Spins and Topology for Quantum Information Applications

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1. Approaching the limits of conventional electronics

2. Spintronics and spin-based quantum devices

3. Topological matter: Discovering new phases, tailoring new particles

4. Topological quantum computing

5. Summary
The team

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Dr. Mohammad Yahyavi  
(Postdoc, Jan. 2020)

Electrical Control of Majorana Bound States Using Magnetic Stripes  

Signatures of Topological Superconductivity in Josephson junctions  
(Work in progress)

Detecting Topological Superconductivity by Using a dc-SQUID  
(Work in progress)

Synthetic Spin-Orbit Memristor: Concept Development  
(Work in progress)

Fault-Tolerant Topological Quantum Computing with Majorana Bound States in Josephson-Junction Arrays

Teaching at WSU:

- Introduction to Modern Physics
- Applied Computational Methods
- Introduction to Quantum Computing

Research in Theoretical Condensed Matter:

- Spintronics
- Topological Phases of Matter
- Solid-State Quantum Computing
Evolution of Logic Electronics

1947
Physics Nobel Prize 1956
J. Bardeen, W. Brattain, W. Shockley

1971
Intel 4004

2015
SPARC M7
IBM5150 1981
CPU@ 4.77 MHz

Boeing 757 (1982)
Cruising speed: 530 mph

More than 500 times

2016 Laptops
CPU@ 2.5 GHz – 4 GHz

FROM THE EARTH TO THE MOON

In less than 1 hour!!!
Approaching the limits of conventional electronics

1969
Apollo 11 Mission

Apollo Guidance Computer (AGC)
64 KB @ 0.043 MHz

IBM System/360 Model 75
1024 KB & 41 MB/s

2018
Smartphones

Any smartphone nowadays has much larger memory capacity and is much more powerful than the computers used in the Apollo 11 mission altogether
Approaching the limits of conventional electronics

Current challenges:

• Increasing heat & power consumption.
• Increasing cost (we run out of money before we run out of physics)
• Ultimate physical limit to miniaturization: We will have to change the rules of the game
Ways out:

• Improve performance by optimizing the device architecture (short lasting solution).

• Revolutionize the “hardware” by implementing an alternative to conventional electronics. → Spintronics (longer lasting solution)

• Revolutionize both “hardware” and “software” by changing the conceptual basis on which classical computing operates. → Quantum computing (ultimate solution)
Magnetic moment

\[ \vec{\mu} = -\frac{|e|}{mc} \vec{S} \]

**Spintronics and spin-based quantum devices**

- **e** charge - classical property
- **\( \vec{S} \)** spin - quantum property \( (\pm \frac{\hbar}{2}) \)

- **“1” (\( \uparrow \)): spin up state**
- **“0” (\( \downarrow \)): spin down state**

**SPIN** \( \rightarrow \) **Magnetism**
Spintronics (spin electronics)

Why not using the spin degree of freedom of the carriers?

Natural advantages of using the spin

- Low energy consumption
- Non volatility
- High integration between logic and memory
- High speed


Giant Magnetoresistance (GMR) and Tunneling Magnetoresistance (TMR)

The Nobel Prize in Physics, 2007

Albert Fert    Peter Grünberg

GMR discovered in 1988

- In 1997 GMR was in magnetic hard drives
- Stuart Parkin, Millenium Technology Prize 2014

In 2004 TMR started to replace GMR
Spintronics and spin-based quantum devices

Spin lasers

Spin batteries

Spin solar cells

Spin photodiodes

Spin Transistor

Spin LEDs

TMR sensors & memories


T. Taniyama et al. Asia Mater. 3, 65 (2011)

J. Sinova et al. Nat. Mater. 11, 368 (2012)

Ultimately, there are certain problems that, for practical purposes, can’t be solved in a classical computer. The need of quantum computers in the future seems inevitable.

Prime factorization problem

• Every integer number can be broken down into prime number factors, e.g. 15 = 5x3, 12 =3x2x2, etc.

• Given the prime factors, finding the number is an easy problem, one just need to multiply the factors.

