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Anisotropic heavy-hole g-factors & relevance to photon-to-spin conversion schemes in semiconductor quantum dot circuits

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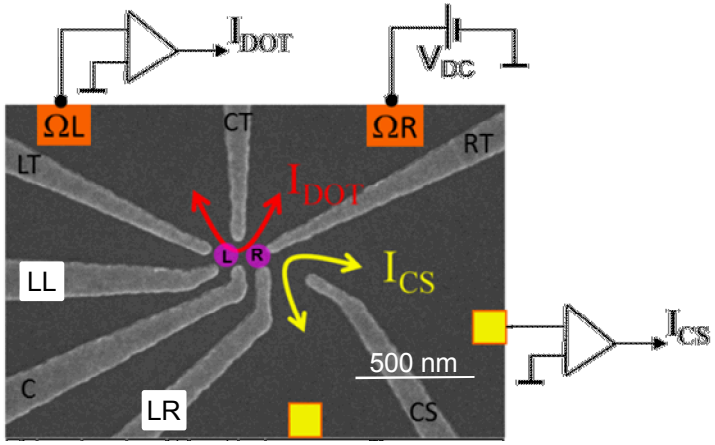
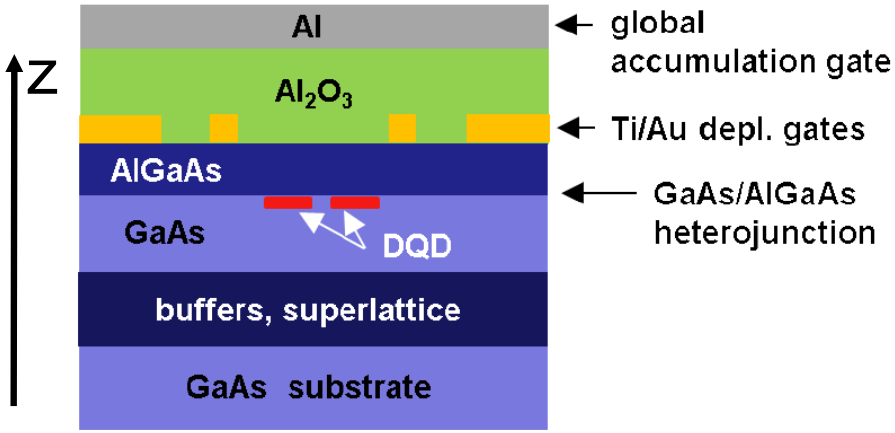
Why holes in GaAs quantum dots?

- Holes:
  - Strongly anisotropic g*-factor (heavy-hole g*-factor tunable to zero in appropriately oriented external magnetic field).
  - Expect reduced coupling to nuclei compared to electrons.
  - Strong spin-orbit interaction.
- GaAs:
  - Traditional workhorse for spin qubits in quantum dots.
  - Direct bandgap semiconductor that can host inter-band excitations necessary for a photon-to-spin interface.
  - Clean and readily available.

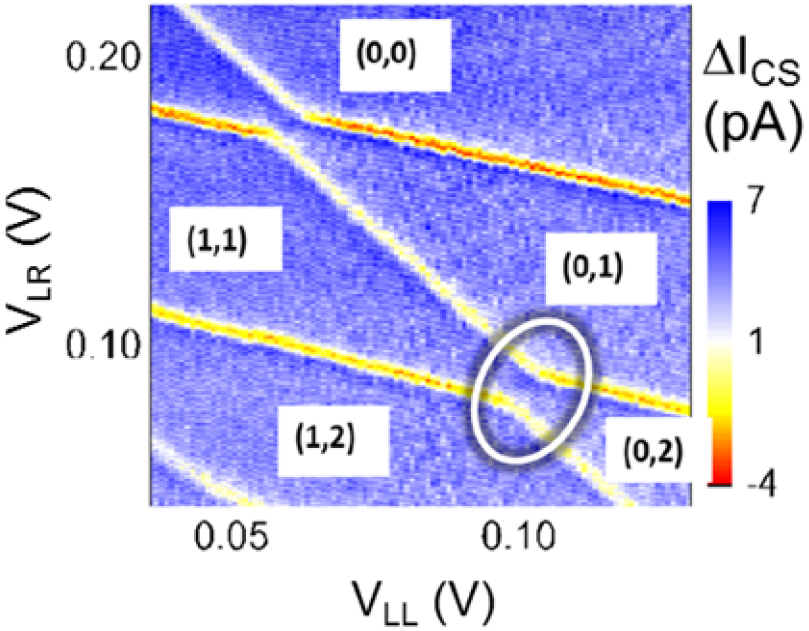
Few-hole double quantum dot device in an undoped GaAs/AlGaAs hetero-structure





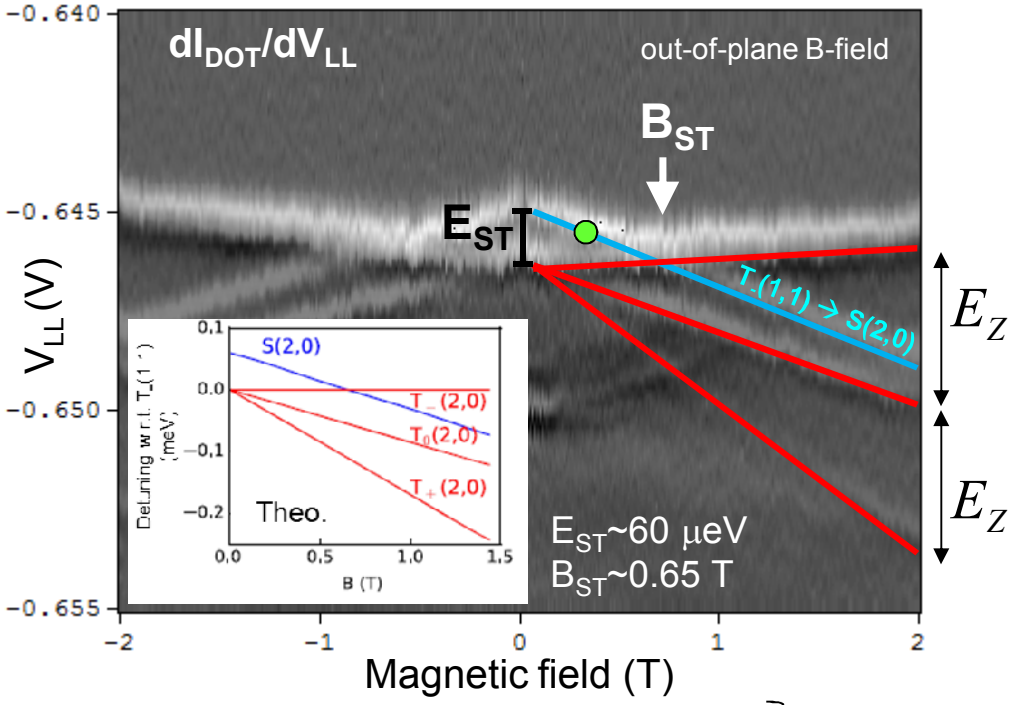
L. A. Tracy et al., Appl. Phys. Lett. **104,** 123101 (2014)
L. A. Tracy et al., Sandia Report SAND2015-8132 (2015)

