

# Transforming Concepts To Reality: New Technologies for New Applications

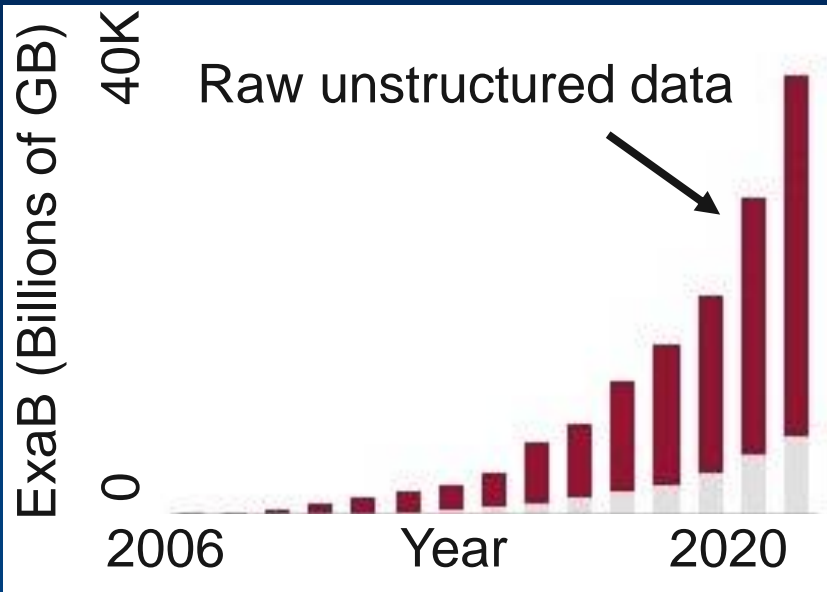
Max M. Shulaker



Massachusetts Institute of Technology

# Data Explosion

“Swimming in sensors, drowning in data”



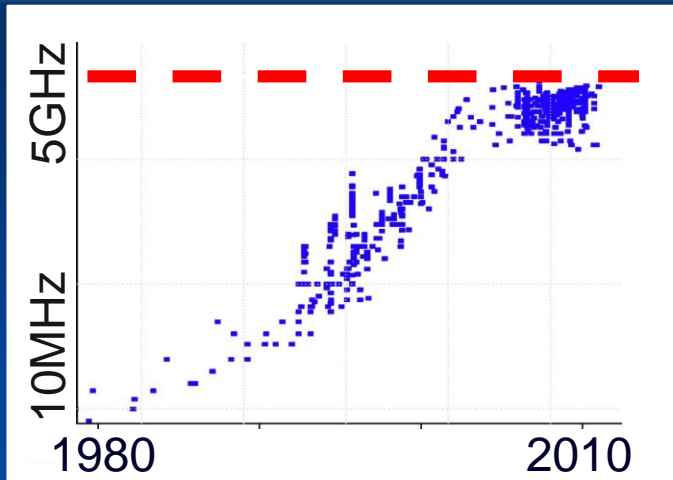
Wide variety & complexity



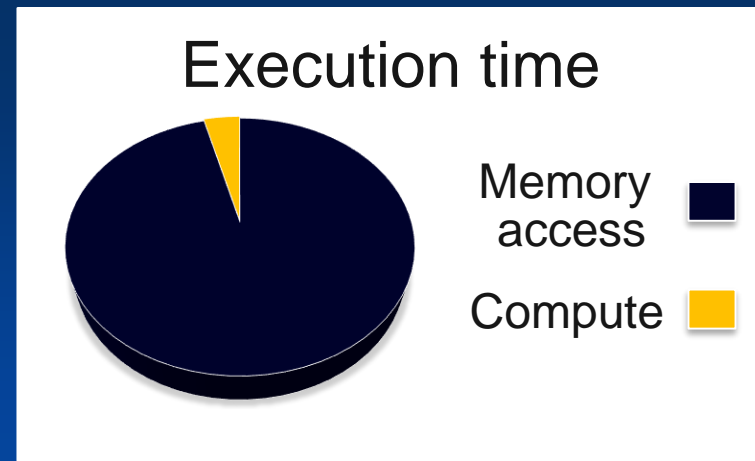
- Mine, search, analyze data in real-time
  - Data centers, mobile phones, robots

# Many Obstacles Simultaneously

## Power Wall



## Memory Wall



## Communication Wall



Also:  
interconnect wall,  
complexity wall,  
resilience wall...

# Enabling New Applications:



new sensors

better transistors

novel memories

new architectures

thermal management

improved algorithms

yield and reliability

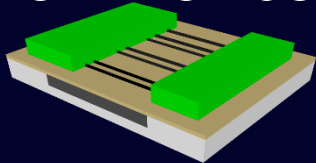
# Solution: Nanosystems

*Transform new nanotech*

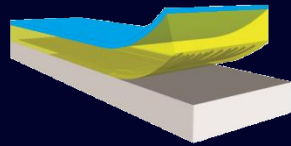
*into new systems*

*enabling new applications*

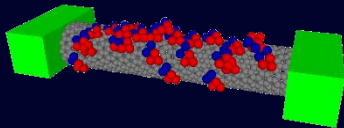
New Devices



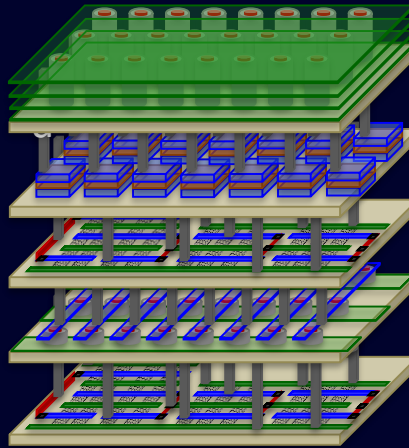
New Fabrication



New Sensors



Revolutionary Architectures

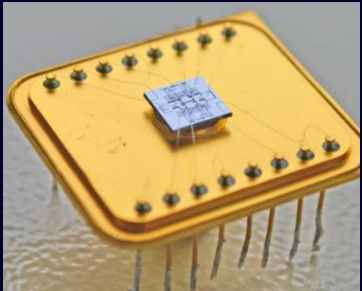


Abundant-Data Applications

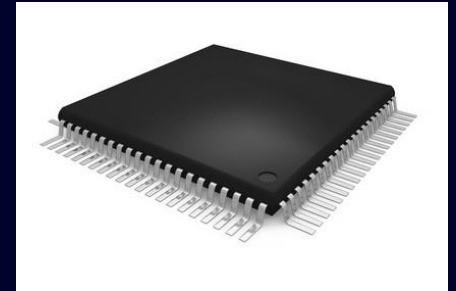


# Systems Today

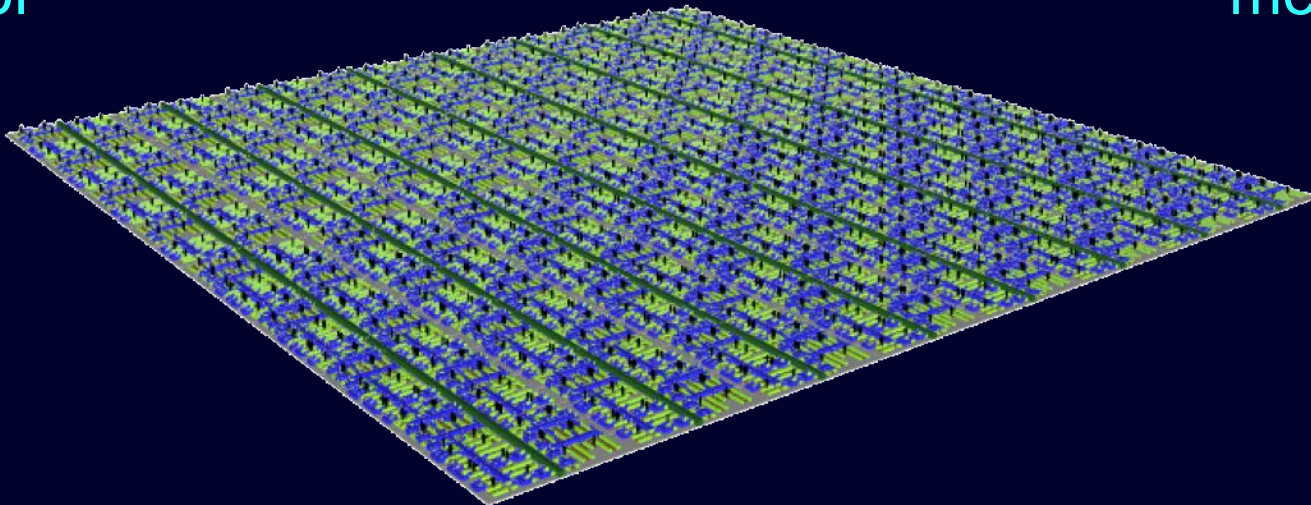
## 2-Dimensional



sensor

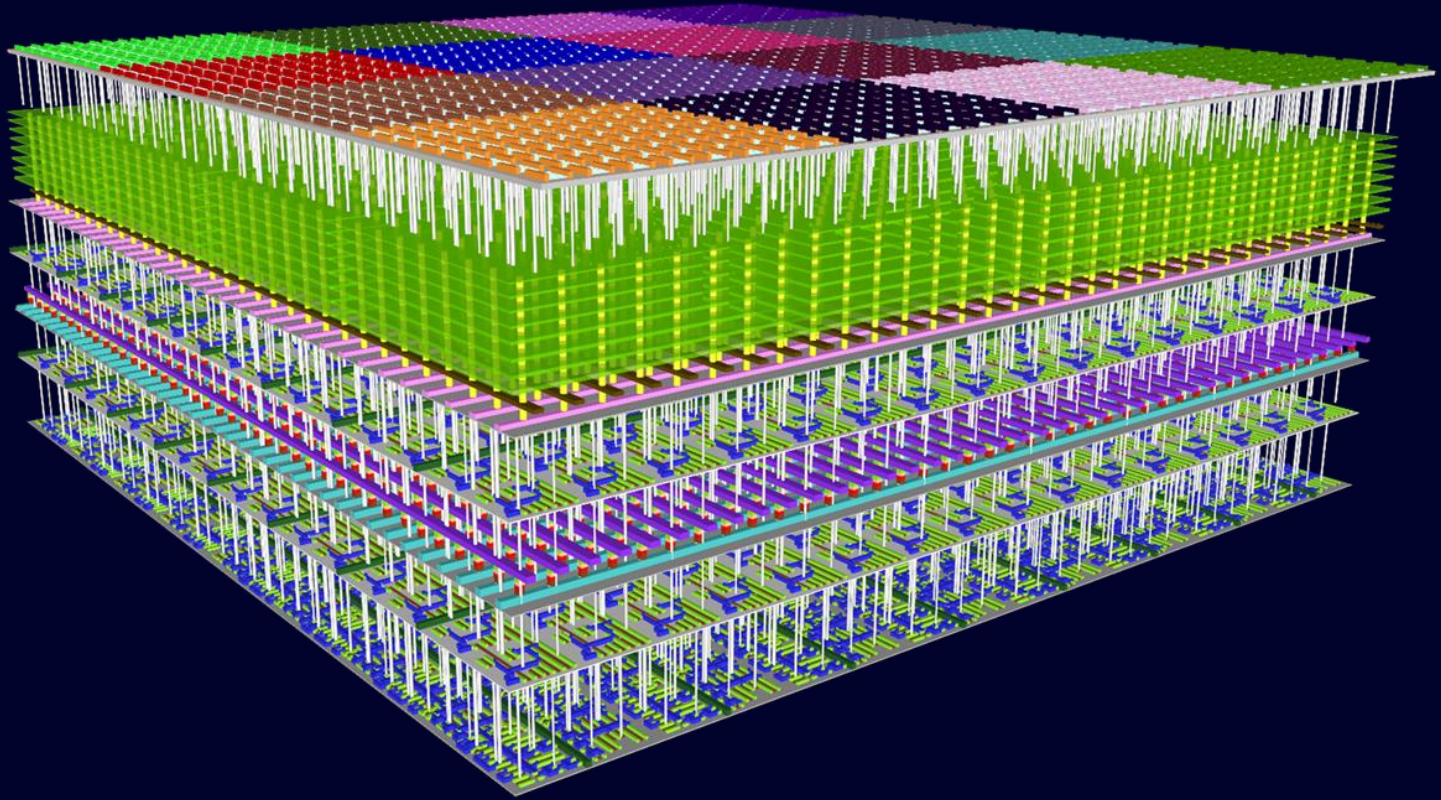


memory



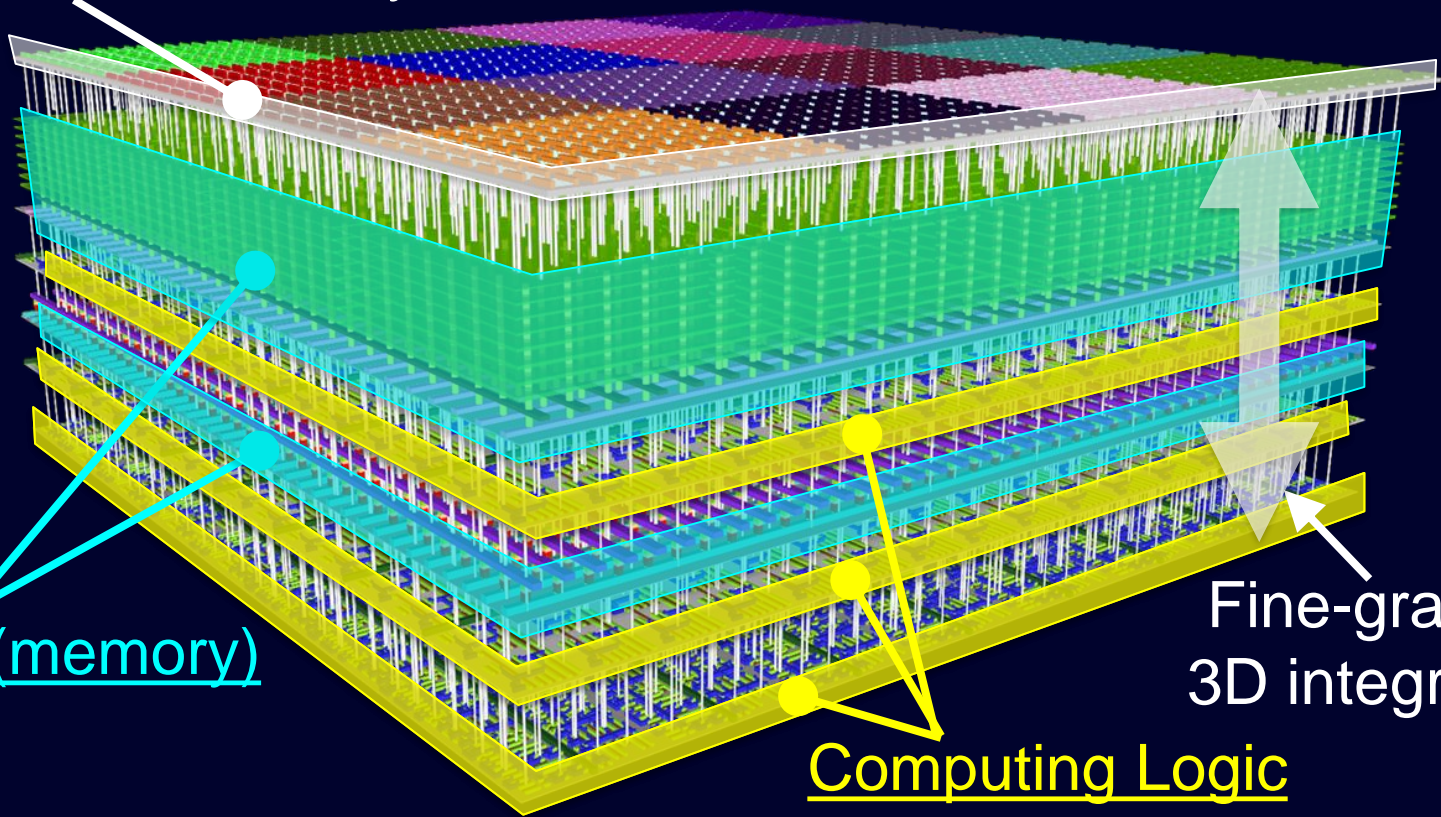
computing

# Future Nanosystems



# Future Nanosystems

Increased Functionality



Fine-grained  
3D integration

Storage (memory)

