New Perspectives in Spintronic and Mesoscopic Physics
ISSP, University of Tokyo, June 10, 2015

Conversion from single photons to single electron spins using GaAs-based quantum dots

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Nano spin conversion

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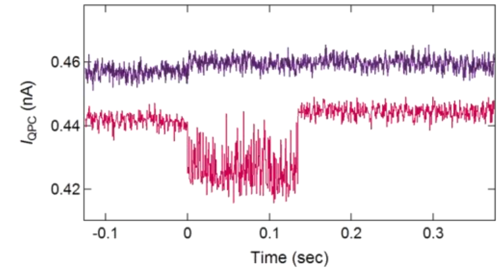
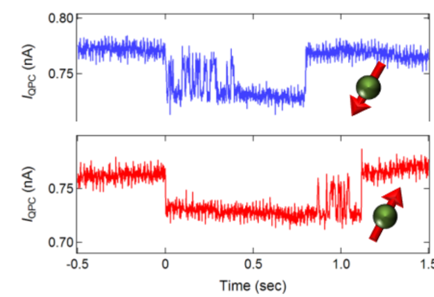
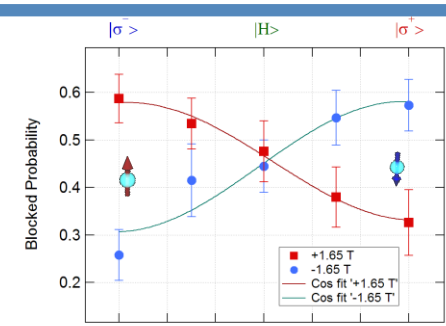
Non-destructive and robust single photon detection using interdot tunneling in double quantum dots



Spin discrimination of the single photoelectrons using Pauli spin blockade

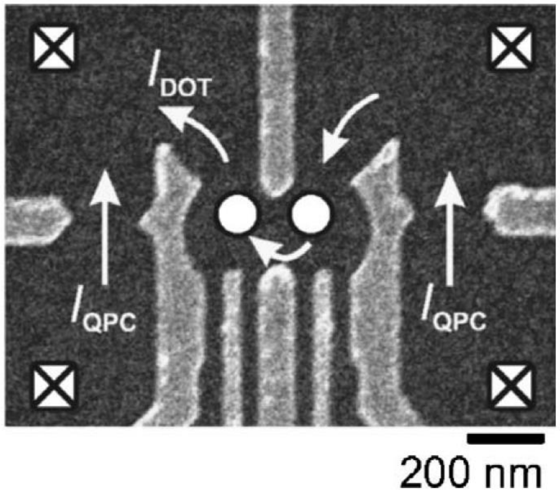


Angular momentum conversion from single photons to single electron spins

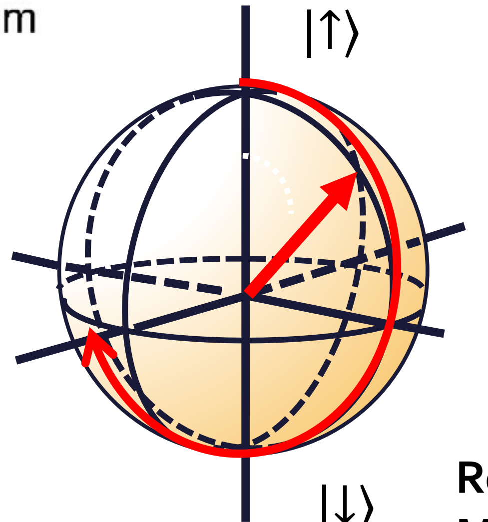


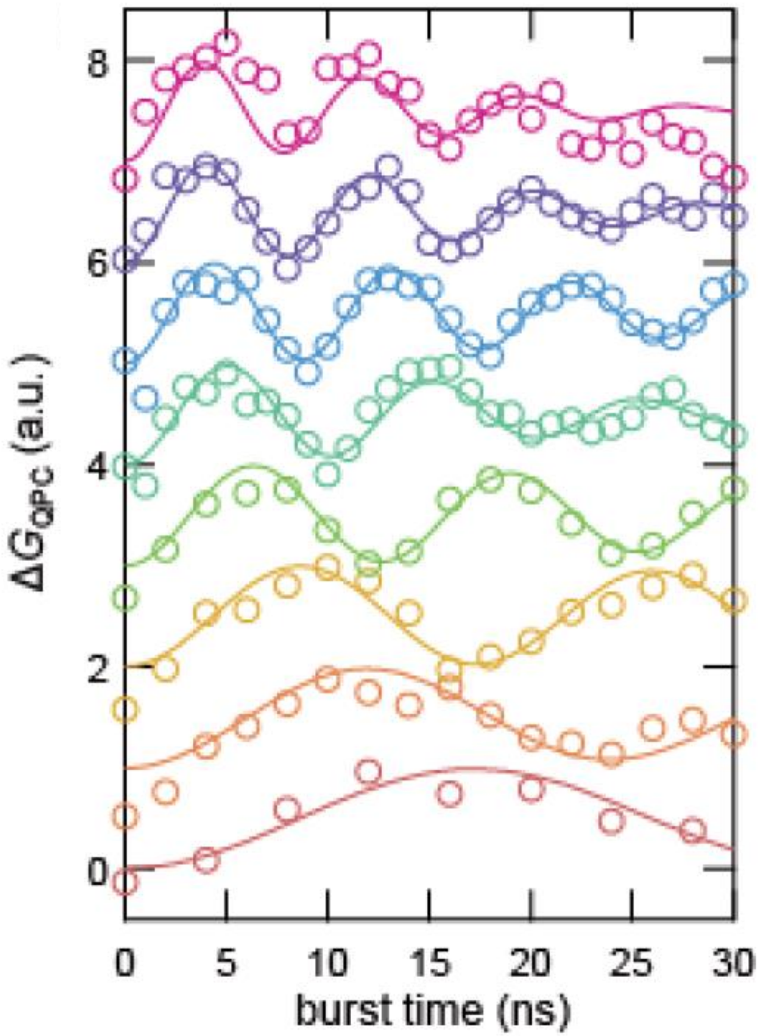
SPIN QUBITS USING GATE-DEFINED QDS

Single spin manipulation



Gate-defined double QD formed in GaAs/AlGaAs





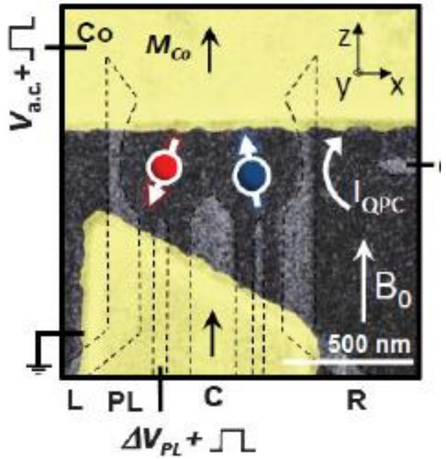
Recently Rabi frequency more than 100 MHz has been achieved. [Yoneda et al., PRL (2013)]

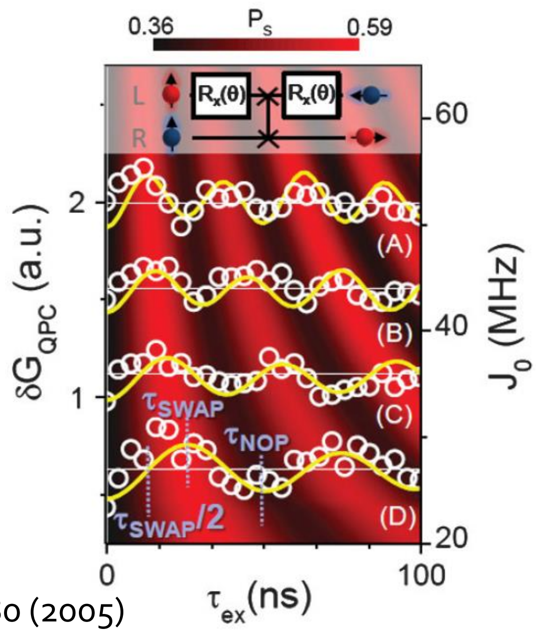
A candidate for spin qubits

SPIN QUBIT IN ELECTRICALLY CONTROLLED QUANTUM DOTS

Two qubit

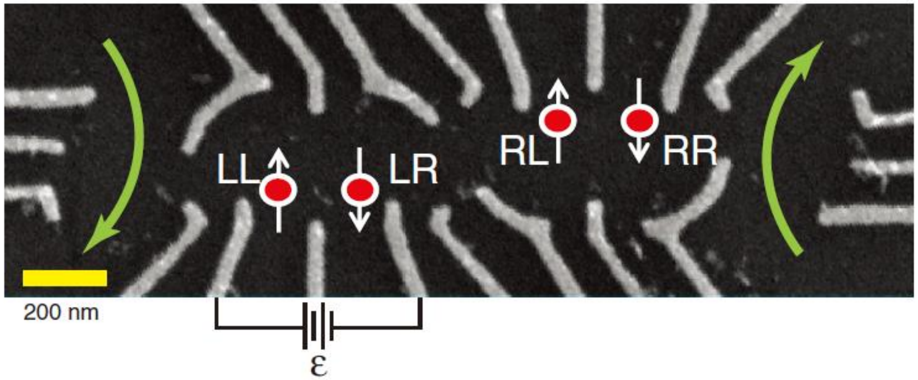
SWAP & $\sqrt{SWAP}$





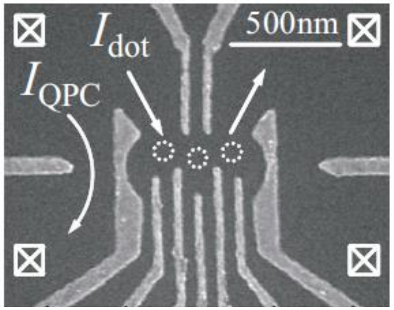
J. Petta et al., Science **309**, 2180 (2005)
R. Brunner et al, Phys. Rev. Lett. **107**, 146801 (2011)

C-Phase gate



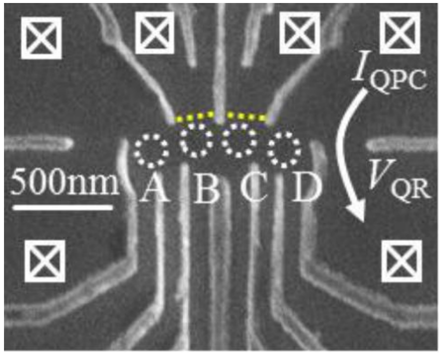
M. D. Shulman et al., Science **336**, 202 (2012).

