Semiconductor qubits based on hole spins in CMOS devices and edge-states in Hall interferometers

Laura Bellentani, Andrea Secchi, Paolo Bordone, Andrea Bertoni and Filippo Troiani

YIQIS 2020

SEMICONDUCTOR QUANTUM BITS

Two different approaches

✓ Exploit the know-how and technological advances in microelectronics

✓ Potential of cointegration into classical devices and scalability

Silicon quantum dots (iQubits EU project)

>> Partners: CNR-Nano and AMat (IT), UofT (CA), AU (DK)

>> Qubit and control circuitry in **commercial CMOS** devices

>> Electron and **hole spin** qubits in **Silicon quantum dots** (QDs)

>> **Scaled up operating temperature** and faster gating times

Hall interferometers

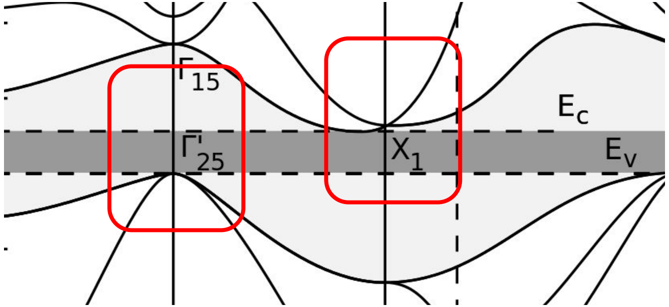
>> **Cyclotron-resolved** edge states in the Integer Quantum Hall regime (IQH)

>> **Flying-qubit** implementation of Hall interferometers as quantum logic gates

>> Long coherence length for qubit operations *on the fly*

Si QDs FOR SPIN QUBITS

Implementation of two-level systems in Silicon nanostructures



1. Weak hyperfine interaction
2. Both CB(X) and VB (Γ) suitable for spin qubits; **hole implementation** preferred for technological reasons

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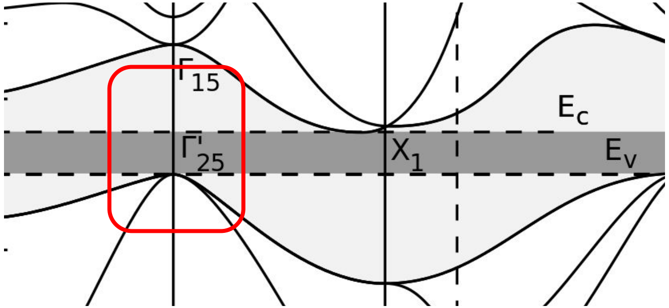

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l=1, s=1/2
J=3/2

Γ

hh: m=±3/2
lh: m=±1/2

4 - fold

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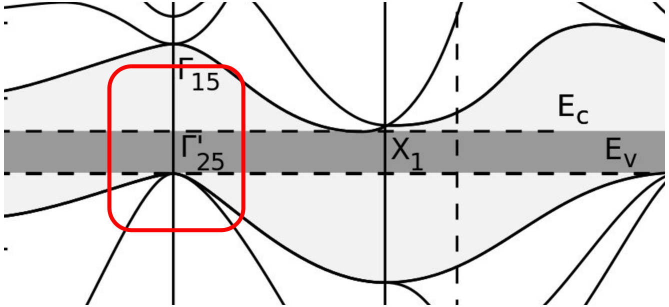

l=1, s=1/2
J=3/2

Γ

hh: m=±3/2
lh: m=±1/2

mixed hh/lh

E1

mixed hh/lh

E0

4 - fold

3D nano + E

1. Weak hyperfine interaction
2. Both CB(X) and VB (Γ) suitable for spin qubits; **hole implementation** preferred for technological reasons
3. Band gap mismatch and/or electrostatic environment mixes hh and lh bands
4. **Magnetic field (B) breaks Kramers degeneracy**
   → computational states , $|0\Downarrow\rangle \equiv |1\rangle$, $|0\Uparrow\rangle \equiv |0\rangle$

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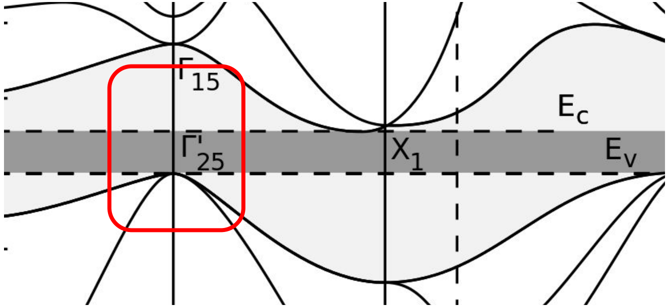

