Shallow Donors in Silicon as Electron and Nuclear Spin Qubits

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Overview

- Electronics – The end of Moore’s law?
- Quantum computing
- Spin qubits
- Relaxation
- Manipulation
- Readout
- FEL EPR
(Gordon) Moore’s law

"The number of transistors incorporated in a chip will approximately double every 24 months."
Spintronics

- Electronics depends on the charge of the electron
- Using the spin: spin transport electronics


Datta-Das Spin Field Effect Transistor
Spintronics device

MRAM

- Universal Memory

**MTJ**
insulating space layer
current perpendicular to plane

- Ferromagnetic electrode 1
- Tunneling barrier
- Ferromagnetic electrode 2

spin-polarized current
un-polarized current

first ferromagnetic electrode acts as spin filter
second FM layer acts as spin detector

**MagRAM Architecture**

Reading a bit

Writing "1"

Writing "0"

- MTJ MagRAM promises
  - density of DRAM
  - speed of SRAM
  - non-volatility

S.S.P. Parkin
December 16, 1998
Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don’t know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there’s no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain.

Peter Shor:
Factorization of a prime number can be solved in many fewer steps in a quantum computer. (1994)
Requirements

• Scalable quantum system that:
  o Can represent quantum information robustly (long-lived: long relaxation times)
  o Perform transformations (operations)
  o Prepare an initial state
  o Measure the results

SPINS

Magnetic moment of electron and nuclear spins is ‘isolated’ from the surroundings
Proposed schemes

- Superconductor-based quantum computers (including SQUID-based quantum computers)\(^{[18]}\)
- Trapped ion quantum computer
- Optical lattices
- Topological quantum computer\(^{[19]}\)
- Quantum dot on surface (e.g. the Loss-DiVincenzo quantum computer)
- Nuclear magnetic resonance on molecules in solution (liquid NMR)
- Solid state NMR Kane quantum computers
- Electrons on helium quantum computers
- Cavity quantum electrodynamics (CQED)
- Molecular magnet
- Fullerene-based ESR quantum computer
- Optic-based quantum computers (Quantum optics)
- Diamond-based quantum computer\(^{[20]}[21][22]\)
- Bose–Einstein condensate-based quantum computer\(^{[23]}\)
- Transistor-based quantum computer - string quantum computers with entrainment of positive holes using an electrostatic trap
- Spin-based quantum computer
- Adiabatic quantum computation\(^{[24]}\)
- Rare-earth-metal-ion-doped inorganic crystal based quantum computers\(^{[25]}[26]\)
Quantum Computing

Bit

1 or 0

QuBit

$\Psi = \cos(\theta)|0> + \exp^{-i\phi}\sin(\theta)|1>$

2 bits: 4 states: 00, 01, 10, 11

2 qubits: $|00>, |01>, |10>, |11>$,

$1/\sqrt{2} \ (|00> + |11>), 1/\sqrt{2} \ (|00> + |01>), \ldots$

$1/2 \ (|00>-|01>+|10>-|11>), \ldots$
The EPR phenomenon

\[ H = \mu_B B \cdot g \cdot S + S \cdot D \cdot S + \sum_j S \cdot A \cdot I_j - \gamma_n I_j B + \sum_k J S_k \cdot S + S_k \cdot T_{\text{dip}} \cdot S \]

Zeeman  Hyperfine structure  Exchange

Fine Structure  Nuclear Zeeman  Dipolar

\[ m_S = +1/2 \]

\[ m_S = -1/2 \]

\[ I = 1/2 \]

Energy  Magnetic Field (T)
Change the reference frame

- In the lab frame
  - Procession around $B_0$

- In the rotating frame ($\omega$)
  - Procession around $B_1$

\[
\frac{dM(t)}{dt} = \gamma M(t) \times B(t)
\]
What is pulse EPR/NMR?

A spin echo seen in the rotating frame

Relaxation parameters

$T_1$ Spin-lattice relaxation time

$T_2$ Spin-memory time, spin-spin relaxation time
Relaxation

\[ \Psi = \cos(\theta)|0> + \exp^{-i\phi}\sin(\theta)|1> \]

Loss of $\theta$: $T_1$ (Energy)
Spin Lattice Relaxation
Longitudinal Relaxation

Loss of $\varphi$: $T_2$ (Phase)
Spin-Spin relaxation
Phase relaxation
Spin memory time
Coherence time
Quantum Dot QC

Loss and DiVincenzo, PRB ‘98

Elzerman, Kouwenhoven et al. (Delft University of Technology)

“Single-shot read-out of a Spin Qubit”
Electron Spin Resonance in quantum dots

Vandersypen et al. "Quantum Computing and Quantum Bits in Mesoscopic Systems", Kluwer
Shallow donors

Periodic Table of Elements

Legend - click to find out more...