Triple qubit



- Univ. of Tokyo.
- NRC
- Delft
- NTT group

Quadruple qubit



T. Takakura et al., APL 2014

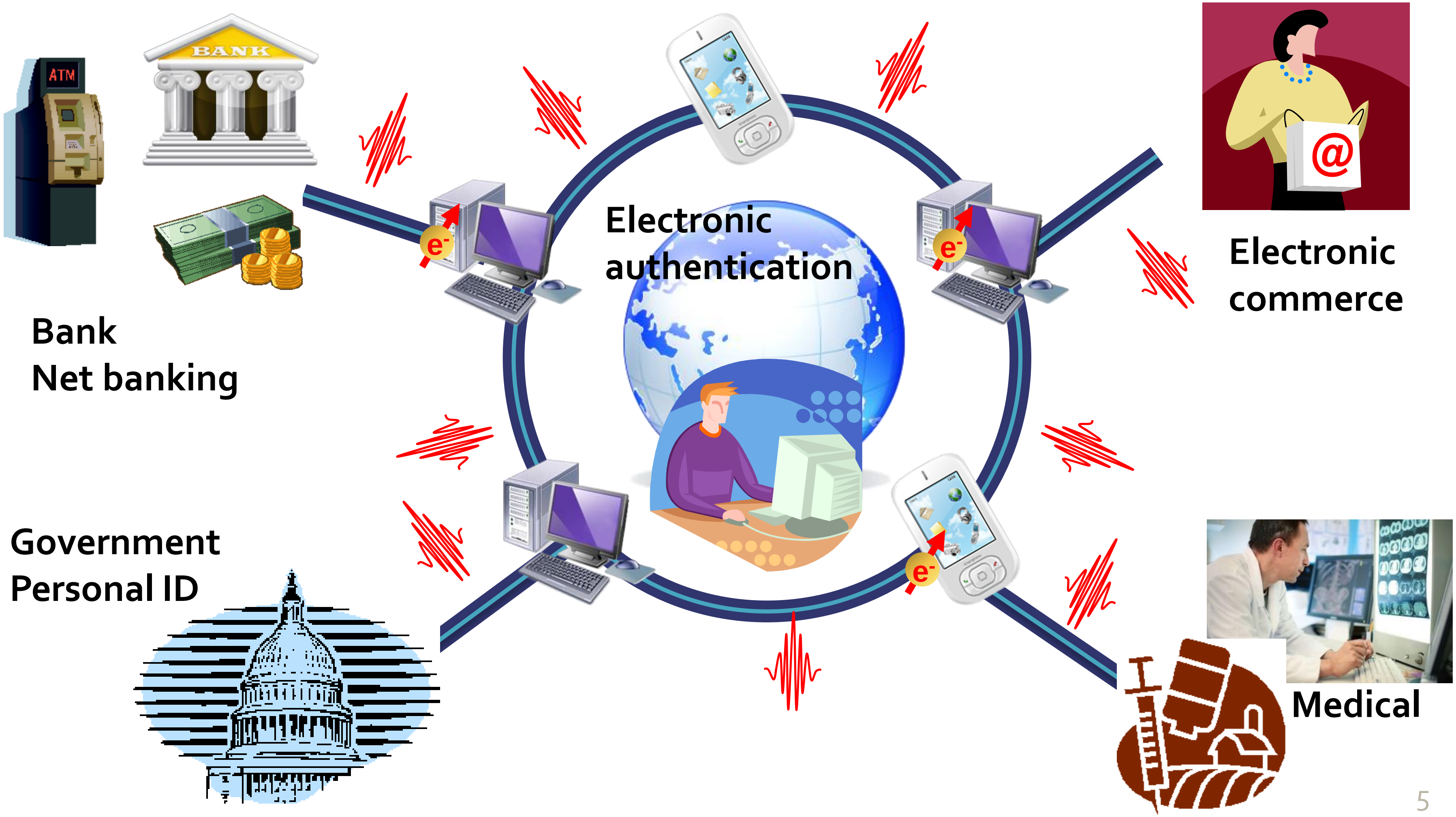
☑ Multi qubit operation (scalability)

☑ Single shot spin readout

GLOBAL QUANTUM NETWORK

- Secure information communications

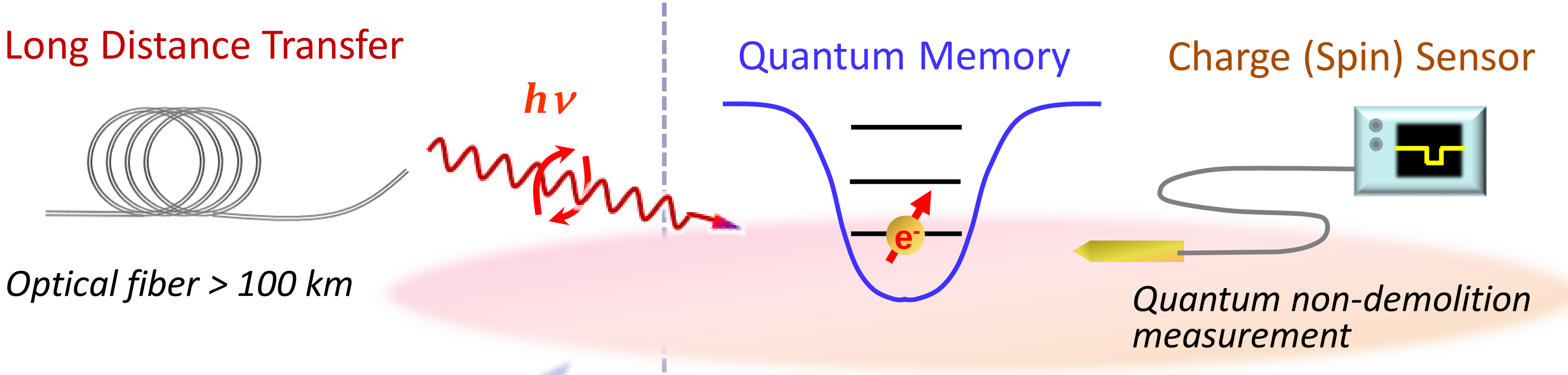
Quantum communications and quantum computing



LONG DISTANCE QUANTUM COMMUNICATION

➢ **Lateral QDs as photon - electron spin quantum interface**

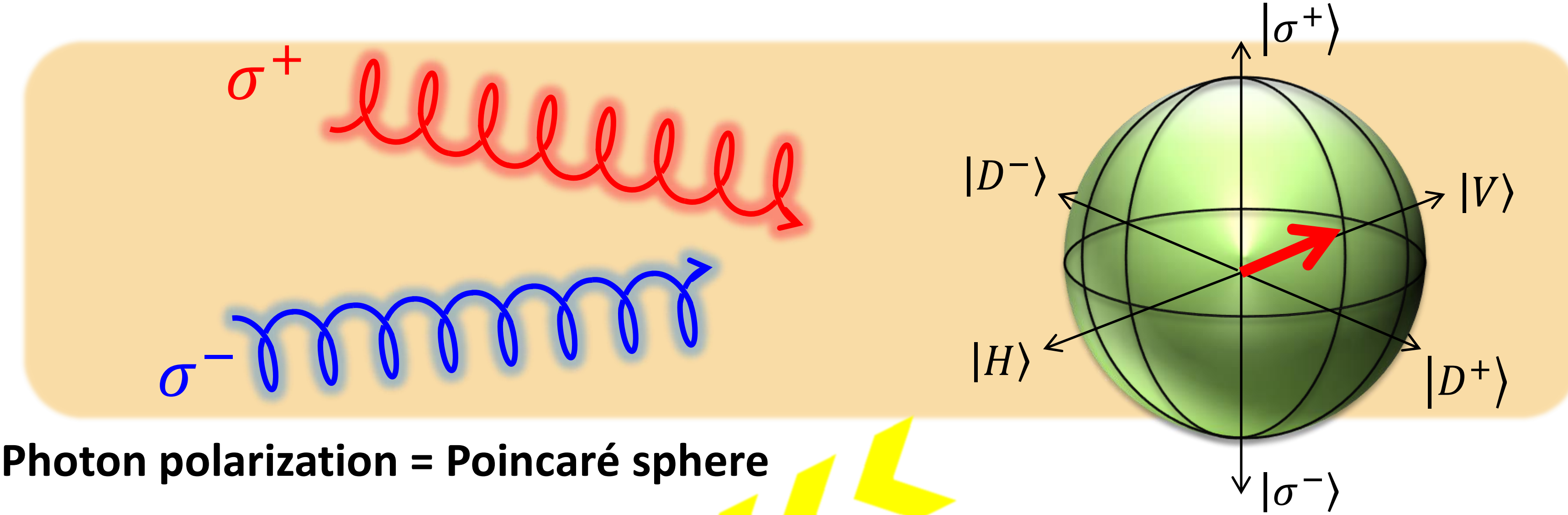
Quantum repeaters



Coherent transfer from single photon polarization to single electron spin

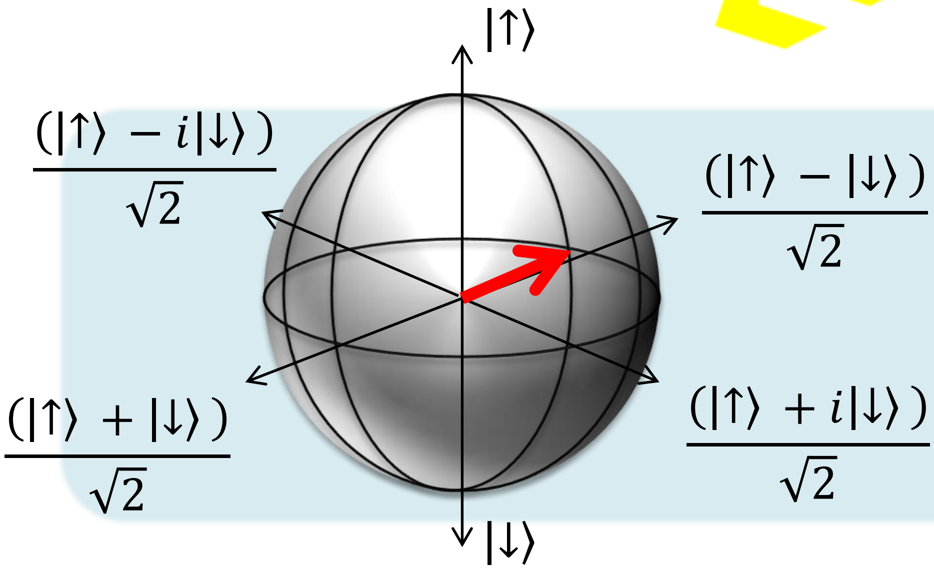
- **Single-shot detection of electron spins**
  [J. M. Elzerman *et al., Nature* **430**, 431-435 (2004).]
- **Long spin coherence time** (T_2 > 200μs)
  [H. Bluhm *et al.*, *Nature Physics* **7**, 109–113 (2011).]
- **Two qubit gate operation**
  [R. Brunner *et al., Phys. Rev. Lett.* **107**, 146801 (2011).]

