Section 8: Semiconductors and Quantum Information

Monday, November 29, 2021 10:07 PM

I. Why Quantum?

a) Solve problems that are hard for classical computers:

- Search large databases (Grover's Algorithm)
- Factor primes and break RSA (Shor's Algorithm)
- Quantum simulation: you need a quantum system to best simulate a quantum system

b) Secure Communication and networks

- Quantum Key Distribution: measurement perturbs the system, so you can easily detect eavesdroppers
- Quantum networks: interface many quantum computers to share entanglement as resource for computing, distributed precision sensors

c) Interesting science + engineering

- Need to make fantastic classical devices along the way ⟶ will help existing applications
- Plus, interesting phenomena inherent

II. Qubits

(II) Qubits

a) Analogy

Consider a spinning coin:

Is it in heads? tails?

In some sense, it is both at the same time.

But when you measure it by slapping the coin down on the table, you only ever get one result — heads or tails.

Let's say you measure heads. Does that actually mean it was in heads the whole time? No.

In quantum mechanics, it truly is both states at once — it is in a <u>superposition</u>.

You might describe the state as

$$\psi = \frac{1}{\sqrt{2}}\psi_{heads} + \frac{1}{\sqrt{2}}\psi_{tails}$$

Moreover, the act of measurement illustrates another phenomenon — <u>measurement collapse</u>.

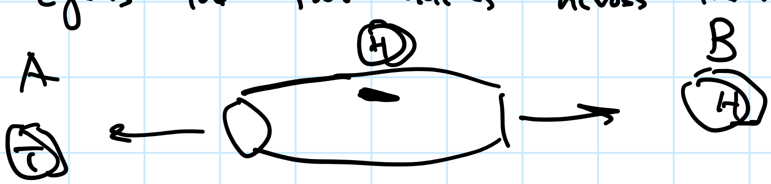
You measure out some observable, and you can only get certain values out. After measuring, the quantum state is fundamentally measuring, the quantum state is fundamentally altered — it collapses to the state which corresponds to the value of the observable you just measured.

$$\psi^{out} = \psi_{heads} \quad \left(\text{if you measured heads}\right)$$

We could have also called the states "0" and "1", in analogy to a classical bit. This forms the basic unit of quantum information — a quantum bit, or "qubit", can be realized by a quantum system that can take on two states, ψ_0 or ψ_1, or any superposition thereof.

$$\psi = c_0 \psi_0 + c_1 \psi_1$$

Let's stretch the analogy a little bit more. Suppose you have a magical cannon that splits a coin in two, and ejects the two halves across the room.



You don't know what the result on any individual side will be — but you do know that the results are correlated. If side A measures tails, you know

If side A measures tails, you know side B has heads; if A measures heads, B has tails.

Is the state just a superposition like before then? Not exactly. You could have the result

$$\psi_0^A \psi_1^B$$

but also get

$$\psi_1^A \psi_0^B$$

So you have a superposition of two-coin states,

$$\psi = \frac{1}{\sqrt{2}} \psi_0^A \psi_1^B + \frac{1}{\sqrt{2}} \psi_1^A \psi_0^B$$

We can't describe each coin individually — we have to describe both at the same time. This is <u>entanglement</u>.

It turns out that superposition and entanglement are some of the most fundamental quantum resources that enable quantum computing and quantum information to tackle problems that would be otherwise impossible for classical computers.

6) Math

A qubit is a two-level quantum system,

A qubit is a <u>two-level quantum system</u>, described by <u>two orthonormal basis states</u>.

"1" ———— $\psi_1 \rightarrow |1\rangle$

"0" ———— $\psi_0 \rightarrow |0\rangle$

Earlier we called these basis states ψ_0 and ψ_1. By convention, we will now refer to them as $|0\rangle$ and $|1\rangle$ (Dirac notation).

The qubit is generally described by a superposition (linear combination) of these basis states:

$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle$$

And entanglement is when a many-body state cannot be factored into individual single-qubit states.

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |01\rangle\right)$$

$$= \frac{1}{\sqrt{2}}|0\rangle\left(|0\rangle + |1\rangle\right) \quad \text{Not entangled!}$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right) \quad \text{entangled!}$$

In other words, qubits are vectors in the vector subspace $\mathbb{C}^2$ such that the length is 1. $\left(|c_0|^2 + |c_1|^2 = 1\right)$

c) Manipulating Qubits

Classical logic: AND, NOR, NOT...

Can think similarly for qubits — develop quantum logic gates.

Single qubit operations should be able to transform one qubit state to another valid qubit state. This means it preserves length, aka a <u>rotation</u>!

Thus, single qubit rotations can be described by 2×2 unitary matrices.

Ex: NOT = X gate

$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

Other things: multi-qubit gates, memory, measurement...