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   → computational states , |0⇓⟩≡ |1⟩, |0⇑⟩≡ |0⟩

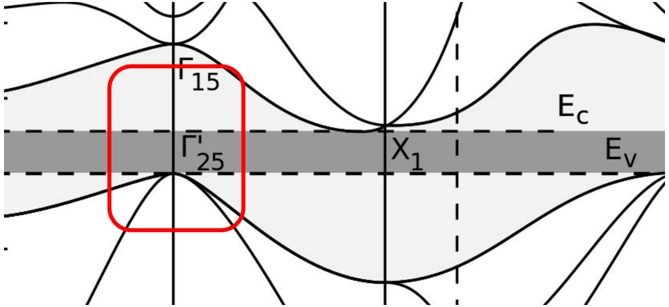
Undesired transition
ΔEorb >> ΔE

Qubit initialization
ΔE >> kT

! ΔE ≈μeV (KbT≈100 mK)

Si QDs FOR SPIN QUBITS

Implementation of two-level systems in Silicon nanostructures

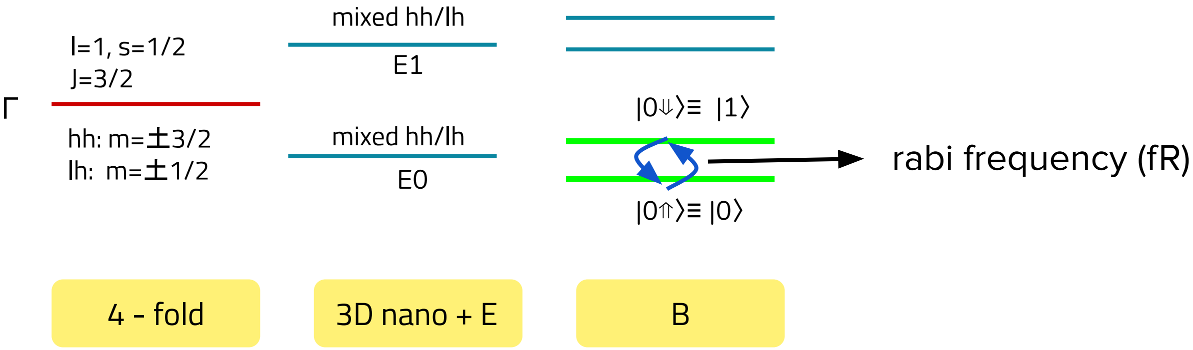


5. Relevant spin orbit interaction

→ PSEUDOSPIN qubit rotation controlled by **EDSR**

$$\delta E(t) = E_{ac} \cos(2\pi f_L t)$$

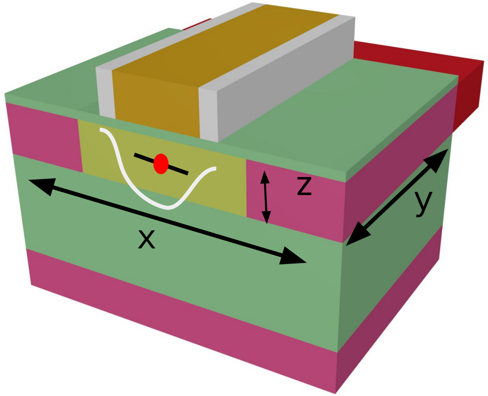
✓ Easier to realize than oscillating B



Si QDs FOR SPIN QUBITS

Fabrication of scalable Si Qubits in CMOS devices

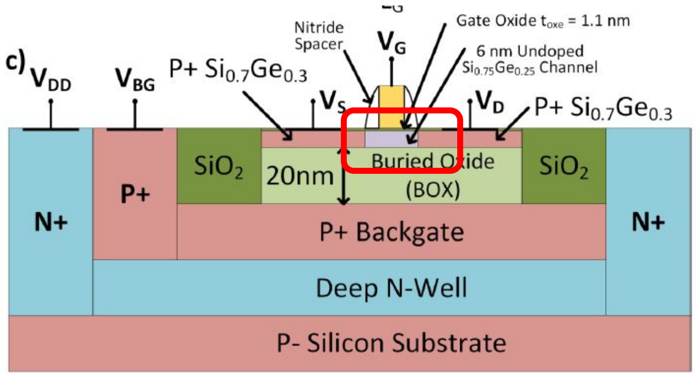
» QD generation in Si channel of **commercial** p-MOSFET



