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Virtual, October 10-21, 2020

CAS

Spintronic/CMOS-Based Thermal Sensors

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Agenda

- **Distributed MTJ-based thermal aware systems**
- **Magnetic tunnel junctions**
- **Thermal sensor figures of merit**
- **MTJ vs CMOS transistor as thermal sensor**
- **Proposed CMOS/MTJ thermal sensors**
- **Distributed MTJ/CMOS sensor network**
- **Summary**

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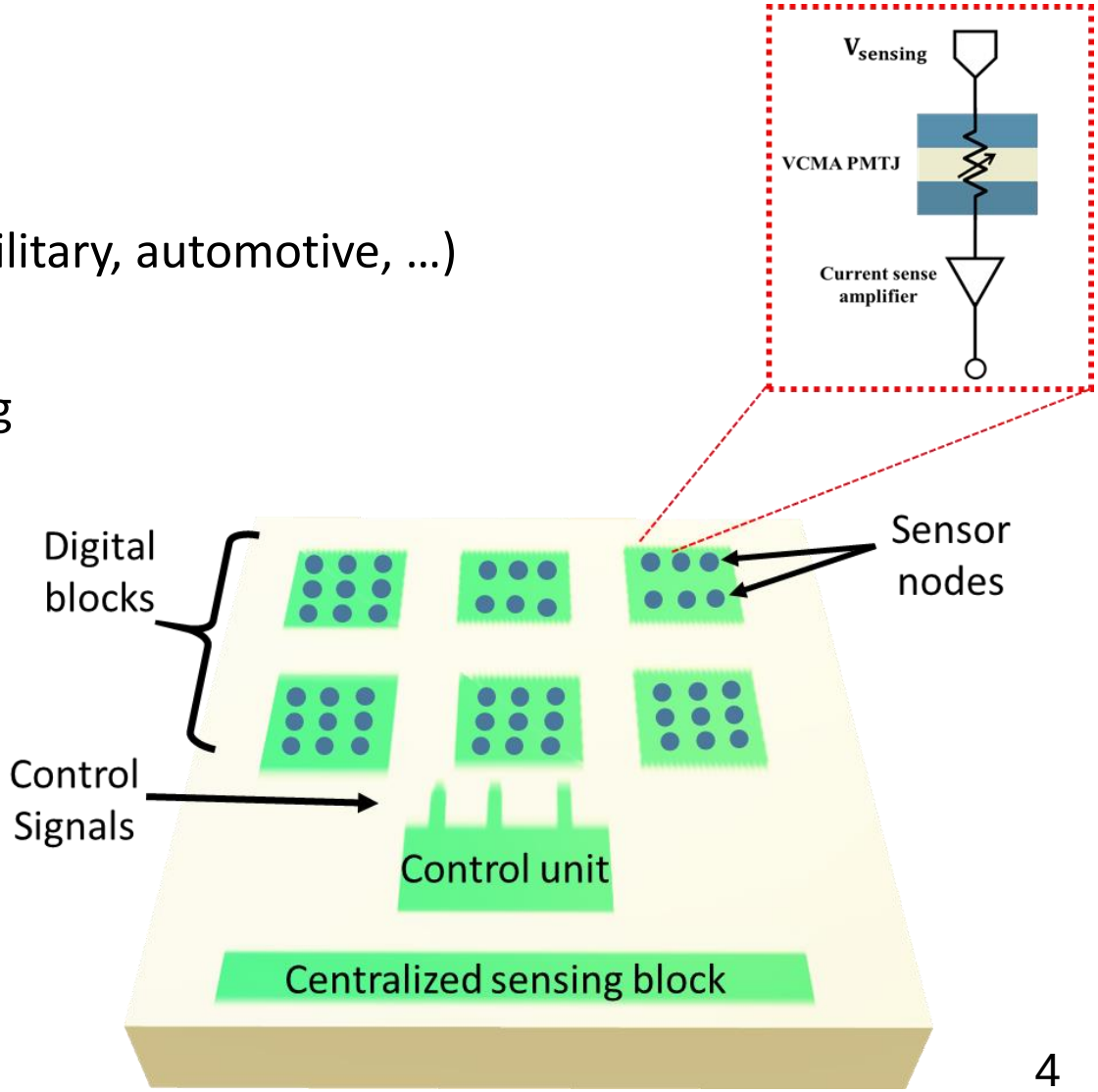
Distributed MTJ-Based Thermal Aware Systems

- Low power
- Small area
- Fast response
- Wide temperature range (military, automotive, …)
- Good linearity
- Stability with thermal cycling
- Sensor calibration capability



