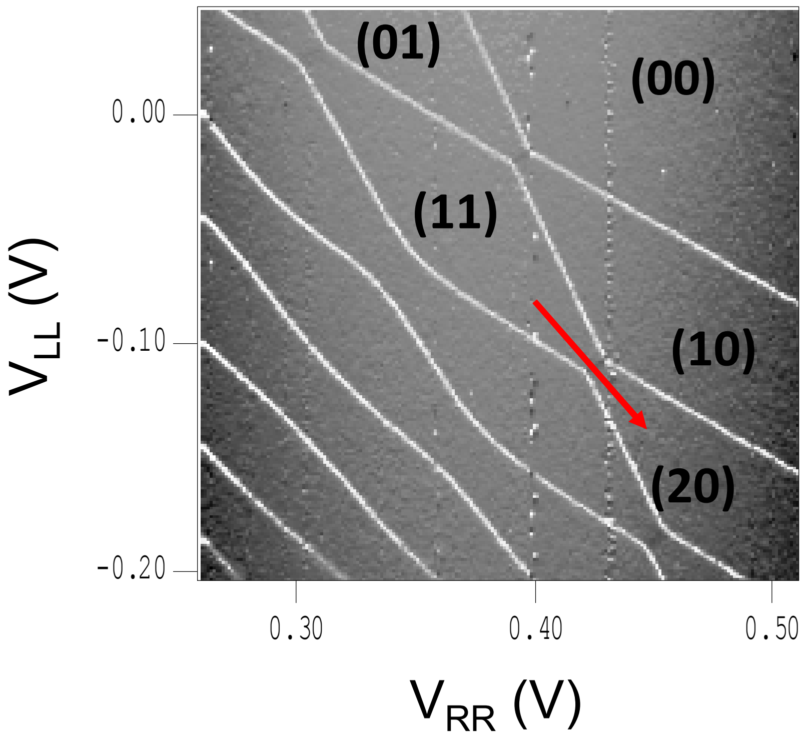


The two holes will relax
to the polarized triplet T-(11)

RESONANT TUNNELING SPECTRA

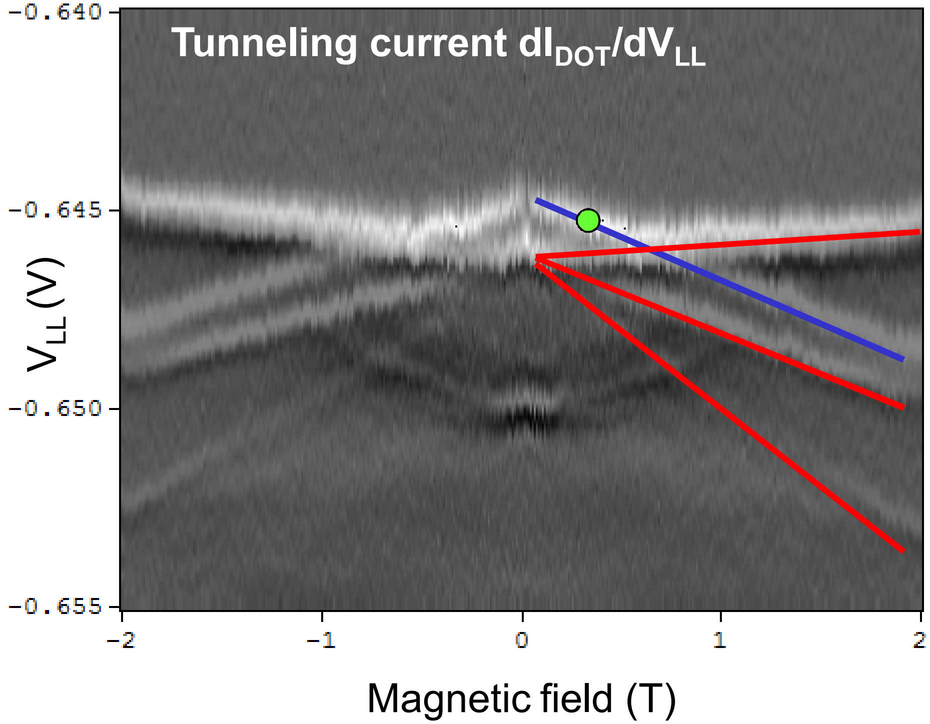
We tune gate voltages to obtain (11) – (20) resonant tunneling



