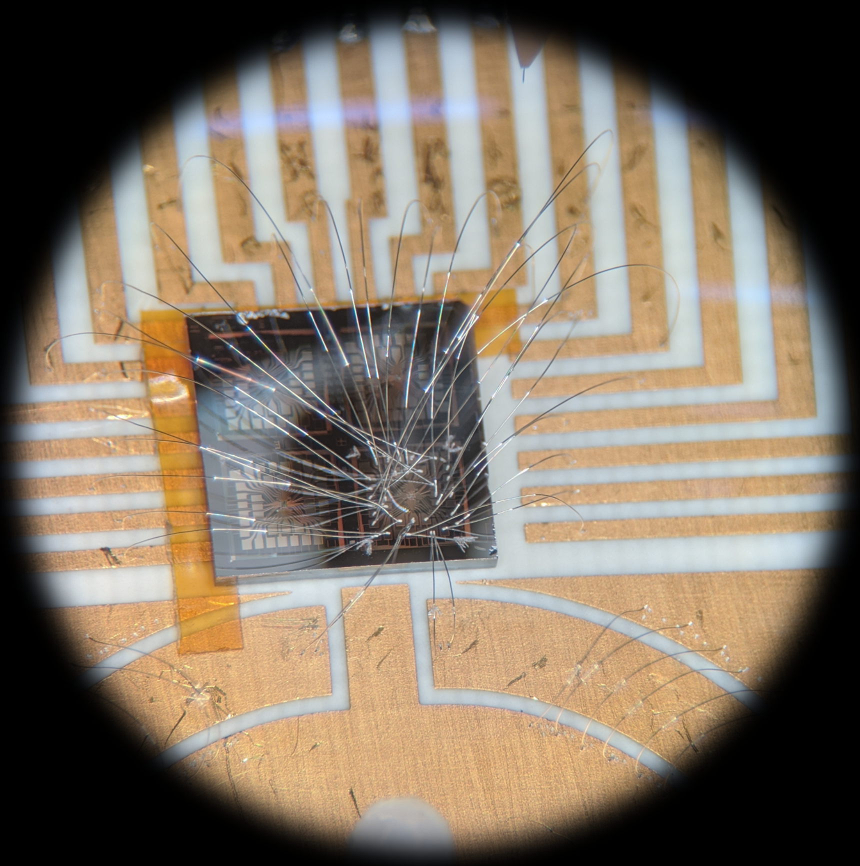
Quantum computing with individual electrons

Benjamin Harpt



NOGS | September 1, 2020

Bits encode information; qubits encode quantum information

0 or 1

classical bits

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

qubits

Quantum superposition, entanglement, and interference enable shortcuts for certain algorithms run on qubits.

Applications for quantum computers

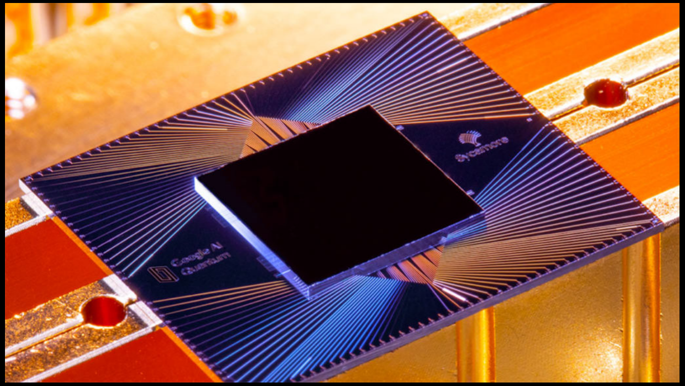
most powerful applications
quantum factoring and search

first useful applications
quantum materials simulation?

$314{,}191 = ? \times ?$

millions of qubits

quantum supremacy
solving a fancy math problem



53 qubits (Google, 2019)

hundreds to thousands of qubits?

How do we get here?
Better hardware.

Electron spins as qubits

0 or 1

classical bits

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

spin qubits

Qubits can be formed from electron spins.

Research in the Eriksson group focuses on creating qubits from individual electrons or groups of electrons in semiconductors.

Requirements for good qubits

(a.k.a. the Divencenzo criteria)

1. scalable physical platform
2. easy to initialize into a known state
3. easy to manipulate in logic operations
4. easy to measure
5. stable and reliable performance over time

D. Divencenzo

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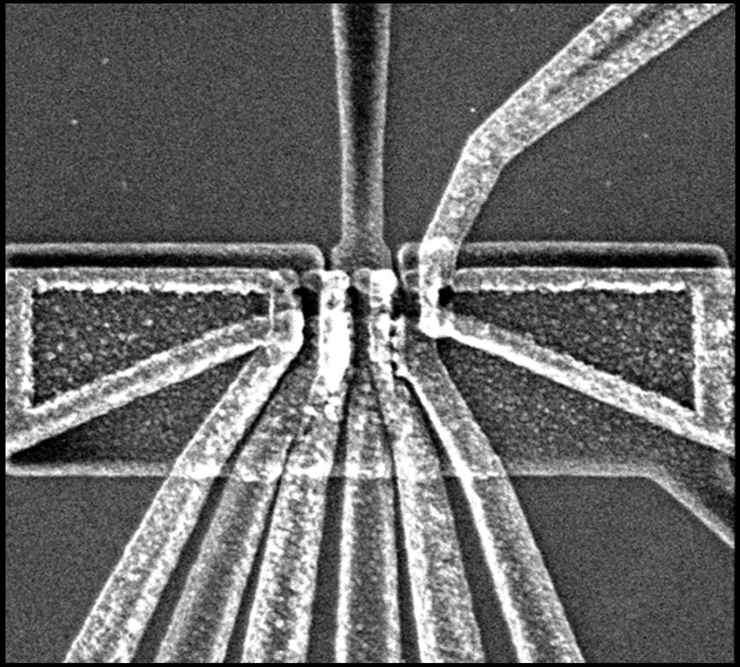
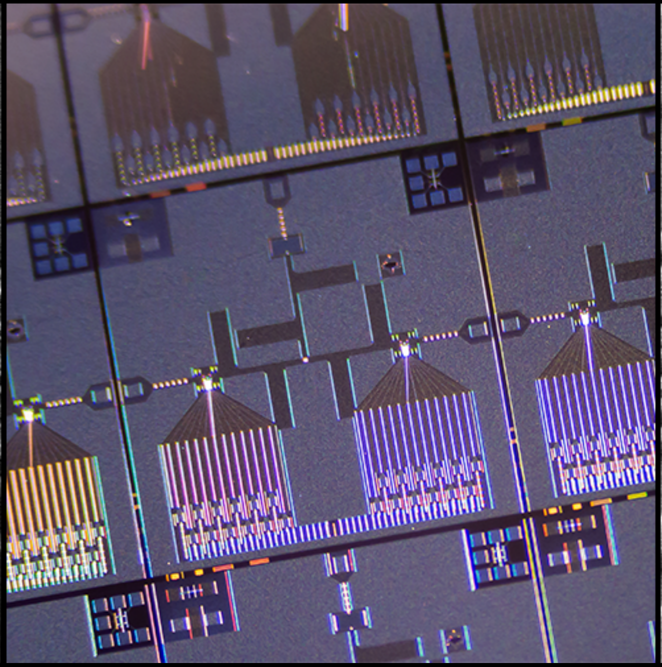
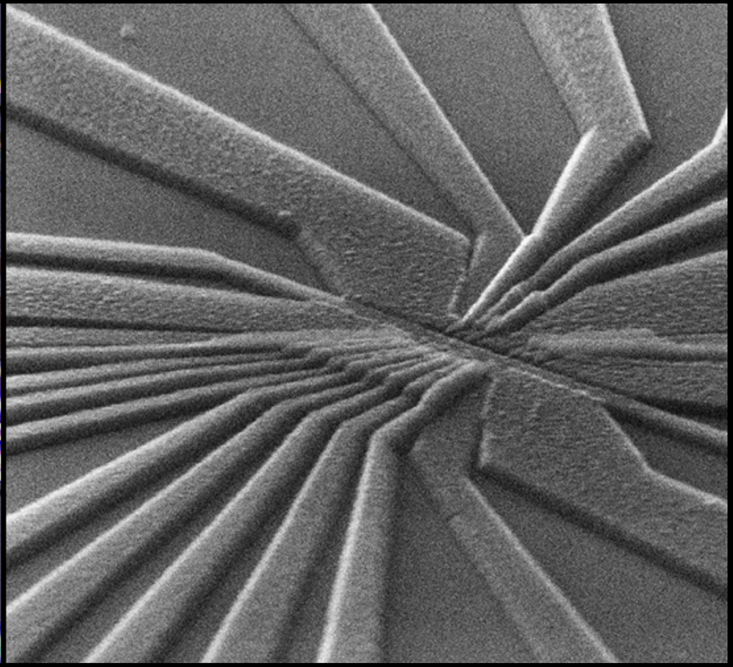
The semiconducting qubit platform

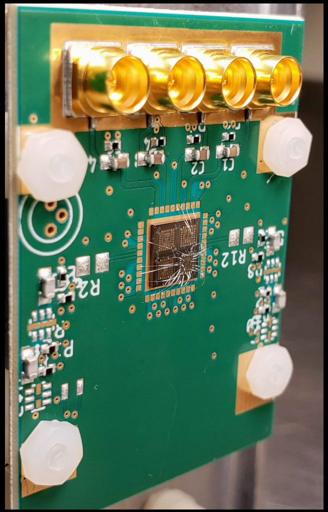




Spin qubits in semiconductors can (in theory) be fabricated at high density using standard semiconductor manufacturing processes.

