WG12: Emerging Research Devices (ERD)

新探究 デバイス

―Beyond CMOS候補の分類と評価 ―

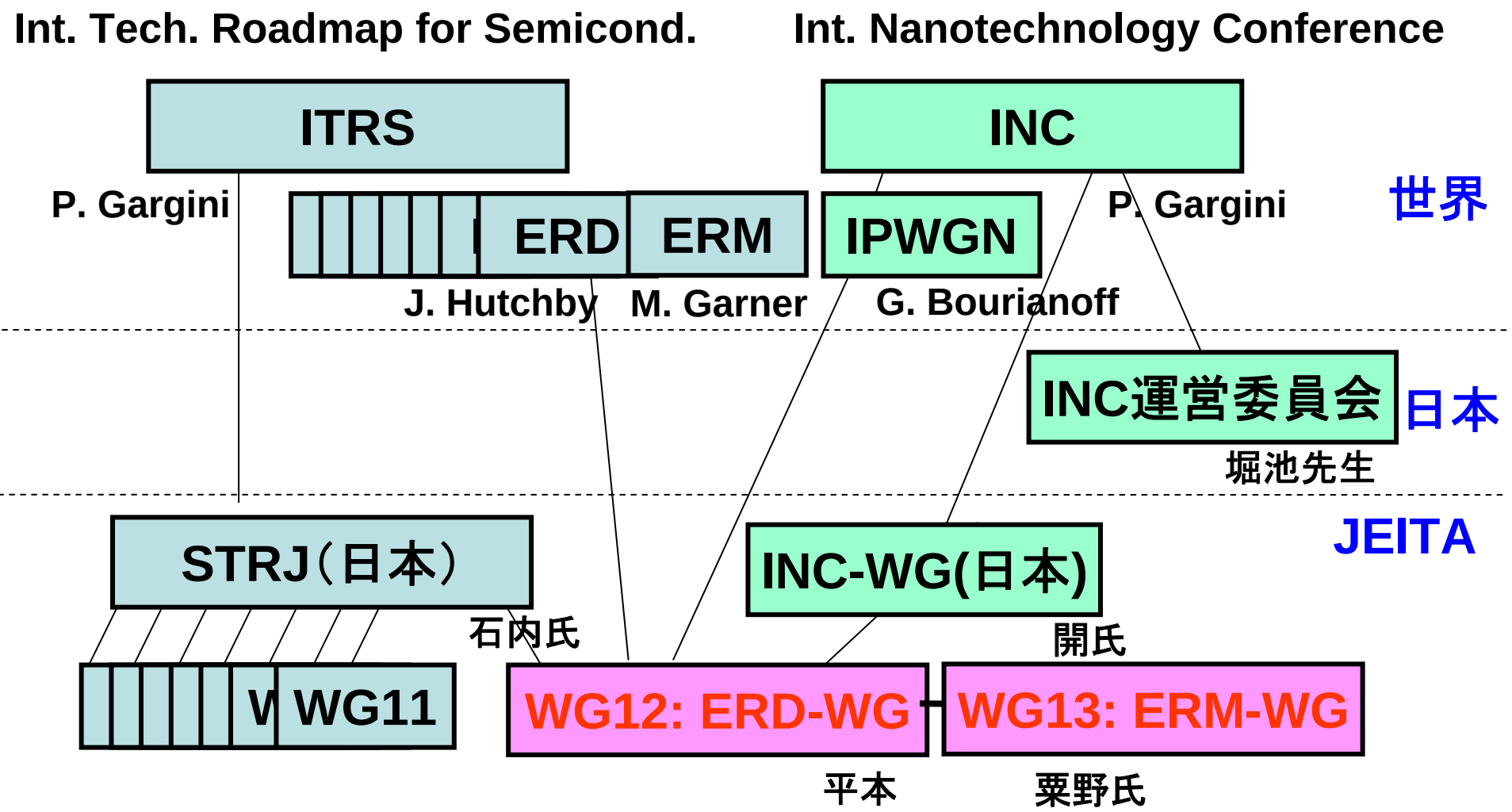
平本俊郎
東京大学生産技術研究所

1. 日本のERD-WGの位置付け
2. ERDのスコープと目的
3. 2007年版の概要
4. 日本のERD-WGの活動
5. まとめ

用語集

CNT	Carbon Nanotube
DFM	Design for Manufacturability
ERD	Emerging Research Device
ERM	Emerging Research Material
FD SOI	Fully Depleted Silicon on Insulator
FET	Field Effect Transistor
GOI	Germanium on Insulator
INC	International Nanotechnology Conference
IPWGN	International Planning WG for Nanoelectronics
NEMS	Nano Electro Mechanical Systems
RTD	Resonant Tunneling Diode