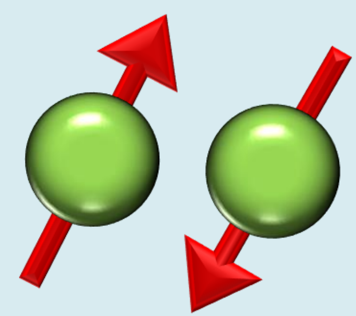
COHERENT QUANTUM STATE TRANSFER



Photon polarization = Poincaré sphere

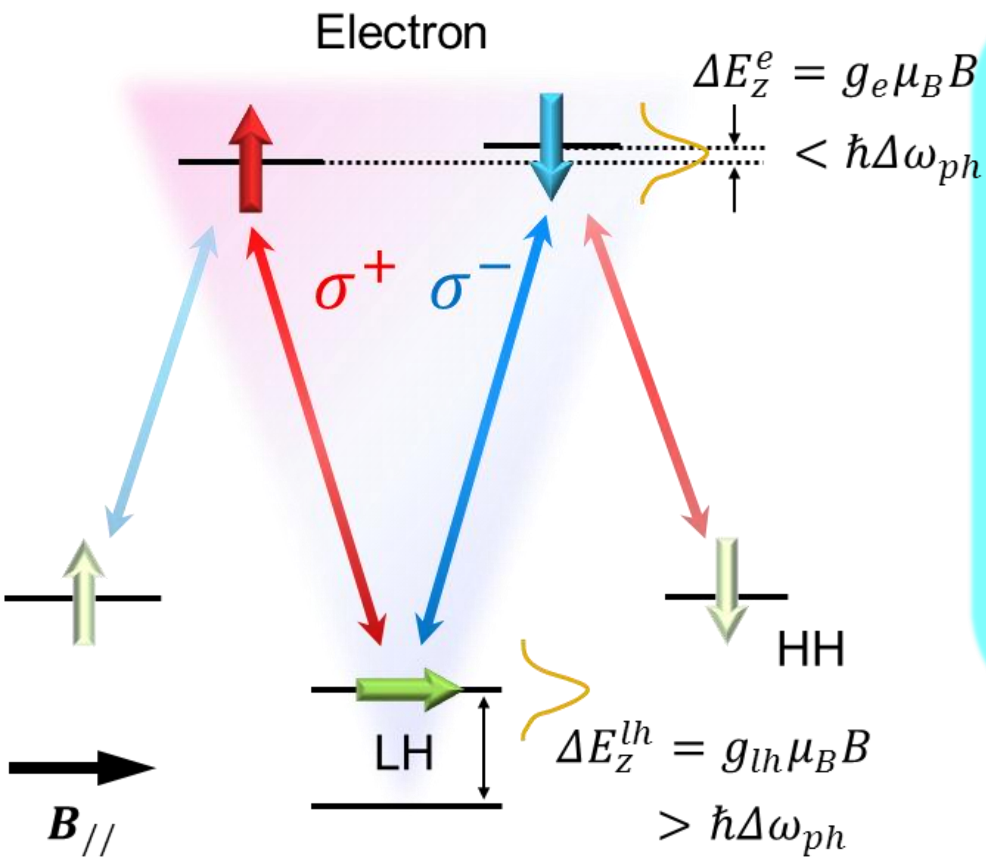
Electron spin = Bloch sphere





COHERENT QUANTUM STATE TRANSFER

- Photon polarization state ⇒ electron spin state



$$|\phi\rangle_{ph} = \alpha|\sigma^+\rangle + \beta|\sigma^-\rangle$$

$$|\phi\rangle_{eh} = |-\rangle_{lh} \otimes \{\alpha|1/2\rangle + \beta|-1/2\rangle\}$$

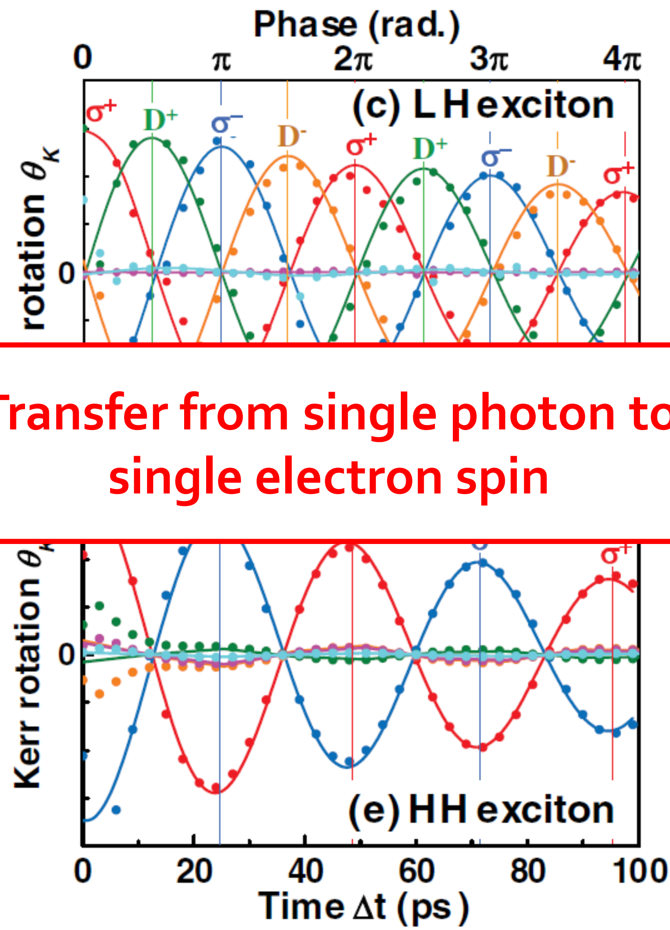
Quantum wells with controlled electron and hole g-factors

Based on spin selective optical excitation

[R. Vrijen and E. Yablonovitch. *Physica E*, **10**, 569 (2001).]

PRECEDING WORKS

Coherent transfer from photon polarization to electron spin in QW in *ensemble*

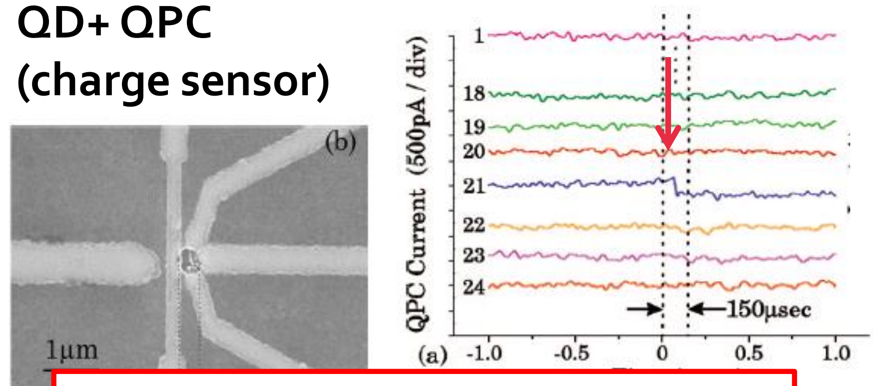


Transfer from single photon to single electron spin

H. Kosaka et al., Phys. Rev. Lett., **100**, 096602 (2008).

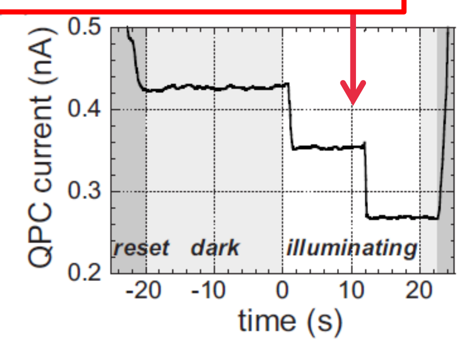
Single photon detection in electrically controllable QDs

QD+ QPC (charge sensor)



[D

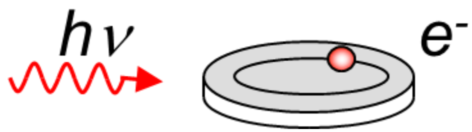
Detection of single photoelectron spin



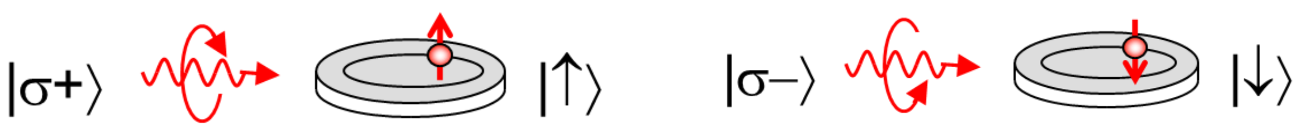
[M. Kuwahara *et al., Appl. Phys. Lett.* **96**, 163107 (2010).]

TOWARDS COHERENT SINGLE QUBIT TRANSFER

- Energy Transfer

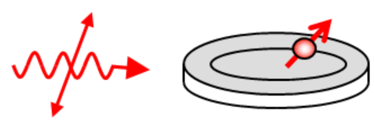


- Angular Momentum Transfer



- Coherent Transfer

$\alpha|\sigma+\rangle + \beta|\sigma-\rangle$

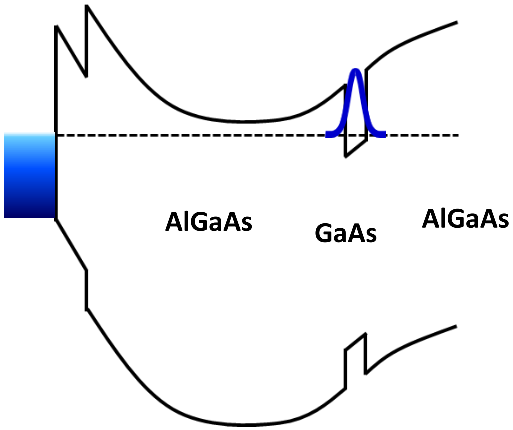


$\alpha|\uparrow\rangle + \beta|\downarrow\rangle$

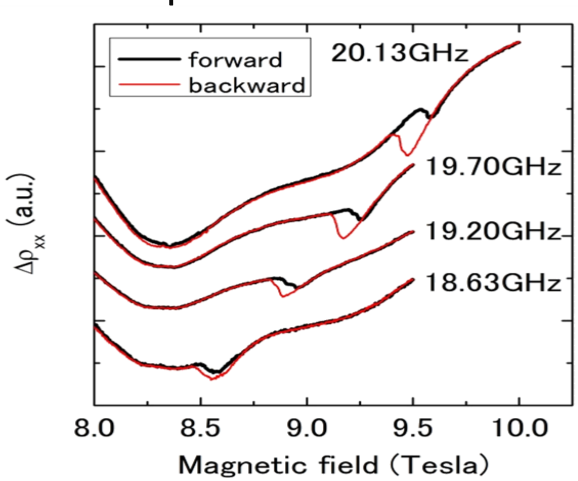
QW ELECTRON g-FACTOR TUNING

➢ Electron g-factors in QW

- QW (double heterojunction)



