Semiconductor Spintronics Electronics for the 21st century

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Semiconductor Spintronics

Objective

To create a revolutionary new class of semiconductor electronics based on the spin degree of freedom of the electron in addition to, or in place of, the charge.

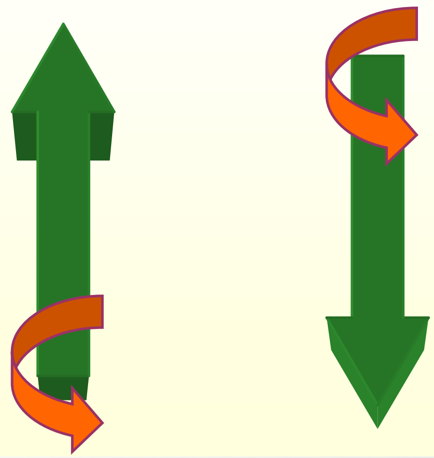
Rationale for Spintronics

Conventional Electronics ⟶ Charge

- *Based on number of charges and their energy*
- *Performance limited in speed and dissipation*

Spintronics ⟶ Spin

- *Based on direction of spin and spin coupling*
- *Capable of much higher speed at very low power*



Spintronics Challange

In March of 1959, Richard Feynman challenged his listeners to build

> **"Computers with wires no wider than 100 atoms, a microscope that could view individual atoms, machines that could manipulate atoms 1 by 1, and circuits involving quantized energy levels or the interactions of quantized spins."**

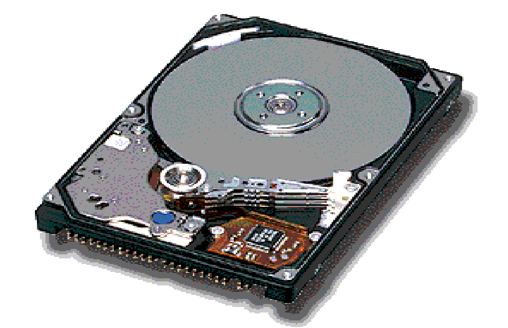
Richard Feynman - "There's Plenty of Room at the Bottom"

1959 Annual Meeting of the American Physical Society

Spintronics

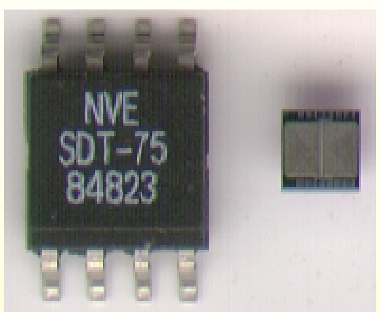
Magnetoresistive thin films and nanostructures are already extremely important scientifically, technologically and economically.

- Economics: -Today
  - Magnetic recording alone is a $100 billion/yr

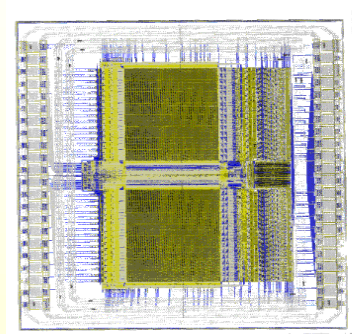


The IBM Travelstar disk drive
uses magnetoresistive devices to achieve 4.1Gb/in^2

  - Tomorrow – Potential additional $100 billion/year



Sensors-Isolators



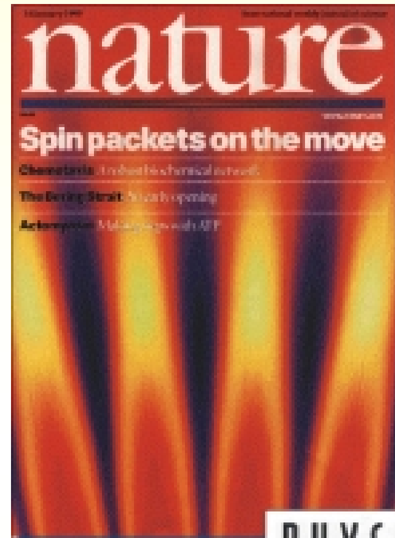
Non-Volatile
Radiation Hard
High Density
Very High Speed
Low Cost

