Emerging Research Materials (ERM)

2nd Deterministic Doping Workshop

Date: November 12, 2010

Place: Whitecotton Room, Hotel Shattuck Plaza, Berkeley

Time: 8:00am – 5:20pm PDT
11:00am – 8:20pm EDT
0:00am – 9:20am (November 13) Japan
1:00am – 10:20am (November 13) Australia
5:00pm – 2:20am Europe

http://www.src.org/calendar/e004100/

Co-chair persons

Daniel Herr/SRC

Takahiro Shinada/Waseda Univ.

Emerging Research Materials (ERM)

2nd Deterministic Doping Workshop

Introduction

Daniel Herr
SRC

Acknowledgments

All for participating in ITRS Deterministic Doping Workshop

All presenters for contribution to the workshop

Prof. Ali Javey/UC Berkeley for hosting the workshop

Ms. Ebony Waller/SRC for IT and accommodation support

Beverage, Lunch and Dinner

Sponsored by SRC

Announcements

Executive summaries are available at the workshop website:
http://www.src.org/calendar/e004100/

Group photo just before lunch or at the end of the workshop

Workshop dinner
Time: 5:30 p.m.
Location: Hotel restaurant "Five Restaurant"
Please let us know if you plan to join us for dinner.
SRC will cover dinner costs, but not alcohol.

Participants as of November 6

	Name	Organization		
1	D. Herr	SRC	Co-chair	Co-chair of ERM, ITRS
2	T. Shinada	Waseda Univ.	Co-chair	Single ion implantation
3	S. Shankar	Intel	Presenter	
4	M. Current	Current Scientific	Presenter	Implant process
5	T. Schenkel	LBNL	Presenter	Single ion implantation
6	A. Javey	UC Berkeley	Presenter	DSA
7	C. Ober	Cornell Univ.	Presenter	DSA
8	M. Simmons	UNSW	Presenter	STM positioning
9	Y.-J. Lee	NDL	Presenter	Dopant activation
10	K. Inoue	Kyoto Univ.	Presenter	Atom probe
11	M. Tabe	Shizuoka Univ.	Presenter	Single dopant device
12	S. Rogge	TU Delft	Presenter	Single dopant device
13	A. Asenov	Univ. Glasgow	Presenter	Device modeling
14	A. Morello	UNSW	Presenter	Single dopant spin control
15	G. Fuchs	UCSB	Presenter	Nitrogen-vacancy center in Diamond
16	B. Naydenov	Stuttgart	Presenter	Nitrogen-vacancy center in Diamond
17	A. Chen	Global Foundries		
18	E. Bielejec	SNL		Single ion implantation
19	M. Garner	Intel		Co-chair of ERM, ITRS
20	T. Hiramoto	Univ. of Tokyo		Ex-chair of Japan ERD, ITRS
21	L. Hollenberg	Univ. Melbourne	Remote	Quantum transport modeling
22	M. Hori	Waseda Univ.		Single ion implantation
23	D. Jamieson	Univ. of Melbourne	Remote	Single ion implantation
24	J. McCallum	Univ. of Melbourne	Remote	Single ion implantation
25	A. Persaud	LBNL		Single ion implantation
26	T. Peterson	Dow Chemical Company		
27	E. Prati	CNR	Remote	Single dopant device
28	A. Vanderpool	Intel	Remote	Implant process
29	C. Weis	LBNL		Single ion implantation

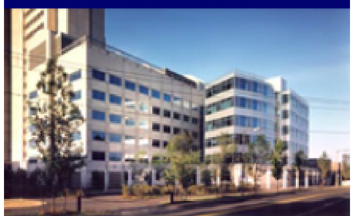
Workshop Objective

- **Gather sufficient information** to draft the revised 2011 ITRS Emerging Research Materials (ERM) chapter on deterministic doping.
- **Clarify projected research requirements** by updating critical challenges, state-of-the-art and key messages.
- **Identify potential application options**, which may leverage emerging materials, devices and processes and enable extensible CMOS technologies to and beyond the 16nm node.

e-Workshop on Deterministic Doping

Date: November 12, 2008, Organizer: Dan Herr/SRC

ITRS ERM
eWorkshop Series:
Deterministic Doping



November 12, 2008
via Adobe Connect,
hosted by SRC
7:00 - 9:30 PM ET

in cooperation with the
National Nanomanufacturing
Network (NNN)