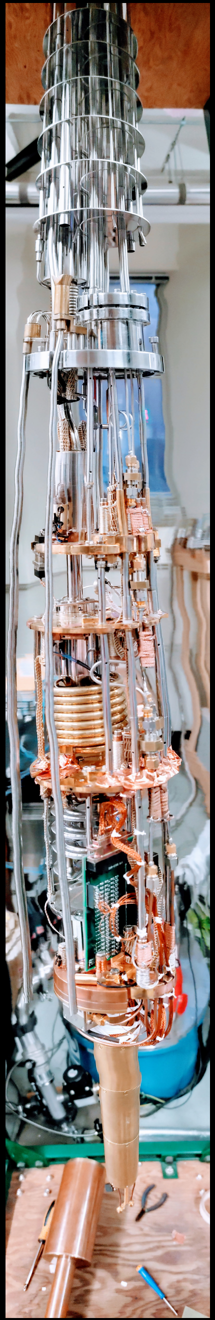
N. Holman, S. Neyens

Device fabrication and setup

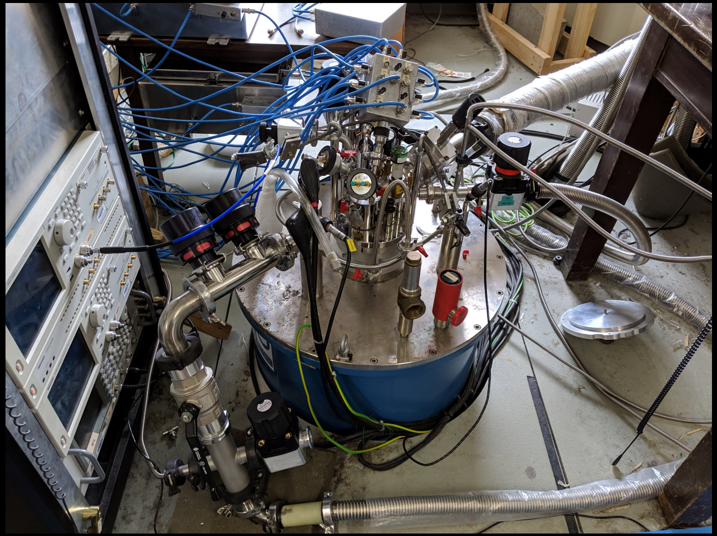
1. fabricate in cleanroom



2. mount to circuit board



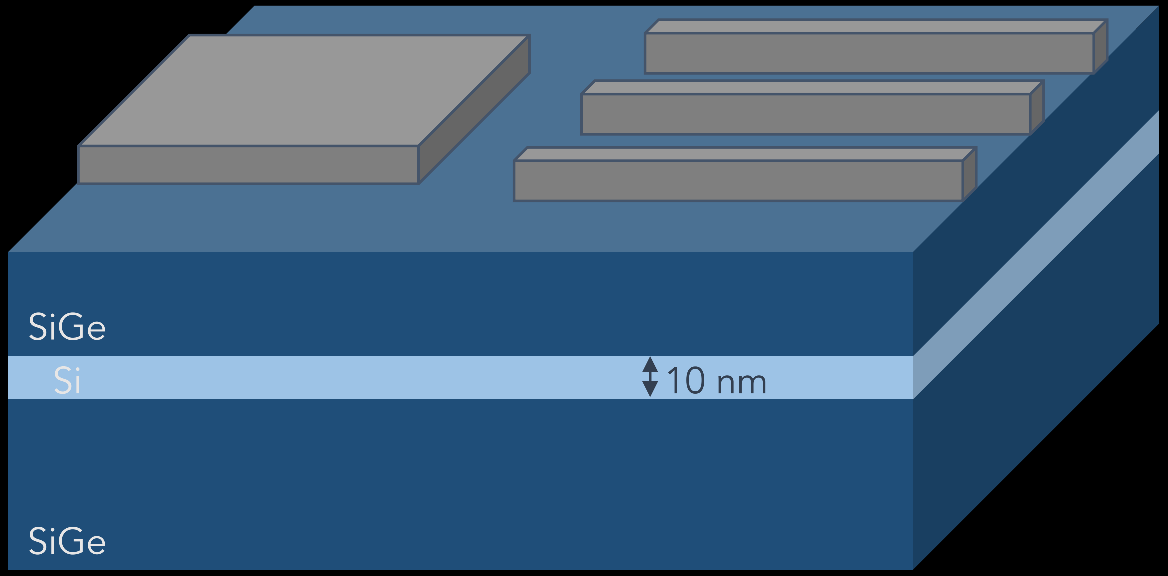
3. insert into dilution refrigerator



4. cool to 10 – 20 mK

M. Wolfe, T. McJunkin

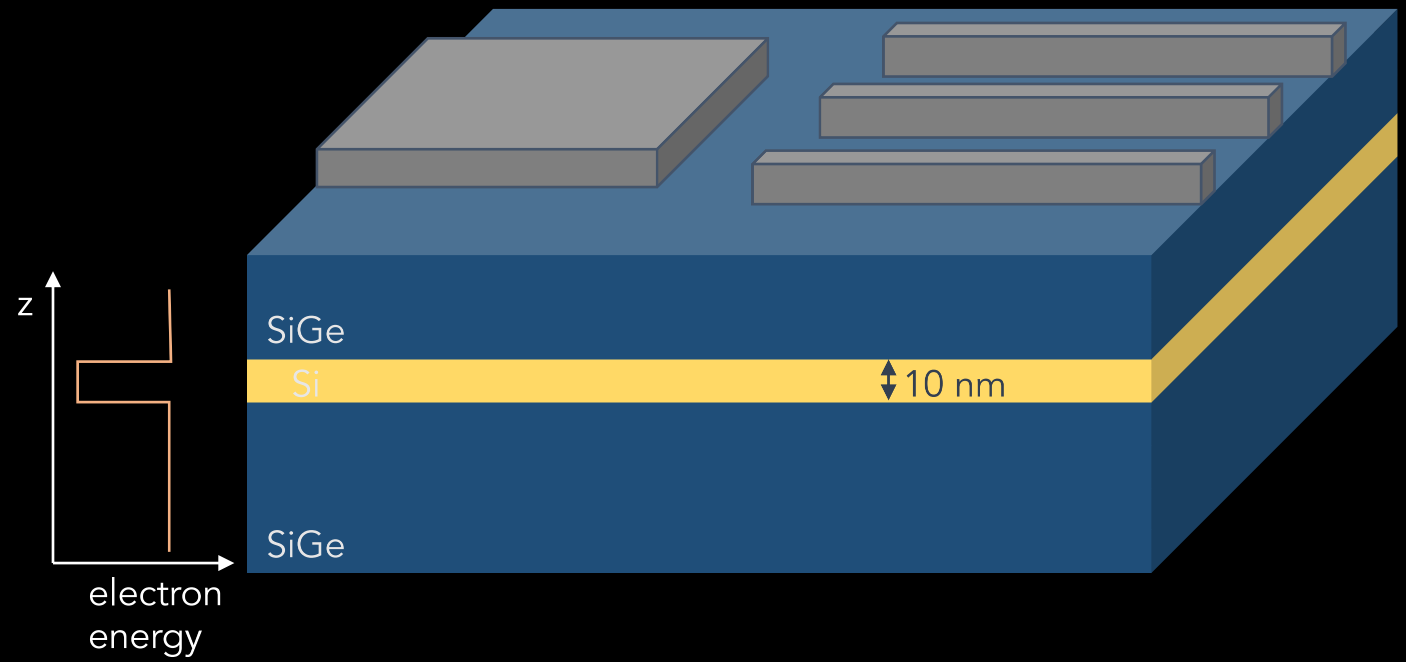
Under the hood: electrons in a semiconductor sandwich



Devices are fabricated on a heterostructure of silicon and silicon-germanium grown together in a 'semiconductor sandwich'.

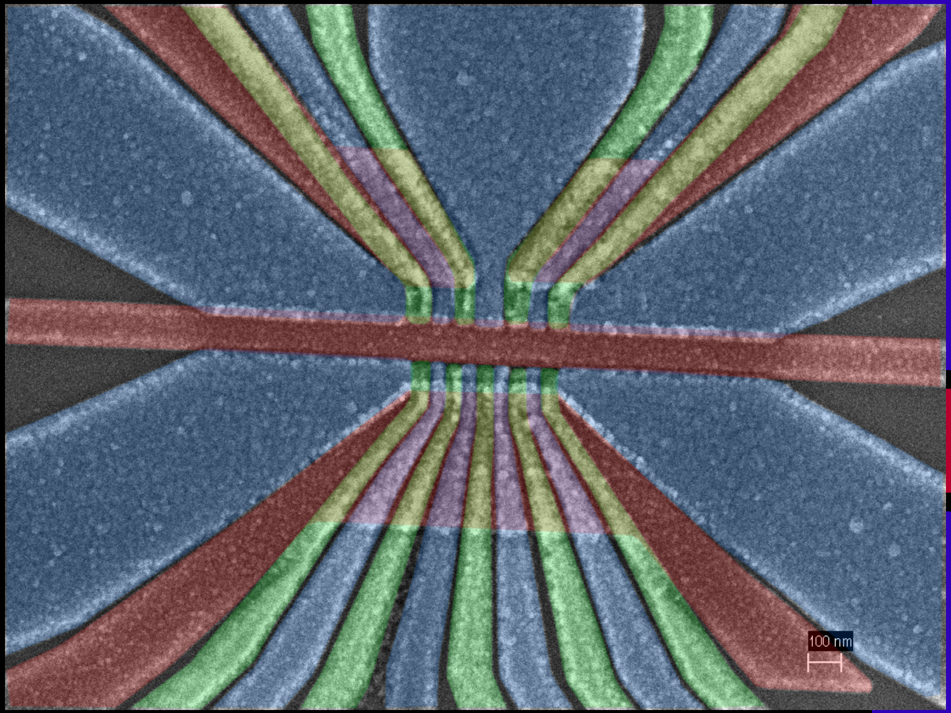
The thin layer of silicon acts as a quantum well.

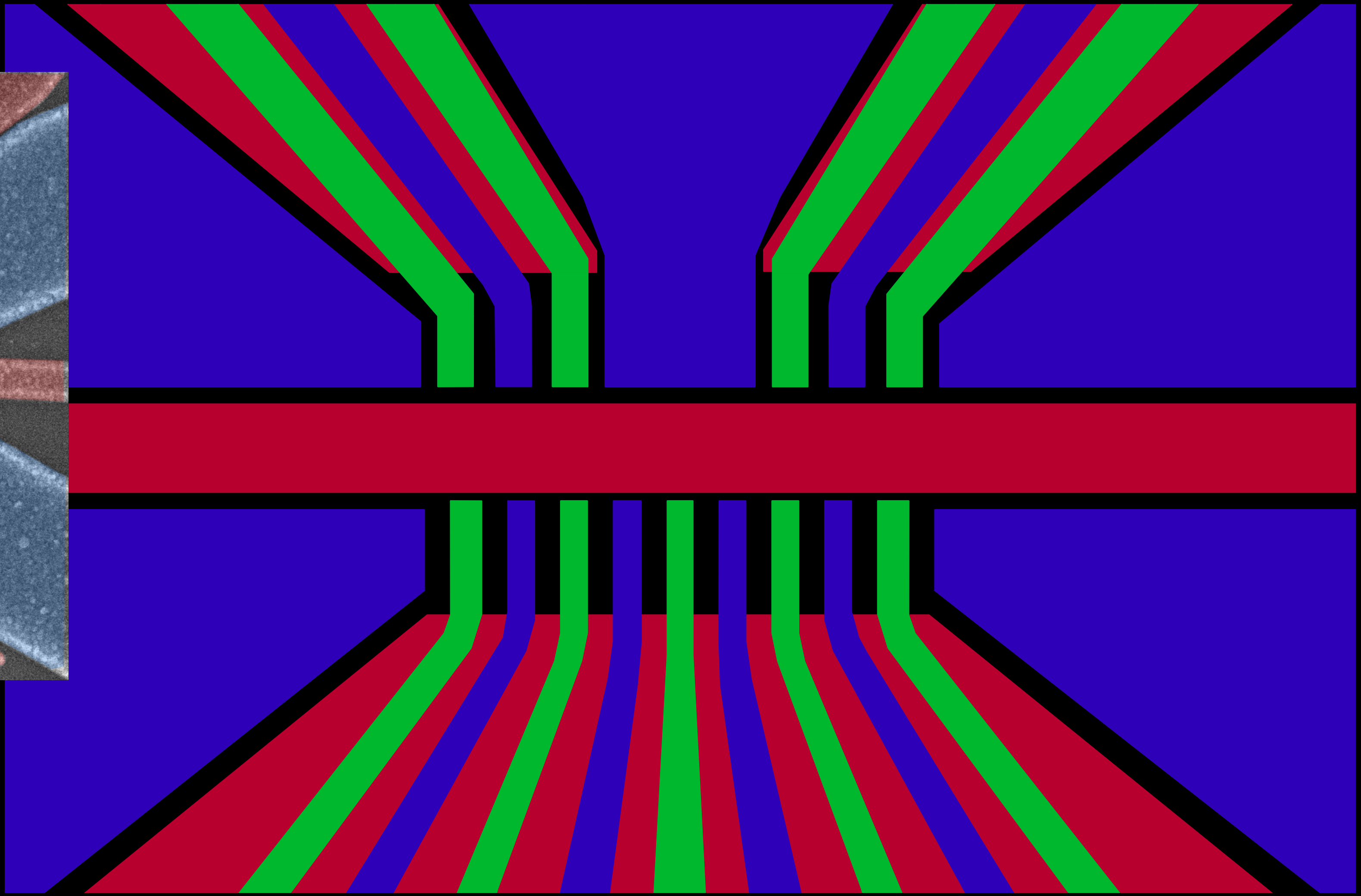
Under the hood: electrons in a semiconductor sandwich



Electrons accumulate in the silicon quantum well, forming a two-dimensional electron gas.