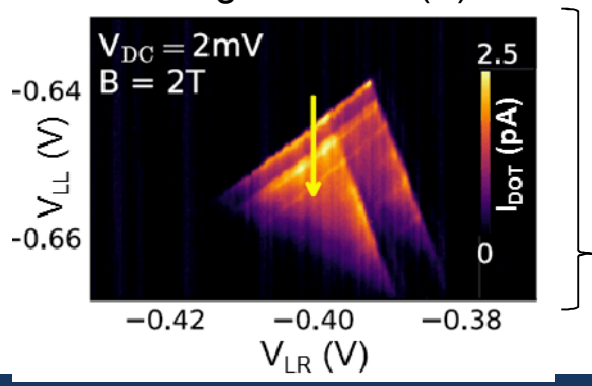
Single-hole limit reached



GaAs dots for holes:
Klochan Appl. Phys. Lett. (2010)
Mak Appl. Phys. Lett. (2013)
Komijani Phys. Rev. B (2013)
Wang Nanoletters (2016)
Wang Nanotechnology (2016)
…

Resonant tunneling spectroscopy of two hole system

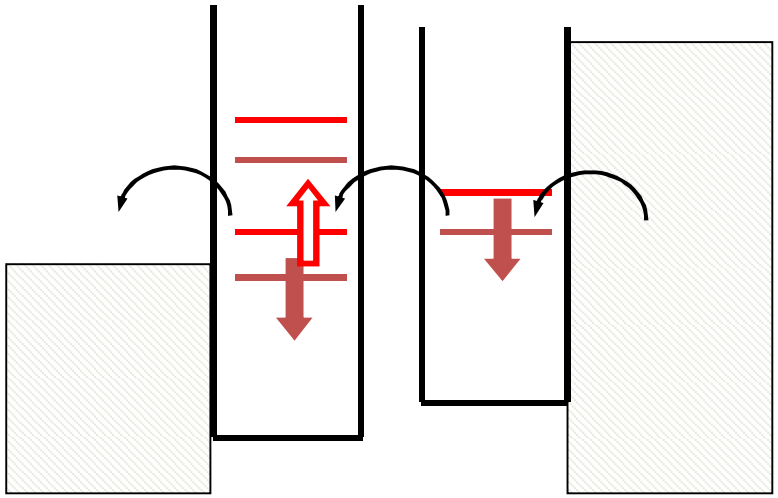




Upper triangle:
(1,0)→(1,1)→(2,0)→(1,0)
Lower triangle:
(2,1)→(1,1)→(2,0)→(2,1)

See Bogan et al., Phys. Rev. Lett. (2017)

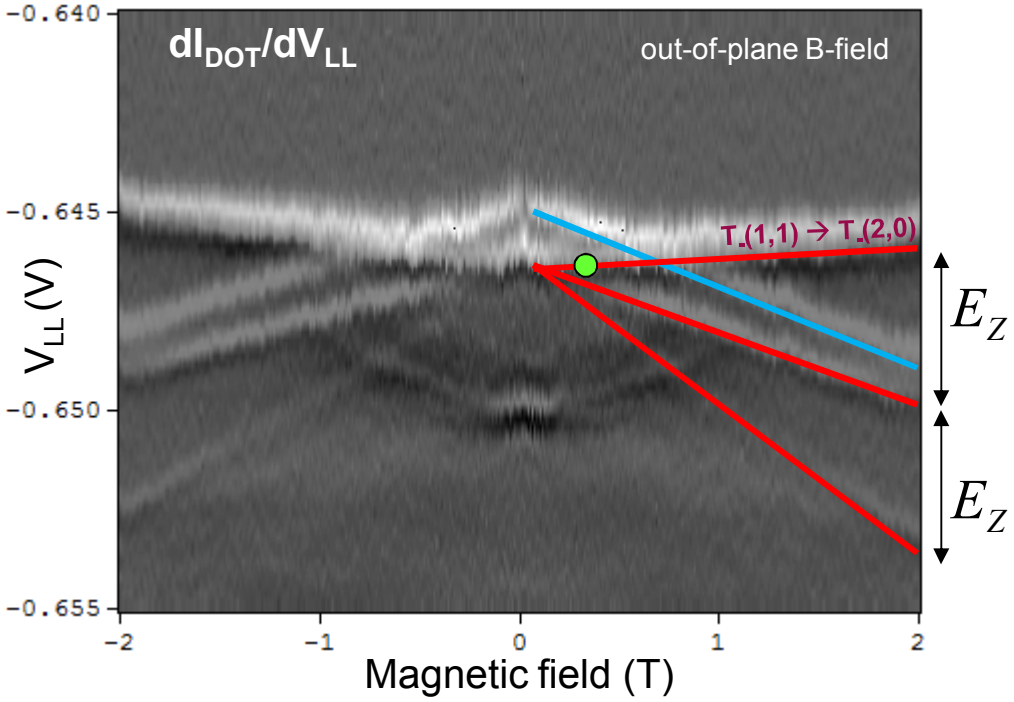
Spin-flip tunneling (via spin-orbit)