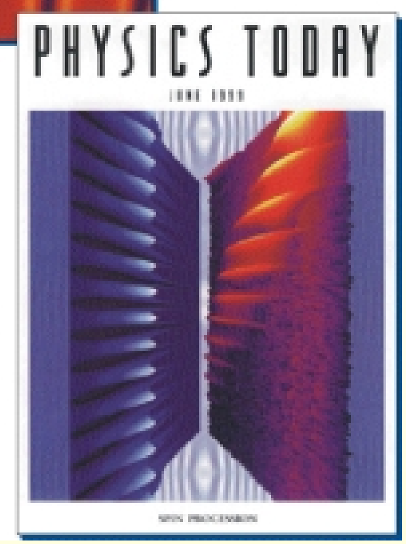
Magnetic RAM

Spins IN Semiconductors

New Direction-SPINS

- Two recent discoveries
  - Optically Induced long lived coherent spin state in semiconductors
  - Ferromagnetism in semiconducting GaMnAs above 120K (Sendai, Japan 1998)

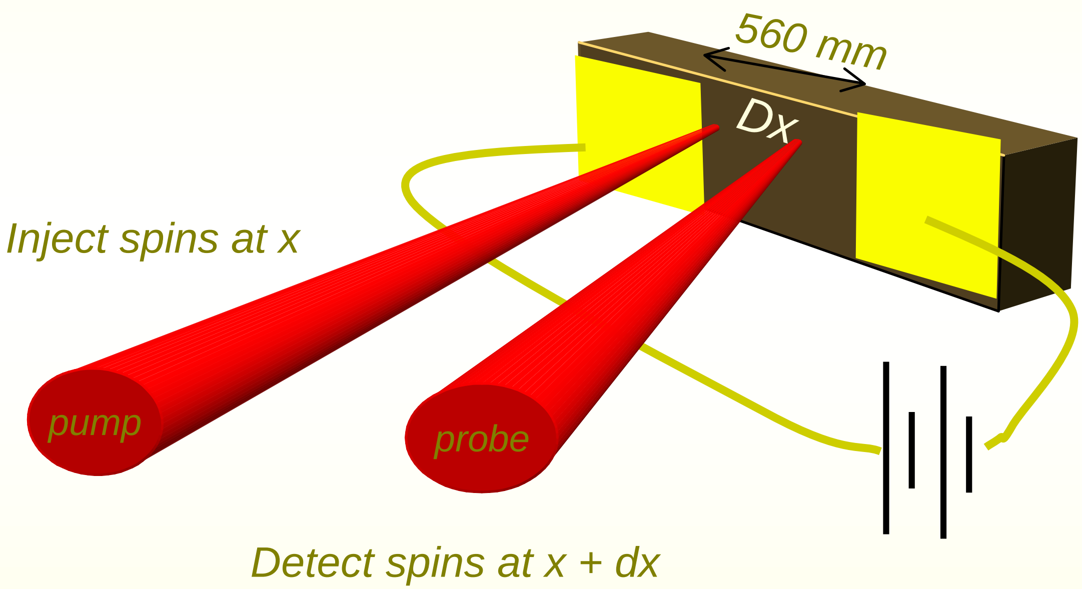


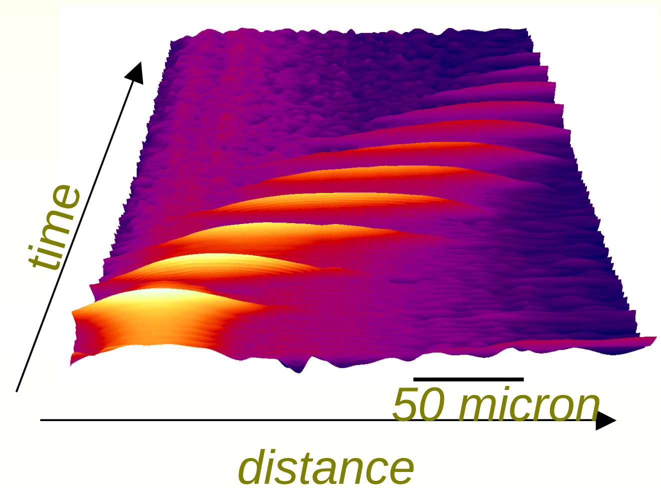


- Will lead to revolutionary advances in 21st Century photonics and electronics such as:
  - Very high performance opto-electronic devices
  - Very fast, very dense memory and logic at extremely low power
  - Spin quantum devices like Spin-FETs, Spin LEDs and Spin RTDs
  - **Quantum computing in conventional semiconductors at room temperature**
  - Many other applications that we can't even envision now

Injection and Motion of Coherent Spins in Semiconductors

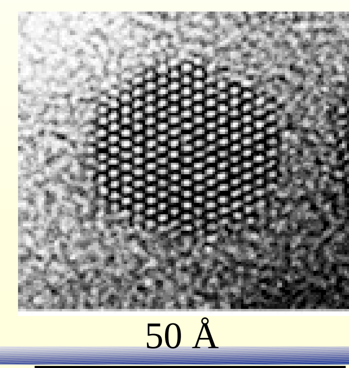
- Spin coherence persists for 100s of nanoseconds over 100s of microns
- Largely insensitive to temperature





- *Spin coherence also demonstrated in CdSe Quantum Dots*
- *Room temperature operation with nanosecond lifetimes*