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- On-chip thermal monitoring
- **Magnetic tunnel junctions**
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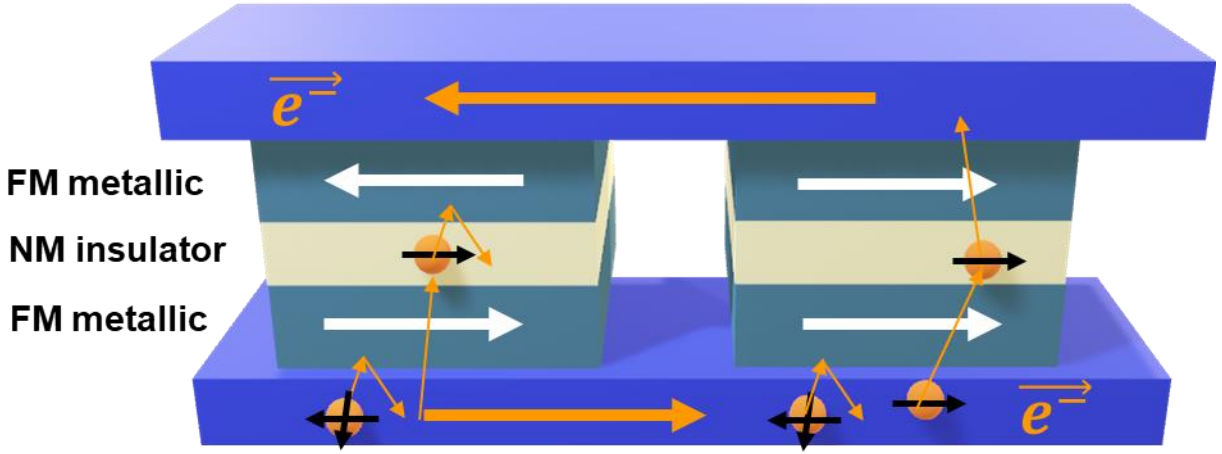
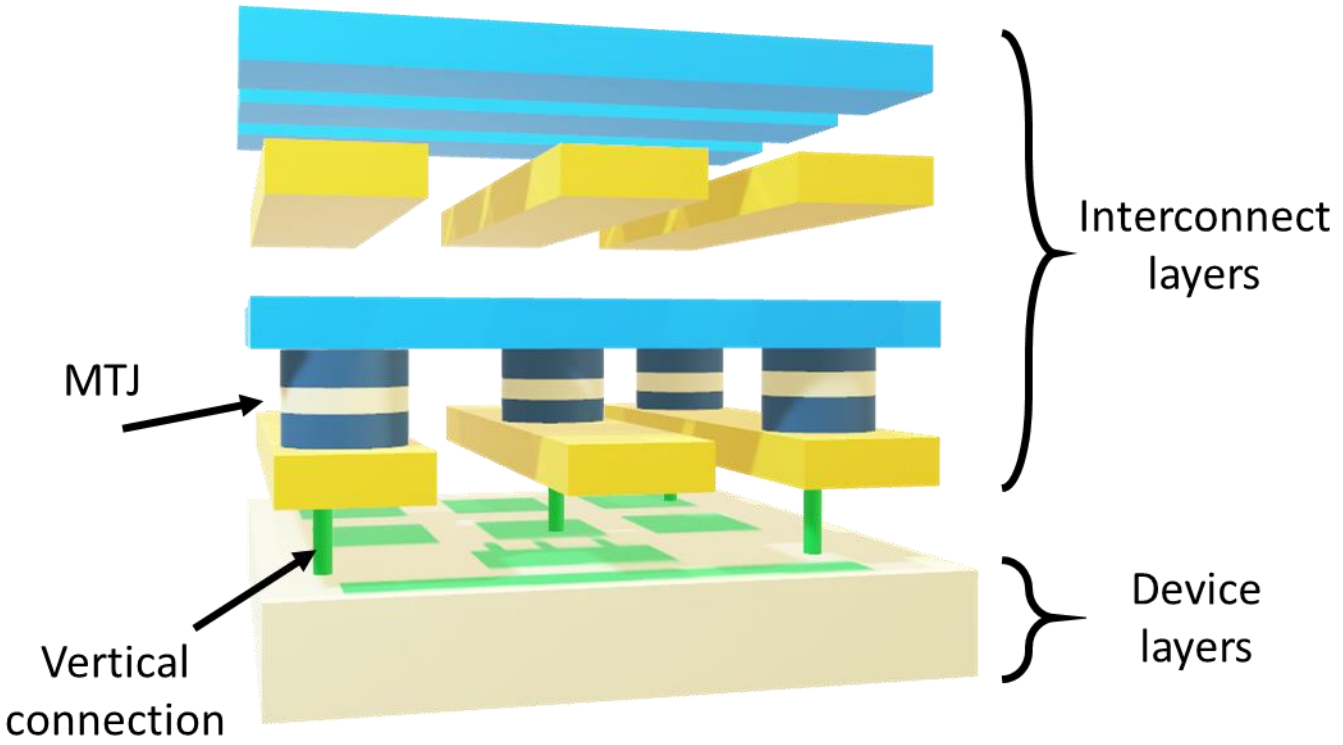
Magnetic Tunnel Junctions (MTJ)