ERD-WGの位置付け

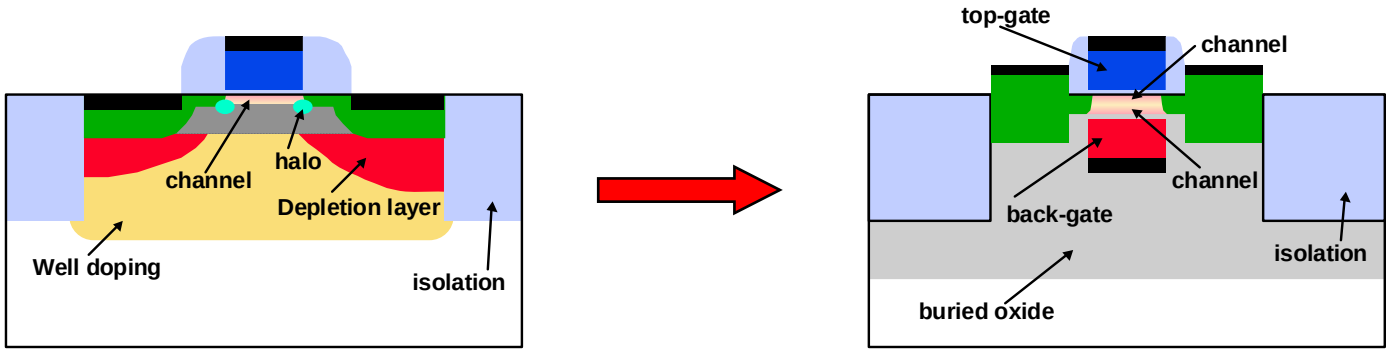


ERD-WG(WG12)は，ITRSのERD-WGとINCのIPWGNを兼ねる．

WG12構成メンバー

リーダー:	平本俊郎(東大)	
サブリーダー	内田　建(東工大)	
幹事:	木下敦寛（東芝）	
企業:	粟野祐二(富士通)	川端清司(ルネサス)
	林　重徳(松下)	小瀧　浩(シャープ)
	二瓶史行(NEC)	屋上公二郎(ソニー)
特別委員:	高木信一(東大)	和田恭雄(東洋大)
	秋永広幸(産総研)	浅井哲也(北大)
	日高睦夫(ISTEC)	伊藤公平(慶應大)
	長谷川剛（NIMS）	菅原　聡(東工大)
	ペパー　フェルディナンド（NICT）	
	藤原　聡(NTT)	河村誠一郎(JST)

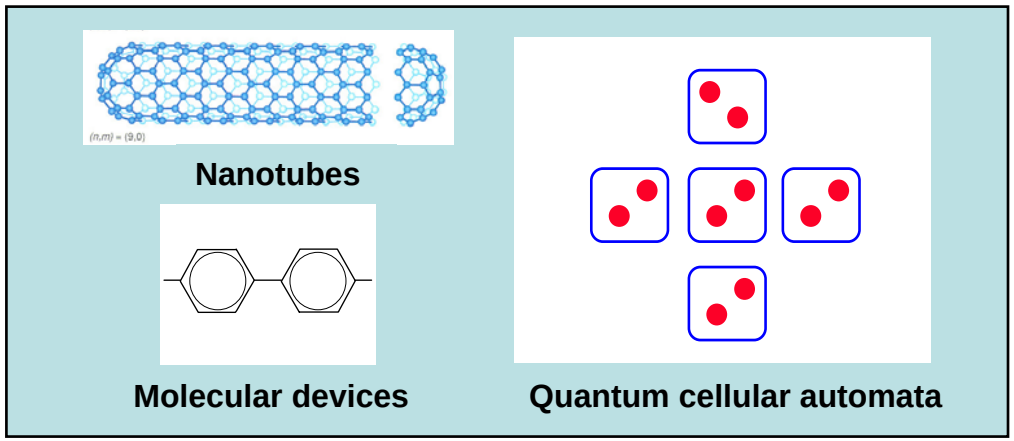
2003年版までのERDのスコープ



Bulk CMOS

Double-Gate CMOS

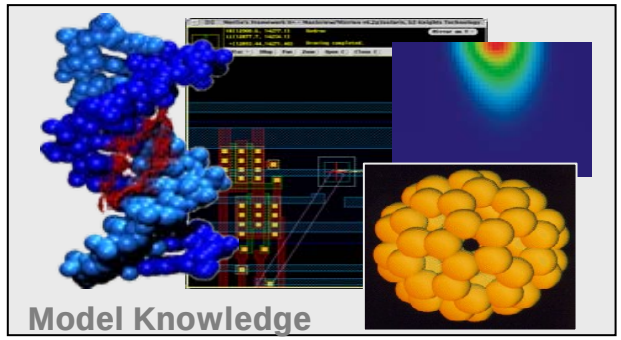
New Memory and Logic Technologies



New Architecture Technologies

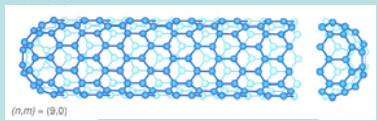
Emerging Information Processing Concepts