Computing Logic

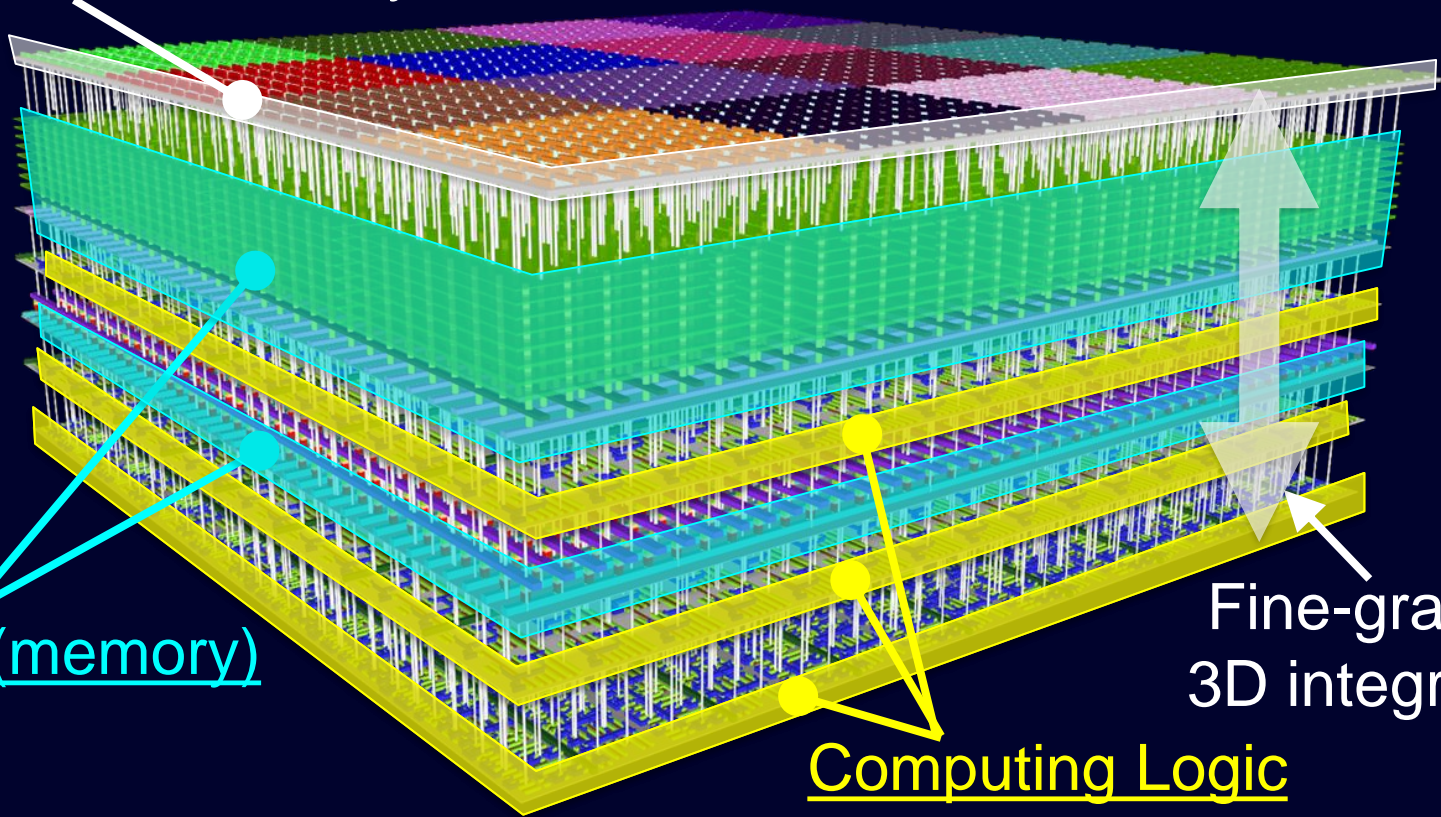
***Impossible with today's technologies***



# Realizing Nanosystems TODAY

## Enabled by Emerging Nanotechnologies

Increased Functionality



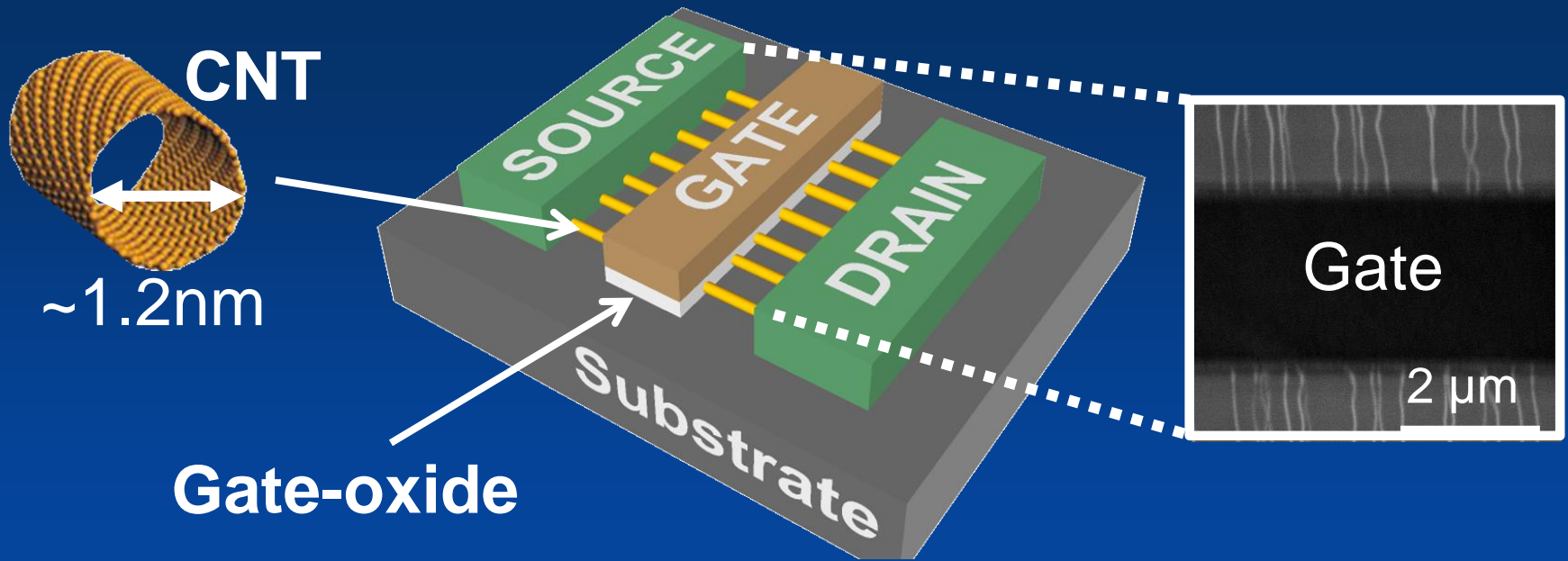
Fine-grained  
3D integration

Storage (memory)

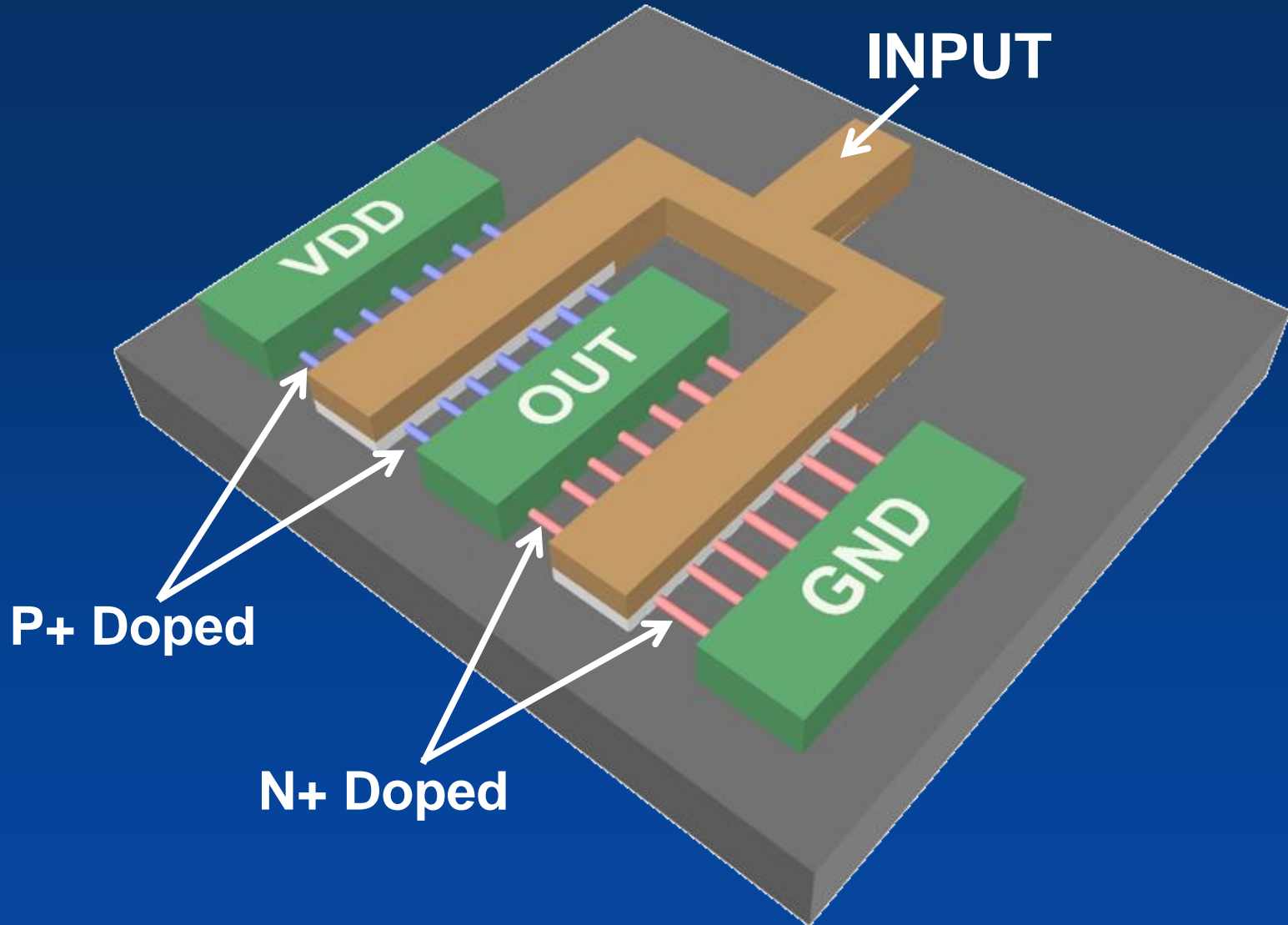
Computing Logic

# Carbon Nanotube FET (CNFET)

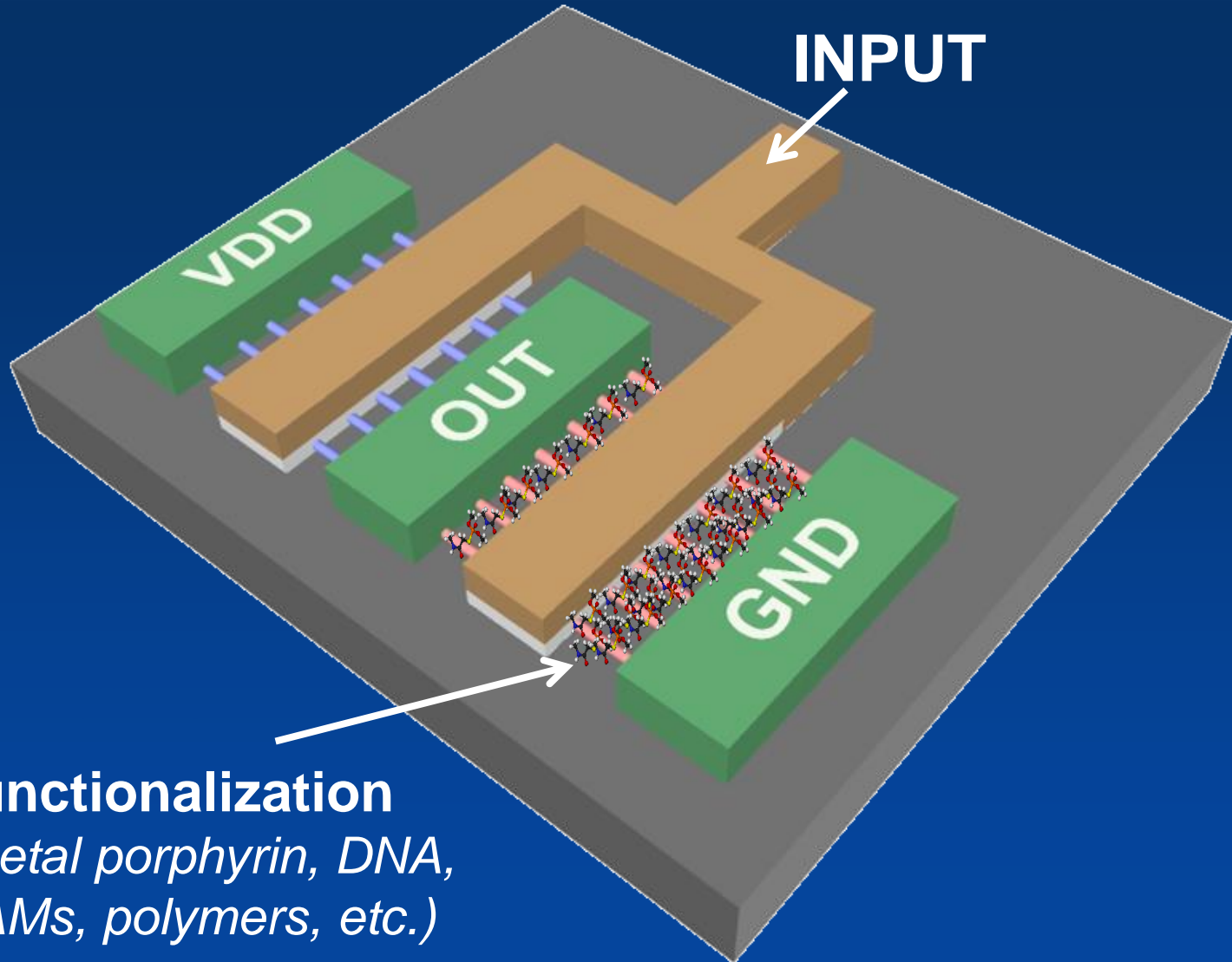
- Energy efficiency: **~10X benefit** <sup>[1]</sup>
- Chemical sensors: **ideal candidate**



