ITRS Public Conference

Emerging Research Devices

San Francisco

Agenda

- ❑ **Technology Workshops**
- ❑ **IRC Request**
- ❑ **ERD/ERM Recommendation**

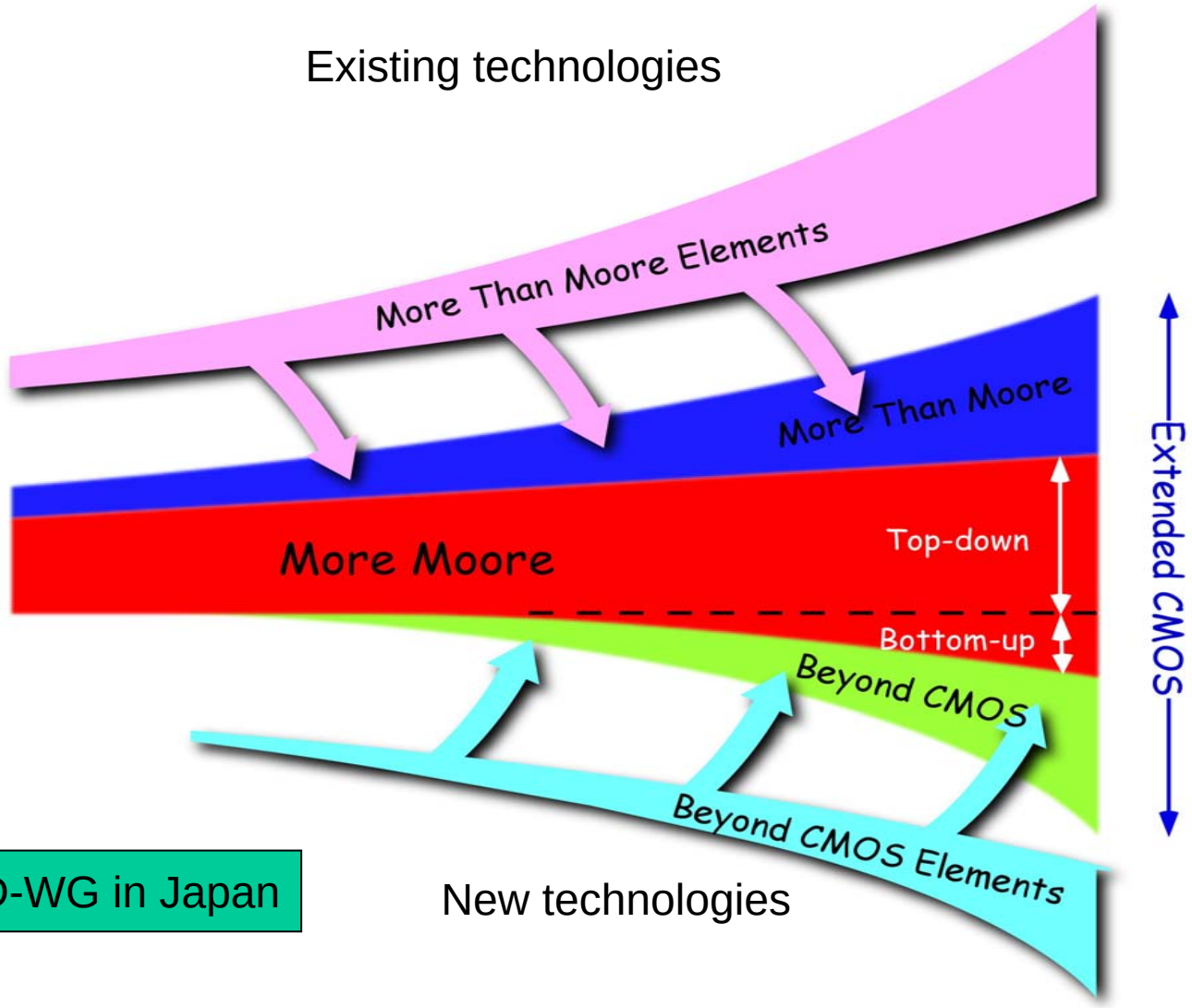
Jim Hutchby – SRC

July 16, 2008

Emerging Research Devices Working Group

Hiroyugi Akinaga	AIST
Tetsuya Asai	Hokkaido U.
Yuji Awano	Fujitsu
George Bourianoff	Intel
Michel Brillouet	CEA/LETI
Joe Brewer	U. Florida
John Carruthers	PSU
Ralph Cavin	SRC
U-In Chung	Samsung
An Chen	AMD
Philippe Coronel	ST Me
Shamik Das	Mitre
Erik DeBenedictis	SNL
Simon Deleonibus	LETI
Kristin De Meyer	IMEC
Michael Frank	AMD
Akira Fujiwara	NTT
Christian Gamrat	CEA
Mike Garner	Intel
Dan Hammerstrom	PSU
Wilfried Haensch	IBM
Tsuyoshi Hasegawa	NIMS
Shigenori Hayashi	Matsushita
Dan Herr	SRC
Toshiro Hiramoto	U. Tokyo
Matsuo Hidaka	ISTEK
Jim Hutchby	SRC
Adrian Ionescu	ETH
Kohei Itoh	Keio U.
Kiyoshi Kawabata	Renesas Tech
Seiichiro Kawamura	Selete
Rick Kiehl	U. Minn
Hiroshi Kotaki	Sharp
Atsuhiro Kinoshita	Toshiba
Franz Kreupl	Qimonda
Nety Krishna	AMAT
Zoran Krivokapic	AMD
Phil Kuekes	HP
Lou Lome	IDA
Hiroshi Mizuta	U. Southampton
Murali Muraldihar	Freescale
Fumiyuki Nihei	NEC
Dmitri Nikonov	Intel
Wei-Xin Ni	NDL
Ferdinand Peper	NICT
Yaw Obeng	NIST
Dave Roberts	Air Products
Kaushal Singh	AMAT
Sadas Shankar	Intel
Thomas Skotnicki	ST Me
Satoshi Sugahara	Tokyo Tech
Shin-ichi Takagi	U. Tokyo
Ken Uchida	Toshiba
Yasuo Wada	Waseda U.
Rainer Waser	RWTH A
Franz Widdershoven	NXP
Jeff Welser	NRI/IBM
Philip Wong	Stanford U.
Kojiro Yagami	Sony
David Yeh	SRC/TI
In-Seok Yeo	Samsung
In-K Yoo	SAIT
Peter Zeitzoff	Freescale
Yuegang Zhang	Intel
Victor Zhirnov	SRC

Evolution of Extended CMOS



ERD-WG in Japan

2008 ERD/ERM Workshops