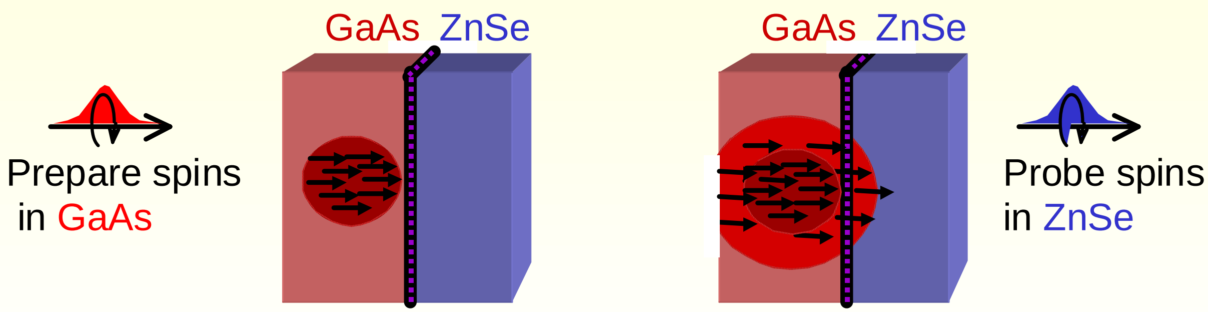
Enabler for Quantum Computation



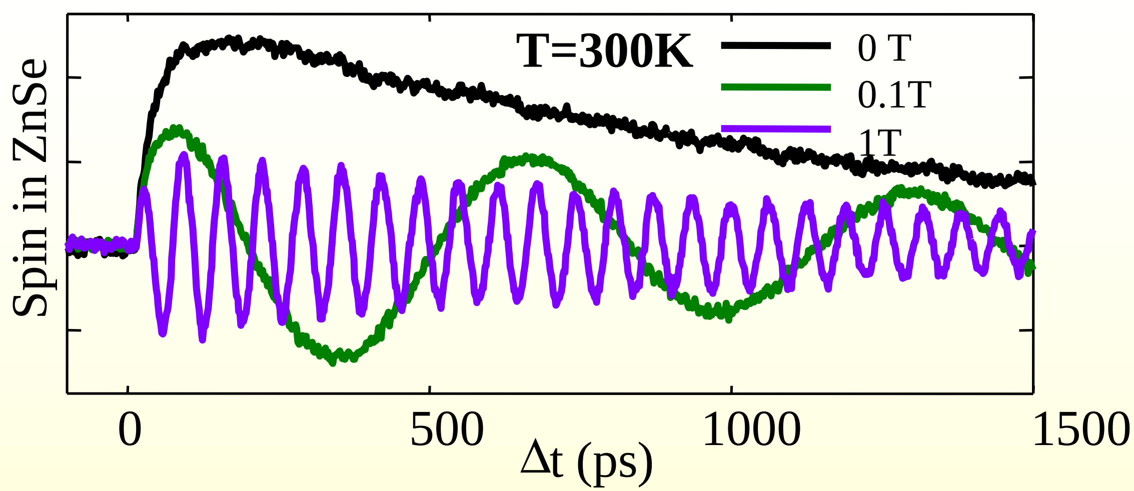
What Needs to be Done

- Since spin effects in semiconductors are largely ***unexplored*** it will be essential to
  - Explore ways to raise Curie temperature of magnetic semiconductors
  - Explore optical and transport properties which offer new spin dependent avenues
    - **Understand and control interface effects and spin transport across interfaces**
  - Demonstate spin coherent optical devices
  - Demonstrate spin quantum devices
  - Demonstrate quantum logic with 8 qubits or more at or near room temperature

Spin Transfer Through Heterointerfaces



- Flow of coherent information across a heterointerface with dissimilar materials with very little scattering



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Spin Enhanced and Enabled Electronics