Trapping electrons in quantum dots

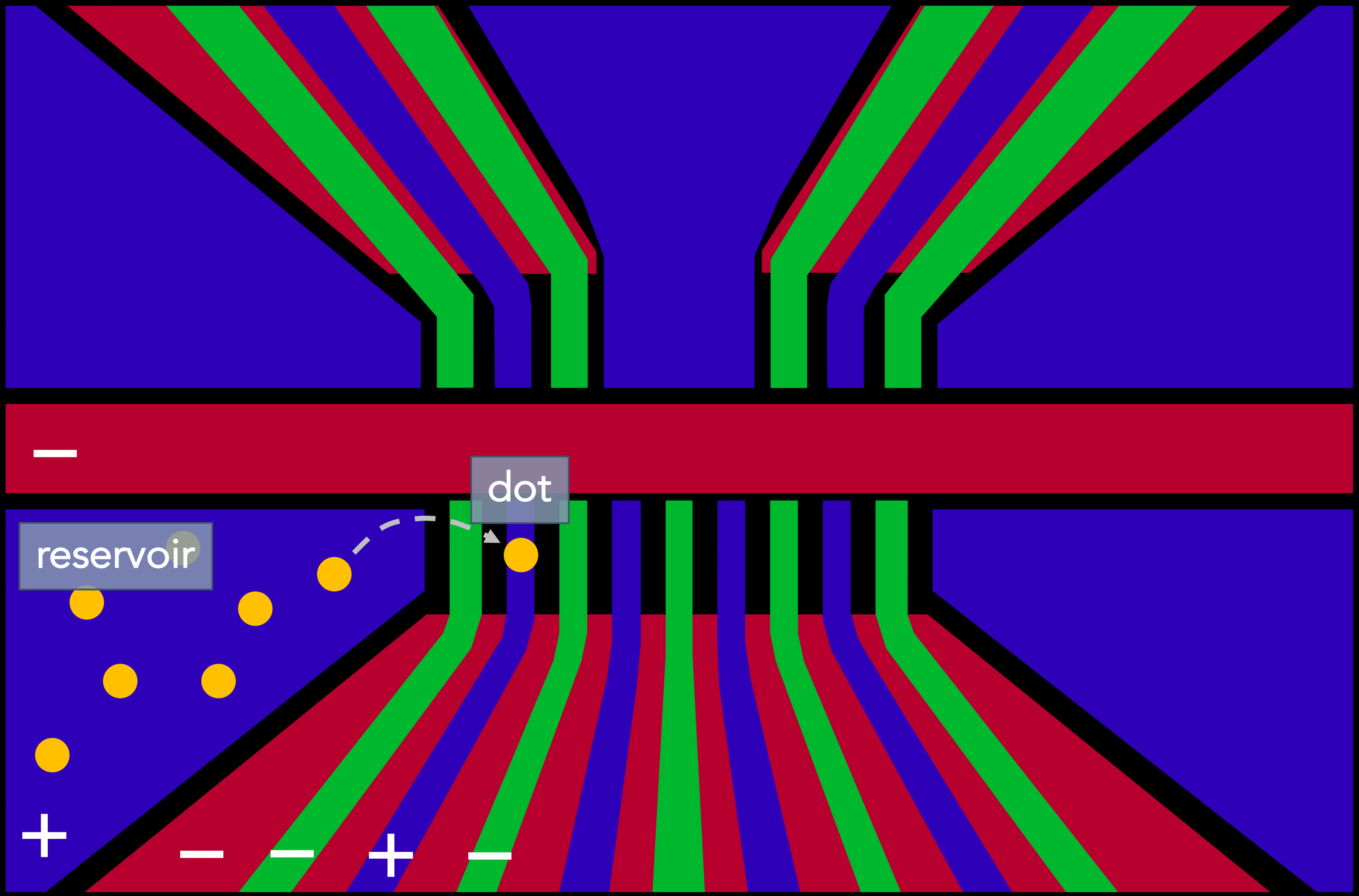




T. McJunkin

Trapping electrons in quantum dots

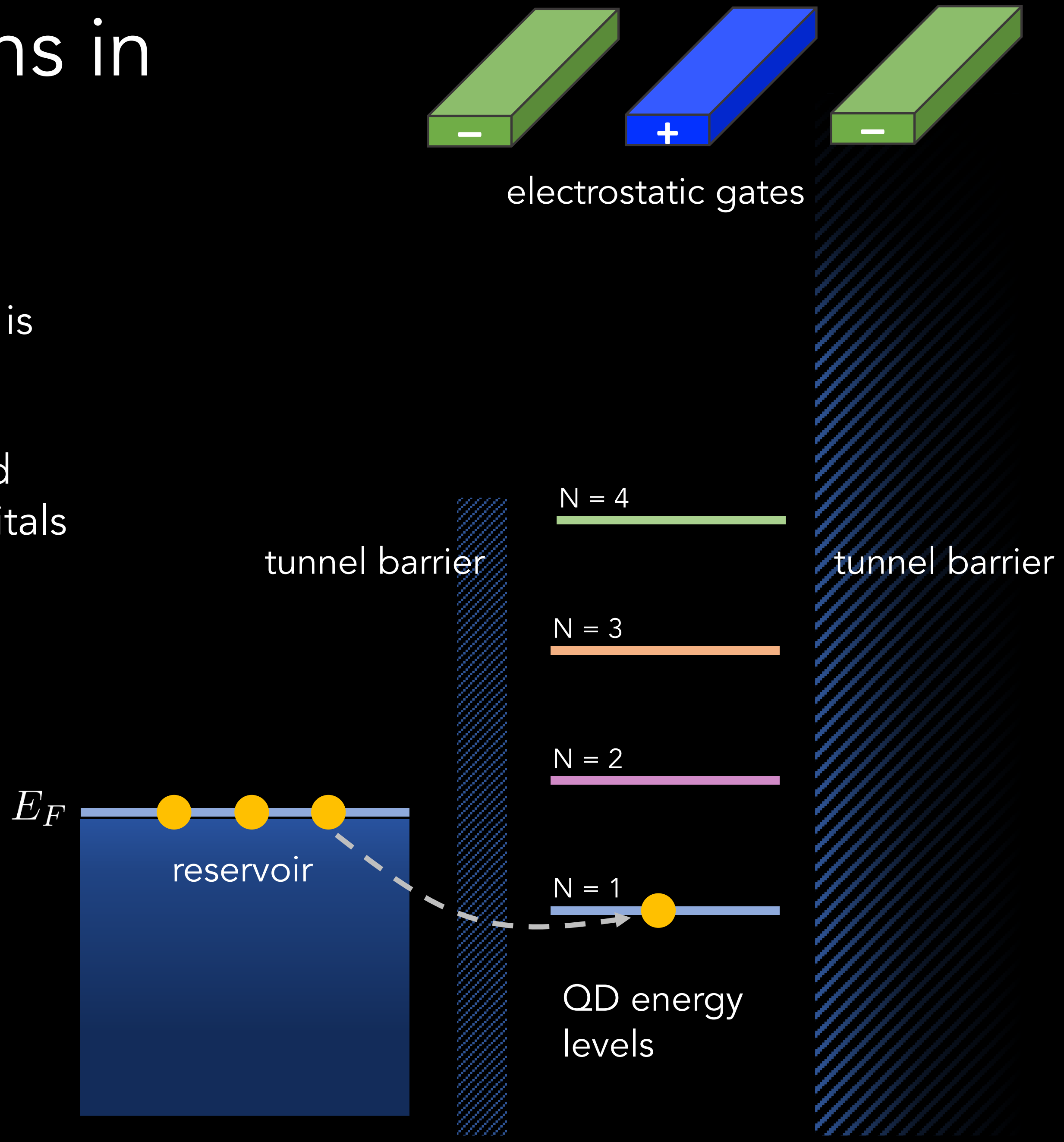
By adjusting electrostatic gate voltages, it is possible to isolate a single electron in a quantum dot.

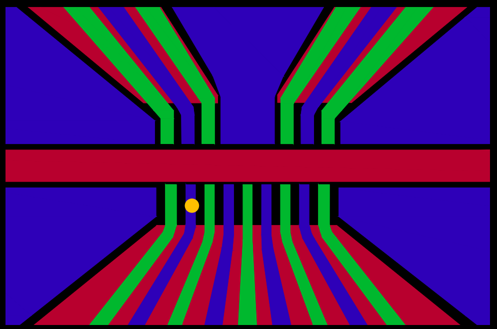


Trapping electrons in quantum dots

An electron in a quantum dot is essentially a particle in a box.

Quantum dots have quantized energy levels that act like orbitals in an artificial atom.





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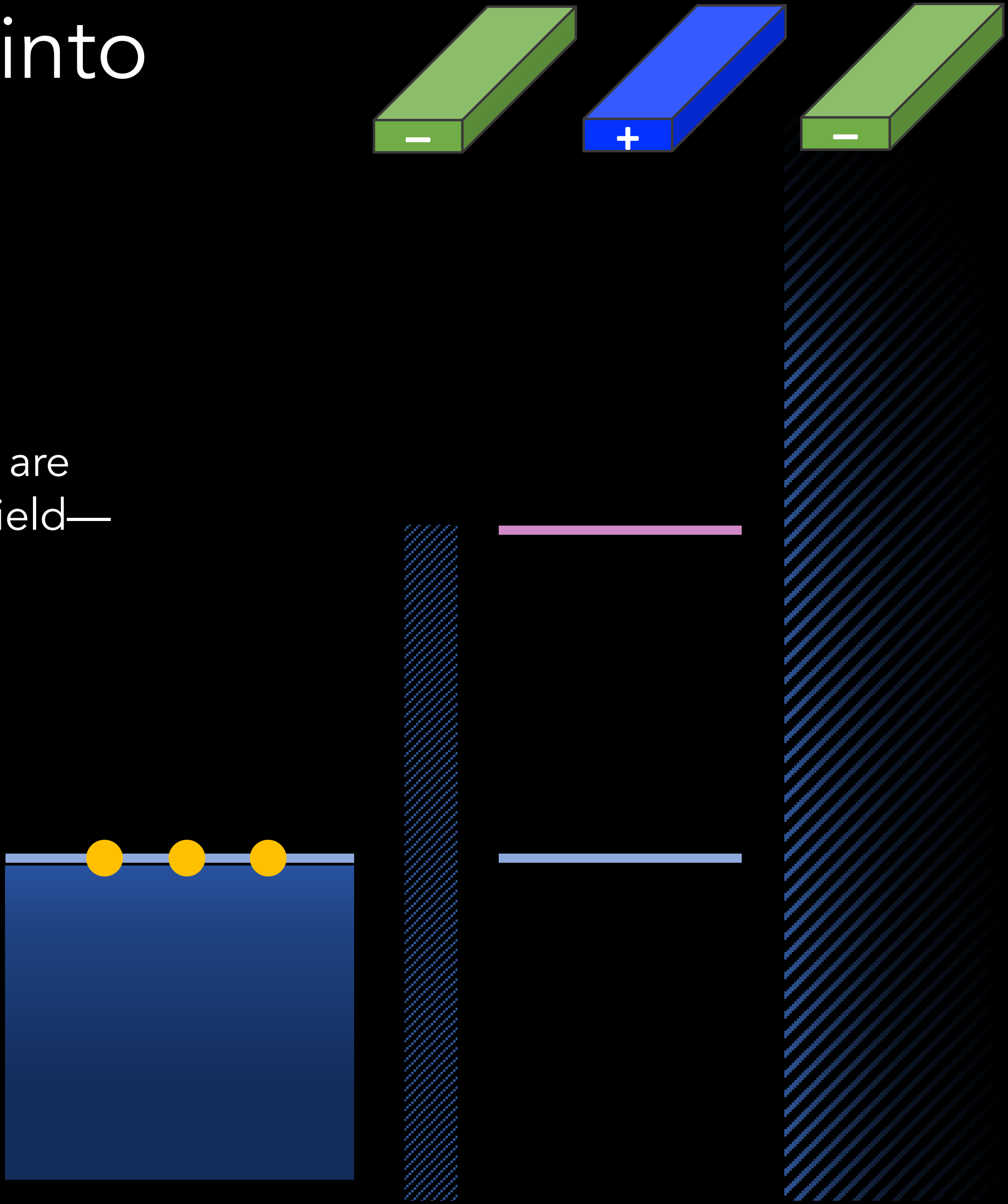
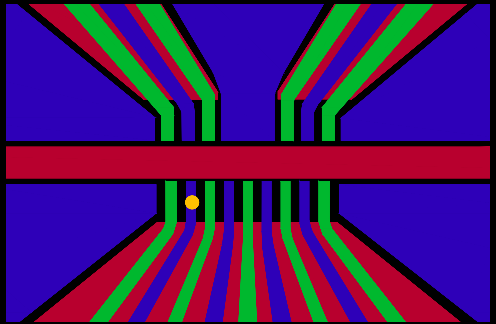
Qubit initialization into the $|0\rangle$ state

Energy levels in an empty dot are split by applying a magnetic field—the Zeeman effect.





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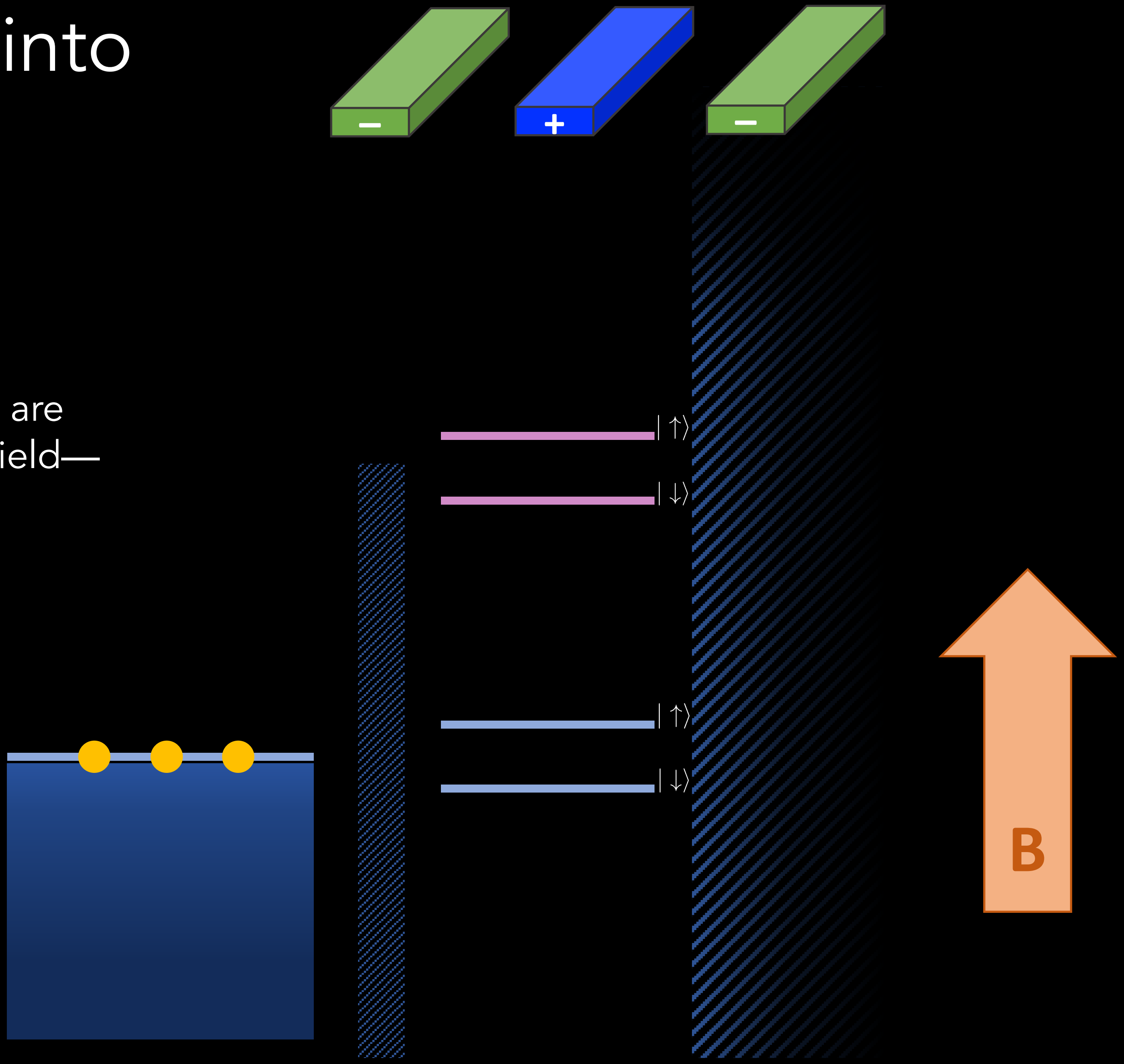
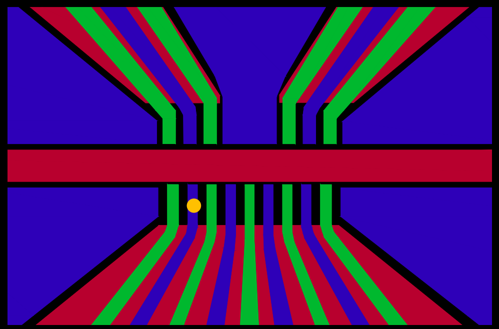
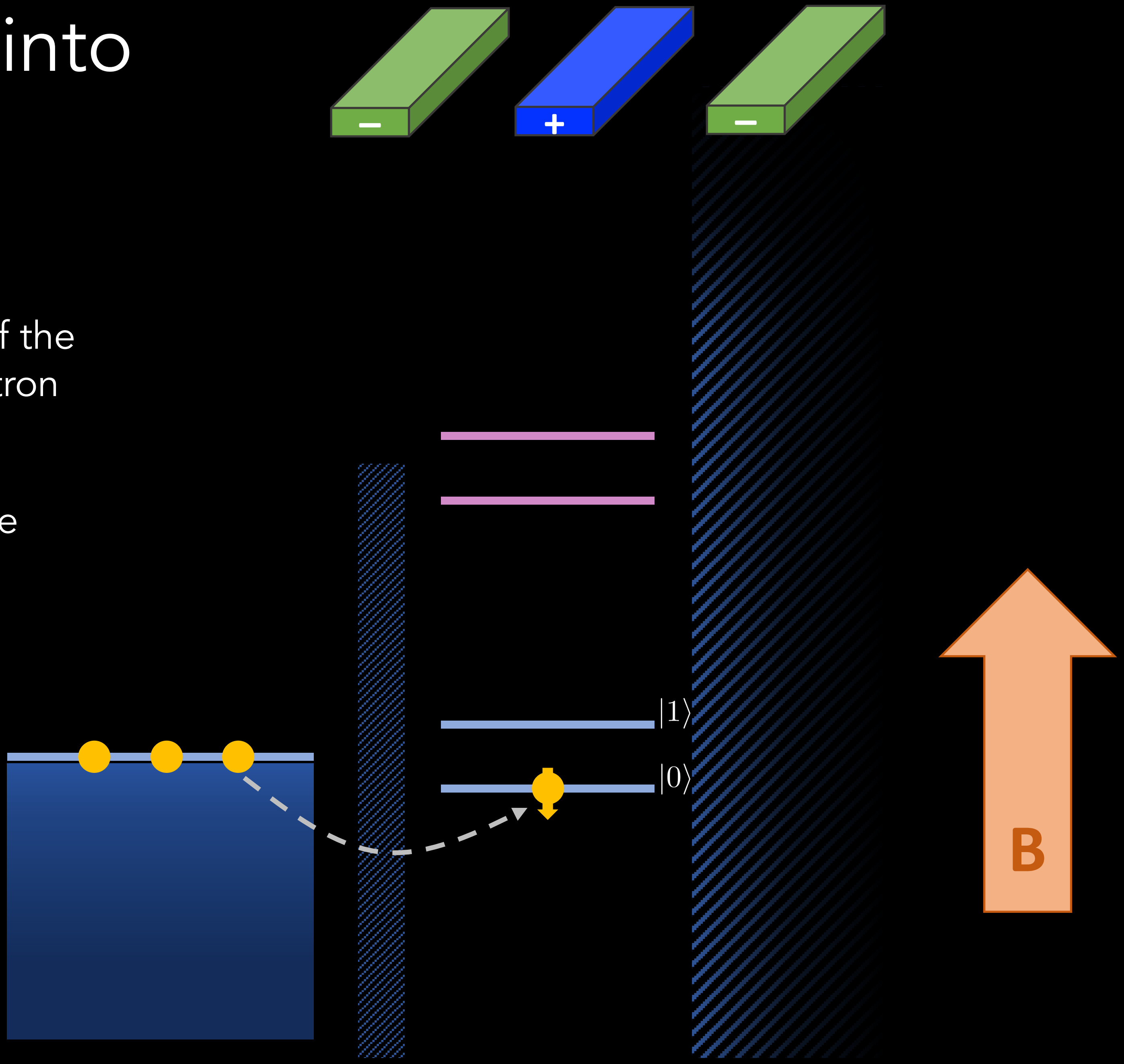


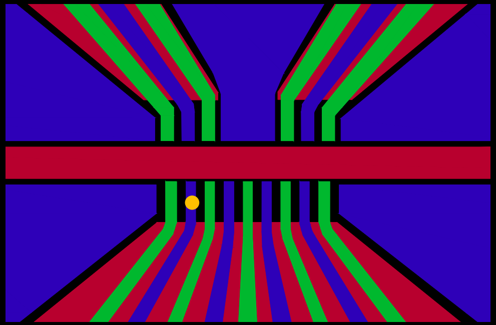


Qubit initialization into the $|0\rangle$ state

When the Zeeman-split energy levels straddle the Fermi level of the reservoir, only a spin-down electron can tunnel in.