Workshop topic	Date	Location	Meeting	Specific technology entries
Emerging Research Memory Devices	April 2 2008	Bonn, Germany	ITRS Spring meeting	- Performance analysis for the various types of memories - Magnetic Race-Track Memory - Nanowire Phase-Change Memory - Polymer/Macromolecular Memory
Emerging Research Architectures	July 10-11 2008	San Francisco, CA, USA	Semicon West	- Chip Multiprocessors - Memory Architectures - Morphic Computational Architectures -Turing-Heisenberg Rapprochement
Evaluation of Beyond CMOS Logic Device Tech	July 12-13 2008	San Francisco, CA, USA	Semicon West	Evaluate Seven Logic Device Technologies to identify those ready for accelerated development
Emerging Research Logic Devices	Sept. 22 2008	Tokyo, Japan	SSDM	- Nonlinear response functions - Devices for "functional diversification"? - Optimum circuit architectures associated with novel devices
Emerging Research Materials	Nov. 10 2008	Austin, TX, USA	MMM*	Materials for Spintronic Devices - Energetics - Transitions - Time scales - Interactions with external fields
Emerging Research Materials	March 2009	Tokyo, Japan		Strongly Correlated Electron Materials

* 53rd Magnetism and Magnetic Materials Conference

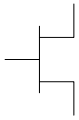
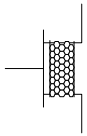
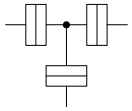
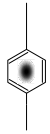
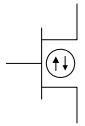
Co-sponsored by the National Science Foundation

International Roadmap Committee Request

Determine which, if any, current approaches to providing a "Beyond CMOS" information processing technology(ies) is (are) ready for more detailed roadmapping and enhanced investment.