Z Confinement (6 nm)
BOX & GATE OXIDE

X Confinement (20 nm)
SiGe interface & NI spacers

Y Confinement (80-10 nm)
STI oxides



S. Bonen et al., *Cryogenic Characterization of 22-nm FDSOI CMOS Technology for Quantum Computing ICs,* IEEE Electron Device Lett., 40, 127-130 (2019)

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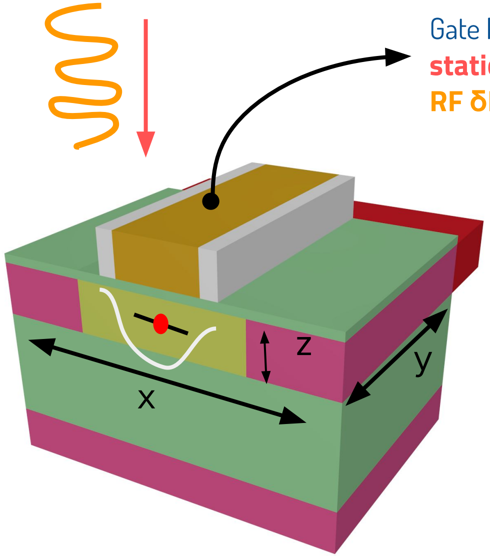

Gate Potential (VG)
static E → single-dot control
RF δE(t) → single-spin rotation

Z Confinement (6 nm)
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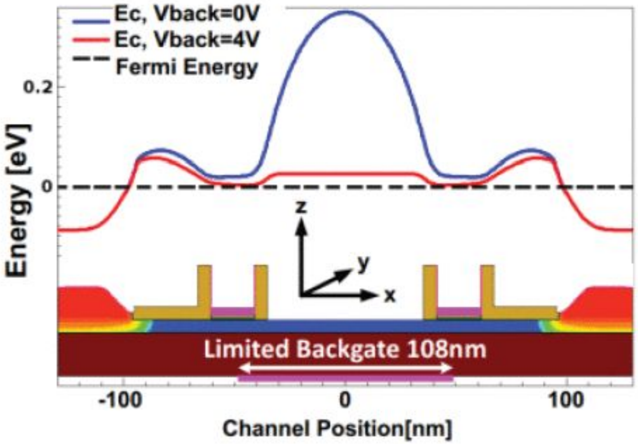
- QD generation in Si channel of **commercial** p-MOSFET
- Manipulation and control circuitry **in the same device**
  - *SQD* : VG + oscillating E for EDSR



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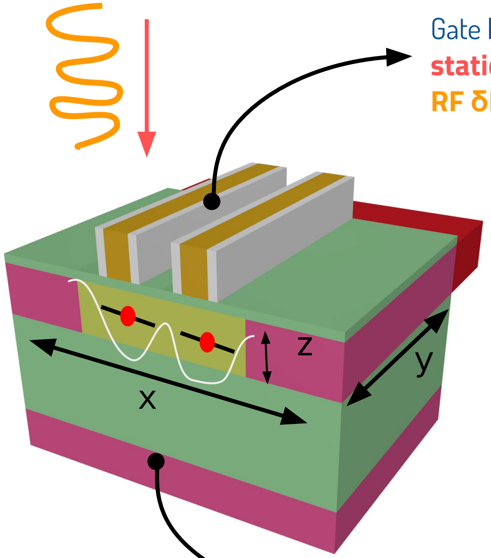

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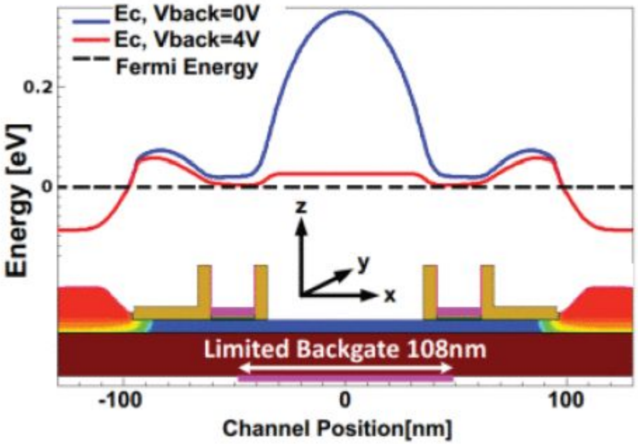
Back Gate (VBS)
Controls dot-dot tunneling barrier

