Probabilistic Computing with Nanomagnets

Kerem Y. Camsari
Post-Doctoral Researcher

Supriyo Datta Group

Collaborators: Samiran Ganguly, Shehrin Sayed, Behtash Behin-Aein, Brian M. Sutton, Zhihong Chen
We established a modular, “spin-circuit” framework connecting experiments to devices and circuits.

Kerem Camsari
https://nanohub.org/groups/spintronics
Modular Approach to Spintronics

We established a modular, “spin-circuit” framework connecting experiments to devices and circuits.

Kerem Camsari  https://nanohub.org/groups/spintronics
We established a modular, “spin-circuit” framework connecting experiments to devices and circuits.
We established a modular, “spin-circuit” framework connecting experiments to devices and circuits.
We established a modular, “spin-circuit” framework connecting experiments to devices and circuits.
We established a modular, “spin-circuit” framework connecting experiments to devices and circuits.

Kerem Camsari

https://nanohub.org/groups/spintronics
We established a modular, “spin-circuit” framework connecting experiments to devices and circuits.

Kerem Camsari

https://nanohub.org/groups/spintronics
Connecting *Experiments to Spin-Circuits*

Gao et al., IEDM (2012) (Chen / Appenzeller)

Kerem Camsari  [https://nanohub.org/groups/spintronics](https://nanohub.org/groups/spintronics)
Connecting *Experiments to Spin-Circuits*

Gao et al., IEDM (2012) (Chen / Appenzeller)

**Recently emerging: Spin Hall / Valley Hall in 2D Systems**


[https://nanohub.org/groups/spintronics](https://nanohub.org/groups/spintronics)
Recently emerging: Spin Hall / Valley Hall in 2D Systems


\[ R_{NL} = \frac{\theta^2 \rho W \left( \exp \left( \frac{-L_3}{\lambda} \right) \right)}{2\lambda} \]

Balakrishnan, J et al., Nature Physics (2013)

Gao et al., IEDM (2012) (Chen / Appenzeller)
Connecting Experiments to Spin-Circuits

Recently emerging: Spin Hall / Valley Hall in 2D Systems

Approach allows direct comparison with experiments and with other theoretical methods.

Kerem Camsari
https://nanohub.org/groups/spintronics
Leveraging Emerging Physics: Pure Spin Conduction

Multi-physics integration of emerging physics with existing “building blocks” leads to new devices
Leveraging Emerging Physics: Pure Spin Conduction

PSC Module = Pure Spin Conductor, e.g YIG

Sayed et al., in review (2016)

Multi-physics integration of emerging physics with existing “building blocks” leads to new devices

Kerem Camsari

https://nanohub.org/groups/spintronics
Leveraging Emerging Physics: Pure Spin Conduction

PSC Module = Pure Spin Conductor, e.g. YIG

Sayed et al., in review (2016)

Multi-physics integration of emerging physics with existing “building blocks” leads to new devices

Kerem Camsari
https://nanohub.org/groups/spintronics
Evaluating Spintronic Alternatives to CMOS
Evaluating Spintronic Alternatives to CMOS

\[ E \times \tau = Q^2 R \]

PMA
\[ \Delta = 60 \, kT \]
\[ H_K^{\text{eff}} = 0.5 \, T \]
\[ M_S V/\mu_B = 1 \times 10^5 \]

CMOS
\[ Q \approx 750 \text{ electrons} \]
\[ W_{\text{eff}} = 56 \, \text{nm} \]

FinFET

Kerem Camsari  
https://nanohub.org/groups/spintronics
Evaluating Spintronic Alternatives to CMOS

No clear alternative to CMOS exists yet, dynamic landscape involving spins & magnets calls for a modular approach

Kerem Camsari  
https://nanohub.org/groups/spintronics
Beyond CMOS: Probabilistic **Magnets**

**Magnets: Many Flavors**

- **Hysteresis:**
  - Non-volatile
  - DETERMINISTIC
  - Boolean

- **Stochastic**
  - PROBABILISTIC

- **Quantum**

**Deterministic, Spin-Switch**

\[ U = 60 \, \text{kT} \]

- Number of spins:
  - \( N_s \approx 1e5 \)
  - \( K_u V = 60 \text{kT} \)

- \( N_s \approx 1e4 \)
  - \( K_u V = 6 \, \text{kT} \)

- \( N_s \approx 1 \)
  - \( K_u V \approx 0 \, \text{kT} \)

Kerem Camsari  
https://nanohub.org/groups/spintronics

PURDUE UNIVERSITY
Beyond CMOS: Probabilistic Magnets

Magnets: Many Flavors

- **Hysteresis:**
  - Non-volatile
  - **DETERMINISTIC**
  - **Boolean**
- **Stochastic**
  - **PROBABILISTIC**
- **QUANTUM**

Number of spins

- $N_s \approx 1e5$
- $K_u V = 60kT$

- $N_s \approx 1e4$
- $K_u V = 6 \text{ kT}$

- $N_s \approx 1$
- $K_u V \approx 0 \text{ kT}$

$U = 60 \text{ kT}$

Magnets as natural hardware ranging from Classical to Quantum: The intermediate regime is probabilistic

Kerem Camsari
https://nanohub.org/groups/spintronics
“Ising Computers” Using Magnets

4x4 Ising Lattice

Behin-Aein et al. (2016) Pre-print

WRITE

READ

$U = 6 \ kT$

Kerem Camsari

https://nanohub.org/groups/spintronics
Ising Lattices can be mimicked using interacting Spin-Switches, involving probabilistic magnets.

\[ U = 6 \, kT \]

Temperature: \( T_c \)

Heat Capacity: 

**References:**

Behin-Aein et al. (2016) Pre-print

**Resources:**

[https://nanohub.org/groups/spintronics](https://nanohub.org/groups/spintronics)
Traveling Salesman Problem using Magnets
Solving (TSP) using a 5x5 Ising Computer, offers unique advantages due to probabilistic magnets

Sutton et al. (2016) Pre-print

https://nanohub.org/groups/spintronics
“Atoms to Systems” using Modular Approach

Modular Approach to Spintronics

Kerem Camsari  
https://nanohub.org/groups/spintronics
“Atoms to Systems” using Modular Approach

New Physics/Experiments

Modular Approach to Spintronics

Kerem Camsari

https://nanohub.org/groups/spintronics
“Atoms to Systems” using Modular Approach

New Physics/Experiments

Theory: Quantum to Semi-Classical Transport, LLG

Modular Approach to Spintronics

Kerem Camsari
https://nanohub.org/groups/spintronics
"Atoms to Systems" using Modular Approach

New Physics/Experiments

Theory: Quantum to Semi-Classical Transport, LLG

CMOS Alternatives

Kerem Camsari

https://nanohub.org/groups/spintronics
“Atoms to Systems” using Modular Approach

New Physics/Experiments

Theory: Quantum to Semi-Classical Transport, LLG

Modular Approach to Spintronics

Oscillators / Sensors / MEMS

CMOS Alternatives

Kerem Camsari

https://nanohub.org/groups/spintronics
“Atoms to Systems” using Modular Approach

New Physics/Experiments

Theory: Quantum to Semi-Classical Transport, LLG

Oscillators / Sensors / MEMS

CMOS Alternatives

Grand Challenge: Creating “Brain-like” Systems

Kerem Camsari

https://nanohub.org/groups/spintronics