Engineering Multi-Electron Interactions for Quantum Logic in Silicon

PHD FINAL EXAMINATION

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Outline

Electron Spin Qubits in Solid-State Architectures

Modeling via Atomsitic Configuration Interaction

- Development
- Simulations
  - Experimental Validation
  - Predictive Modeling of Qubits

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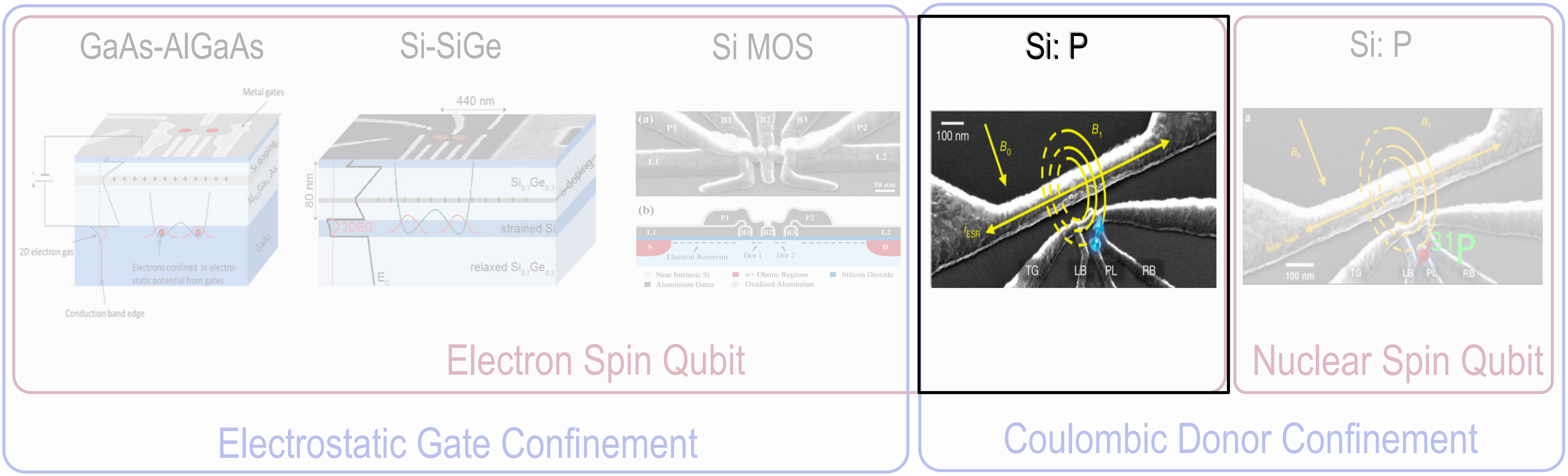
Solid-State Quantum Computing Architectures

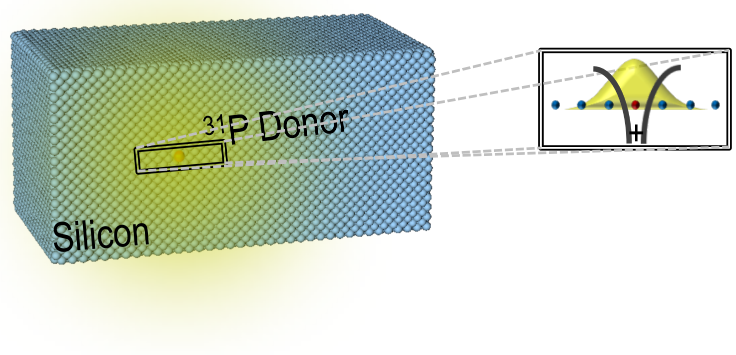
✓ Advantages with fabrication technologies of modern electronics



Electron spin qubits bound to dopant atoms in silicon

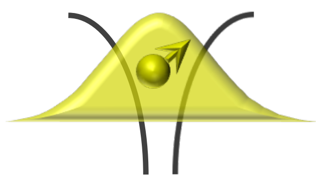
[1,3]http://www.accent.rwth-aachen.de/
[2]Lai, N. S., et al. Scientific reports (2011)
[4]Pla, Jarryd J., et al. Nature489.7417 (2012)

Single electron spin qubits bound to dopant atoms in silicon



Coulombic potential
- ➢ Spherically symmetric

Confines electron in 3D



✓ Single electron spin qubit demonstrated successfully

LETTER

doi:10.1038/nature11449

A single-atom electron spin qubit in silicon

Jarryd J. Pla[1], Kuan Y. Tan[1]†, Juan P. Dehollain[1], Wee H. Lim[1], John J. L. Morton[2]†, David N. Jamieson[3], Andrew S. Dzurak[1] & Andrea Morello[1]

LETTER

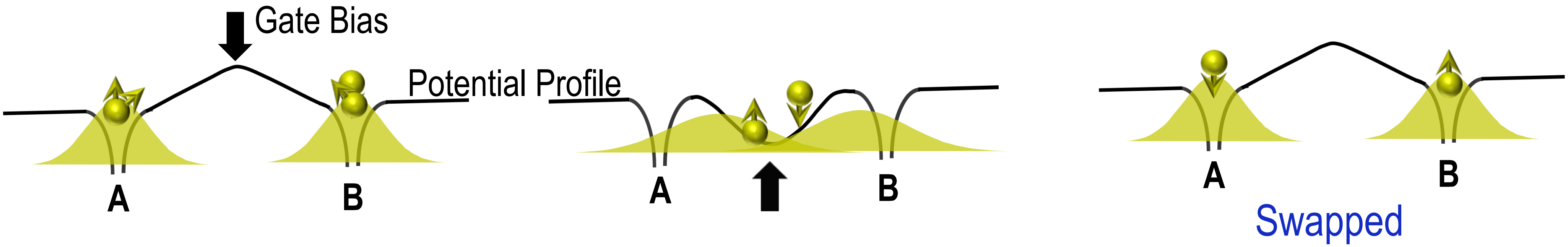
doi:10.1038/nature09392

Single-shot readout of an electron spin in silicon

Andrea Morello[1], Jarryd J. Pla[1], Floris A. Zwanenburg[1], Kok W. Chan[1], Kuan Y. Tan[1], Hans Huebl[1]†, Mikko Möttönen[1,3,4], Christopher D. Nugroho[1]†, Changyi Yang[2], Jessica A. van Donkelaar[2], Andrew D. C. Alves[2], David N. Jamieson[2], Christopher C. Escott[1], Lloyd C. L. Hollenberg[2], Robert G. Clark[1]† & Andrew S. Dzurak[1]

Two qubit gates are the next big challenge for quantum computing applications

Example: **SWAP Operation**



Electron spins rotate in presence of each other

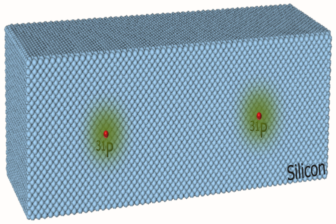
When to stop applying the gate bias?

- Speed of electron spin rotation → Electron-Electron Interaction

✓ Two Qubit operations rely on interaction strength between two electrons

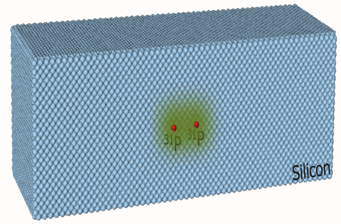
Electron-Electron Interactions must be accurately estimated for precise qubit control

Models to estimate Electron-Electron Interactions



Heitler-London Approximation

✓ Well separated donors

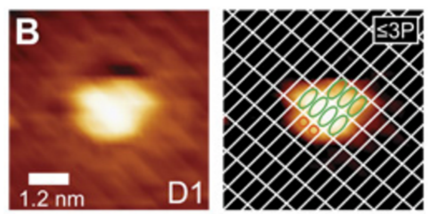


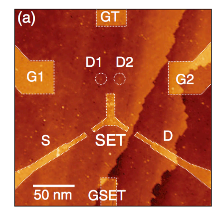
Hartree-Fock Approximation

✓ Closely spaced donors

Realistic Quantum Computing Devices

Donor separations range from 1nm (donor clusters) to 25nm (spin qubit)





Exact electron-electron interactions for precise qubit control

GOAL

Model to capture electron-electron interactions accurately for ALL donor separations

[1]Watson, Thomas F. et al. Science Advances 3.3 (2017)
[2]Watson, T. F., et al. Physical review letters 115.16 (2015)

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Electron Spin Qubits in Solid-State Architectures

Modeling via Atomsitic Configuration Interaction

Development

Methodology

Challenge

Solutions

Applications

Simulations

Experimental Validation

Predictive Modeling of Qubits

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GOAL: Model electron-electron interactions accurately

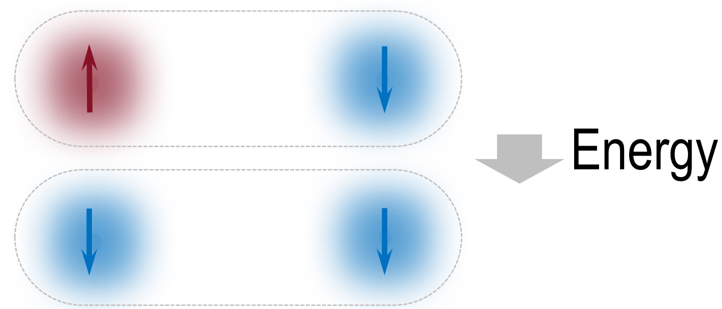
ALL electron-electron interactions

✓ Coulomb repulsion

Electron charge clouds

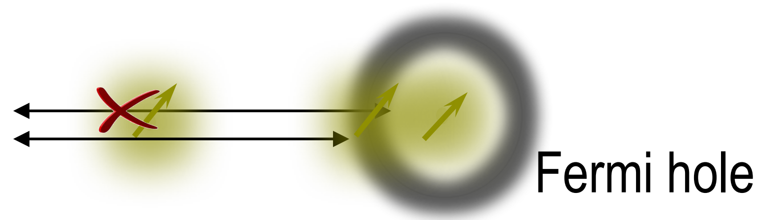
✓ Exchange interactions

Parallel electron spins (Hund's Rule)



✓ Correlations

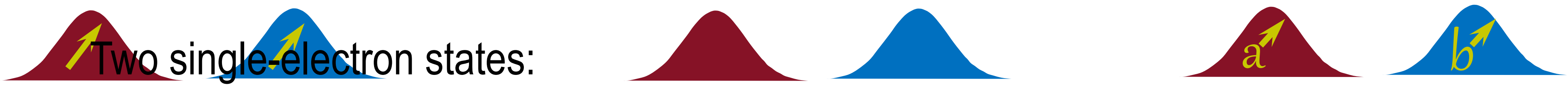
Correct overestimated repulsion



Full Configuration Interaction (FCI) to model electron-electron interactions

Two-electron Wavefunction

Two single-electron states:



$\psi_i(\vec{r}\,)$ $\psi_j(\vec{r})$ $\psi_i(\vec{r}\,)$ $\psi_j(\vec{r})$ $\psi_i(\vec{r}\,)$ $\psi_j(\vec{r})$

Two electrons:

$$\Psi_{ij}(\vec{r}_a, \vec{r}_b) = \psi_i(\vec{r}_a)\, \psi_j(\vec{r}_b) - \psi_i(\vec{r}_b)\, \psi_j(\vec{r}_a)$$

