

**PAST**



Semiconductor Research Corporation

Pioneers in Collaborative Research®

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About

**Mission:** Carrying CMOS to its ultimate limits and beyond, keeping the United States and its industries at the forefront of technology, *i.e.*, "scaling"



In a world increasingly reliant on technology, SRC research will move in **new directions** to address challenges for industries adjacent to semiconductors. New SRC research efforts will lead to innovation in energy, security and healthcare.

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#### Our Research Programs



GRC

Global Research Collaboration



FCRP

Focus Center Research Program

FCRP focuses on carrying CMOS to its ultimate limits and beyond, keeping the United States and its industries at the forefront of technology.



NRI

Nanoelectronics Research Initiative

#### New Research Programs

#### NEWS & PRESS RELEASES

Feb 02, 2011



##### NOTICE: SRC website to be offline for server maintenance

Routine web server maintenance between 10 AM Saturday February 12 and 8 AM Sunday Feb 13. » [Read More](#)

Jan 17, 2011



##### TECHCON 2011 - Call for Abstracts

The TECHCON 2011 call for abstracts is now open. Deadline is February 22 at 3:00 p.m. ET. » [Read More](#)

Jan 24, 2011

SRC and Stanford Develop Unique Combination of Elements for

Jan 11, 2011

Potential opportunities for nanotechnology in electronics

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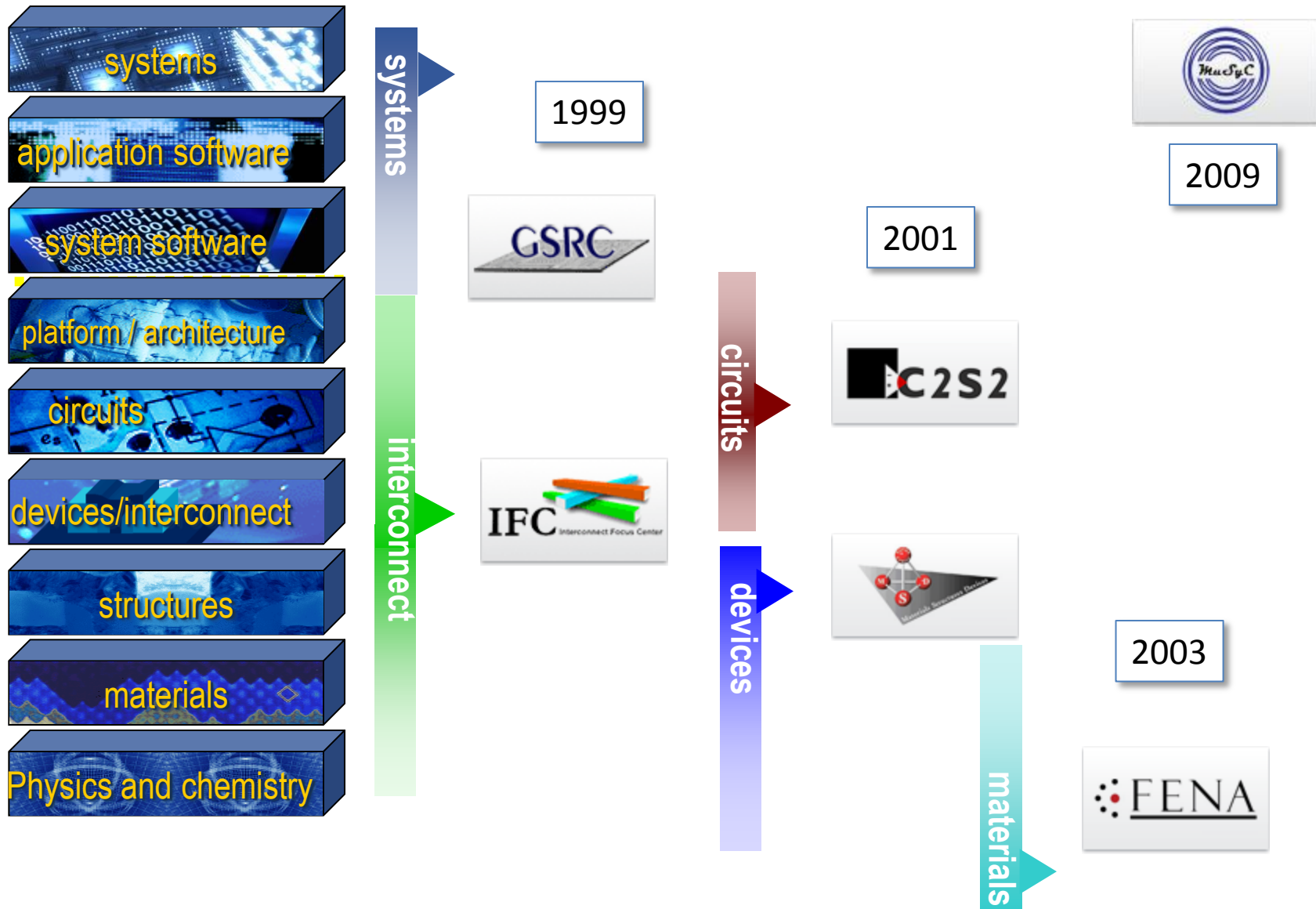
#### RESEARCH FUNDING OPPORTUNITIES



SRC funnels millions of dollars to research teams at universities worldwide. Visit our [research funding opportunities](#)

Internet

# FCRP Center Evolution

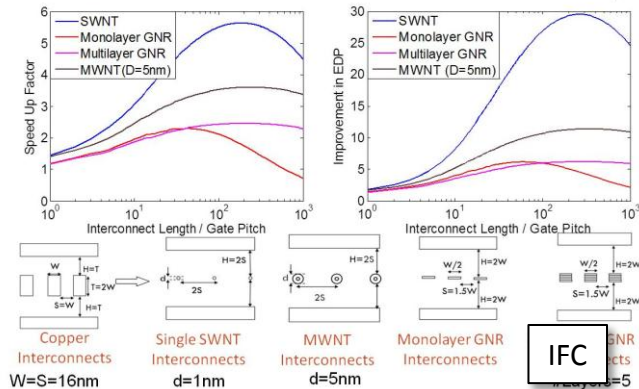


# **PRESENT**

# Example Projects

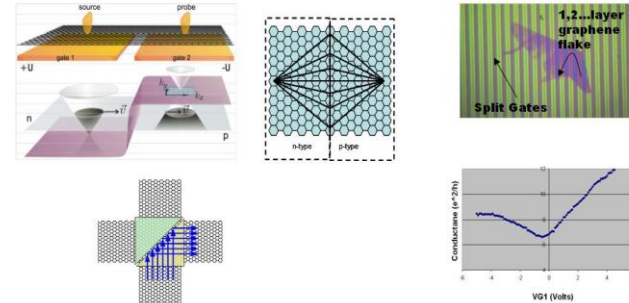
Task 5.1.2 Interconnect Options for Subthreshold Circuits (16 nm Technology Node)