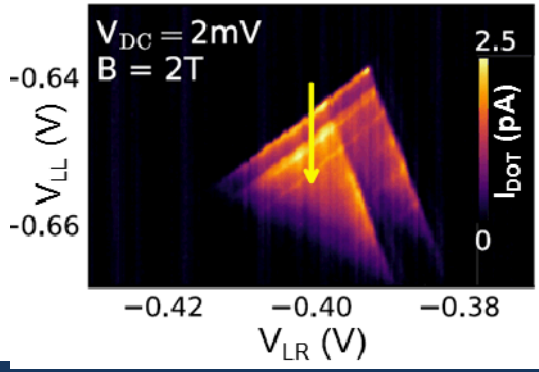


(2,0) state is a singlet

Similar situation with electrons :
Pfund Phys. Rev. B (2007) [InAs nano-wire DQD]
…

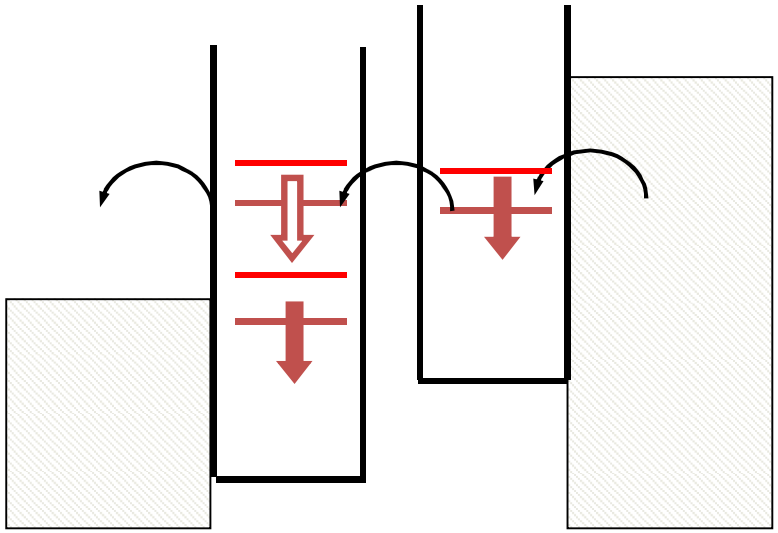
Resonant tunneling spectroscopy of two hole system





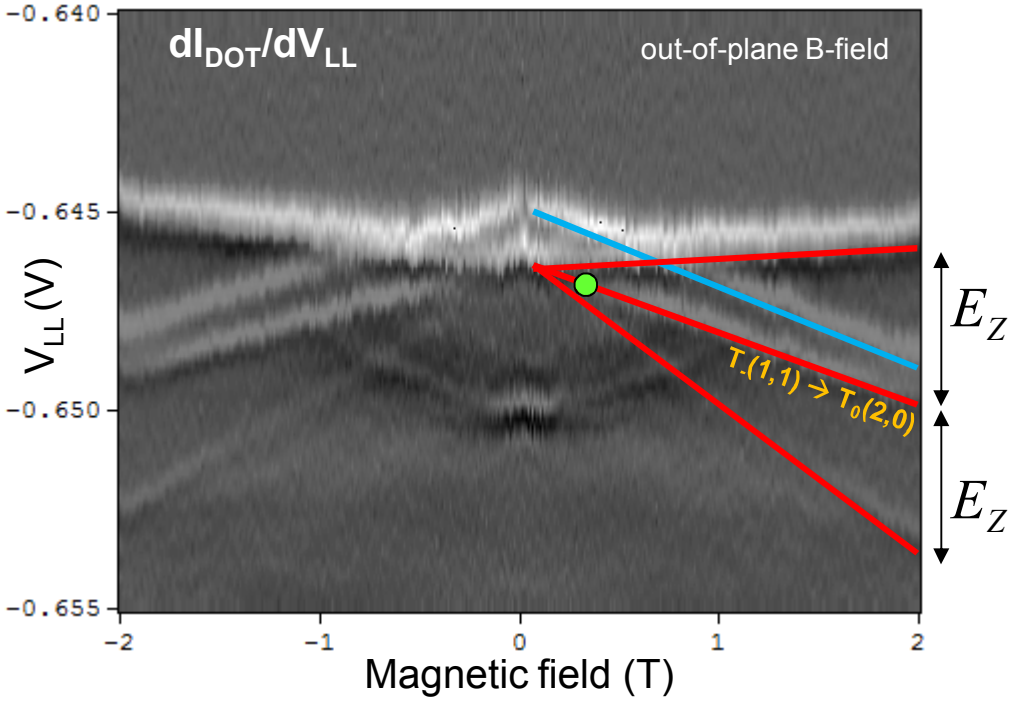
See Bogan et al., Phys. Rev. Lett. (2017)