The qubit always starts with state $|0\rangle$.





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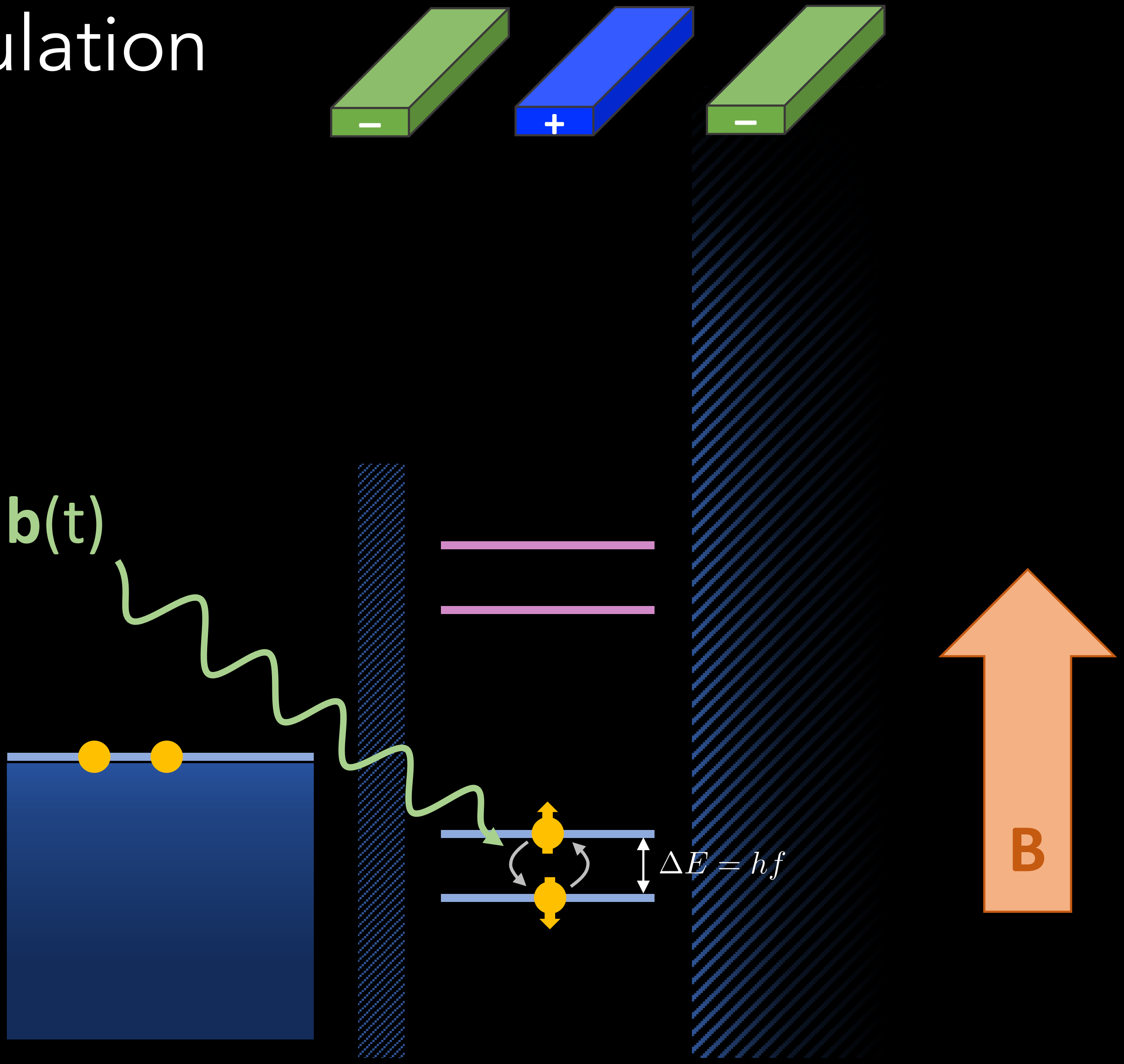
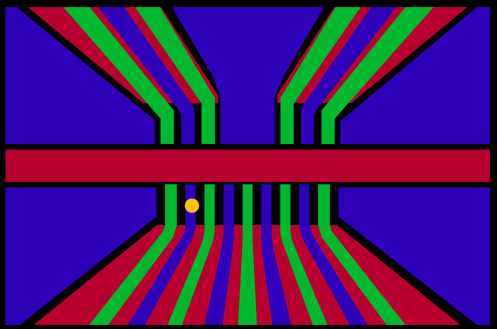
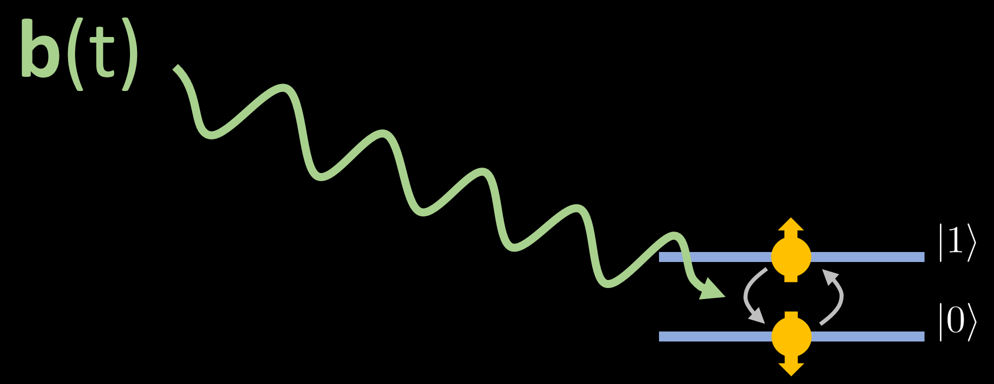
Qubit state manipulation via Rabi flopping

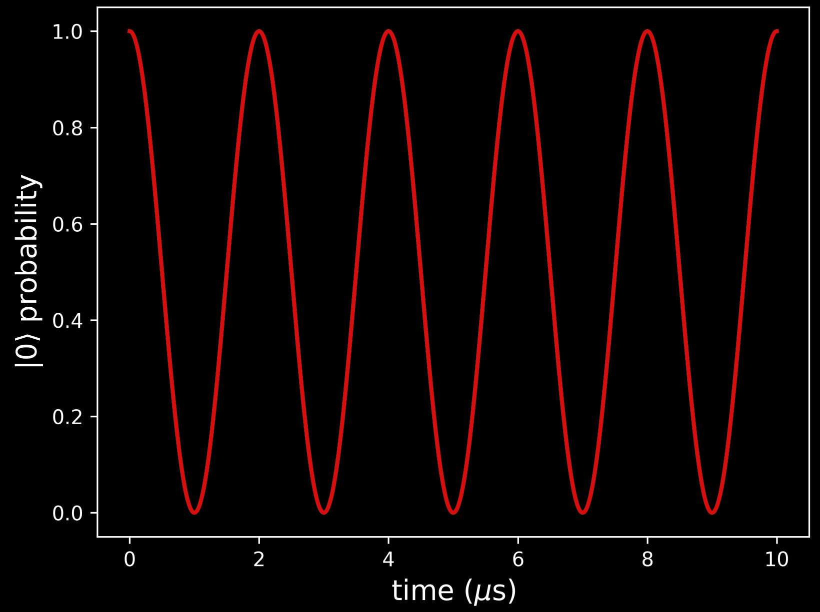
An oscillating magnetic field resonant with the Zeeman splitting drives the qubit state into a superposition.





Qubit state manipulation via Rabi flopping





$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

qubit wavefunction

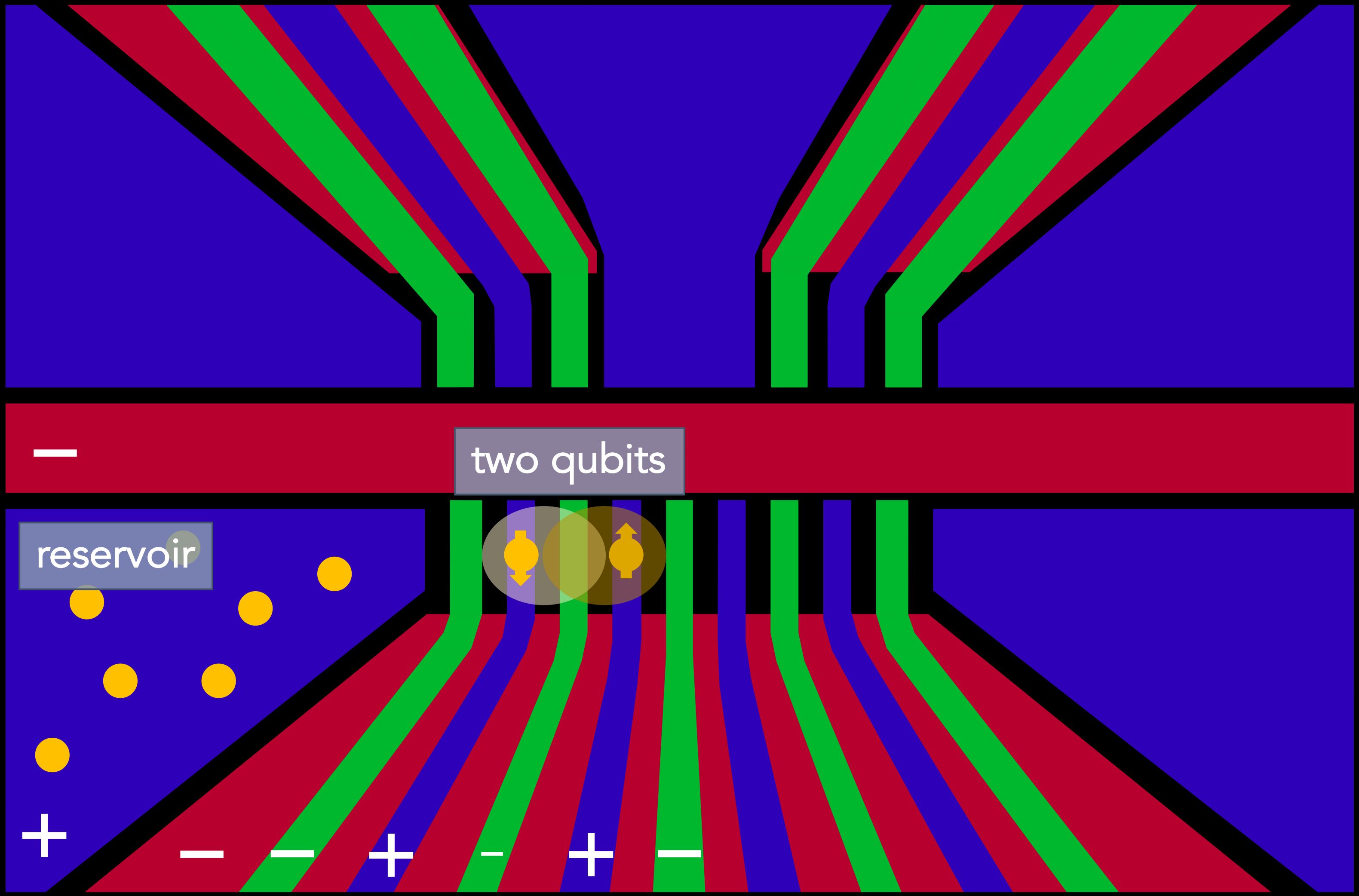
Driving the qubit in this manner generates oscillation between $|0\rangle$ and $|1\rangle$ called Rabi flopping.

By timing the magnetic field burst right, the qubit state can be manipulated to execute quantum logic operations.

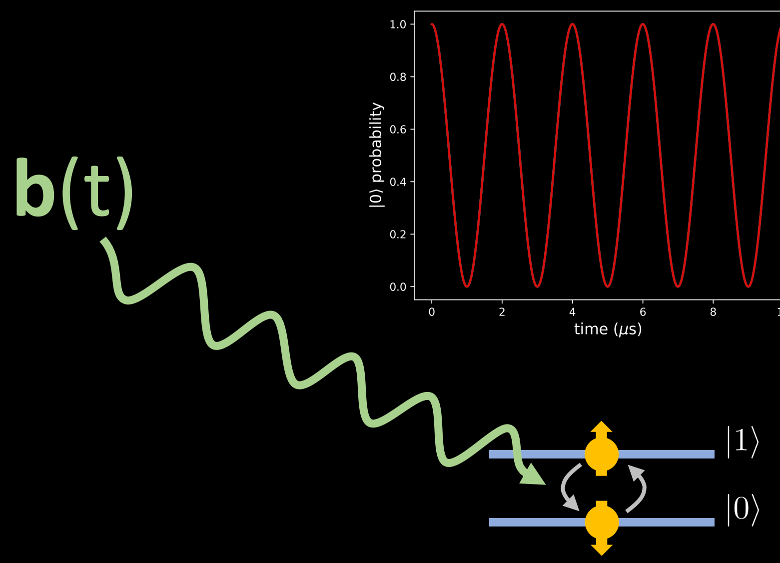
Two-qubit operations

Also need to perform operations that entangle pairs of qubits. This can be accomplished through the spin exchange interaction.