- QD generation in Si channel of **commercial** p-MOSFET
- Manipulation and control circuitry **in the same device**
  - *SQD* : VG + oscillating E for EDSR
  - *DQD* : VB controls the interdot coupling



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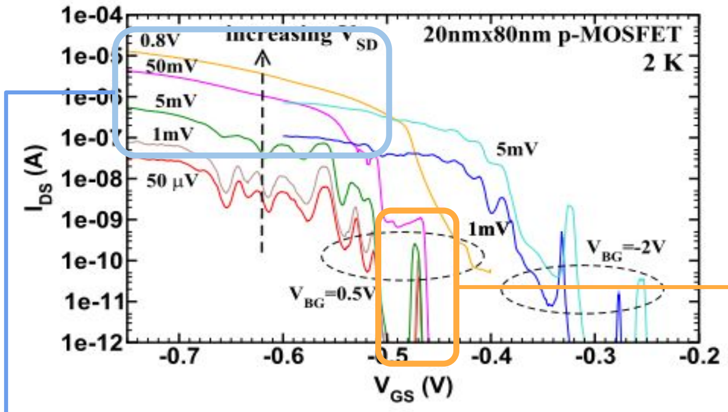

VSD > Vth → traditional I(VGS) of p-MOSFET

VSD < Vth → Coulomb blockade peaks

- QD generation in Si channel of **commercial** p-MOSFET
- Manipulation and control circuitry **in the same device**
  - *SQD* : VG + oscillating E for EDSR
  - *DQD* : VB controls the interdot coupling
- Charge quantization effect **up to few K**

Si QDs FOR SPIN QUBITS

Numerical design and simulation in p-MOSFETs

$$|n\rangle = \sum_B \psi_{n,B}(r)|B\rangle, \ \epsilon_n$$

$$H = \boxed{H_{LK}} + V(r)I + H_Z + H_p + H_d$$

- **k.p multiband modelling** of single-hole states
  - *Luttinger Kohn Hamiltonian* for Si bandstructure Γ (VB)
  - *Realistic 3D electrostatic potential* in MOSFETs from **Ginestra** software (AMAt)
  - *Zeeman, paramagnetic and diamagnetic* Hamiltonian to break Kramers degeneracy

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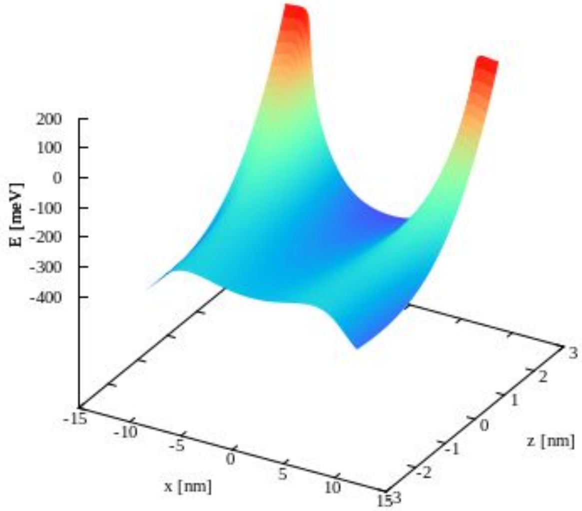

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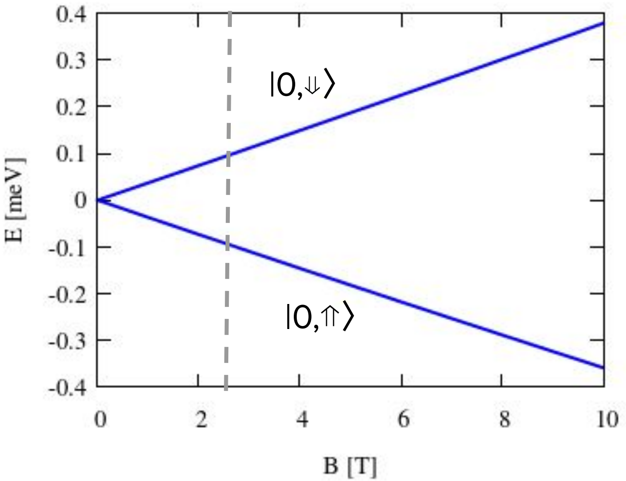

