Emerging Research Materials (ERM)

2nd Deterministic Doping Workshop

Summary

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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.

Participants

	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
30		LBNL		Single ion implantation
31		LBNL		Single ion implantation

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 & Adjourn	D. Herr, T. Shinada

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** potential application opportunities through the atomistic control of materials, devices, processes and characterizations for better device performances.

SUMMARY SESSION I : ITRS Requirements Perspectives

Perspectives	Key messages
End-user community perspective	• Thermodynamics and statistics may limit with scaling • Alternate options: materials and processes, doping can be achieved during deposition • Technology challenges and focus: Presence of interfaces, thermal processes, scaling, cost
Supplier community perspective	• Atomic scale processed materials and devices need to be developed and articulated to engage the inventiveness of the “doping” community. • Implant evolving to be more precise, much like CVD has evolved towards ALD • Enhance damage accumulation • Photonic world of integrated phonon and electron signal processing and communication

SUMMARY SESSION II : Deterministic Processes
Progress and difficult challenges (1/2)

Processes	Progress	Difficult challenges
Single ion implantation	• Reliable single-ion counting • Understanding dopant specific mechanism	• Dopant placement < 10nm • Activation • Higher throughput
Directed self-assembly	• Patterning: BCPs 20nm size • Dopants loaded with bio-inspired polymers • Monolayer doping + Spike annealing, sub-5nm junction	• Long range order, smaller size <5nm • Triblock polymers • Crystalizable and functional blocks • Defects and contamination • 2D dopant control, i.e. ordered dopant arrays
STM positioning	• World highest precision transistor • True deterministic single dopant device • 3D atomistic control, 3D device architectures • High stability, all epitaxial in plane highly phosphorus doped gates with densities of ~$2 \times 10^{14} cm^{-2}$. • Full activation in high density n-type • Low temperature process • Single shot read-out of single P donor spin in silicon with lifetimes of seconds for electron spin qubit applications	• Higher temperature operation • Higher throughput • Device modeling • Extending to different materials and dopants
Activation	• Microwave Anneal <500ºC for B, P, As in Si, Ge, poly-Si • Laser Anneal, Flash Anneal	• Microwave uniformity, especially impact on dense metal lines
Imaging	• 3D atom probe tomography(APT), LEAP • SSRM, Kelvin force microscopy(KFM) • STEM	• Detection efficiency > 50% • Improve S/N ratio • Artifact of 3D reconstruction • Specimen preparation

SUMMARY SESSION III : Deterministic Devices
Progress and difficult challenges (2/2)

Devices	Progress	Difficult challenges
Modeling	• Drift diffusion (DD), Monte Carlo (MC), Quantum transport (QT) simulations • Hierachical approach simulation from first principle to compact model	• DD: mobility model capturing impact individual dopants in various configuration • MC: short range corrections near interface • QT: incorporation of phonon scattering • Computational efficiency • Accurate model for dopant potential
Single dopant transport	• Transport through single donor/acceptor • Memory effect in 2-donor system • Single electron transport in multi-donor system • Charge pumping • Single-dopant current spectroscopy • Atomistic understanding of donor in nanodevices	• Room temperature operation • Precise dopant placement • Push transport combined with modeling toward full metrology • Device with immunity from fluctuation • Single dopant electronics • Go beyond boolean logic (more than Moore)
Single dopant spin control	• Single shot readout of electron spin of single P donor in Si with lifetime of seconds for electron spin qubit application • ESR single donor in Si • Lifetime up to 6s • 92% readout visibility	• Coherent spin transport • High quality isotopically purified silicon • 2-qubit devices with controllable coupling • ESR single-donor in channel of transistor
Single nitrogen-vacancy (N-V) spin control in diamond	• Single spin readout at room temperature • Room temperature operation 2.4ms of spin coherence • Yield depends on energy: 1 to 60% • Initialization time ~us • Single shot readout at room temperature	• N-V color center yield improvement to 100% • Improve lateral resolution of ion implantation • Collection efficiency photons