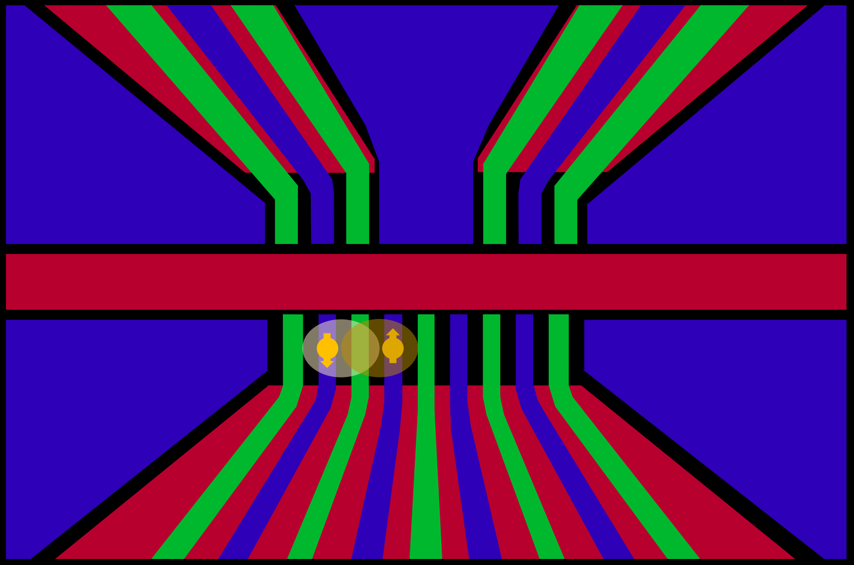
To perform an entanglement operation, carefully control the wavefunction overlap between neighboring qubits.



Universal set of quantum logic operations



single-qubit operation



two-qubit operation

Any computational task can be broken down into single- and two-qubit operations.

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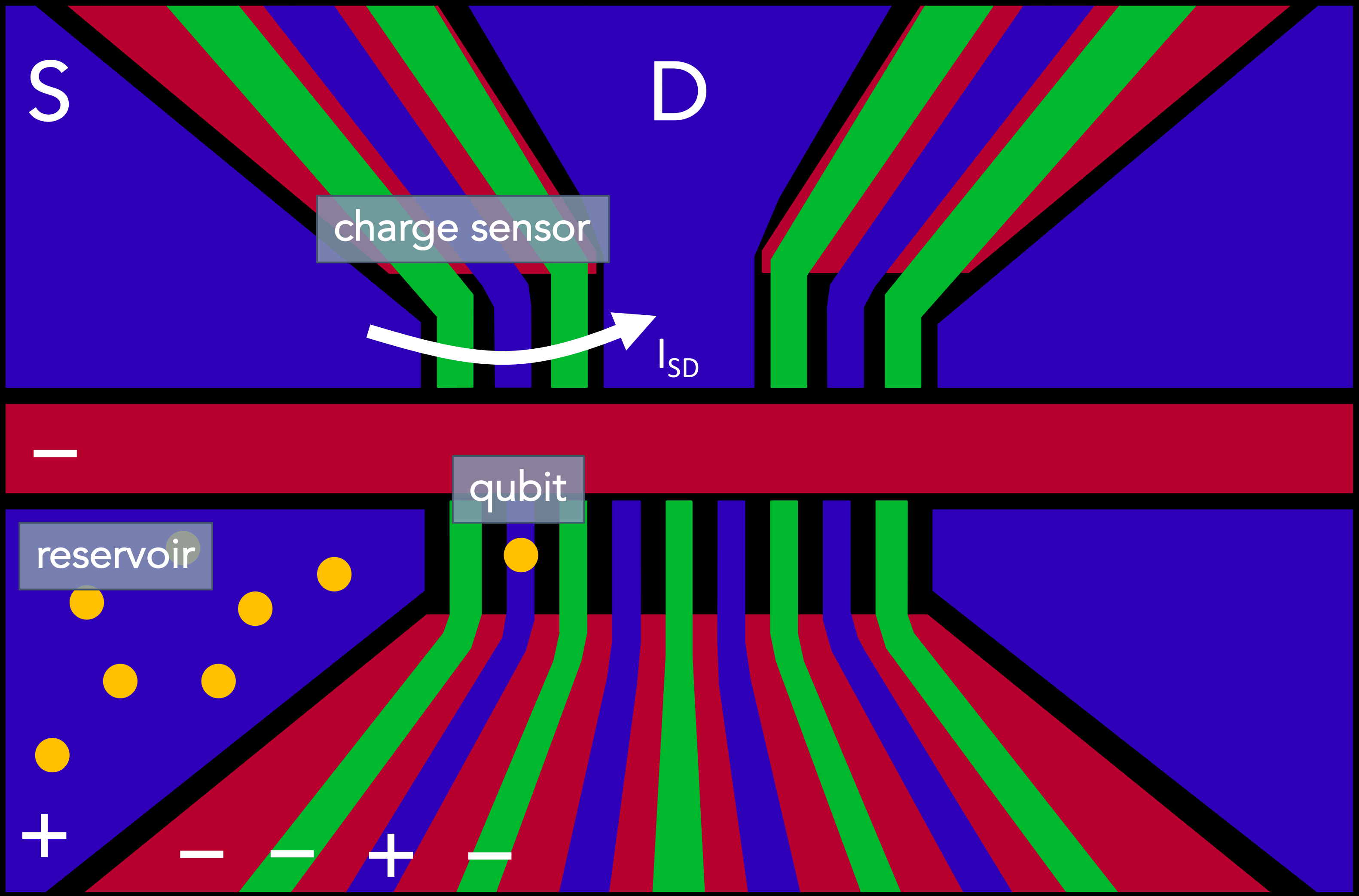
Qubit measurement with an integrated charge sensor

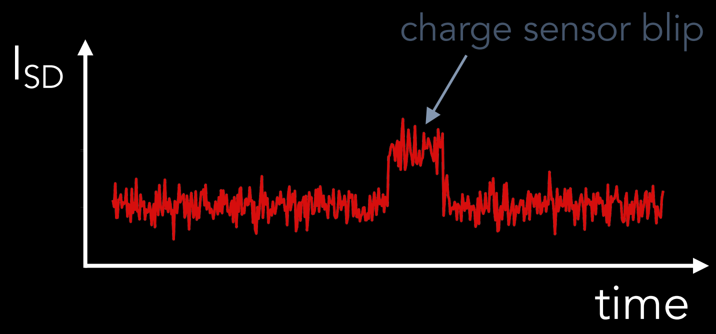
Neighboring single-electron transistor acts as an integrated charge sensor to detect electron occupation in the quantum dot.

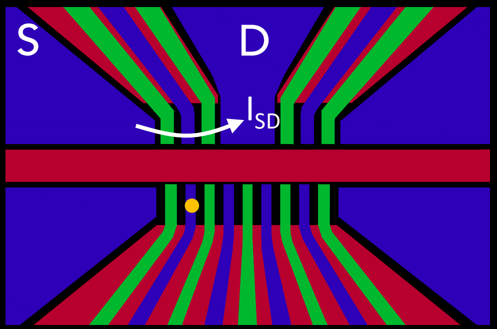
Adding/removing the electron from the dot capacitively changes the current flowing through the charge sensor.

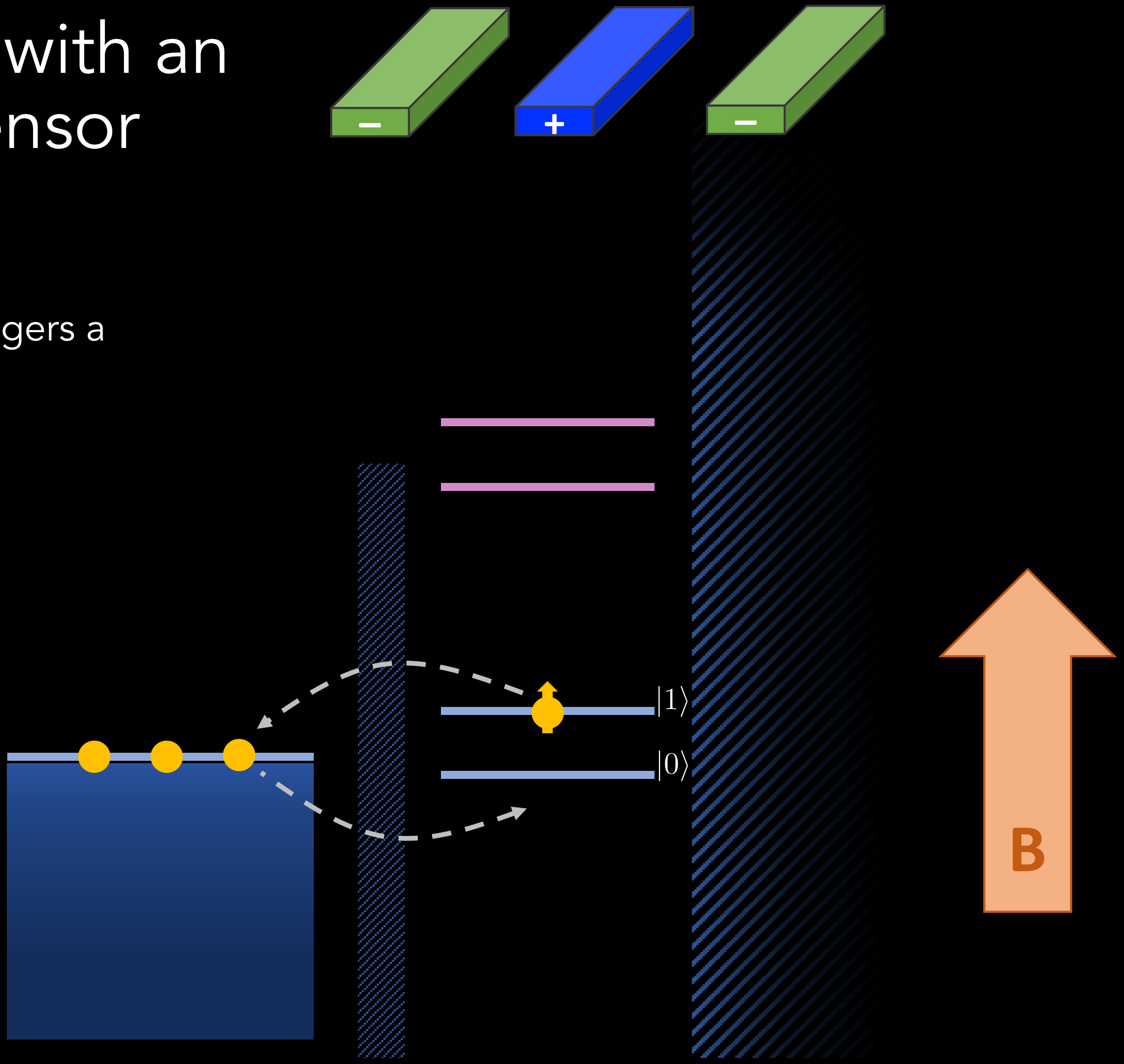


Qubit measurement with an integrated charge sensor

Measurement in the |1⟩ state triggers a tunneling event.