• Given the number, finding the prime factors is a hard problem. The time a classical computer needs to find the prime factors of the number $N$ scales exponentially with $\ln(N)$. However, the time it takes a quantum computer to solve the problem is polynomial in $\ln(N)$. If $N$ is sufficiently large the prime factorization becomes intractable for a classical computer, while a quantum computer could still quickly find the prime factors.
Spintronics and spin-based quantum devices

Classical bits

\[ 0 \quad \text{or} \quad 1 \]

Quantum bits (qubits)

\[ c_1 |0\rangle + c_2 |1\rangle \]

\[ P_0 = |c_1|^2 \]

\[ P_1 = |c_2|^2 \]

\( n \) qubits encode as much information as \( 2^n \) bits!

A register with \( n \) qubits may contain more integer numbers (\( 2^{500} \)) than the number of atoms in the known universe (\( \sim 2^{330} \))!

Unlike a classical bit, the state of a single qubit is not 0 or 1 but a superposition of 0 and 1 (i.e. 0 and 1 at the same time). Therefore, a \( n \)-qubit quantum computer can do operations involving the equivalent of \( 2^n \) bits in parallel (i.e., at once). This quantum parallelism allows a quantum computer to solve certain class of problems much faster than a classical computer. Quantum computers can also solve certain problems that are completely intractable with a classical computer.

**Example**: Finding a secret number
Google 53-qubit quantum computer solved a problem in 200 seconds that the most powerful supercomputer in the world (IBM’s Summit) will need 10,000 years (according to Google) or 2.5 days (according to IBM) to solve it.
Spintronics and spin-based quantum devices

Companies Developing Quantum Computing Devices

- IBM
- Google
- IonQ
- Quantum Circuits, Inc (QCI)
- Rigetti
- Intel
- Microsoft

IBM Q Experience provide open access to some of their quantum computers

Research division on topological quantum computing but no actual quantum computer yet. Partnering with IonQ and QCI will provide access to quantum computers through Microsoft Azure cloud service
General idea:
Use the interaction between spin and magnetic field texture to control the motion and state of electrons

Remarks:
• Magnetic textures can lead to quasiparticle confinement
• Magnetic textures produce synthetic spin-orbit coupling

Requirements for magnetic textures to be used in quantum device applications:
• Inhomogeneity at the nanoscale
• Tunability at the nanoscale

Spintronics to the rescue

- Use fringe fields of spin valve arrays
- Modulate the texture by spin valve switching

Spintronics and spin-based quantum devices
Probability density (normalized to its maximum) of ground state for a 5-nanopilar array on a (Cd,Mn)Te two-dimensional electron gas (2DEG)
Quantum Computing with Quantum Dots

Spintronics and spin-based quantum devices
Synthetic Spin-Orbit Memristor: A Theoretical Proposal

Artificial Neural Networks for AI

Topology is a branch of mathematics concerned with spatial properties preserved under continuous deformation. It is a characterization of geometric objects on the basis of continuous transformations rather than on their specific shapes or form.

Example: A coffee mug and a donut are topologically equivalent.

Example: Three topologically non-equivalent objects.
Topological classes are characterized by topological invariants (topological numbers).

Gauss-Bonnet Theorem \rightarrow \text{Number of holes as a topological invariant}

\begin{align*}
  n = 0 & \quad \text{annulus} \\
  n = 1 & \quad \text{torus} \\
  n = 2 & \quad \text{Klein bottle} \\
  n = 3 & \quad \text{double torus}
\end{align*}
Topological matter: Discovering new phases, tailoring new particles

Nobel Prize 2016

D. J. Thouless  F. D. M. Haldane  J. M. Kosterlitz

Topological Phase Transitions

Example of topological changes of a material

<table>
<thead>
<tr>
<th>No. of holes</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Integer Quantum Hall Effect

Nobel Prize 1985

Klaus von Klitzing

\[ \sigma_{xy} = \frac{I_x}{V_y} = \nu \frac{e^2}{h} \]

\[ \nu = 0, 1, 2, \ldots \]

Accuracy of 1 in a billion!!!
1. Dissipationless edge (surface states)
2. Spin-momentum locking
3. Massless Dirac fermions (Cond. Mat. meets Special & General Relativity)

Magnetic control of carriers motion
Electric generation of spin polarization
Electric generation of spin currents

Experimental signatures of topological transition in the presence of a magnetic field:

B Scharf, A Matos-Abiague, J Fabian, Physical Review B 86 (7), 075418
B Scharf, A Matos-Abiague, I Žutić, J Fabian, Physical Review B 91 (23), 235433
Topological Superconductors

- New properties
- Not found in nature but can be artificially engineered
- Support Majorana bound states