National Nanomanufacturing Network

ITRS ERM eWorkshop Series: Deterministic Doping - Agenda

Event Home | **Agenda** | Presenters | Pre-reading Briefs | Registration | Log In

Meeting Date: Wednesday, November 12, 2008 @ 7:00 PM to 9:30 PM EDT
Meeting Place: via Acrobat Connect, hosted by GRC, Research Triangle Park, NC, USA

Adobe Connect URL: http://src.na3.acrobat.com/itrsewksp/
Telecon /Audio Bridge: Telecon / Audio Bridge: 866-244-8528; Participant Code: 984244

7:00 - 7:05 p.m.	Welcome and Guidelines	Dan Herr SRC
Session I: Requirements and Potential Benefits (Leads: An Chen/AMD and Atsushi Shiota/JSR Micro)		
7:05 - 7:25 p.m.	End User Community Perspective	Rich Klein AMD
7:25 - 7:45 p.m.	Supplier Community Perspective	Masayasu Tanjyo NISSIN
Session II: State-of-the-Art and Recent Results (Lead: Dave Roberts/Air Products)		
7:45 - 8:05 p.m.	Overview of Emerging Research Landscape	Mark Tuominen UMASS - Amherst
8:05 - 8:15 p.m.	Ion Implantation Methods	Thomas Schenkel LBNL
8:15 - 8:25 p.m.	Arrays of Single Atoms in Silicon by Deterministic Single Ion Implantation	David Jamieson U of Melb-Aus
8:25 - 8:45 p.m.	Shallow Doping Methods	Ali Javey UC-Berkeley
8:45 - 9:05 p.m.	STM Positioning Methods	Michelle Simmons UNSW
Session III: Discussion and Wrap-up (Facilitator: Dan Herr/SRC)		
9:05 - 9:30 p.m.	Discussion on Key Messages	All
9:30 p.m.	Adjourn e-Workshop (Face-to-face discussions to continue as warranted)	

Deterministic doping in ERM Chapter

Critical Challenges

Emerging Front End Processes' and Process Integration, Devices, and Structures' Material Challenges and Options

Key challenges for future FEP and PIDS materials and processes are to support extending CMOS to smaller dimensions with reduced variation in device performance. This will require more accurate placement of dopants in active device areas, directed self assembly of useful nanomaterials, and materials to enable selective deposition, etch, and cleans to enable self aligned structures in future devices. The requirements and challenges for ERM applied to FEP and PIDS applications are summarized in Table ERM8.

Doping and Deposition

Critical Challenges: The Importance of Deterministic Fabrication

Table ERM8 FEP / PIDS Challenges for Self Assembly

A key challenge for scaling semiconductor devices towards 10 nm is the ability to achieve high doping levels within source/drain regions, with abrupt dopant gradients with small variations at the source/drain interface to the channel, as well as controlled dopant positions within the channel. For example, the series resistance of a MOSFET continues to be a difficult challenge that becomes more severe with scaling. A large part of the parasitic series resistance critically depends on the lateral doping and the abruptness of the source/drain junction. Currently, the total series resistance degrades the on-current by more than 30%. To a lesser degree, variations in S/D interface doping degrade on-current uniformity. It will be difficult to maintain the same degradation percentage variation for smaller gate lengths. This S/D doping interface profile determines the length of the transition region between the S/D regions and the channel. An ideal transition is a step profile. In practice, this transition region must be small compared to the channel length. One way to control the doping profile is by deterministic processing and doping. Additionally, the threshold voltage, V_t, is sensitive to small variations in channel dimensions, the gate stack structure, and dopant variations in the depletion layer. V_t variability will gate the extensibility of bulk planar CMOS device technology.[242] Over the next six to thirteen years, MPU physical gate lengths,

Deterministic doping in ERM Chapter

Critical Challenges (Continued)

L_{gate}, are projected to scale from 17 nm to 9 nm. Also, the trend in the number of channel electrons suggests that by the year 2014 there may be less than one hundred active dopants in the channel region[243] For channel doped devices, this low number of channel dopants may emerge as a another critical performance and yield limiter. (A more detailed discussion on the number of dopants in the channel can be found in the supplemental document.).[244, 245] In general, dimensional control and variability are emerging as key materials challenges. Ideally, source-channel-drain interfaces would be atomically abrupt and exhibit atomically precise control of dopant position and composition. Research is needed to develop new materials and fabrication methods that enable deterministic control of the composition and structure of doped material and gradient systems.