$$TMR = \frac{G_P - G_{AP}}{G_{AP}}$$

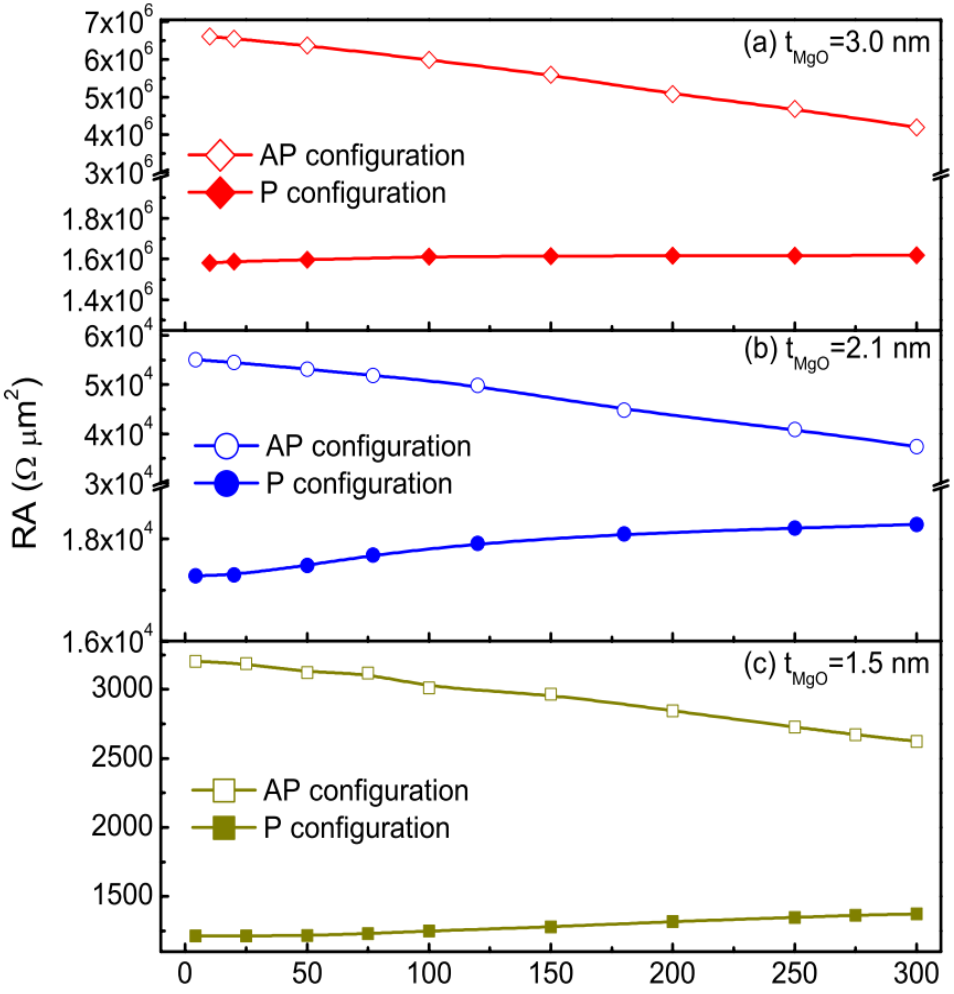
TMR: Tunneling magnetoresistance
FM: Ferromagnetic
NM: Nonmagnetic
G_P: Parallel conductance
G_{AP}: Antiparallel conductance

Compatibility of MTJ with CMOS Technology



MTJ Parallel and Antiparallel States

- MTJ temperature dependence
  - Device material
  - Physical size
  - Fabrication method
    - Thermal relaxation
    - Annealing
- MTJ parallel resistance R_P
  - Almost independent of temperature
- MTJ antiparallel resistance $R_{AP}(T.V)$
  - Decreases with temperature
  - Changes with applied voltage



Q. L. Ma *et al.*, "Temperature Dependence of Resistance in Epitaxial Fe/MgO/Fe Magnetic Tunnel Junctions," *Applied Physics Letters*, vol. 95, no. 5, pp. 4–6, July 2009

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Thermal Sensor Figures of Merit

- Temperature Coefficient of Resistance (***TCR***)
  - ***TCR*** measures relative change of thermal resistor to temperature
  - Higher ***TCR***
    - Better thermal sensitivity

- Linearity ($\boldsymbol{R^2}$)
  - $\boldsymbol{R^2}$ measures linearity change of thermal resistor to temperature
  - Higher $\boldsymbol{R^2}$
    - Less need for additional circuitry to predict temperature