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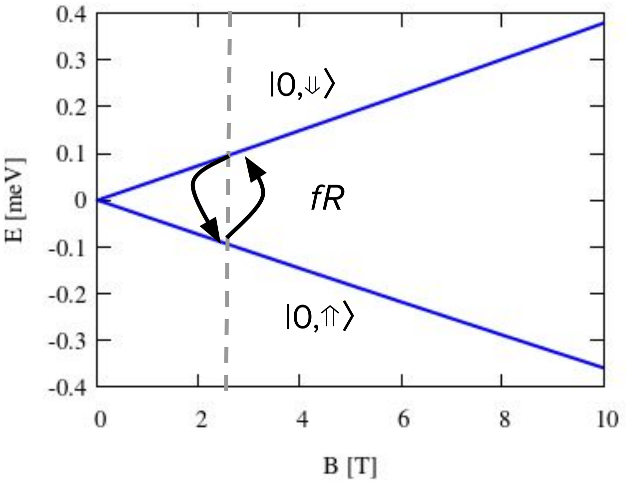

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→ Qubit spectrum

» *fR :* Simulation of the EDSR protocol for spin manipulation

→ **Optimization of structural properties** for faster gating times

Si QDs FOR SPIN QUBITS

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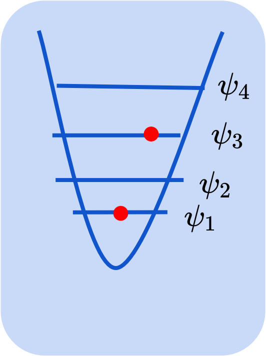

- Encoding, manipulation and readout strategies in **few-hole systems**.

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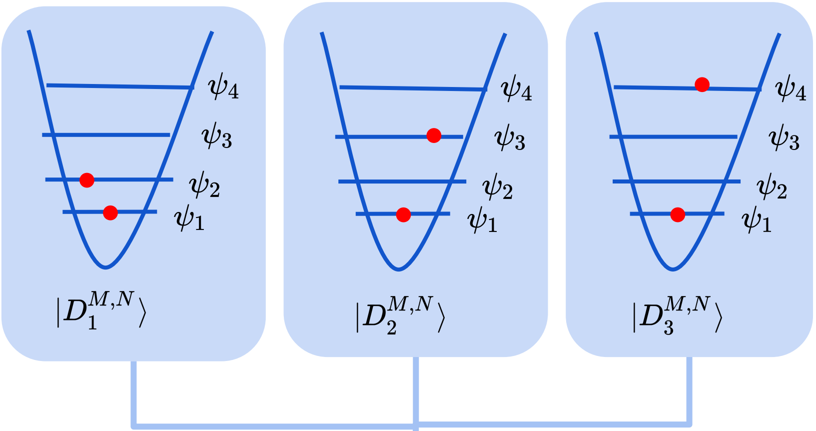

- Encoding, manipulation and readout strategies in **few-hole systems**.
- **Full Configuration Interaction** technique for exact few-hole states.
- **Intraband and interband** Coulomb scattering

$$|\Psi_n\rangle = \sum_{l=i}^{L} C_l^n |D_l^{M,N}\rangle$$

$$V_{n_1n_2n_3n_4} = \boxed{\sum_{B_1B_2B_3B_4}} \int dr \int dr' \, \psi^*_{n_1,B_1}(\boldsymbol{r})\psi^*_{n_2,B_2}(\boldsymbol{r}') \boxed{W_{B_1B_2B_3B_4}(\boldsymbol{r}-\boldsymbol{r}')} \psi_{n_3,B_3}(\boldsymbol{r}')\psi_{n_4,B_4}(\boldsymbol{r})$$

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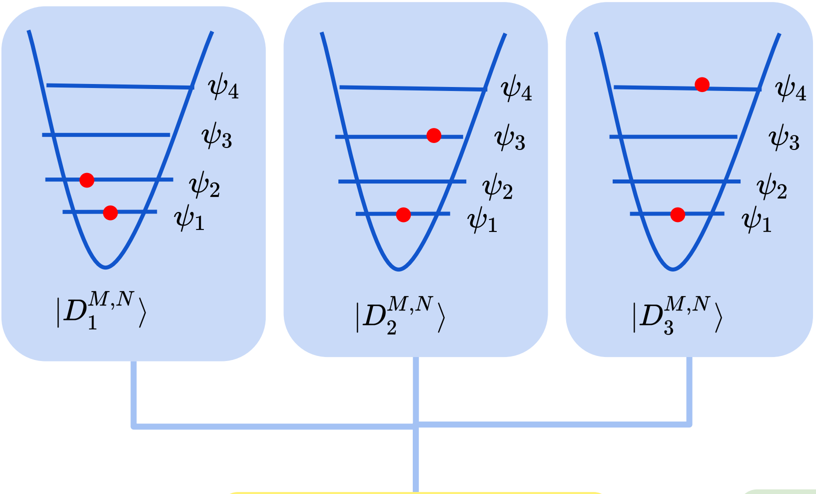