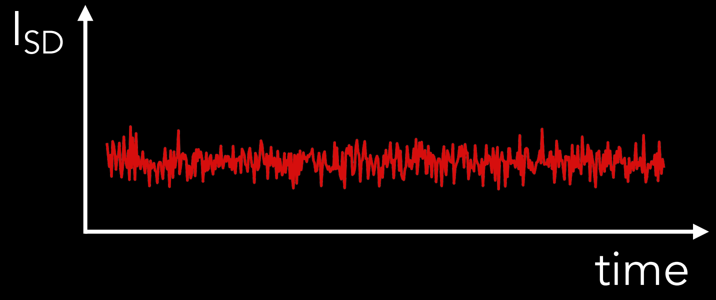


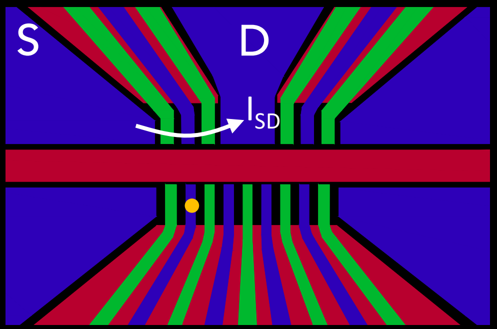


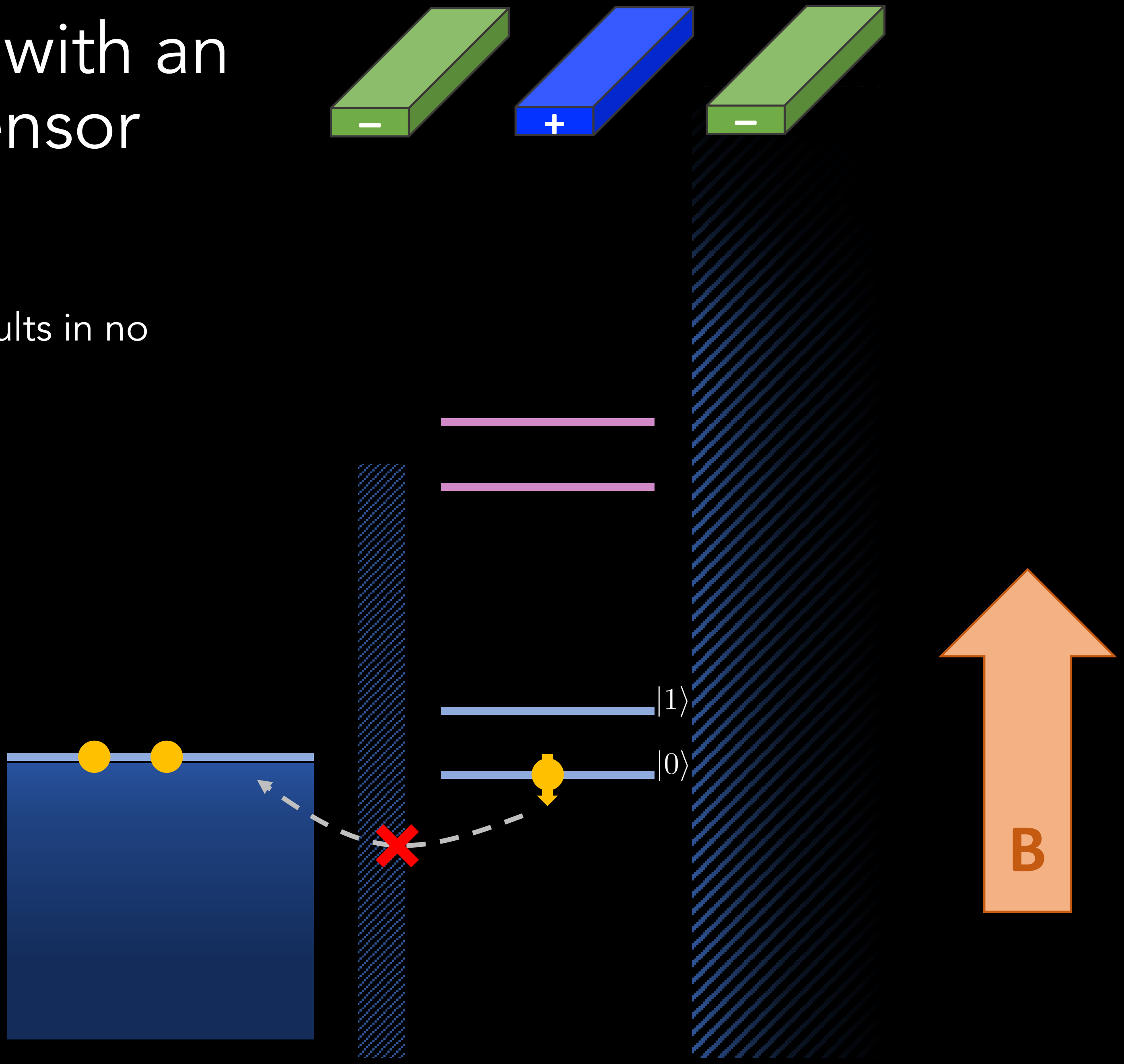


Qubit measurement with an integrated charge sensor

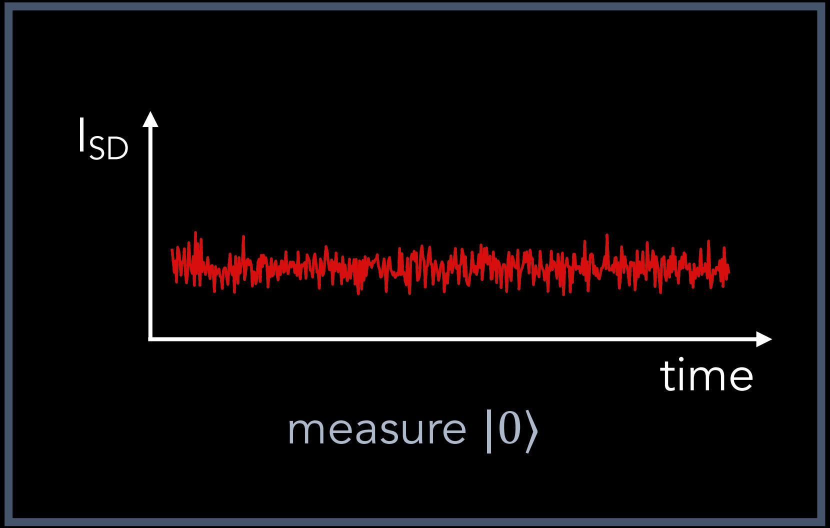
Measurement in the $|0\rangle$ state results in no tunneling.

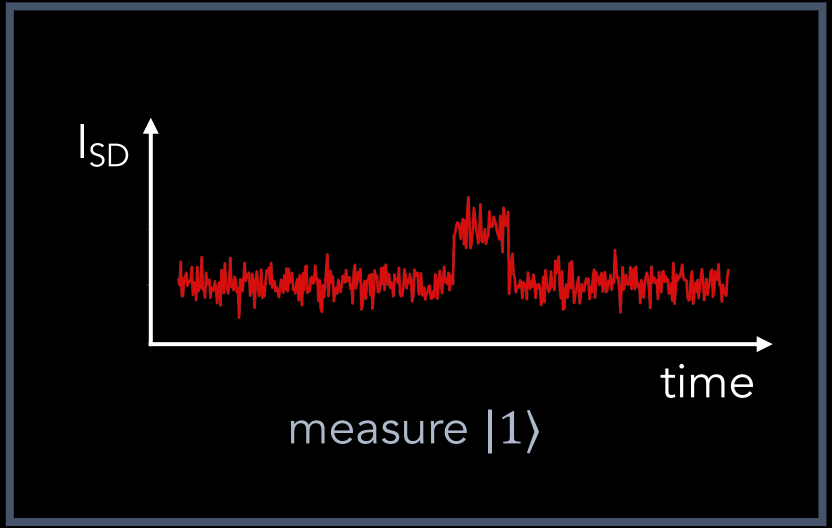






Readout summary





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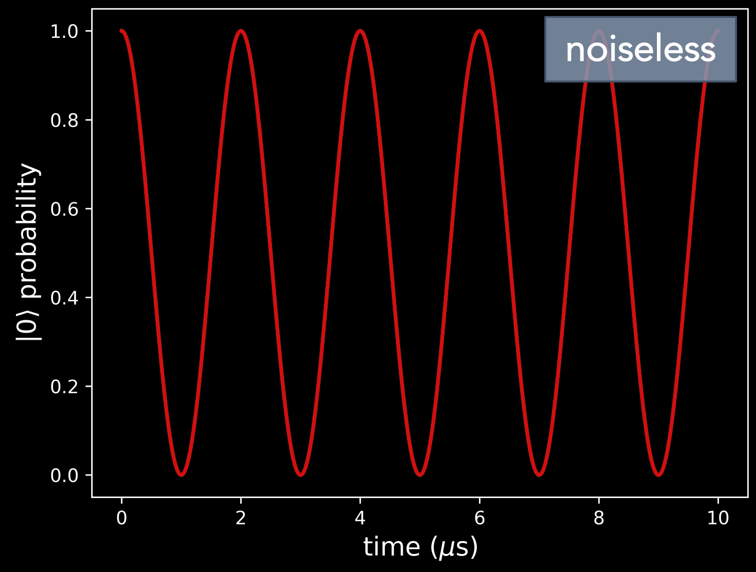
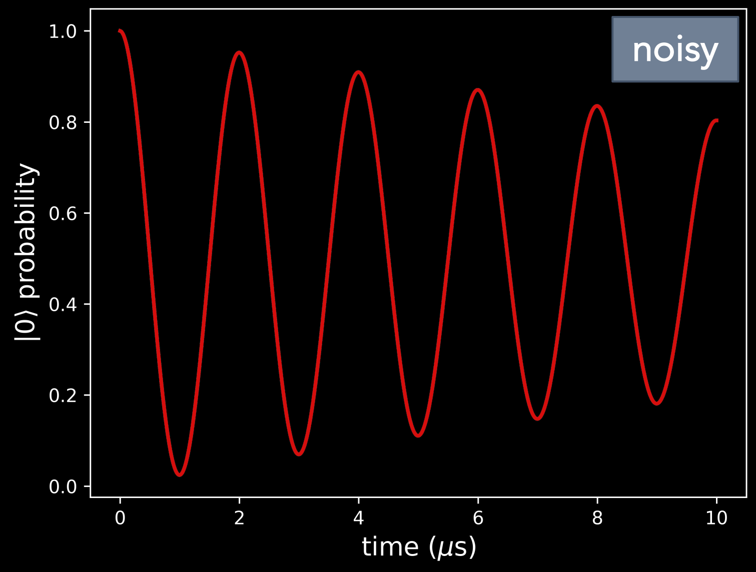
Decoherence degrades qubit performance

Unwanted noise and environmental disturbance causes qubit decoherence and computational errors. These effects worsen over time.

Eventually, control over the qubit state is lost entirely.





Decaying Rabi oscillation amplitude is one signature of decoherence.

Sources of noise in spin qubits

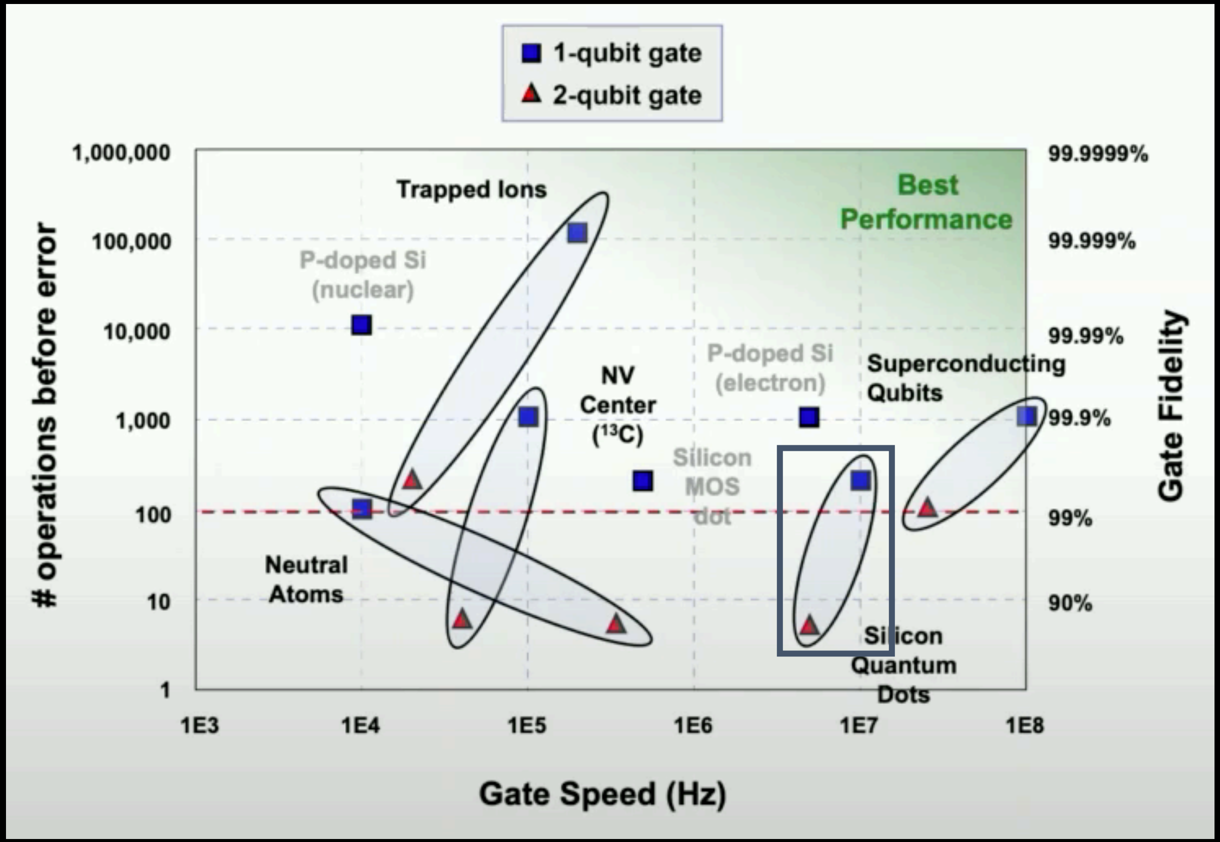
- instrument noise from control electronics
- coupling to nuclear spins in surrounding material
- fluctuating trapped charges in surrounding material
- phonons and thermal excitations

How many operations can be carried out within the qubit's lifetime?

~100 ns operation time

~10 μs qubit lifetime

Summary of qubit performance across platforms

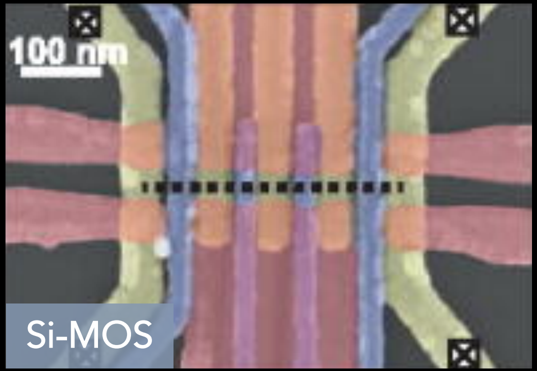


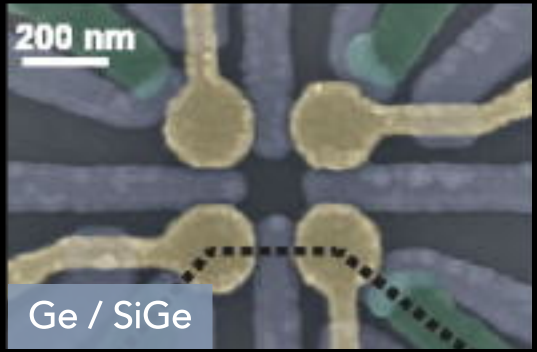
Engineering qubits to be faster and less prone to decoherence is a major priority for all qubit platforms.

