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A New Synapse For Non-Von Neumann Architectures Based On Switching

A Correlated-Electron Random Access Memory (CeRAM) Cell

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University of Colorado Colorado Springs
and
Symetrix Corporation

Key Collaborators:
Jolanta Celinska
Chris McWilliams

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Contents

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1. How Did We Get Here?

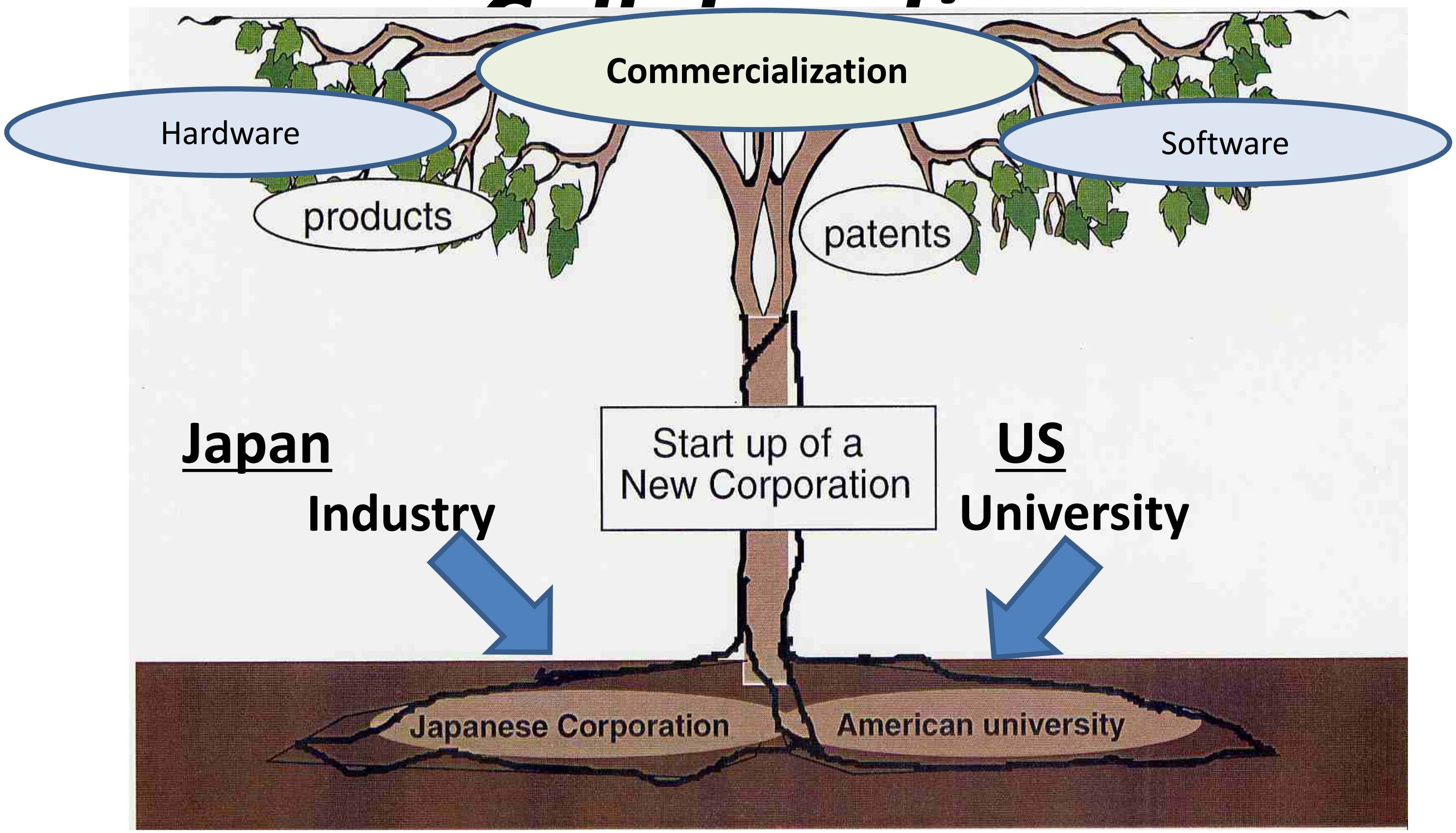
!984 – We looked a lot better.
But we dreamed and We Believed So That We Could See..

COLABORATIVE RESEARCH
Started in 1984
With Prof. Dr. Gota Kano,
Dr. Larry McMillan
and a 32 Year old
Yong Engineer.

Let's Salute these Men in
This Great 20^{th} Anniversary
Of the Formal Beginning
OF Entrepreneur Engineer.

(Last Picture We took Together.
. Colorado Springs 2016)

Case Study
US/Japan Complementary



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FATIGUE FREE*

- We used this for our Ferroelectric Memory. We were
- The First In The world to Show “Fatigue Free (Almost Infinite Endurance Ferroelectric Memories).
- This was 1991. Little we knew that we were describing OURSELVES.

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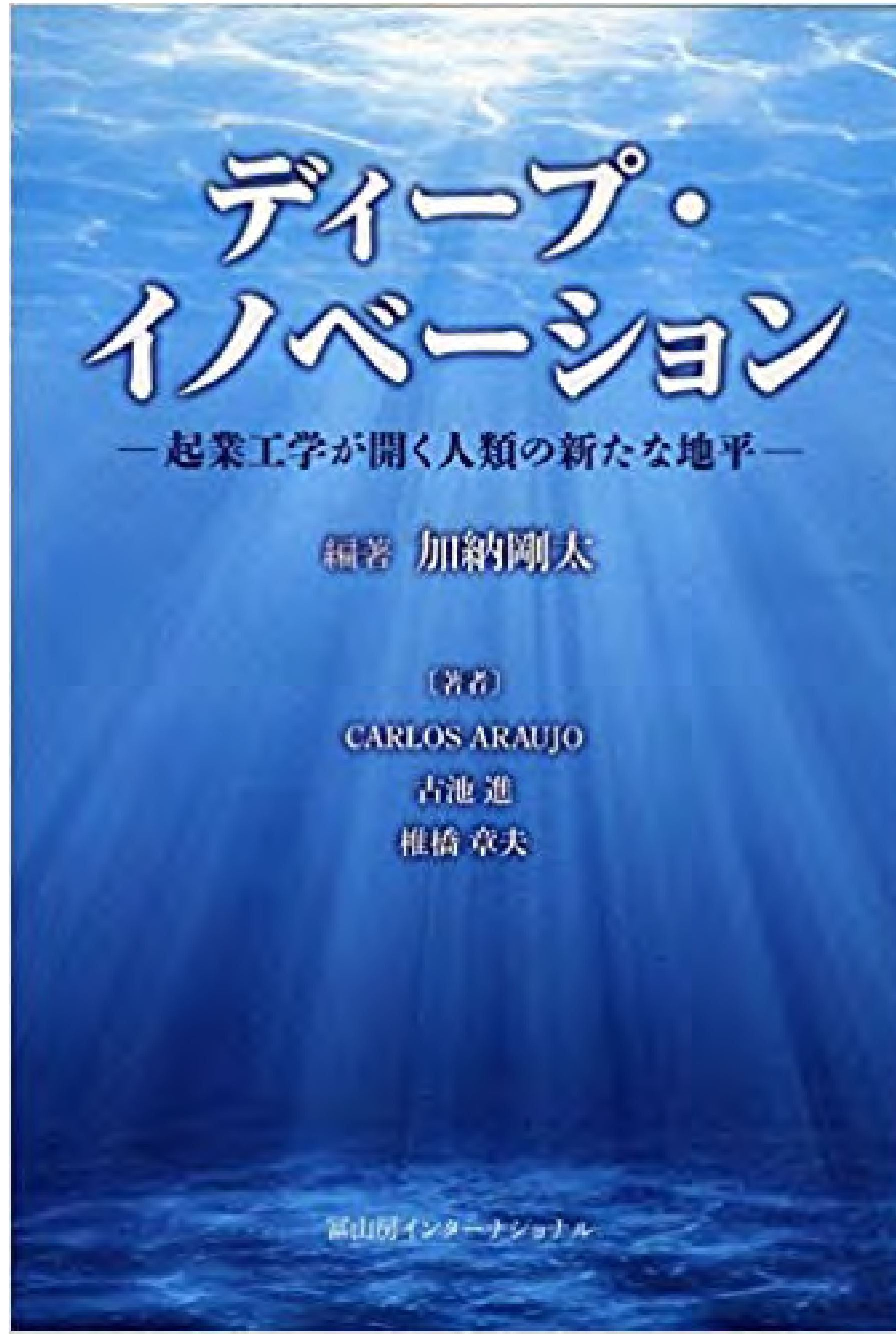
The Future Will Belong To Those
Who Now Have The Passion
To Dive Deep Into The Sea Of Knowledge.
In so Doing, They May Contribute More
To Human Society Then Many Others,
And Even If They
Fail Or Are Forgotten,
They Truly Lived, And
Lived FREE.



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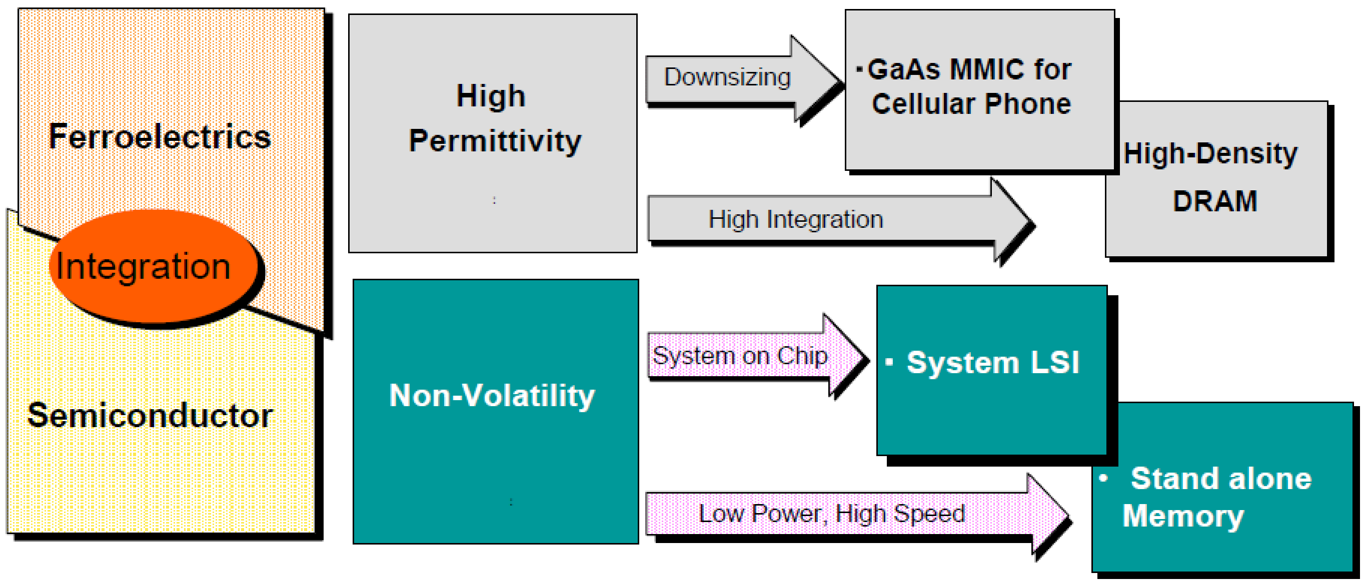
Concept of LSI integrated with Ferroelectrics