2005年版ERDのスコープ

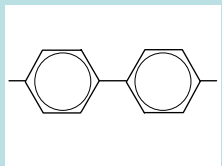


新材料

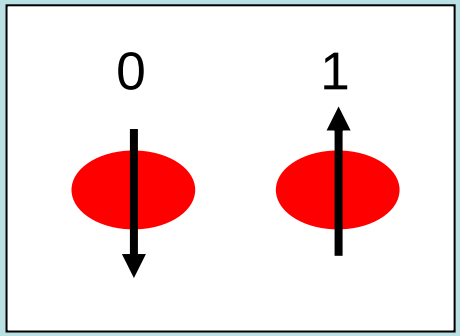
新メモリとロジック技術



Nanotubes



Molecular devices



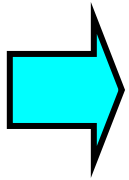
Spin states

新アーキテクチャ技術

新情報処理のコンセプト
「Beyond CMOS」

求められる機能

- 要求される特性:
  - スケーラビリティ
  - 性能
  - エネルギー効率
  - 利得
  - 信頼性
  - 室温動作
- 望まれる特性:
  - CMOSプロセスとの互換性
  - CMOSアーキテクチャとの互換性



他の状態変数
(電荷だけでなく)

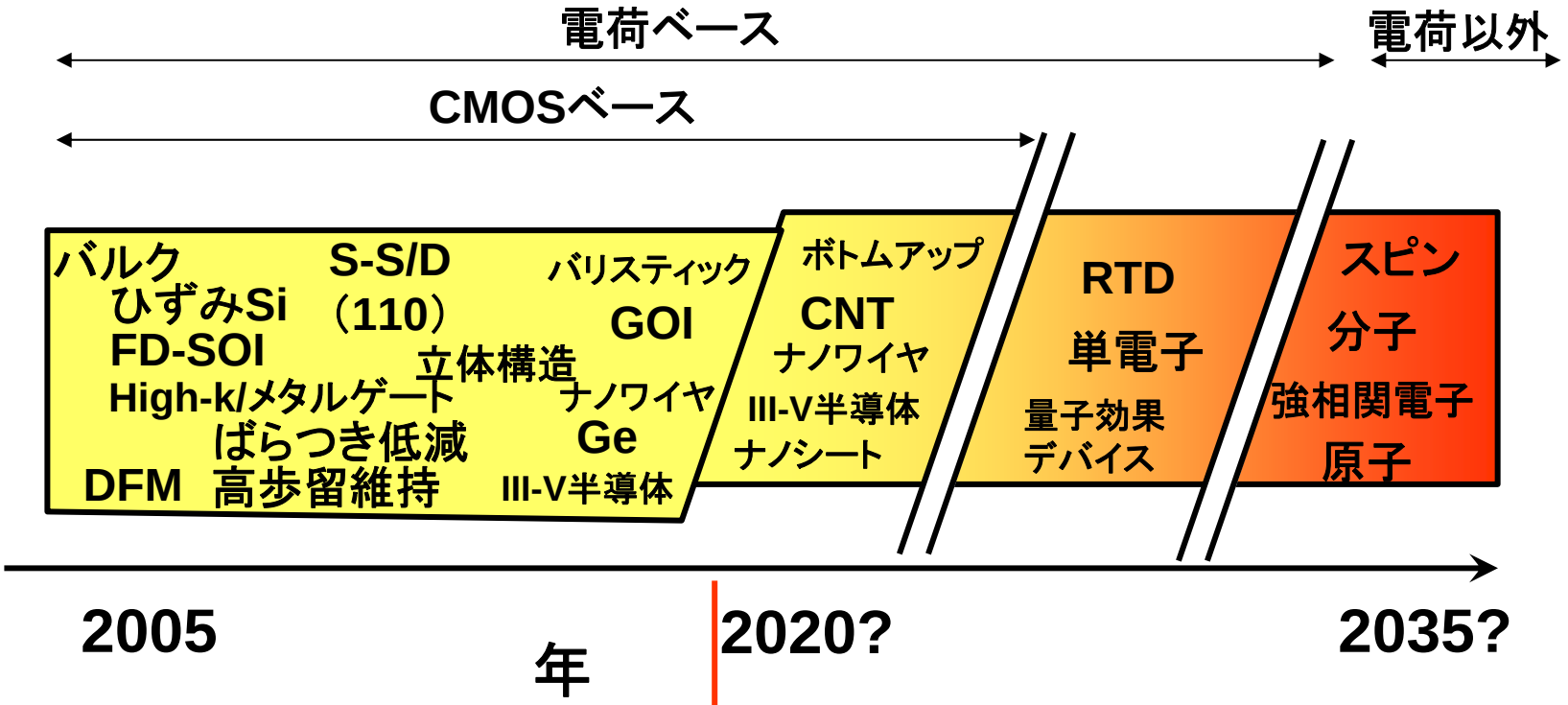
- スピン状態
- 分子状態
- 強相関電子状態
- 位相状態
- 量子状態
- 磁気単一量子磁束
- 機械的変形
- ダイポール