For FEP and PIDS applications, deterministic fabrication refers to 3D nanopatterning and assembly methods that provide sufficient control of the composition and structure of doped interfaces and components to yield several orders of magnitude improvements in device to device performance variability.[246] Doping processes with atomic-scale placement and concentration control will enable tunable device performance characteristics and reduced device-to-device variations. A reduction in device noise enlarges the useable design space, circuit-level uniformity, and system performance. The ability to accurately place dopants also may enable radically new device concepts, such as emerging quantum computing devices, based on coherent manipulation of single dopant atomic states within Si[247] or diamond matrices.[248] Candidate doping options must address the following: 1) accurate control of the number and position of dopants; 2) statistical fluctuation of dopant numbers on device characteristics; 3) compatibility and integration with existing fabrication platforms; and 4) economics, which depends upon on R&D and equipment costs, yield, and throughput.

Deterministic doping in ERM Chapter

State-of-the-Art

STATE-OF-THE-ART

A. **Single ion implantation (SII)**[249]—This technology seeks to deposit a specified number of desired dopant ions at precise locations within the active region. Key objectives are to achieve ion implantations with:

- High spatial resolution and flexibility in dopant species, as well as 100% single dopant detection.
- Scanning probe alignment, combined with single ion impact sensing through monitoring of 2DEG upsets, as a universal tool for single atom placement

Key research challenges include: dopant counting and dopant placement. Single ion implantation can be measured by the detection of secondary electrons, photons, electron-hole pairs, changes in transistor channel currents, or direct imaging changes in surface topography. Significant sources of dopant positioning errors, such as implantation spot size, range straggling, and diffusion and segregation during annealing, must be addressed for SII to be relevant for ultimately scaled doped devices and related application opportunities, such as:

- Single atom device development, which requires a method for reliable single atom doping
- Systematic studies of dopant fluctuation effects and tests of quantum computer architectures (qubit readout, control and coupling) in relevant device platforms and substrates, e.g., silicon and diamond

B. **Self-assembly and surface chemistry**[250]—This chemistry based approach teaches that the dose can be modulated precisely by the formation of a mixed monolayer, consisting of tunable blank and active precursor components. Additionally, controlled nanoscale semiconductor doping by self-assembled molecular monolayers can achieve sub-5 nm ultra-shallow junctions with spike anneals, due to the lack of transient enhanced diffusion often encountered in ion implantation. A key objective is to heavily dope ‘self aligned’ semiconductor materials for nanowire and planar device applications.

C. **STM positioning**[251]—Fabrication of atomically precise devices has been demonstrated in silicon, using a combination of scanning probe microscopy and molecular beam epitaxy. Potential benefits of the STM approach include: The ability to pattern with atomic precision in three dimensions; extremely high density, atomically planar and abrupt doping profiles; the ability to pattern sub 10nm MOSFET architectures; the investigation of novel device architectures; and applicability to other dopant sources/metal/organics. It is highly unlikely that this technique will warrant consideration as a potential solution for advanced device fabrication, because of low throughput, STM tip stability, reproducibility. On the other hand, the patterning accuracy of this technique may enable exploration of unique devices.

Deterministic doping in ERM Chapter

Key Messages

KEY MESSAGES

Extremely high placement accuracy, <1 nm, doping methods, e.g., STM, are not likely to become manufacturable, as the proposed massively parallel approaches face significant data management challenges. However, these methods may enable the exploration of fundamental device limits and new functionality, such as symmetry and quantum effects. Medium placement accuracy, ~10 nm, doping methods (i.e., single ion implantation) exhibit the potential for device development applications. The projected manufacturing requirements create a need for new doping concepts. Research is needed on high throughput doping options that also deliver high placement accuracy. Emerging candidate doping research focus areas include directed self assembly and the use of molecular monolayers as scaffolds for controlled dopant delivery.

Goals

- **Define** the difficult challenges
- **Share** the concept of “Deterministic doping”
- **Review** the progress in the last five years
- **Identify** the critical targets and potential solutions for the next 10 – 15 years
- **Identify** the potential applications
- **Identify** experts and expertise

Emerging Research Materials (ERM)

2nd Deterministic Doping Workshop

Overview

Takahiro Shinada

Waseda Univ.