Innovation by a New Combination of Ferroelectrics and Semiconductor



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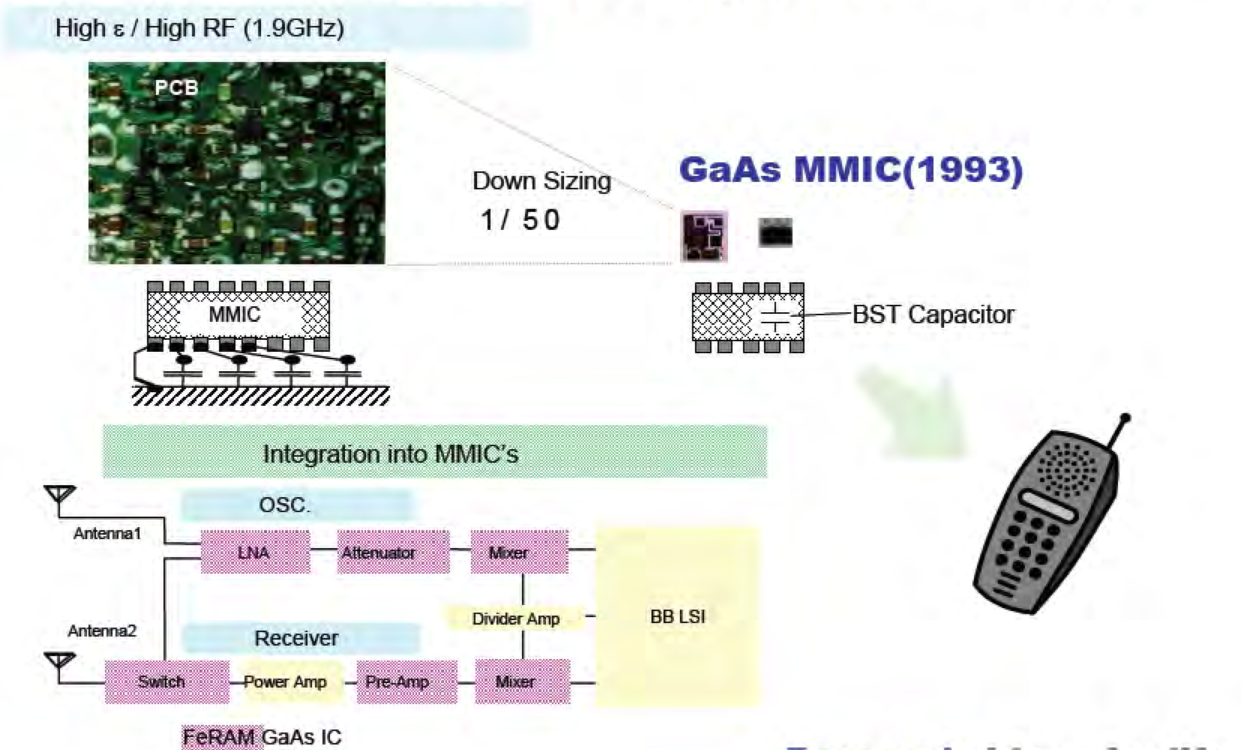
First Commercialization in Mass Market

GaAs MMIC with Integrated BST Cap for Cellular Phone



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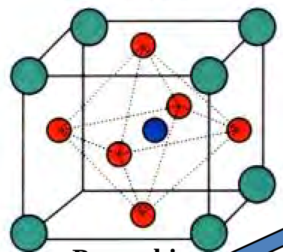
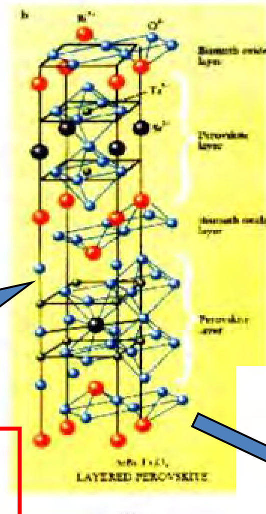
The Serendipitous Discovery of Y-1
8/29/91

PZT



Perovskite

SBT



SBT Chemical Formula:

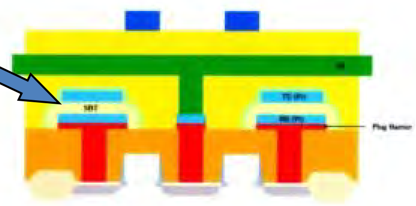
$A_{m-1}Bi_2B_mO_{3m+3}$

A → Ca, Sr, Ba, Pb

B → Ti, Nb, Ta

$Sr\,Bi_2\,Ta_2\,O_9$

Layered Perovskite Superlattice



$SrBi_2Ta_2O_9$

tantalum butoxide + 2-ethylhexanoic acid + xylenes

↓

react 48 hours on 185°C hot plate

↓

add metallic strontium

↓

allow strontium to react completely

↓

distill off butanol and water

↓

add bismuth 2-ethylhexanoate

Reactions:

$Ta(OC_4H_9)_5 + 5\ HO_2C_8H_{15} \rightarrow Ta(O)(O_2C_8H_{15})_3 + H_2O + 3\ HOC_4H_9 + 2\ H_9C_4O_2C_8H_{15}$

$Sr + 2\ HO_2C_8H_{15} \rightarrow Sr(O_2C_8H_{15})_2 + H_2$

Second implementation of FE concept

Directed at improving retention, imprint, reliability and endurance (superior to PZT)

United States Patent [19] | [11] Patent Number: 5,688,565
McMillan et al. | [45] Date of Patent: *Nov. 18, 1997

[54] MISTED DEPOSITION METHOD OF FABRICATING LAYERED SUPERLATTICE MATERIALS

4,792,463 12/1988 Okada et al. 427/126.3
4,811,684 3/1989 Tadano et al. 118/50.1
(List continued on next page.)

License
Matsushita
IC's: 100 million sold

Journal, Nature,
Vol. 374, pp.627-629, 1995

1. Inventions and basic research of Integrated Ferroelectrics

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<u>Case Study</u>
US-Japan

~1987~

Believe Me !
Believe Me !

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Early FeRAM Applications

Data collection & logging

Smart Cards

SRAM Replacement & expansion

Configuration storage for sudden power loss

Video Games

Nonvolatile buffer for operating data

2012 11・12
Gota Kano

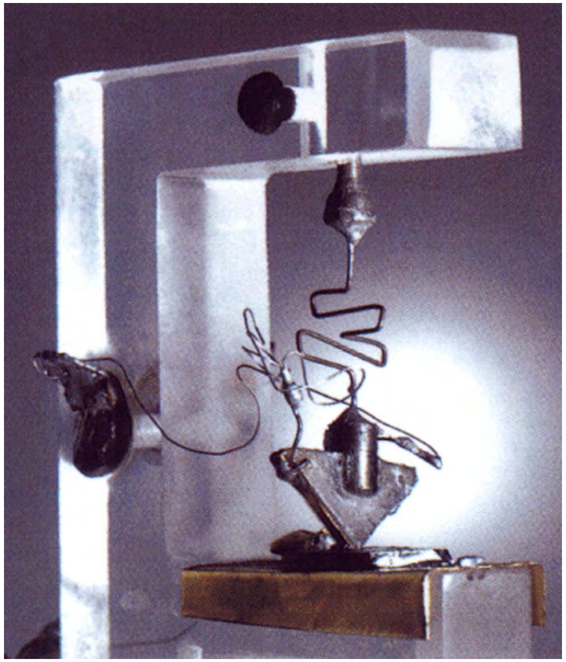
Symetrix

Our “Young Engineer”
Masamichi Azuma
(Now not so young now)

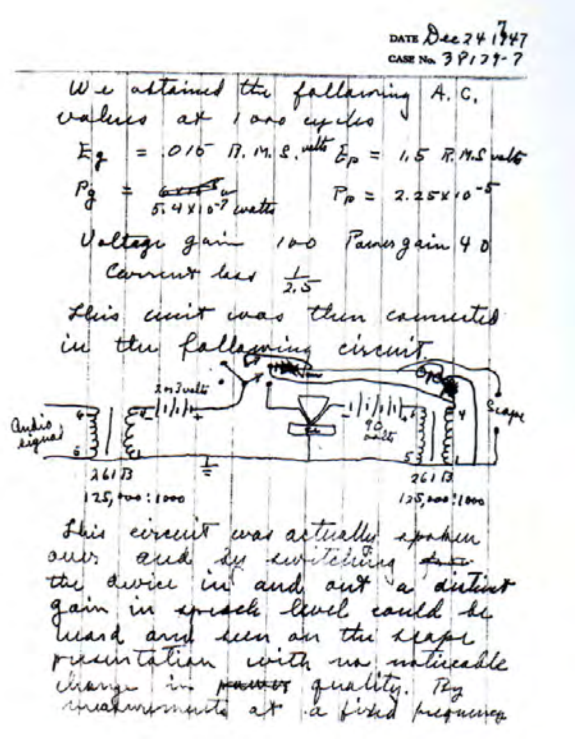
Dr. Tatsuo Otsuki
Deserves All Honor
For being “The Youngest Engineer” behind all of “This Great Success Story”. He and so many others are the Heroes that should not be forgotten.
They all BELIEVED Without Seeing. And they still have the FIRE THAT BURNED WITHIN US…

KNOWLEDGE THAT IMPACTED ALL

TRANSISTOR **1947**



What If they Had NOT BELIEVED?


DATE Dec 24 1947
CASE No. 38139-7

We obtained the following A.C. values at 1000 cycles

Eg = .015 R.M.S. volts Ep = 1.5 R.M.S volts

Pg = 5.4 x 10-7 watts Pp = 2.25 x 10-5

Voltage gain 100 Power gain 40

Current loss 1/2.5

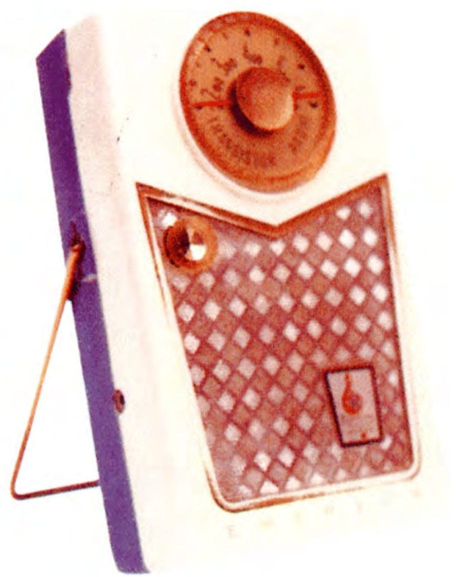
This unit was then connected in the following circuit.

This circuit was actually spoken over and by switching the device in and out a distinct gain in speech level could be heard and seen on the scope presentation with no noticeable change in quality. By measurements at a fixed frequency

SHOCKLEY' S NOTEBOOK
QUANTUM MECHANICS MEETS ELECTRICAL ENGINEERING

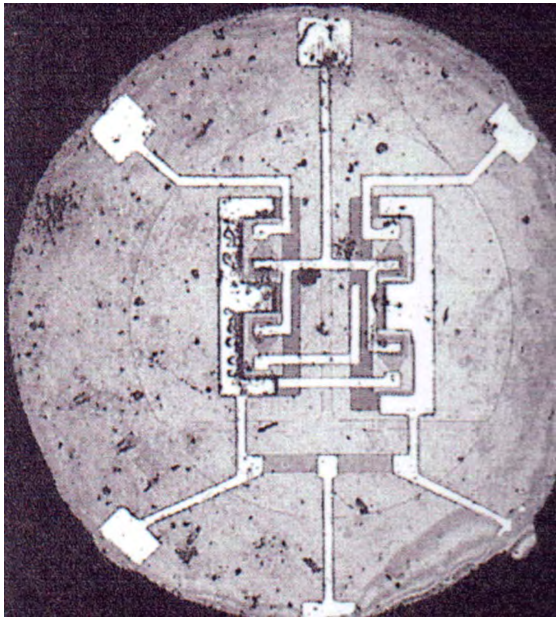
Our World is so dependent on DREAMERS with the passion to search for the seemingly IMPOSSIBLE, and yet the future would never really be THE FUTURE without them.