2007年版ロジックデバイスの結論

- 代替デバイスの検討を続けるほど同じ結果にたどり着いてしまう.
  - **MOSトランジスタを総合的に凌ぐデバイスは，ブール代数ロジック演算を行う限りにおいては（極めて高いリスクを負わない限り）存在しない.**
- 特定のある機能（例えば，画像認識など）に限れば，ブール代数ロジックゲート以外の方法で，もっと効率的に行うことが可能であろう.

2007 ITRS Winter Public Conference, 5 December 2007, Makuhari Messe, Chiba, Japan

将来の集積ナノエレクトロニクス



1. CMOS Extension
(More Moore)

3. Beyond CMOS

2. Added to CMOS (Application Dependent)
(More Than Moore)

2008 ERD/ERM Workshops

Workshop topic	Date	Location	Meeting
Emerging Research Memory Devices	April 2 2008	Bonn, Germany	ITRS Spring meeting
Emerging Research Architectures	July 10-11 2008	Santa Cruz, CA, USA	Semicon West
Evaluation of Beyond CMOS Logic Device Tech	July 12-13 2008	San Francisco, CA, USA	Semicon West
Emerging Research Logic Devices	Sept. 22 2008	Tsukuba, Japan	SSDM
Emerging Research Materials	Nov. 10 2008	Austin, TX, USA	MMM*
Emerging Research Materials	March 2009	Okinawa, Japan	

* 53rd Magnetism and Magnetic Materials Conference

Co-sponsored by the National Science Foundation

Beyond CMOS Maturity Evaluation WS

Date : 7/12 8:00 – 22:00, 7/13 9:00 – 16:30

Place : San Francisco Marriott Hotel

1. **NEMS Switch Technology,**
   Akarvardar (Stanford) and Elata (Technion)
2. **Spin Torque Transfer Technology,**
   Allen (UCSB) and Yablonovitch (UC Berkeley)
3. **Carbon-based Nanoelectronics,**
   Kim (Columbia U.) and Javey
4. **Atomic Switch / Electrochemical Metal Switch,**
   Kuekes (HP) and Chen (AMD)
5. **Collective Spin Devices (including M-QCA),**
   Wang (UCLA) and Bandyopadhyay (VCU)
6. **Single Electron Transistors,**
   Fujiwara (NTT) and Likharev (Stony Brook U.)
7. **CMOL and FPNI,**
   Likharev (Stony Brook U.) and DeHon (U. Pa.)

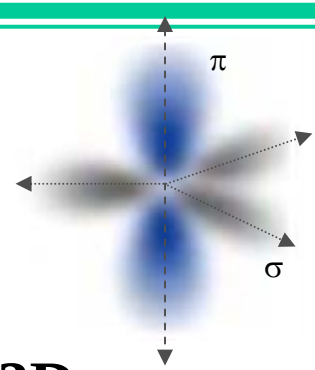
Beyond CMOS Maturity Workshop

	最終順位
Carbon-based Nanoelectronics	1
Collective Spin Devices	2
Spin Torque Transfer Technology	3
Atomic Switch/Electrochemical Metal Switch	4
CMOL and FPNI	
NEMS Switch Technology	
Single Electron Transistors	

まとめ:

- ”Carbon-based Nanoelectronics”を最も有望なBeyond CMOSとして選出
- ただし，CNTもグラフェンもBeyond CMOSというよりMore Moore.
- 結局，電荷以外を状態変数とする新デバイスはまだまだ遠いという結論.

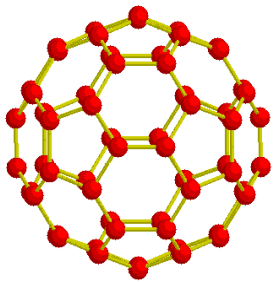
SP_2 Carbon: 0-Dimension to 3-Dimension



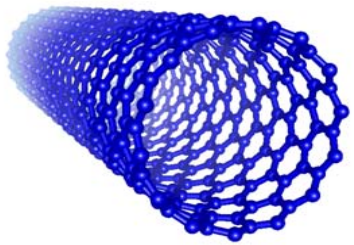
Atomic orbital sp_2

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

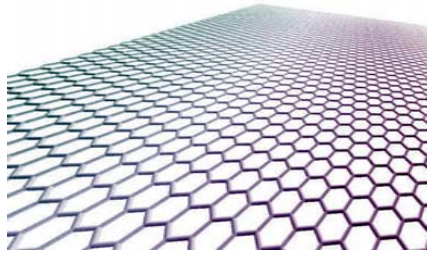
Fullerenes (C_{60})