✗ Distinguishable electrons

✓ Indistinguishable electrons

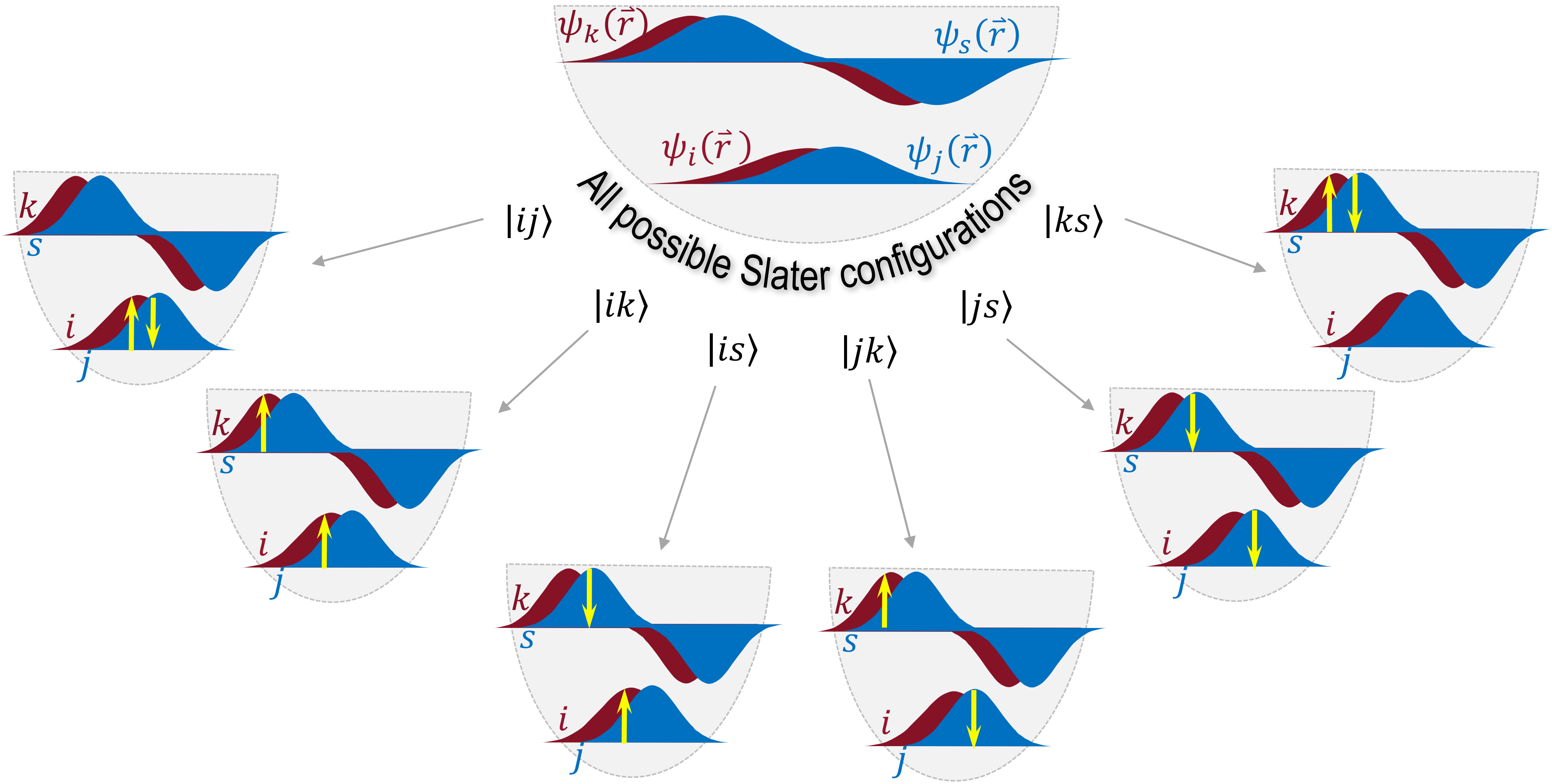
$$\Psi_{ij}(\vec{r}_a, \vec{r}_b) = \begin{vmatrix} \psi_i(\vec{r}_a) & \psi_j(\vec{r}_a) \\ \psi_i(\vec{r}_b) & \psi_j(\vec{r}_b) \end{vmatrix} = |\, ij\, \rangle$$

Slater Determinant

2 indistinguishable electrons
2 single-electron wavefunctions

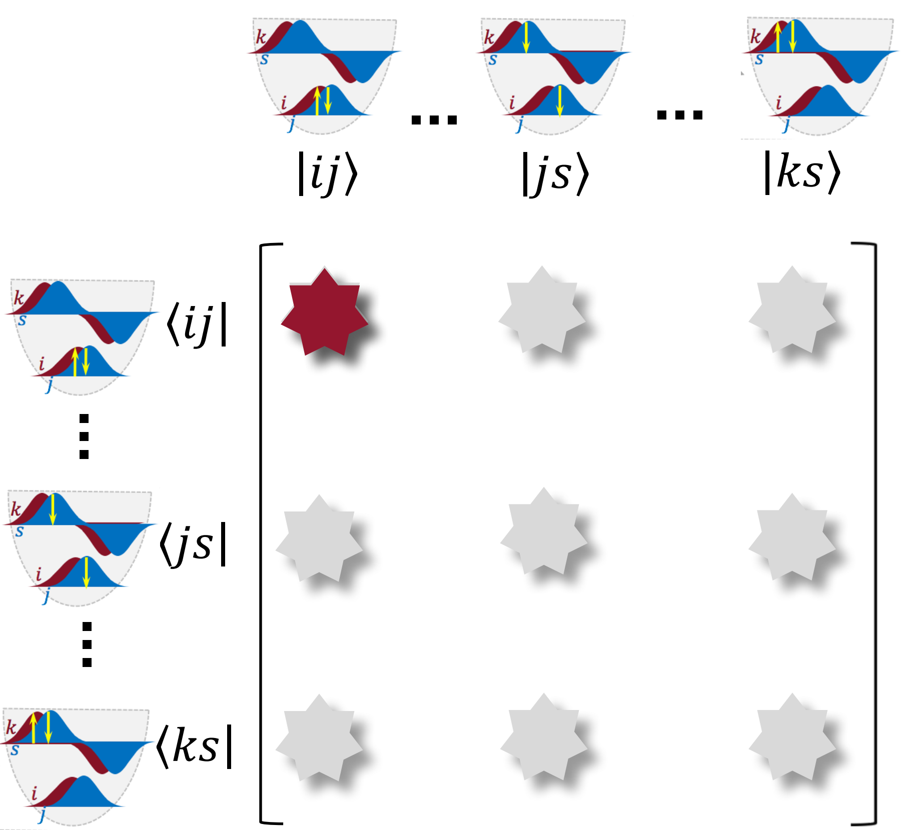
Complete set of two-electron Slater Determinants

Complete set of single-electron states



Complete set of Slater determinants as basis for two-electron Hamiltonian

Two-electron FCI Hamiltonian in Slater Determinant basis



$\langle \, ij \, |\mathcal{H}| \, ij \, \rangle$

$\langle \, ij \, |\mathcal{H}^{(1)}| \, ij \, \rangle + \langle \, ij \, |\mathcal{H}^{(2)}| \, ij \, \rangle$

$$E_i + E_j + \langle \, ij \, | \frac{1}{|\vec{r}_a - \vec{r}_b|} | \, ij \, \rangle$$

Single electron in ψ_i

Single electron in ψ_j

Interactions between electrons in ψ_i and ψ_j

- Coulomb Interactions

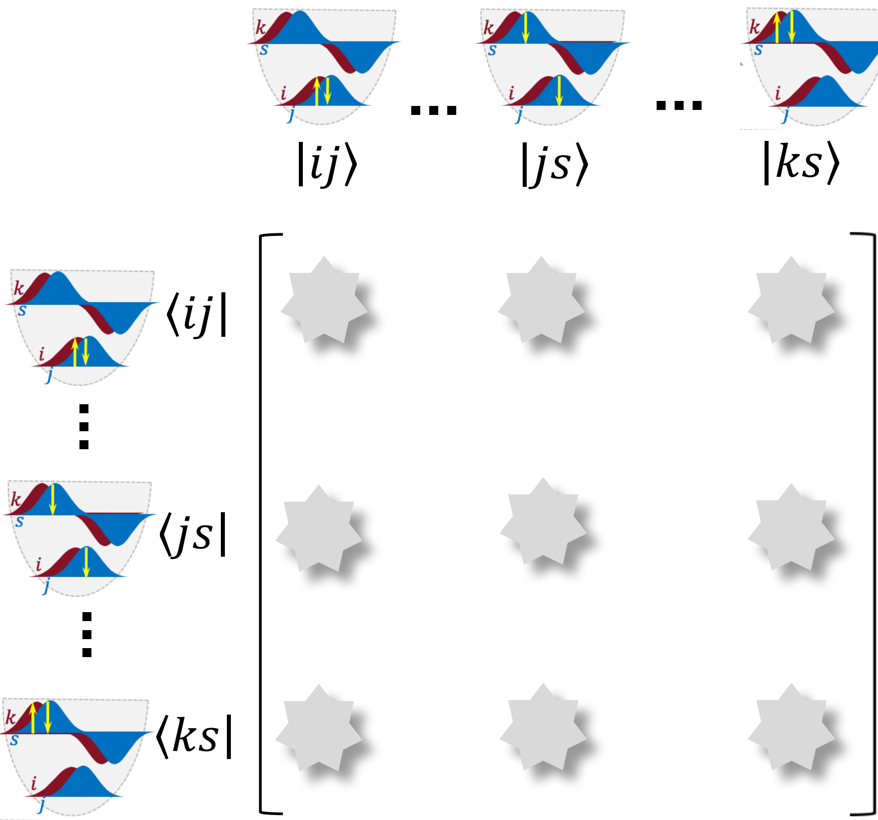
$$\iint_V \psi_i^*(\vec{r}_a)\, \psi_j^*(\vec{r}_b) \frac{1}{|\vec{r}_a - \vec{r}_b|} \psi_i(\vec{r}_a)\, \psi_j(\vec{r}_b)\, d\vec{r}_a d\vec{r}_b$$

- Exchange Interactions

$$\iint_V \psi_i^*(\vec{r}_a)\, \psi_j^*(\vec{r}_b) \frac{1}{|\vec{r}_a - \vec{r}_b|} \psi_j(\vec{r}_a)\, \psi_i(\vec{r}_b)\, d\vec{r}_a d\vec{r}_b$$

FCI is EXACT in the space spanned by the basis

Diagonalization of two-electron FCI Hamiltonian: Two-Electron States

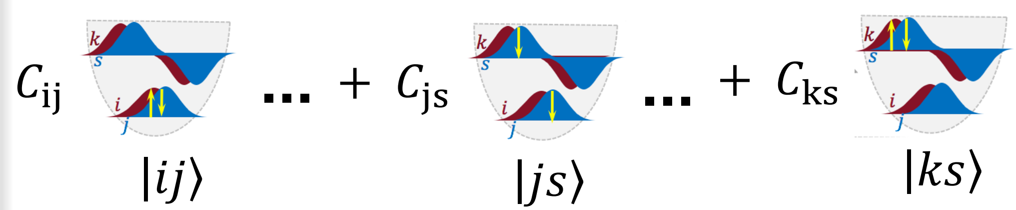


Eigensolvers: LAPACK + FEAST

✓ Faster than using either one

Two-electron energy levels

Two-electron wavefunctions

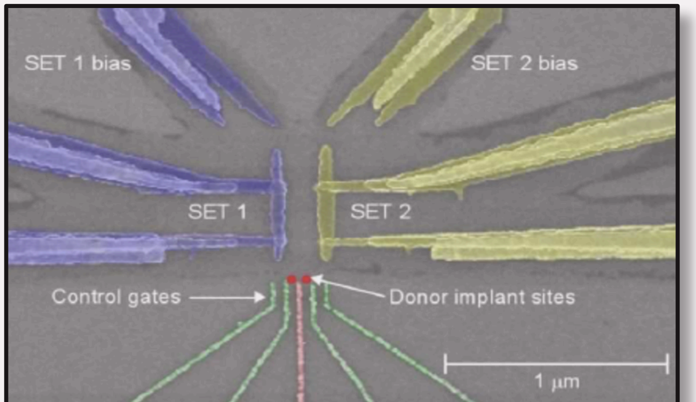


Exact Spectrum and Configuration of multi-electron states from FCI

Modeling donor based quantum computing architectures

Single-Electron States → Two-Electron Slater Determinants

Atomistic Tight-Binding



- ✓ Multi-million atom domain
- ✓ Complex geometries
- ✓ Atomistic effects of interfaces
- ✓ Incorporate bandstructure effects

Full Configuration Interaction

- ✓ Coulomb repulsion
- ✓ Exchange interactions
- ✓ Correlations

Multi-Electron States

Atomistic Configuration Interaction (ACI) to model multi-electron devices

Dzurak, A. S., et al. arXiv 0306265(2003)

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Complexity of ACI

Challenge: $\vartheta(N^2 n^e)$

N: # atoms

n: # single-electron states in the basis
e: # electrons

ACI matrix elements

$$\iint_V \psi_i^*(\vec{r}_a)\,\psi_j^*(\vec{r}_b)\,\frac{1}{|\vec{r}_a - \vec{r}_b|}\,\psi_k(\vec{r}_a)\,\psi_l(\vec{r}_b)\;d\vec{r}_a d\vec{r}_b$$

✘ Double integrals over all atoms in the simulation domain

$\vartheta(N^2)$

 # Slater determinants in ACI basis

e electrons n in states: ${}^{n}_{e}C$

$\vartheta(n^e)$

ACI is computationally intensive for large N or n or e

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Complexity of ACI

Challenge: $\vartheta(N^2 n^e)$?