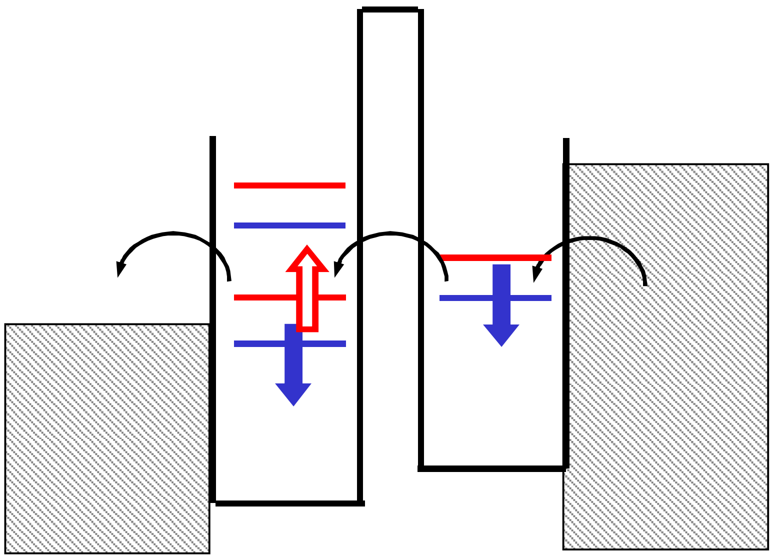


The hole will tunnel from the right to the left
Tunneling current will flow

RESONANT TUNNELING SPECTRA

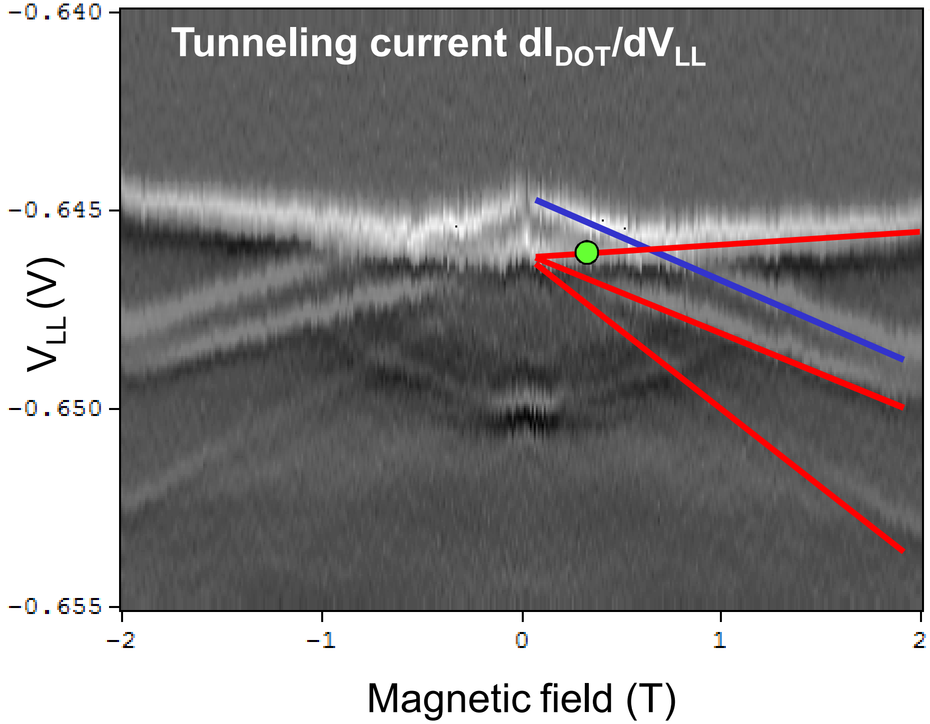


Spin-flip tunneling

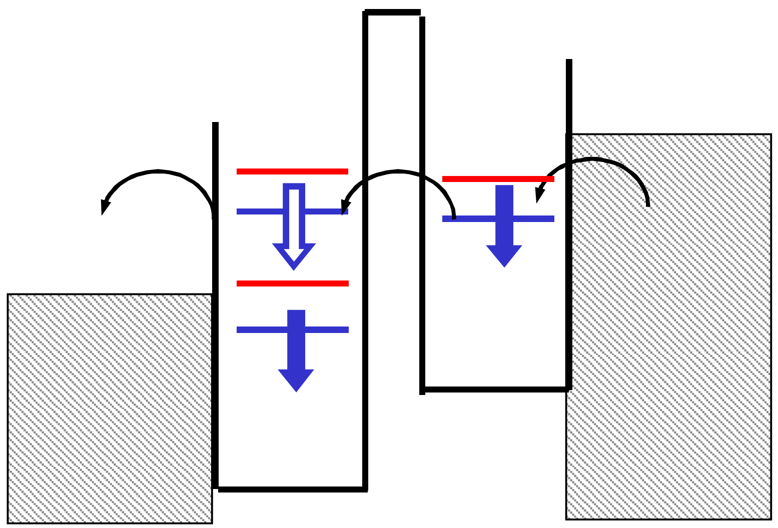