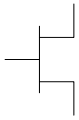
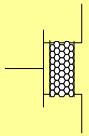
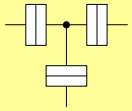
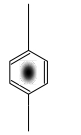
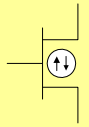
2007 ITRS ERD

Emerging Research Logic Devices

Device							
		FET Extension					
	FET [A]	*1D structures*	*Channel replacement*	*SET*	*Molecular*	*Ferromagnetic logic*	*Spin transistor*
Typical example devices	Si CMOS	CNT FET NW FET NW hetero-structures Nanoribbon transistors with graphene	III-V compound semiconductor and Ge channel replacement	SET	Crossbar latch Molecular transistor Molecular QCA	Moving domain wall M: QCA	Spin Gain transistor Spin FET Spin Torque Transistor

2007 ITRS ERD

Emerging Research Logic Devices Evaluated

Device							
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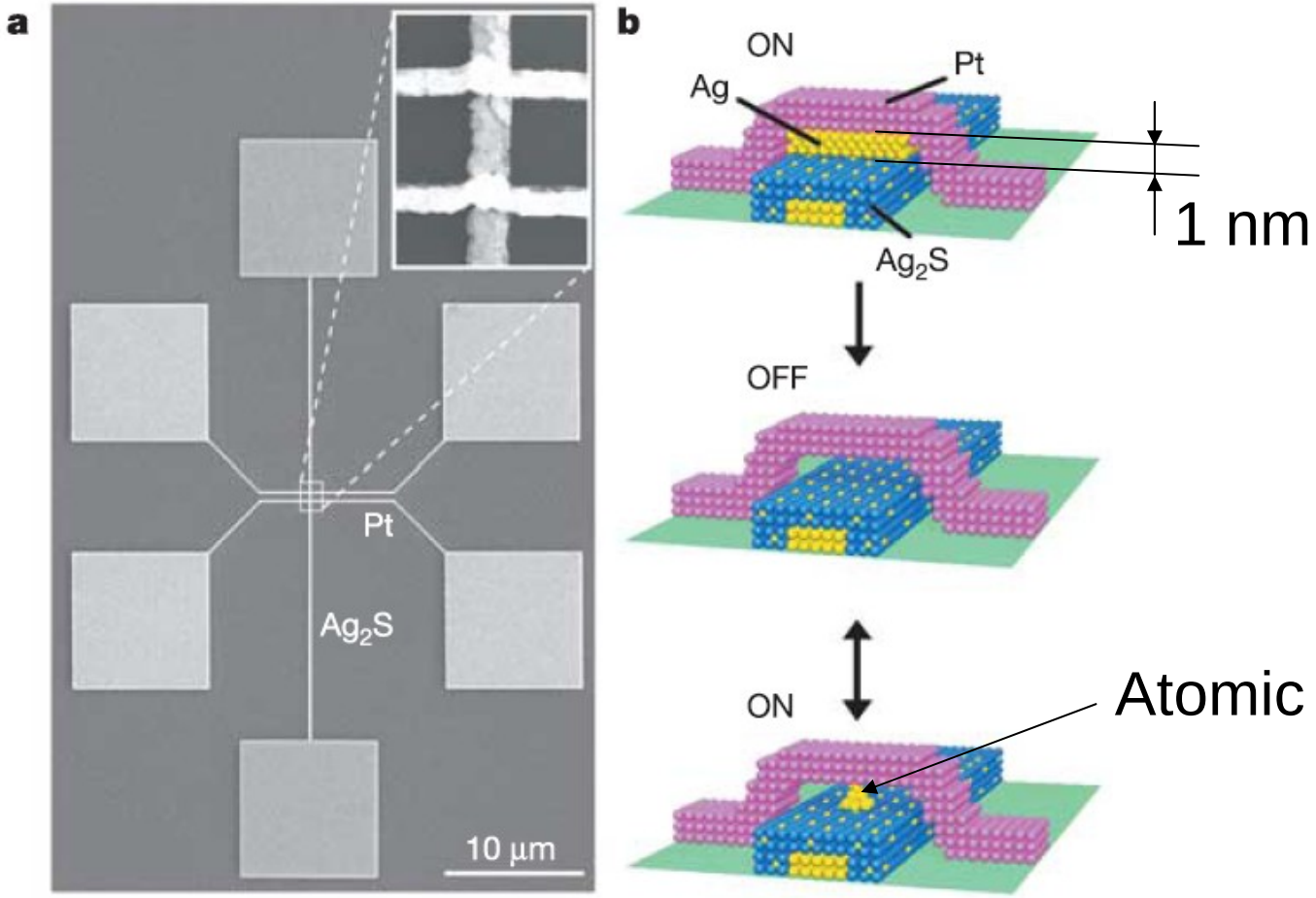
Emerging Research Device Technology Candidates Evaluated

- Nano-electro Mechanical Switches
- Collective Spin Devices
- Spin Torque Transfer Devices
- Atomic Switch / Electrochemical Metallization
- Carbon-based Nanoelectronics
- Single Electron Transistors
- CMOL / Field Programmable Nanowire Interconnect (FPNI)