Concept of deterministic doping

DEFINITION:

- **Introduce** single-dopant/few-dopants within the channel as well as source/drain regions with placement accuracy of less than 10nm.
- **Activate** the introduced single-dopant/few-dopants properly.
- **Measure** & **image** single-dopant/few-dopants precisely.
- **Explore** appropriate combinations of single-dopant/few-dopants and host materials for new functionalities.

Scope of this workshop

- **ITRS requirements** — Session I
- **Deterministic doping**
  - Single ion implantation
  - Directed self-assembly (Doping, Patterning)
  - STM positioning
- **Activation** (Laser Anneal, Flash Anneal, Mircowave Anneal)
- **Measurement & imaging**

  (Scanning Spreading Resistance Microscopy: SSRM,

  Kelvin Force Microscopy; KFM, 3D Atom Probe; 3DAP, etc)

Session II

- **Applications**
  - Reduced dopant variation
  - Ultra shallow junction
  - Donor spin in silicon
  - Nitrogen-Vacancy (NV) in diamond

Session III

Agenda (1/3)

Session I : ITRS requirements		
8:00-8:10am	Welcome, introduction and guidelines	D. Herr/SRC
8:10-8:20am	Overview	T. Shinada/Waseda Univ.
8:20-8:45am	End user community perspective	S. Shankar/Intel
8:45-9:10am	Doping of Atomic-scale Processed Materials and Devices	M. Current/Current Scientific

Agenda (2/3)

Session II : Deterministic processes		
9:10-9:35am	Single ion implantation	T. Schenkel/LBNL
9:35-10:00am	Directed self-assembly: Doping	A. Javey/UC Berkeley
10:00-10:25am	STM positioning	M. Simmons/UNSW
10:25-10:45am	Break	
10:45-11:10am	Dopant activation	Y.-J. Lee/National Nano Device Lab. Taiwan
11:10-11:35am	3D atom probe	K. Inoue/Kyoto
11:35-12:00pm	Nitrogen-Vacancy spin control in diamond: Ultrafast single spin manipulation	G. Fuchs/Prof. Awschalom group, UCSB
12:00-12:30	Walk-on presentation Round table discussion Group Photo	TBA
12:30-1:30pm	Lunch	

Agenda (3/3)

Session III: Deterministic devices		
1:30-1:55pm	Single dopant devices: Quantum confinement transition of single dopant in FinFET	S. Rogge/Delft Univ. of Technology
1:55-2:20pm	Single dopant devices: Single-electron transport through single-dopants	M. Tabe/Shizuoka Univ.
2:20-2:45pm	Device Modeling	A. Asenov/Univ. Glasgow
2:45-3:10pm	Single dopant spin control in SET	A. Morello/UNSW
3:10-3:30pm	Break	
3:30-3:55pm	Nitrogen-Vacancy spin control in diamond	B. Naydenov/Prof. Wrachtrup & Jelezko group, Stuttgart
3:55-4:20	Directed self-assembly: Patterning	C. Ober/Cornell Univ.
4:20-4:50	Walk-on presentation/Round table discussion	Moderator: D. Herr
4:50-5:05pm	Brief break	
5:05-5:20pm	Wrap up discussion and action items	Moderator: D. Herr
5:20	Closing remarks, Group photo & Adjourn	D. Herr, T. Shinada

Requests for presenters

Presentations will be solicited to address following issues:

- **Start** the presentation from general interest
- **Review** the progress of selected topics over the past five years
- **Consider** potential application opportunities, if possible (What is the potential impact on ITRS?)
- **Identify** the difficult challenges and potential solutions for the next 10 – 15 years
- **Identify** experts and expertise
- **Provide** permissible PowerPoint slides before dinner

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2nd Deterministic Doping Workshop

Let’s start the session

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2nd Deterministic Doping Workshop

Walk-on Presentation
Round Table Discussion
(12:00 - 12:30 p.m.)