# Ideal CNFET Inverter



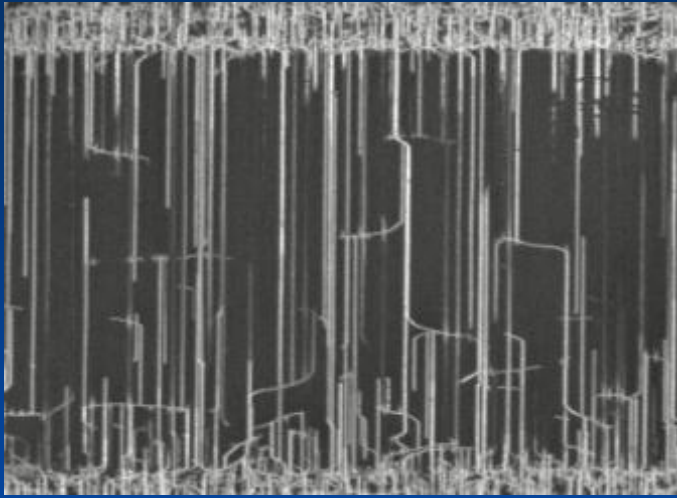
# Ideal CNFET sensor



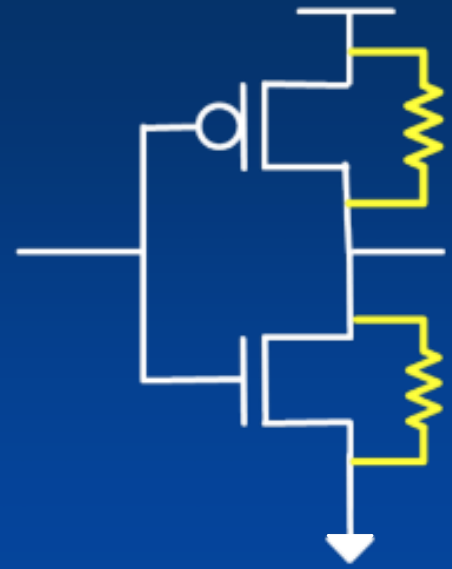
**Functionalization**  
(*metal porphyrin, DNA, SAMs, polymers, etc.*)

# BIG Promise, BUT Major Obstacles

Mis-positioned CNTs



Metallic CNTs

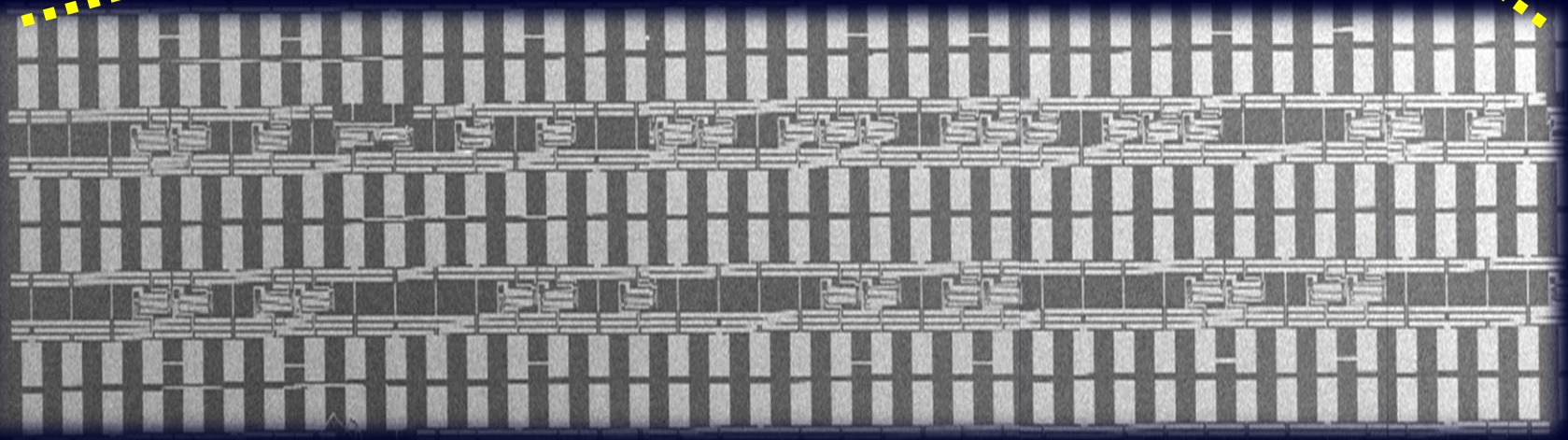
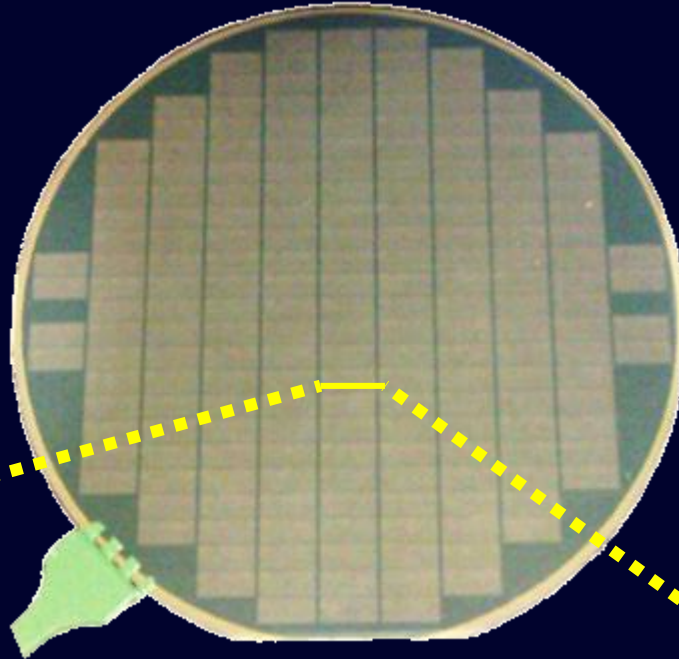


**Combined processing + design solutions**

# Most Importantly

- VLSI processing
  - No per-unit customization
- VLSI design flow
  - Immune CNT library

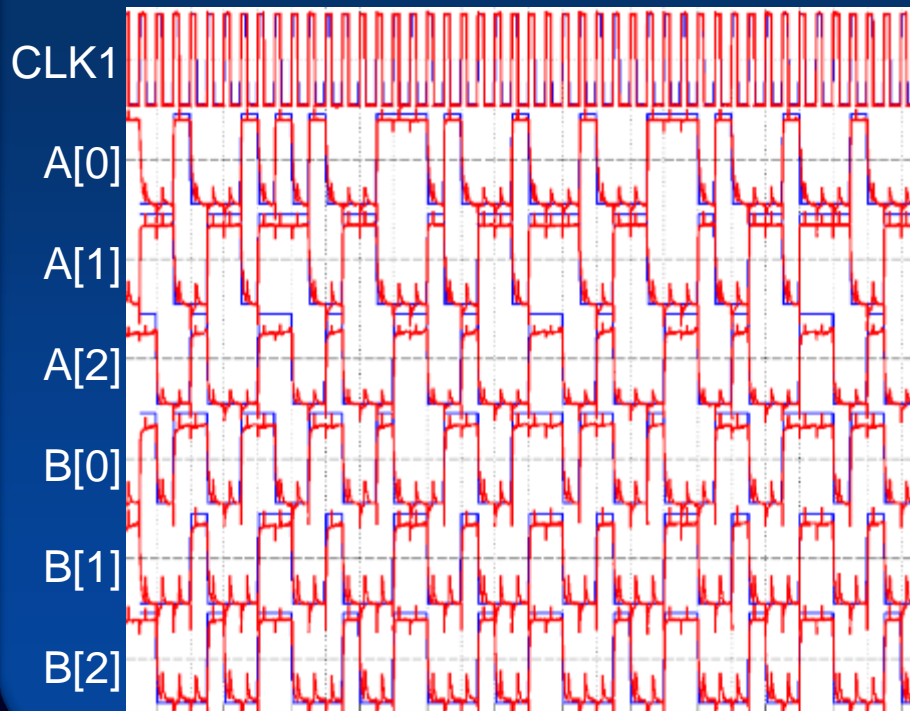
# CNT Computer



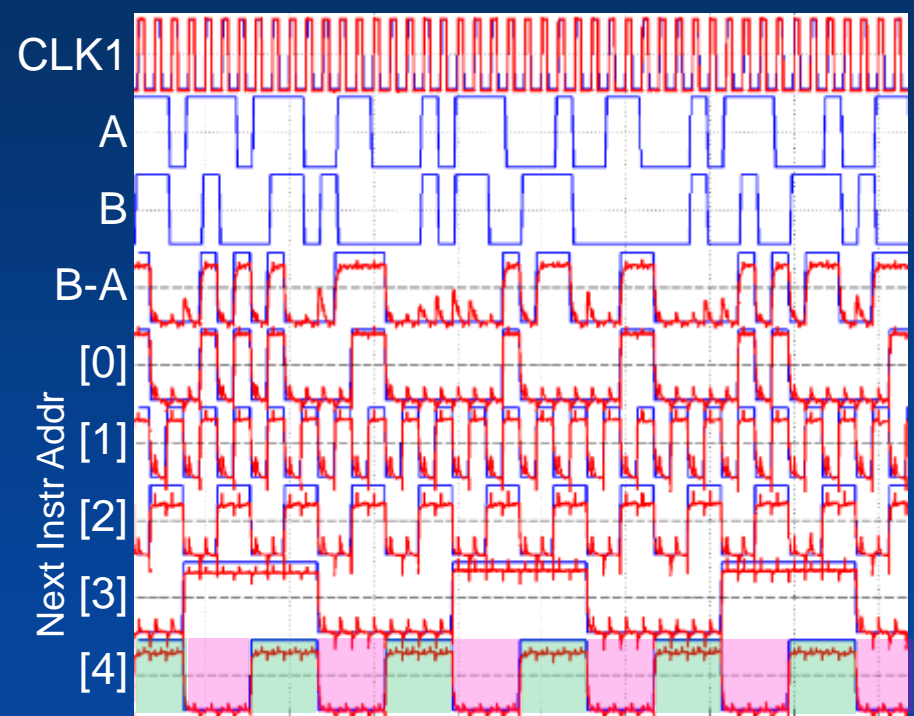
# Multi-Tasking

## Concurrent programs: Sort, Count

Data fetch addresses



ALU result & next instruction



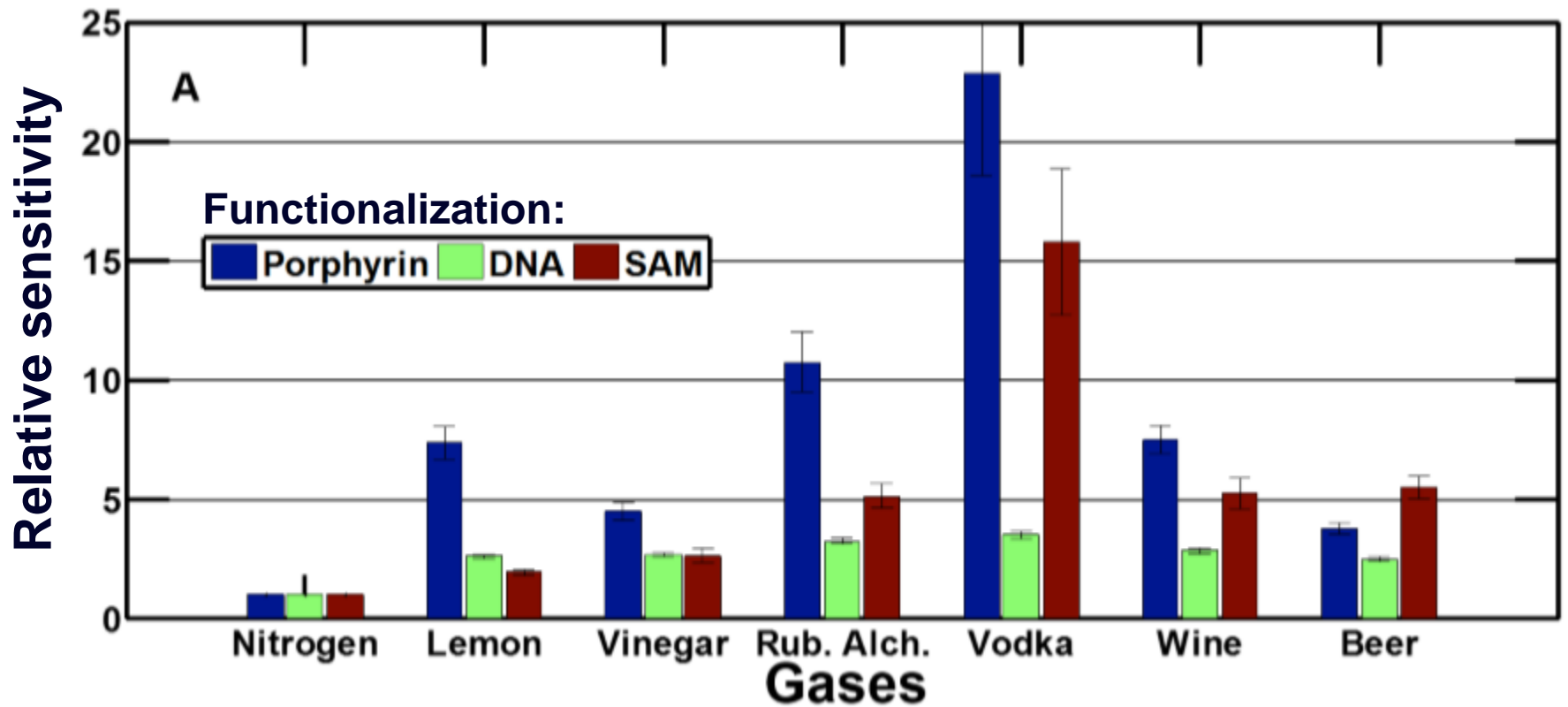
MIPS  
instructions  
emulated



- AND
- ANDI
- BGEZ
- BLEZ
- BLTZ
- BNE
- J
- LB
- NOOP
- OR
- ORI
- SB
- SLL
- SLLV
- SRA
- SRL
- SRLV
- SUBU
- XOR
- XORI