Research goals:
- Explore new phases of matter in heterostructures with proximity effects
- Identify new phenomena and their signatures
- Investigate potential applications

Review Article:
Topological matter: Discovering new phases, tailoring new particles

**Particle Physics**

- Discover of new particles
- Need of ever higher energies (Currently in the order of TeV)
- Use collisions to break down interactions and decompose particles into smaller ones

**Condensed Matter Physics**

- Discover of new quasiparticles
- Need very low energy excitations (Currently from meV to μeV)
- Integrate various interactions to build new quasiparticles
Exotic Quasiparticles in Condensed Matter Physics

- Skyrmions (as magnetic textures)
- Dirac Fermions (graphene, topological insulators)
- Weyl Fermions (Weyl semimetals)
- Composite Fermions (Fractional Quantum Hall systems)
- Anyons (excitations in Fractional Quantum Hall systems)
- Majorana Modes (Topological superconductors)
- Parafermions (Fractional Quantum Hall systems & Topological superconductors)
- ...
Majorana fermions are their own antiparticles

\[ \gamma^\dagger = \gamma \]

E. Majorana, Il Nuovo Cimento 14, 171 (1937)

Majorana: Real Field

Dirac: Complex Field

Majorana Bound States:
- Zero energy pairs of degenerate states
- Protected by energy gap

1. Chargeless
2. Spinless
3. Massless

Majoranas in Kitaev’s chain

A. Y. Kitaev, Phys. Usp. 44, 131 (2001)
Conventional Qubits vs Topological Qubits

**Conventional Qubits:**
- Information is stored locally and qubits are fragile
- Local perturbations can cause errors
- Large amount of error corrections needed

**Topological Qubits:**
- Information is stored non-locally
- Qubits are protected against local perturbations
- Small or no error corrections needed
Braiding Operations for Fault-Tolerant Topological Quantum Computing

Matrix depends only on the topology of the braid swept out by anyon world lines!

Robust quantum computation?

Kitaev, ‘97 ; Freedman, Larsen, and Wang, ‘01
MRAM-like architecture for fault-tolerant topological quantum computing

(d) A. D. Kent et al., Nat. Nanotech. 10, 187 (2015)
Goal: To develop theoretical prototypes of wireless quantum circuits by using topological superconductors

Remarks:
• The effective topological wires are reconfigurable and programmable, and so is the circuit
• The circuit is non-volatile
• If coupled to an artificial neural network of magnetic nanopillars the circuit can become intelligent

A $n$-terminal quantum device can support $2^n$ different connectivity patterns
How to induce a topological phase transition from the trivial superconducting to the topological superconducting state?

How to measure such a transition?

In the topological superconducting phase, two Majorana states form at the ends of the N region.

Phase Signature of Topological Transition in Josephson Junctions

• First experimental realization of self-tuned phase transition into the topological superconducting state
• First clear signatures of topological superconductivity by two different measurements

Theory developed @ WSU

Experiment @ NYU

Closing and re-opening of the superconducting gap

Self-tuned phase jump

Scientists discover new state of matter

by James Devitt, New York University

Further theoretical developments @ WSU

- Joseph Pakizer (Master)
  Topological superconductivity in proximitized transition metal dichalcogenide Josephson junctions (APS March meeting, 2020)

- Benjamin Hawn (Undergrad)
  Detecting topological superconductivity by using a dc-SQUID (APS March meeting, 2020)
Available Financial Support

Engineering Topological States Using Electrically-Tunable Magnetic Chains
WSU, NYU, SUNY Buffalo

Nanoelectronics with Proximitized Materials
WSU, SUNY Buffalo
Spintronics uses the spin degree of freedom in addition to charge to provide faster and less energy consuming devices for both memory and logic. Typical examples are spin valves, which applications range from sensors to magnetic random access memories.

The coupling of spin to a tunable magnetic texture produced by an array of magnetic tunnel junction nanopilars provides new possibilities for controlling electronic states.

Topological phases (e.g., topological insulators and superconductors) are protected against local perturbations and can therefore encode quantum information immune to the undesired effects of the environment. In particular, Majorana modes are very promising for the implementation of fault-tolerant topological quantum computing.

Reconfigurable magnetic textures could be used for building a versatile architecture for topological quantum computing and for the design of programmable, intelligent quantum circuits.

Join us!

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