- **Li** - solid
- **Br** - liquid
- **Tc** - synthetic

- Transition Metals
- Rare Earth Metals
- Halogens
- Alkali Earth Metals
- Other Metals
- Inert Elements

Fig. 1 - (Color) Electron probability density on the (001) plane of bulk Si for the ground state of a donor in Si within the Kohn-Luttinger effective mass theory. The white dots give the in-plane atomic sites.
\[ H = g u_B \vec{S} \cdot \vec{B} - \gamma_n \vec{B} \cdot \vec{I} + a \vec{S} \cdot \vec{I} \]

\[ S_z I_z + \frac{1}{2}(S^+ I^- + S^- I^+) \]

\[ + \text{ } ^{29}\text{Si} \ldots \]

4 CNOT gates

Universal set of quantum gates
Kane’s model

Tuning the hyperfine

- Dreher et al. PRL 106, 037601 (2011)
• $T_1$ exponential temp. dependence: shallow donor excited state
• $T_2$ is constant $\sim 200$-$300$ $\mu$s due to $^{29}$Si
• No field/frequency dependence up to 95 GHz down to 7 K

130 K $= 11.2$ meV
Temperature dependence $T_1$, $T_2$

- In $^{28}$Si samples $T_{2e}$ is limited by dipolar interactions
**Strong TRIPLE enhancement**

The pulsed $^{31}$P TRIPLE spectrum in both Davies and Mims ENDOR is much stronger than the pulsed ENDOR itself, due to the slow relaxation of the nuclear spins. After a typical Davies-ENDOR sequence, followed by electron-spin $T_1$ decay, the populations of the levels end up as shown below – after the electron spin inversion pulse, the RF pulse has no effect.
$^{31}$P free induction decay, measured by "ENDOR"

The pulsed-ENDOR sequence can be used to both induce the nuclear polarization and to detect the NMR signal of the $^{31}$P nuclei. The repetition rate is slow with respect to the electron spin $T_1$, but fast with respect to the nuclear $T_1$. The first RF pulse induces the free-induction decay, the second translates the nuclear coherence to a population difference, and is detected with the pulsed ENDOR sequence.
“NMR” echo, detected on EPR/ENDOR signal (10 K)

→ Nuclear coherence time $T_{2N}$ seems to be close to $T_{1e}$
Si:P  ([P] \sim 10^{15}-10^{16}) Below 20 K no conduction electrons: Nicely isolated from surroundings
Long relaxation times

\begin{itemize}
  \item T_{1e} exponential temp. dependence: shallow donor excited state
  \item T_{2e} is constant \sim 200-300 \mu s due to $^{29}$Si
  \item No field/frequency dependence up to 95 GHz
  \item The $^{31}$P nuclear $T_{1N}$ relaxation rate at these temperatures and at 0.35 T is about 2 orders of magnitude slower than $T_{1e}$, while the nuclear $T_{2N}$ of the phosphorus spins is limited by the spin-lattice relaxation rate of the electron spins ($T_{2N}\sim T_{1e}$)
\end{itemize}
$^{29}$Si ENDOR from different shells. Strongly coupled Si relax much slower than the weakly coupled Si.

In principle they could add another qubit to the system.
High-field dynamic nuclear polarization at $h\nu >> kT$

Creation of close to 100% polarized initial state
Polarization decay after 5 min irradiation in high-field transition at 240 GHz

Initialization/Relaxation of nuclear spin polarization
The relaxation to equilibrium spin polarization is well described with a single exponential. The temperature dependence indicates a thermally excited process with an energy close to the electron spin Zeeman splitting at these fields. No polarization is achieved by saturation of the low-field hyperfine component.
Bismuth in Silicon

- $I=9/2$
- Relaxation times similar to phosphorus
- Much larger hyperfine splitting $\rightarrow$ individual addressing
- Larger valley orbit splitting
- 20 states: 4 qubits at once?
Another candidate: Bi in Si

Electron Nuclear Double Resonance and coherent manipulation

Bismuth is the heaviest stable element. It has a large nuclear spin $\frac{9}{2}$ -> More information can be stored

*Nature Materials* 9, 725 (2010)
What about Read-out?

- Long relaxation times
- Initialization
- Manipulation
- Readout ??
  - Read-out is usually destructive
  - Magnetic resonance is not very sensitive $10^9$ spins
Detection

MOSFET: spin-dependent recombination
High frequency advantage: Boltzmann populations
Electrical detection of Magnetic Resonance (Read out)

- Electrical detection can be very sensitive
- At low frequencies a $P_b$ (surface) center is involved
  - In order to measure a current we use light excitation to create carriers
    - $T_1$ is shortened, $T_2$ more or less unchanged
EDMR spectra

Up to 10% current changes on phosphorus resonance

McCamey et al., PRB 2008
Coherence?

- At low frequency the electrically detected spin coherence lasts for ~2 μs due to fast recombination of electron-hole pairs.
- At high frequency the main mechanism is dominated by spin traps -> longer coherence times.

\[ \text{Morley et al, PRL 101 (2008)} \]
Light Induced Nuclear Polarization

McCamey et al. PRL 102 (2009)
Storage of information

• Use the nuclear spin to store electron spin

Electrical storage and readout of spin information

A minute or so...

How strong is the spin dependent current
Slices pulses from microseconds to nano-seconds
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