Solution 1:

High Performance Computing
Parallelize data and computations

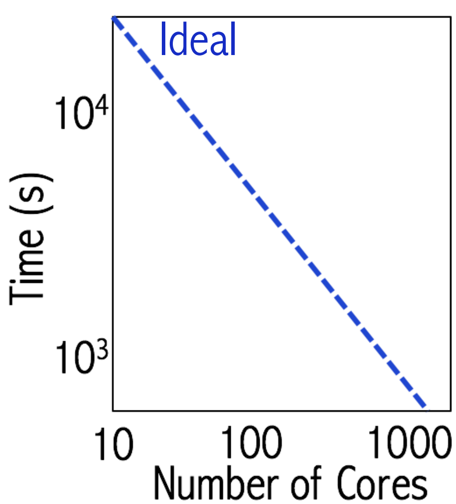
Solution 2:

Optimized Algorithms
Complexity Reduction from N^2 to NlogN

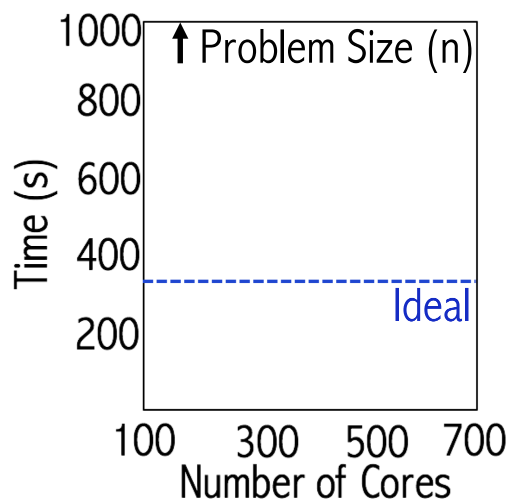
Parallelization of ACI

"Efficiently" distribute the data and computations to several CPUs

Strong Scaling



Weak Scaling



Overhead

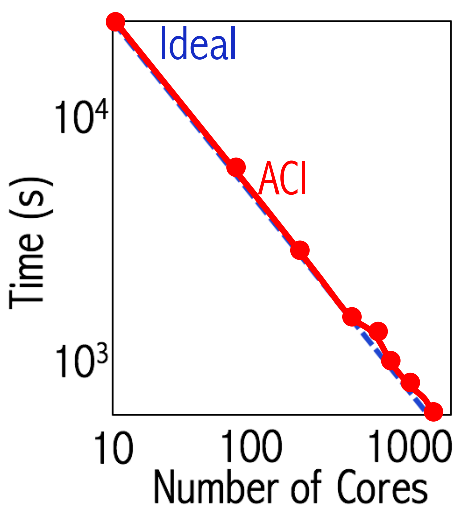
< 5%

IO and communication

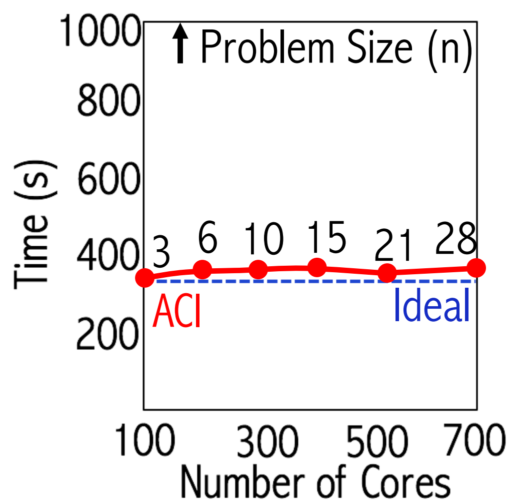
Parallelization of ACI

"Efficiently" distribute the data and computations to several CPUs

Strong Scaling



Weak Scaling



Overhead

< 2%
IO and communication

ACI scales close to ideal

Complexity of ACI

Challenge: $\vartheta(N^2 n^e)$

Solution 1:

High Performance Computing

Parallelize data and computations

Solution 2:

Optimized Algorithms

Complexity Reduction from N^2 to NlogN

Complexity reduction of ACI

Identify the most demanding computations

$$\langle\, ij \mid kl \,\rangle = \iint_V \psi_i^*(\vec{r}_a)\, \psi_j^*(\vec{r}_b)\, \frac{1}{|\vec{r}_a - \vec{r}_b|}\, \psi_k(\vec{r}_a)\, \psi_l(\vec{r}_b)\, d\vec{r}_a d\vec{r}_b$$

: 6D Integral !

$$\sum_{a=1}^{N}\sum_{b=1}^{N} Q_{ik}(\vec{r}_a)\, \frac{1}{|\vec{r}_a - \vec{r}_b|}\, Q_{jl}(\vec{r}_b)$$

Mathematically similar in form to the very well known N-Body Problem!

Interactions between EVERY pair of particles of an N-particle system

masses : Gravitation

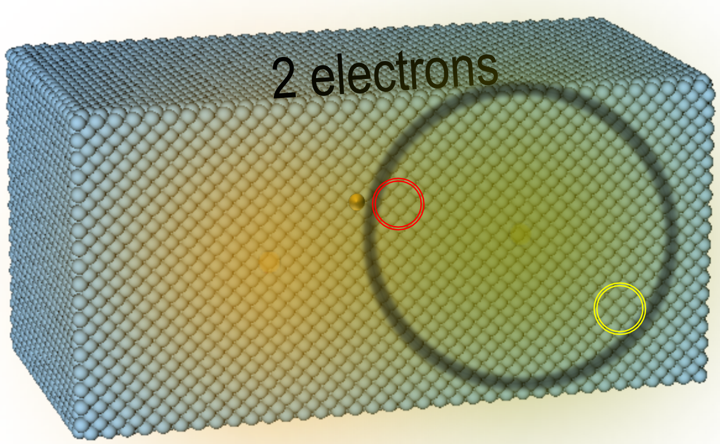
atoms : Molecular Dynamics

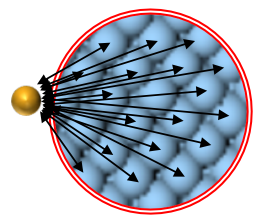
charges : Electrodynamics

Complexity reduction of ACI

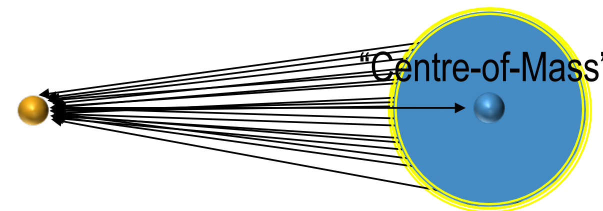
Fast Multipole Method for N-Body problems

Acclaimed as one of the top 10 algorithms of the 20th century
$O(N^2)$ complexity to $O(N \log N)$ or $O(N)$





Particle-Particle Interaction



Averaged effective interaction from the far away atoms

Upto 100x speed up in ACI achieved with Fast Multipole Method

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NEMO: Atomistic Configuration Interaction Tool

Accurately model electron-electron interaction in realistic quantum computing devices

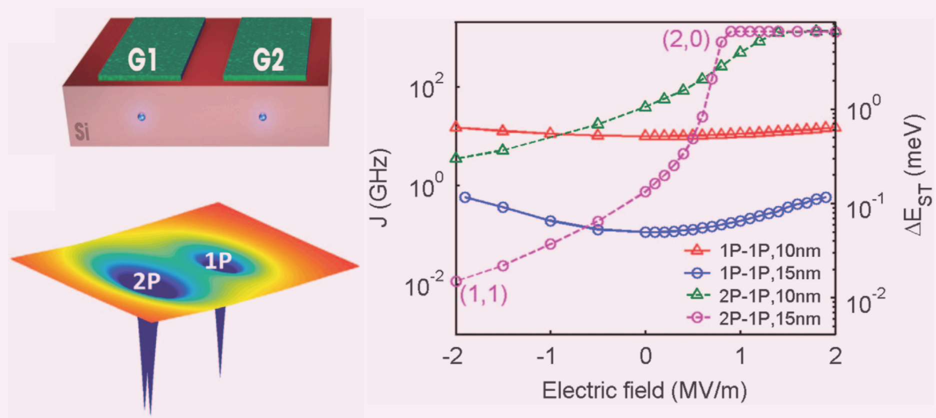
Applications of NEMO: Atomistic Configuration Interaction Tool

npj | Quantum Information

ARTICLE OPEN

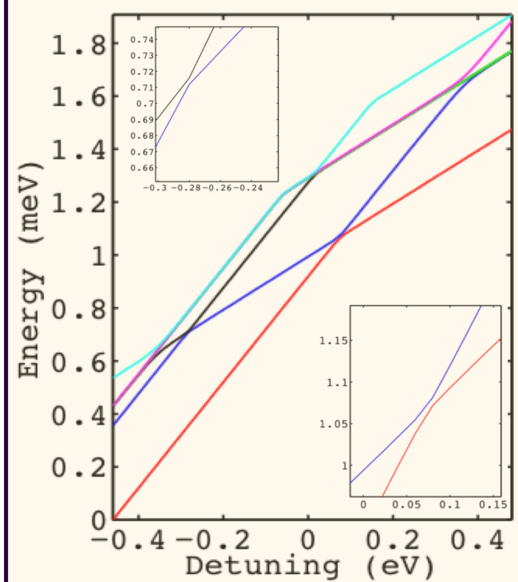
Highly tunable exchange in donor qubits in silicon

Yu Wang[1], Archana Tankasala[1], Lloyd CL Hollenberg[2], Gerhard Klimeck[1], Michelle Y Simmons[3] and Rajib Rahman[1]



Quantum Dot Hybrid Qubit

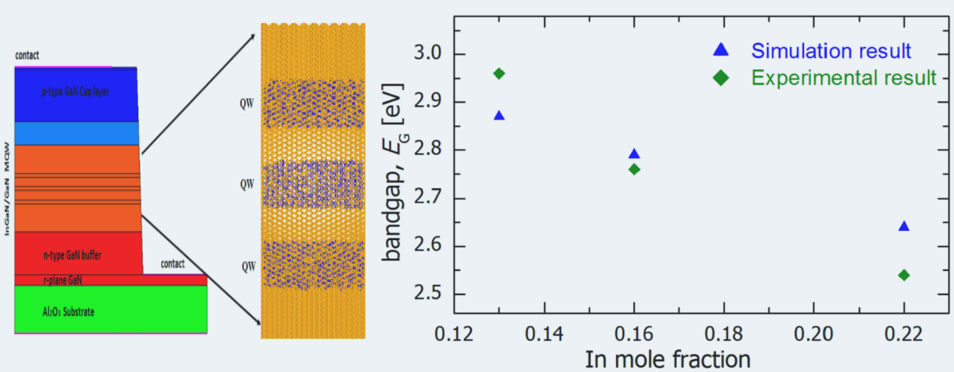
C. Chen et. al. (unpublished)