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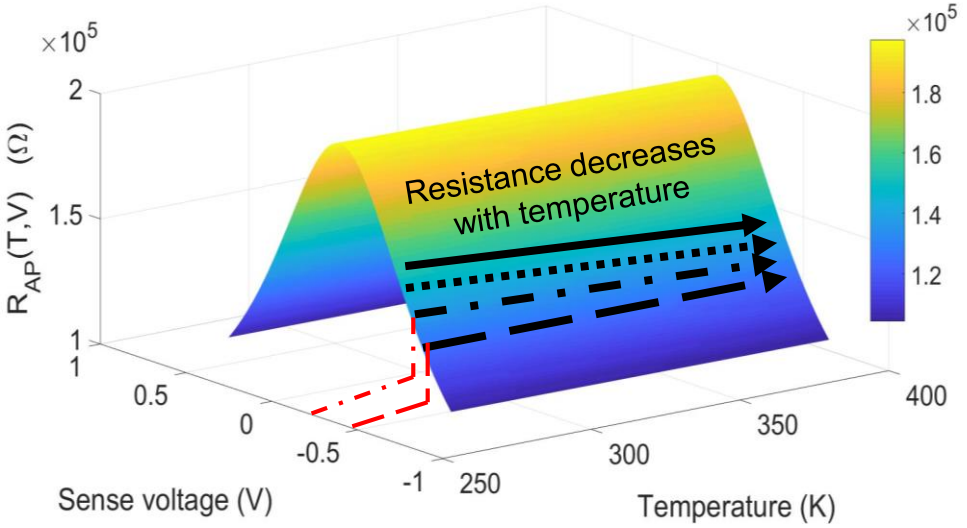
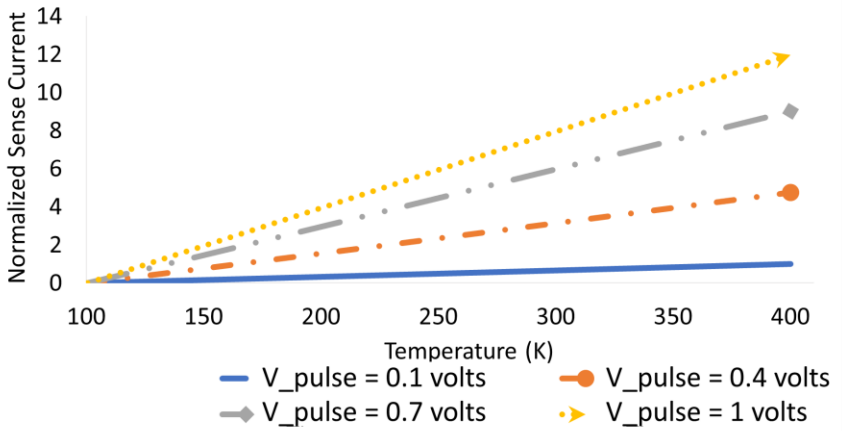
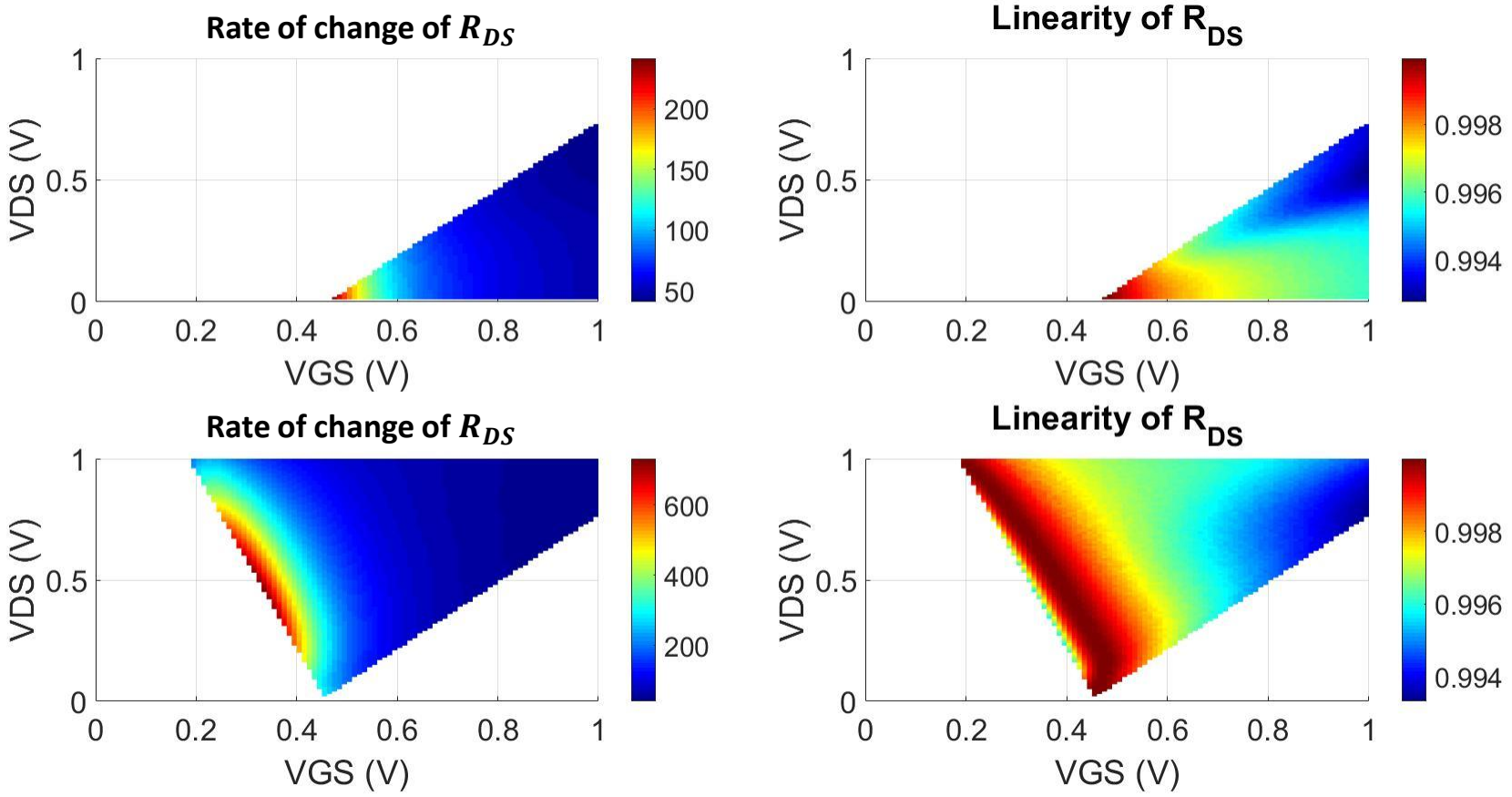
Thermal Behavior of MTJ





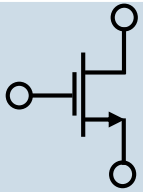
- Linear behavior
  - Gradual change in resistance with temperature

Thermal Behavior of CMOS Transistor



- Simulations at temperature range (0 to 85)^{o}C

Comparison of Thermal Characteristics of MTJ and CMOS

	MTJ	CMOS
Symbol		
TCR	-8 × 10^{-5} 1/°C	53 × 10^{-4} 1/°C
R^2	0.99999	0.9992
$\partial R/\partial T$	-4 ohm/K	600 ohm/K
Characteristics	Less sensitive to bias point	Sensitive to biasing point
	Above device layer	Within device layer
	Almost linear with temperature	Exponential with temperature
Benefits of merging both	• Sensor above device layer • Linear with temperature • Small size	