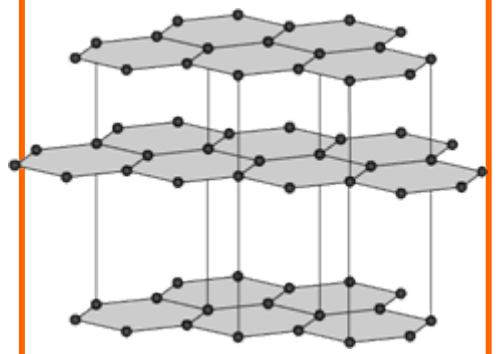
Carbon Nanotubes



Graphene



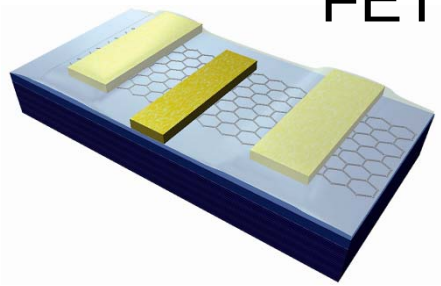
Graphite



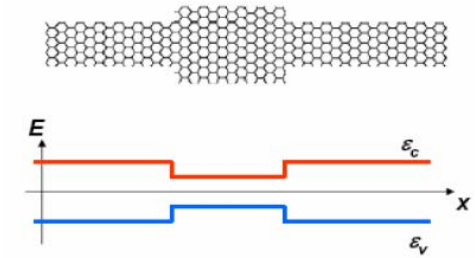
Graphene Electronics: Conventional & Non-conventional

Conventional Devices

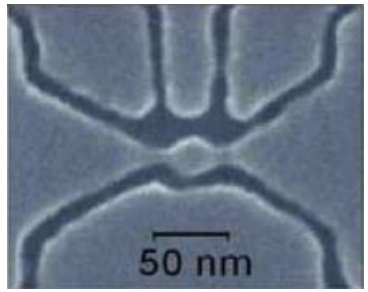
FET



Band gap engineered
Graphene nanoribbons

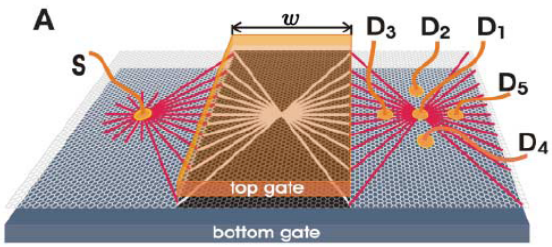


Graphene quantum dot



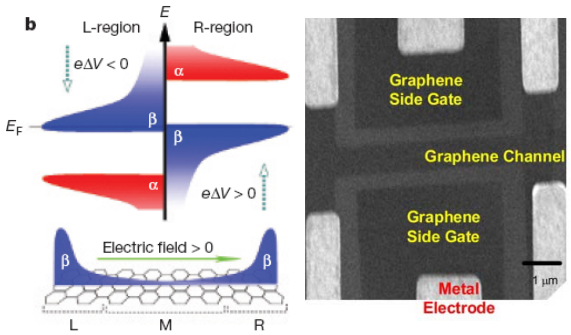
(Manchester group)

Nonconventional Devices



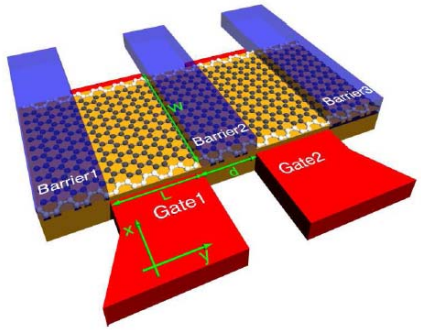
Graphene Veselago lense

Cheianov *et al. Science* (07)



Graphene Spintronics

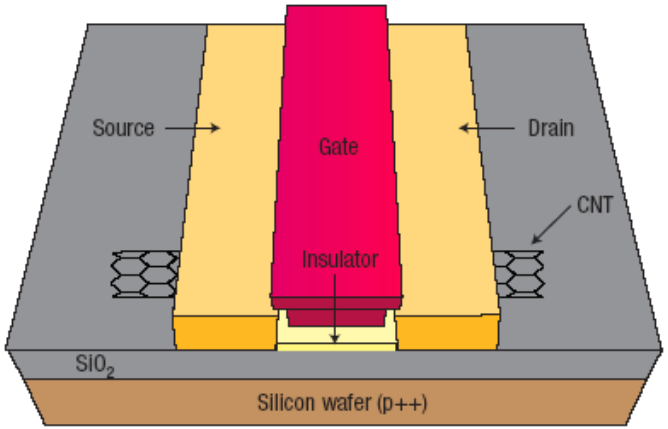
Son *et al. Nature* (07)