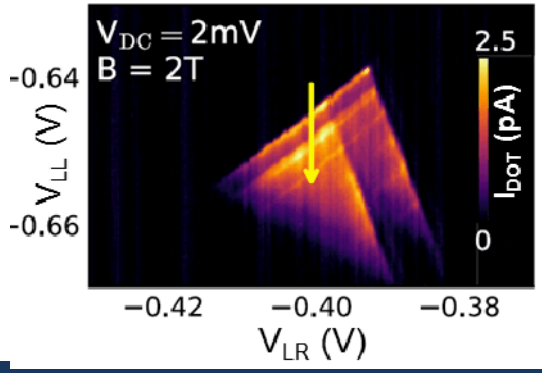
Spin-conserving tunneling



(2,0) state is a triplet

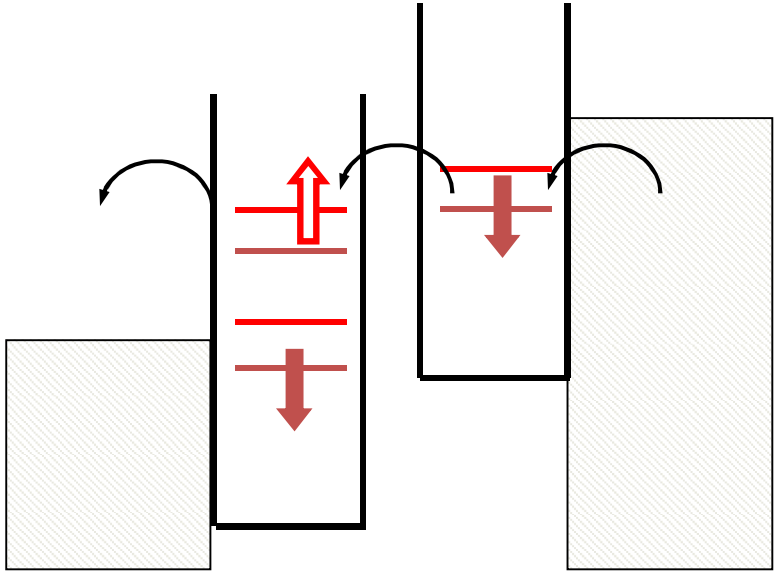
Resonant tunneling spectroscopy of two hole system





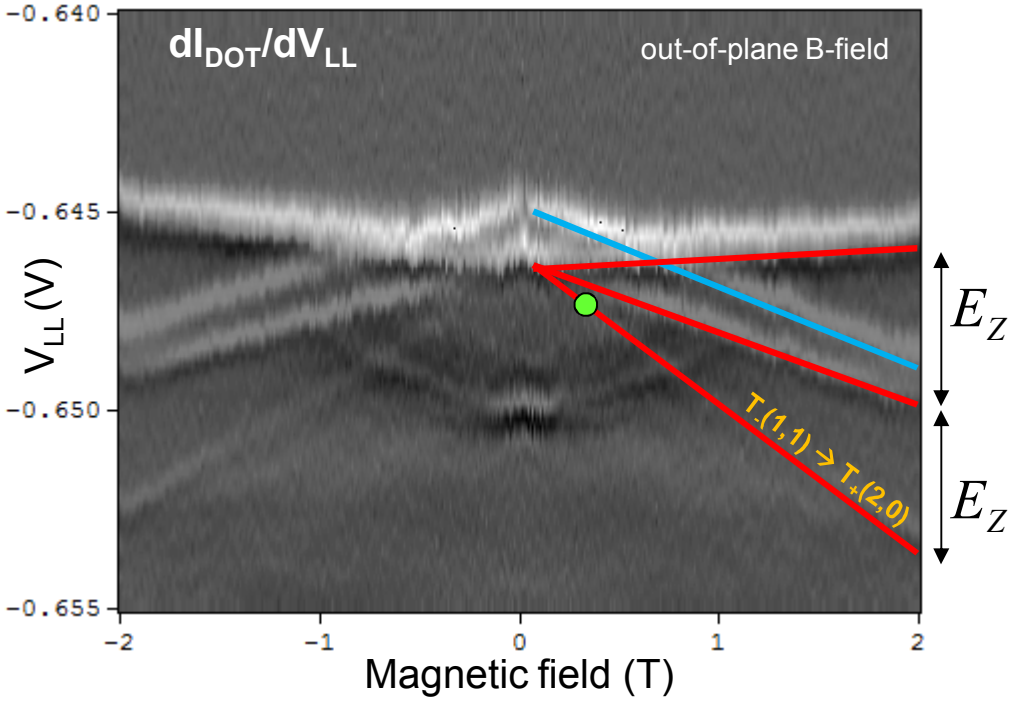
See Bogan et al., Phys. Rev. Lett. (2017)

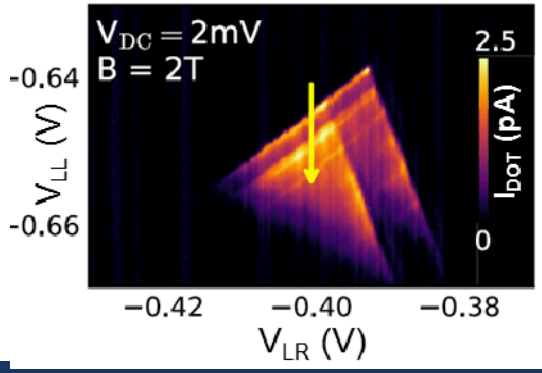
Spin-flip tunneling



(2,0) state is a triplet

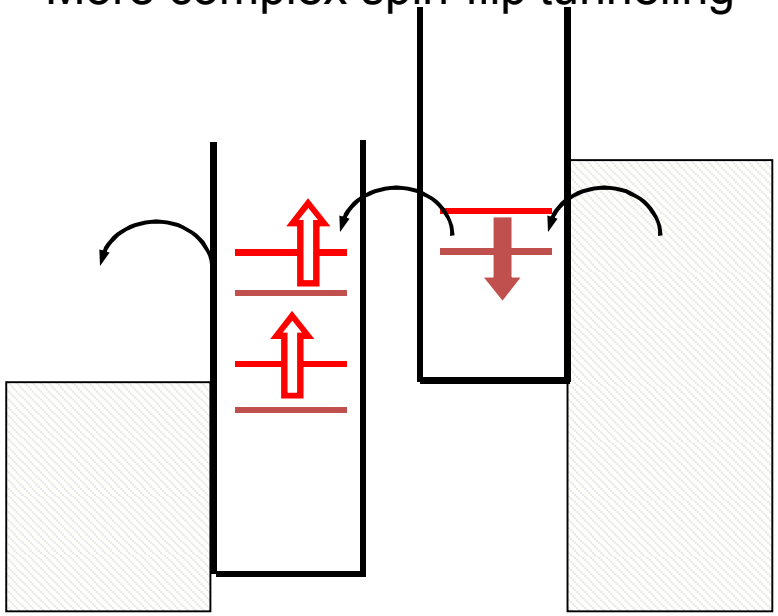
Resonant tunneling spectroscopy of two hole system





See Bogan et al., Phys. Rev. Lett. (2017)