Quantum Spin Electronics

- Tunneling/transport of quantum confined spin states: natural frequency scale given by spin splitting: GHz-THz
- Spin dependent resonant tunneling diodes and spin filtering
- Spin FETs (“spin gating”)
- Spin transistors
- Spin LEDs, electroluminescent devices, and spin Lasers

Coherent Spin Electronics

- Optically generated coherent spin states and coherent control of propagating spin information - optical encoders and decoders
- Directly generated coherent spin state and coherent control of propagating spin information

Quantum Information Processing

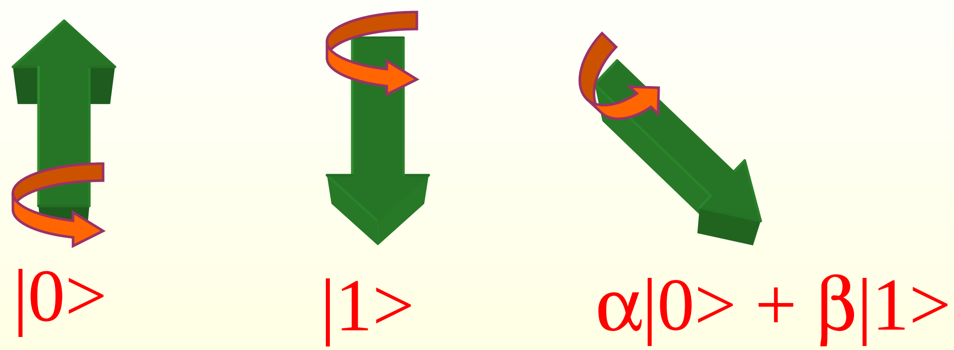
- Qubits using coherent spin states in quantum dots – quantum networks

Quantum Semiconductor Spintronics

Classical Bit (Boolean)   0 or 1   Two states

Quantum Bit (Qubit) $\alpha|0\rangle + \beta|1\rangle$ "Infinite" number of states