FIRST TRANSISTOR RADIO **1955**



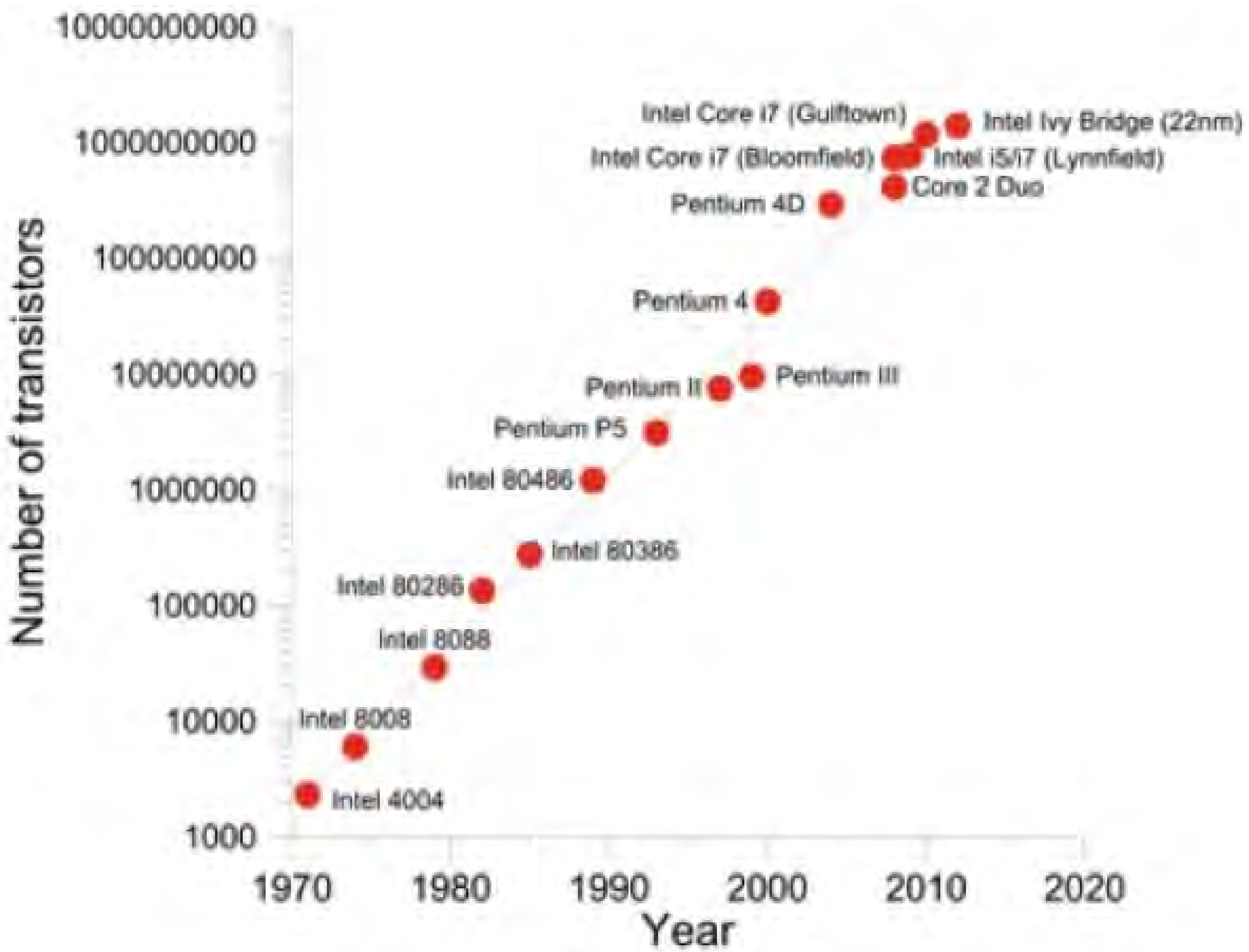
THE USE OF THE PORTABLE AMPLIFIER

INTEGRATED CIRCUITS **1961**



THE BIRTH OF THE IC. With The Transistor as THE FIRST DIGITAL SWITCH

2. How Did the Industry Get Here?



3. Why Innovation is Needed?

5 nm Fabs will Cost 20 Billions USD

Over 80% of the area of a SoC Chip is Memory

FLASH cannot be reliable below 32 nm (cell Design Rule)

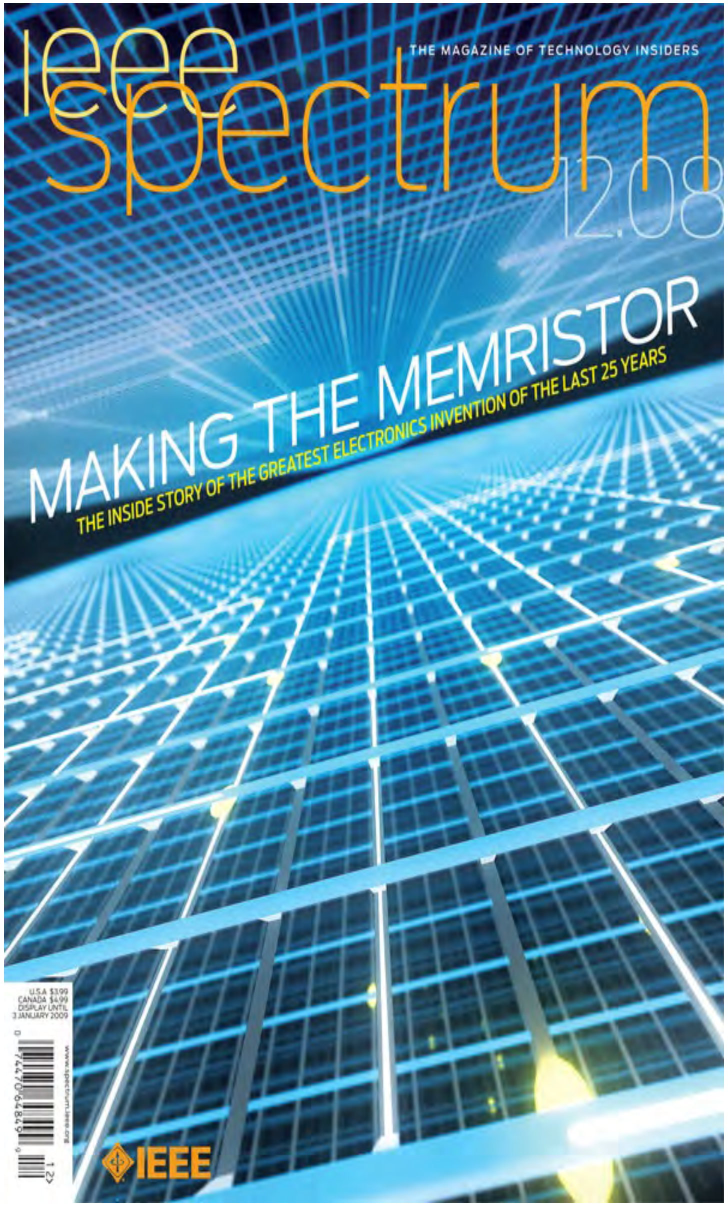
FLASH has less than 50 electrons at 32 in the Floating Gate

Nonvolatile memory at low cost is NEEDED - IoT

Non-Von Neumann (AI) Architectures will need a new Nonvolatile Switch

SPEED at Low Power is needed

FPGAs need small NV Fuses



A False Start?

$$dV = R\,dI + I\,dR$$

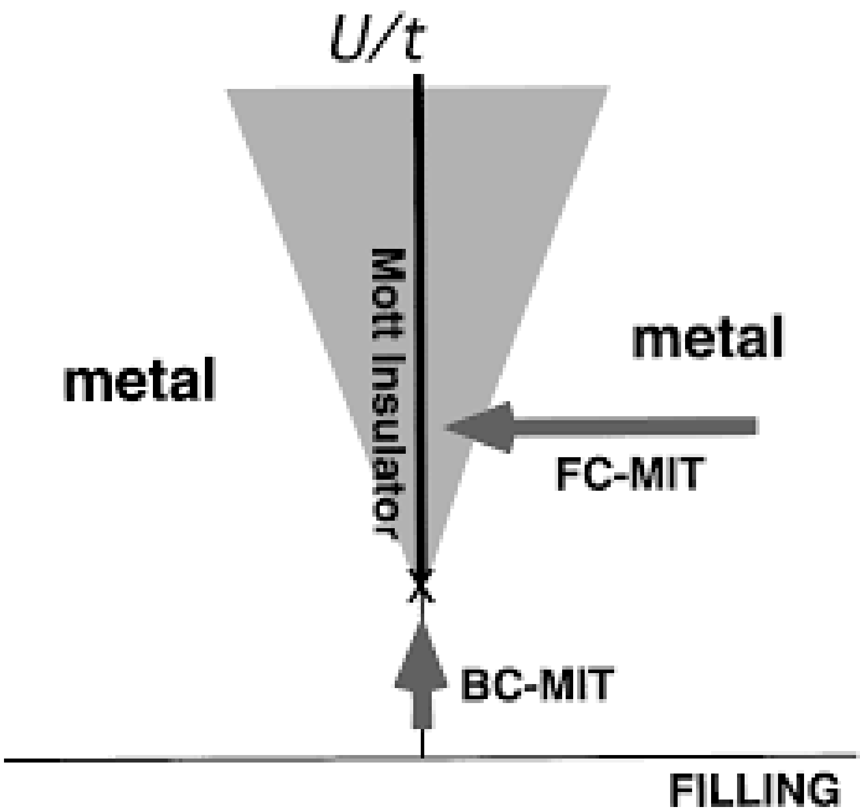
dR? –YES. But not via Oxide Breakdown.

JAPAN WAS OVER 21 YEARS AHEAD

THE MASTERS

IMADA-SAN and Collaborators

I Salute You.



Metal-insulator transitions

Masatoshi Imada
Institute for Solid State Physics, University of Tokyo, Roppongi, Minato-ku, Tokyo, 106, Japan
Atsushi Fujimori Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, 113, Japan
Yoshinori Tokura Department of Applied Physics, University of Tokyo,
Hongo, Bunkyo-ku, Tokyo, 113, Japan

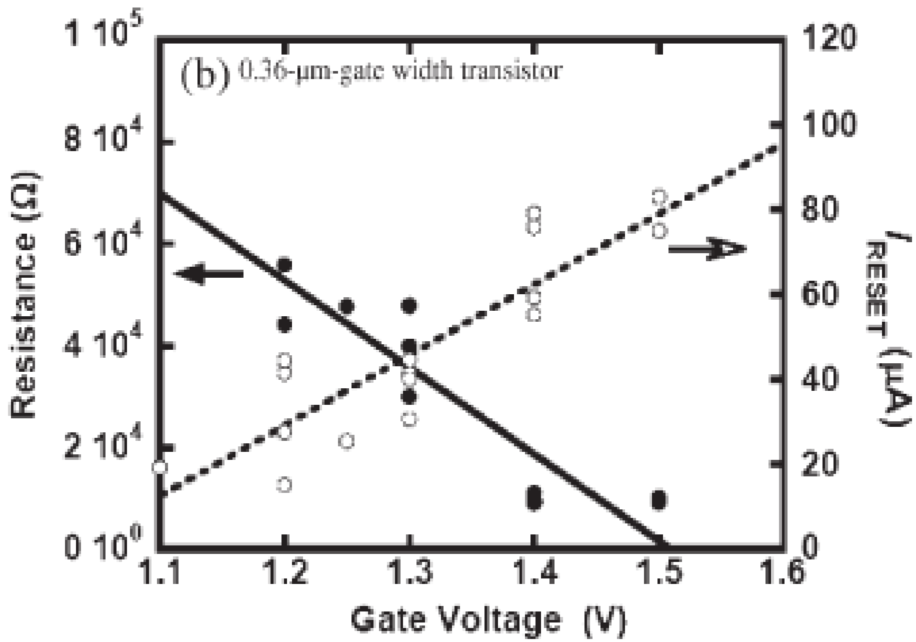
ABSTRACT

Metal-insulator transitions are accompanied by huge resistivity changes, even over tens of orders of magnitude, and are widely observed in condensed-matter systems…….. Rev. Mod. Phys., Vol. 70, No. 4, October **1998**

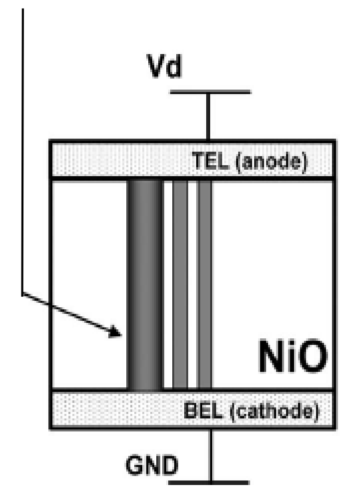
2018 School of Engineering
Professional Retirement Party
(March 7, 2019)

Professor Imada

The Beginning of The SEARCH OF A NEW SWITCH



Filament size determined by SET current compliance



- Fatter filament if higher SET current → Harder to break → Higher RESET current
- Careful transient current control for SET important, for both RRAM device development and array architecture. Keep parasitic capacitances in your test setup in mind while

Ref: Y. Sato, et al., TED 2008, [2] F. Nardi, et al, IMW 2010.