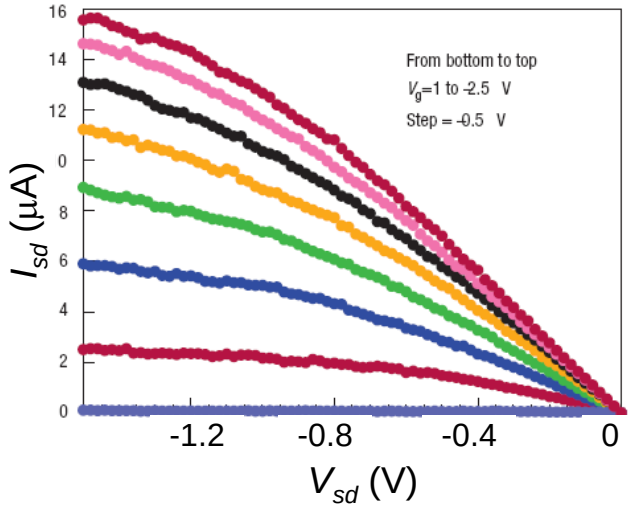


Graphene psedospintronics

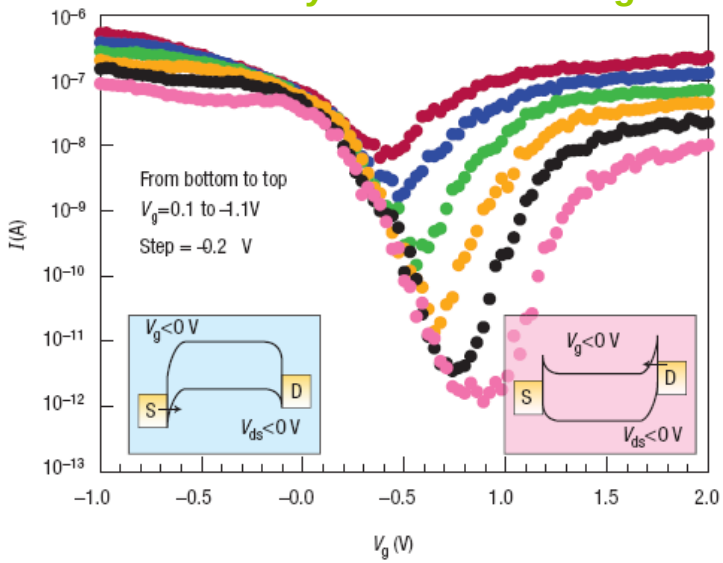
Trauzettel *et al. Nature Phys.* (07)

Nanotube FET





Schottky barrier switching

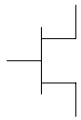
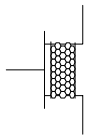
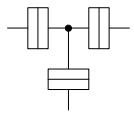
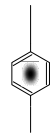
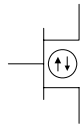


Band gap: 0.5 – 1 eV
On-off ratio: ~ 10^6
Mobility: ~ 100,000 cm^2/Vsec @RT
Ballistic @RT ~ 300-500 nm
Fermi velocity: 10^6 m/sec
Max current density > 10^9 A/cm^2

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

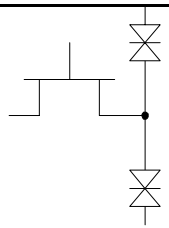
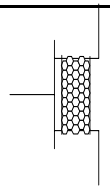
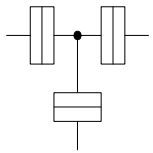
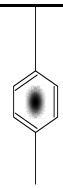
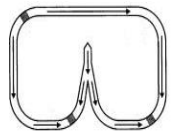
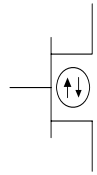
2007 ITRS ERD

CMOS Scaling & Replacement Devices (1st)

Device							
	FET	**CMOS Extension 低次元構造**	**CMOS Extension III-V チャネル**	**単電子トランジスタ**	**分子**	**強磁性ロジック**	**スピントランジスタ**
	Ref.	**CMOS Extension**			**Beyond CMOS**		
Types	Si CMOS	•CNT FET •NW FET •NW hetero-structures •Nanoribbon transistors	•III-V compound semiconductor channel replacement	SET	•2-terminal •3-terminal FET •3-terminal bipolar transistor •NEMS •Molecular QCA	•Moving domain wall •Hybrid Hall effect •Magnetic Resistive Element •M: QCA	•Spin Gain transistor •HMF Spin MOSFET •Spin Torque Transistor
Supported Architectures	Conventional	Conventional	Conventional	Threshold logic	Memory-based QCA	Lithographically defined	conventional