# CNFET Gas Sensors

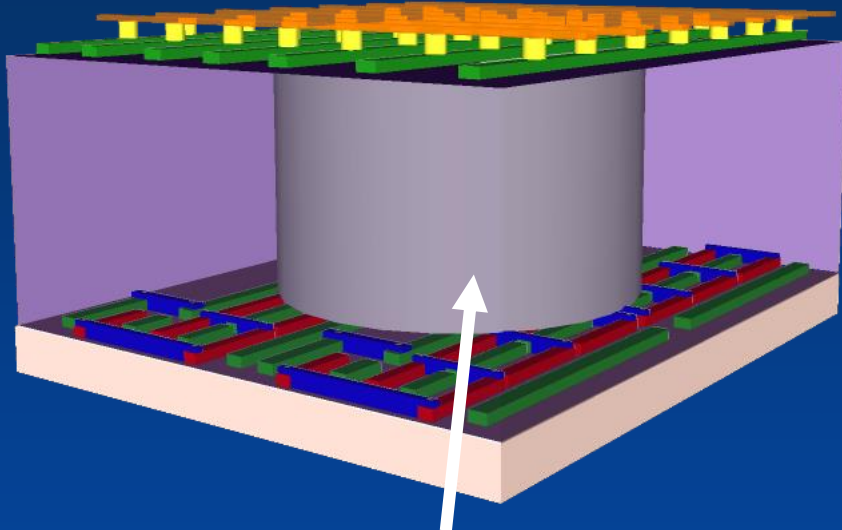


***How do we do better?***

# 3D Integration

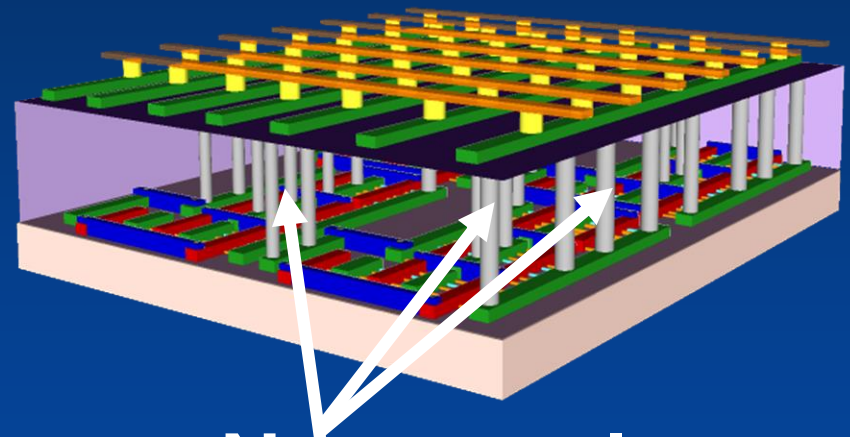
- Massive ILV density  $\gg$  TSV density

## TSV (chip stacking)



Through silicon via  
(TSV)

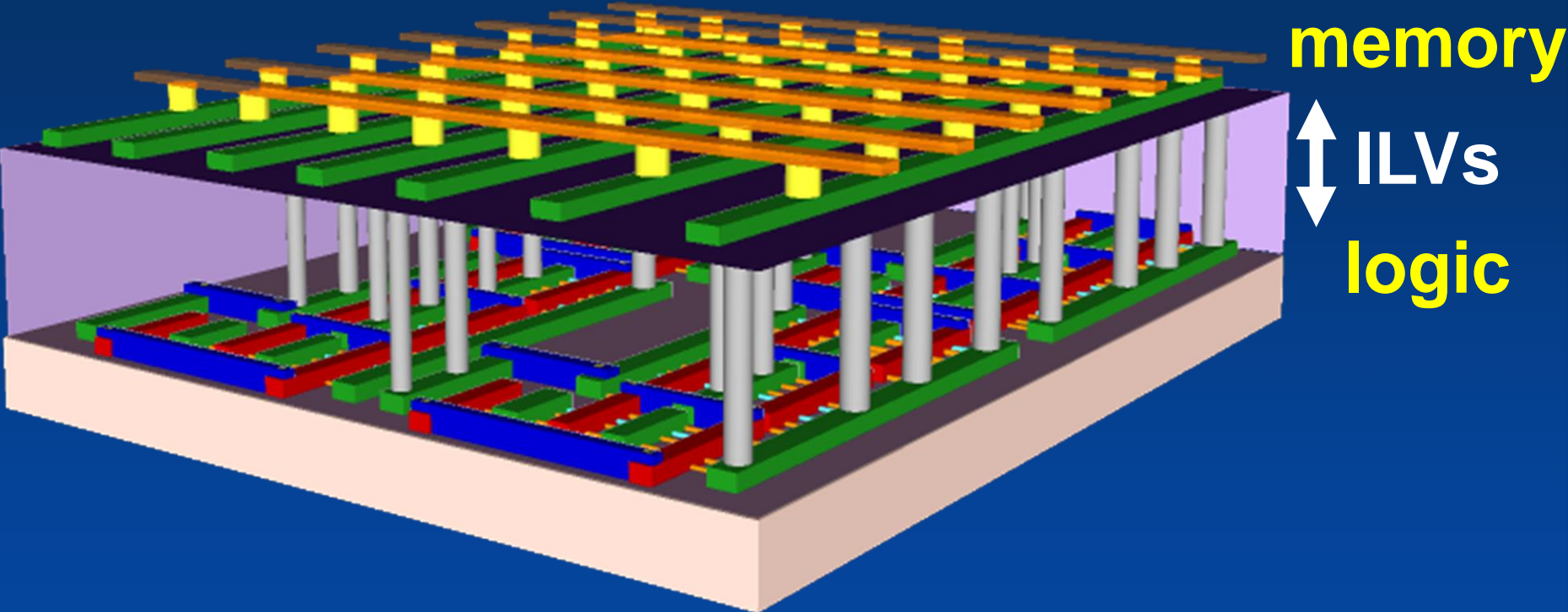
## Monolithic



Nano-scale  
inter-layer vias (ILVs)

# Monolithic 3D: Logic + Memory + Sensing

- Increased data bandwidth



# Energy and Performance Benefits

- **Memory access time**
  - Less processor idle time
- **Memory access energy**
  - Memory + logic stacking
- **Resource Contention**
  - Wide connectivity