This work was supported in part by the member companies of the Stanford Non-Volatile Memory Technology Research Initiative (NMTRI).

Multi-level control of conductive nano-filament evolution in HfO_2 ReRAM by pulse-train operations†

L. Zhao [a], H.-Y. Chen [a], S.-C. Wu [b], Z. Jiang [a], S. Yu [c], T.-H. Hou [b], H.-S. Philip Wong [a] and Y. Nishi *[a]

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[b]*Department of Electronics Engineering, National Chiao Tung University, ED-309C, 1001 University Road, Hsinchu 300, Taiwan*

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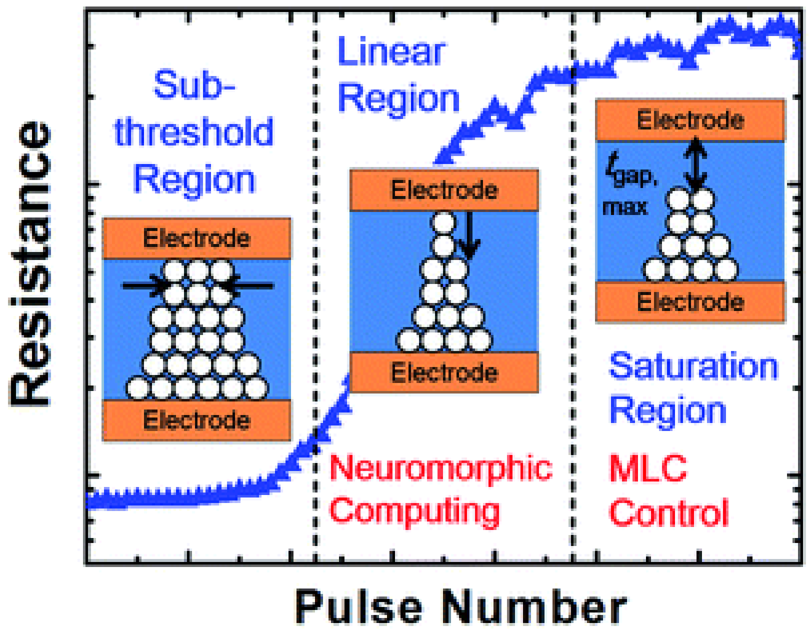
Received 24th January 2014 , Accepted 16th March 2014

Nanoscale, 2014, 6, 5698



THE SEMICONDUCTOR INDUSTRY CONTINUES TRYING THIS TO TODAY. LOOKING FOR THE GOLDEN FILAMENT AND MISSING THE BEAUTIFUL PHYSICS OF PROFESSOR IMADA'S PAPER.

AN INTELLECTUAL MISTEP

SEMICONDUCTORS:

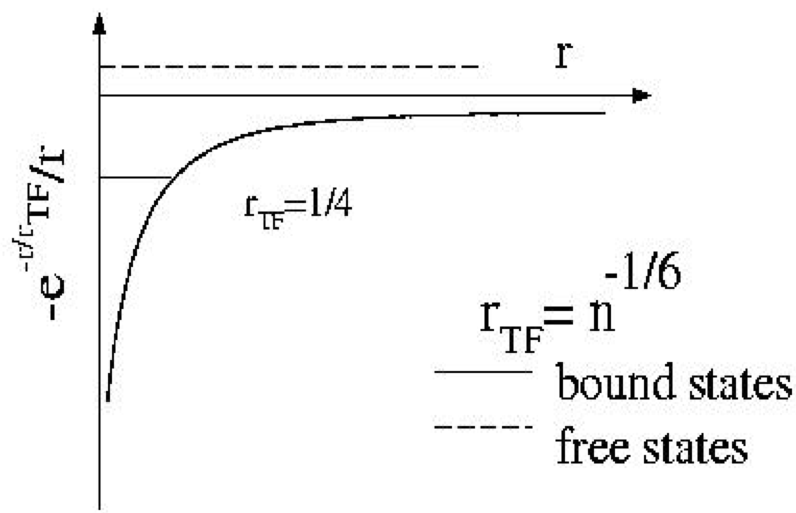
$$\frac{-\hbar^2}{2m}\nabla^2\Psi(\mathrm{r}) + V(r)\Psi(\mathrm{r}) = E\Psi(\mathrm{r})$$

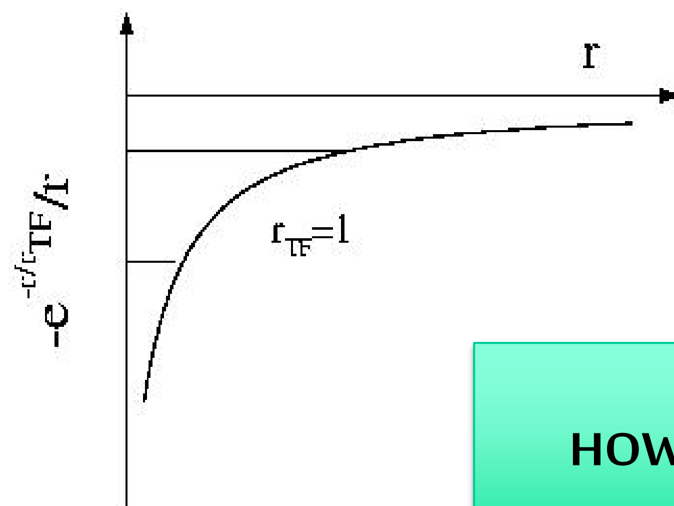
Kinetic Energy + *Potential Energy* = *Total Energy*

This IGNORES ELECTRON STRONG CORRELATIONS

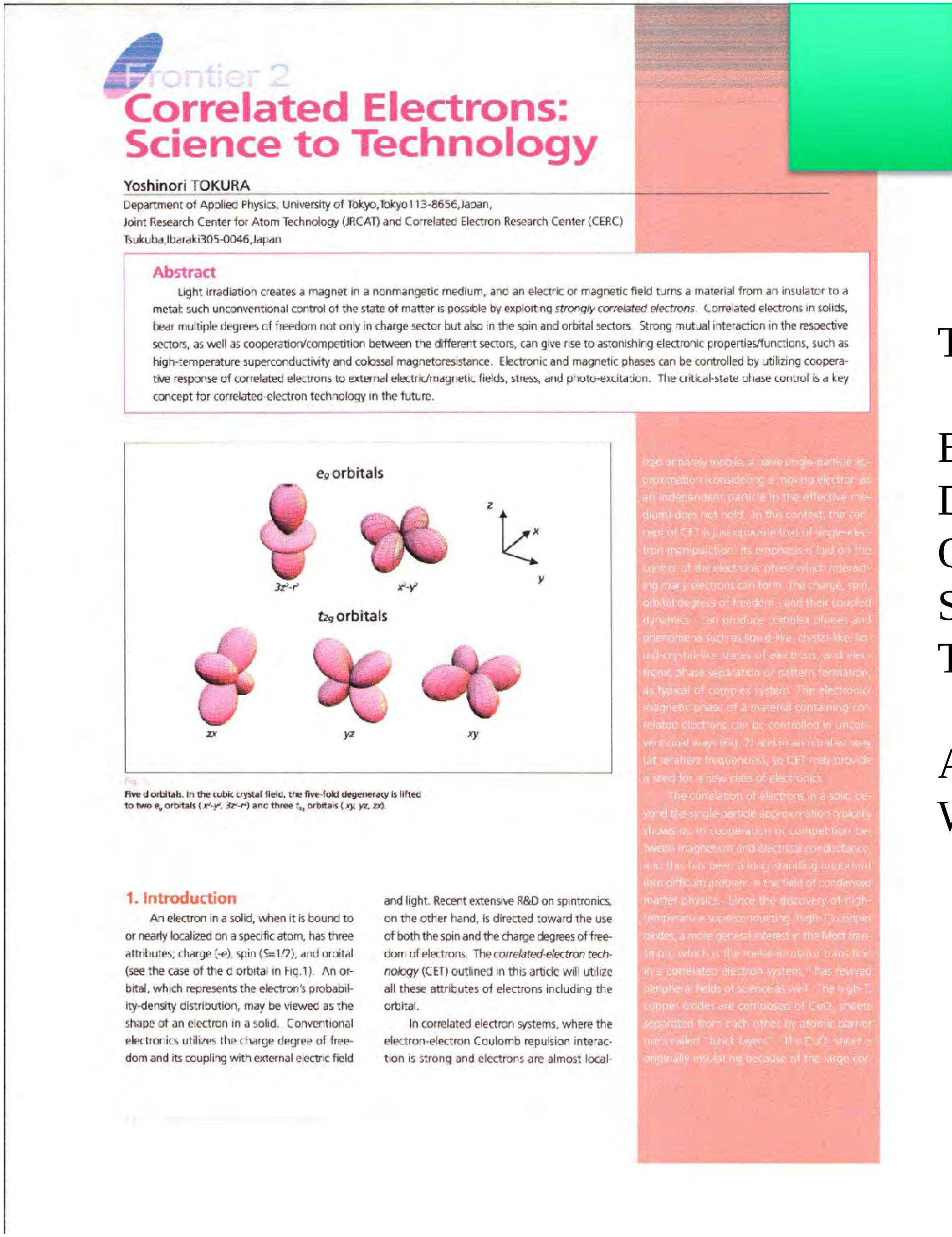
MOTT INSULATORS:

V(r) Can Be Controlled: a 120 PICOMETER DIAMETER SWITCH





HOW????



Frontier 2

Correlated Electrons: Science to Technology

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Department of Applied Physics, University of Tokyo, Tokyo113-8656, Japan,
Joint Research Center for Atom Technology (JRCAT) and Correlated Electron Research Center (CERC)
Tsukuba, Ibaraki305-0046, Japan

Abstract

Light irradiation creates a magnet in a nonmangetic medium, and an electric or magnetic field turns a material from an insulator to a metal: such unconventional control of the state of matter is possible by exploiting *strongly correlated electrons*. Correlated electrons in solids, bear multiple degrees of freedom not only in charge sector but also in the spin and orbital sectors. Strong mutual interaction in the respective sectors, as well as cooperation/competition between the different sectors, can give rise to astonishing electronic properties/functions, such as high-temperature superconductivity and colossal magnetoresistance. Electronic and magnetic phases can be controlled by utilizing cooperative response of correlated electrons to external electric/magnetic fields, stress, and photo-excitation. The critical-state phase control is a key concept for correlated-electron technology in the future.

Fig. 1
Five d orbitals. In the cubic crystal field, the five-fold degeneracy is lifted to two e_g orbitals (x^2-y^2, $3z^2-r^2$) and three t_{2g} orbitals (xy, yz, zx).

1. Introduction

An electron in a solid, when it is bound to or nearly localized on a specific atom, has three attributes; charge (-e), spin (S=1/2), and orbital (see the case of the d orbital in Fig.1). An orbital, which represents the electron's probability-density distribution, may be viewed as the shape of an electron in a solid. Conventional electronics utilizes the charge degree of freedom and its coupling with external electric field and light. Recent extensive R&D on spintronics, on the other hand, is directed toward the use of both the spin and the charge degrees of freedom of electrons. The *correlated-electron technology* (CET) outlined in this article will utilize all these attributes of electrons including the orbital.

In correlated electron systems, where the electron-electron Coulomb repulsion interaction is strong and electrons are almost localized or barely mobile, a naive single-particle approximation (considering a moving electron as an independent particle in the effective medium) does not hold. In this context, the concept of CET is just opposite that of single-electron manipulation: its emphasis is laid on the control of the electronic phase which interacting many electrons can form. The charge, spin, orbital degrees of freedom - and their coupled dynamics - can produce complex phases and phenomena such as liquid-like, crystal-like, liquid-crystal-like states of electrons, and electronic phase separation or pattern formation, as typical of complex system. The electronic/magnetic phase of a material containing correlated electrons can be controlled in unconventional ways (Fig. 2) and in an ultrafast way (at terahertz frequencies), so CET may provide a seed for a new class of electronics.