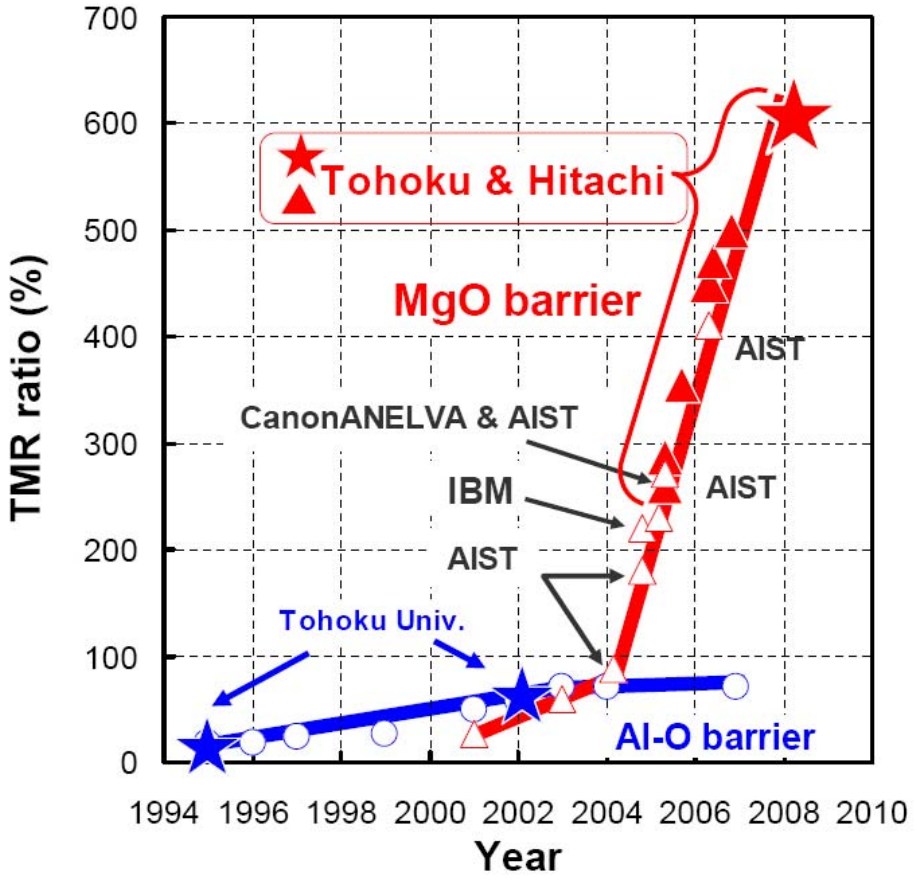
Atomic Switch



K. Terabe et al. Nature 433 (2005) 47

H. Ohno, “Spintronics”

Seminar, UCSB May, 2008



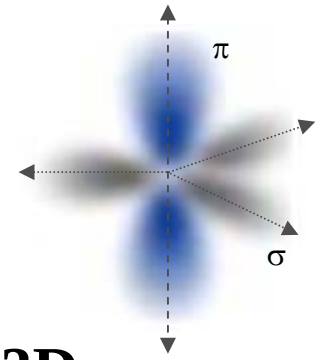
604%@300K

(1144% @5K)

Intermag 2008 HR-01
S. Ikeda et al.

For MgO barrier MTJs,
AIST(S.Yuasa et al.): JJAP43(2004)L588, Nature Mater. 3(2005)868; APL89(2006)042505.
IBM (S.S.P.Parkin et al.): Nature Mater. 3(2005)862.
CanonANELVA & AIST: APL 86(2005) 092502
Tohoku Univ. & Hitachi:
JJAP44(2005)L587;JJAP44(2005)L1442;
JAP99(2006)08A907; APL 89(2006)042506.
APL89(2006)232510; APL90(2007)212507.
IEEE T-ED 54(2007)991.