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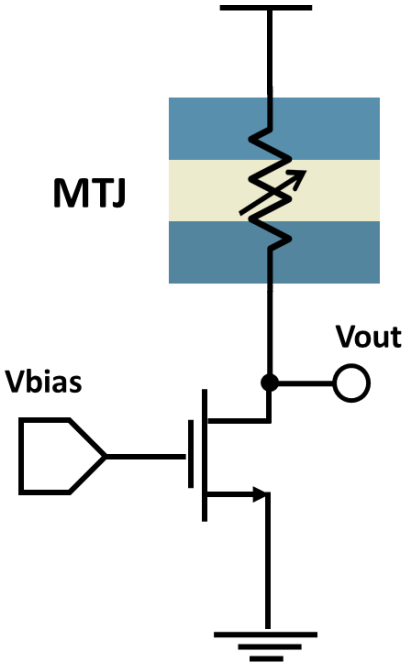
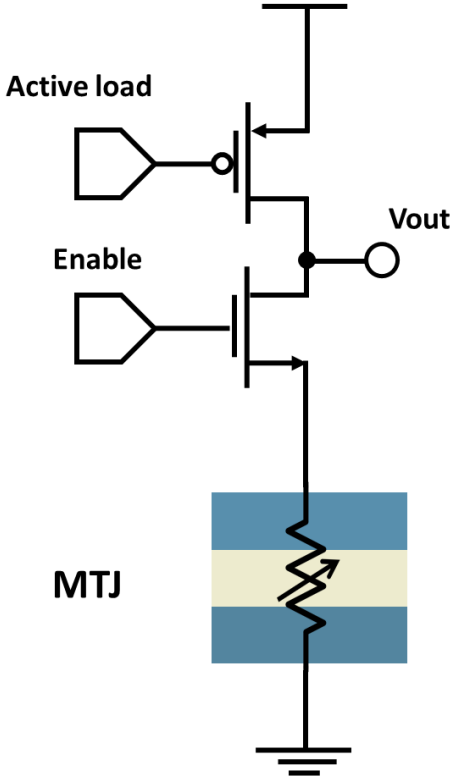
Proposed CMOS/MTJ Thermal Sensors



Hybrid I



Hybrid II

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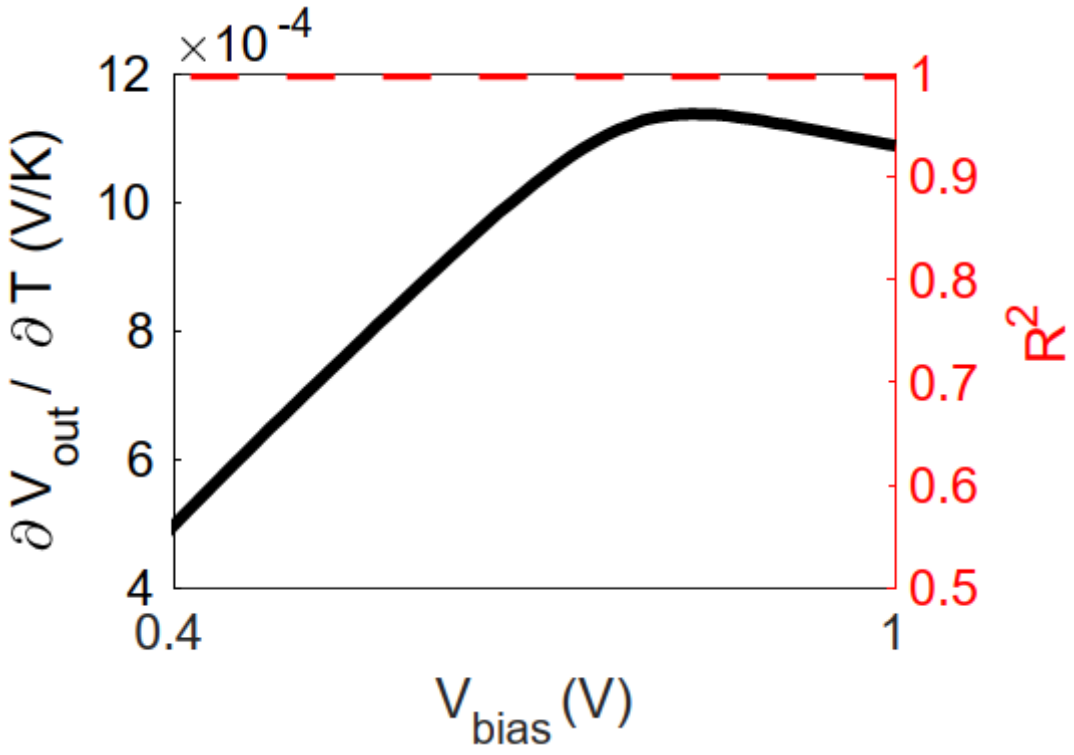
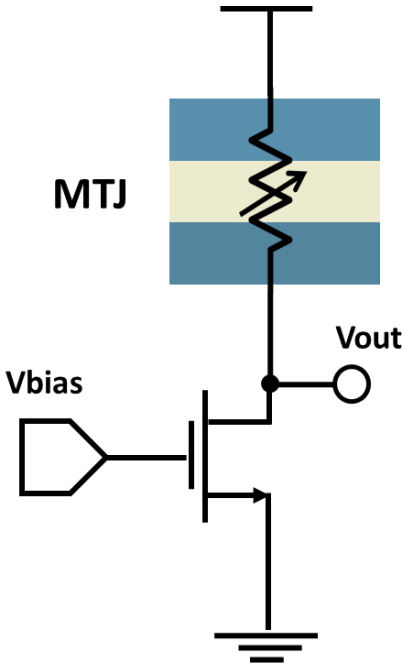
Hybrid I, MTJ/CMOS Sensor