(20) state is a singlet

RESONANT TUNNELING SPECTRA



Spin-conserving tunneling



(20) state is a triplet

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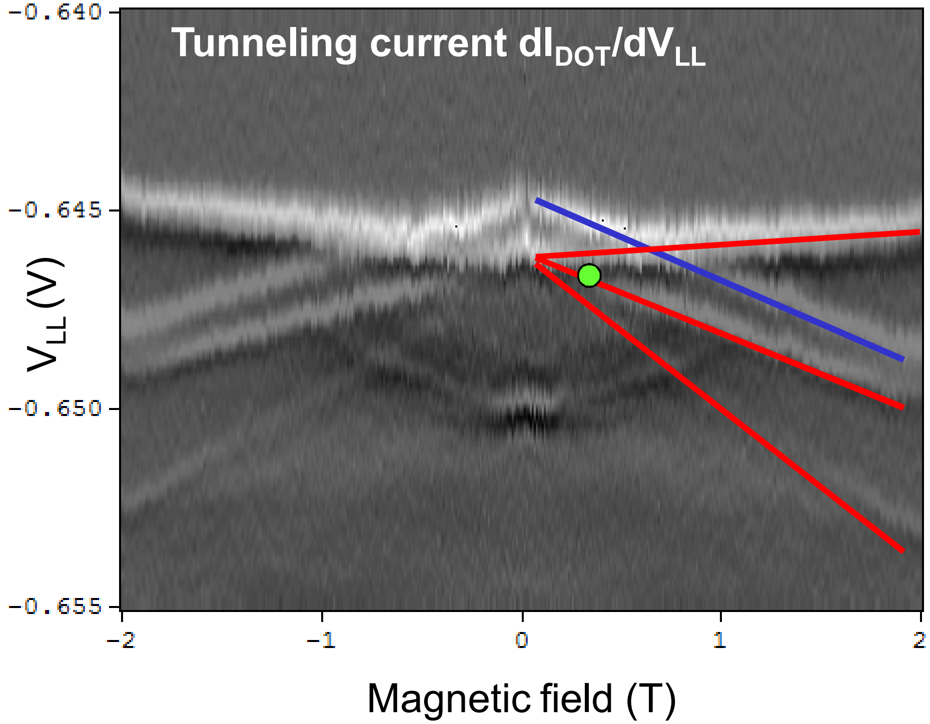
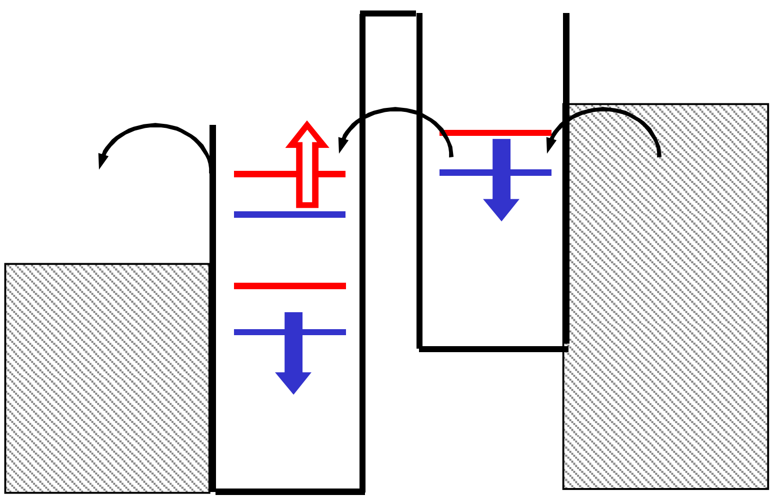
RESONANT TUNNELING SPECTRA