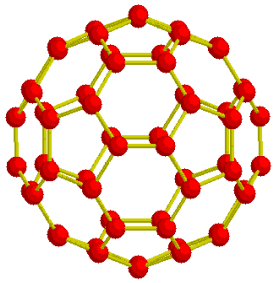
SP_2 Carbon: 0-Dimension to 3-Dimension



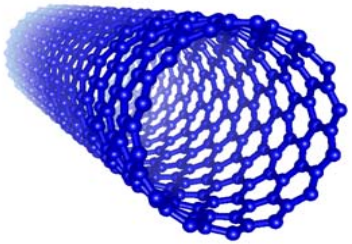
Atomic orbital sp_2

0D **1D** **2D** **3D**

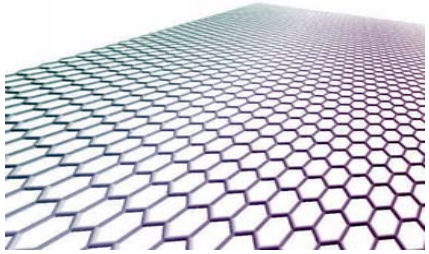
Fullerenes (C_{60})



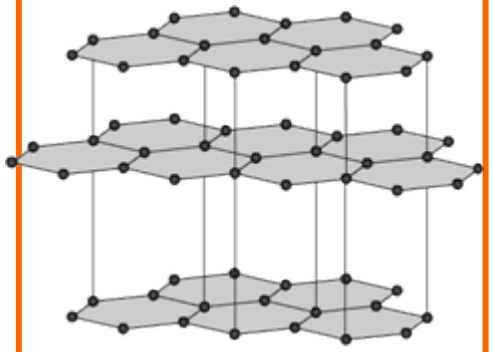
Carbon Nanotubes



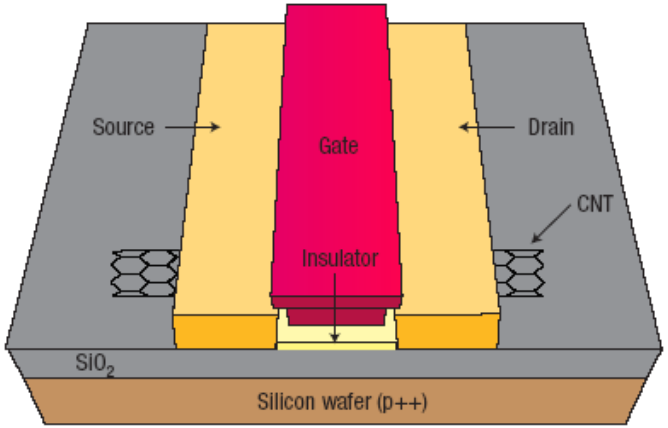
Graphene

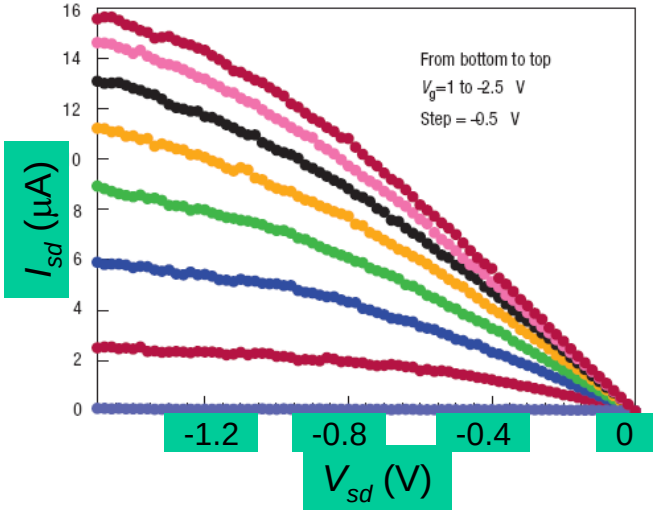


Graphite

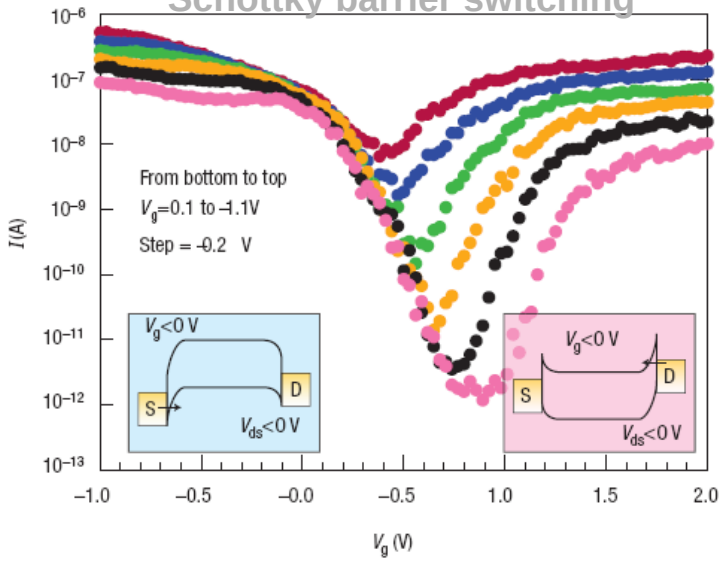


Nanotube FET





Schottky barrier switching



Band gap:	0.5 – 1 eV
On-off ratio:	~ 10^6
Mobility:	~ 100,000 cm^2/Vsec @RT
Ballistic @RT	~ 300-500 nm
Fermi velocity:	10^6 m/sec
Max current density	> 10^9 A/cm^2