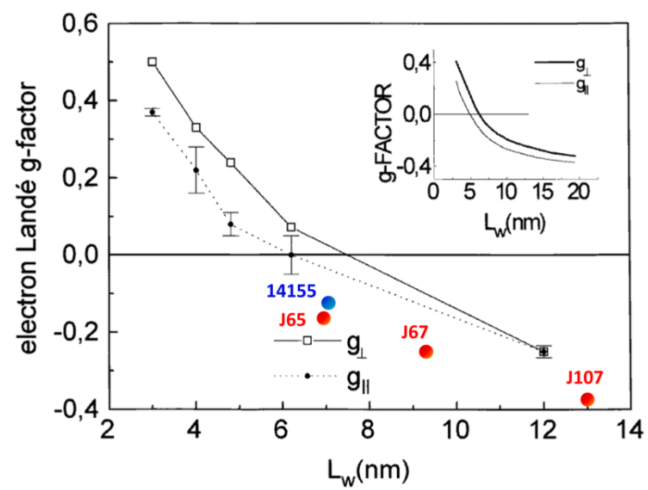
- Resistive measurement of electron-spin resonance



- QW parameters

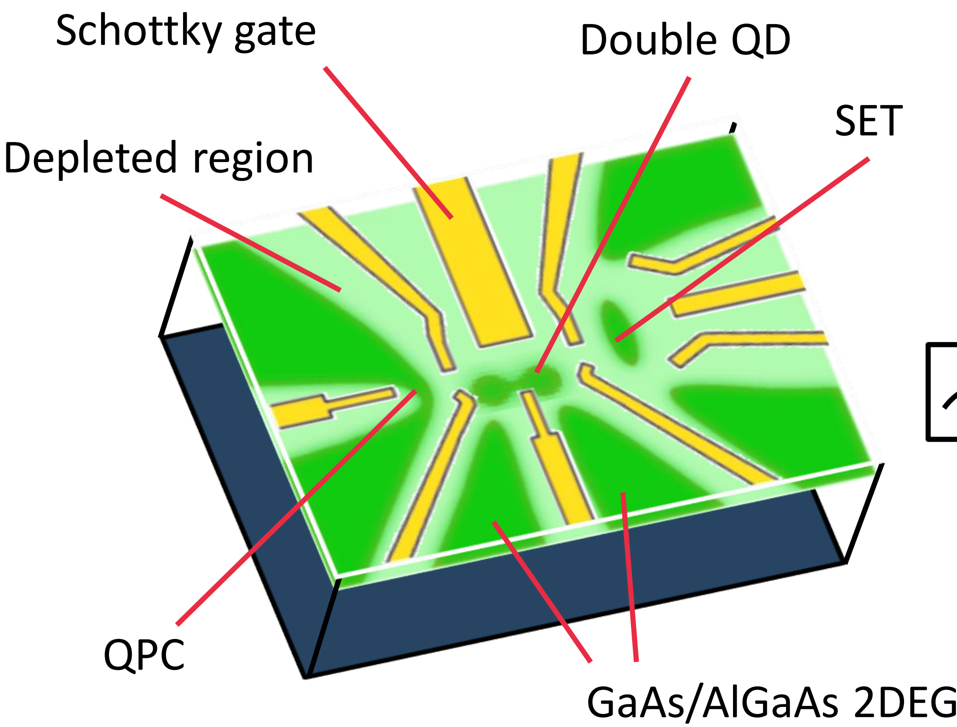
Wafer	J65	J67	J107	14155
Well width (Å)	70	92	130	73
Carrier density (x 10^{11} cm^{-2})	2.1	2.3	3.9	2.1
Mobility (x 10^6 cm^2/Vs)	0.50	0.37	-	0.10
g_e-factor $\|g_e\|$	0.18	0.26	0.39	0.12

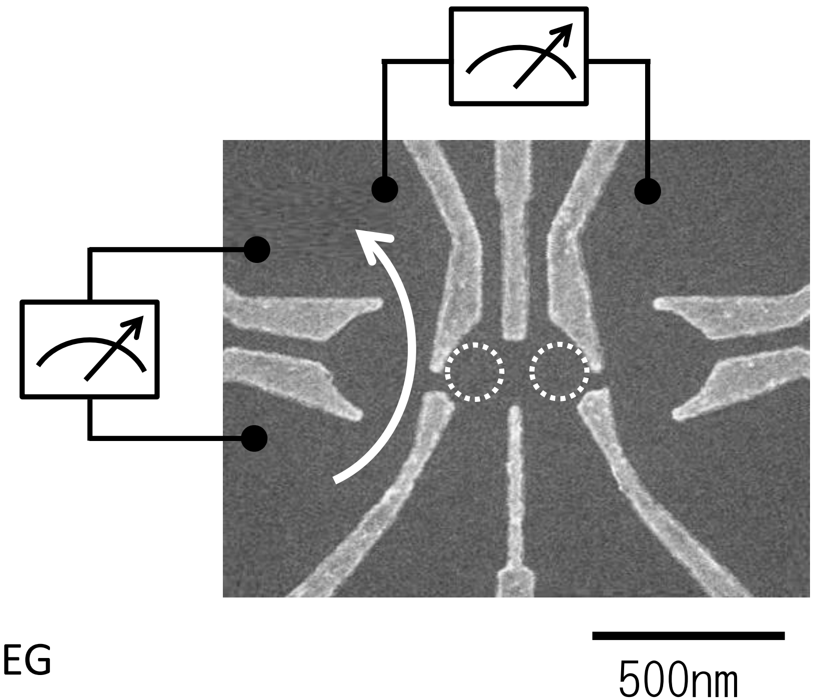
- Well width dependence of g-factors



[G. Allison et al., submitted; T. Fujita *et al.*, ICPS, Zurich (2012). Invited]

LATERAL QUANTUM DOTS

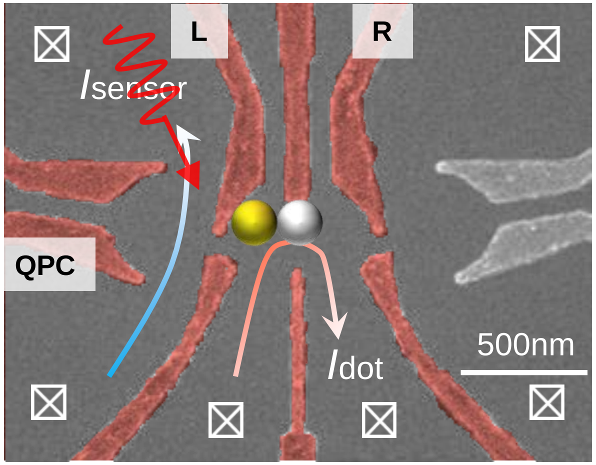




Flexibility in gate geometry
Highly controllable
Highly sensitive charge detection

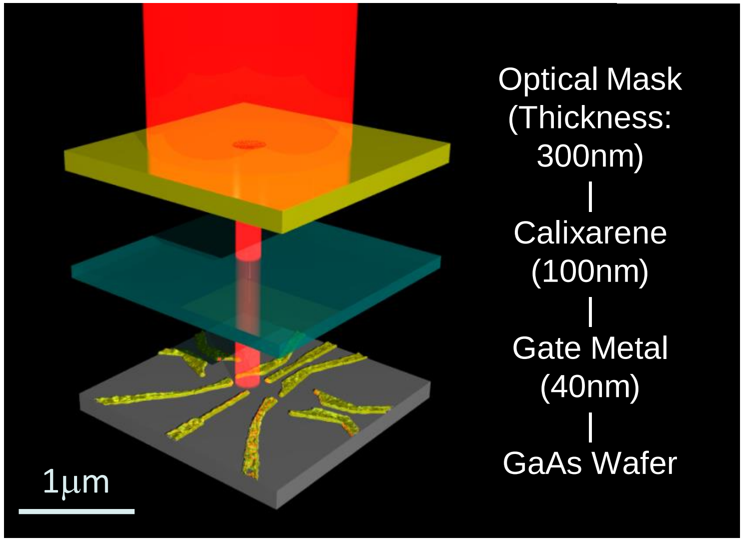
MEASUREMENT

SEM picture

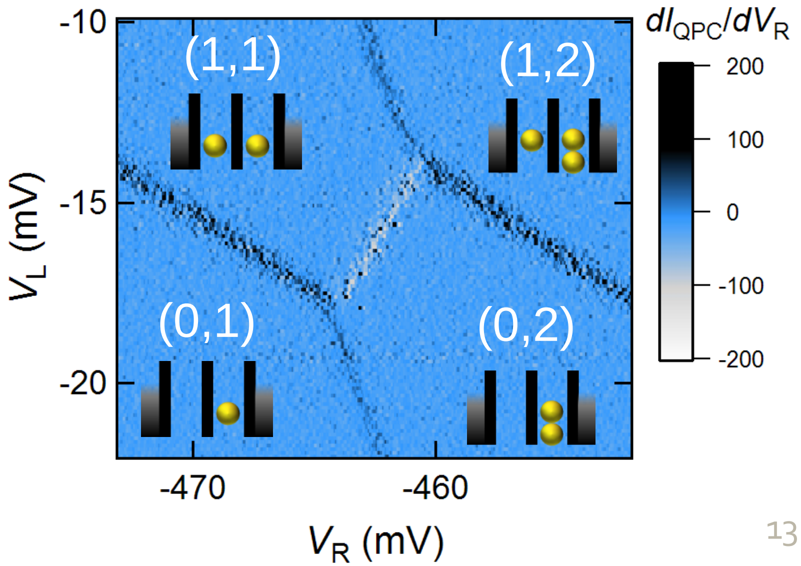


- Laterally defined DQD on GaAs/AlGaAs QW
- QPC or QD charge sensor (Left side)
- Metal mask with small aperture (400nm diameter) on left QD
- Cryogen free dilution fridge (base *T*=25mK)

Optical Mask



Double dot (charge sensing)



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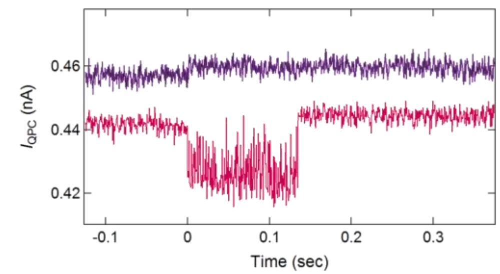
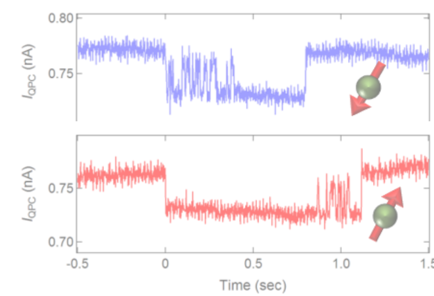
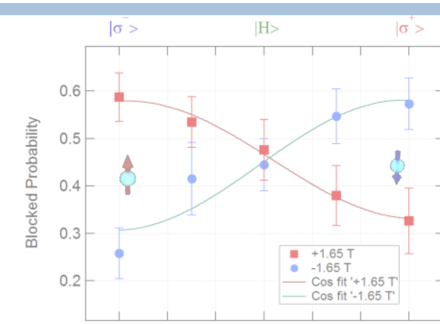