# Realizing Monolithic 3D

- Low-temperature fabrication: **<400 °C**
  - Major obstacle for silicon CMOS

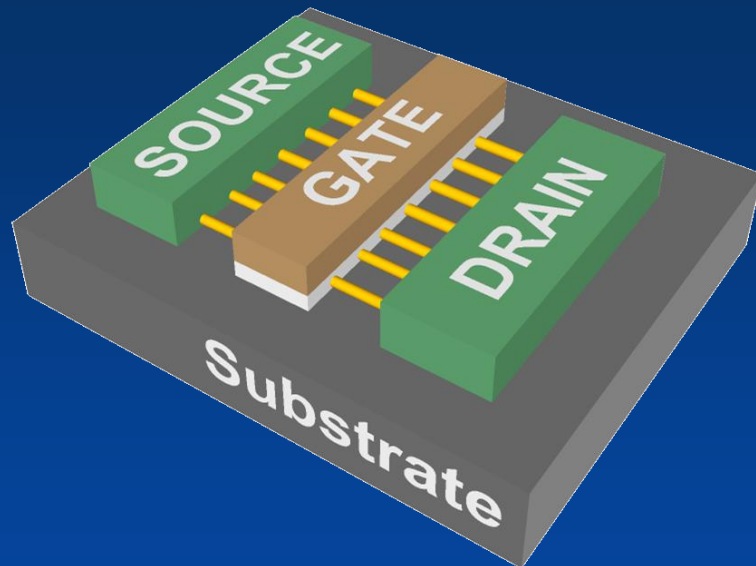
# Realizing Monolithic 3D

- Low-temperature fabrication:  $<400\text{ }^{\circ}\text{C}$

Logic/ Sensing

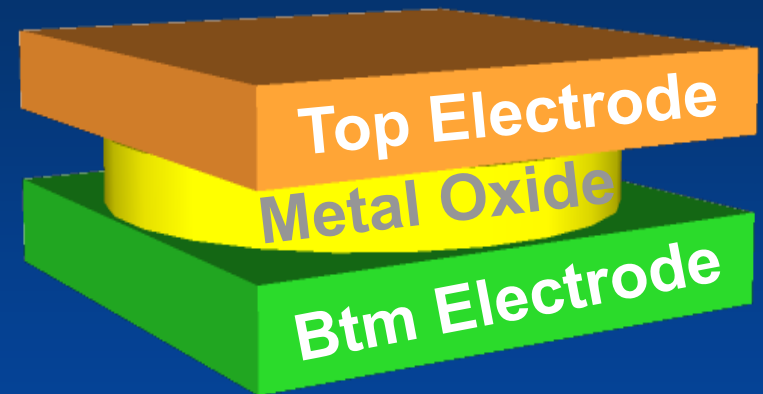
Memory

CNFETs



$<200\text{ }^{\circ}\text{C}$

RRAM

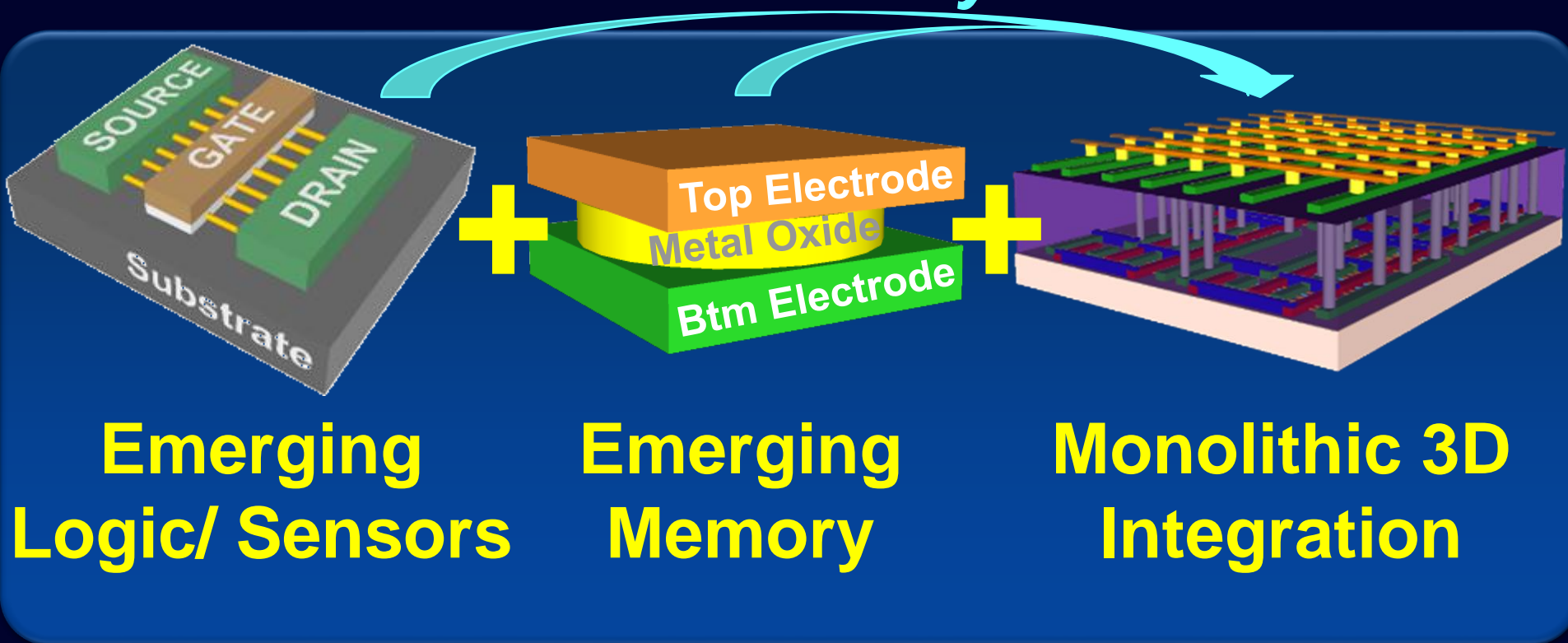


$<200\text{ }^{\circ}\text{C}$

# Realizing Monolithic 3D

- Combine device + architectural benefits

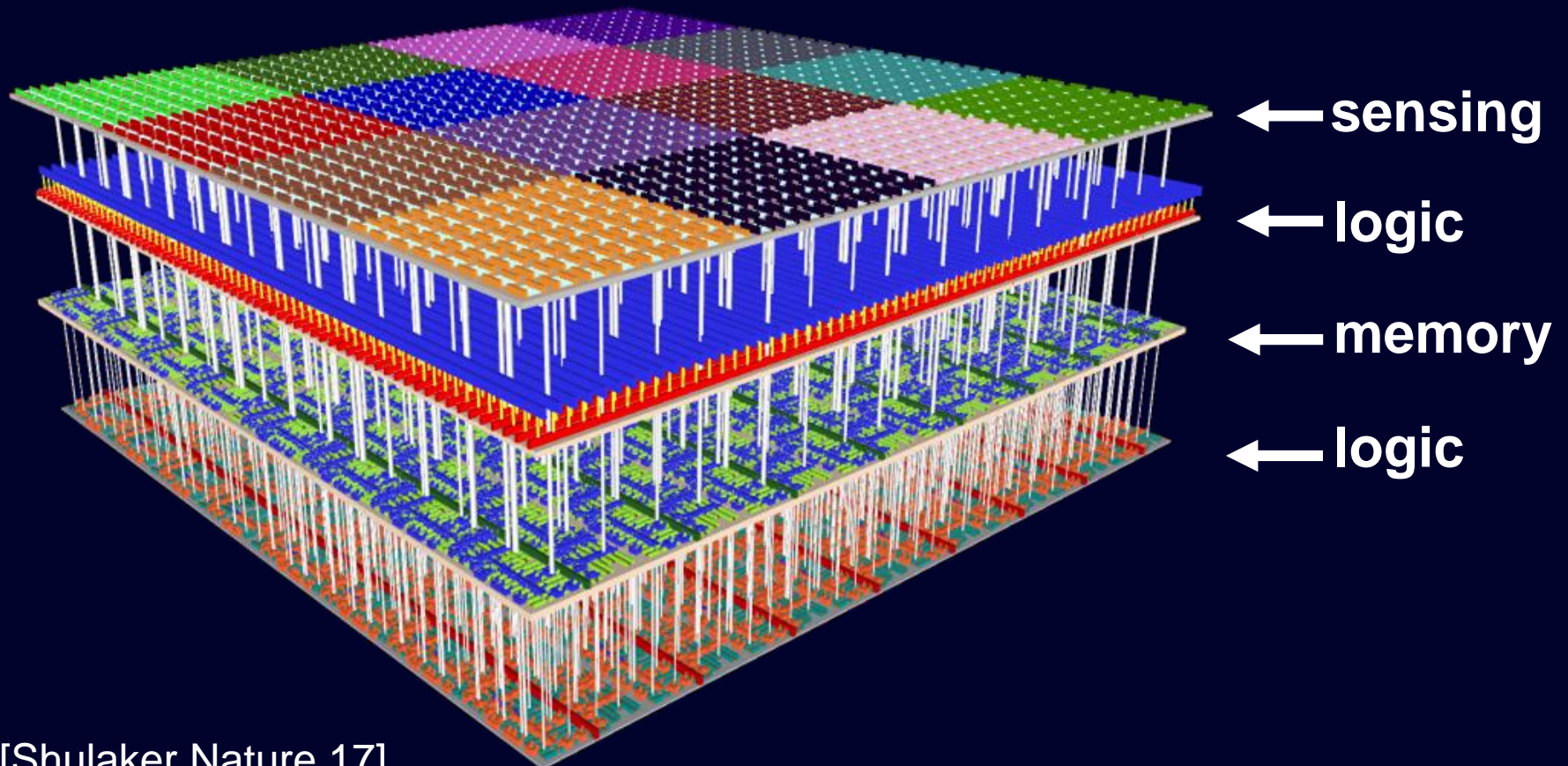
*Naturally enabled*





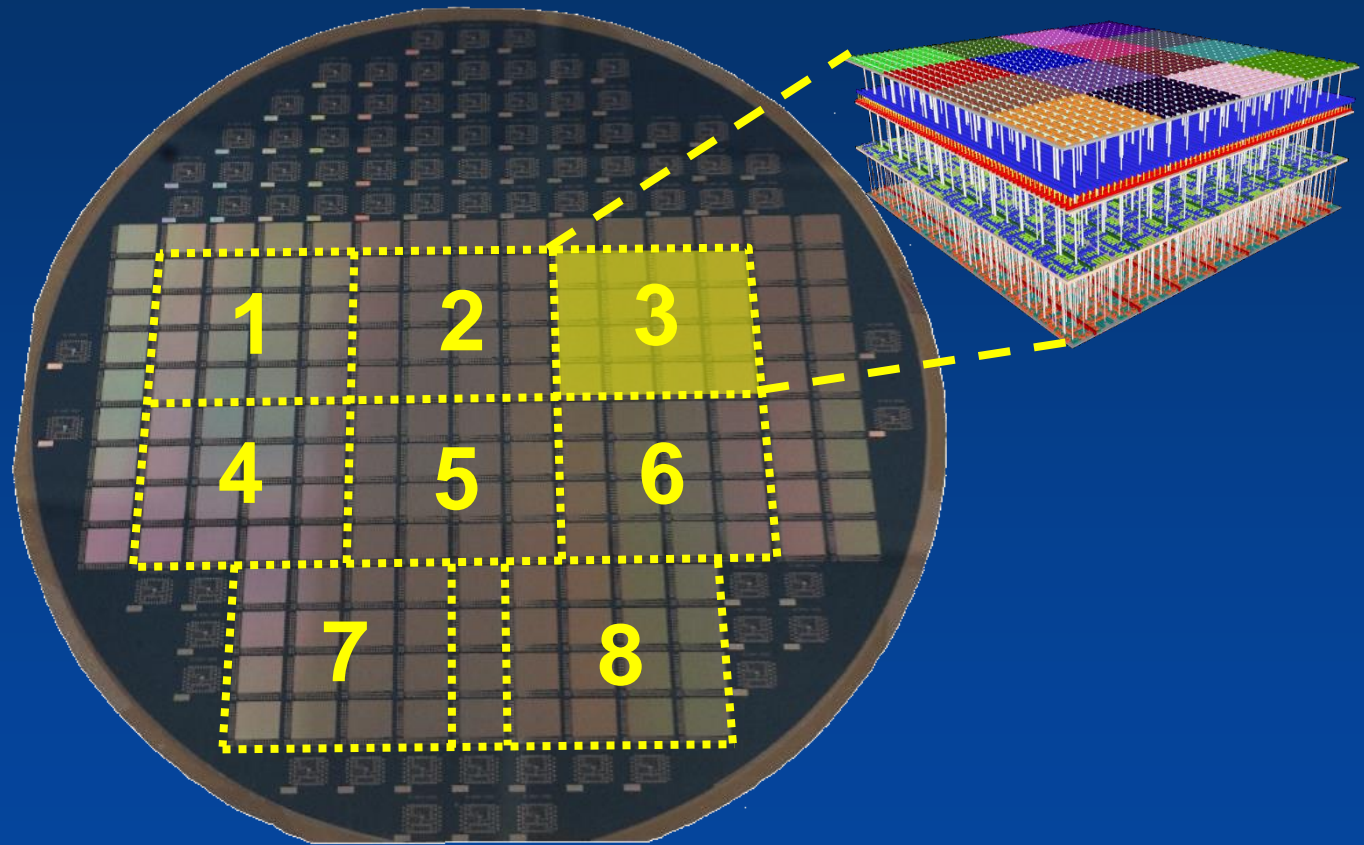
# 3D NanoSystem

- **First monolithic 3D system**
- **>2 Million CNFETs, 1 Mbit RRAM**



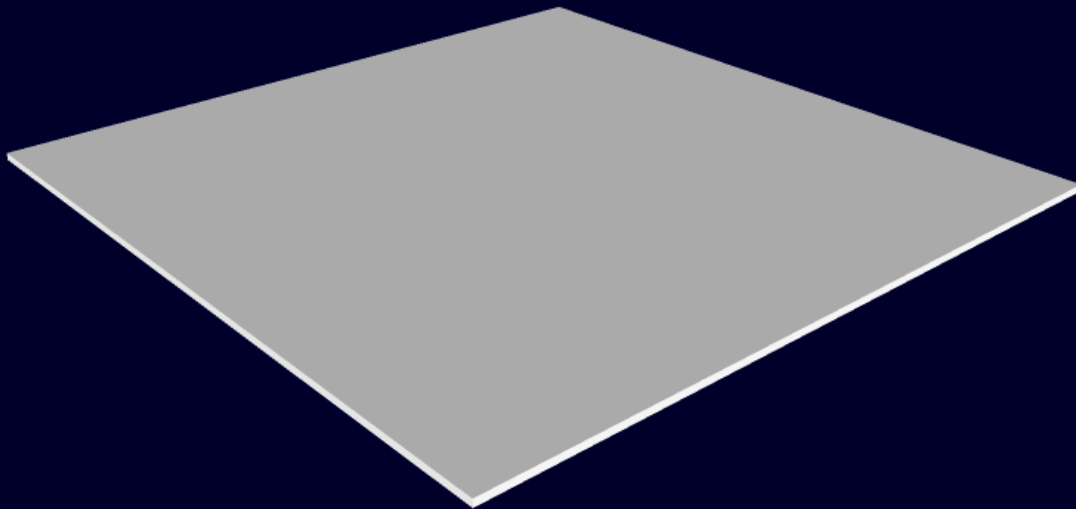
# NOT Just a Cartoon

## Wafer-scale design + fabrication



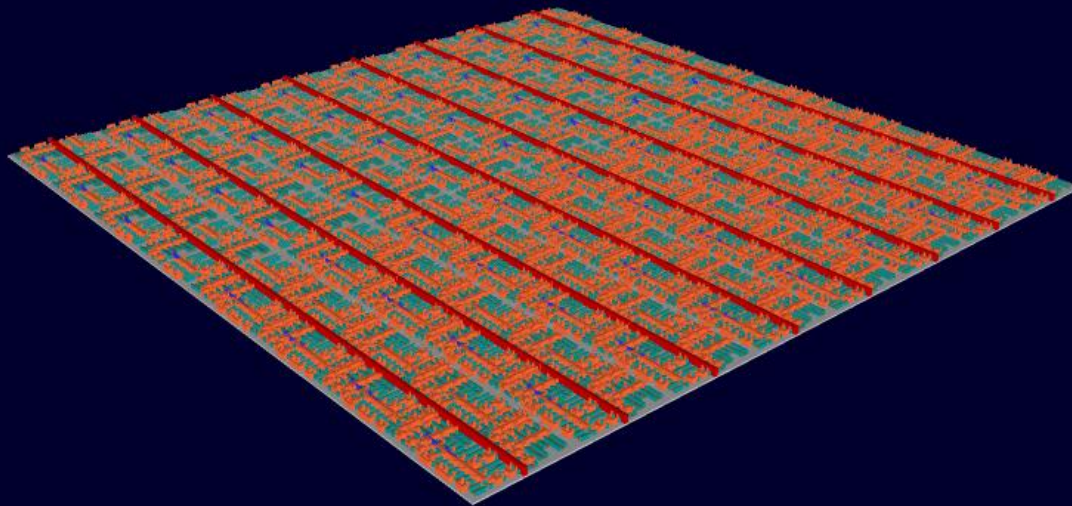
# 3D NanoSystem: Fabrication

- **Starting substrate**



# 3D NanoSystem: Fabrication

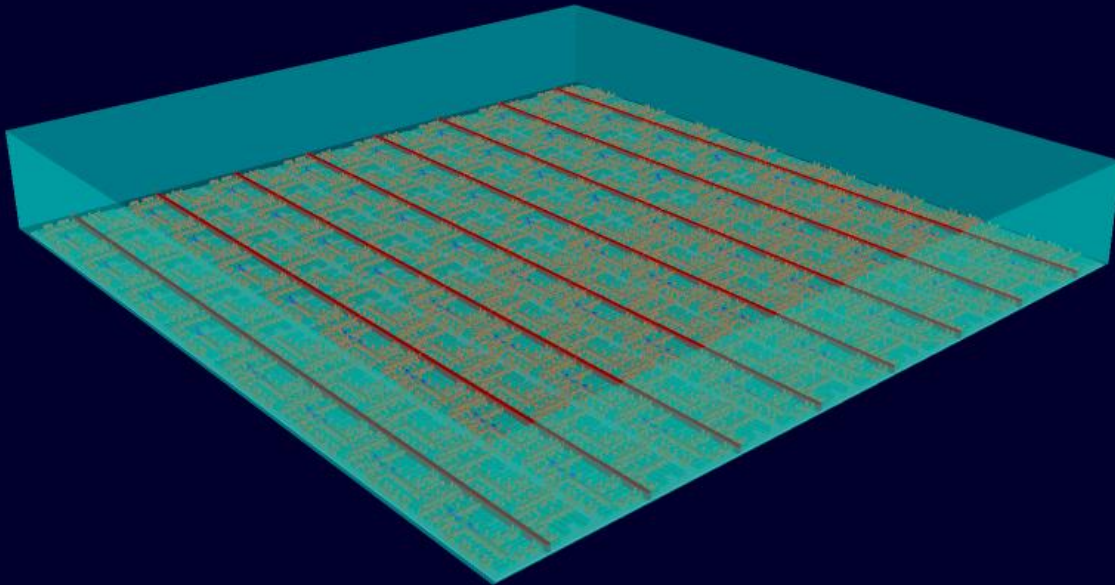
- **Silicon FETs**
  - 1050 °C dopant activation