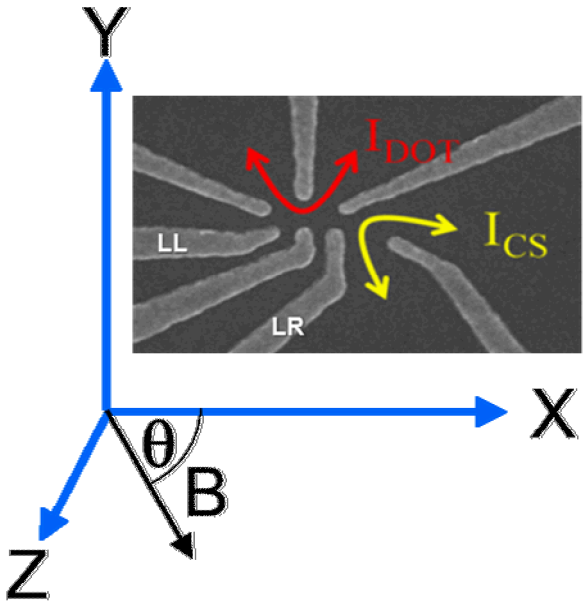
More complex spin-flip tunneling

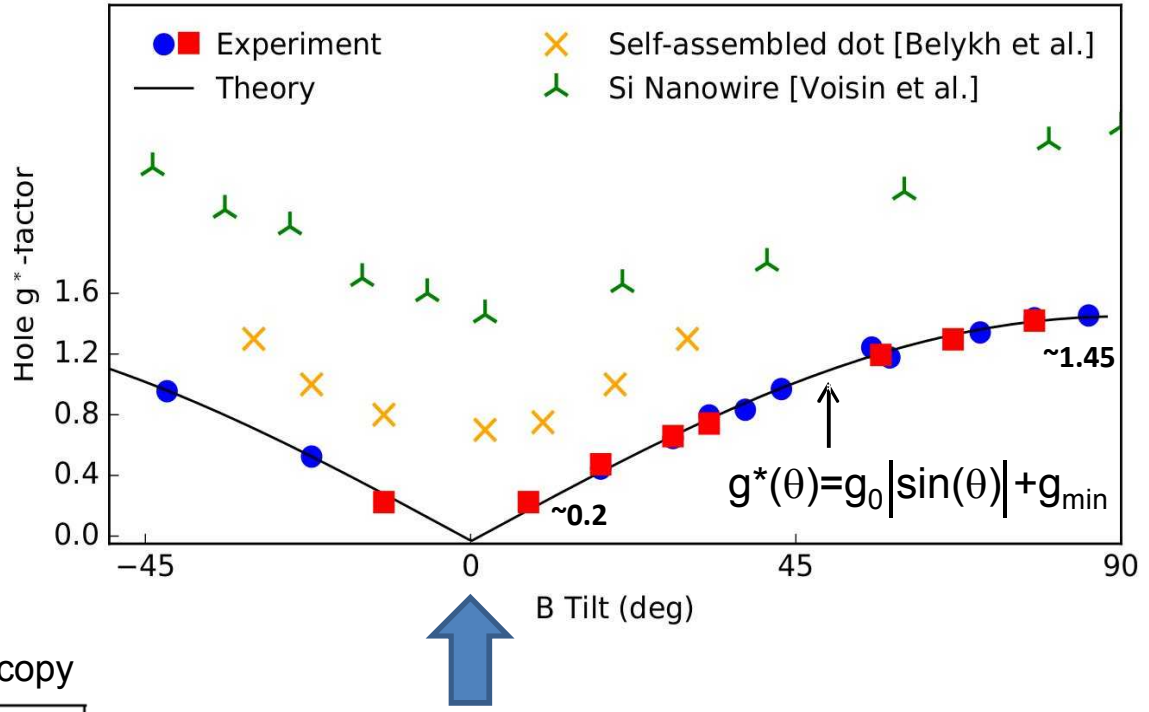


(2,0) state is a triplet

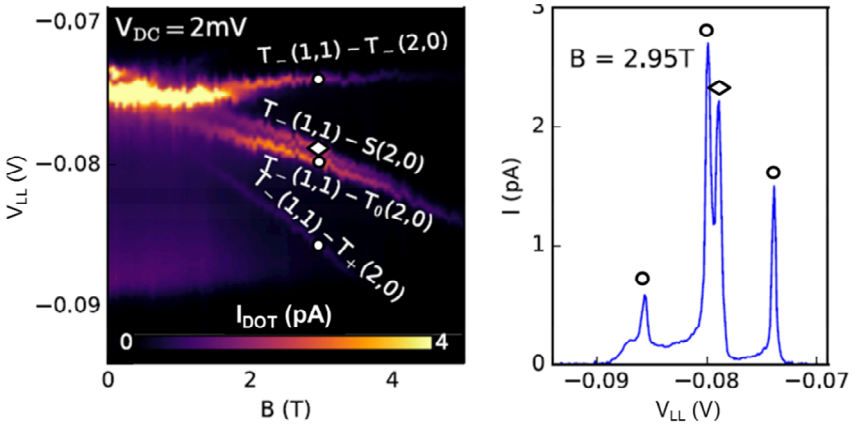
Effective heavy-hole g*-factor in tilted magnetic field: g*-factor anisotropy

See Bogan et al., Phys. Rev. Lett. (2017)





Two-Hole Transport Magneto-Spectroscopy



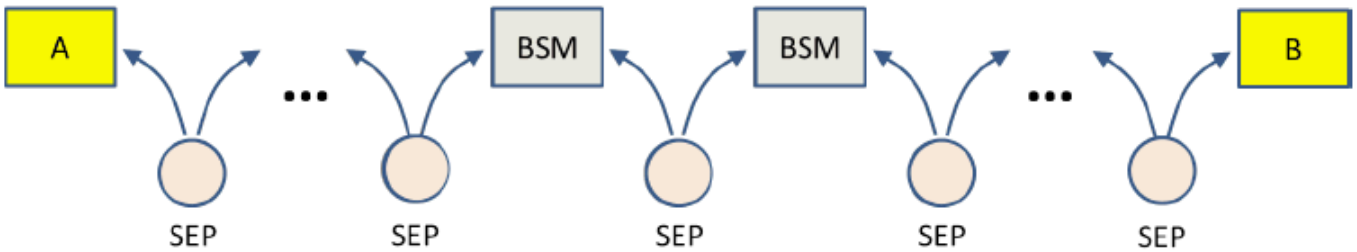
g_{min}=0.04±0.04 (for in-plane B-field)