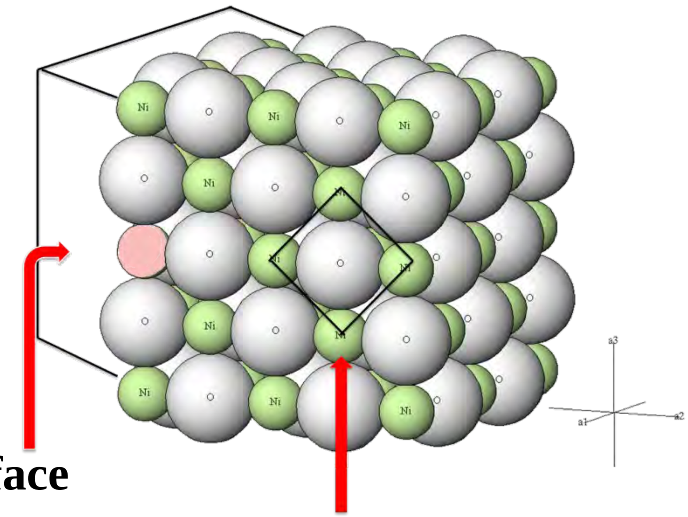
The correlation of electrons in a solid beyond the single-particle approximation typically shows up in cooperation or competition between magnetism and electrical conductance, and this has been a long-standing important (but difficult) problem in the field of condensed matter physics. Since the discovery of high-temperature superconducting (high-T_c) copper oxides, a more general interest in the Mott transition, which is the metal-insulator transition in a correlated electron system,[1] has revived peripheral fields of science as well. The high-T_c copper oxides are composed of CuO_2 sheets separated from each other by atomic barrier units called "block layers". The CuO_2 sheet is originally insulating because of the large cor-

Text Books Explain This…

But Today's Semiconductor Engineers
Do Not Have the Education in
Quantum Field Theory Applied to
Solid State (Condensed Matter Physics)
To Understand How to do This.

Also, a Materials Breakthrough
Was Needed.

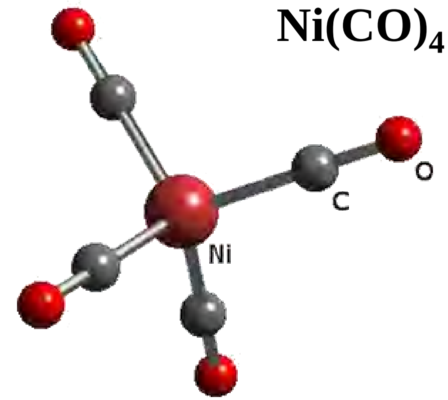
Ligand Doping



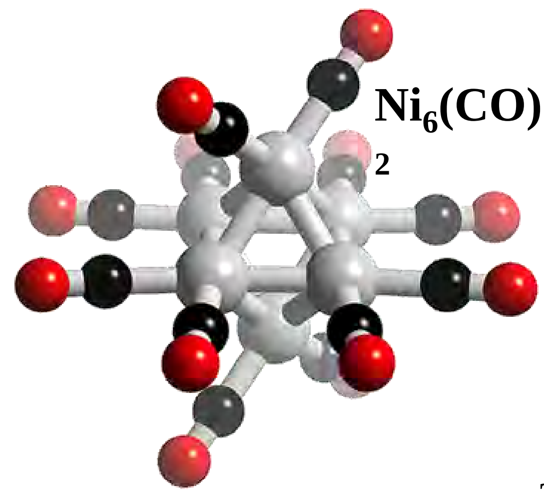
Surface defects

NiO Octahedral

$Ni(CO)_4$



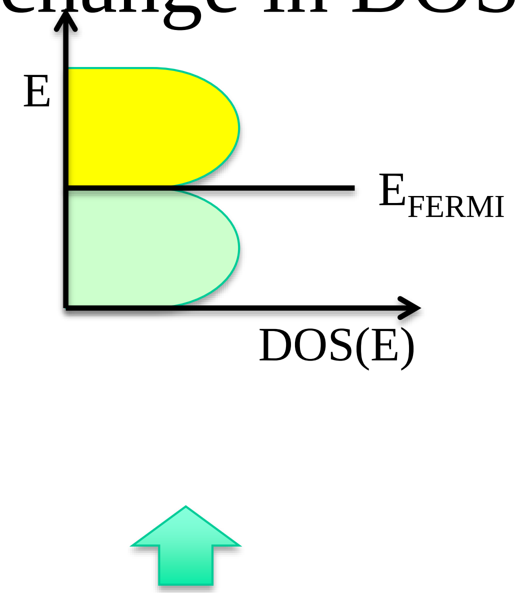
$Ni_6(CO)_{12}$



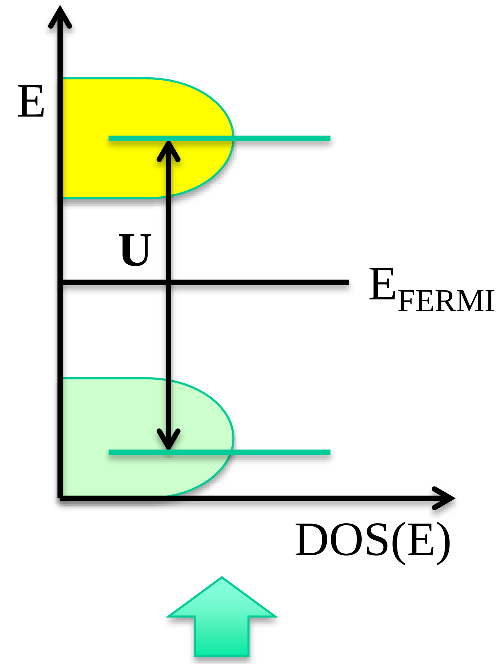
Lattice defects at the surface are compensated by Nickel carbonyl complexes. (Patented: All TMOs with Carbon or Carbon Compounds)

The CeRAM Mechanism

- Use the "natural ability" in Transition Metal Oxides that allows a Change in n due to a change in DOS(E)

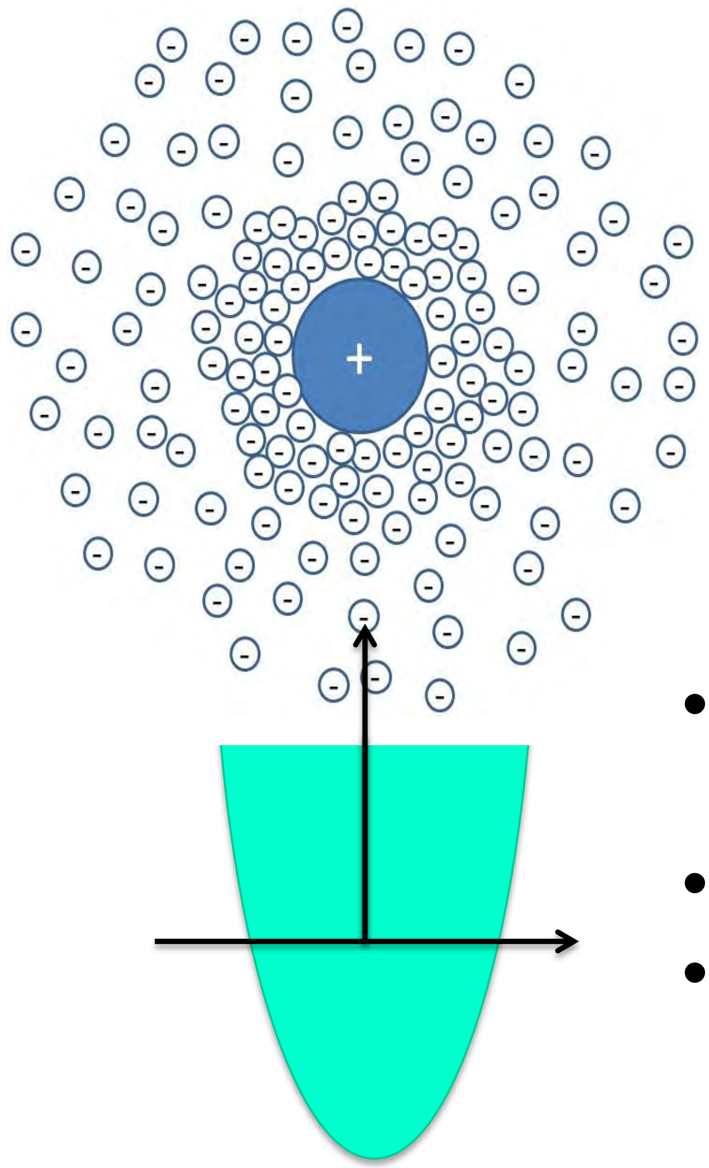


R = small

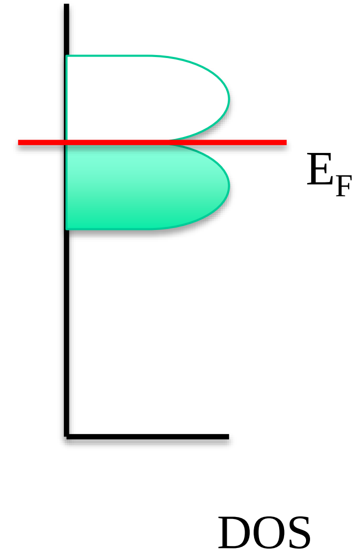


R = Large

Screening

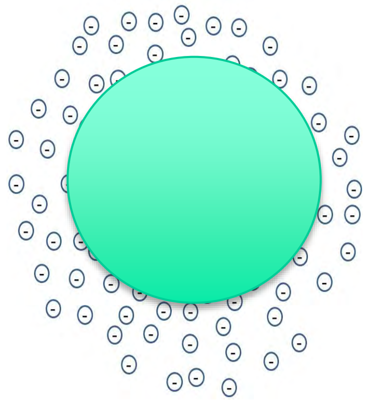


METAL

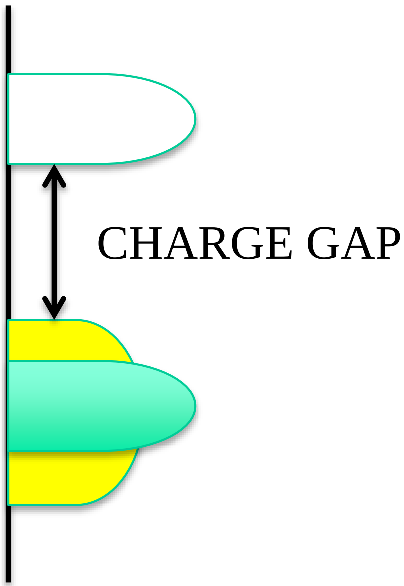


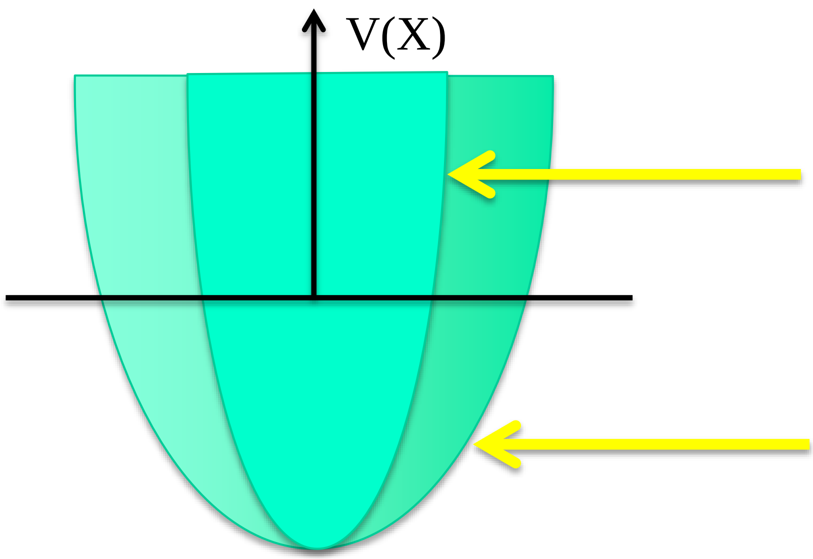
- Valence electrons screen the transition metal atom (ion)
- Narrows the potential well v(x)
- Releases localized electron – closes the gap