Agenda for walk-on presentation

- Introduction of “Extended CMOS” concept (5-10min)

  T. Hiramoto / Univ. of Tokyo (Ex-chair Japan ERD)

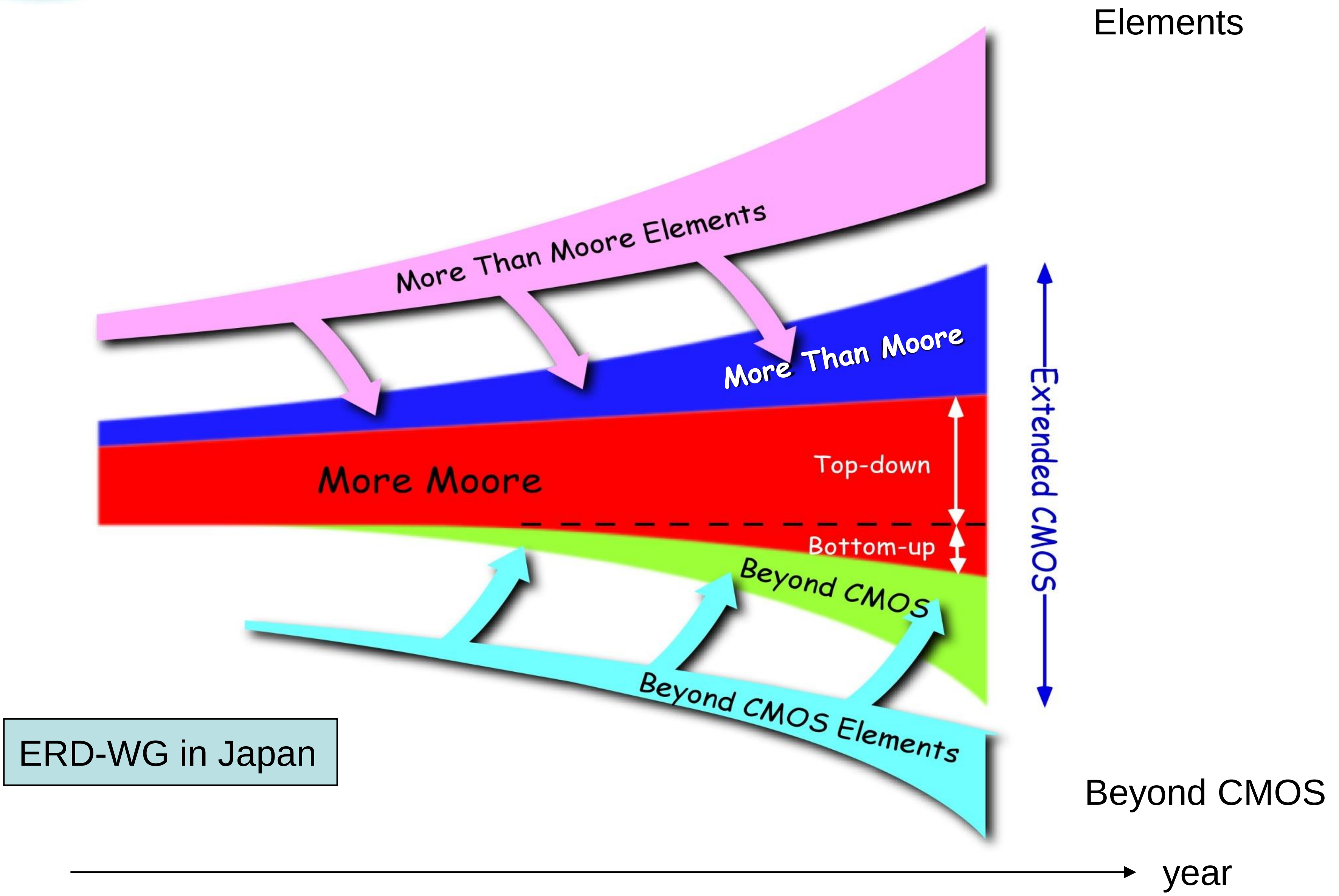
- Material solutions (5-10min)

  T. Peterson on behalf of P. Trefonas/ Dow Chemical Company

- Trends in device technologies ? (5-10min)

  M. Garner / Intel

Evolution of Extended CMOS



J. Hutchby, "Emerging Research Devices", 2010 ITRS Summer Public Conference, July 14,2010

Emerging Research Materials (ERM)

2nd Deterministic Doping Workshop

Walk-on Presentation
Round Table Discussion
(4:20 – 4:50 p.m.)

Agenda

- Additional walk-on presentations
- Confirm the definition of “Deterministic doping”
- Summarize the five-year progress and identify the difficult challenges

Concept of deterministic doping

DEFINITION:

- **Introduce** single-dopant/few-dopants within the channel as well as source/drain regions with placement accuracy of less than 10nm.