Minimal heavy-hole light-hole mixing

See recent review Gaudreau et al., Semicond. Sci. Technol. (2017)

Problem of long distance entanglement distribution

(a) BSM=Bell state measurement, SEP=Source of entangled photons



Entanglement Distribution

Attractive Aspects:

1. Photo-generated spins can be heralded by non-destructive charge detection techniques.
2. Long spin coherence time (aka native quantum memory), e.g., 200 μs [Bluhm Nat. Phys. (2011)].
3. BSM with 100% success probability can in principle be achieved [Engel & Loss Science (2005); Yokoshi Phys. Rev. B (2010)].
4. Spin-to-photon conversion not required.

BSM node with for example atomic ensemble quantum memory…

Challenges:

1. Non-destructive signaling of successful photon storage challenging.
2. Stored photons must be regenerated before BSM which is an extra step.
3. BSM with linear optics succeeds with probability of 50% at most.

CD=Charge detector

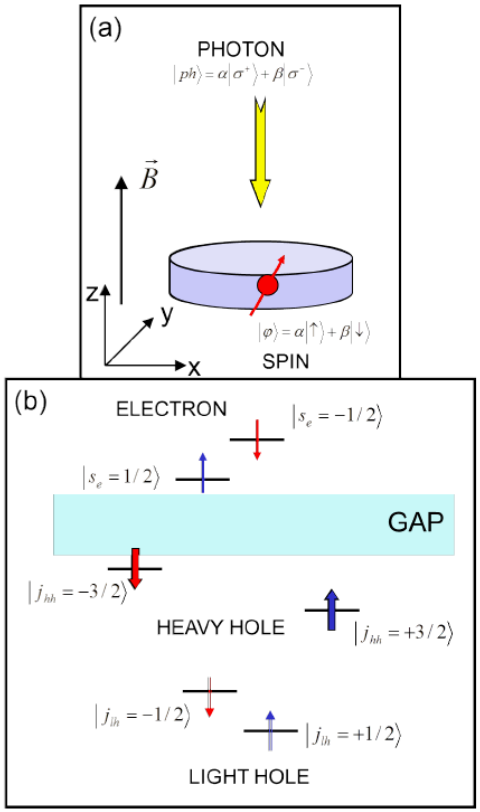
on-to-spin
on schemes
D circuits

itch Physica E (2001)
c IEEE (2003)
hys. (2011)
5)
Jpn (2017)

Polarization schemes

For transfer
of polarization-encoded state of photon
to spin state of QD

FARADAY CONFIG.



Vrijen & Yablonovitch, Physica E (2001)
Yablonovitch et al, Proc. IEEE (2003)
Kosaka, J. Appl. Phys. (2011)
Oiwa, J. Phys. Soc. Jpn (2017)

See also time-bin schemes: Kosaka Phys. Rev. A (2012)

A (near) zero g-factor is an important property to realize the necessary V- or Λ-shaped three-level system for a coherent photon-to-spin interface

Transfer
state of photon
polarization
→ state of heavy-hole

Natural anisotropy gives
heavy-hole g-factor ~0
for in-plane B-field
[Bogan PRL (2017)].

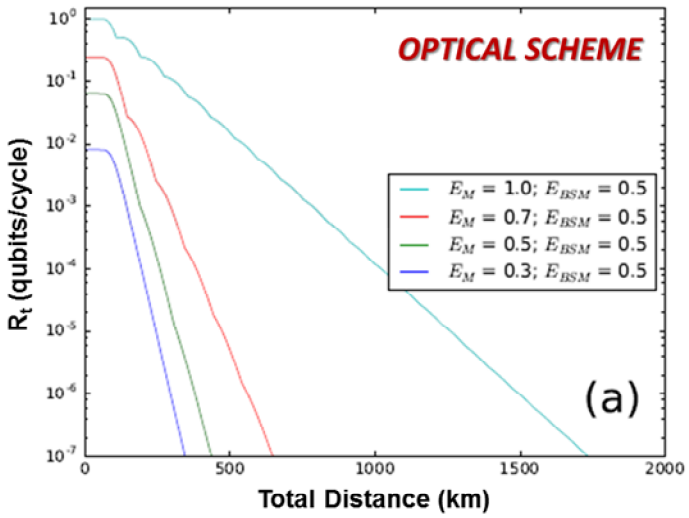
Transfer
state of photon
polarization
→ state of electron

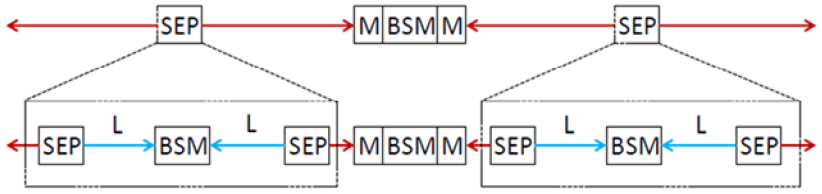
Need to engineer
electron g-factor ~0
[e.g., see Allison PRB
(2014)]
& strain…

Throughput scaling model

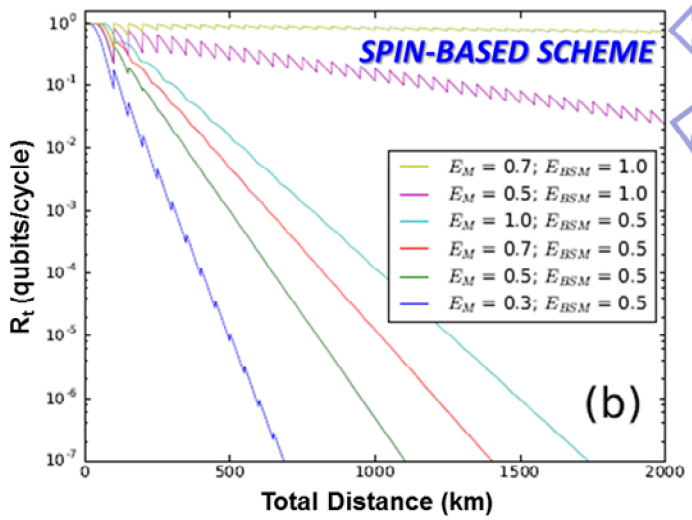
To demonstrate potential performance advantage of full BSM capability in spin-based QD scheme over optical scheme with linear optics and atomic ensemble QMem