Naeemi (GaTech)



23

Use the unique electronic structure of graphene to demonstrate optics-like manipulation of electrons: focusing and reconfiguration

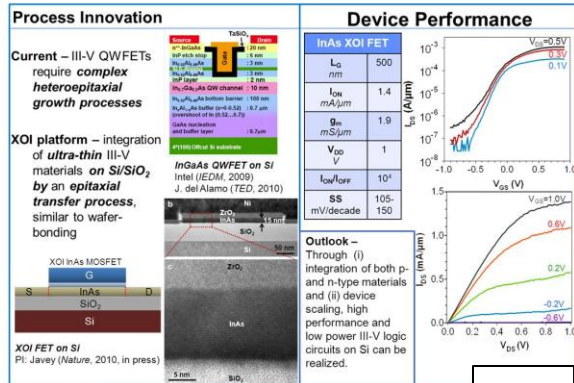


Use graphene as a reconfigurable wire in a CMOS circuit based on electron reflection at a p-n junction conductor

Asymmetry is a measure of p-n dopant profile match model

IFC & NRI

## Compound Semiconductor on Insulator (XOI)

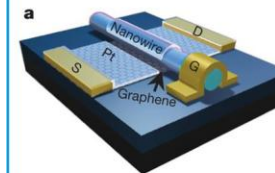


Javey group, UCB

MSD

## RF FET >300GHz using Graphene

- $f_t=300\text{ GHz}$
- $f_{\text{max}}=500\text{ GHz}$



High-speed graphene transistors with a self-aligned nanowire gate

nature

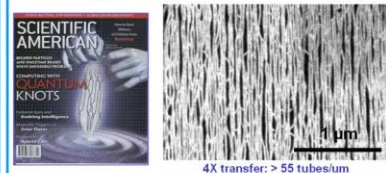
Full text access provided to University of Twente

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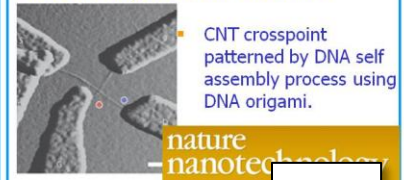
Volume 461 7 June 2015 Letters

Loi Lian, Yung Chen Lin, Mingming Shen, Ralf Chiriac, Jingwei Bai, Yuan Liu, Yongqian Gu, Xiang L. Wang, Yu Huang & Xiangdong Duan

## Super High Density CNTs > 60 tubes/ $\mu\text{m}$



## DNA CNT Alignment and Placement



FENA

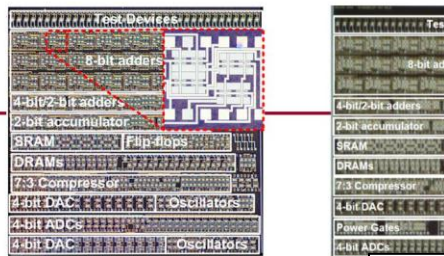
Source: FCRP Highlights, Nov 2010



# Example Projects

## NEMS/MEMS Relay Logic Circuits

- Circuits based on micro-mechanical “switch” controlled by electro-static voltages
- Adders, flip-flops, memories, DACs, ADCs have been fabricated and demonstrated

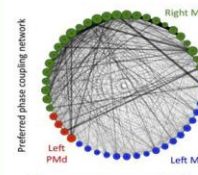


C2S2

## Communication in Brain Networks

**Unsolved problem:** Network coordination in brain

**Possible answer:** Coordinated action via neuronal oscillations



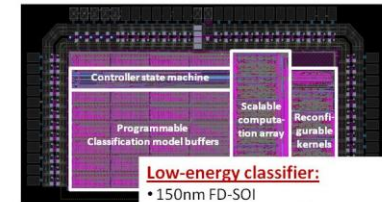
**Result:** Detected network of coupled neural oscillators that help predict firing rates of individual neurons

PL: Carmena

MuSync

Closed loop (*intelligent*) implantables:  
10-100μW budget

**Key Direction:** Machine-learning based  
embedded/implanted devices

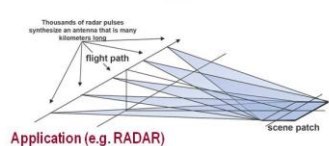


### Low-energy classifier:

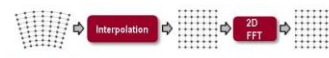
- 150nm FD-SOI
- Programmable classification models
- Programmable features
- Reconfigurable computation
- ~100x energy reduction

GSRC

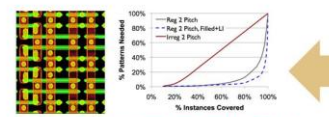
## Affordable Application-Specific Systems



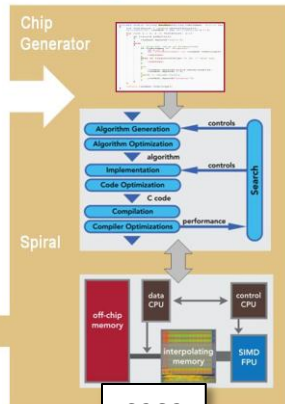
Application (e.g. RADAR)



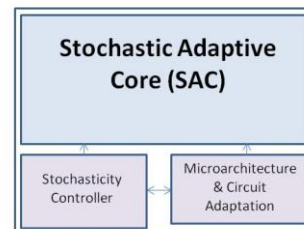
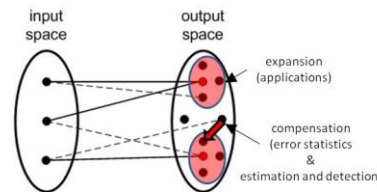
Algorithm-Specific Architectures and Memories