- **Activate** the introduced single-dopant/few-dopants properly.

- **Measure** & **image** single-dopant/few-dopants precisely.

- **Explore** appropriate combinations of single-dopant/few-dopants and host materials for new functionalities.

Summary
Progress and difficult challenges (1/2)

Deterministic Processes	Progress	Difficult challenges
Single ion implantation	• Reliable single-ion counting	• Dopant placement < 10nm • Higher throughput
Directed self-assembly	• Patterning • Doping	
STM positioning	• True single atom device	
Dopant activation	• Laser Anneal • Flash Anneal • Microwave Anneal <<500^{o}C	
Imaging	• SSRM • 3D atom probe tomography • Local electrode atom probe (LEAP) • Low temperature Kelvin force microscopy • STEM	• Specimen preparation

Summary

Progress and difficult challenges (2/2)

Deterministic devices	Progress	Difficult challenges
Single dopant transport		• Room temperature operation
Single dopant spin control	• Readout of electron spin of single donor • Lifetime up to 6s	• High quality isotopicaly purified silicon
Single nitrogen-vacancy spin control in diamond	• Room temperature operation • 1ms lifetimes of spin coherence	• N-V color center yield improvement

Summary
Experts and expertise (1/2)

Deterministic processes	
Single ion implantation	Schenkel/LBNL, Jamieson/Melbourne, Shinada/Waseda
Directed self-assembly: Doping	Javey/UC Berkeley
Directed self-assembly: Patterning	Ober/Cornell
STM positioning	Simmons/UNSW
Dopant activation	Lee/NDL
Imaging	Inoue/Kyoto, Zhang/Toshiba

Summary
Experts and expertise (2/2)

Deterministic devices	
Single dopant transport	Rogge/DUT, Tabe/Shizuoka, Pierre/LETI, Sanquer/LETI, Ono/NTT Asenov/Glasgow
Single dopant spin control	Morello/UNSW Hollenberg/UNSW
Single nitrogen-vacancy spin control in diamond	

Emerging Research Materials (ERM)