Spin discrimination of the single photoelectrons using Pauli spin blockade

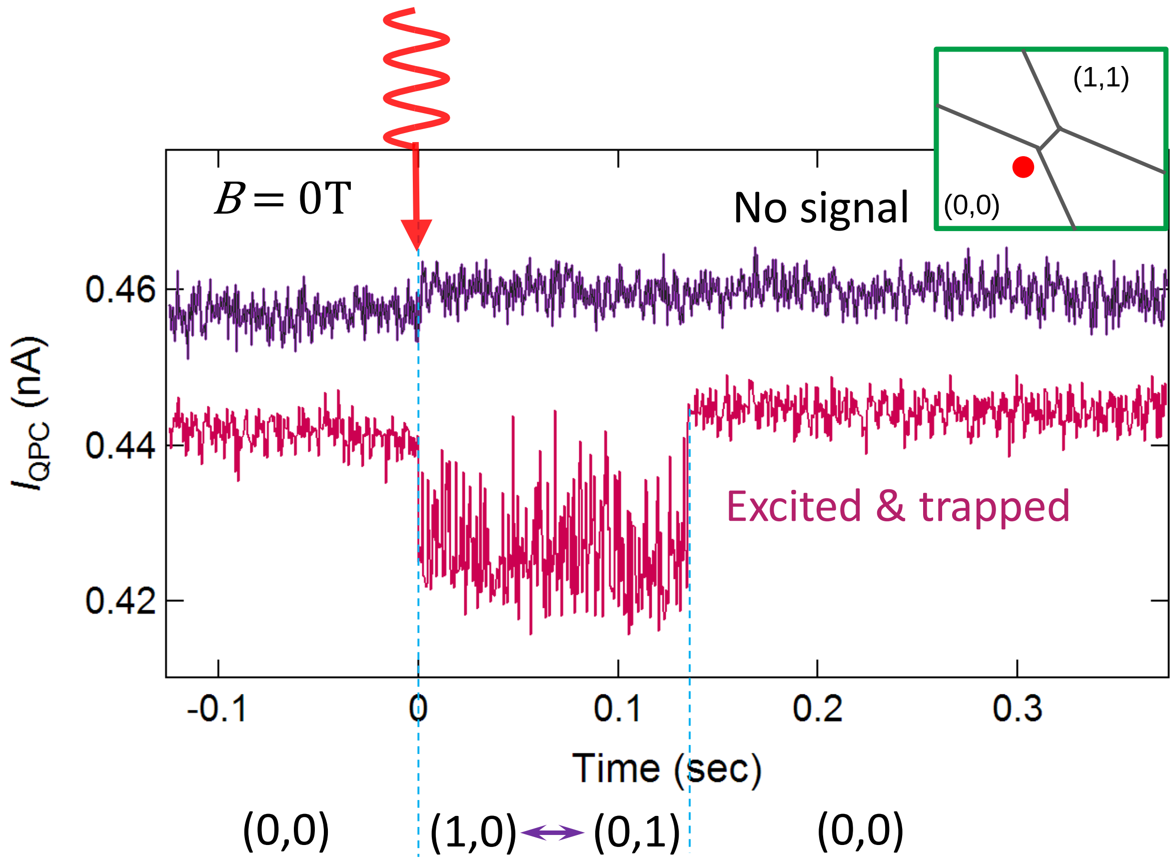


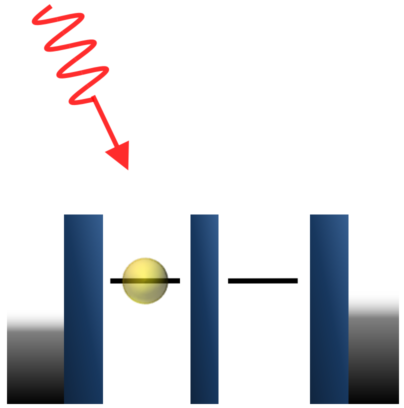
Angular momentum conversion from single photons to single electron spins



SINGLE PHOTO-ELECTRON TRAPPING

➢ Single-shot photon irradiation





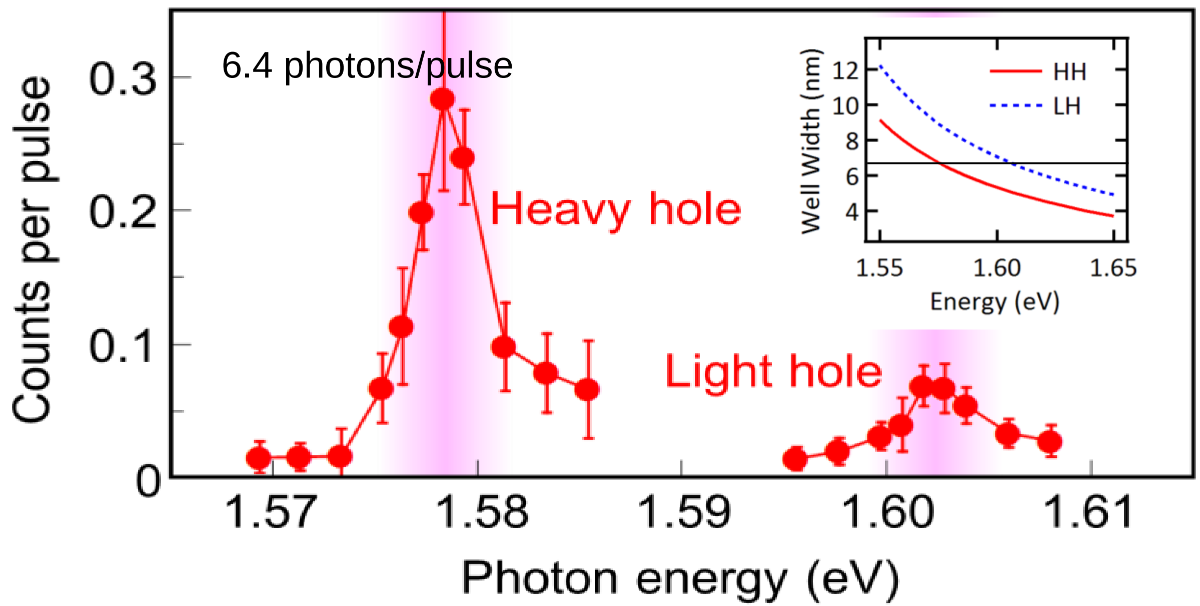
- Average photons through aperture : ~3 photons/pulse
- Clear discrimination of single photo-electrons with resonant inter-dot tunneling

Stable photon irradiation and single photo-electron trapping

[T. Fujita *et al.*, Phys. Rev. Lett. **110**, 266803 (2013).]

WAVELENGTH DEPENDENCE

- Resonant excitation in quantum well



- Efficiency : 4.5±1.5 % (λ = 785.5 nm) → **HH excitation**
  1.1±0.5 % (λ = 774.0 nm) → **LH excitation**
  < 0.2 % (λ = 790.0 nm)

Resonant excitation in quantum well

Demonstration of wavelength selectivity in g-engineered QDs

[K. Morimoto et al., PRB **90**, 085306 (2014).]

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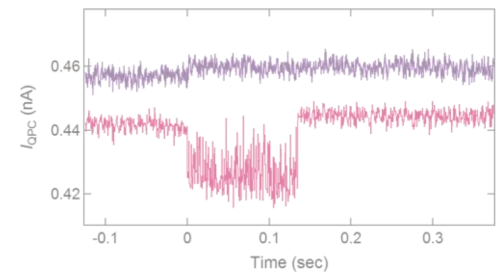

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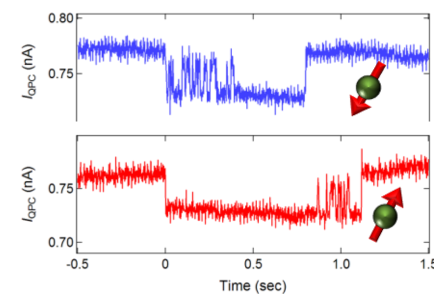
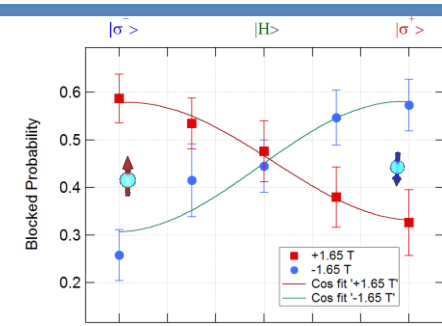
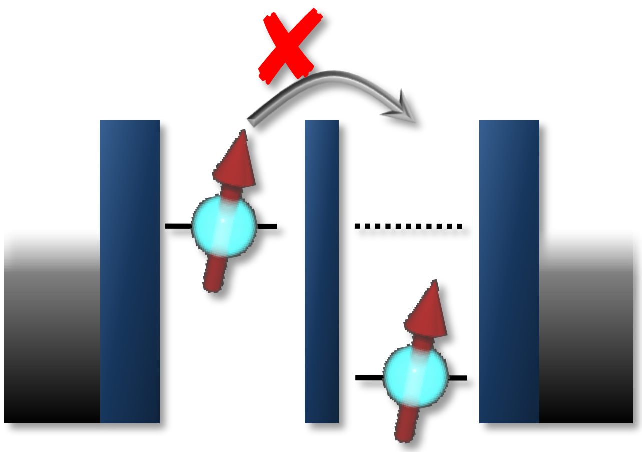


Angular momentum conversion from single photons to single electron spins

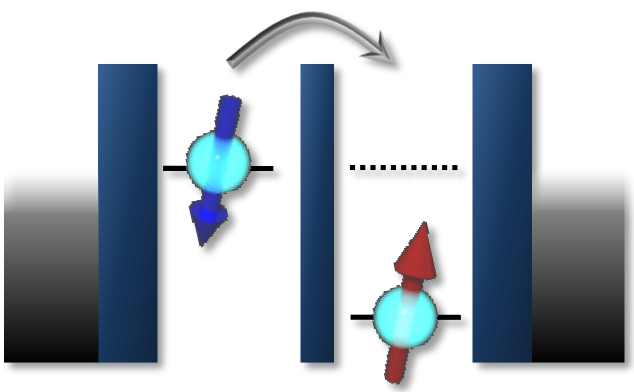


REAL-TIME SINGLE-SHOT SINGLE SPIN READOUT

- Pauli spin blockade as a single spin detector

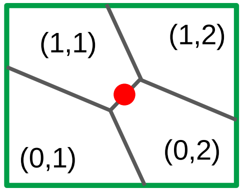


Parallel : (1,1)