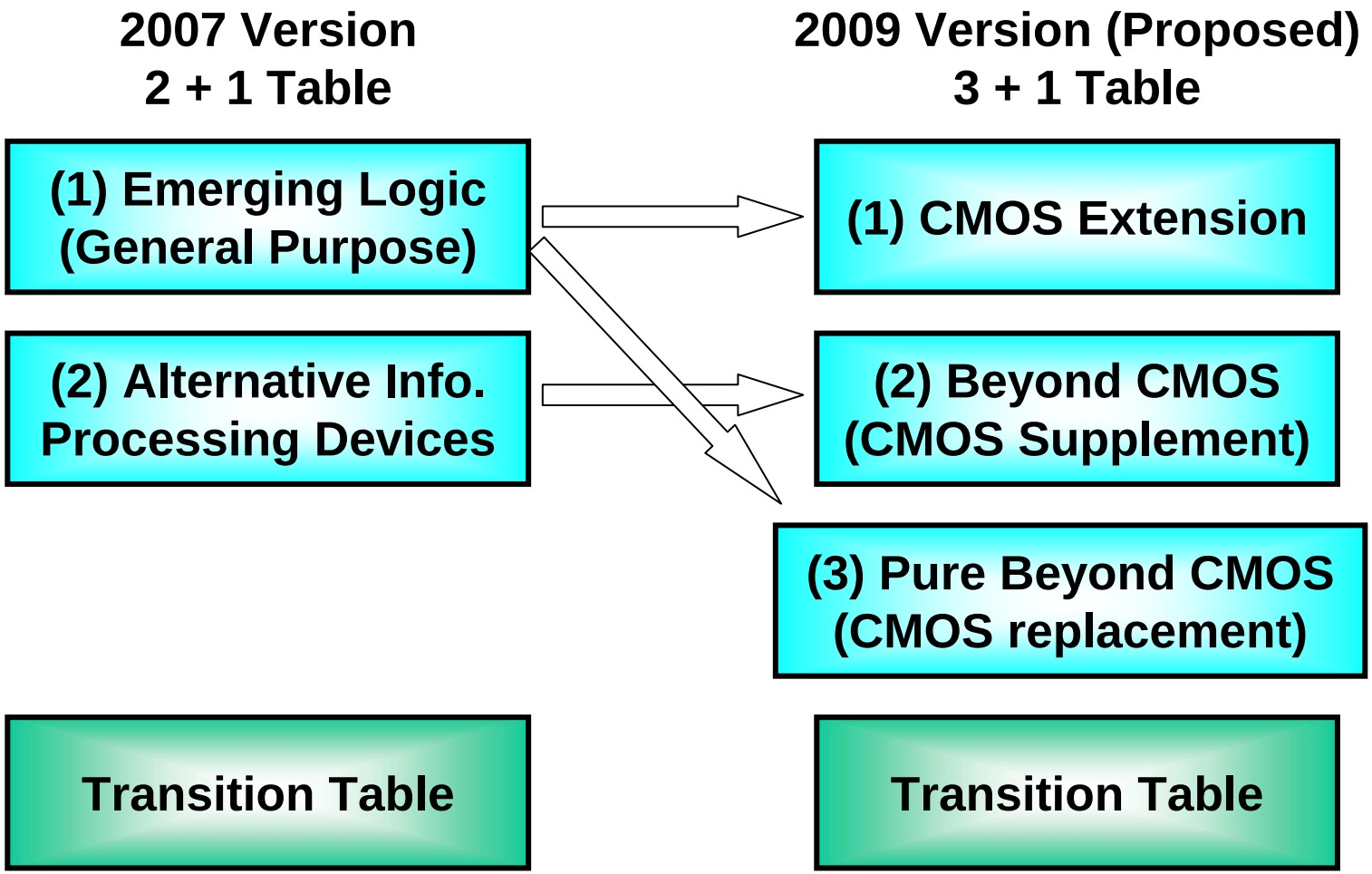
2007 ITRS ERD

CMOS Supplement Devices (2nd Table)