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- Additional **channel for band mixing** in QDs with double dot occupancy (with magnetic field and spin orbit)

A. Secchi et al, *Inter- and intra-band Coulomb interactions between holes in Silicon nanostructures*, to be submitted (2020)

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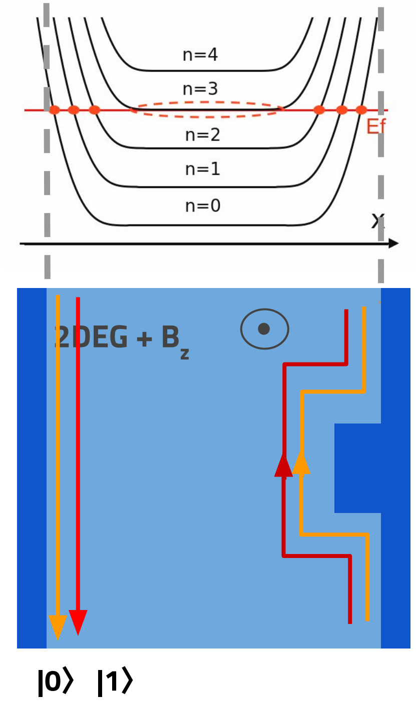
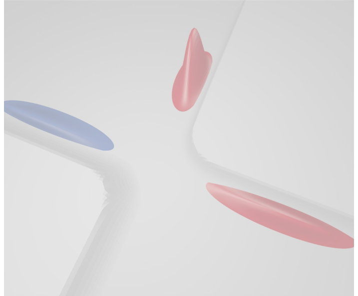
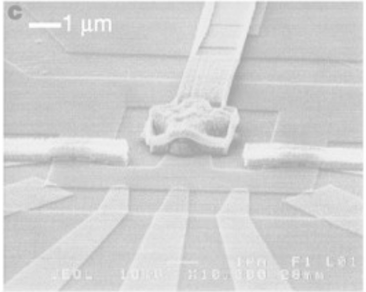
FLYING-QUBITS WITH EDGE STATES

State of the art and numerical modelling







- **Chiral conductive channels** in the IQH regime
- Qubit encoded in the cyclotron index n=0,1
- Single-charge injection with long coherence length, up to **10 µm**
- QPCs or sharp potential dips for **interferometry**

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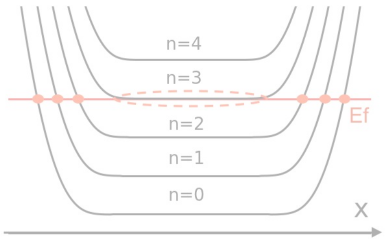
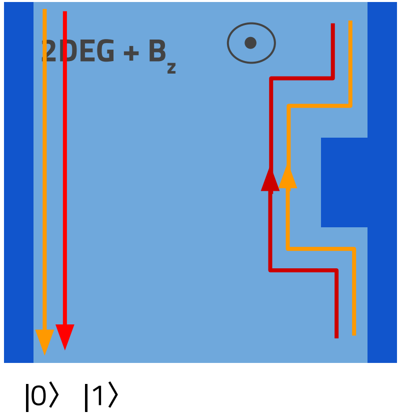
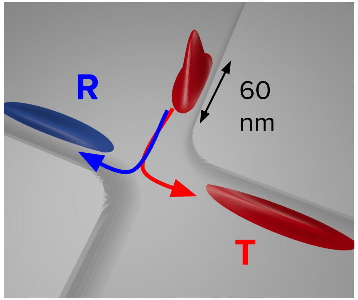
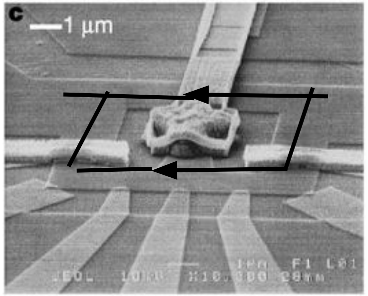