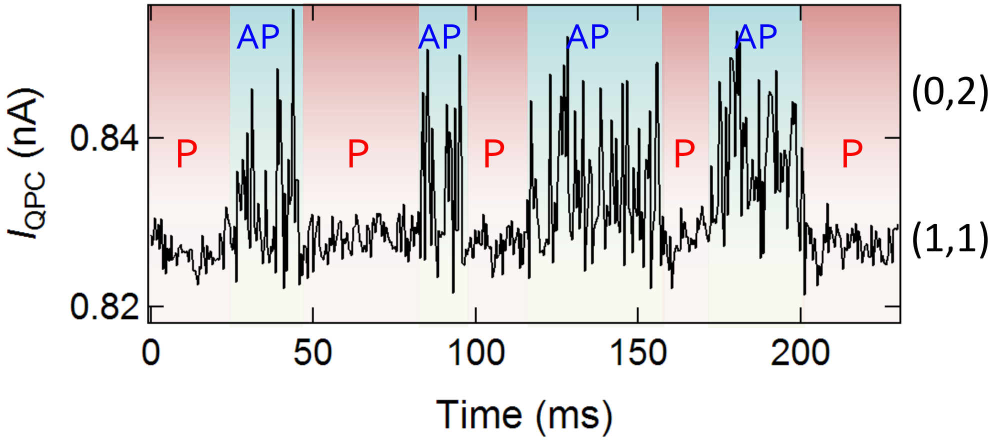
Anti-parallel: (1,1)→(0,2)

Real-time Spin Blockade

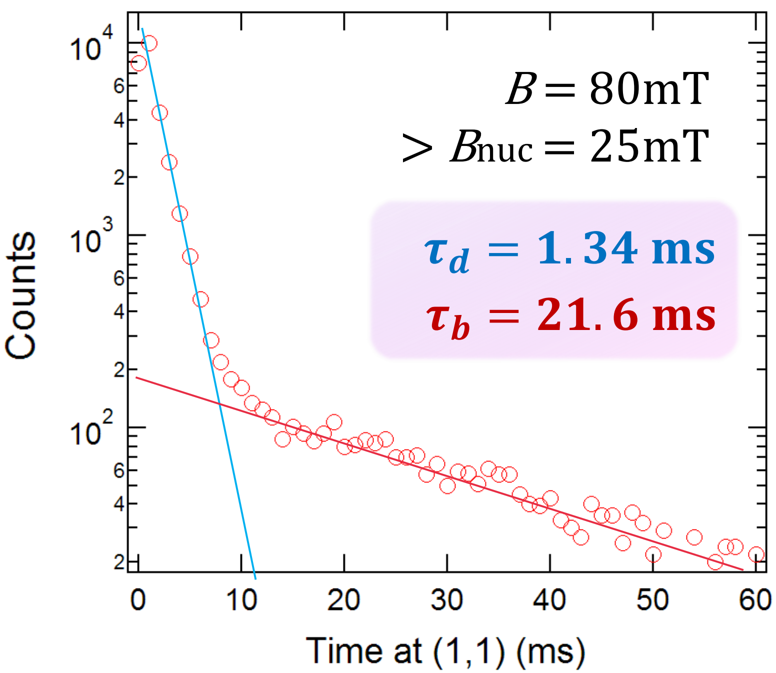


➢ (1,1)↔(0,2) resonance in finite field

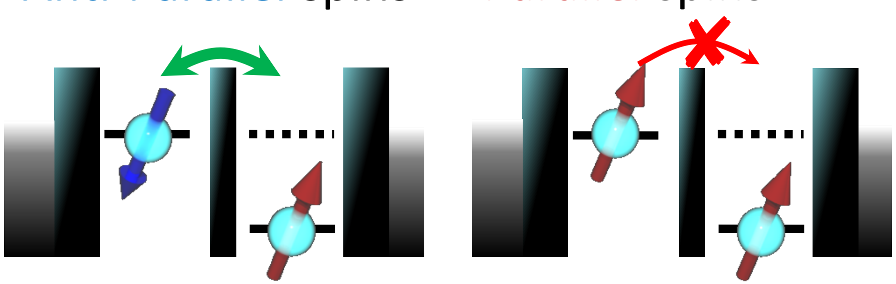
- Real-time signal



- Double exponential histogram

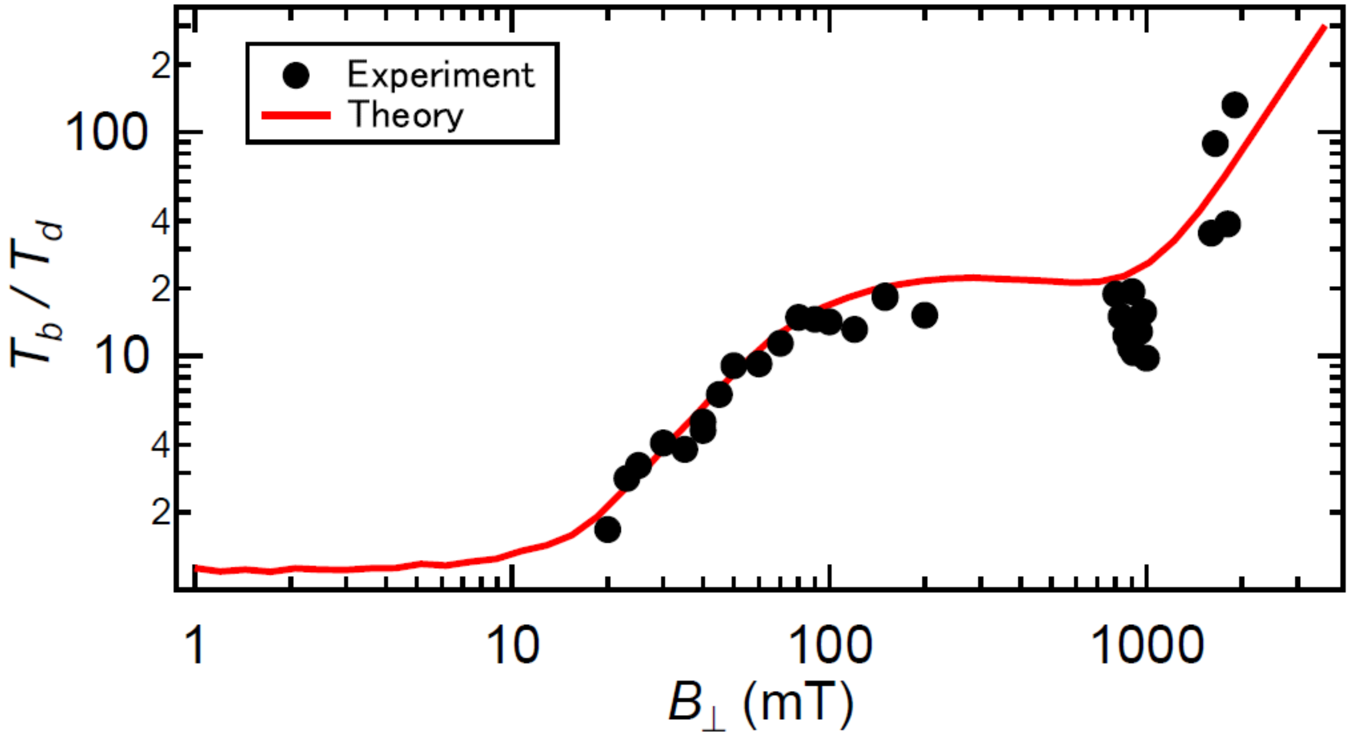


- Anti-Parallel spins ▪ Parallel spins



Spin detection with resonant inter-dot tunneling

Spin blocakde lifting mechanisms



<u>Low field (hyperfine)</u>

$$\frac{T_b}{T_d} \propto \frac{B^2}{B_{\text{nuc}}^2}$$

$B_{\text{nuc}} = 2{\sim}3$ mT in a single heterojunction wafer

[A. C. Johnson *et al.*, Nature **435**, 925 (2005).]

<u>Middle field (SOI)</u>

$$\frac{T_b}{T_d} \propto \left(\frac{l_{\text{SO}}}{d}\right)^2$$

l_{SO} : spin − orbit length,
$2d$: separation between dots

<u>High field (charge decoherence)</u>

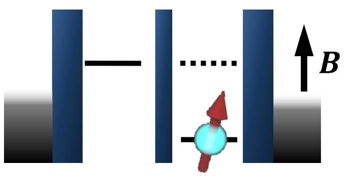
The spectral overlap of a polarized triplet states and S(02) state drops.

[T. Fujita, P. Stano AO et al., in preparation]

PHOTO-ELECTRON SPIN DETECTION

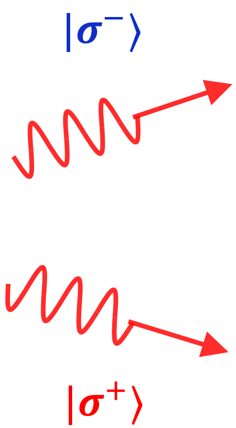
- **Measurement scheme of photo-electron spin detection with spin blockade**

- Preparation

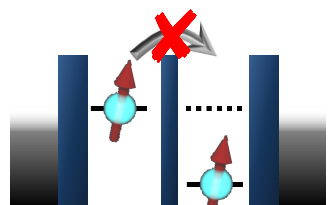


Reference spin

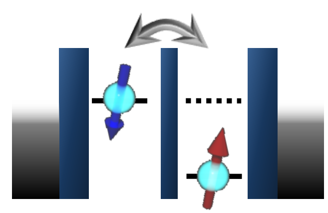
- Laser pulse irradiation



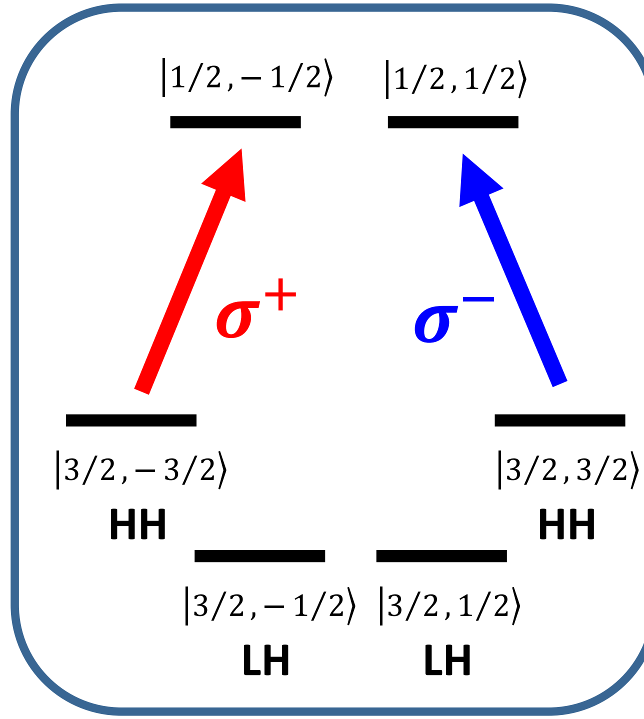
- Measurement



Blocked at (1,1)