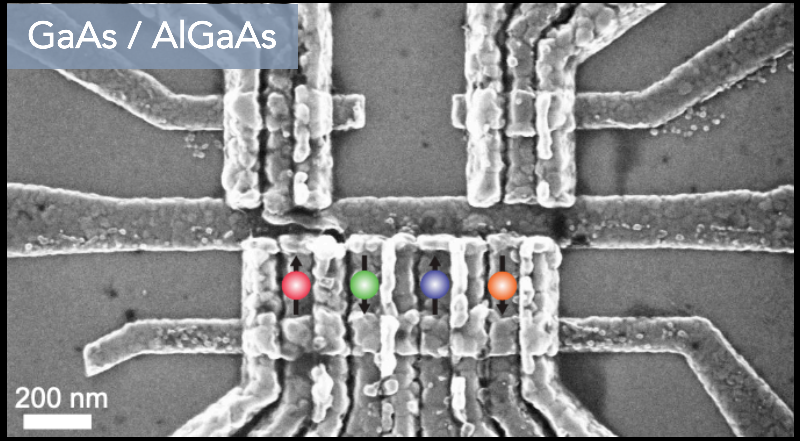
W. Oliver

research frontiers

Alternative materials and device architectures







W. Lawrie et al., H. Qiao et al.

New fabrication methods for more robust devices

Fabrication process and failure analysis for robust quantum dots in silicon

J. P. Dodson,[1] Nathan Holman,[1] Brandur Thorgrimsson,[1] Samuel F. Neyens,[1] E. R. MacQuarrie,[1] Thomas McJunkin,[1] Ryan H. Foote,[1] L. F. Edge,[2] S. N. Coppersmith,[1,3] and M. A. Eriksson[1]

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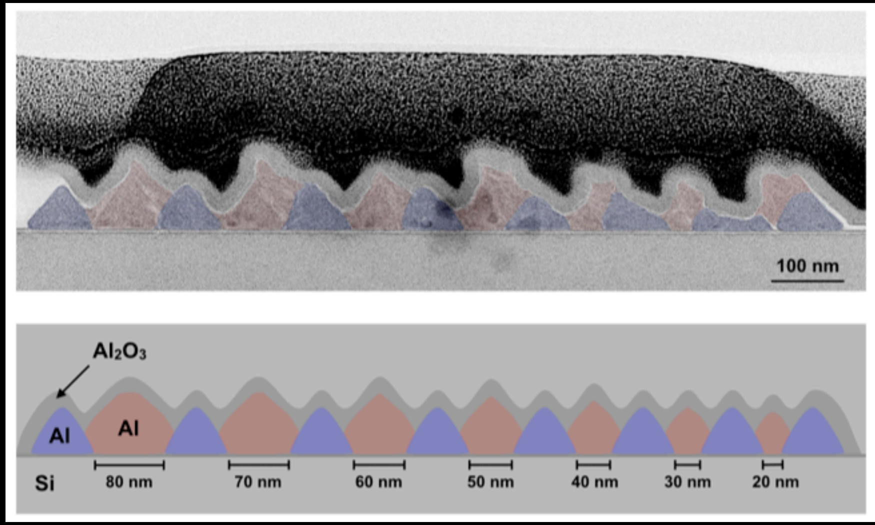
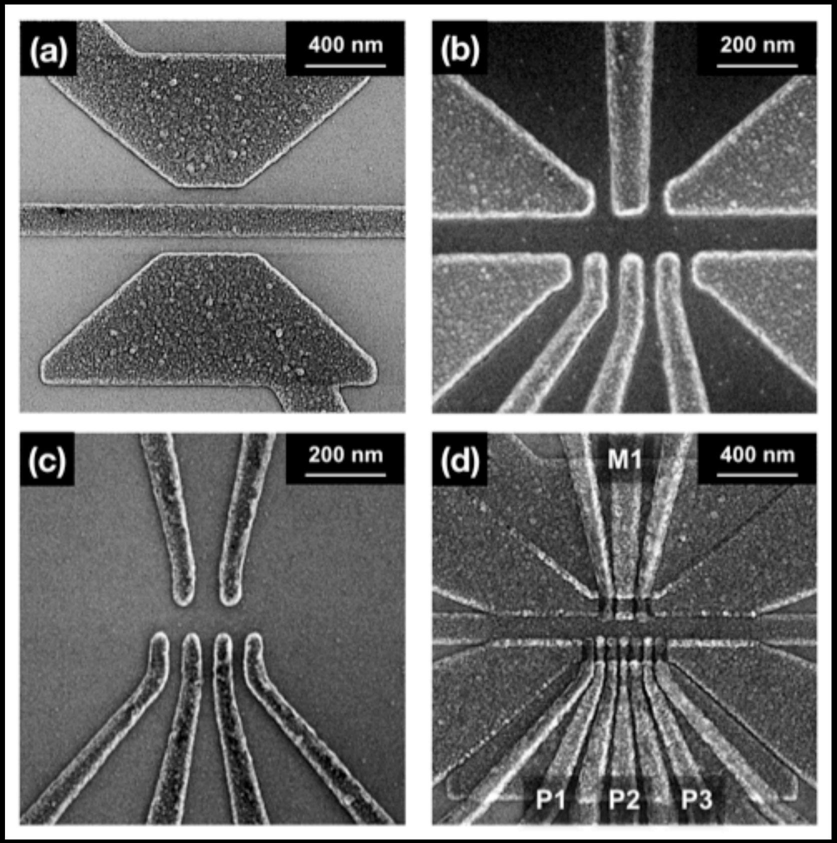
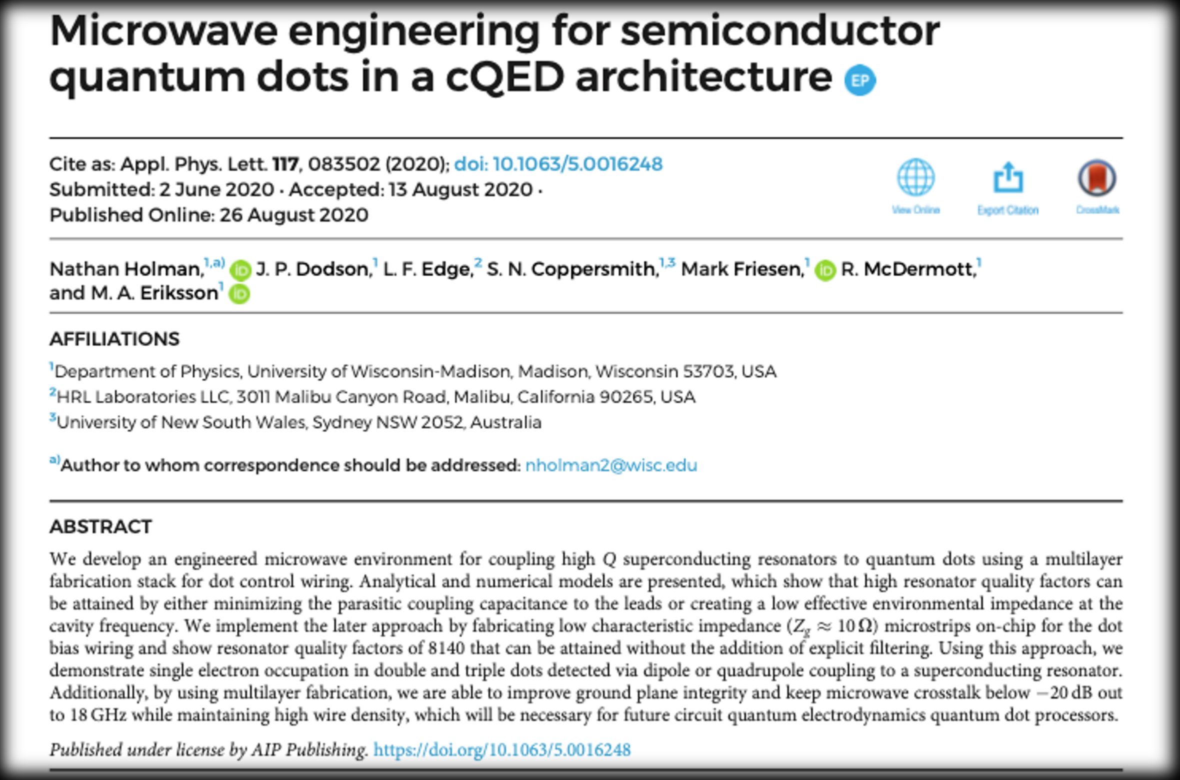
We present an improved fabrication process for overlapping aluminum gate quantum dot devices on Si/SiGe heterostructures that incorporates low-temperature inter-gate oxidation, thermal annealing of gate oxide, on-chip electrostatic discharge (ESD) protection, and an optimized interconnect process for thermal budget considerations. This process reduces gate-to-gate leakage, damage from ESD, dewetting of aluminum, and formation of undesired alloys in device interconnects. Additionally, cross-sectional scanning transmission electron microscopy (STEM) images elucidate gate electrode morphology in the active region as device geometry is varied. We show that overlapping aluminum gate layers homogeneously conform to the topology beneath them, independent of gate geometry, and identify critical dimensions in the gate geometry where pattern transfer becomes non-ideal, causing device failure.





Long-range qubit coupling via superconducting resonators



Microwave engineering for semiconductor quantum dots in a cQED architecture

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Nathan Holman,[1,a)] J. P. Dodson,[1] L. F. Edge,[2] S. N. Coppersmith,[1,3] Mark Friesen,[1] R. McDermott,[1] and M. A. Eriksson[1]

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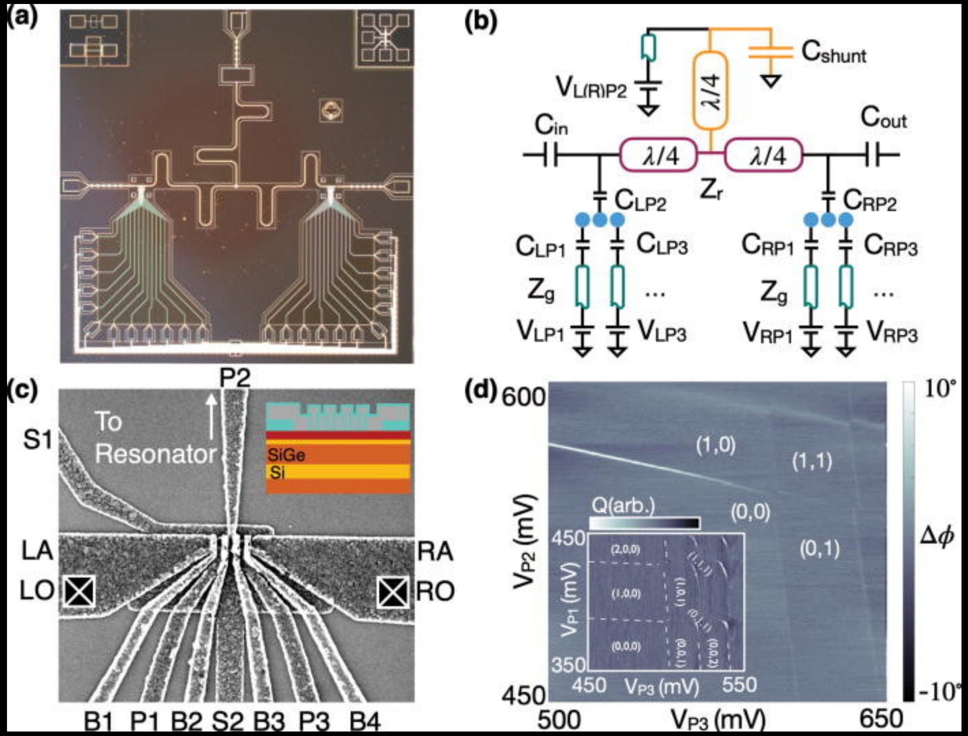
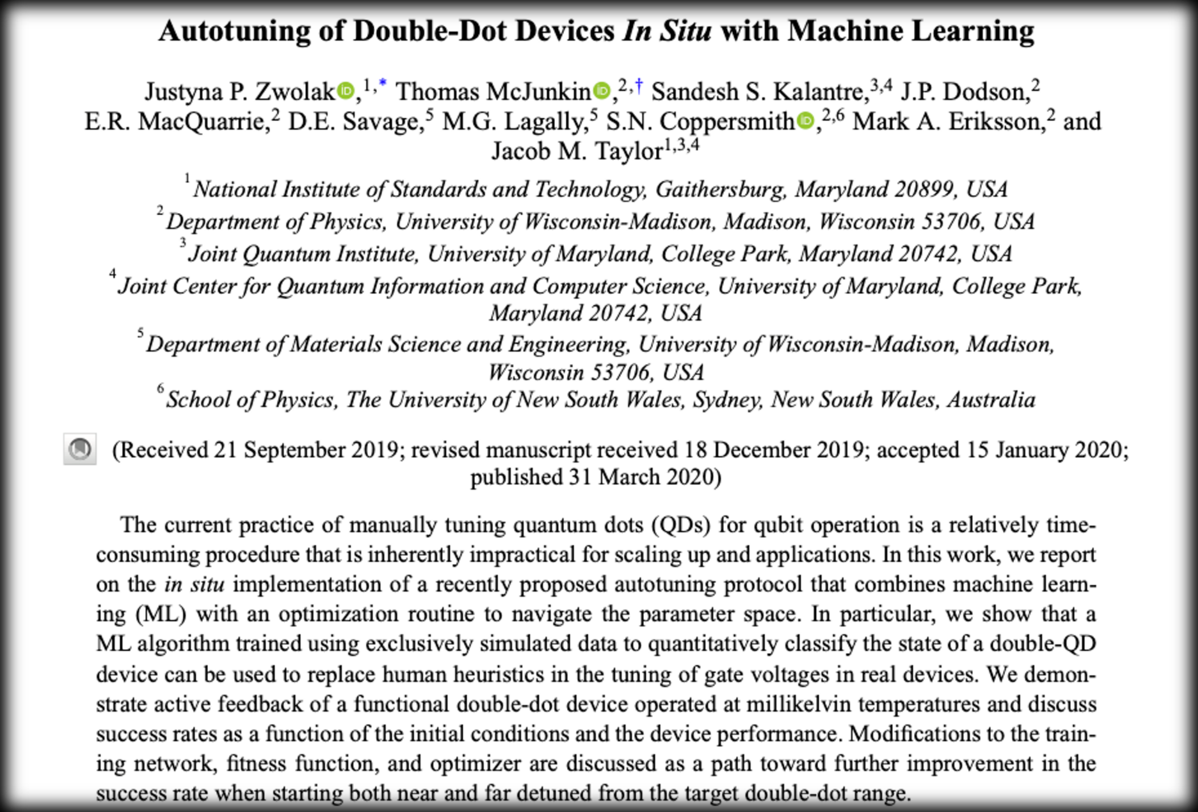
ABSTRACT

We develop an engineered microwave environment for coupling high Q superconducting resonators to quantum dots using a multilayer fabrication stack for dot control wiring. Analytical and numerical models are presented, which show that high resonator quality factors can be attained by either minimizing the parasitic coupling capacitance to the leads or creating a low effective environmental impedance at the cavity frequency. We implement the later approach by fabricating low characteristic impedance ($Z_g \approx 10\,\Omega$) microstrips on-chip for the dot bias wiring and show resonator quality factors of 8140 that can be attained without the addition of explicit filtering. Using this approach, we demonstrate single electron occupation in double and triple dots detected via dipole or quadrupole coupling to a superconducting resonator. Additionally, by using multilayer fabrication, we are able to improve ground plane integrity and keep microwave crosstalk below -20 dB out to 18 GHz while maintaining high wire density, which will be necessary for future circuit quantum electrodynamics quantum dot processors.