Ph. Avouris et al, Nature Nanotechnology **2**, 605 (2007)

ERD/ERM TWG Recommendation

The ERD/ERM TWGs recommend to the International Roadmap Committee ---

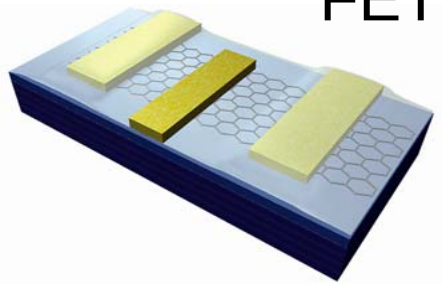
Carbon-based Nanoelectronics to include carbon nanotubes and graphene

For additional resources and detailed road mapping for ITRS as promising technologies targeting commercial demonstration in the 5-10 year horizon.

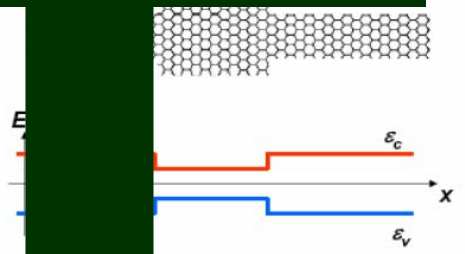
Graphene Electronics: Conventional & Non-conventional

Conventional Devices

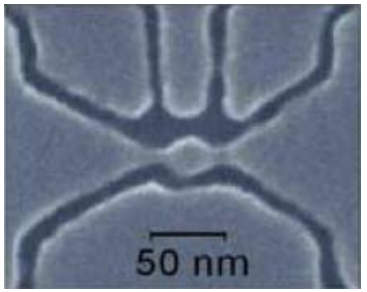
FET



Leverage R & D

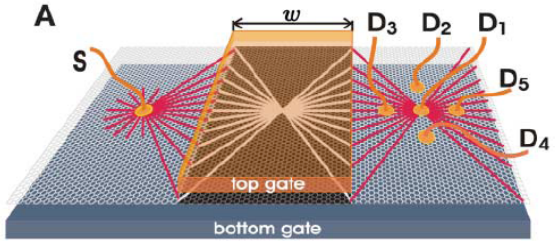


Graphene quantum dot



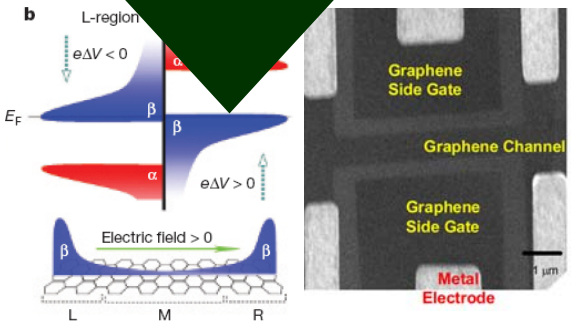
(Manchester group)

Nonconventional Devices



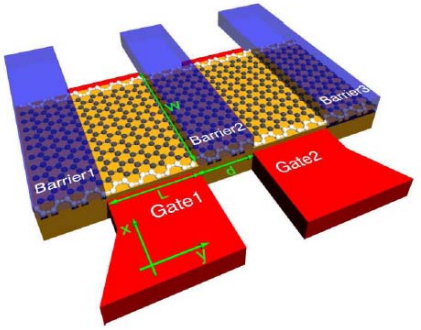
Graphene Veselago lense

Cheianov *et al. Science* (07)



Graphene Spintronics

Son *et al. Nature* (07)



Graphene psedospintronics

Trauzettel *et al. Nature Phys.* (07)

Advantages
Carbon-based Nanoelectronics ---

For scaled CMOS, potentially can ..

- Impact geometric scaling by providing an alternate MOSFET structure, and
- Provide a high mobility, high carrier velocity, MOSFET channel replacement material.

For a new information process technology, potentially can ...