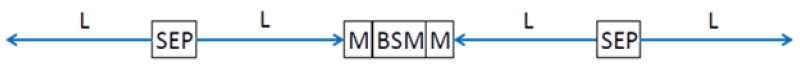
See Gaudreau et al., Semicond. Sci. Technol. (2017)





$P_h = 10^{-(2L/L_0)/10}$	Fiber losses
$R_t = E_M^{2N}$	Memory losses (in)
$\cdot\, E_M^{2N}$	Memory losses (out)
$\cdot\, (1-(1-P_h)^K)^N$	Heralded photon losses
$\cdot\, E_{BSM}^{N-1}$	Incomplete BSM

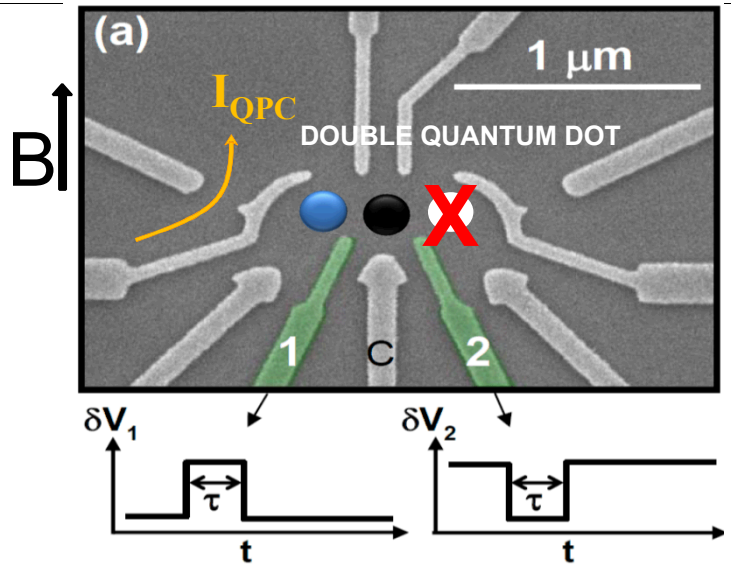


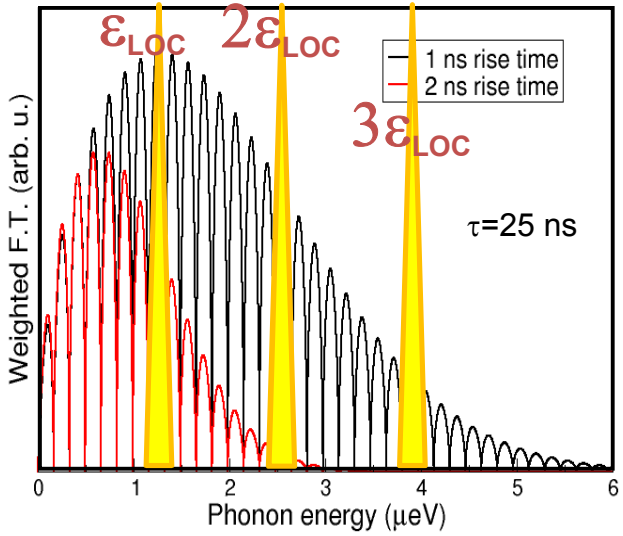


$P_h = 10^{-(2L/L_0)/10}$	Fiber losses
$\cdot\, E_M^2$	Memory losses (in)
$R_t = (1-(1-P_h)^K)^N$	Heralded photon losses
$\cdot\, E_{BSM}^{N-1}$	Incomplete BSM

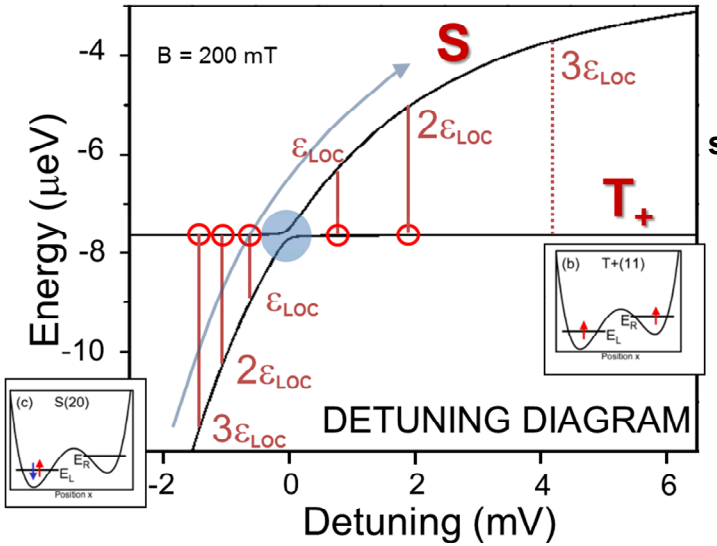
Coherent hybrid interplay between phonon & spin in piezoelectric material such as GaAs during manipulation & measurement of QDs

See Korkusinski et al., Phys. Rev. Lett. (2017)