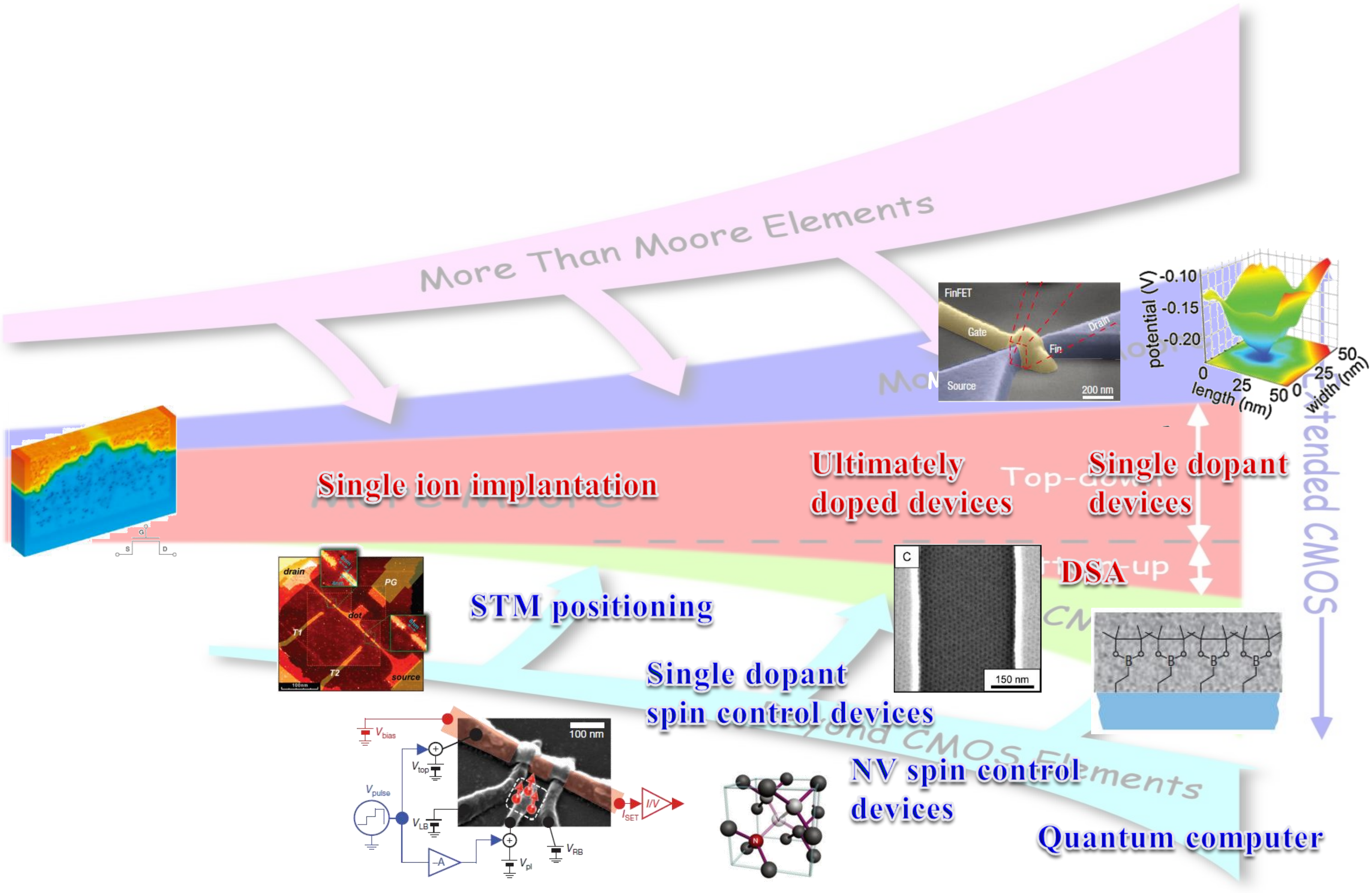
2nd Deterministic Doping Workshop

Wrap up discussion and action items (5:05 – 5:20 p.m.)