Customized Memory and Logic on Limited Set of Pattern Constructs

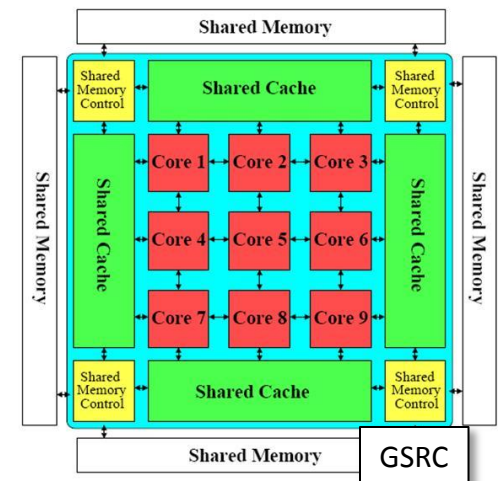


C2S2



(Workload, Environment)

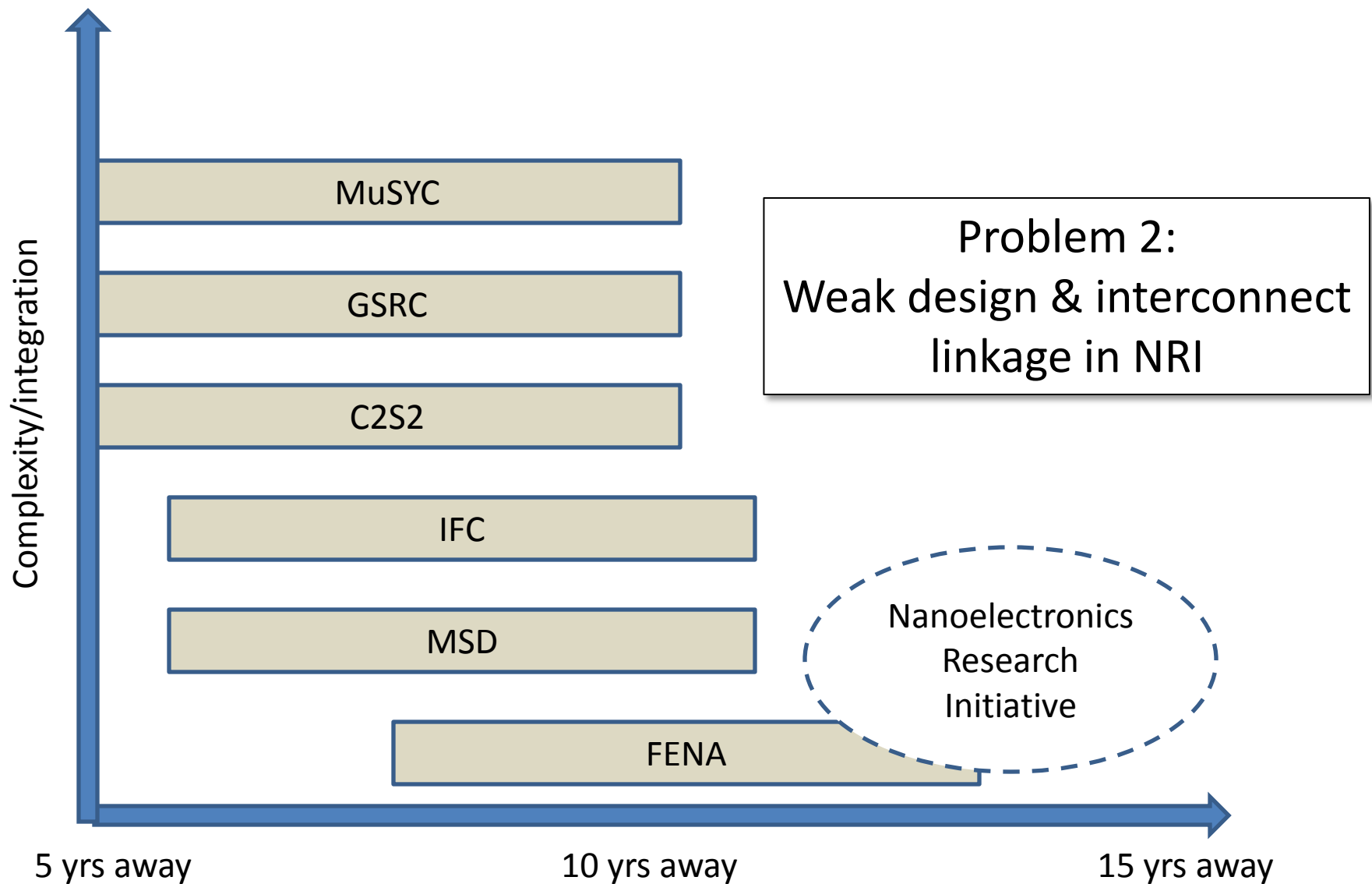
GSRC



GSRC

**WE GAVE YOU WHAT YOU ASKED FOR,  
WHAT'S THE ISSUE?**

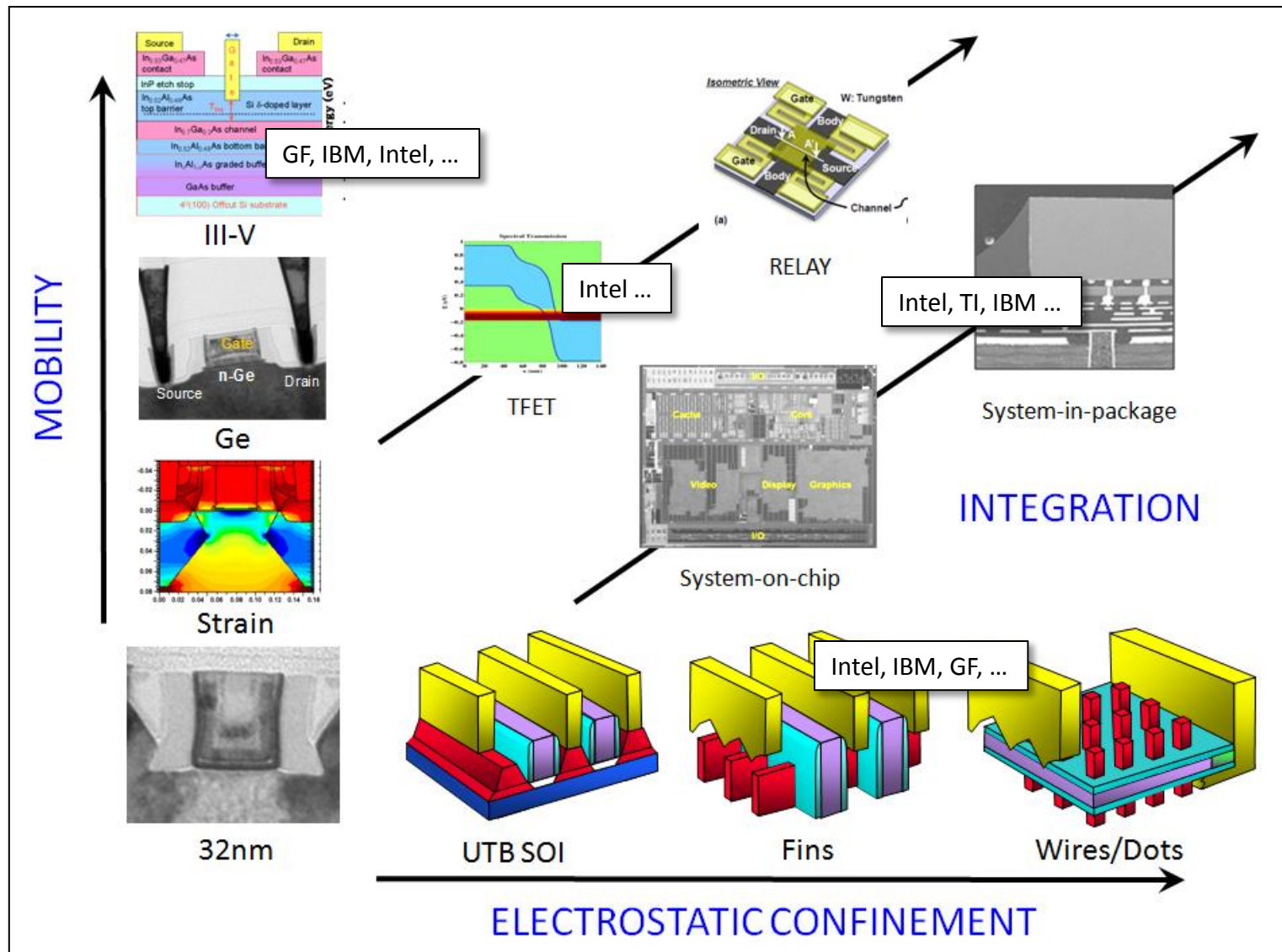