1. Bottom layer only
2. Silicon **OR** CNFET

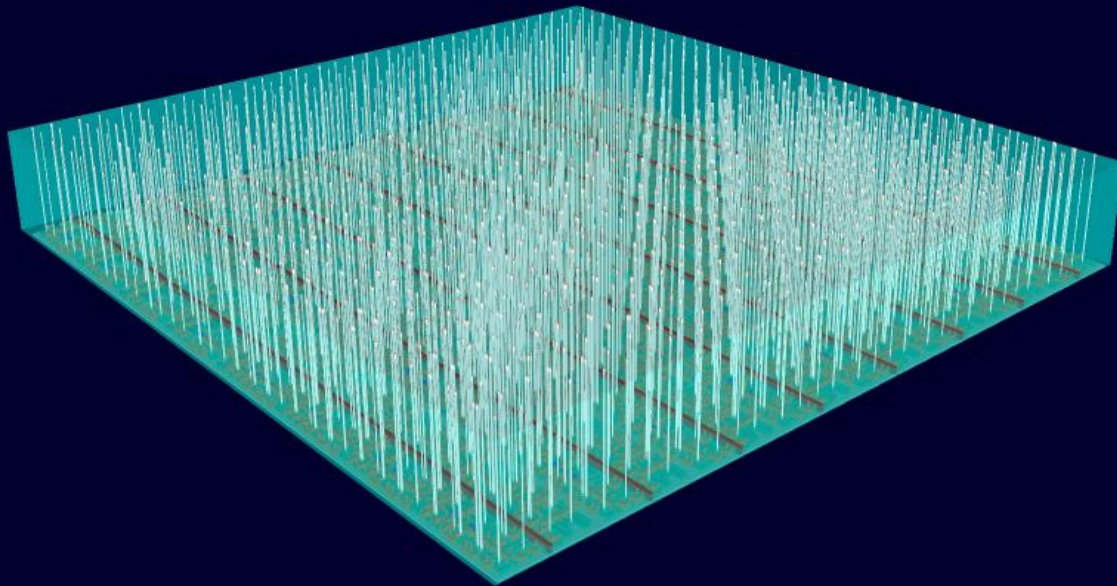
# 3D NanoSystem: Fabrication

- **Inter-layer dielectric (ILD)**



# 3D NanoSystem: Fabrication

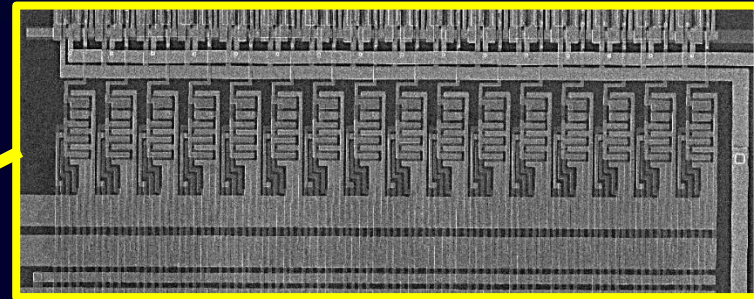
- **Inter-layer vias (ILVs)**
  - Ultra-dense vertical inter-connects



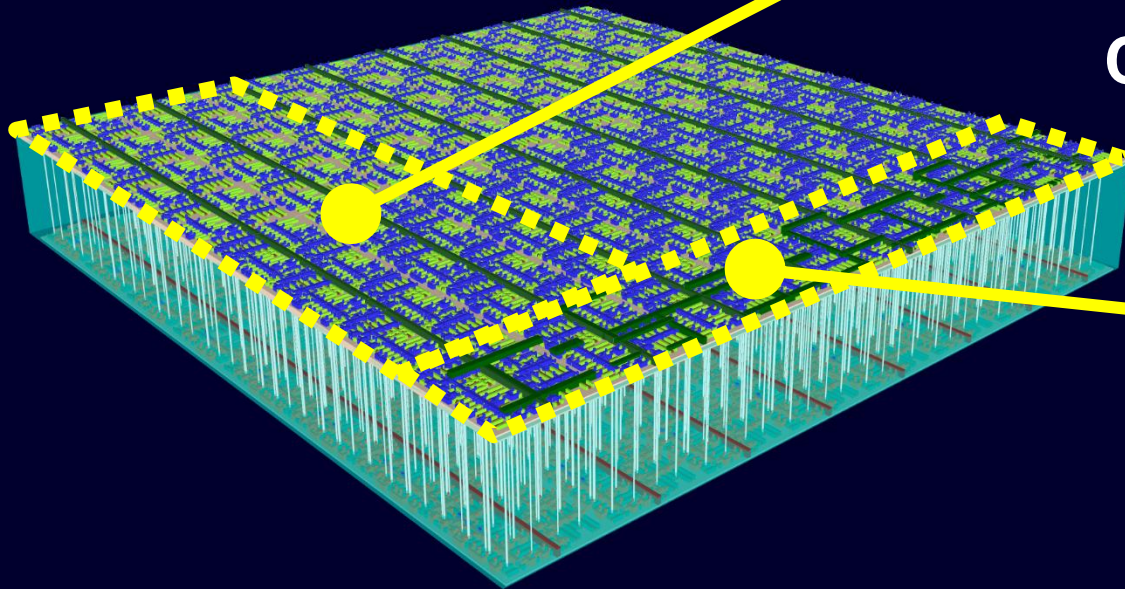
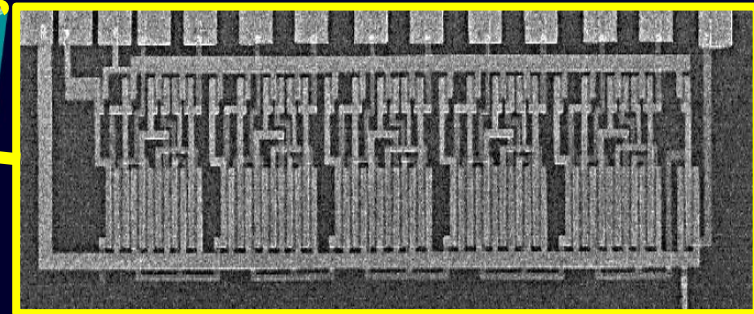
# 3D NanoSystem: Fabrication