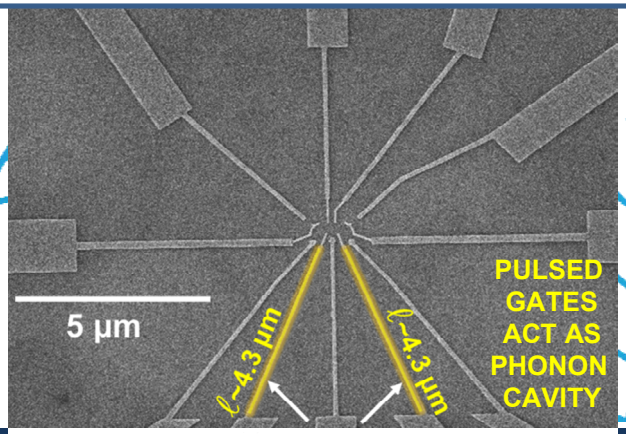




For surface phonon velocity 2700 m/s,
$\lambda=2\ell=8.6$ μm gives $\varepsilon_{LOC}=1.3$ μeV

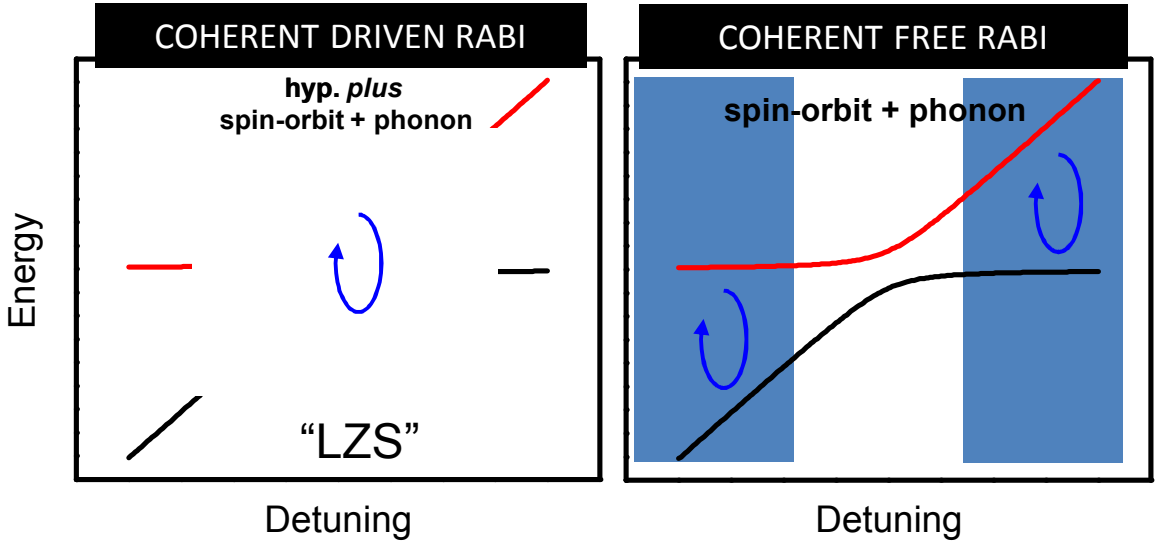


LZS spectroscopy of S-T_+ qubit

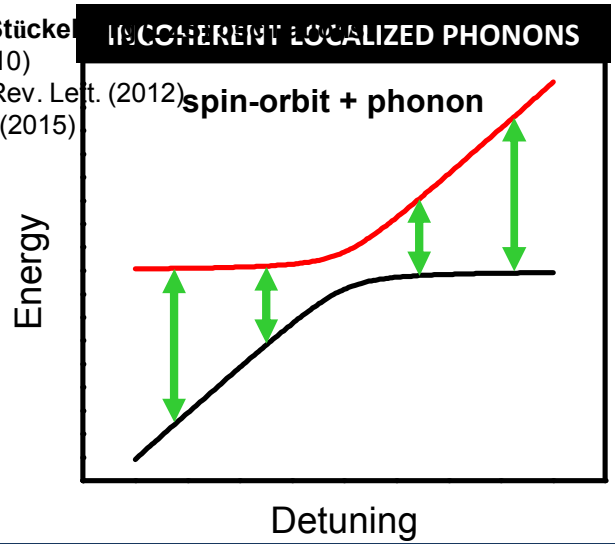


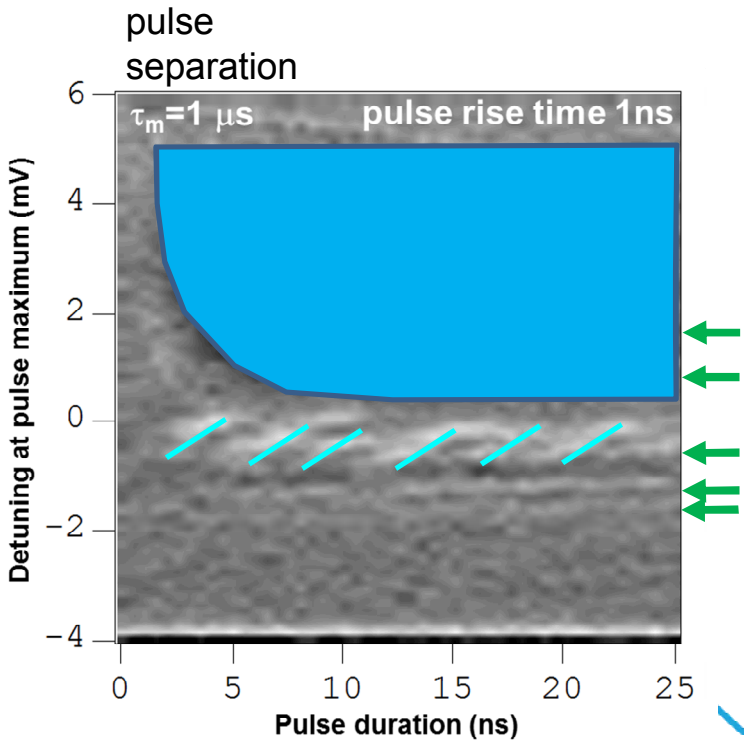
Features related to coherent and incoherent driving by phonon bath

See Korkusinski et al., Phys. Rev. Lett. (2017)



Landau-Zenner-Stückel
Petta Science (2010)
Studenikin Phys. Rev. Lett. (2012)
Nichol Nat Comm (2015)
…





Features related to phonon bath:

- Visibility of LZS pattern (+ve detuning),
- New interference fringes (below anti-crossing),
- Extra horizontal lines either side of anti-crossing.