- 3-electron states of double quantum dots
- $|0\rangle - |E\rangle$ and $|1\rangle - |E\rangle$ anti-crossings for qubit operation

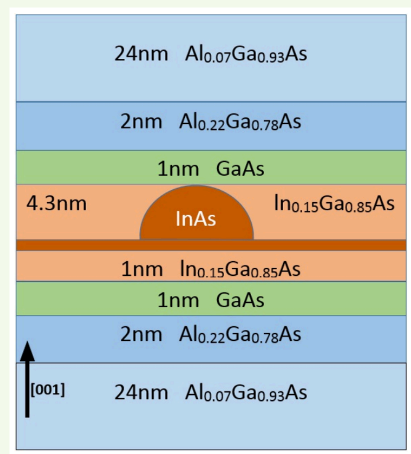
Multiscale-Multiphysics Modeling of Nonpolar InGaN LEDs*

Md Rezaul Karim Nishat, Archana Tankasala, Neerav Kharche, Rajib Rahman, and Shaikh S. Ahmed



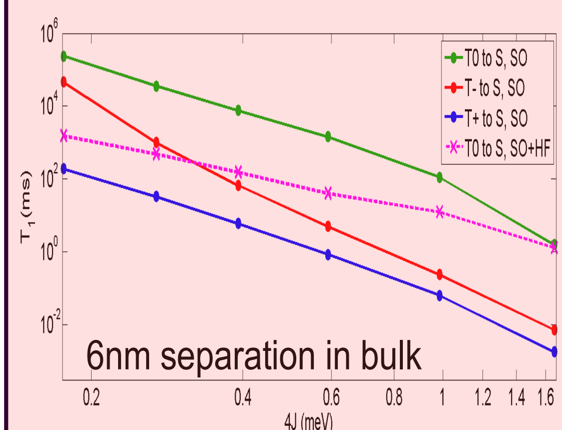
Optical Quantum Dots

T. Ameen et. al. (unpublished)



T_1 Relaxation Donor Pairs

Y. Hsueh et. al. APS 2016



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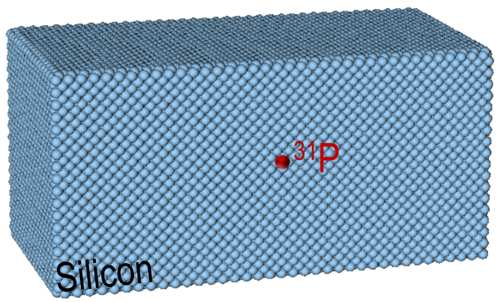
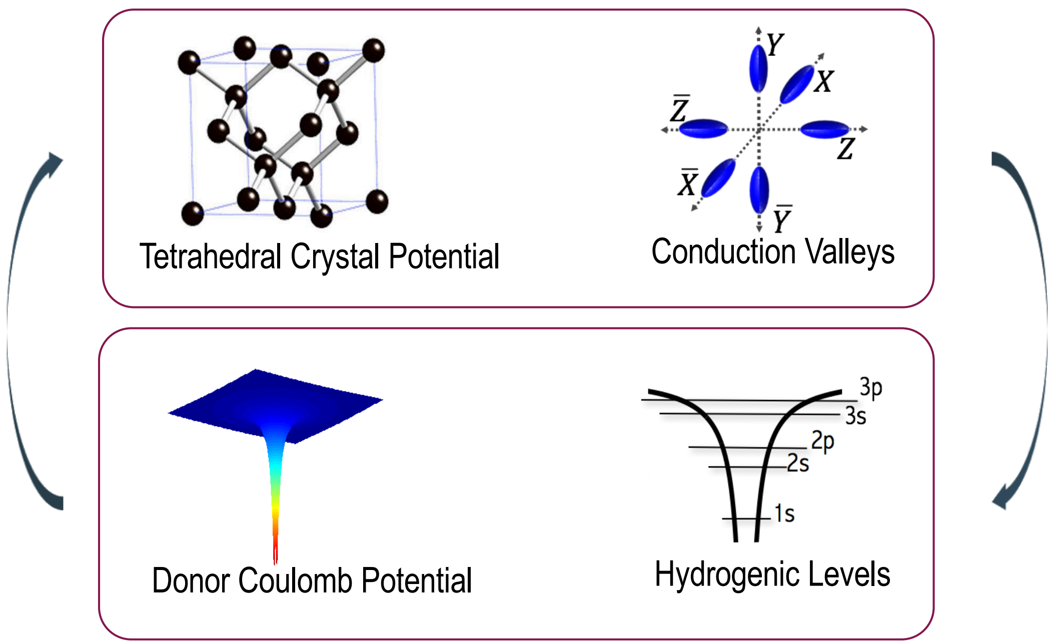
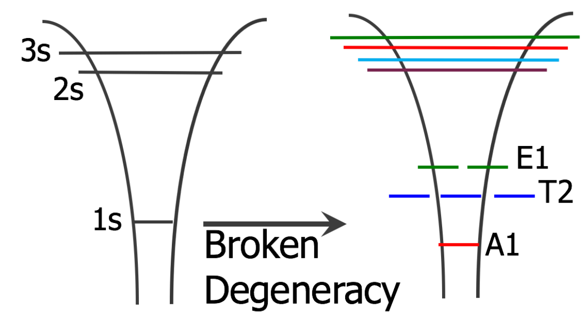
Donor single-electron states from Atomistic Tight-Binding





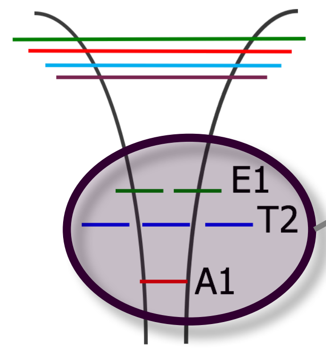
Valley-Orbit Coupling



Atomistic Tight-Binding accurately captures the single electron energy spectrum of donor

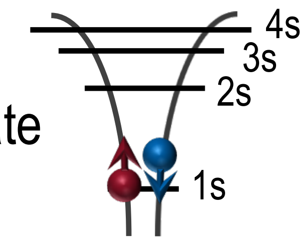
Two-electron state of a single donor in bulk silicon

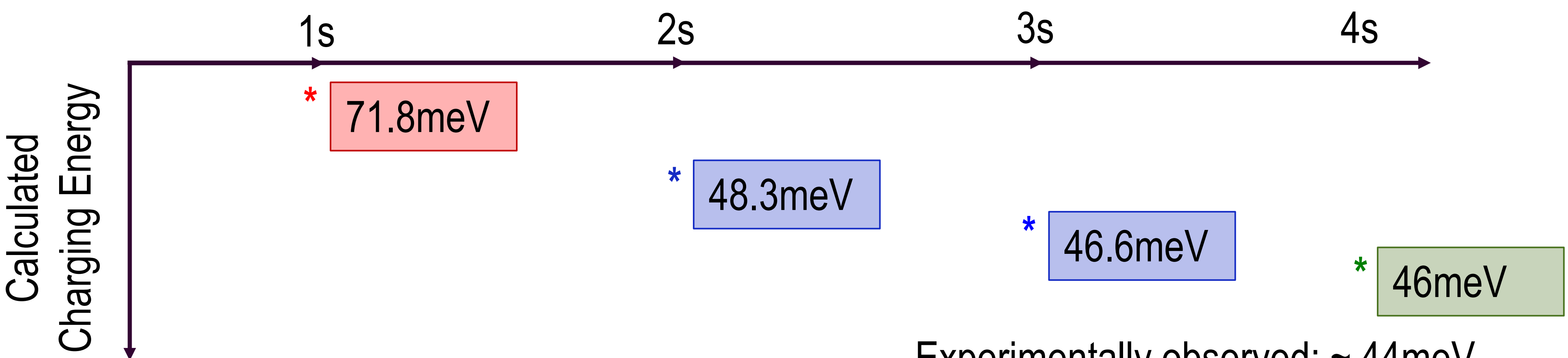
Energy spectrum of a donor in silicon



Typically considered for D^- calculation

Assumption:
Both electrons in 1s-like state





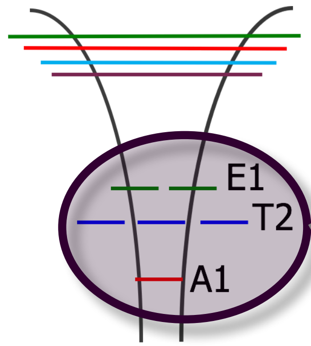
Experimentally observed: ~ 44meV

Two-electron charging energy of single donor matches with experiments

A. Tankasala et al. arXiv:1703.04175.

Moreover...

Energy spectrum of a donor in silicon



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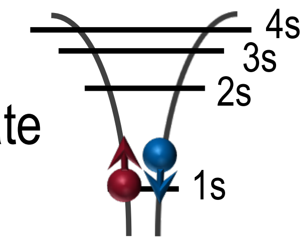
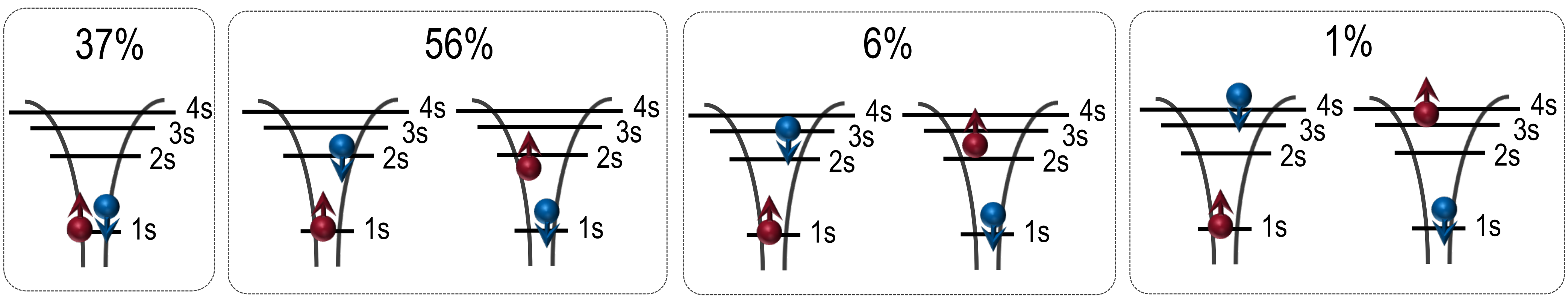


Two-electron wavefunction from ACI



ACI gives the configuration of the two-electron state of a bulk donor

A. Tankasala et al. arXiv:1703.04175.

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Electron-electron interactions in donor pairs

Two qubit operation of donor based electron spins

Example: **SWAP Operation**

Electron-electron interactions in donor pairs: Two qubit operations

Electron spins rotate in presence of each other

When to stop applying the gate bias?