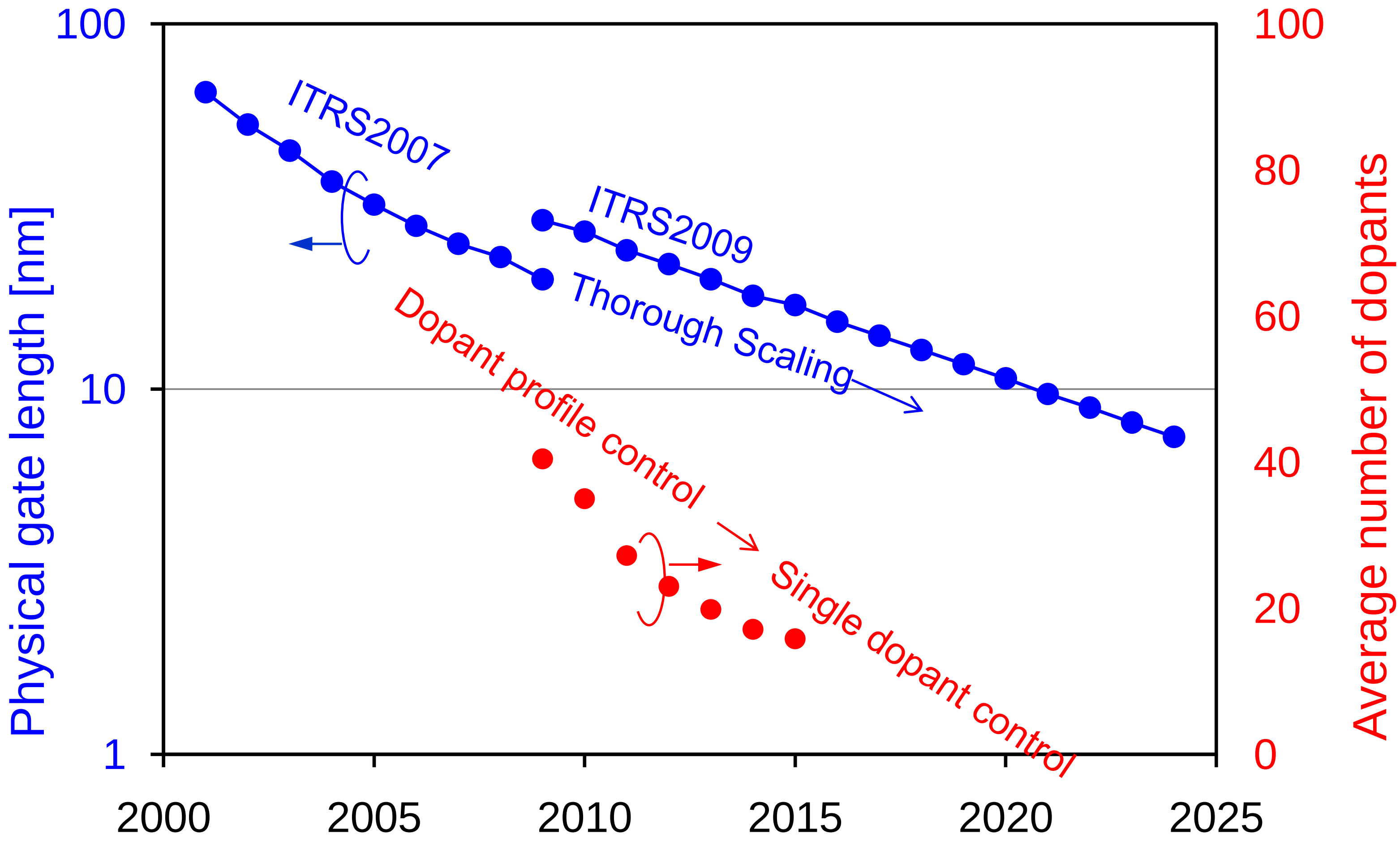
Agenda

- Key questions from co-chairs
  - Contribution to “Extended CMOS”?
  - Timeline?
  - Advantages against non-doped devices?
  - Compatibility and integration with CMOS platform
  - Cost

Concept of deterministic doping



Trends in number of channel dopants

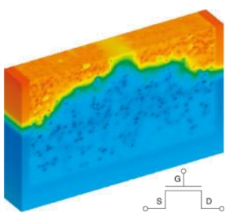


Trends in device technologies

2010	2012	2015	2020	2030
hp45	hp32	hp21		

Doped channel

Bulk silicon MOSFET



Random dopant fluctuation

Single dopant control →

Work function control ↓

Ultimate doped channel
(Limit of traditional transistors)

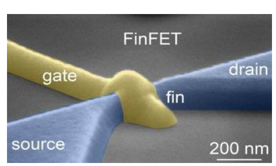
Single dopant devices

Single spin devices

Single NV diamond devices

Nondoped channel

FD SOI MOSFET



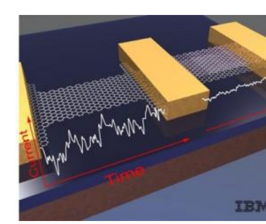
FD Multi gate devices

Nanowire FETs

III-V & Ge FETs

Graphene FETs

Ultimate non-doped channel
(All metal transistors?)



Target of deterministic doping

2010	2012	2015	2020	2030
hp45	hp32	hp21		

Deterministic doping for:

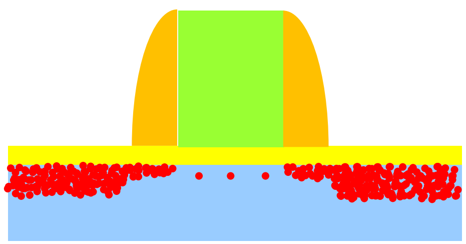
(1) Channel — Controlled dopant number and location

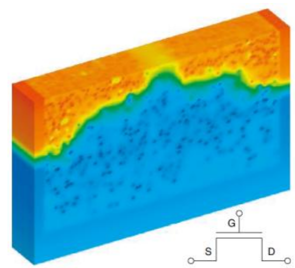
(2) Interface of channel and junction (Extension) for doped and undoped devices

Abrupt transition

(3) Source and drain (Junction)

High doping level
Ultra shallow junction





Asenov, Science 2005

Deterministic doping technologies:

Single ion implantation
Extremely low energy implantation
Pre-amorphization implantation
Co-implantation
Molecular implantation
Plasma doping
DSA doping

Laser anneal
Flash anneal
Microwave anneal

SSRM
Atom probe tomography

Action items

- **Provide** permissible PowerPoint slides
- **Share** the presentation files and contact information through the workshop website
- **Draw up** minutes of the workshop
- **Report** to ITRS Winter Meeting on December, 2010 in Tsukuba, Japan
- **Work on** ITRS 2011 Edition