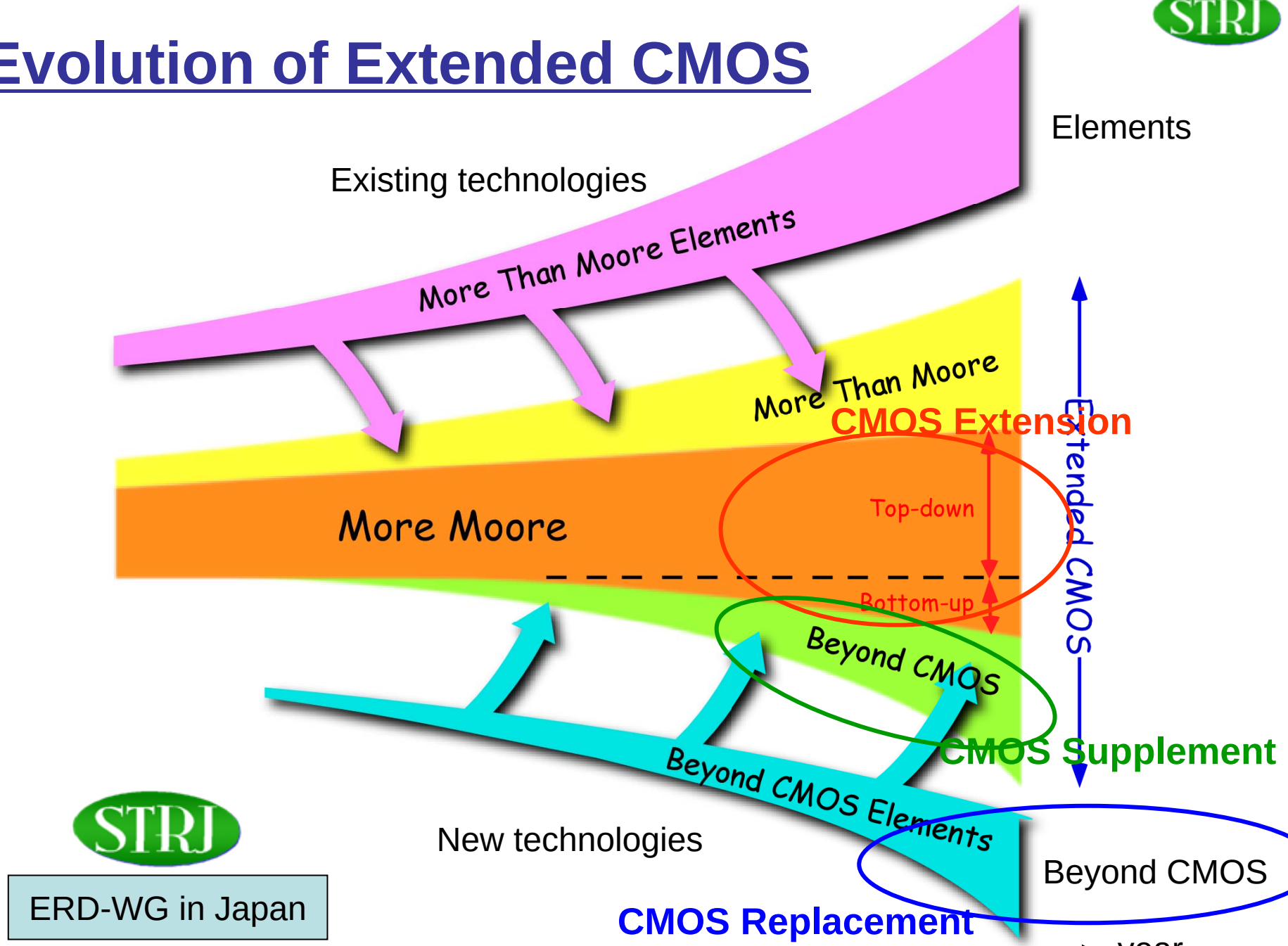
						
Device	共鳴トンネルダイオード	マルチフェロイックトンネル接合	単電子トランジスタ	分子デバイス	強磁性デバイス	スピンデバイス
State variable	Charge	Dielectric and magnetic domain polarization	Charge	Molecular Conformation	Ferromagnetic polarization	Precession frequency
Response function	Negative differential resistance	Four resistive states	Coulomb blockade	Hysteritic	Non-linear	Nonlinear

Logic Table日本案

T. Hiramoto, Dec. 14, 2009.



Evolution of Extended CMOS



ERD-WG in Japan

ロジックテーブル分類案

Titles for the three Emerging Research Logic Tables

Table 1: "MOSFET: Extending the Channel of MOSFETs to the End of the Roadmap"

Table 2: "Non-Conventional FET, Charge-based Extended CMOS Devices"

Table 3: "Non-FET, Non Charge-based 'Beyond CMOS' Devices"

Emerging Research Device Work Groups

International Emerging Research Devices (ERD) Work Group

US ERD WG	Japan ERD WG	Korea ERD WG	European ERD WG
		Dr. U-In Chung	

まとめ

1. Beyond CMOSのみで情報処理を行うことは困難との考え方が広まる. Beyond CMOSがCMOSに融合する考え方が一般化.
2. もっとも集中すべきBeyond CMOSは「カーボンナノエレクトロニクス」.
3. Beyond CMOSの再定義が必要.
4. 韓国のERD-WGが発足. メモリ候補の絞り込みの議論が始まる予定.