*YOU WILL MISS OPPORTUNITIES IF YOU  
ONLY LOOK FOR BETTER VERSIONS OF  
TODAY'S TECHNOLOGY AND PRODUCTS*



**Problem 1:**  
Industry research catching up to current FCRP research



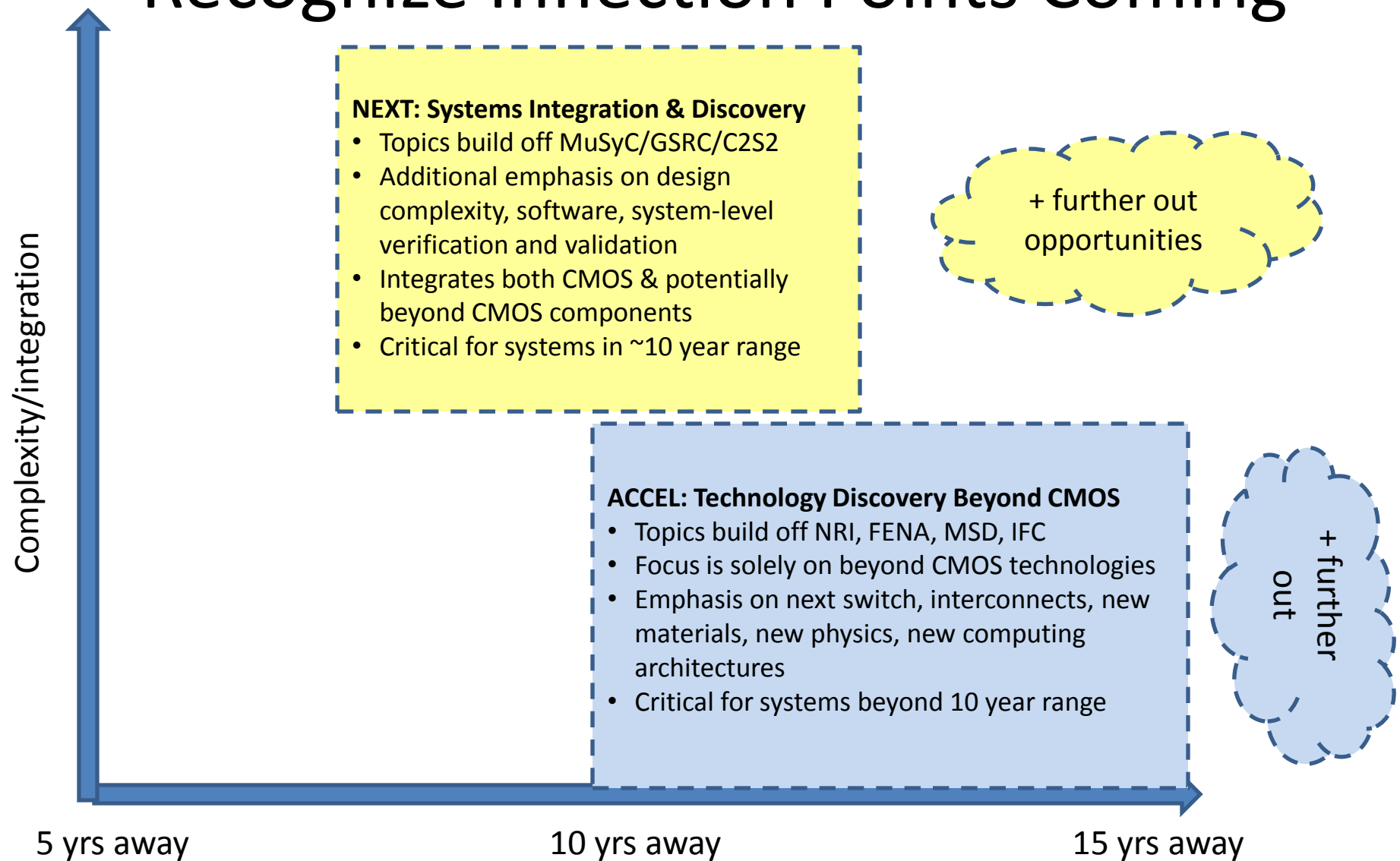
# Example: FCRP research becoming industry research