Screening



INSULATOR

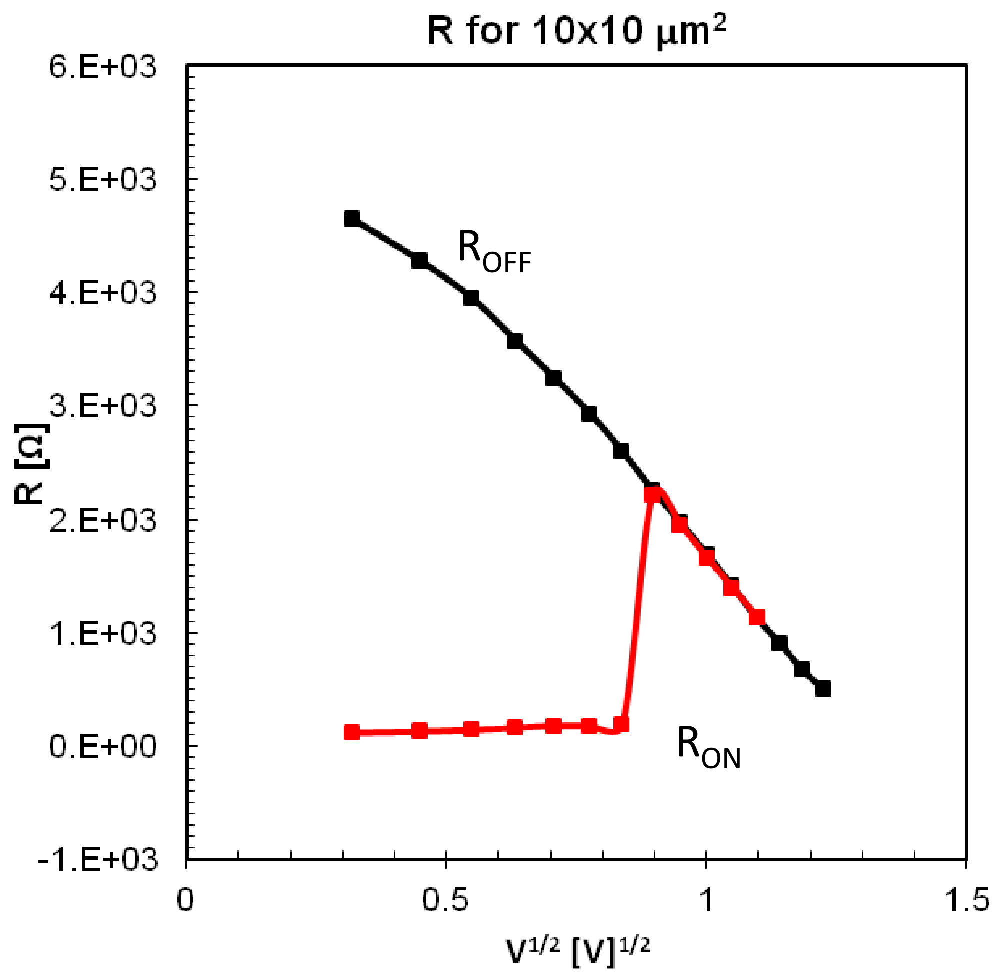




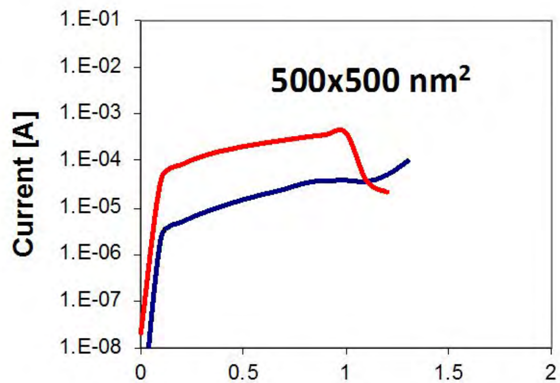
Releases localized electron. Metal.

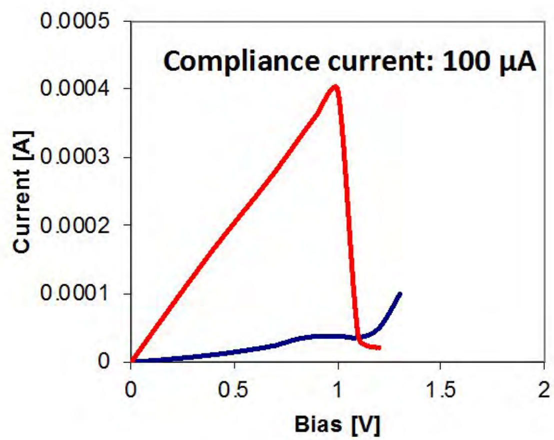
Captures and localizes Electron – repulsive U Opens the gap. Insulator.

R_{on} and I_{on} Scaling

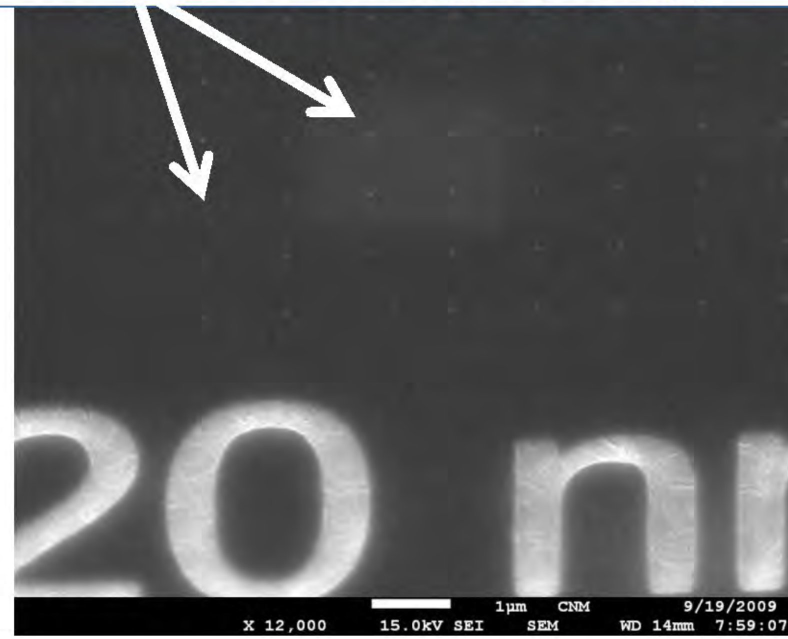


Scaling - CeRAM Nanostructures





~20 nm dotes etched into HSQ (20 nm design)



Direct-write electron beam lithography

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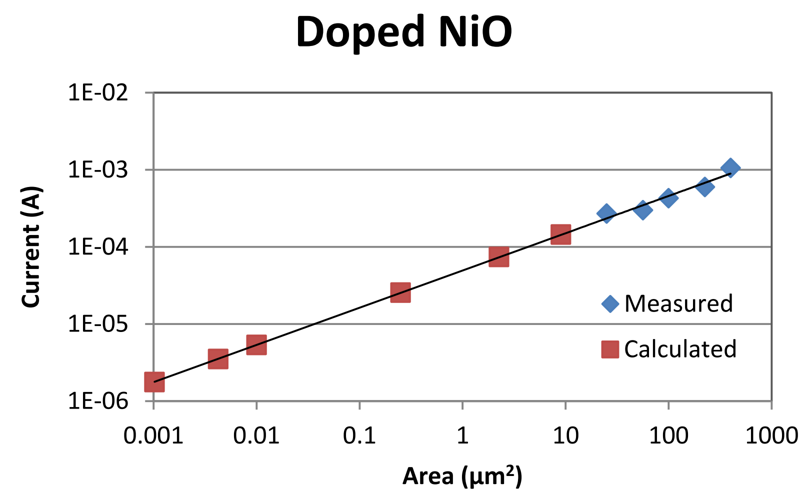
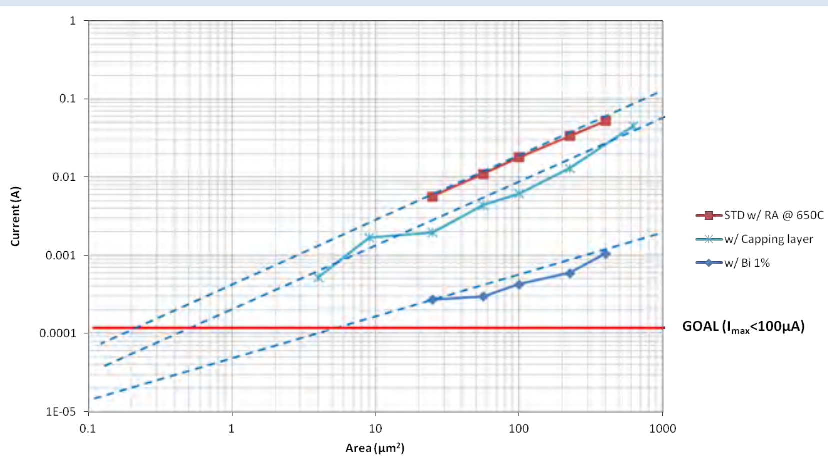
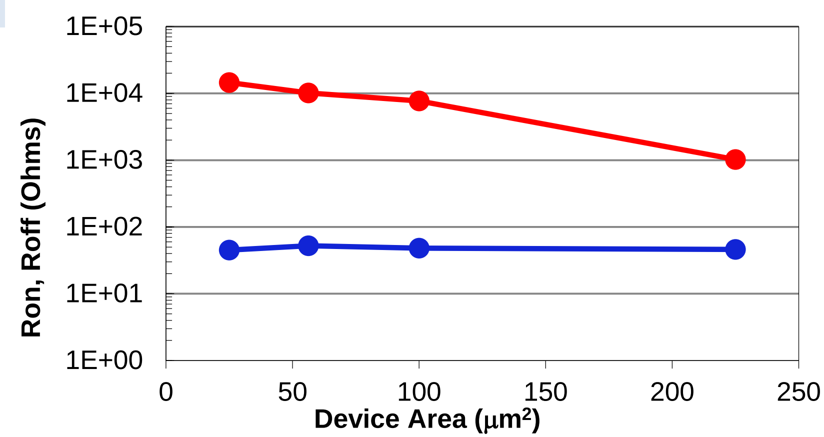
Scalability: Current Density kept at 3kA/cm² (or less)

2000 Times less than The Best (Grandis) STTRAM

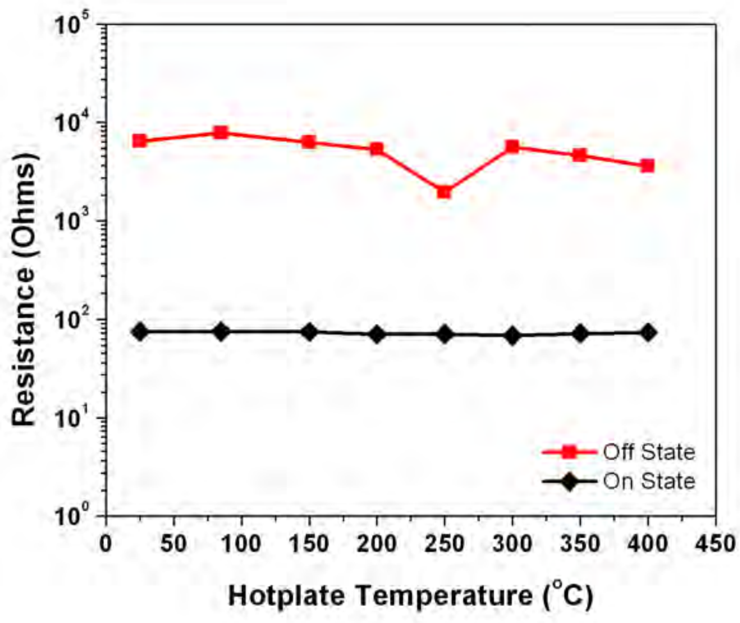
- Programming currents scale nicely as area decreases
- Maximum current scales with process modifications
- Read memory window widens with device area scaling
- CeRAM has desirable characteristics for high density memory application