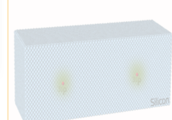
- Speed of electron spin rotation → Electron-Electron Interaction

✓ Two Qubit operations rely on interaction strength between two electrons

Electron-Electron Interactions must be accurately estimated for precise qubit control

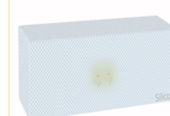
Purdue University — Archana Tankasala — 5

Models to estimate Electron-Electron Interactions



Heitler-London Approximation

✓ Well separated donors



Hartree-Fock Approximation

✓ Closely spaced donors

Realistic Quantum Computing Devices

Donor separations range from 1nm (donor clusters) to 25nm (spin qubit)

Available models NOT valid over all donor separation regimes and are only approximate

Exact electron-electron interactions for precise qubit control

Model to capture electron-electron interactions accurately for ALL donor separations

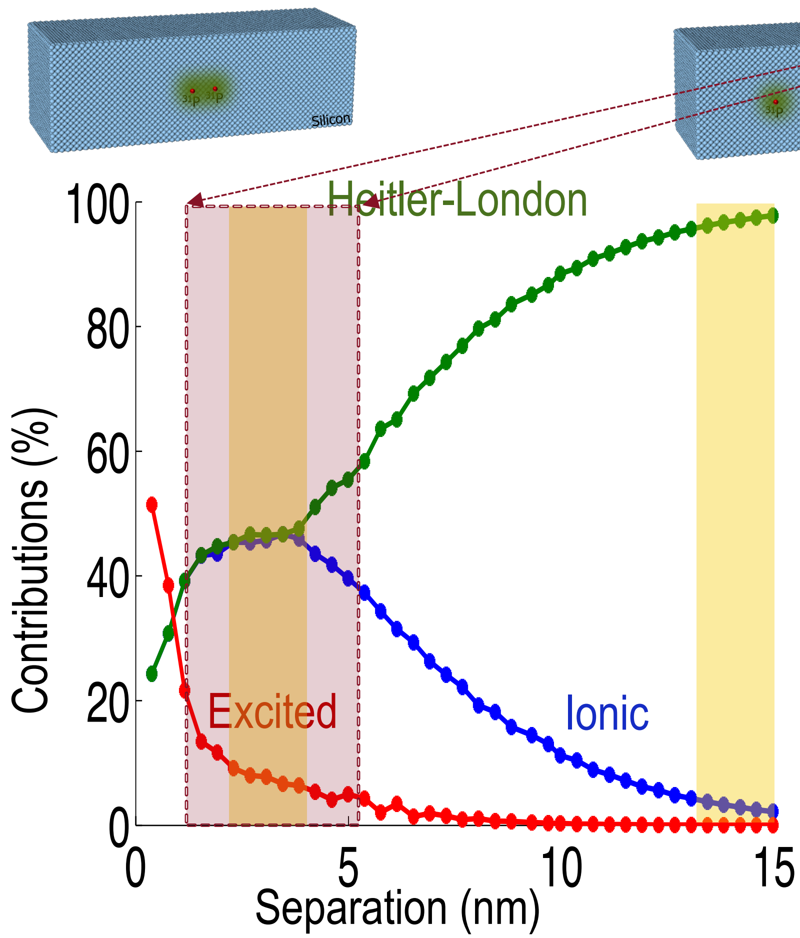
Purdue University — [1]Watson, Thomas F. et al. Science Advances 3.3 (2017) [2]Watson, T. F., et al. Physical review letters 115.16 (2015) — Archana Tankasala — 6

NEMO5

Approximate models to determine exchange in donor pairs

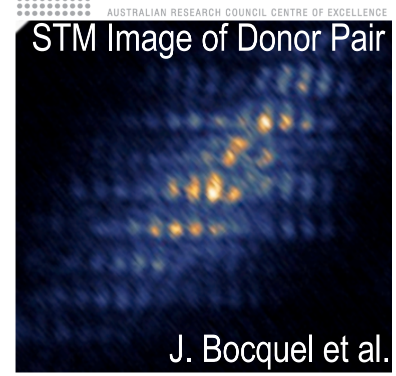
Hartree-Fock Regime

Heitler-London Regime



STM Experiments on donor pairs

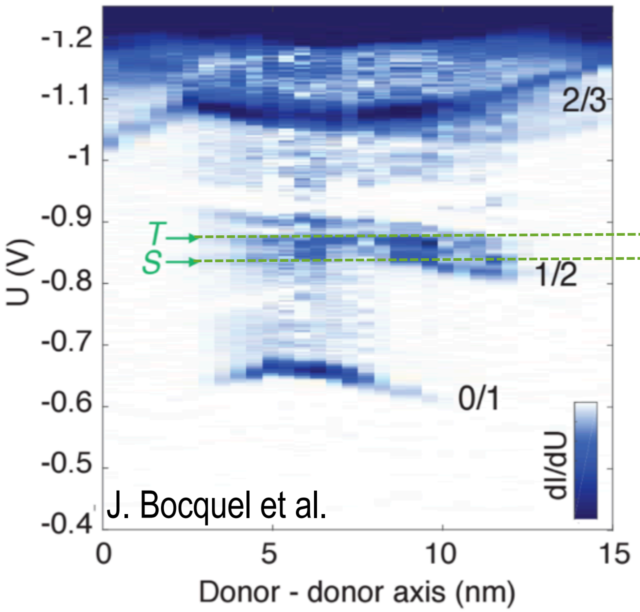
CENTRE FOR QUANTUM COMPUTATION & COMMUNICATION TECHNOLOGY
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE



Closely spaced donors 2nm-5nm

Approximate models invalid for donors in STM experiments

Phosphorous donor pairs probed in STM experiments

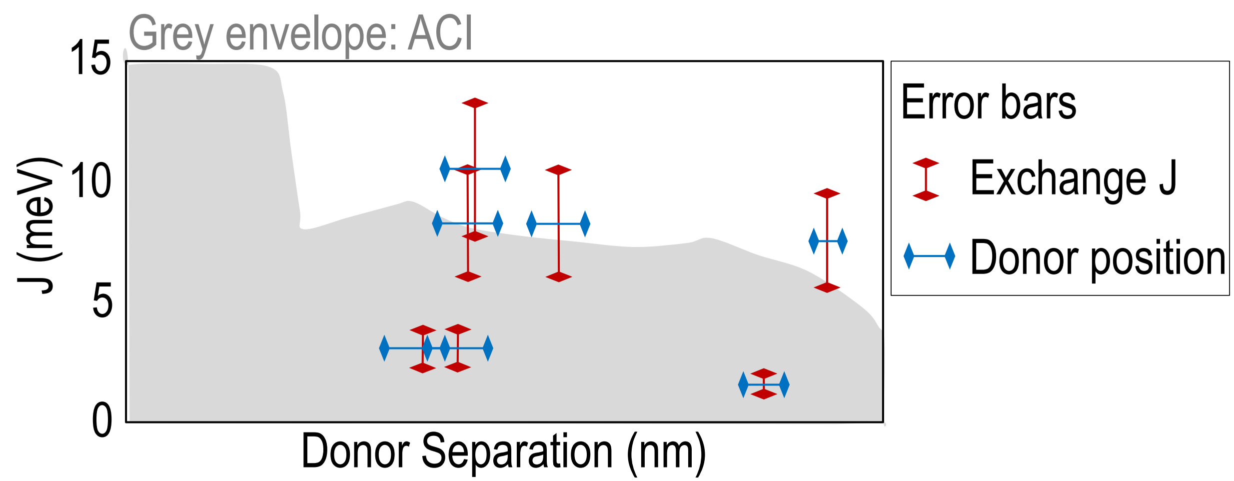


Two-electron energy spectrum of the donor pair

Singlet-Triplet Splitting: Exchange Energy **J**

- Electron-electron interactions
- Crucial for qubit operations

Exchange for several donor pairs:



Exchange from ACI agrees well with the STM measurements

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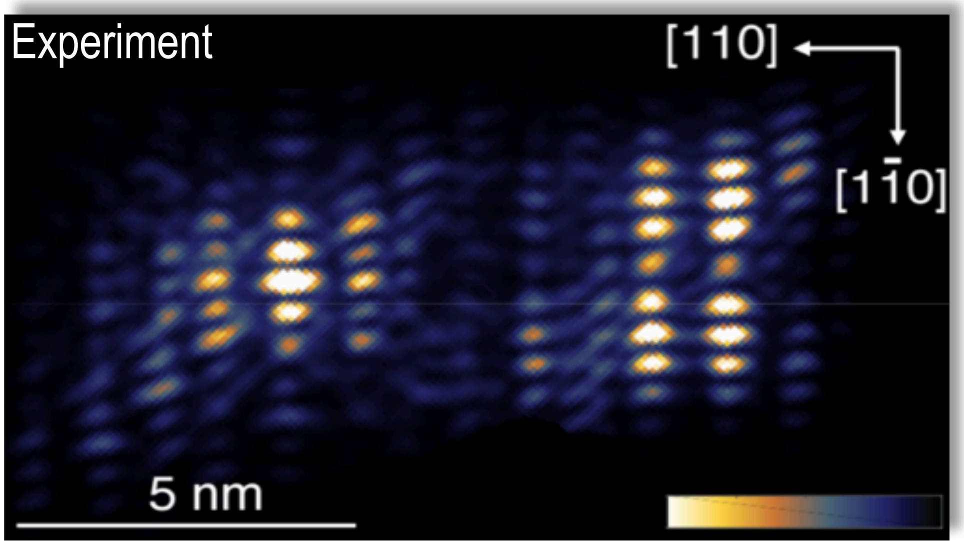
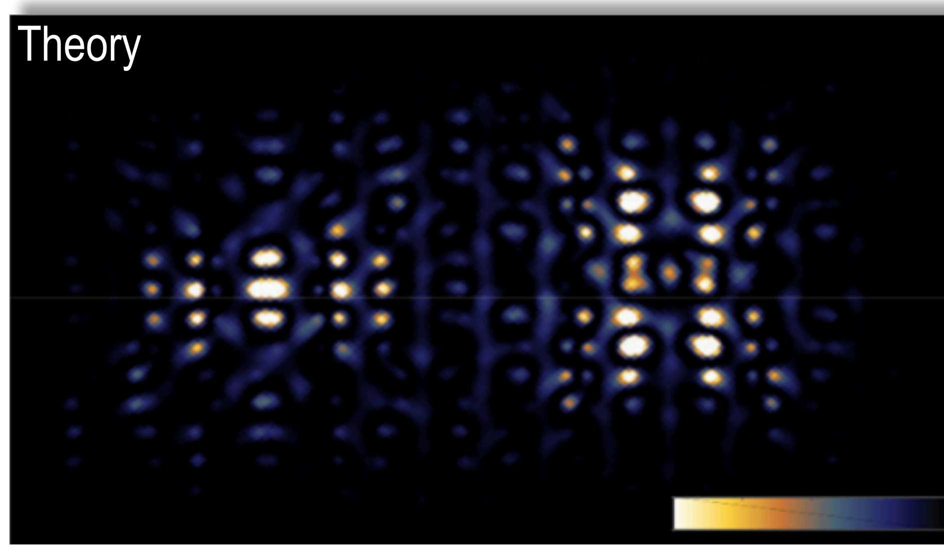
Phosphorous donor pairs probed in STM experiments