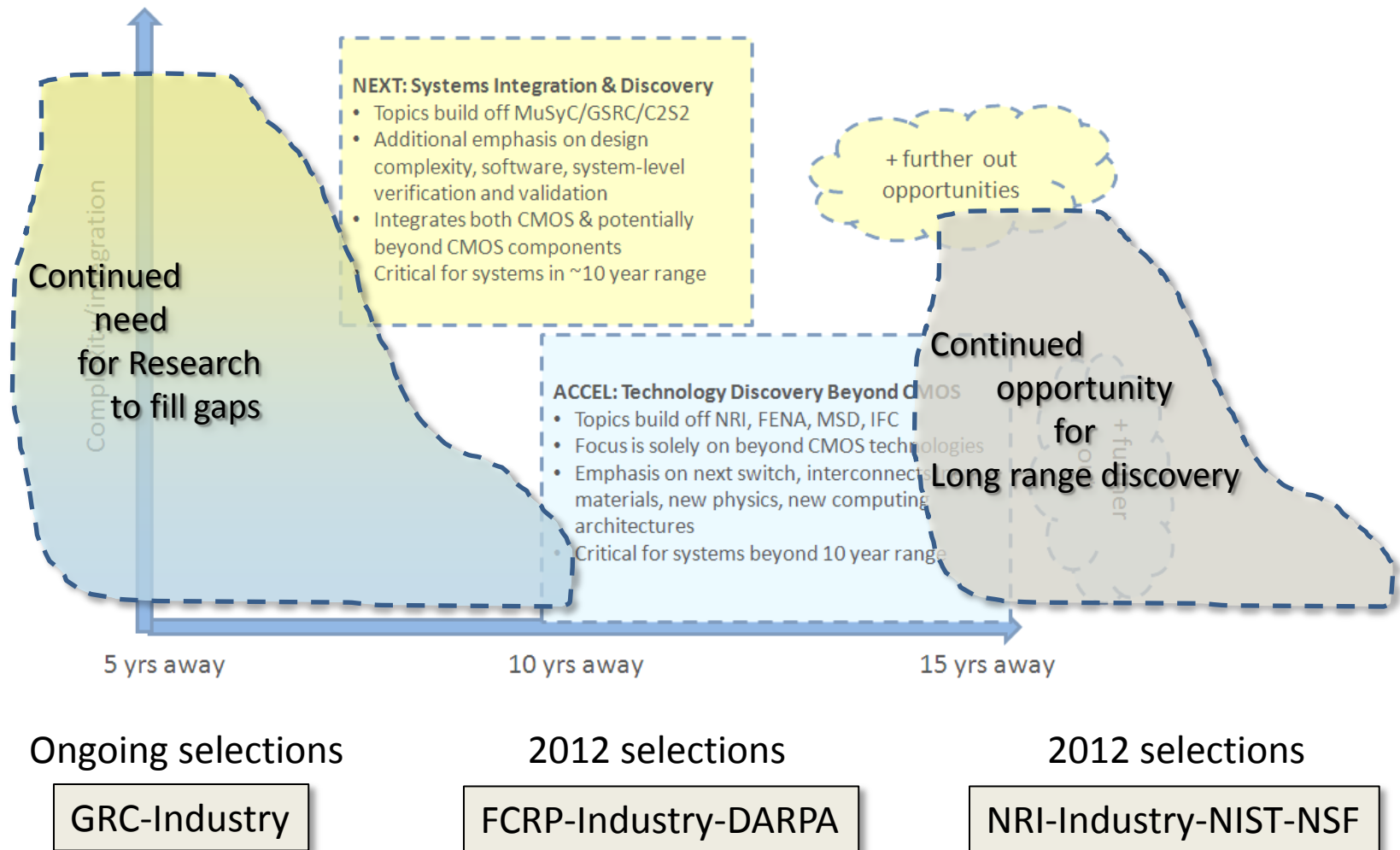
# **FUTURE**

# Push Further Out

## Recognize Inflection Points Coming



# Planned Research Landscape



# NEXT – Highly Complex Systems

**Mission: Enable highly complex systems with capabilities well beyond those available today, i.e., to augment beyond the “sum of the parts.”**

**Focus on system** – building blocks, methods, capabilities

- Zone 1: Complex heterogeneous networked systems
- Zone 2: Highly parallel centralized computation systems

**Technology Areas for NEXT –**

- High performance analog for high speed wireless; THz electronics for imaging, sensing, novel power devices
- Vehicle and Distributed Sensor Networks
- Computing System Architectures based on CMOS technology
- Tools and methods for design, verification, and predictive modeling, including physical modeling of thermal and structural impacts on functionality and the physics of failure of proposed components.

Opportunity to fund some emerging areas  
as special projects outside of main focus areas

# ACCEL – Semiconductor Technologies Beyond CMOS

Mission: Identify and accelerate progress for new mainstream technologies beyond digital CMOS

- Focus areas structured with both focus on most promising concepts and continued seeding future technology ideas
- Necessary to look beyond simple replacements of existing digital CMOS elements, building blocks alone are not sufficient
- Anticipate and work at or beyond inflection points

## **Technology areas for ACCEL –**

- Nonconventional material systems
- Quantum engineered devices and new sensors and transducers
- Integrated circuits and computing architectures

Opportunity to fund some emerging areas  
as special projects outside of main focus areas

# Example Inflection Points

## End of Scaling is Near – Decades of predictions

“Optical lithography can’t do sub-micron”

“Optical lithography will reach its limits in the range of 0.75-0.50 microns”

“Optical lithography should reach its limits in the 1990-1994 period”

“X-ray lithography will be needed below 1 micron”

“Minimum geometries will saturate in the range of 0.3 to 0.5 microns”

“Channel lengths can be reduced to approximately 0.2 microns”

“Minimum gate oxide thickness is limited to ~2 nm”

“Oxide reliability may limit oxide scaling to 2.2 nm”

“Plasma etched aluminum will not happen in our lifetime”

“Copper interconnects will never work”