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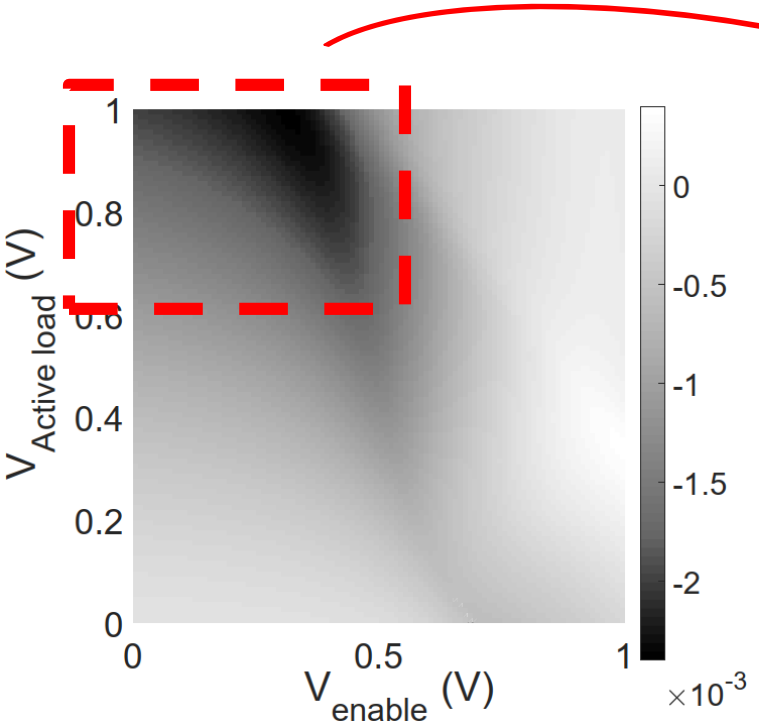
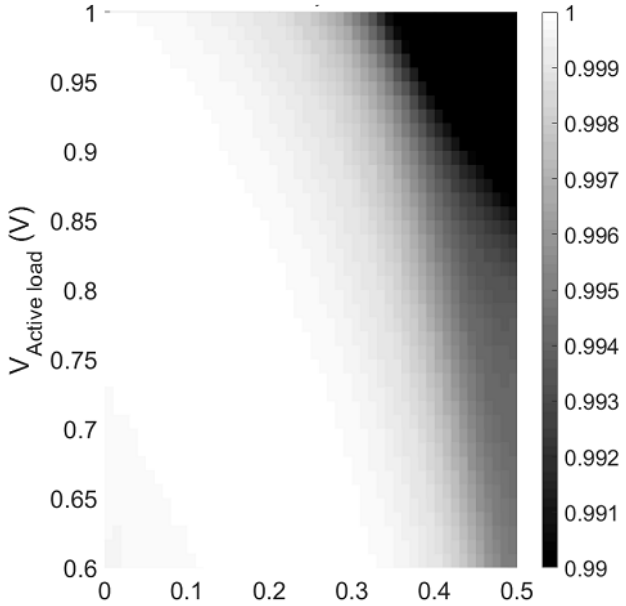
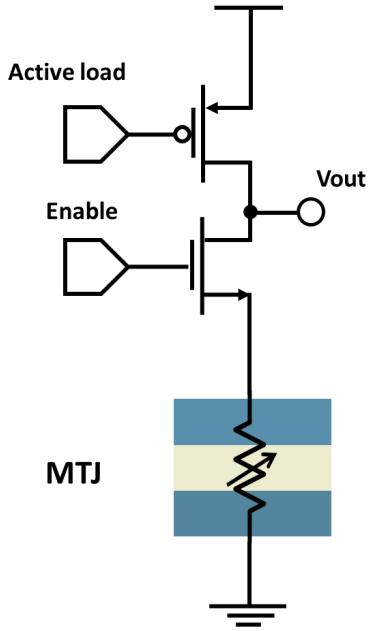
Hybrid II, MTJ/CMOS Sensor