STM Image of donor pair corresponding to 2e→1e transition





* Calculated by M. Usman from ACI wavefunctions

Real space 2e→1e images from ACI agree well with the STM images

J Bocquel, A Tankasala et al. In Preparation

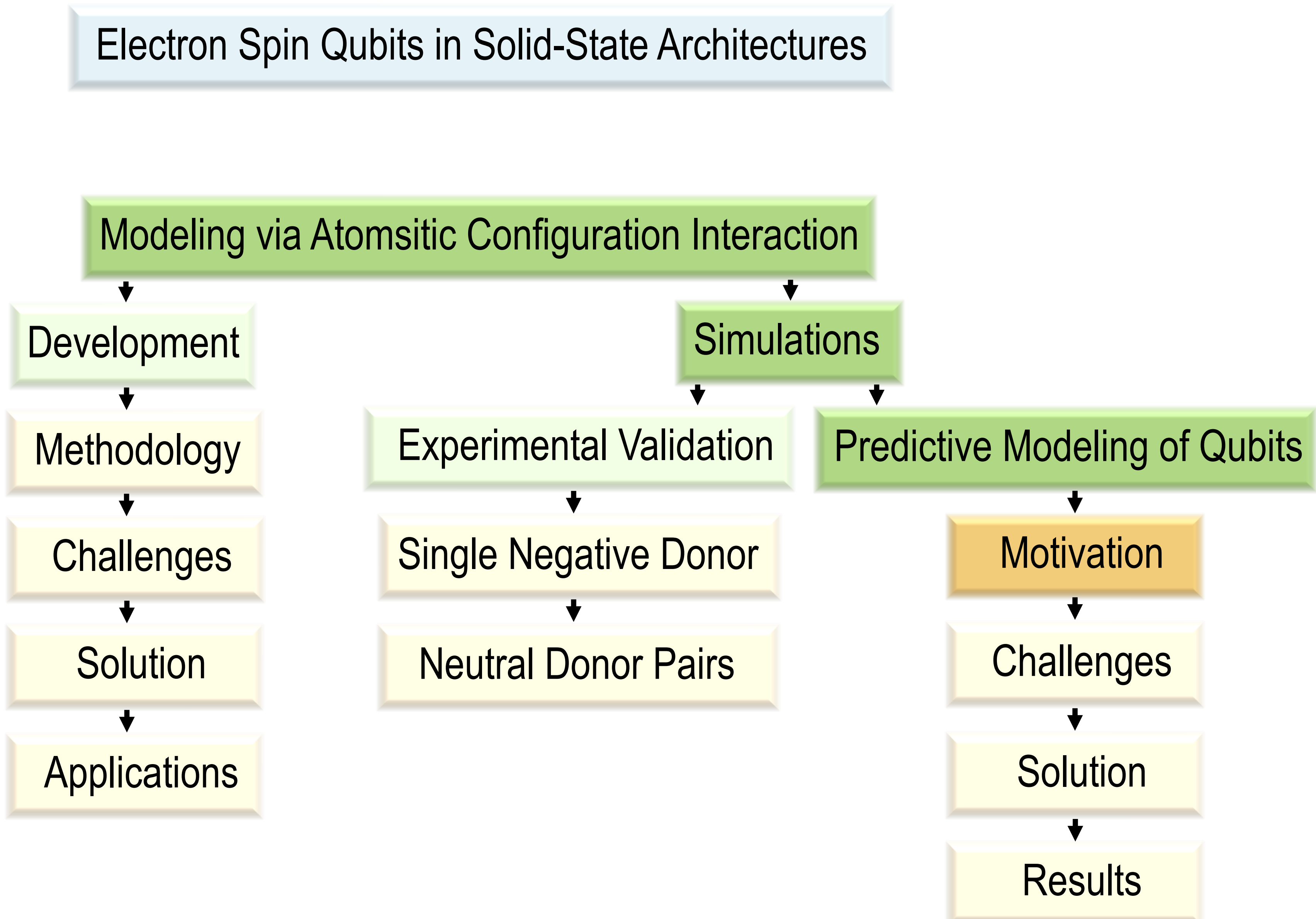
Outline

Electron Spin Qubits in Solid-State Architectures

Modeling via Atomsitic Configuration Interaction

- Development
  - Methodology
  - Challenges
  - Solution
  - Applications
- Simulations
  - Experimental Validation
    - Single Negative Donor
    - Neutral Donor Pairs
  - Predictive Modeling of Qubits
    - Motivation
    - Challenges
    - Solution
    - Results

Outline


Electron Spin Qubits in Solid-State Architectures
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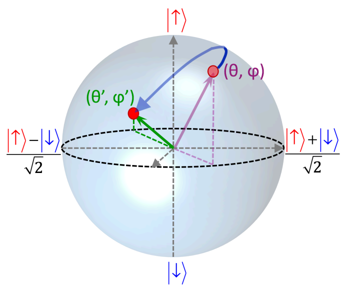
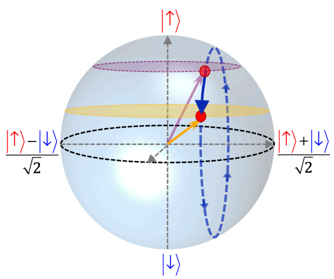
Results

Spin Qubit Manipulation in Electrostatic Quantum Dots

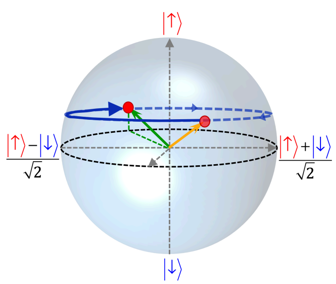
Arbitrary Rotation



Rotations about two fixed axes

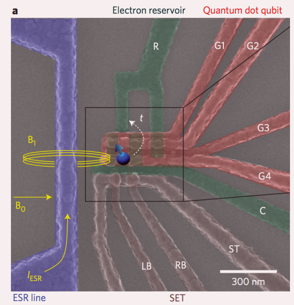


X-Rotation



Z-Rotation

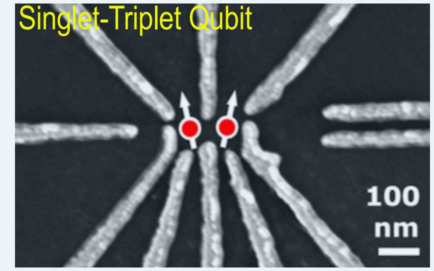
Single Spin Qubit



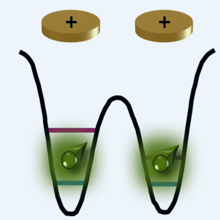
Microwave Pulse

0.3 MHz

Two Spin Qubit

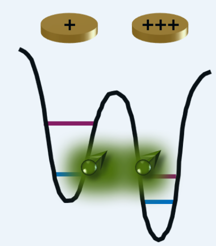


Electrical Pulse



14 MHz

Isolated electrons



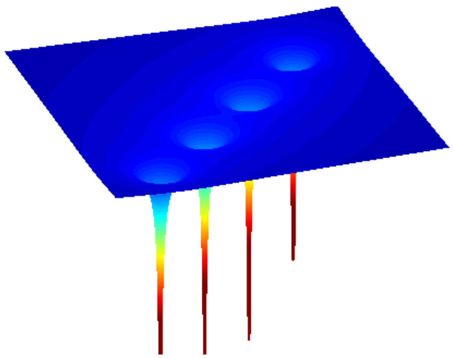
20 GHz

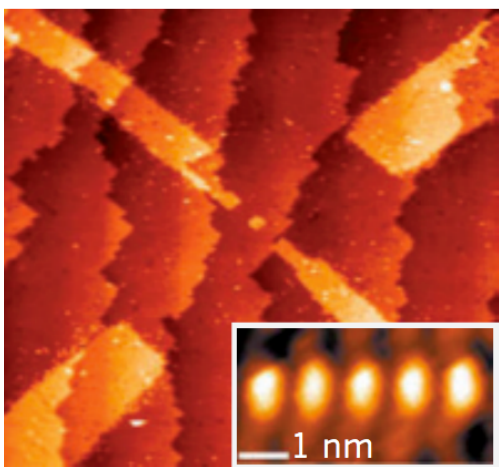
Interacting electrons

Two-spin qubits are faster due to electrical manipulation of electron exchange interactions

[1]Veldhorst, M., et al. Nature nanotechnology 9.12 (2014)
[2]https://www.quantuminfo.physik.rwth-aachen.de/

Advantages of multi-spin qubits bound to dopants in silicon





- Compatibility with current C-MOS technology
- Natural confinement of dopant atoms
- Consistency of dopant atom potentials in an atomically precise array as against lithographically defined dots
- STM lithography allows deterministic donor placement
- Extremely long spin coherence times

  Electrostatic dots : $T_1 > 2s$ & $T_2 > 48ms$

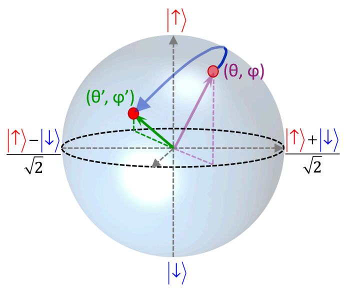
  Donors : $T_1 > 1000s$ & $T_2 > 0.5s$ at 1.8K

Donor bound electron spin qubits are promising towards scalable architectures

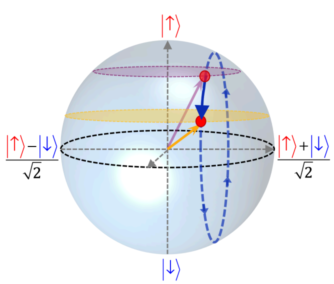
[1]Schofield, S. R., et al PRL 91.13 (2003)
[2]Tyryshkin, Alexei M., et al. *Nature materials* 11.2 (2012

Two-spin qubit architectures based on dopants in silicon

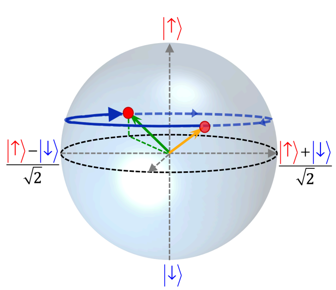
Arbitrary Rotation



Rotations about two fixed axes

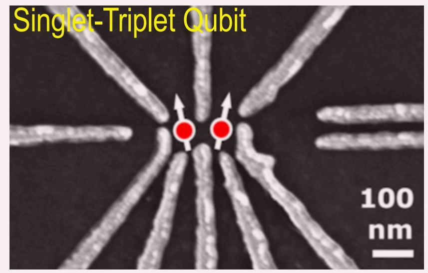


X-Rotation

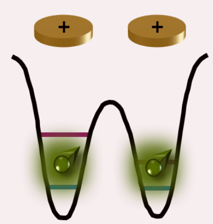


Z-Rotation

Electrostatic Dots

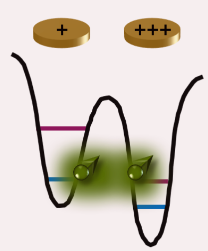


Electrical Pulse



14 MHz

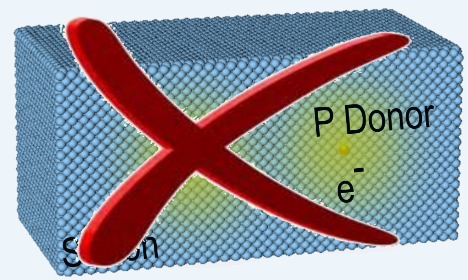
Isolated electrons



20 GHz

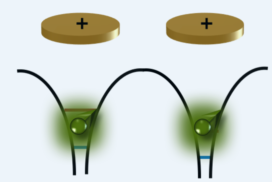
Interacting electrons

Donors in silicon

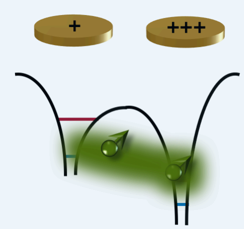


Feasible ?

Electrical Pulse



Fast ?



Fast ?

What are the challenges in realization of two-spin donor qubits?