Resonant tunneling

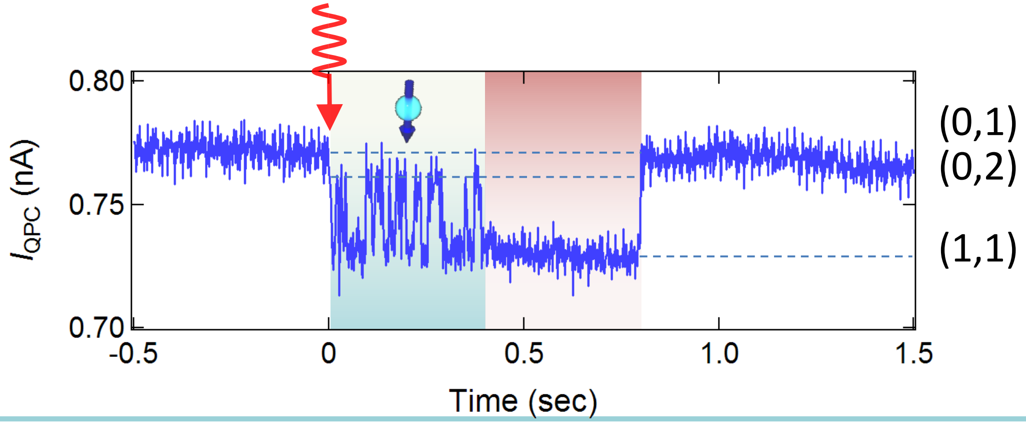


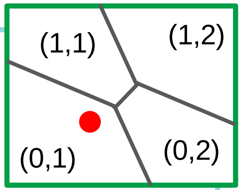
Observe spin of photoelectrons

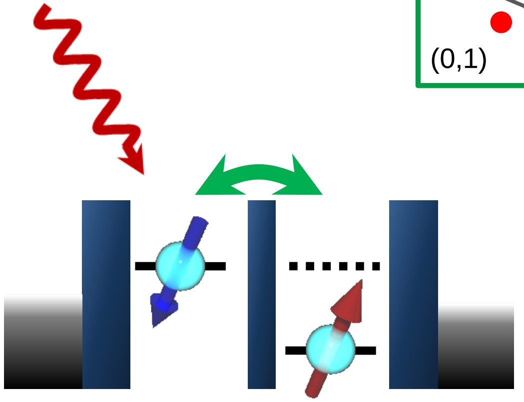
SINGLE PHOTO-ELECTRON SPIN DETECTION

➢ Initially unblocked

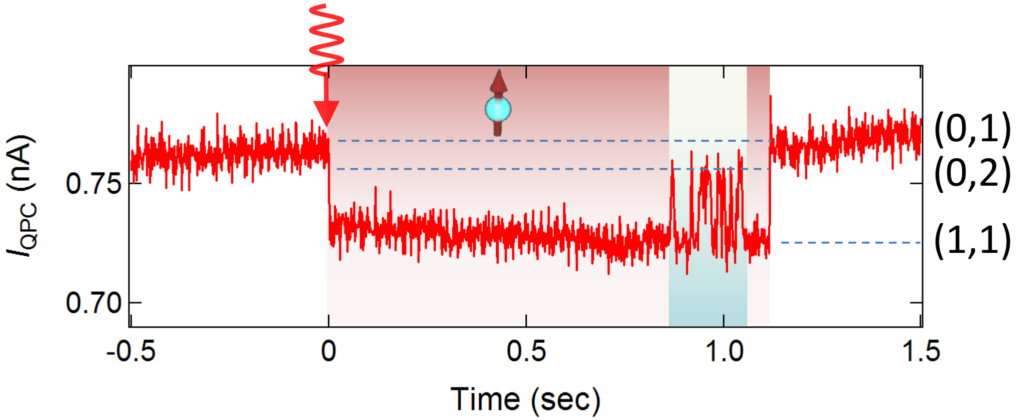
(B=1.65T, $1/\Gamma_C \sim$20ms) HH excitation

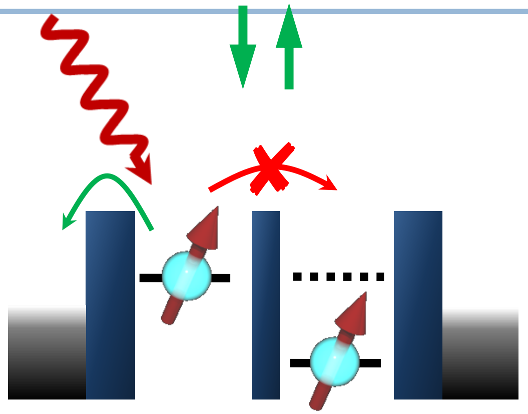






➢ Initially blocked

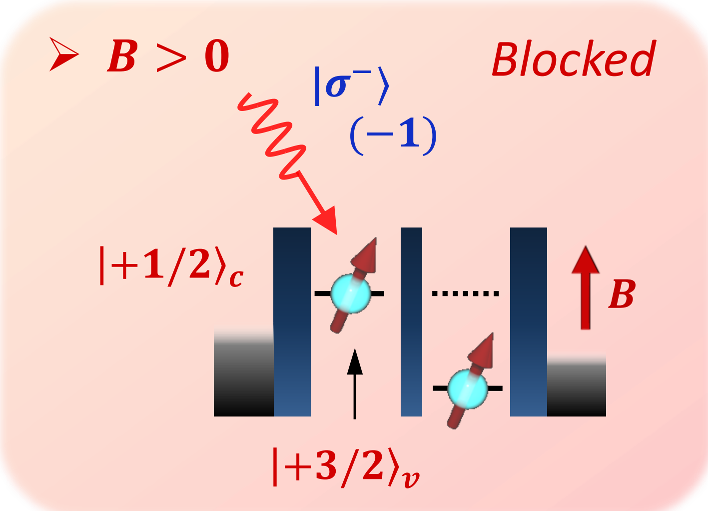


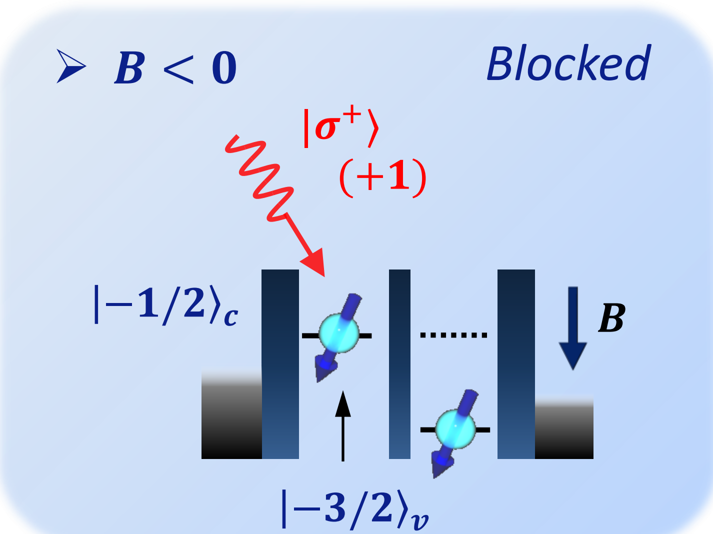


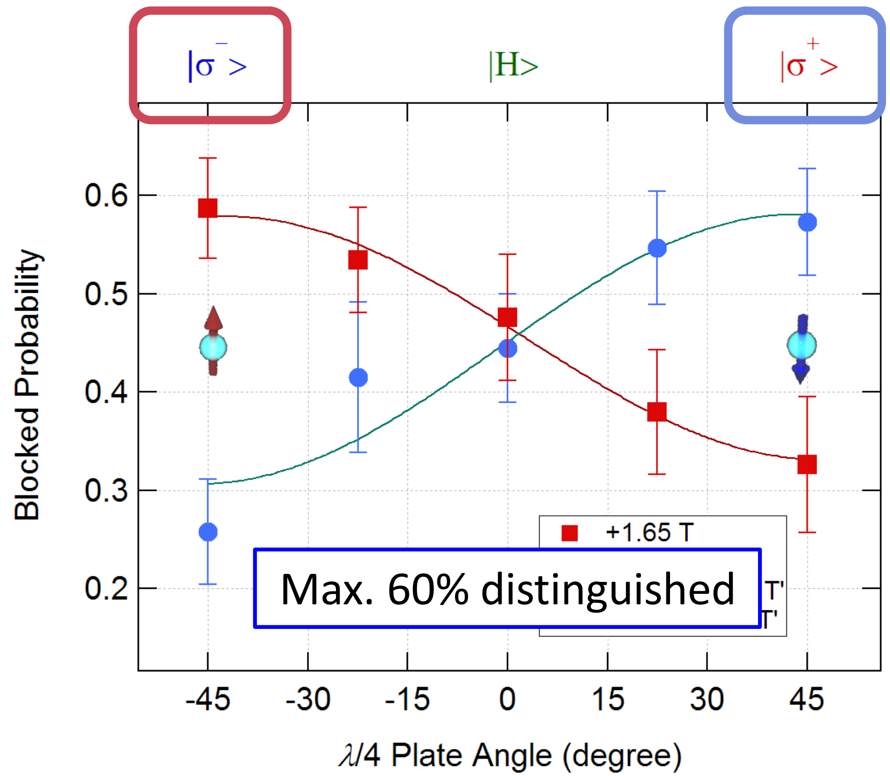
Detection of photo-generated electron spins

PHOTON POLARIZATION DEPENDENCE

➢ Polarization dependence of excited spins







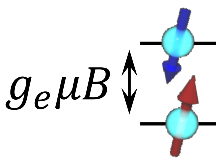
Angular momentum conversion from single photons to single electron spin

[T. Fujita *et al.*, In preparation]

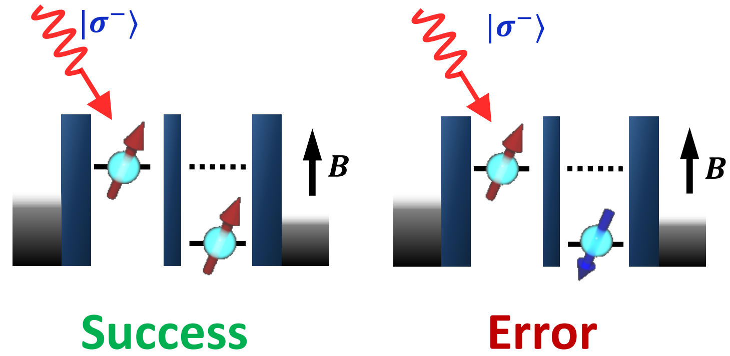
DISTINGUISHABILITY OF PHOTOELECTRON SPINS