Temperature Robustness



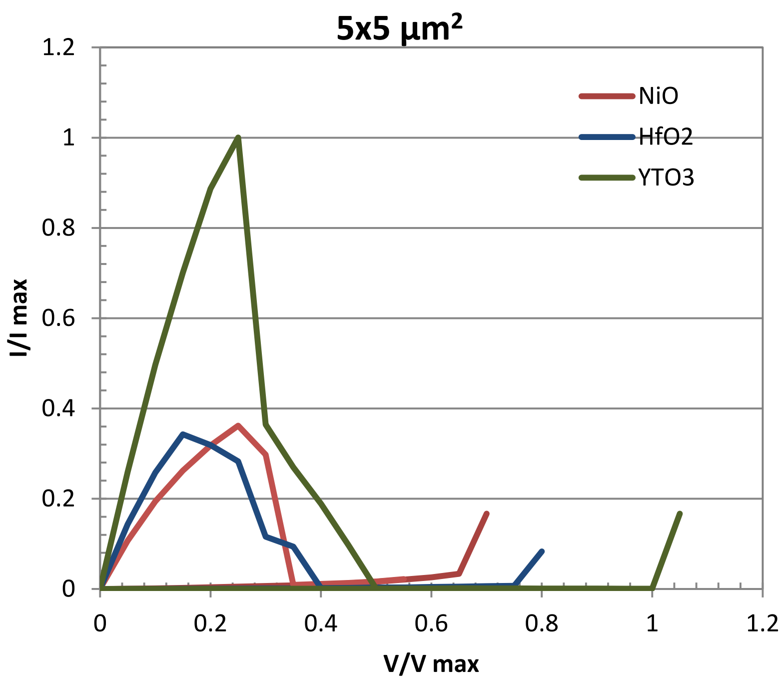
Retention Testing

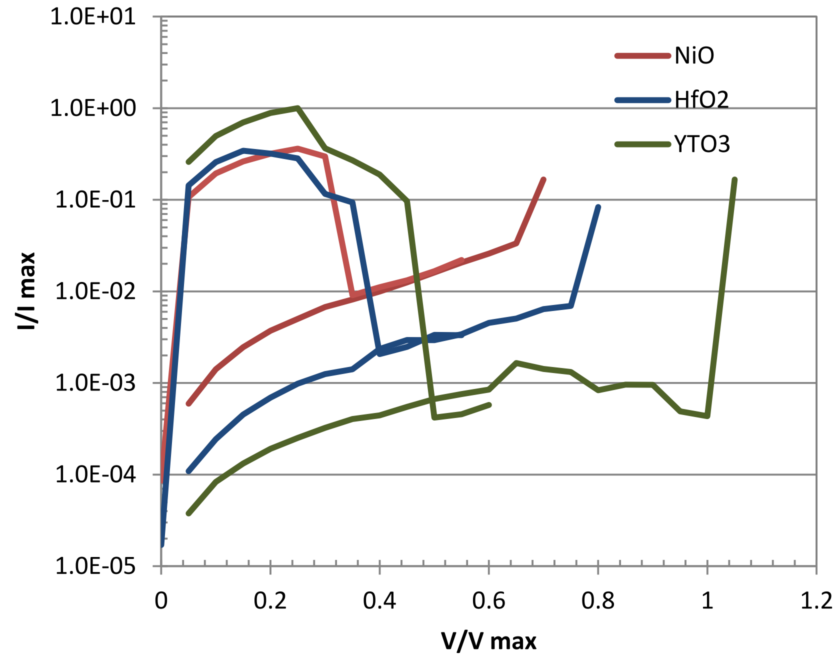
- Two devices were written with one in ON state and one in OFF state
- Devices were baked on hotplate for 1 hour
- Resistance state was measured after bake

Minimal degradation in ON and OFF resistance states up to 400°C

Normalized I/I_{Max} (V/V_{Max})

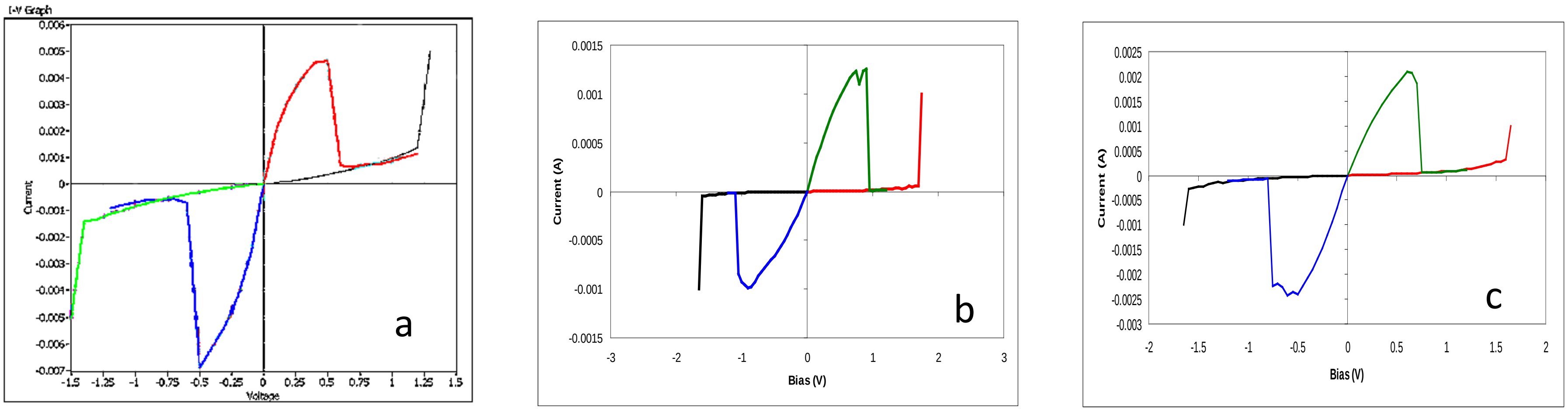
- NiO: Spin-on NiO:HiC, 600A, 16TMO31_3
- HfO2: ALD HfO2:C(6%), 300A, 16TMO36_1C
- YTO3: Spin-on YTiO3, 750A, 15TMO1_3





Operating Range

Ramp Switching from -260 C to 150 C
showing operation while under extreme Temperatures

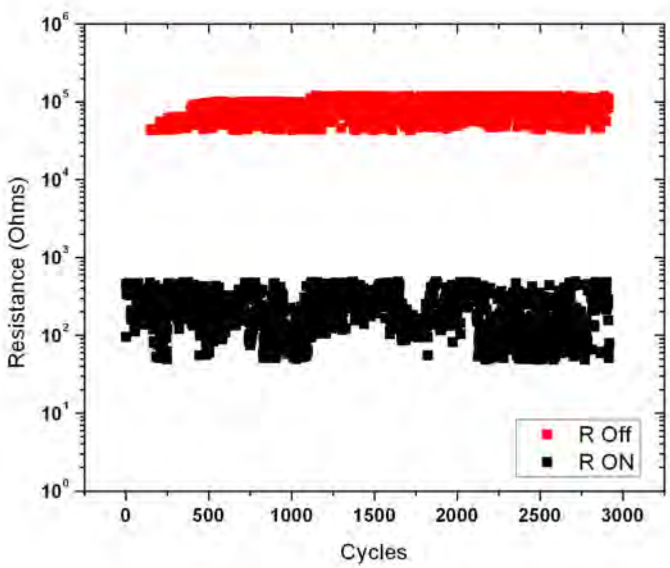


* Figures a, b, and c show bi-stable behavior at operating temperatures of -260̊ C, 25̊ C, and 150̊ C respectively

- Bi-stable operation for a large range of temperatures has been confirmed
- Switching parameters are stable through temperature range.

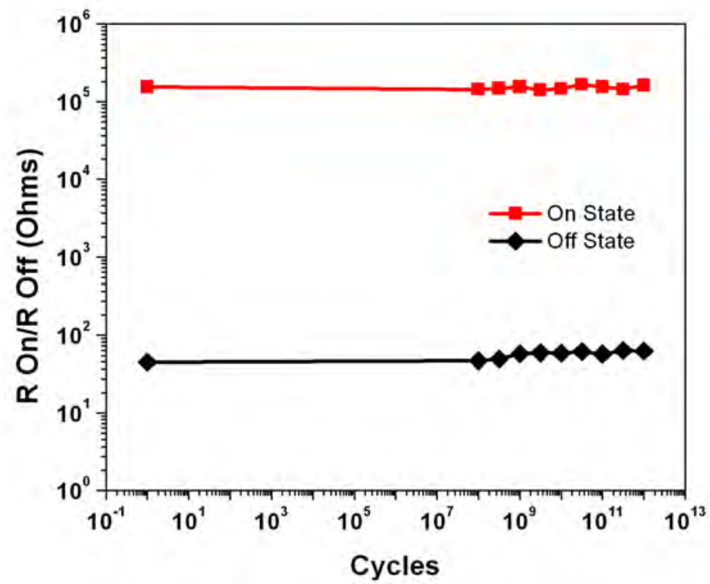
Reliability

Ramp quasi-static write pseudo endurance(Not pulse endurance*)



* Pulse Endurance not possible in large areas due to current sourcing limitations. The step size of the ramp is 3 ms

Read Endurance



No fatigue observed up to10^{12} cycles for R_{OFF} and $R_{ON,}$ respectively at 25C

IoT eNVM Specification

	IoT Spec	
Vmax	1.2	
Endurance	>1mil	
Retention	20yrs @85C	
Temperature Operation	-40C to 150C	
Forming Voltage	NONE	
Roff/Ron	>>100x	
Read	<1V (CeRAM 0.2V)	
Set/Reset (program/erase)	Voltage	1.2/0.6
	Current	50uA
	Pulse Width	10ns
	Energy	1pJ
Read Disturb	~0	

Energy = V*I*Δt, CeRAM < 0.1 FEMTOJoules

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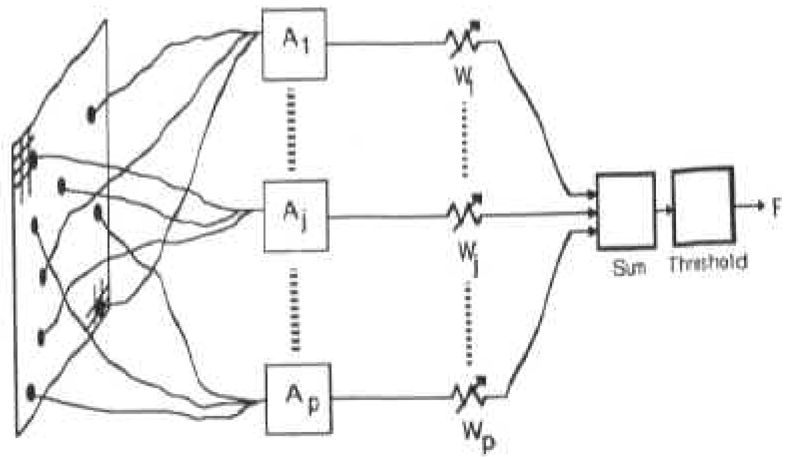

The following people and institutions are participating in the DARPA SyNAPSE program:[5]

IBM team, led by Dharmendra Modha

•Stanford University: Brian A. Wandell, H.-S. Philip Wong
•Cornell University: Rajit Manohar
•Columbia University Medical Center: Stefano Fusi
•University of Wisconsin–Madison: Giulio Tononi
•University of California, Merced: Christopher Kello
•iniLabs GmbH: Tobi Delbruck [6]
•IBM Research: Rajagopal Ananthanarayanan, Leland Chang, Daniel Friedman, Christoph Hagleitner, Bulent Kurdi, Chung Lam, Paul Maglio, Dharmendra Modha, Stuart Parkin, Bipin Rajendran, Raghavendra Singh