[1]https://www.quantuminfo.physik.rwth-aachen.de/

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Electron Spin Qubits in Solid-State Architectures

- **Modeling via Atomsitic Configuration Interaction**
  - Development
    - Methodology
    - Challenges
    - Solution
    - Applications
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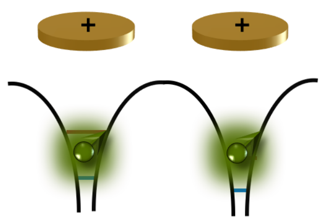
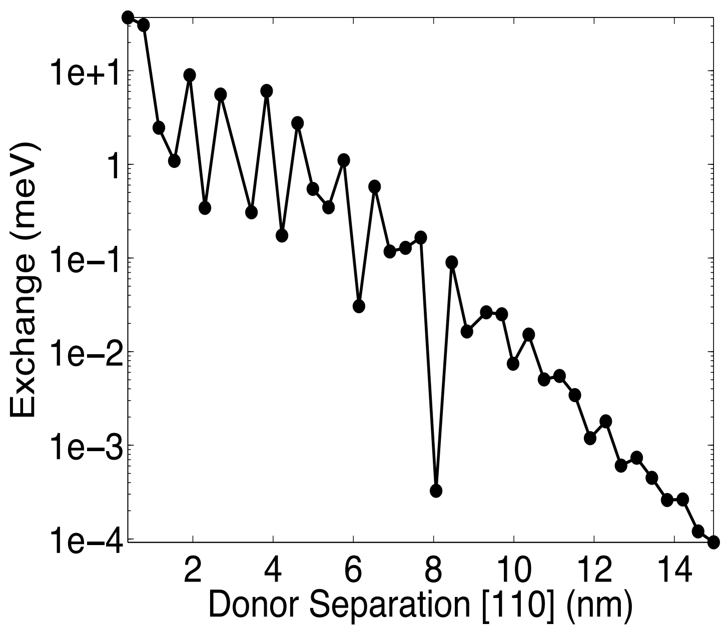
Challenges in realization of dopant based two-spin qubits

Challenge 1: Exchange oscillations affect qubit manipulation



Electron exchange interactions control qubit operations



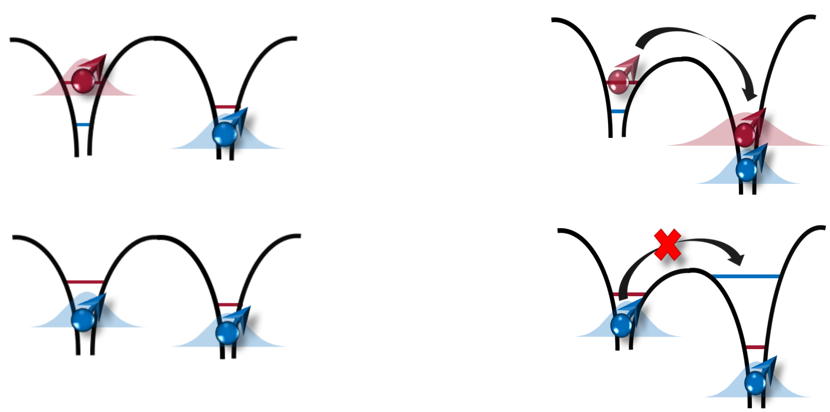
- Exchange interactions sensitive to donor positions
- Violent oscillations in electron exchange interactions

Demand precise gate control of electron interactions for a qubit operation

Challenges in realization of dopant based two-spin qubits

Challenge 2: Lack of bound triplets for qubit read-out

	Qubit State	Spin-to-Charge Conversion	# electrons
Singlet:			$(0_{Left},2_{Right})$
Triplet:			$(1_{Left},1_{Right})$



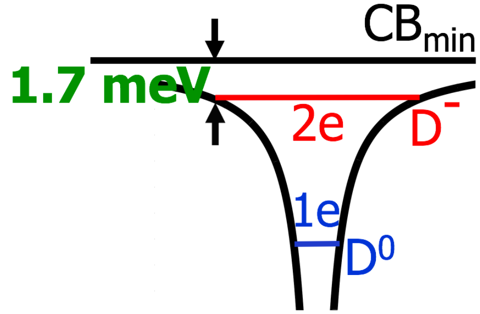
Charge sensing the dot for measurement

Bound Triplet States on single donor are important for qubit state read-out

Challenges in realization of dopant based two-spin qubits

Challenge 2: Lack of bound triplets for qubit read-out

Spectrum of Single Phosphorous Donor in Silicon



D^0: Donor binding single electron

D^-: Donor binding two electrons

- 2-electron ground state is only **1.7 meV** from silicon CB$_{min}$
- 2-electron excited states (triplets) are not bound

Difficult to confine two electrons on a donor in bulk silicon: No bound triplets

Challenges in realization of dopant based two-spin qubits

Challenge 3: Gradient magnetic fields for X-rotation of qubit

Arbitrary Rotation

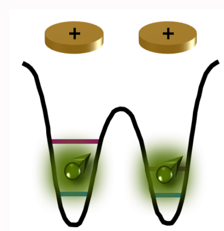
Rotations about two fixed axes

X-Rotation

Z-Rotation

Two Spin Qubit

Electrical Pulse

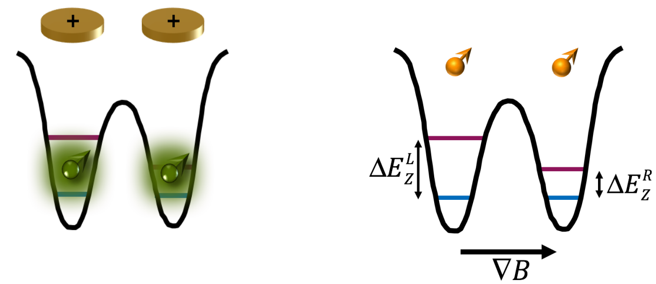


14 MHz

Isolated electrons

20 GHz

Interacting electrons



- Different Zeeman splitting in dots
- Isolated electrons evolve differently
- Develop a phase difference

Gradient Magnetic Field

- ✘ Micromagnets
- ✘ Nuclear spins

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      - **Solution**
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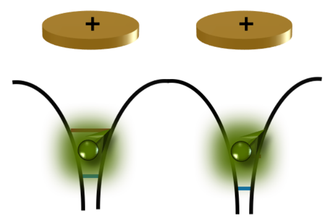
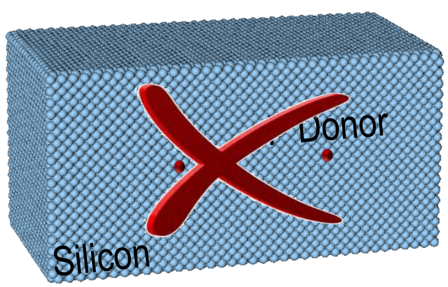
Architectures of two-spin qubits bound to dopants in silicon

Two Spin Qubit

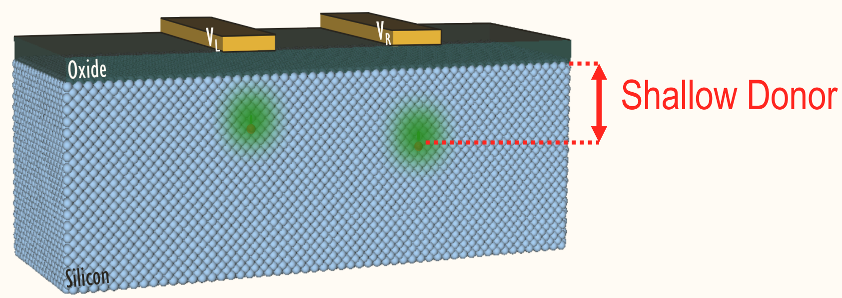


Donors in bulk silicon



SOLUTION

Sub-surface donors in silicon

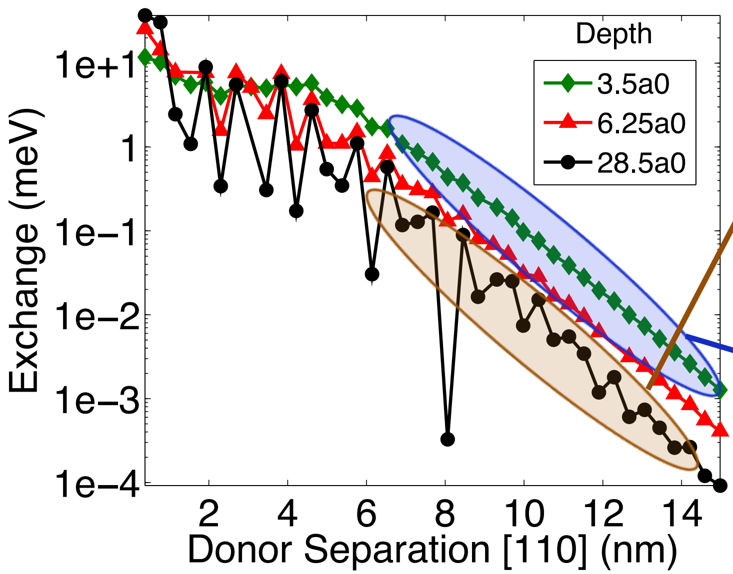


Confine electrons to SHALLOW dopant atoms in silicon for two-spin qubits

Challenges in realization of dopant based two-spin qubits

Challenge 1: Exchange oscillations affect qubit manipulation

Solution : Exchange oscillations suppressed for shallow donors



Donors away from interface:

- X & Y valley interferences change with XY separation
- Causes oscillations in electron wavefunction overlap
- Oscillations in exchange interactions

Donors close to interface:

- Donor states Z valley dominant
- XY separation does NOT effect electron overlap
- Suppressed oscillations in exchange

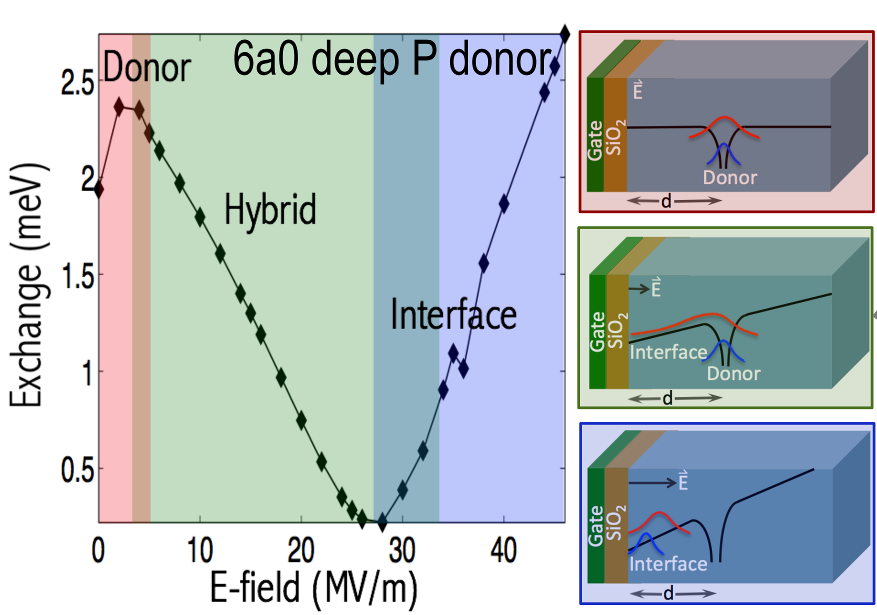
Better gate control of electron exchange interactions due to suppressed oscillations

Challenges in realization of dopant based two-spin qubits

Challenge 2: Lack of bound triplets for qubit read-out

Solution : Bound triplets for shallow donors under applied fields

Singlet-Triplet splitting for sub-surface donor under applied gate field from ACI



Hybridized Regime (Moderate Fields):

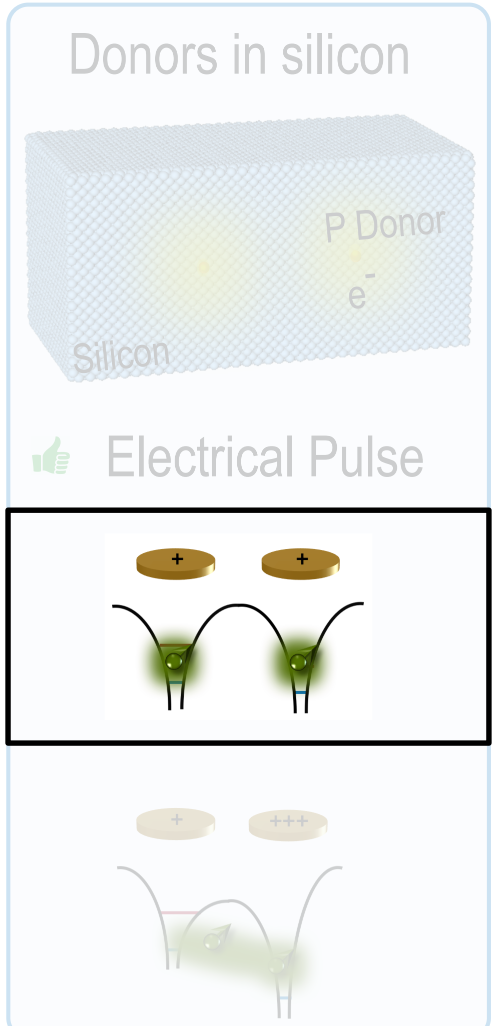
- ✓ Electrons can physically avoid one another
- ✓ Decreases electron exchange interactions: singlet-triplet splitting
- ✓ Triplets lower in energy and confined