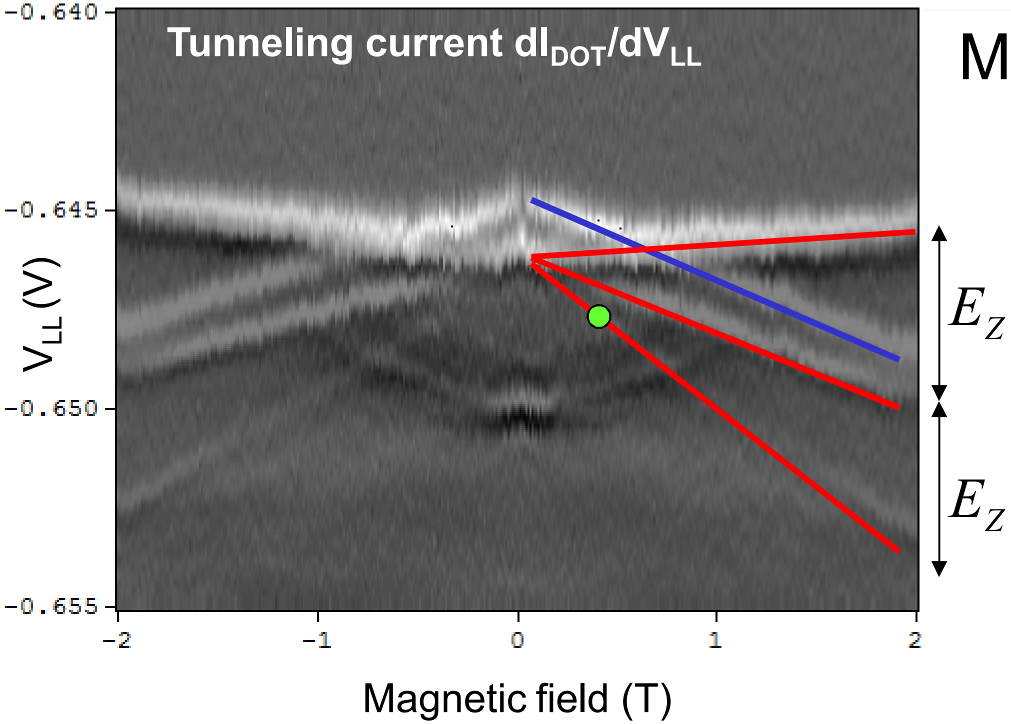


Spin-flip tunneling

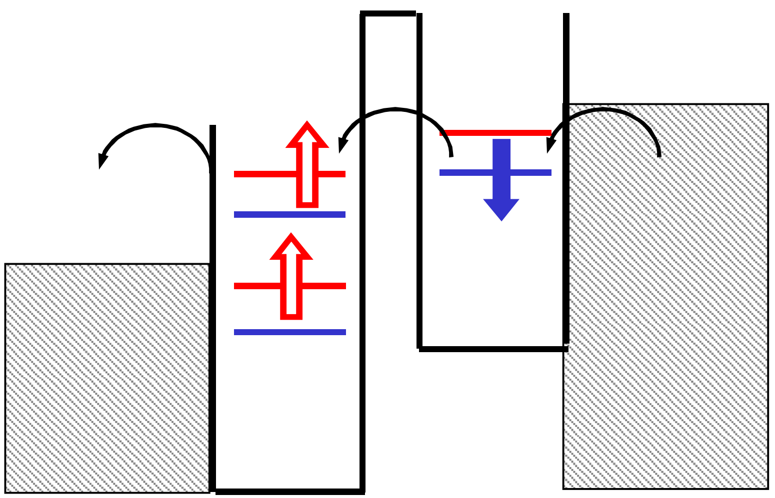


(20) state is a triplet

RESONANT TUNNELING SPECTRA



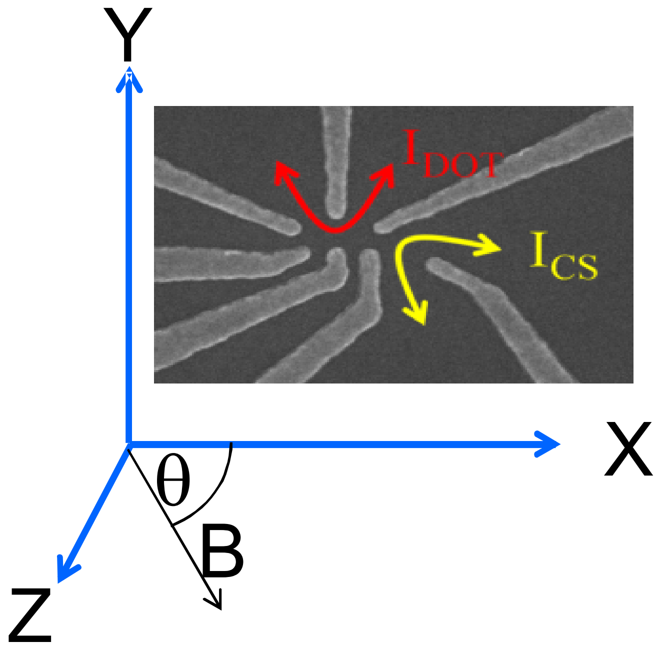
More complex spin-flip tunneling

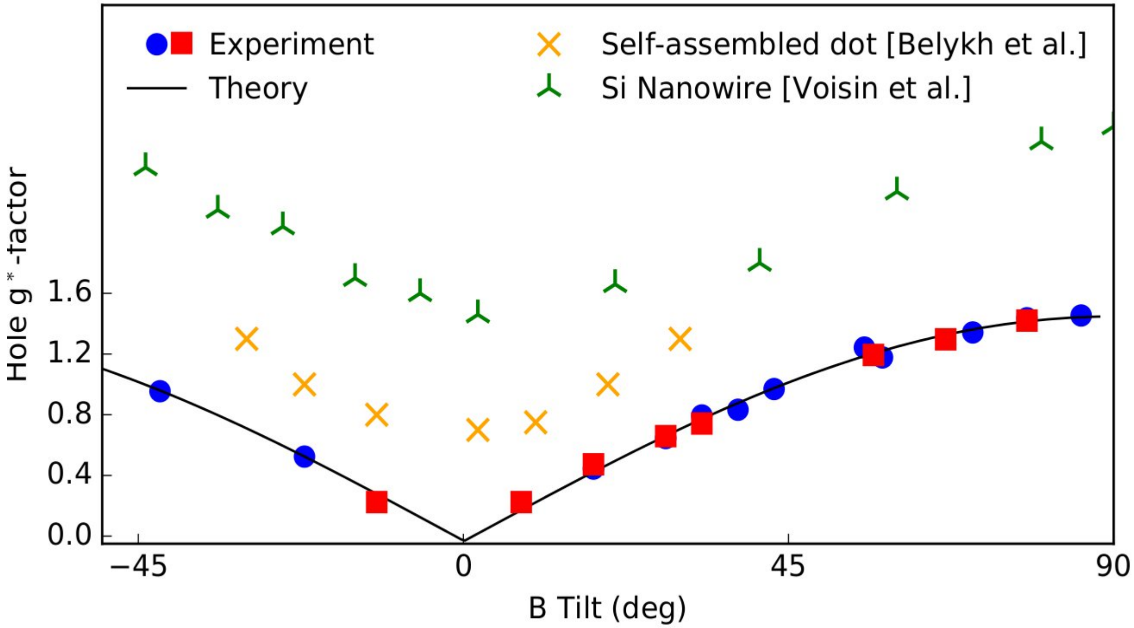


(20) state is a triplet

EXTRACTION OF g FACTOR

Effective g-factor in tilted magnetic field





The g-factor is anisotropic: g* ~ 0 for in-plane magnetic field
Our confined states are nearly pure heavy-holes
The g-factor is tunable in-situ

CONCLUSIONS

1. Motivation: Photon - to - spin interface
2. Holes in semiconductors: a brief reminder
3. Heavy-hole single-subband regime:
   Anisotropic g factor, spin-orbit interactions
4. Single hole in a gated double dot:
   Coherent spin-flip tunneling – theory and experiment
5. Two holes in a double dot: Lifting of Pauli blockade,
   strong g-factor anisotropy