Where $(\alpha^2 + \beta^2) = 1$

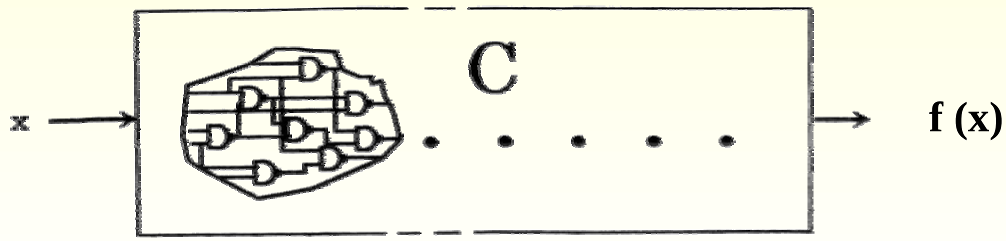


"n Qubits is worth 2^n Boolean bits"

Quantum Spintronics

“Intel”

10,000,000 Bits



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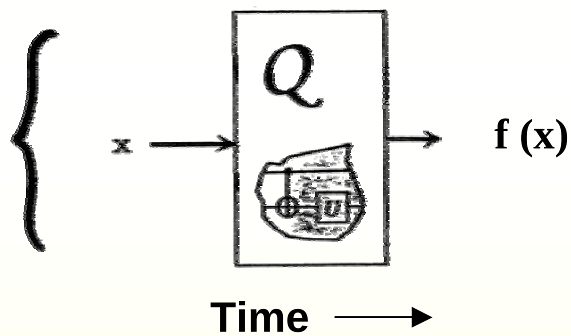
“Quintel”

30 Qubits



Factoring: *Given integer* ***N****, find integers* ***p*** *and* ***q*** *such that* ***N=pq****.*
Exponential Speedup: $2^{N^{1/2}} \longrightarrow N^2$

Optimization: Given algorithm for computing a function ***g****, find input* ***s*** *such that* ***g(s)*** *is minimal.*
Quadratic Speedup: $2^k \longrightarrow 2^{k/2}$

Quantum Spintronics

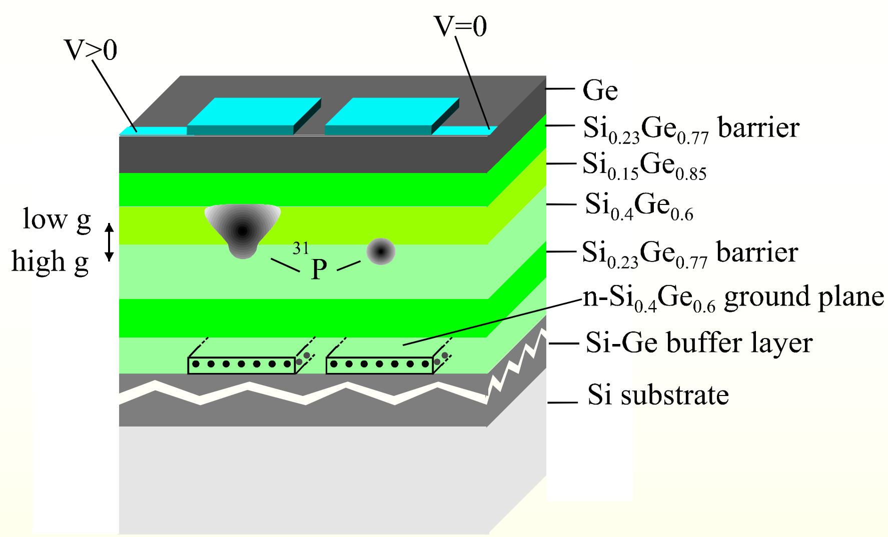
Qubit Implementations

- **Electron-Spin Resonance Transistor (ESRT):**

- **Long Dephasing Times (msec)**

- **High Switching Speed (GHz)**

- **Uses Silicon Technology And quantum dot expertise**



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I predict that there will be SPINS in your future