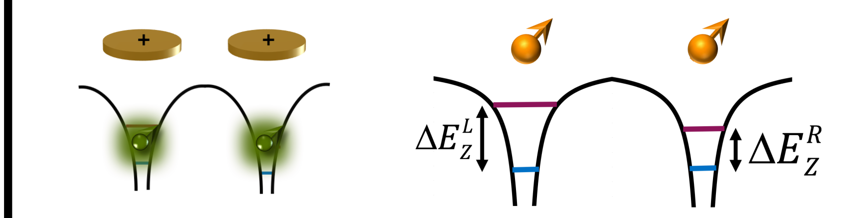
Bound triplet states of shallow donors under electric fields allow multi-spin qubit read-out

Challenges in realization of dopant based two-spin qubits

Challenge 3: Gradient magnetic fields for X-rotation of qubit

Solution : Tuning donor depth and fields for X-rotation





- Different Zeemann splitting in donors
- Isolated electrons evolve differently
- Develop a phase difference

Electron g-factor difference

- ✓ Tuning donor depth
- ✓ Tuning gate biases

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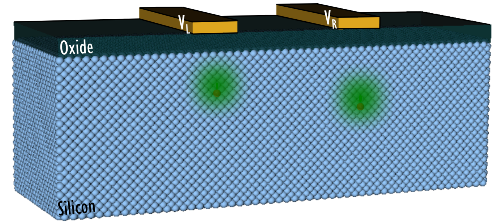
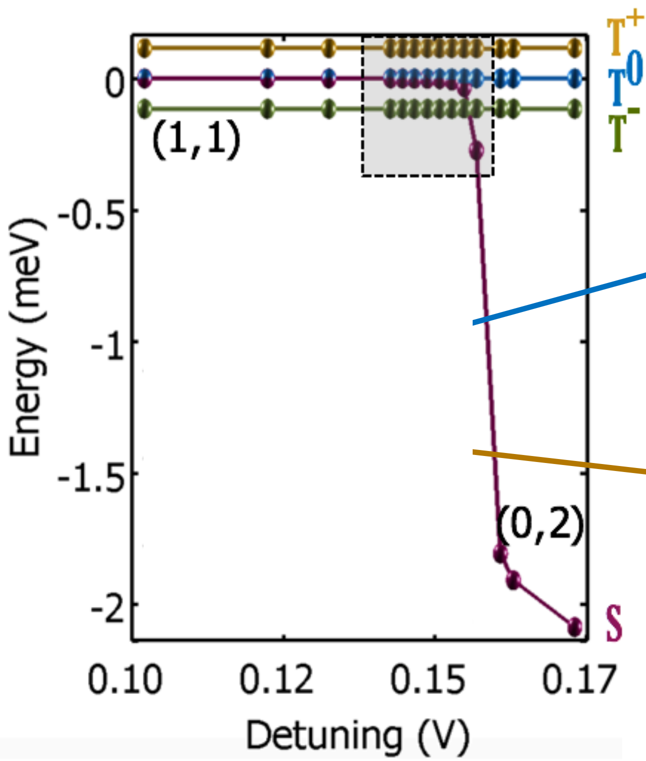
Two-spin Singlet-Triplet qubits based on donors

Two electron spectra from ACI

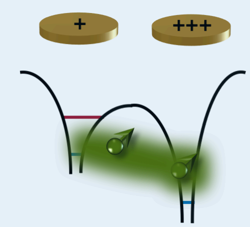


4a0 and 8a0 deep P donors
Separation 15nm [100]
1T magnetic field along Z

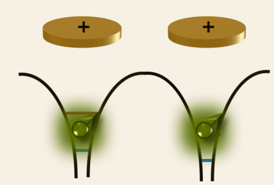


Qubit Manipulation

Large electron exchange
- ✓ Z Rotation
- ✓ 2 GHz



Isolated electrons
- ✓ X Rotation
- ✓ 60 MHz



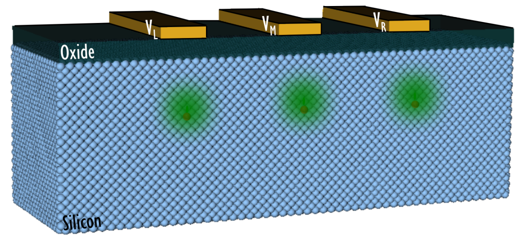
Two-axis rotations of donor based Singlet-Triplet Qubit

PURDUE UNIVERSITY

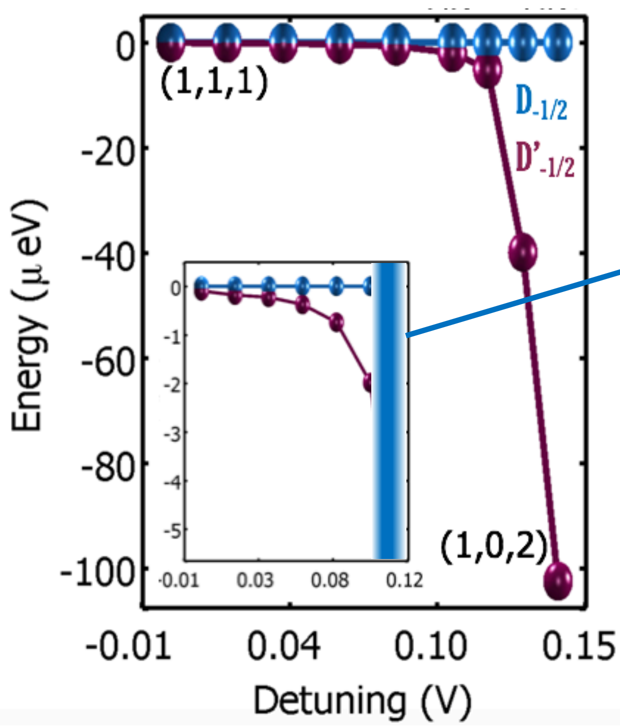
Archana Tankasala A Tankasala et al. In Preparation

Three-spin exchange-only qubits based on donors

Three electron spectra from ACI
(Spin -1/2 Qubit States)

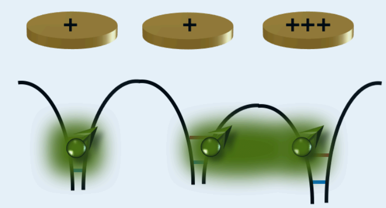


6a0 deep P donors
Separation 15nm [100]
0.1T magnetic field along Z

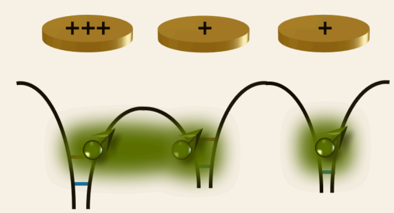


Qubit Manipulation

Large M-R electron exchange
- ✓ Detuning right donor
- ✓ 10 GHz



Large L-M electron exchange
- ✓ Detuning left donor
- ✓ Symmetric E vs. detuning
- ✓ 10 GHz



Two-axis rotations of donor based Exchange-Only Qubit Isolation of qubit from leakage states

Archana Tankasala A Tankasala et al. In Preparation

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Summary

Atomsitic Configuration Interaction Tool in NEMO

- ✓ Massively parallelized and improved performace
- ✓ Large scale simulations of realistic multi-electron devices
- ✓ Validated against experimental data

Physical Insights

- ✓ For a single negative donor, second electron prefers to occupy excited states
- ✓ Approximate models to evaluate exchange in donor pairs inaccurate for large range of separations
- ✓ Exchange oscillations are suppressed for sub-surface donor pairs
- ✓ Exchange saturates for closely spaced donors in a donor pair
- ✓ Multi-spin qubits are feasible in donors without integrated micromagnets or nuclear spins

Publications

Tankasala A, Salfi J, Bocquel J, Voisin B, Usman M, Klimeck G, Simmons MY, Hollenberg LC, Rogge S, Rahman R. Two-electron states of a group V donor in silicon from atomistic full configuration interaction. arXiv preprint arXiv:1703.04175. 2017 Mar 12.

Wang Y, **Tankasala A**, Hollenberg LC, Klimeck G, Simmons MY, Rahman R. Highly tunable exchange in donor qubits in silicon. npj Quantum Information. 2016 Apr 12;2:16008.

Usman M, Bocquel J, Salfi J, Voisin B, **Tankasala A**, Rahman R, Simmons MY, Rogge S, Hollenberg LC. Spatial metrology of dopants in silicon with exact lattice site precision. Nature nanotechnology. 2016 Sep 1;11(9):763-8.

Salfi J, Voisin B, **Tankasala A**, Bocquel J, Usman M, Simmons MY, Hollenberg LC, Rahman R, Rogge S. Valley filtering and spatial maps of coupling between silicon donors and quantum dots. arXiv preprint arXiv:1706.09261. 2017 Jun 28.

Tankasala A, Ilatikhameneh H, Klimeck G, Simmons MY, Rahman R. All-electrical control of exchange based donor electron qubits in silicon. In preparation

Bocquel J, **Tankasala A**, Salfi J, Voisin B, Usman M, Klimeck G, Simmons MY, Hollenberg LC, Rahman R, Rogge S. Quantum interferences in two exchange coupled dopant atoms. In preparation

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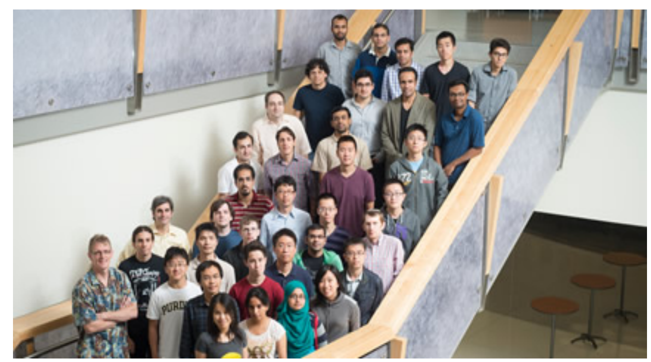
Dr. Juanita Bocquel, Dr. Joseph Salfi, Dr. Muhammed Usman, Dr. Benoit Voisin

Dr. Jim Fonseca, Prof. Michael Povolotskyi, Dr. Bozidar Novakovic, Dr. Jun Huang, Prof. Tillmann Kubis

Fan Chen, Hesameddin Ilatikhameneh, Tarek Ameen, Daniel Valencia, YuanChen Chu, Kuang-Chung Wang, Yui-Hong Matthias Tan, Mehdi Salmani, Kai Miao, Yaohua Tan, Junzhe Geng, Daniel Lemus, James Charles, Daniel Mejia, Prasad Sarangapani, Evan Wilson, Pengyu Long, Gustavo Valencia, Xinchen Gao, Samik Mukherjee, Enrique Aldana



Ashley Byrne, Vicki Johnson

THANK YOU !

Questions/Comments/Suggestions from Prof. Rogge

Q1. On slide 10, how should the hydrogenic spectrum look like? Is the energy spacing correct?

Q2. What does using shared memory model or parallelization schemes mean in terms of the hardware?

Q3. Why are multi-electron spins better? If it is because of AC electric fields instead of AC magnetic fields, what about their coherence times? What is the metric that matters for a qubit operation?

C1. “Doubly charged donor” is preferred over “Negative donor”.

C2. For a physics audience, the explanation on Hartree-Fock wavefunction can be briefer.

S1. On slide 12, it appears the second electron occupies an excited orbital state. It is confusing since the same notation is not used in slide 30.

S2. Clarify the error bars in experimental data and the reason for the J oscillations.

S3. White ellipse highlighting the two-electron spectrum is not clear. For someone looking at it for the first time, the spectrum is not very obvious.