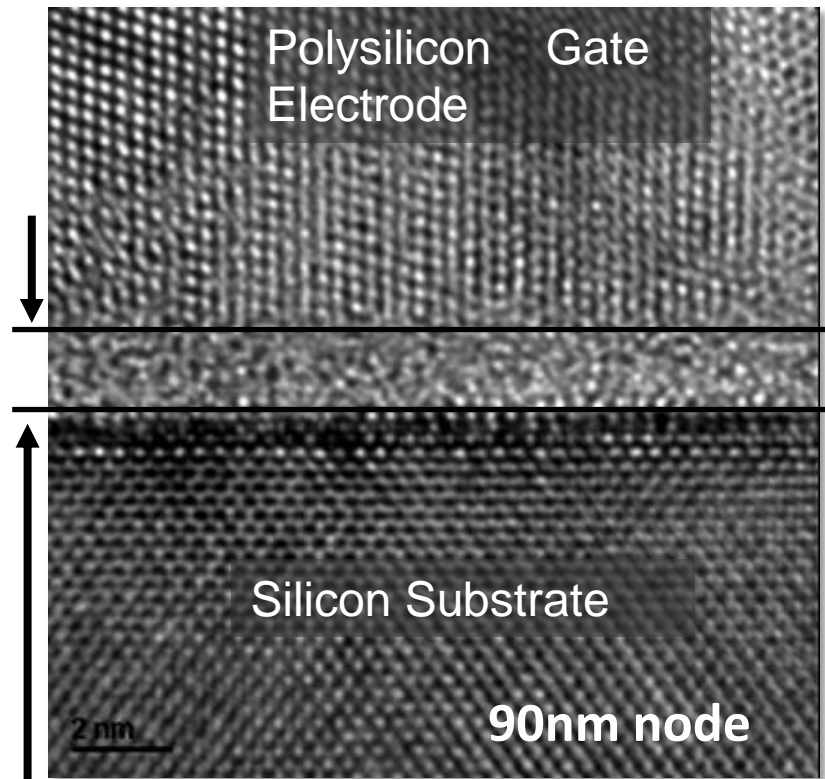
“Scaling will end in ~10 years”

## Inflection Points

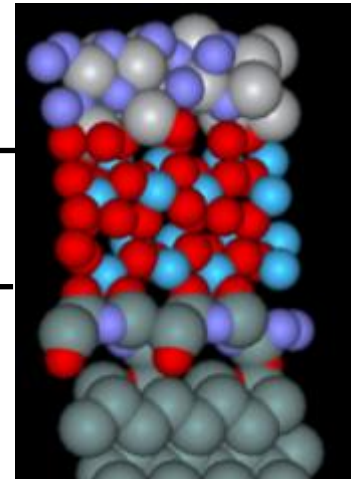
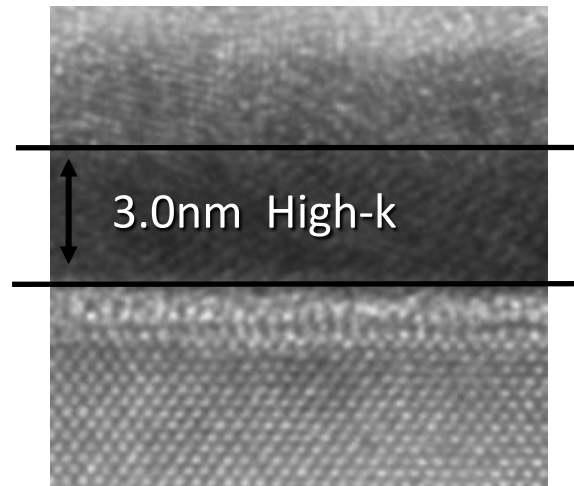
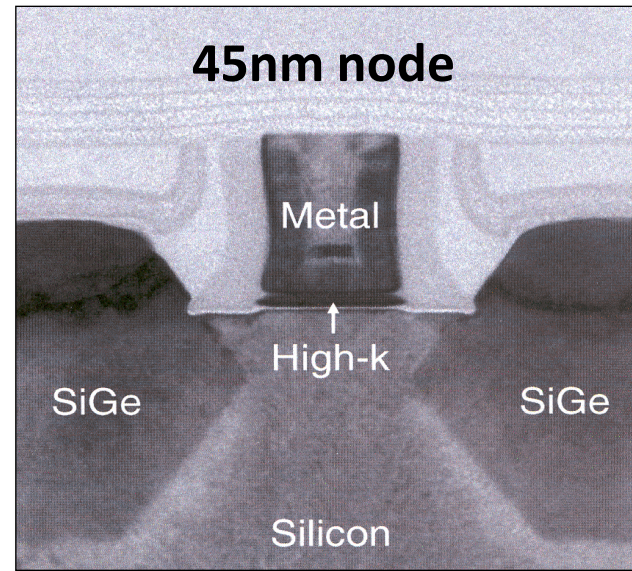
- Size Limited by Granularity, Process Control
- Size limited by Electrical behavior (tunneling)
- Voltage scaling limited by Mobility
- Interconnects limit Performance
- ...