- Leverage R & D for CMOS (above) to …
- Provide a technology platform enabling a new "Beyond CMOS" information processing paradigm

Caveat
Carbon-based Nanoelectronics

The intent of this recommendation is to highlight Carbon-based Nanoelectronics for additional roadmapping and investment ---

--- but not at the expense of investment in or exploration of other candidate approaches for "Beyond CMOS" information processing technology.

We are not picking winners and losers

Summary

- Preparing for 2009 ERD Chapter re-write
- Conducting six workshops in collaboration with NSF, SRC, and ERM (Three accomplished)
  - Evaluate technology entries for 2009
  - Respond to IRC request (see next bullet)
- Responded to IRC request to identify one or more Beyond CMOS technologies for road mapping and enhanced investment
  - Conducted in-depth evaluation of seven Beyond CMOS technologies (including one device architecture)
  - Recommended Carbon-based Nanoelectronics to IRC

Backup Slides

Objectives and Agendas of the ERD/ERM Technology Workshops

2008 ERD/ERM Workshops

Workshop topic	Date	Location	Meeting	Specific technology entries
Emerging Research Memory Devices	April 2 2008	Bonn, Germany	ITRS Spring meeting	- Performance analysis for the various types of memories - Magnetic Race-Track Memory - Nanowire Phase-Change Memory - Polymer/Macromolecular Memory
Emerging Research Architectures	July 10-11 2008	San Francisco, CA, USA	Semicon West	- Chip Multiprocessors - Memory Architectures - Morphic Computational Architectures -Turing-Heisenberg Rapprochement
Evaluation of Beyond CMOS Logic Device Tech	July 12-13 2008	San Francisco, CA, USA	Semicon West	Evaluate Seven Logic Device Technologies to identify those ready for accelerated development
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Emerging Research Materials	March 2009	Tokyo, Japan		Strongly Correlated Electron Materials

* 53rd Magnetism and Magnetic Materials Conference

Co-sponsored by the National Science Foundation

ERD ITWG

Emerging Research Devices Working Group

Face-to-Face Meeting

MEMORY DISCUSSION

Victor Zhirnov and Rainer Waser - Facilitating
Grand Hotel Steigenburger Petersberg
Rheinblick
Koenigswinter (near Bonn), Germany
Wednesday April 2, 2008
8:00 a.m. – 1:30 p.m

Objectives

- **To develop quantitative estimates of performance for the various types of memories**
  - We need to discuss and agree on the methodology we use and the numbers we obtained
  - It is highly desirable to document the results, ideally as a journal publication
- **To discuss new possible memory candidates**

ERD ITWG Memory Discussion
Agenda

8:00	Review meeting objectives and agenda	Hutchby
8:15	Introductory remarks on Memory Discussion	Zhirnov
8:30	Nanowire Phase-change memory	Meyyapan
9:30	Magnetic Race-Track & Spin-torque Transfer Memories	Zhirnov
10:30	Break	
10:45	**Quantitative estimates of performance for the various types of memories**	
	❑ **Engineered barrier**	**Muralidhar & Zhirnov**
	❑ **Ferroelectric**	**Waser**
	❑ **Nanoelectromechanical**	**Zhirnov**
	❑ **Fuse/Antifuse**	**Waser & Akinaga**
12:00	Lunch	
12:30	**Continue quantitative estimates …..**	
	❑ **Ionic**	**Waser & Akinaga**
	❑ **Electronic Effects**	**Waser**
	❑ **Macromolecular**	**Zhirnov**
	❑ **Molecular**	**Waser**
1:30	**Break - Adjourn Memory Discussion**	
2:00	**ERD Business Meeting**	

SRC/NSF/ITRS Forum on Emerging nano-CMOS Architectures in Conjunction with Frontiers of Extreme Computing 2008: 2020 Virtual Immersion Architectures

July 10-11, 2008

Univ. of California/Santa Cruz, Seymour Marine Discovery Center at Long Marine Laboratory, La Feliz Room

Santa Cruz, California

This forum is to explore the potential capabilities and applications of virtual immersion technologies given extremely scaled CMOS devices. Please note that the deadline for registering for this event is **Friday, June 27, 2008**

Expected Outcome

Definition of promising research directions to enable virtual immersion applications in the 2020 timeframe.

ITRS / ERD ITWG

Emerging Research Devices Work Group

Workshop & Work Group Meeting

Evaluation of Selected Beyond CMOS Emerging Technologies

Jim Hutchby - Facilitating

San Francisco Marriott Hotel

55 Fourth Street, San Francisco, CA

Nob Hill D Room

Yerba Buena Level

Saturday, July 12 (Workshop)
8:00 a.m. – 10:00 p.m
Sunday, July 13 (ERD Working Group Meeting)
9:00 a.m. – 5:45 p.m.