- CNFET logic

Memory access circuitry

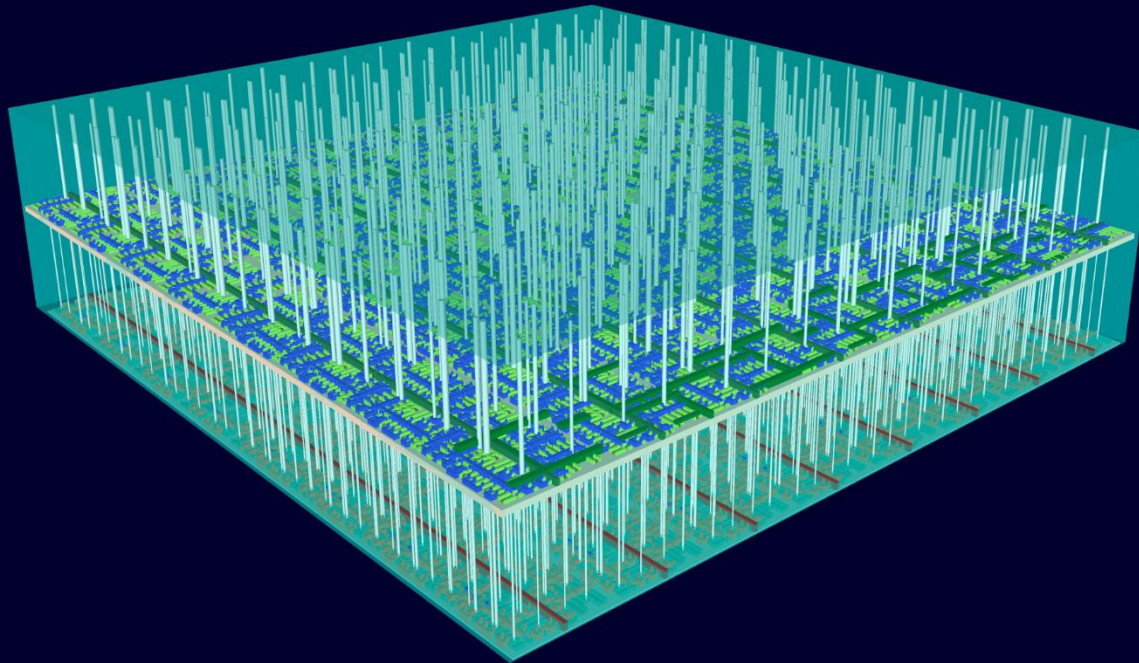


Classification accelerator  
*on-chip computation*



# 3D NanoSystem: Fabrication

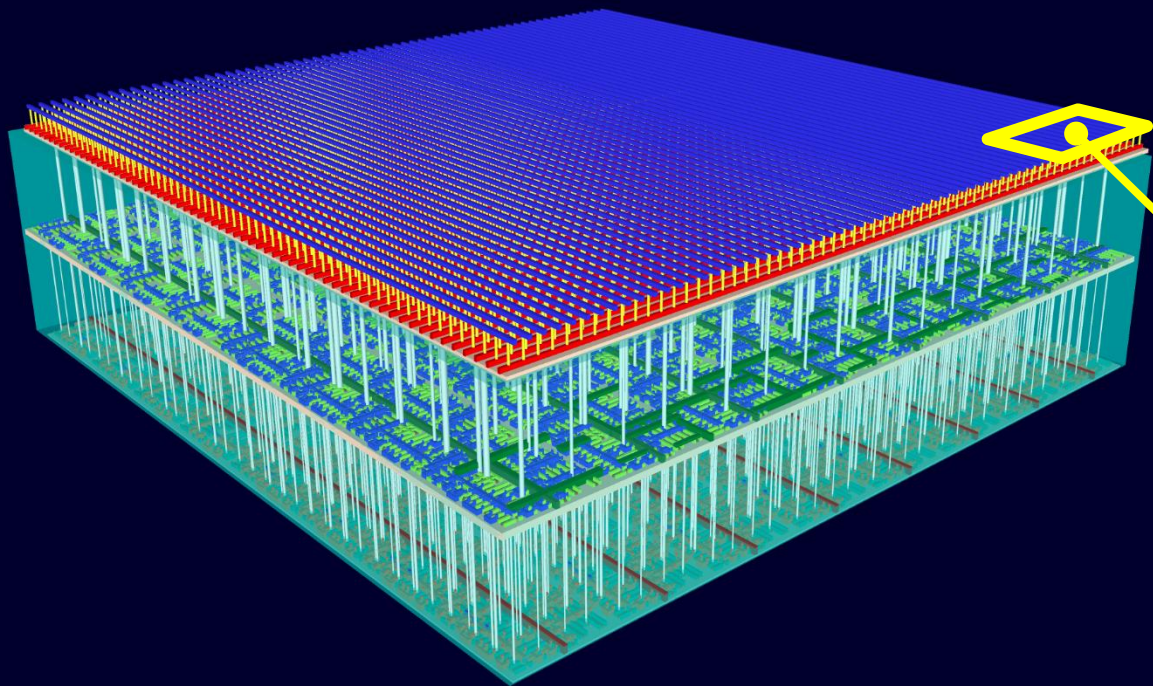
- **2<sup>nd</sup> ILD + ILVs**



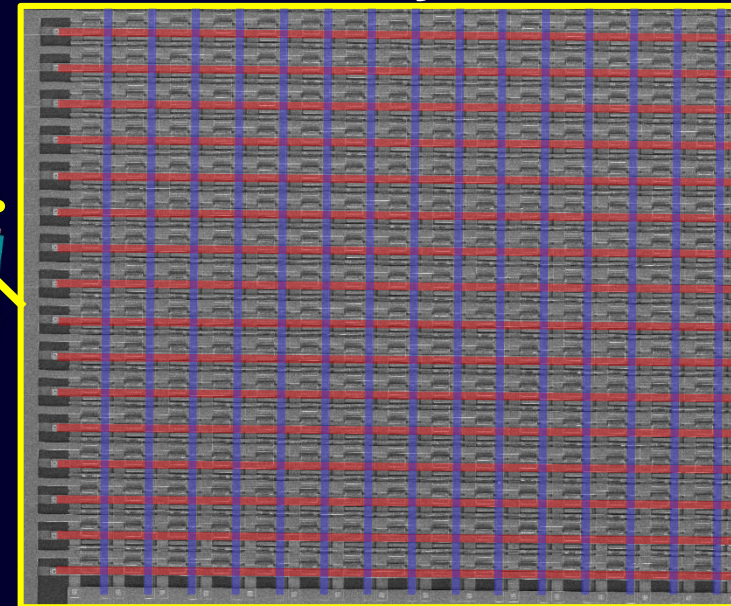


# 3D NanoSystem: Fabrication

- Memory: RRAM

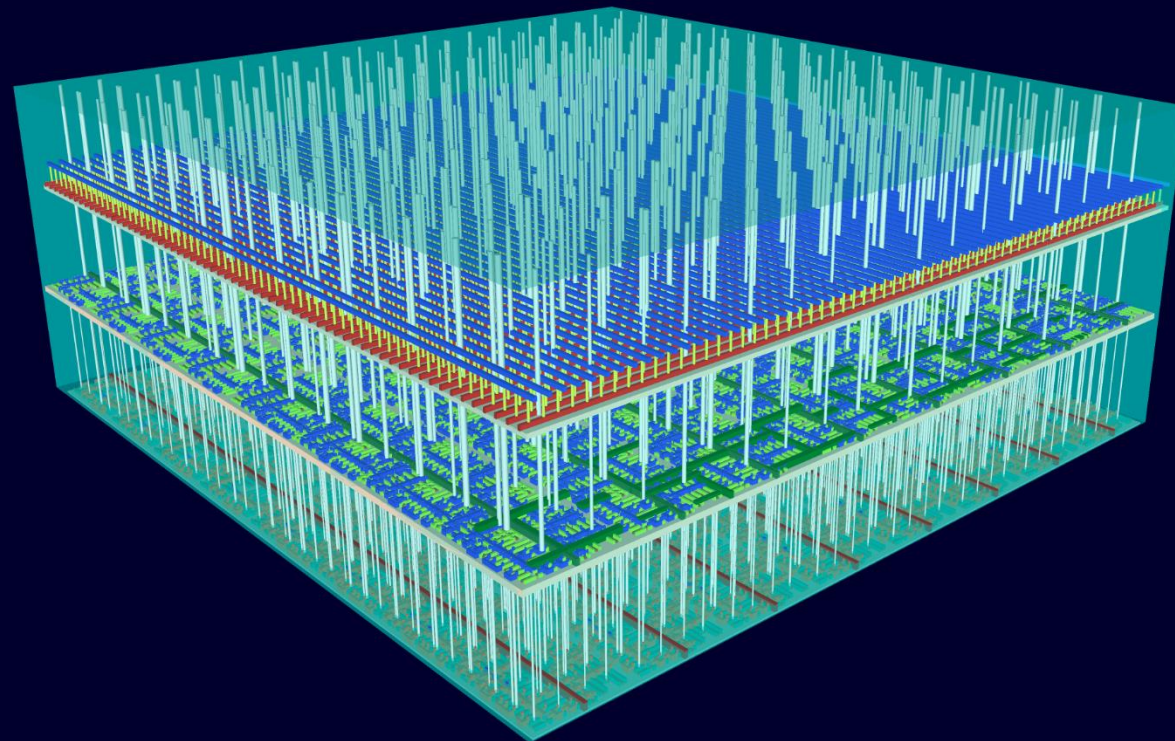


RRAM array: **1 Mbit**



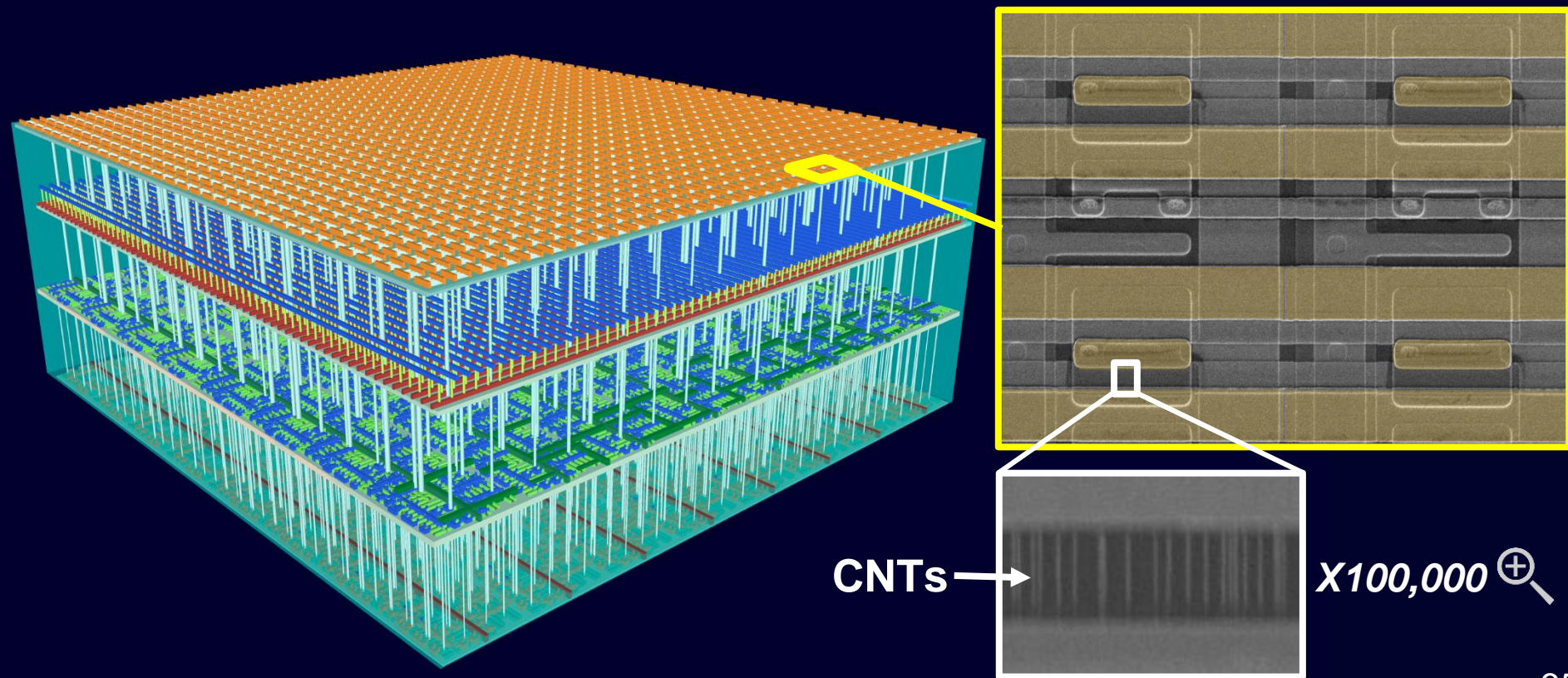
# 3D NanoSystem: Fabrication

- **3<sup>rd</sup> ILD + ILVs**



# 3D NanoSystem: Fabrication

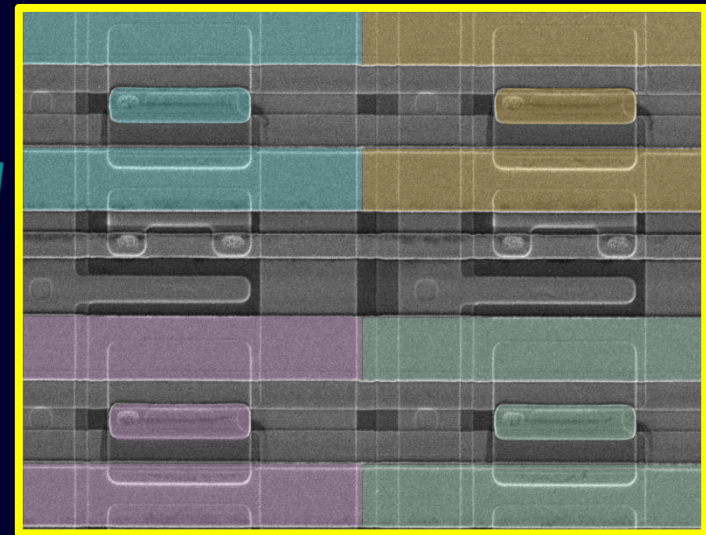
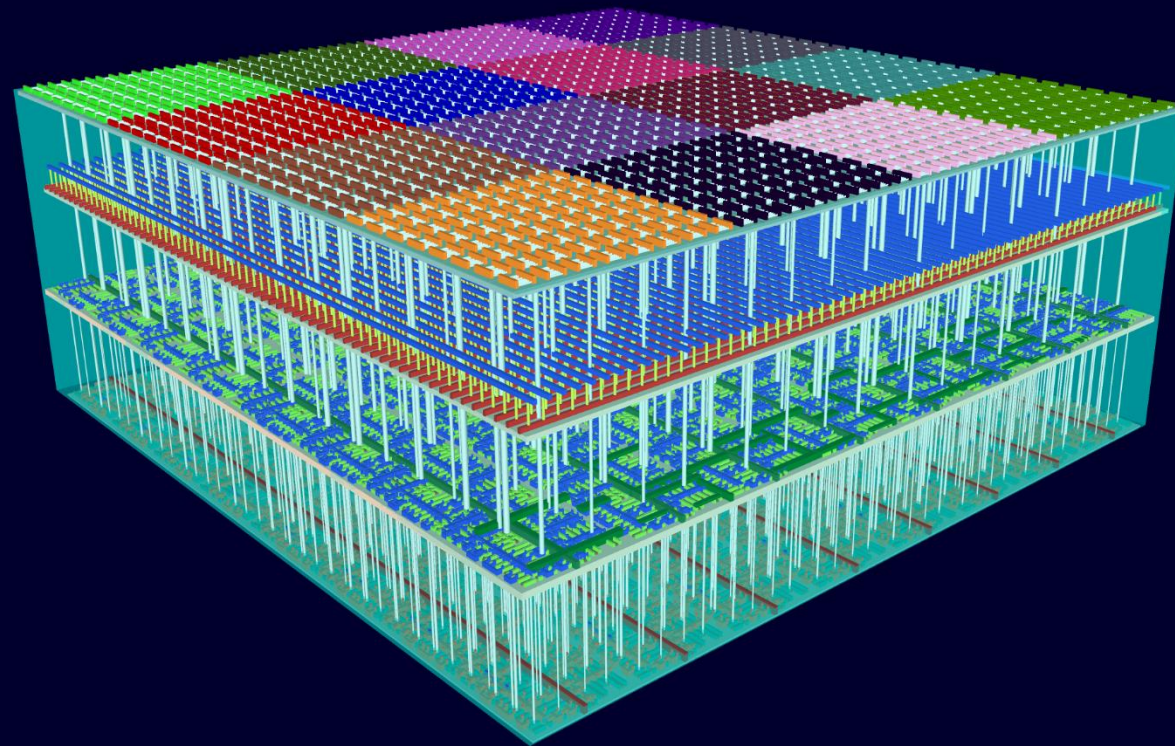
- CNFET logic



# 3D NanoSystem: Fabrication

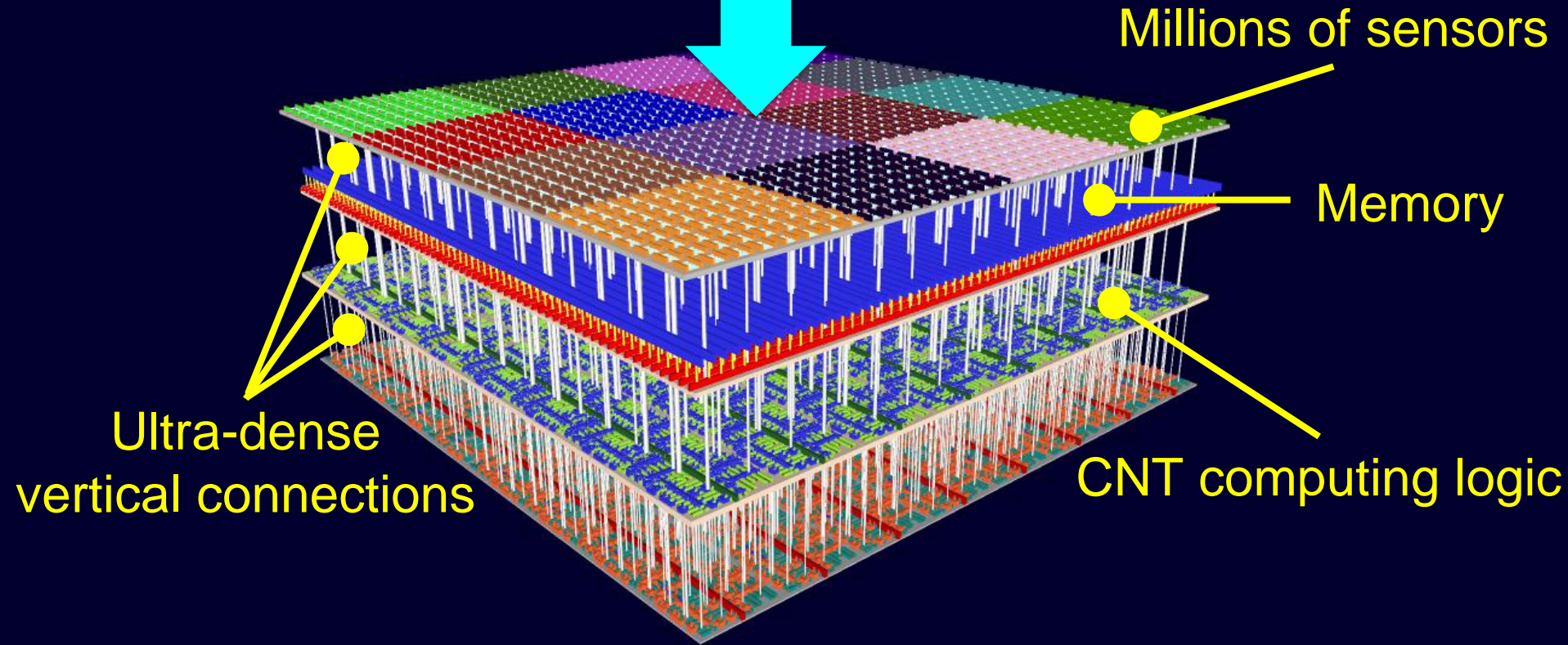
- CNFET functionalization

**>1 million** gas sensors



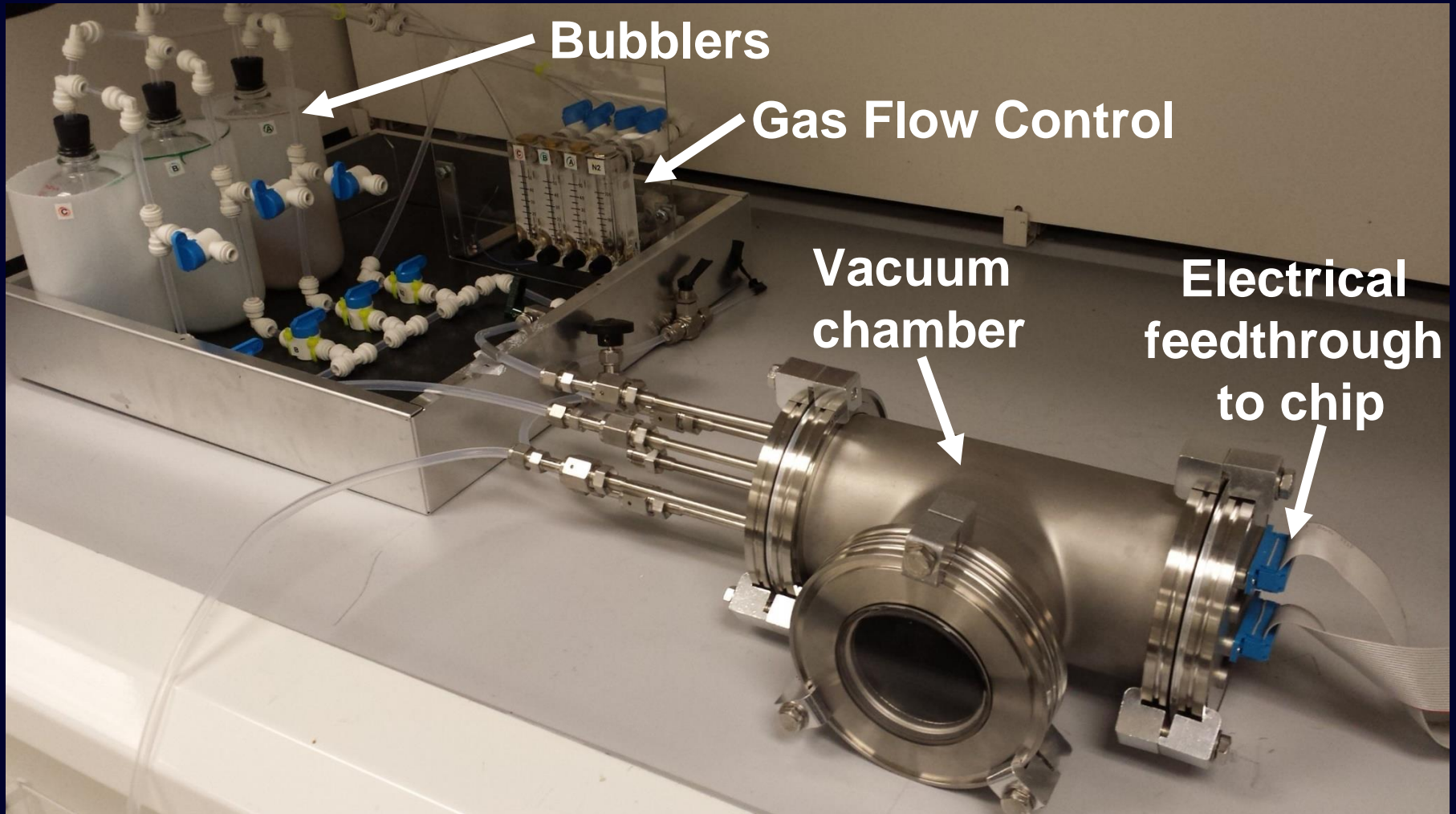
# Integrated Computation + Memory + Sensing