# Inflection Point: Granularity Limits Size Switch to Chemistry Driven Processes



1.2 nm  $\text{SiO}_2$   
3-4 atoms thick



# Inflection Point: Size limited by Electrical behavior

## Switch to Different Device Operation

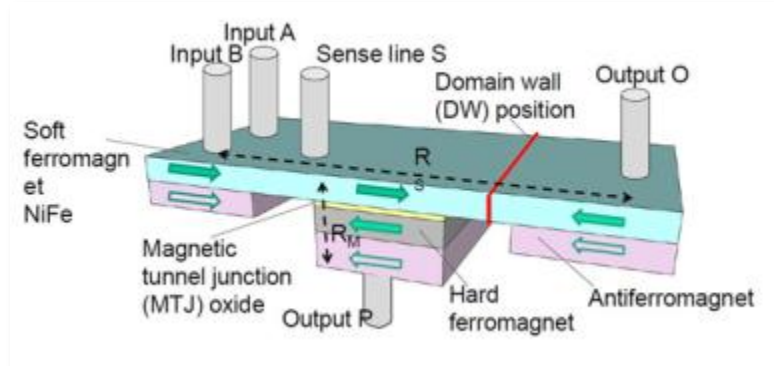
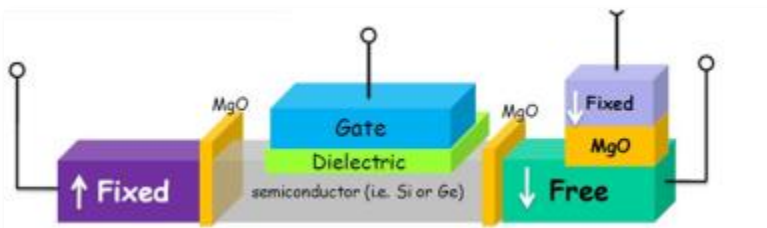
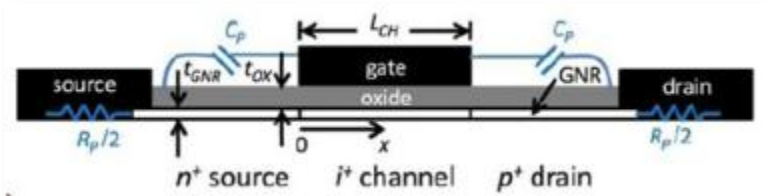
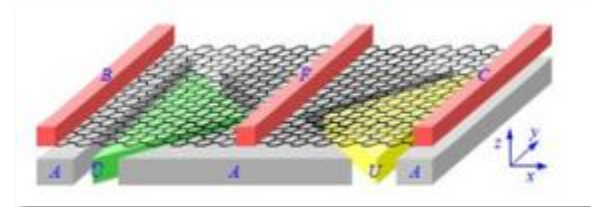
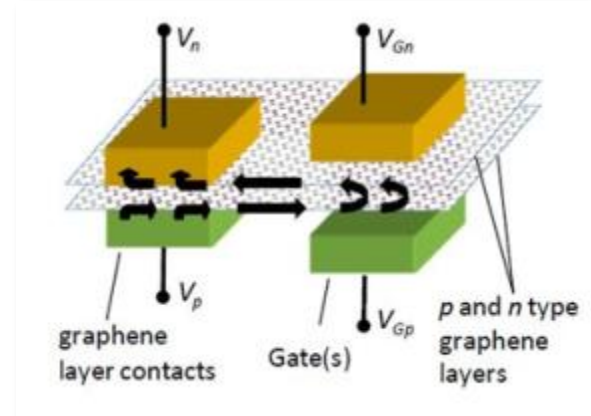
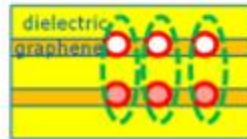
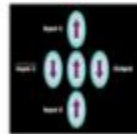
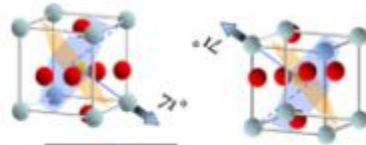
Nanoelectronic Research Initiative – Search for Next Switch

1. Charge, current, voltage ( $Q, I, V$ )

2. Electric dipole ( $P$ )

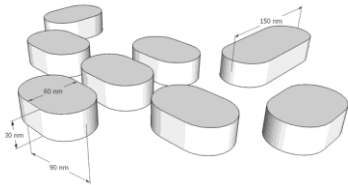
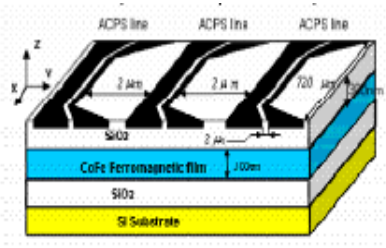
3. Magnetic dipole = spin ( $M$ )

4. Orbital state (Orb) in e.g. quantum well, molecule, crystal, also excitons, esp. Bose condensate (Cond)

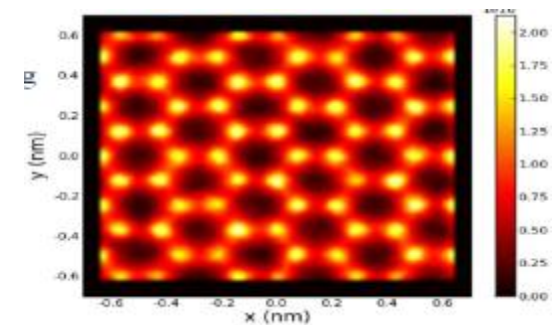
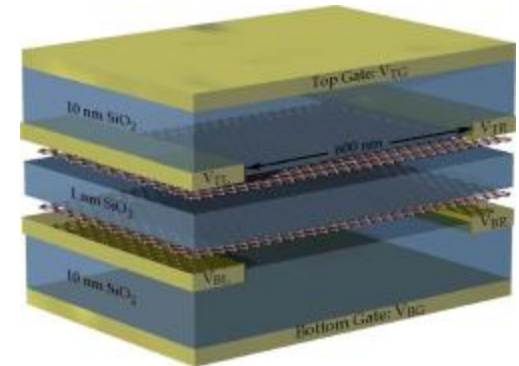


# NRI: 18 New Devices Benchmarked as a Next Switch

## Most can be built with multiple active layers


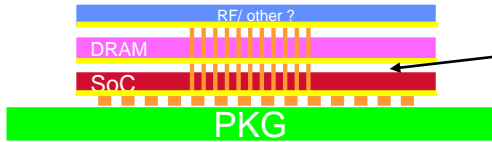

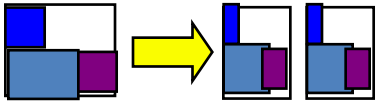
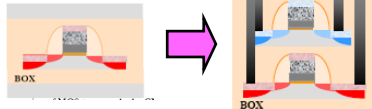


Code	Device
Units	
REF-H	15 nm CMOS
REF-L	15 nm CMOS
I-01	Excitonic FET
I-04	MTJ Logic Switch
I-05	All Spin Logic
I-07	Graphene PN Junction
I-08	Electronic Ratchet
M-01	Graphene thermal logic
M-02	BDD Architecture
M-04	Nanomagnet logic
M-05	gnrTFET
M-06	InAs TFET
N-02	e-Struct. Modulation Trans
N-03	RAMA
S-01	BiSFET
S-02	RIEFET
S-03	HetTFET
W-02	Spin Wave
W-04	MTJ/STT
W-05	Spin Torque Amplifiers