Ji et al, Nature 422 415-418 (2003)



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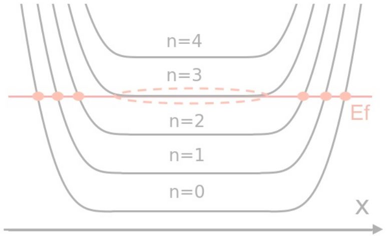

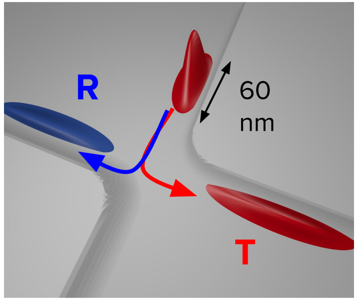

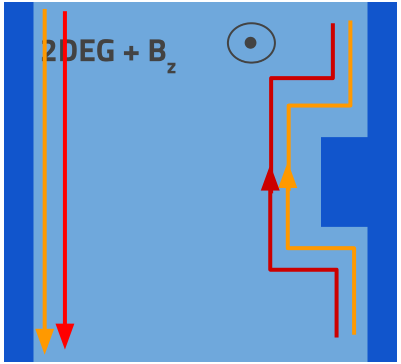

$|0\rangle$ $|1\rangle$

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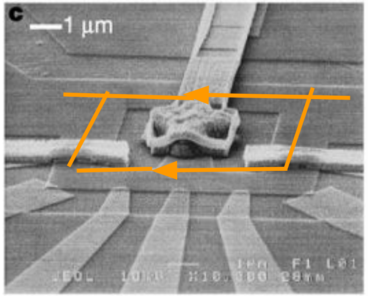

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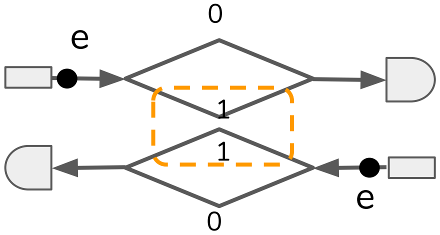
- *Time-dependent numerical solver* for the **4D Schroedinger equation**

$$i\hbar\frac{\partial\Psi}{\partial t} = \hat{H}\Psi = (\hat{T} + \hat{V}_{2D} + H_{int})\Psi$$

- **Full-scale 2D potential** mimicking top gates
- Gaussian **WPs** of edge states
- **HPC techniques** to tackle memory burden