II. What do you need to make a quantum computer?

a) Di Vincenzo's Criteria

1. Scalable physical system w/ well characterized qubit

2. Ability to initialize qubit state

   ↳ i.e. set all qubits to $|0\rangle|0\rangle|0\rangle \ldots$

3. Long decoherence times

   ↳ Roughly, usable time before system is no longer usable

4. "Universal" set of quantum gates

   ↳ to a theorist, usually means something like "Clifford gate set"

   ↳ to an experimentalist, usually means something like arbitrary single qubit rotations and a two-qubit entangling gate

5. Measurement

b) Example systems

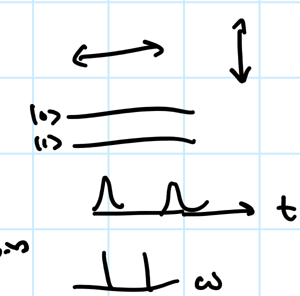
- Photons

  ↳ polarization

  ↳ path

  ↳ time bin

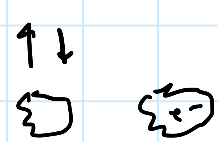
  ↳ frequency bin



- Electrons

  ↳ spin

  ↳ charge



- Atom
  - ↳ excited state vs ground state $|e\rangle$ $|g\rangle$

III. What role can semiconductors play?

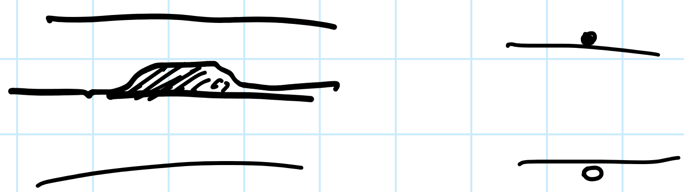
Why semiconductors?

↳ Primarily a scalability argument

↳ General approach: use "artificial atoms" in the solid-state

a) Quantum Dots

Essentially, as close to particle in a (3D) box we can get:



$$H = H_e + H_h + H_c$$

H_e: electron, H_h: hole, H_c: Coulomb

$$H_e = -\frac{\hbar^2}{2m_e^*}\nabla^2 + V_e(\vec{r})$$

$$H_h = \frac{-\hbar^2}{2m_h^*}\nabla^2 + V_h(\vec{r})$$

$$H_c = -\frac{e^2}{4\pi\epsilon}\frac{1}{|r_e - r_h|}$$

To first order, ignore Coulomb potential:

Potential modeled as:

$$V(x,y,z) = \Big(\frac{1}{2} m_{eff}\,\omega_0^2 (x^2+y^2) \quad z \le L$$

$$V(x,y,z) = \begin{cases} \frac{1}{2} m_{eff}\, \omega_0^2 (x^2+y^2) & z \le L \\ \infty & z > L \end{cases}$$

(Infinite well in z-direction, locally harmonic in xy)

$$\Rightarrow E_{e/h} = (n_x + n_y + 1)\hbar\omega_0 + \frac{1}{2m_{eff}} \left(\frac{\pi \hbar n_z}{L}\right)^2$$

Use as:

- single photon source
  - ↳ highest "purities" in solid state ("single-photon ness", >99% in GaAs)
  - ↳ many of the first impressive displays of quantum protocols with optics, cavity QED, etc.
  - ↳ Challenge: no two QDs exactly the same, controllable fabrication is nontrivial
- spin/electron qubits
  - ↳ e.g., work by Amir Yacoby

b) Defects ("Color centers")

- Missing or replaced atoms in crystal

↳ Diamond (NV, SiV, GeV, SnV)

↳ SiC (V_{Si}, $V_C V_{Si}$, $N_C V_{Si}$)

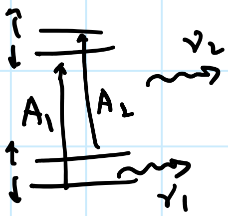
↳ SiC (V_{Si}, $V_C V_{Si}$, $N_C V_{Si}$)

↳ Si (P donors, T centers)

- "Color" ⟶ luminescent

Most studied defects don't just fluoresce, but also have <u>spin</u> (magnetic) properties

Simplified picture:



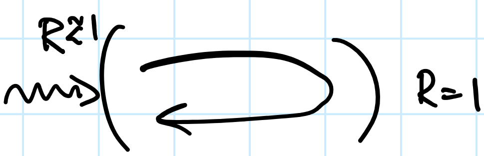
⟹ use spin as qubit, and interface interface with photons (map qubit from spin to photon) to send for distances for communication

⟹ use as <u>memories</u> (can interface with long-lived nuclear spins)

- Challenges: relatively dim, controllable creation, local environmental inhomogeneities

c) Nanofabricated devices

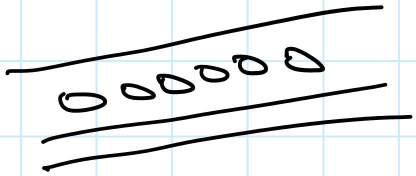
- Cavities



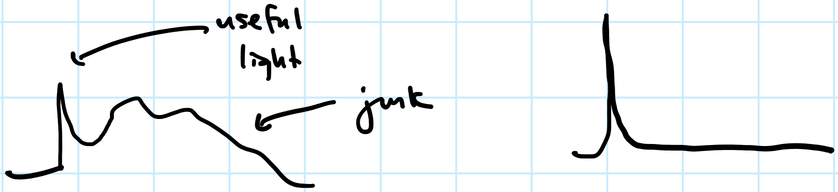
(two mirrors)

Light circulates in cavity many times, <u>enhances</u> light-matter interaction (more chances to hit atom / atom-like system).

Especially enhanced if electric field mostly in <u>small volume</u> ⟹ nanofabrication!



photonic crystal cavity



before cavity   after cavity

Put in color center, quantum dot ... or even other platforms!

Heterogeneous integration with atoms, exotic emitters (e.g. $Er : Y_2O_3$) ... take advantage of mature and scalable fab!

- Other material "knobs"?
  - mechanical strain / acoustics
  - electric field (Stark tuning)
  - electrically-driven single photons? (usually, optically driven)
  - chemical functionalization?
  - And much more!