Autonomous device operation through machine learning



Autotuning of Double-Dot Devices *In Situ* with Machine Learning

Justyna P. Zwolak,[1,*] Thomas McJunkin,[2,†] Sandesh S. Kalantre,[3,4] J.P. Dodson,[2] E.R. MacQuarrie,[2] D.E. Savage,[5] M.G. Lagally,[5] S.N. Coppersmith,[2,6] Mark A. Eriksson,[2] and Jacob M. Taylor[1,3,4]

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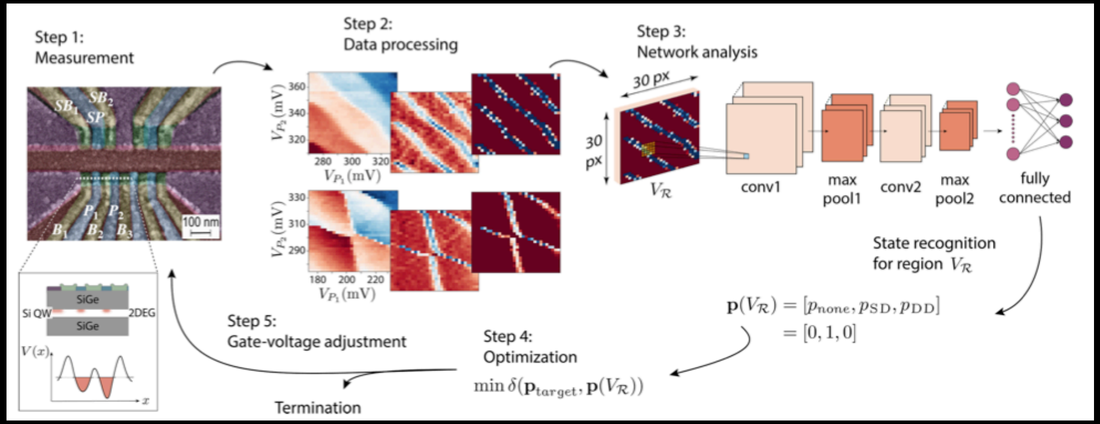
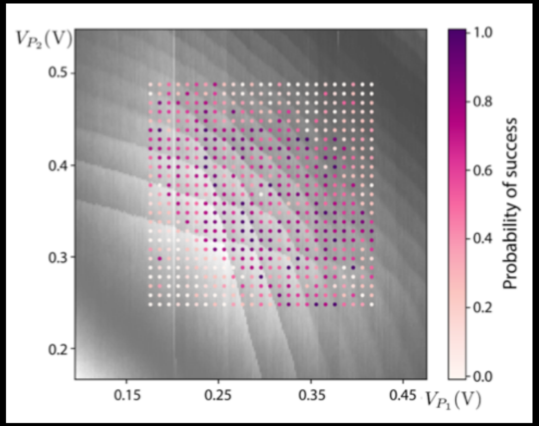
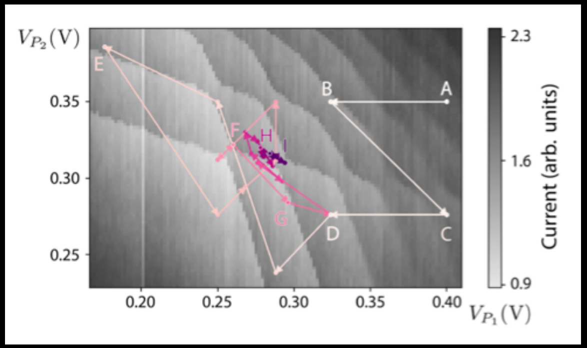
(Received 21 September 2019; revised manuscript received 18 December 2019; accepted 15 January 2020; published 31 March 2020)

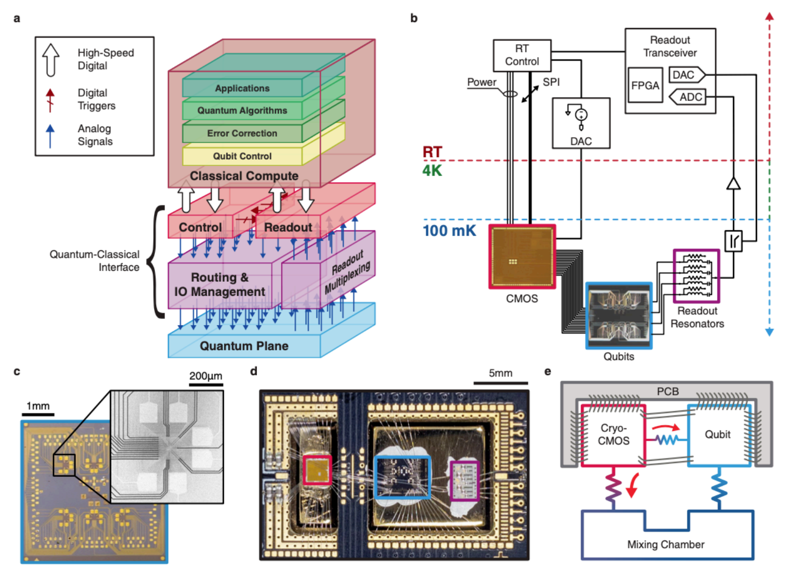
The current practice of manually tuning quantum dots (QDs) for qubit operation is a relatively time-consuming procedure that is inherently impractical for scaling up and applications. In this work, we report on the *in situ* implementation of a recently proposed autotuning protocol that combines machine learning (ML) with an optimization routine to navigate the parameter space. In particular, we show that a ML algorithm trained using exclusively simulated data to quantitatively classify the state of a double-QD device can be used to replace human heuristics in the tuning of gate voltages in real devices. We demonstrate active feedback of a functional double-dot device operated at millikelvin temperatures and discuss success rates as a function of the initial conditions and the device performance. Modifications to the training network, fitness function, and optimizer are discussed as a path toward further improvement in the success rate when starting both near and far detuned from the target double-dot range.







On-chip control electronics to interface with many qubits



PAPER

Quantum–classical interface based on single flux quantum digital logic

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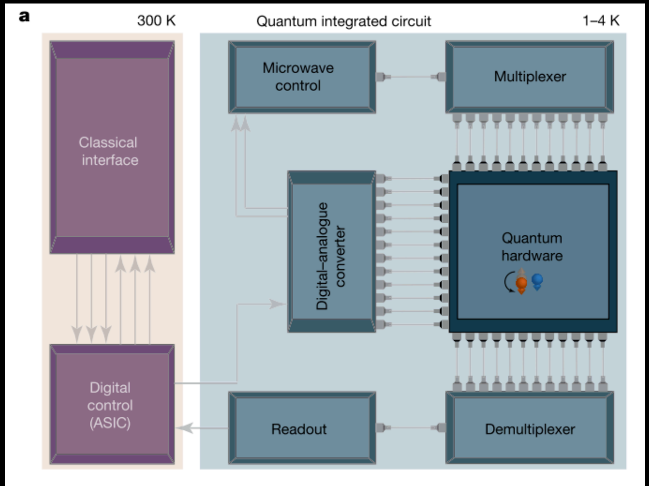
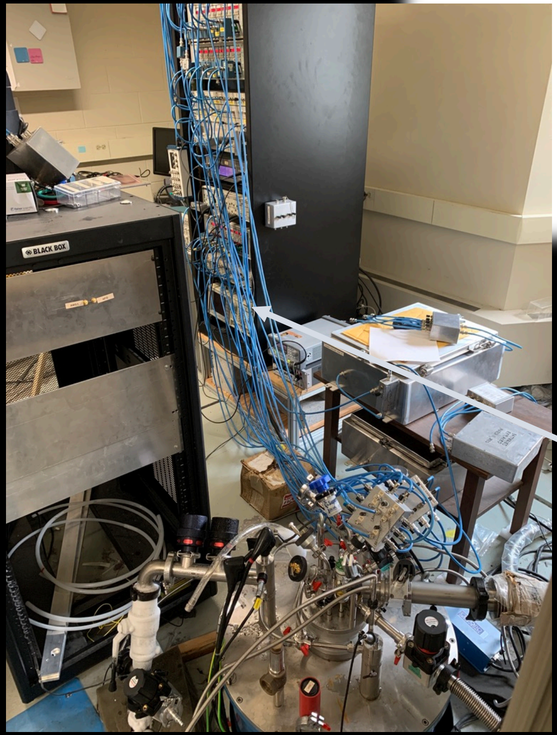
Abstract

We describe an approach to the integrated control and measurement of a large-scale superconducting multiqubit array comprising up to 10^8 physical qubits using a proximal coprocessor based on the Single Flux Quantum (SFQ) digital logic family. Coherent control is realized by irradiating the qubits directly with classical bitstreams derived from optimal control theory. Qubit measurement is performed by a Josephson photon counter, which provides access to the classical result of projective quantum measurement at the millikelvin stage. We analyze the power budget and physical footprint of the SFQ coprocessor and discuss challenges and opportunities associated with this approach.

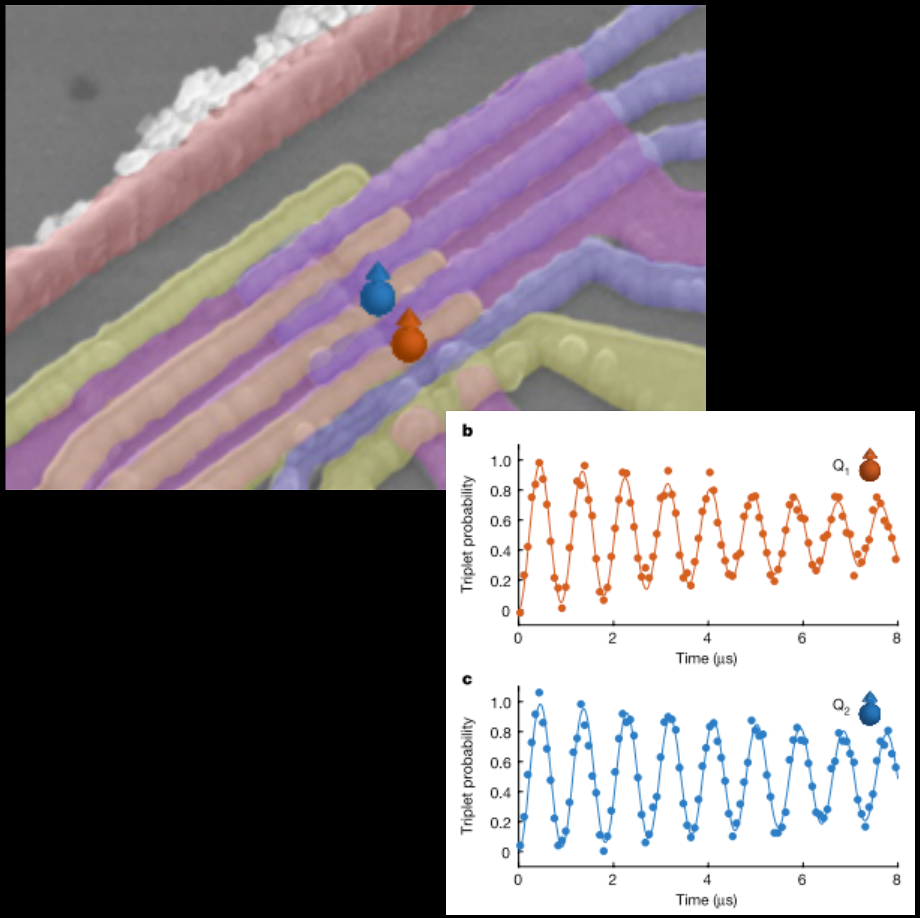


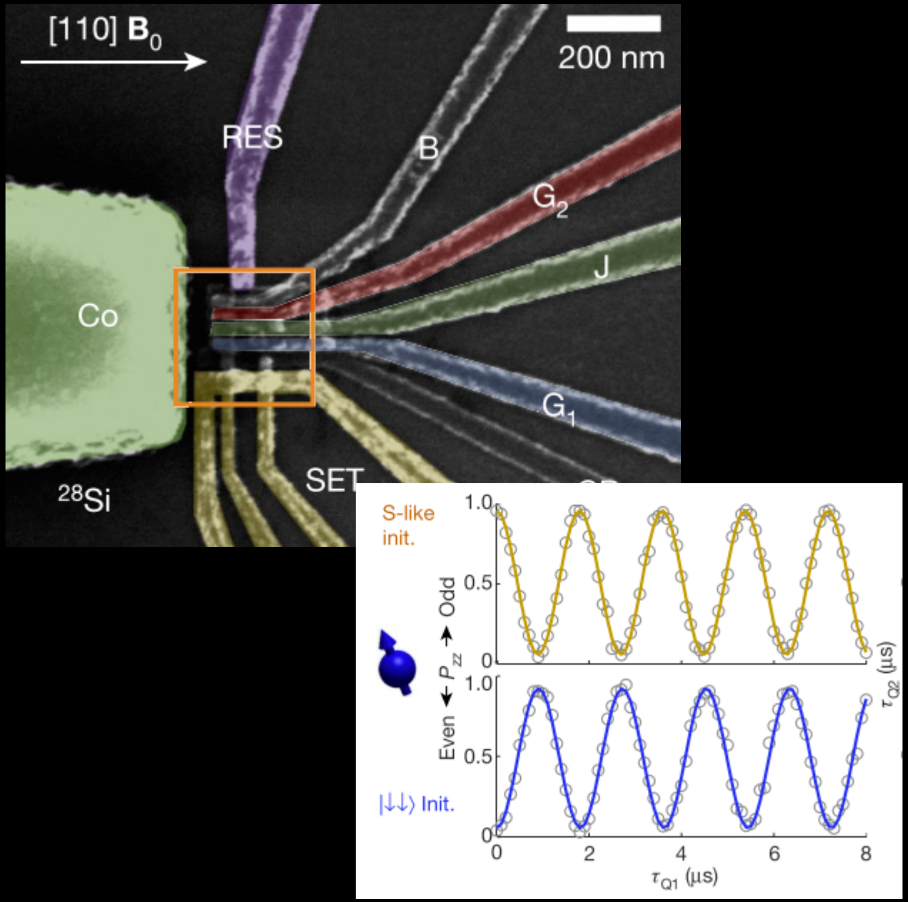


Cut down on all of this!

S. Pauka et al.,
L. Petit et al.

‘Hot qubits’ operate at temperatures above 1K





L. Petit et al., C. Yang et al.

thank you