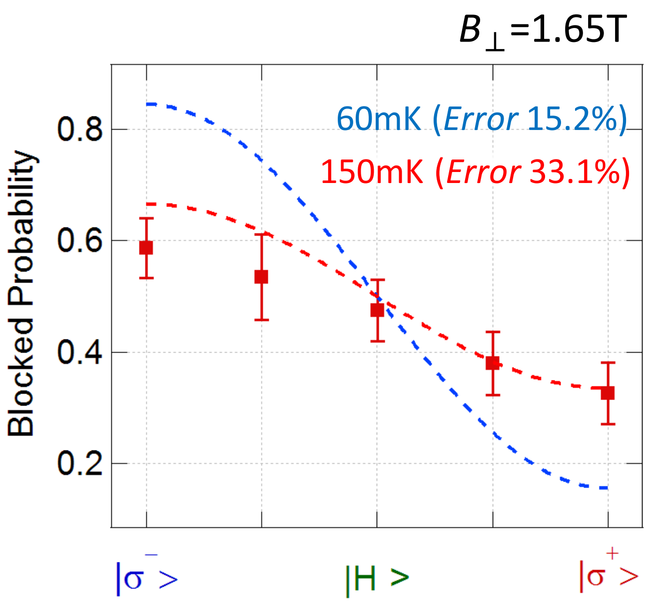
- Spin of prepared electron

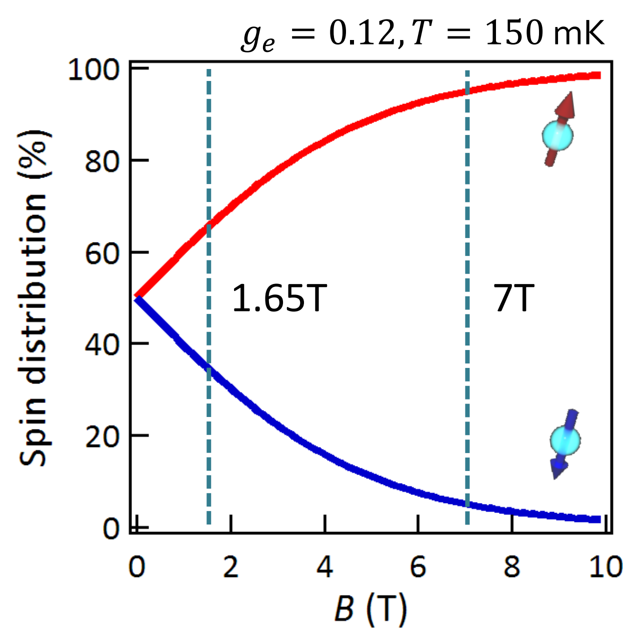
Boltzmann distribution of down spin



$$\frac{\exp\left(-\frac{g_e \mu B}{k_B T}\right)}{1+\exp\left(-\frac{g_e \mu B}{k_B T}\right)} = Error$$



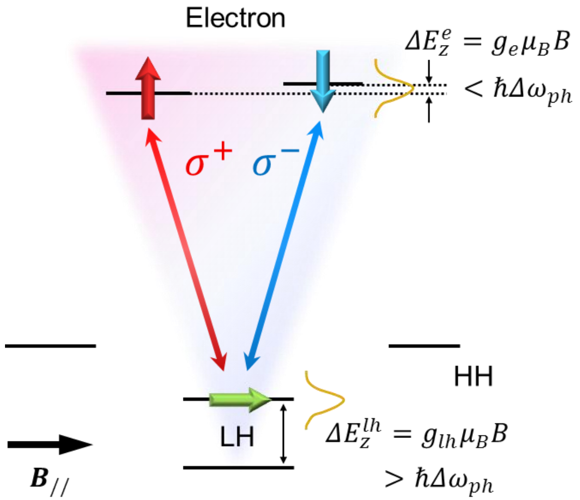


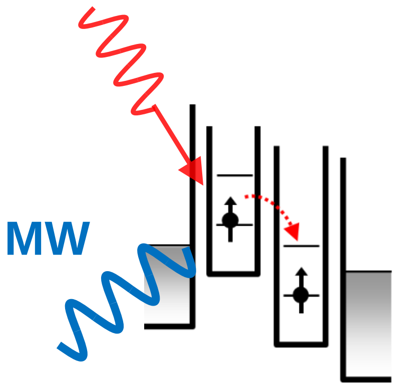


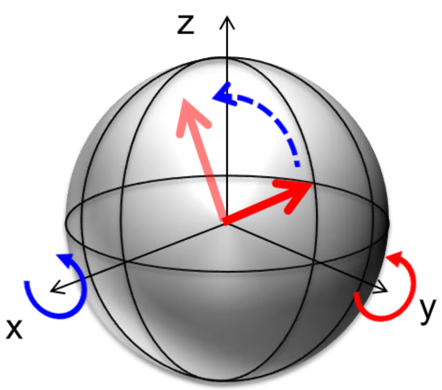
Possible increase of distinguishability

FUTURE PLAN

- **Towards coherent angular momentum transfer**
  - LH excitation
  - Faster spin detection
  - Spin manipulation for tomography measurement
- **Improvement of trapping efficiency**
  - Cavity structure, micro lens



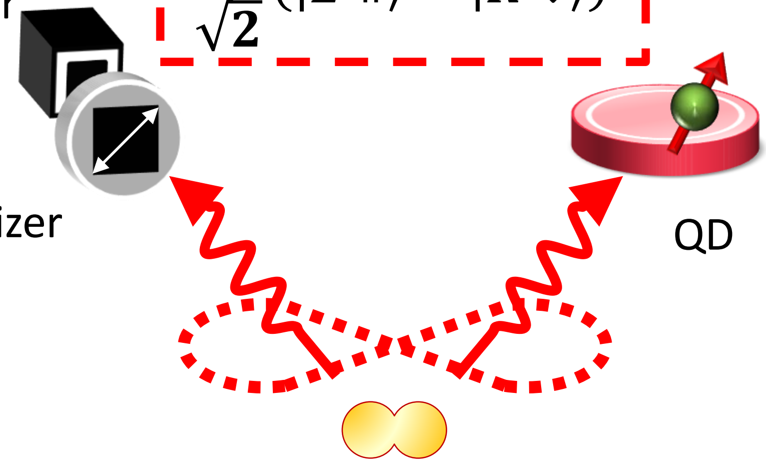




ENTANGLEMENT BETWEEN A PHOTON AND A SPIN

Single photon counter

$$\frac{1}{\sqrt{2}}\left(|L \Uparrow\rangle - |R \Downarrow\rangle\right)$$



polarizer

Entangled Photon

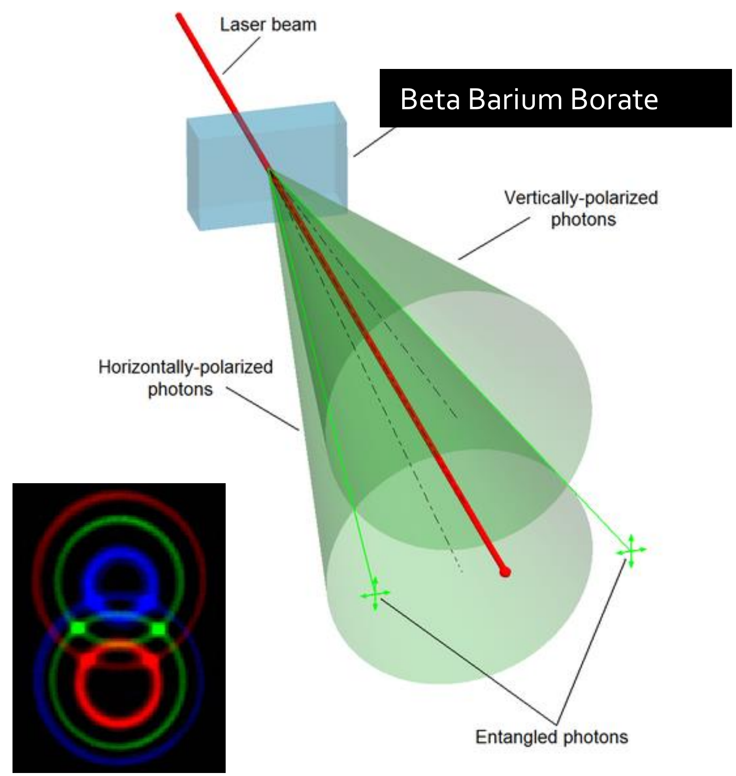
$$\frac{1}{\sqrt{2}}\left(|LR\rangle - |RL\rangle\right)$$

- **Entanglements between two spins in distant two QDs**

$$\frac{1}{\sqrt{2}}\left(|\Uparrow_1 \Downarrow_2\rangle - |\Downarrow_1 \Uparrow_2\rangle\right)$$

Poster PS33 Kuroyama et al.

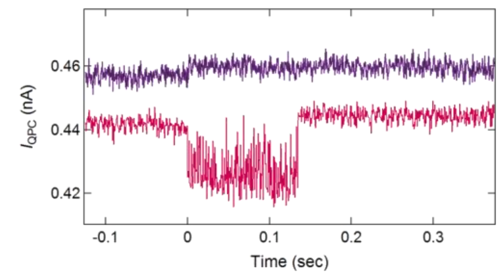
<u>Spontaneous Parametric down conversion</u>



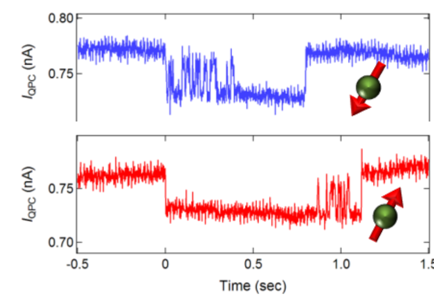
Kwiat *et al.*, PRL 75, 4337 (1995).

SUMMARY

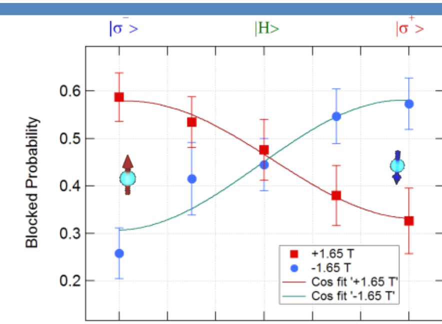
Non-destructive and robust single photon detection using interdot tunneling in double quantum dots



Spin discrimination of the single photoelectrons using Pauli spin blockade



Angular momentum conversion from single photons to single electron spins



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