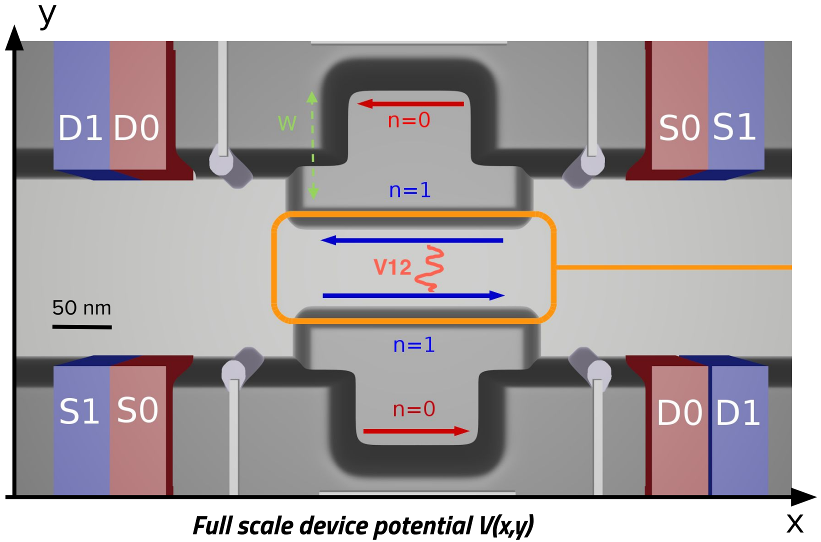
EDGE STATES FOR FLYING QUBITs

Numerical engineering of the Hall conditional Phase Shifter

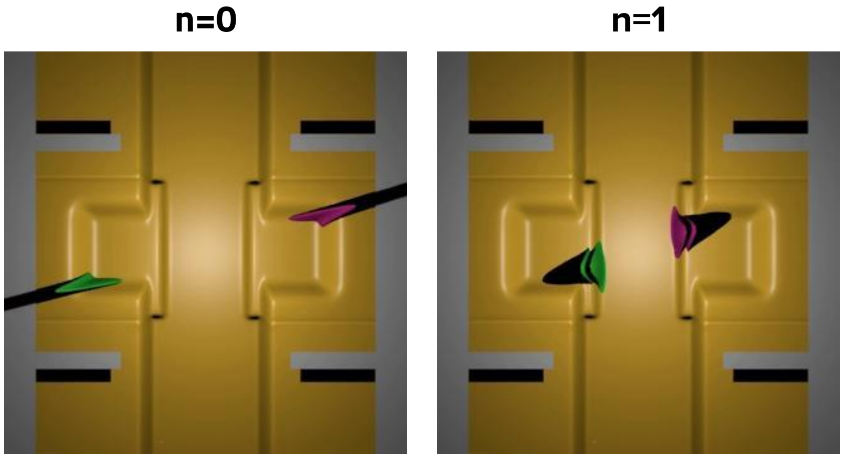


$$\hat{T}(\gamma) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & e^{i\gamma} \end{pmatrix}$$

- **Scalable geometry** at bulk filling factor two (n=0, n=1)
- Parallel MZI with selective interaction between n=1
- **Exact interplay** between 2D Coulomb repulsion, geometry and exchange correlation



Full scale device potential V(x,y)



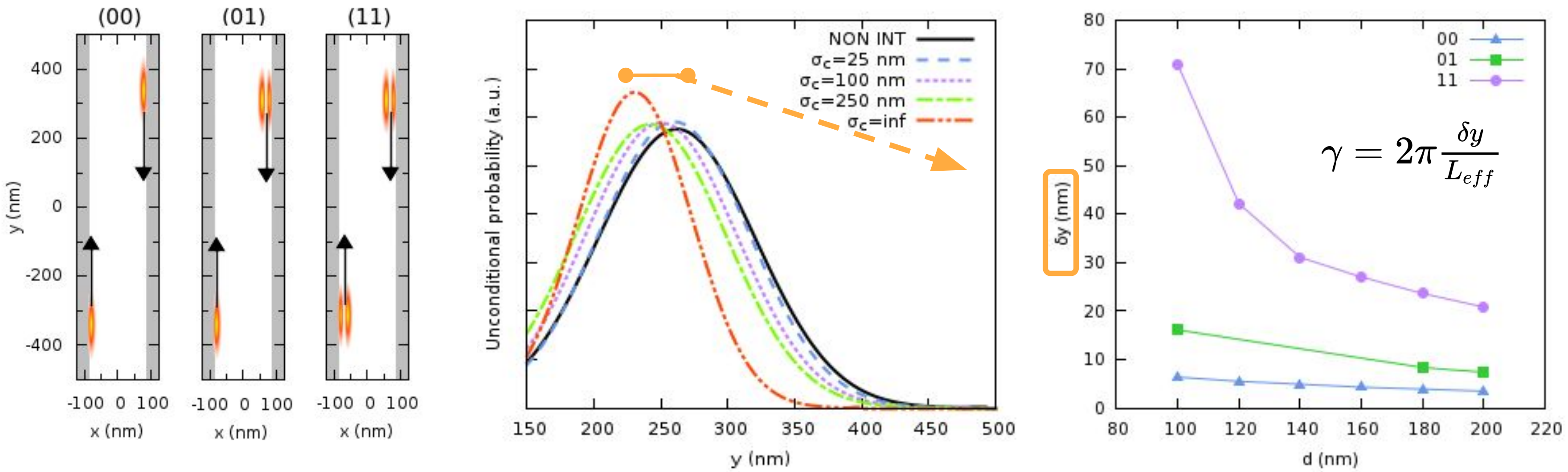
Time dependent simulation of two wavepackets in channel 0 and 1

EDGE STATES FOR FLYING QUBITs

Time-dependent simulation of two-electron dynamics with selective Coulomb interaction

✓ **Phase rotation γ in Hall device up to π**, tunable with geometry and screening

L Bellentani, G Forghieri, P Bordone, and A Bertoni, Phys. Rev. B 102, 035417 (2020)



SEMICONDUCTOR QUANTUM BITS

Conclusions

IQubits project

→ High-T spin qubits in Silicon commercial devices

→ Control of QD at high temperatures

→ Scalable monolithic integration on the same chip

Hall interferometers

→ Flying-qubit operations in a scalable geometry

→ Single-charge injection and detection in IQH

THANK YOU FOR YOUR ATTENTION

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