Objectives

Workshop (For each of the seven technologies)

- Receive expert inputs on the seven technologies for future information processing (pro & con)
- Clarify status, potential, and remaining challenges
- Formulate discussion/decision points to be considered in the Sunday ERD/TWG meeting
- Consider if one or more of the seven candidate technologies is ready for enhanced engineering development and detailed roadmapping (Sunday)

Information Requested (1/2)

- **Proposed device technology (device, physics, interconnect, input/output functions)**
  - "Beyond CMOS" technologies that extend the functional scaling of CMOS beyond that attainable with dimensional scaling
  - Device technologies that provide a new "Beyond CMOS" paradigm for highly scalable information processing
- **Scaling potential (device or functional density) compared to ultimately scaled CMOS)**
  - Geometric (size, density, etc.)
  - Dissipated power density (dynamic, static, …)

Information Requested (2/2)

- **Projected performance (power, speed, gain, throughput per Joule, etc. …) at maturity**
- **Reduction to practice - status**
  - Demonstration of “proof-of-concept” of device, unit cell and functional circuit
  - Fabrication technology – challenges
  - Progress in past four years
- **Current state-of-the-art using the provided metrics as a guide (Appendix 2 of request for white papers)**
- **Key scientific and technological issues remaining to accept the technology for manufacture.**
- **Technology roadmap outlining a 5-15 year develop path leading to manufacture in 5-10 years.**

"Beyond CMOS" Technology Maturity Workshop
Agenda – Saturday, July 12

8:00	**Welcome and Introductions**		Hutchby
8:10	**Background, Workshop & ERD Meeting Objectives**		Hutchby
8:20	**NEMS Switch Technology**		
	❑ Proponent Presentation	(40 minutes)	**Akarvardar**
	❑ Friendly Critic Presentation	(20 minutes)	**Elata**
	❑ Discussion for clarification	(20 minutes)	
9:40	**Spin Torque Transfer Technology**		
	❑ Proponent Presentation	(40 minutes)	**Allen**
	❑ Friendly Critic Presentation	(20 minutes)	**Yablonovitch**
	❑ Discussion for Clarification	(20 minutes)	
11:00	**Break**		
11:20	**Carbon-based Nanoelectronics**		
	❑ Proponent Presentation	(40 minutes)	**Kim**
	❑ Friendly Critic Presentation	(20 minutes)	**Javey**
	❑ Discussion for Clarification	(20 minutes)	
12:40	**Lunch (Working)**		

"Beyond CMOS" Technology Maturity Workshop
Agenda – Saturday, July 12 (Cont'd)

1:10 Atomic Switch / Electrochemical Metal Switch

❑ Proponent Presentation	(40 minutes)	**Kuekes**
❑ Friendly Critic Presentation	(20 minutes)	**Chen**
❑ Discussion for Clarification	(20 minutes)	

2:30 Collective Spin Devices (including M-QCA)

❑ Proponent Presentation	(40 minutes)	**Wang**
❑ Friendly Critic Presentation	(20 minutes)	**Bandyopadhyay**
❑ Discussion for Clarification	(20 minutes	

3:50 Break

4:10 Single Electron Transistors

❑ Proponent Presentation	(40 minutes)	**Fujiwara**
❑ Friendly Critic Presentation	(20 minutes)	**Likharev**
❑ Discussion for Clarification	(20 minutes)	

5:30 CMOL and FPNI

❑ Proponent Presentation	(40 minutes)	**Likharev**
❑ Friendly Critic Presentation	(20 minutes)	**DeHon**
❑ Discussion for Clarification	(20 minutes)	

6:50 Dinner Break (Return @ 8:00 p.m.)

"Beyond CMOS" Technology Maturity Workshop
Agenda – Saturday, July 12 (Cont'd)

8:00	Summary Session – introduction & Objective	Hutchby
8:10	NEMS Switch	Franzon
8:25	Spin Transfer Torque	Bourianoff
8:40	Carbon-based Nanoelectronics	Brillouet
8:55	Atomic Switch / Electrochemical Metal Switch	Haensch
9:10	Collective Spin Devices (including M-QCA)	Shankar
9:25	Single Electron Transistors	Hiramoto
9:40	CMOL and FPNI	DeBenedictis
10:00	Adjourn	

* Volunteer Discussion Leaders Needed