HRL Team led by Narayan Srinivasa

•HRL Laboratories: Narayan Srinivasa, Jose Cruz-Albrecht, Dana Wheeler, Tahir Hussain, Sri Satyanarayana, Tim Derosier, Youngkwan Cho, Corey Thibeault, Michael O' Brien, Michael Yung, Karl Dockendorf, Vincent De Sapio, Qin Jiang, Suhas Chelian
•Boston University: Massimiliano Versace, Stephen Grossberg, Gail Carpenter, Yongqiang Cao, Praveen Pilly
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•University of Michigan: Wei Lu
•University of California, Irvine: Jeff Krichmar
•George Mason University: Giorgio Ascoli, Alexei Samsonovich
•Portland State University: Christof Teuscher
•Stanford University: Mark Schnitzer
•Set Corporation: Chris Long

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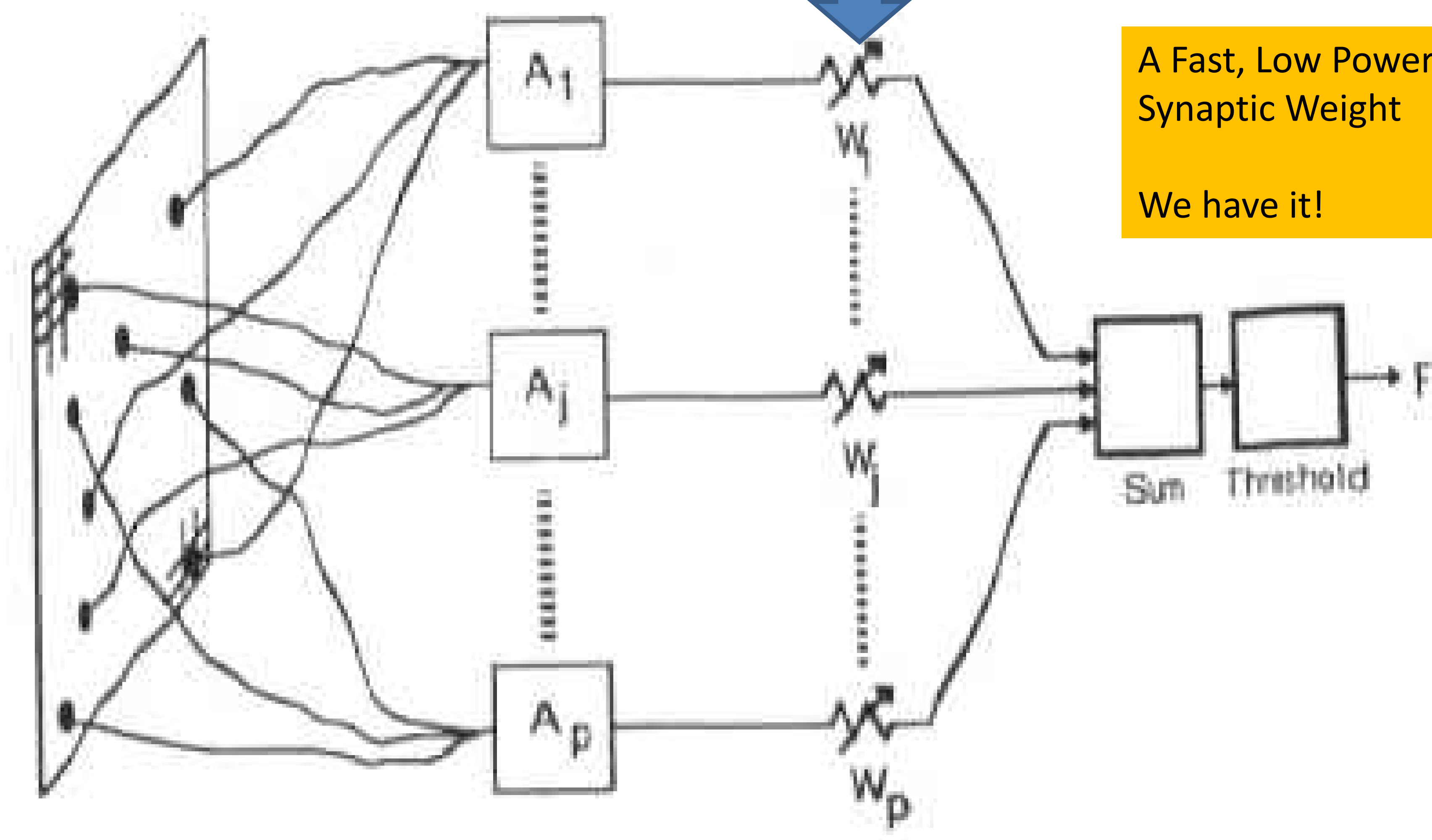
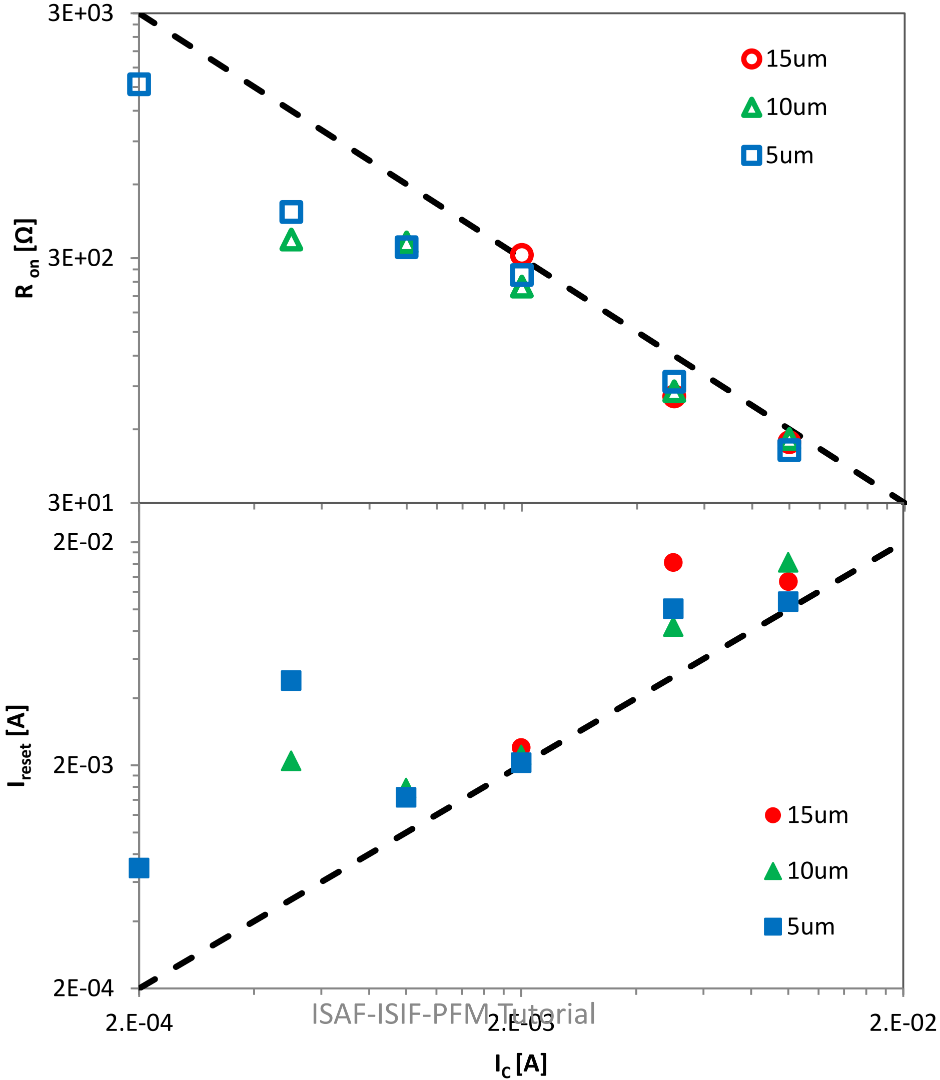
THEY ARE ALL MISSING THIS

A Fast, Low Power Synaptic Weight

We have it!



The Current at Set Programs the Resistance of the Synapse in CeRAMs



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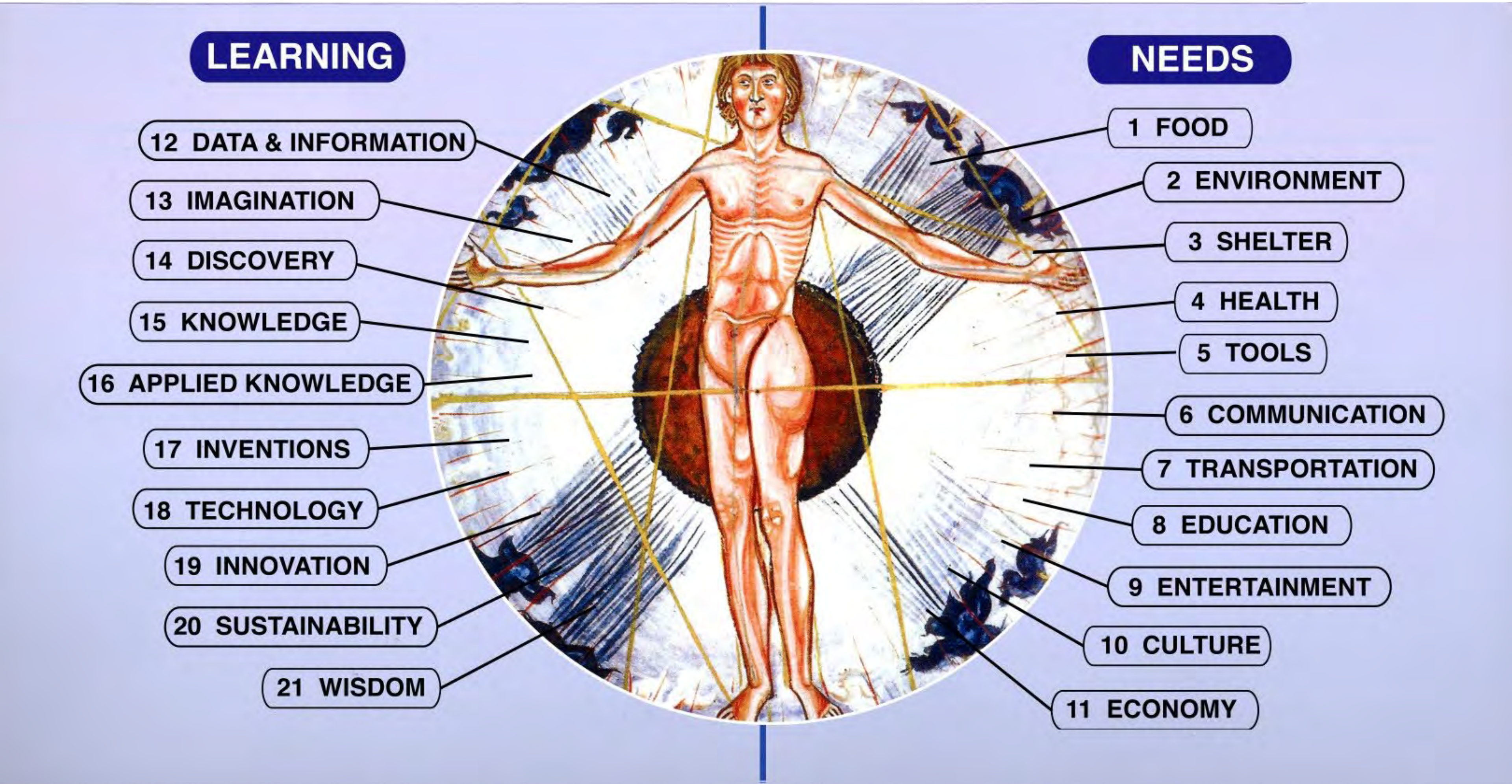
6. Conclusions

1. Never, Never Give up.

2. There is a world of opportunities out there. See the next Slide.

OPPORTUNITIES EVERYWHERE. START SOMETHING GREAT.
HAPPY ANIVERSARY ENTREPRENEUR ENGINEERING.



ありがとうございました

THANK YOU