$$\frac{\partial V_{out}}{\partial T}$$

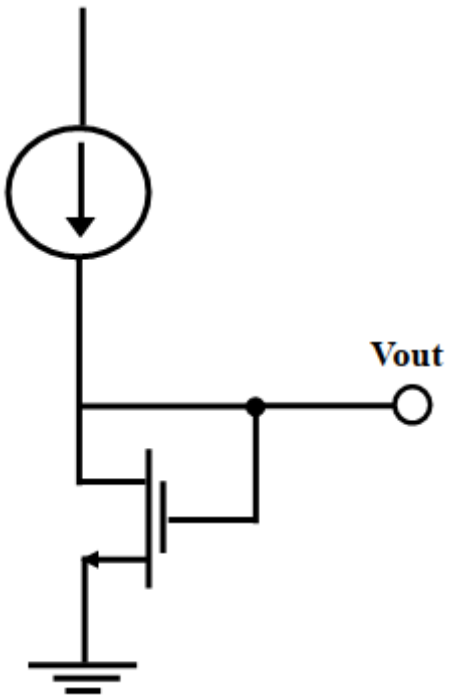


$$R^2$$

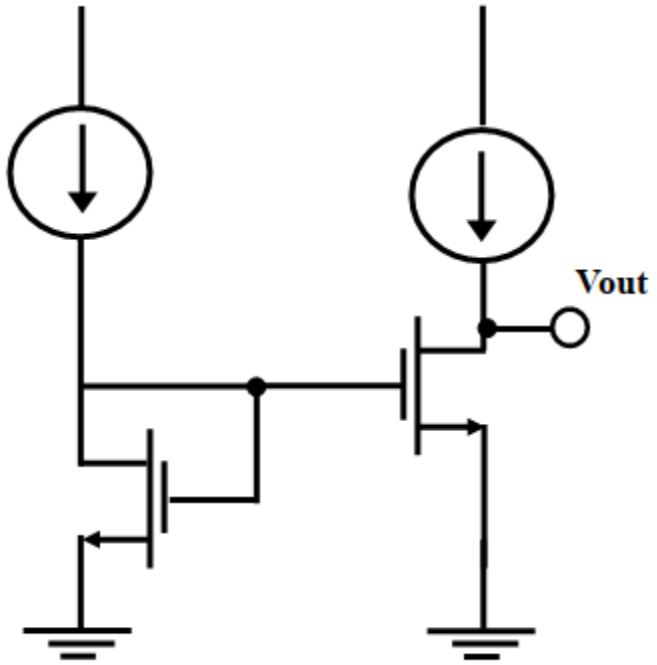


- Simulations at temperature range (0 to 85)^{o}C

Conventional CMOS Sensor

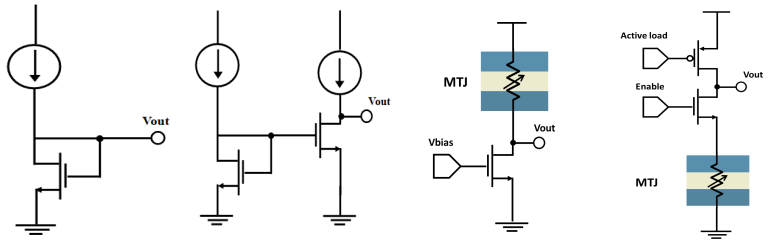


CMOS I



CMOS II

Comparison of MTJ Sensor with Conventional CMOS Sensors



		CMOS I	CMOS II	Hybrid I	Hybrid II
Sensitivity mV/K	Commercial (0 to 85) °C	0.51	0.51	0.4	1.91
	Industrial (-40 to 100) °C	1.03	1.03	0.64	3.78
	Automotive (-40 to 125) °C	1.08	1.08	0.77	3.97
	Military (-55 to 125) °C	1.35	1.35	0.81	4.8
Linearity	Commercial (0 to 85) °C	0.985	0.985	1.0	0.983
	Industrial (-40 to 100) °C	0.953	0.953	0.999	0.96
	Automotive (-40 to 125) °C	0.941	0.941	0.999	0.947
	Military (-55 to 125) °C	0.919	0.919	0.996	0.936
Power Consumption at 27°C (μW)		40	80	18	11.9
Area (μm^2)		4 X	8 X	1 X	2 X

Simulation performed for T ranged 0:85 °C

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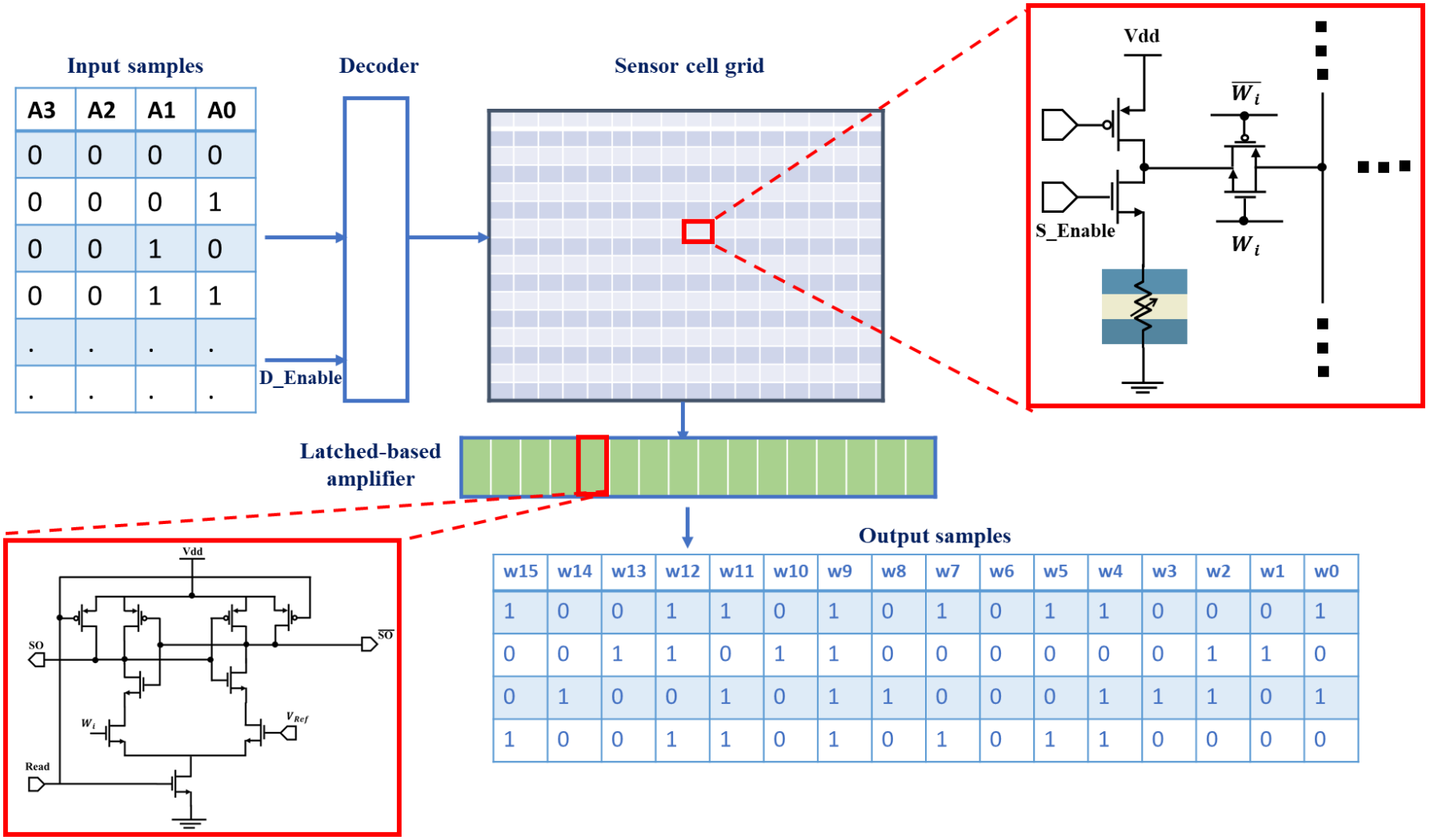
Distributed MTJ/CMOS Sensor Network