Conventional →

# Rethinking 3D

Possible Application	Bonding/ Fabrication Method	Connections	Stacking Objective
Memory + Logic		~1000s	Reduce wiring/ form factor
Multiple die stacking		~1000s	Reduce wiring/ form factor
Smart unit repartitioning (logic+logic)	<p>Face to face/ WtW or DtD</p> 	~1M+	Reduce wiring (upper layer)
Within unit repartitioning (logic+logic)	 <p>Face to face/ WtW or DtD</p>	1μm/0.5μm ~10M-100M	Reduce wiring/ density?
Circuit /device repartitioning	<p>Sequential processing</p>  <p>NOT TSV</p>	5-10nm ~10B+	Density/ Disparate Integration

Novel →



# Rethinking Computation

Conventional →

Novel →

## Compact Full Adder: Non-Boolean Logic

- **Option1:** conventional ASL (44 magnets)
- **Option2:** functionality enhanced ASL (5 magnets)

Inputs: A, B and C

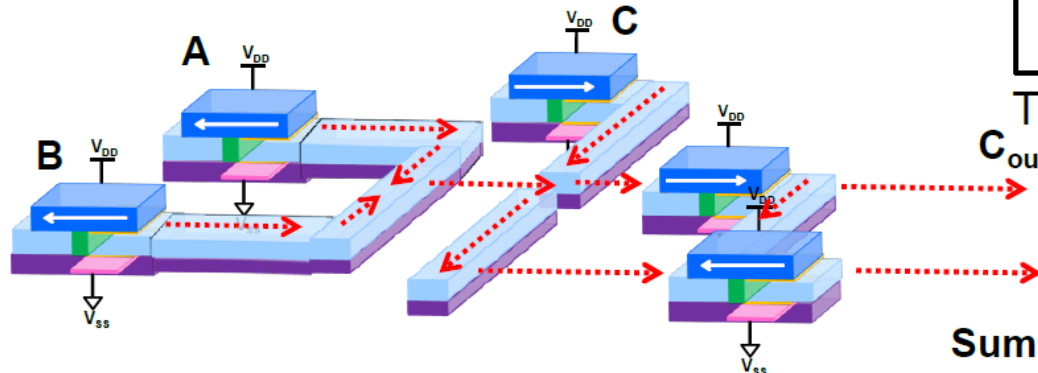
Outputs: Sum and Cout

$$Sum = A \oplus B \oplus C$$

$$C_{out} = AB + AC + BC = M(A, B, C)$$

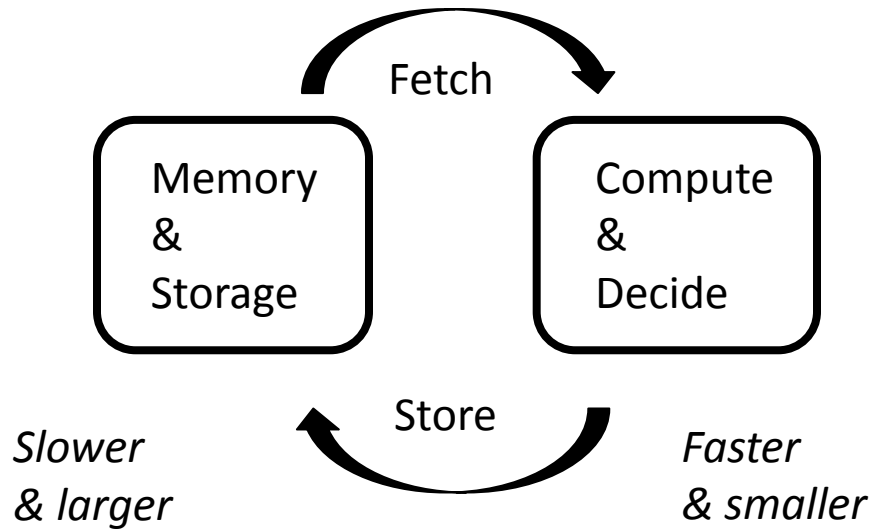
A	B	C	C' <sub>out</sub>		Sum
0	0	0	1	1	0
0	0	1	1	1	1
0	1	0	1	1	1
0	1	1	0	0	0
1	0	0	1	1	1
1	0	1	0	0	0
1	1	0	0	0	0
1	1	1	0	0	1

Truth Table for SUM



Functionality Enhanced ASL (FEASL)

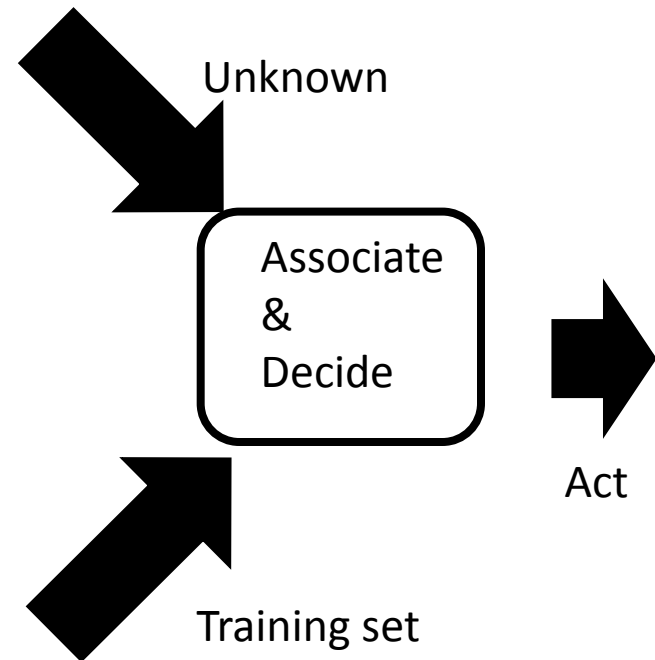
# Exploring Other Ways to Compute



“Von Neumann”

*Bottleneck = memory/storage*  
*Transport limited devices make it worse*

Conventional



*Bottleneck = training*  
*Potentially favorable*  
*for novel devices*

Novel

# Interconnects are Pervasive

- New materials needed for novel interconnects
- Not sufficient to only explore device behavior
- Transducers to convert between domains
- Novel transport in highly interconnected 3D
- Working around transport limited computation
- ...



# Key Messages

- All Paths forward require Materials Research
- We need to rethink our approaches to both device & design technologies
  - Systems can have unique abilities not planned at building block level. Use cross-functional approaches
  - Interconnects and transport work differently for novel devices, how can we exploit that ?
  - Optimal computation might be very different, where are the opportunities ?
- We want to identify & fund **novel** long term research, not just gaps that we can see
- Surprise us !