Terabytes / second



***Abundant sensor data:  
Extensive + accurate classification***

# Experimental Demo

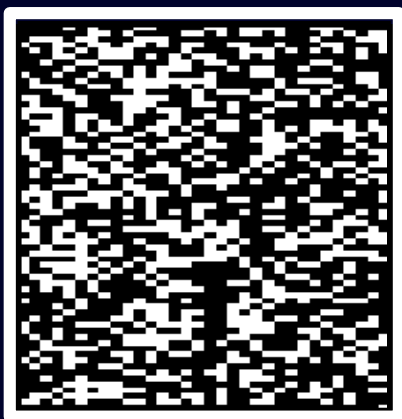


# Raw Data

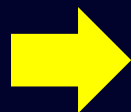
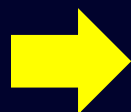
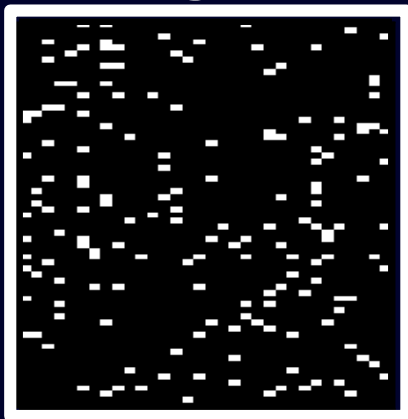
Sensor data written  
to RRAM array

CNFET classification accelerator

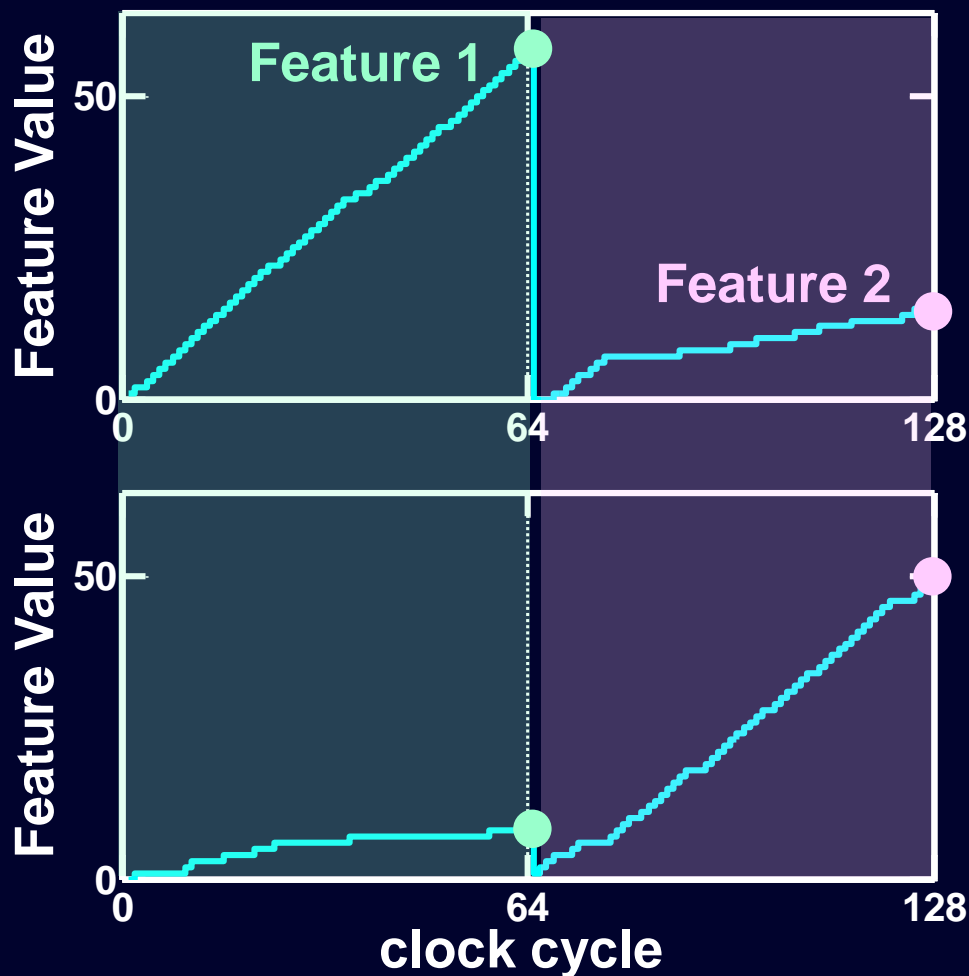
Lemon Juice



Rubbing Alcohol

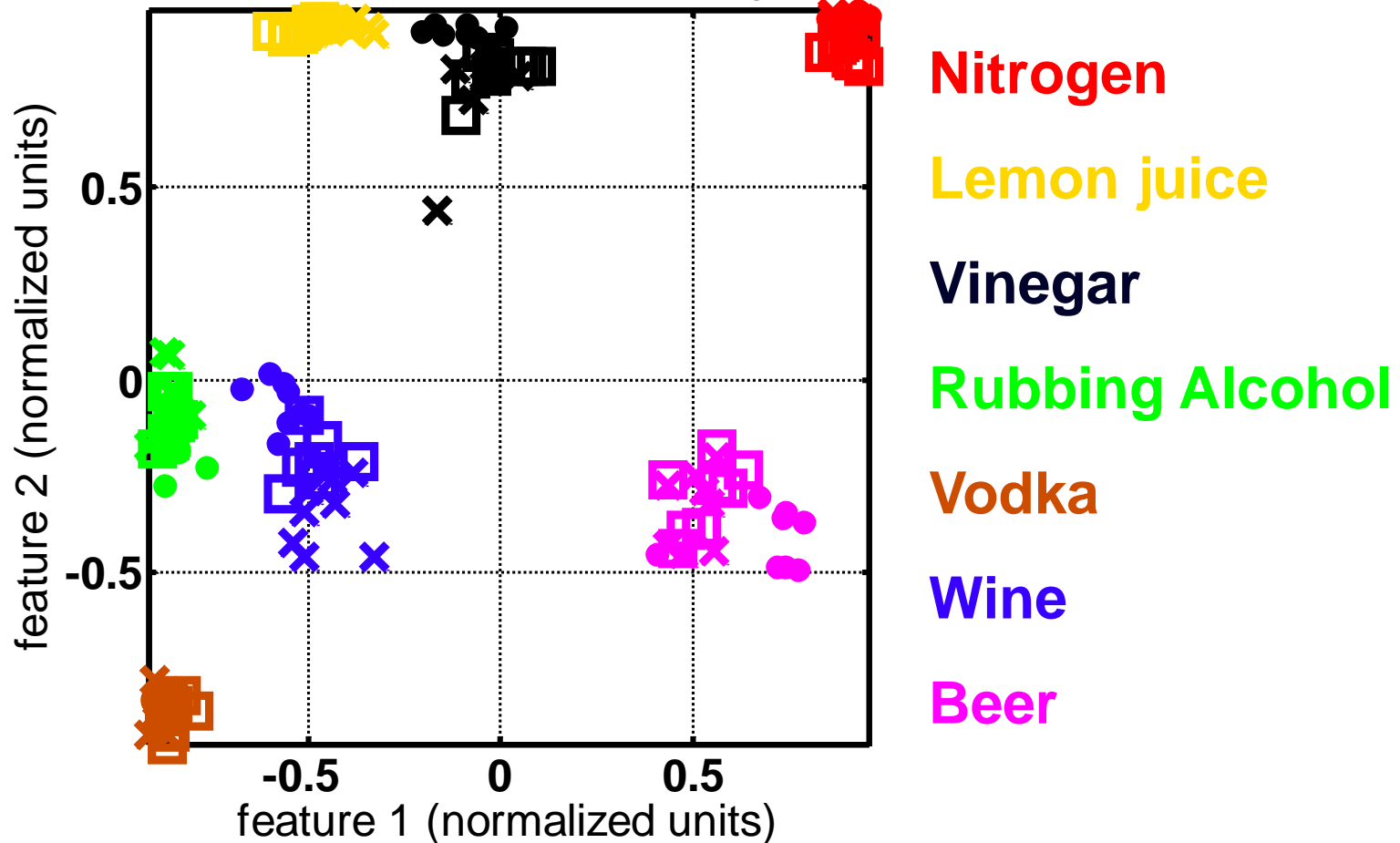


Measured Output



# Experimental Results

## Principle Component Analysis (PCA)





# 3D NanoSystem: Take-Away

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- **Energy-efficient logic + memory**
  - Heterogeneous integration

# 3D NanoSystem: Take-Away

- **Energy-efficient logic + memory**
  - Heterogeneous integration
- **High bandwidth communication**
  - Fine-grained 3D integration

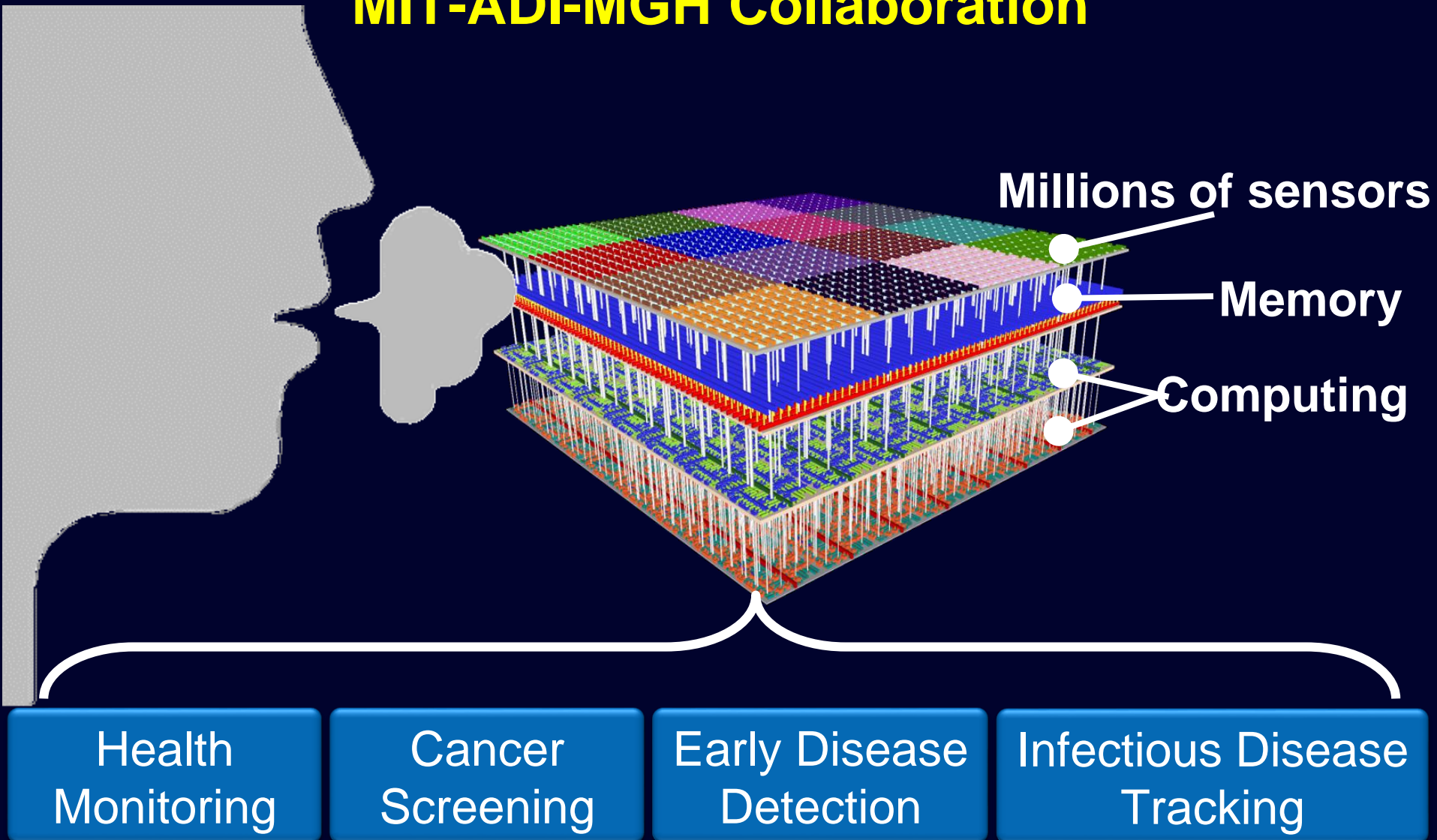
# 3D NanoSystem: Take-Away

- **Energy-efficient logic + memory**
  - Heterogeneous integration
- **High bandwidth communication**
  - Fine-grained 3D integration
- **Transform massive data into useful info**
  - Sensing immersed in computation + memory

# Big-Data Healthcare Analytics:

*Massively Parallel Sensing Immersed in Computation*

**MIT-ADI-MGH Collaboration**



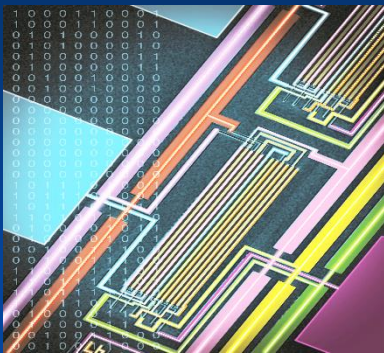
# New Technologies → New Applications



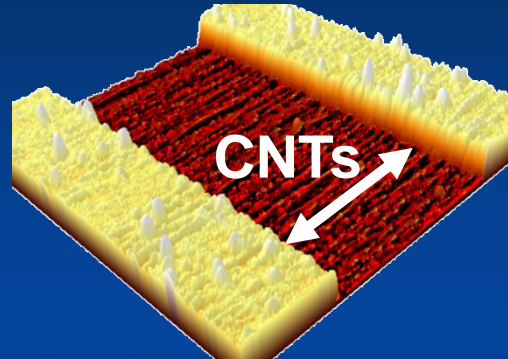
# Conclusion

- Nanosystems useful **today**
  - Exciting opportunities
- New solutions: elegantly simple
  - Combined processing + circuit design

First Nanosystem Demos



High Performance CNFETs



Future Nanosystem Prototypes