Proposed System for Different Grid Sizes

System size	Energy consumption (pJ)	Relative path delay to read the grid w.r.t 4x4	System size #	
			Transistor	MTJs
4 x 4	1.32	1 X	90	16
8 x 8	8.96	2 X	304	64
16 x 16	65.5	4 X	1,120	256
32 x 32	499	8 X	4,980	1,024

1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0
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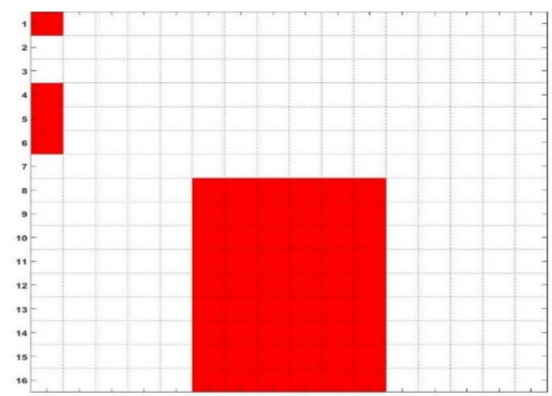
0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0
0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0



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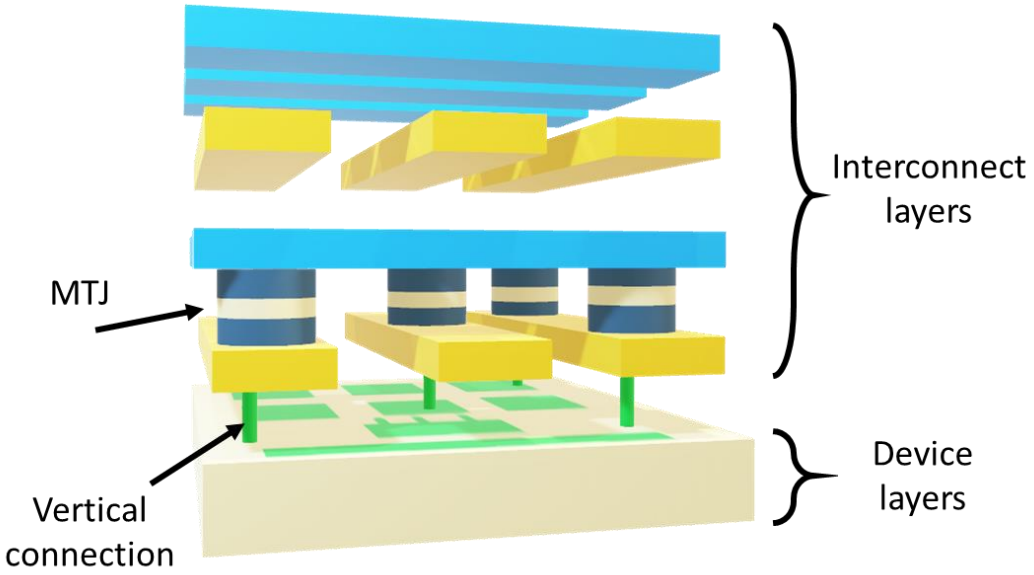
Summary

- Need for small size, low power distributed thermal monitoring system
- Antiparallel resistance of MTJ strongly sensitive to temperature
- Proposed two MTJ/CMOS sensors
  - Sensitivity of 3.78 mV/K and Linearity of 0.96 over (-40 to 125) ^{o}C
- MTJs distributed throughout thermal network
  - Consuming 500 pJ to read 1,024 sensors



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Thanks