Key messages

Design for variability

Interface control

Metrology

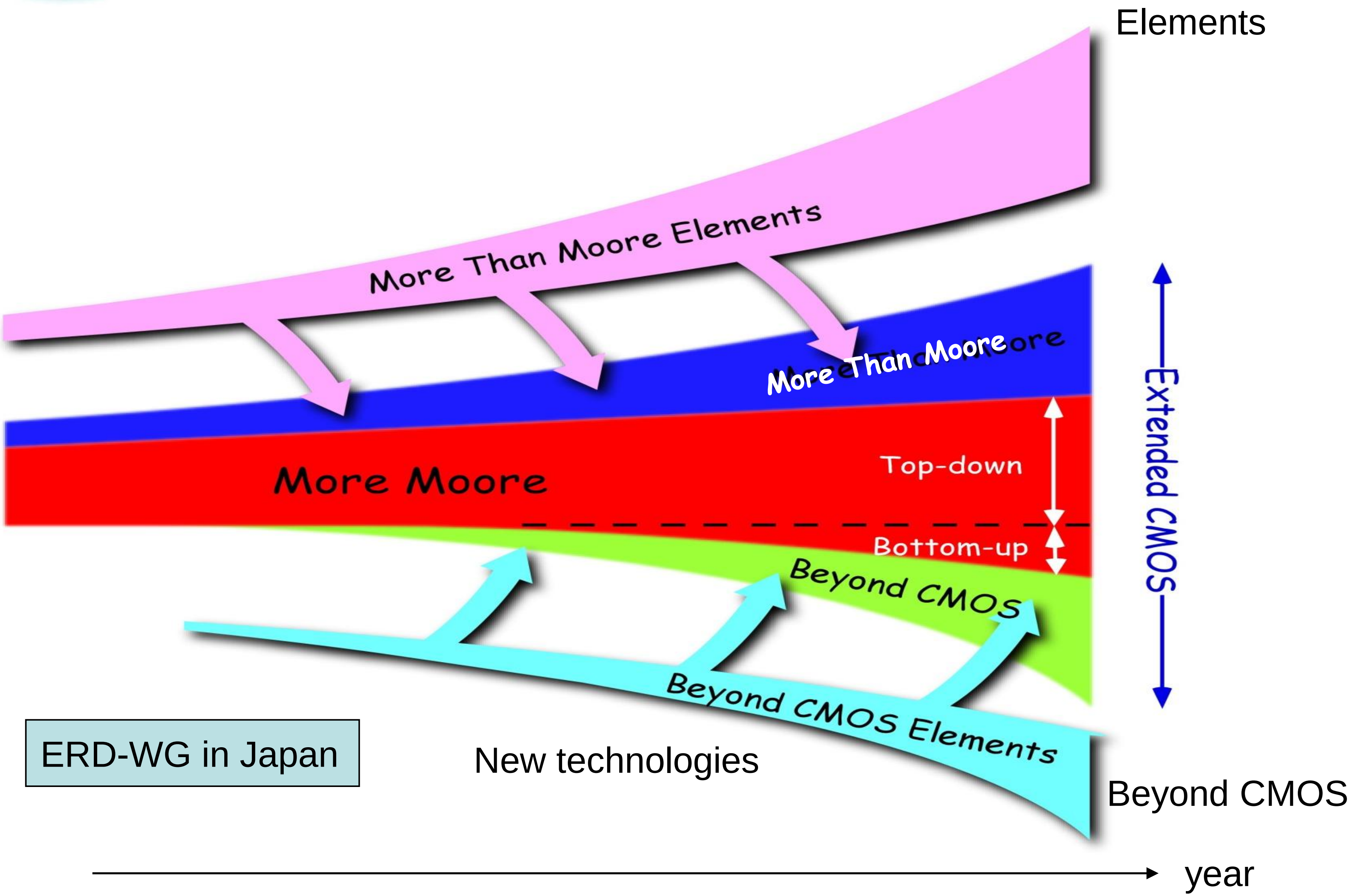
Quantum confinement

Junction abruptness

Physics of close couple dopant and interface

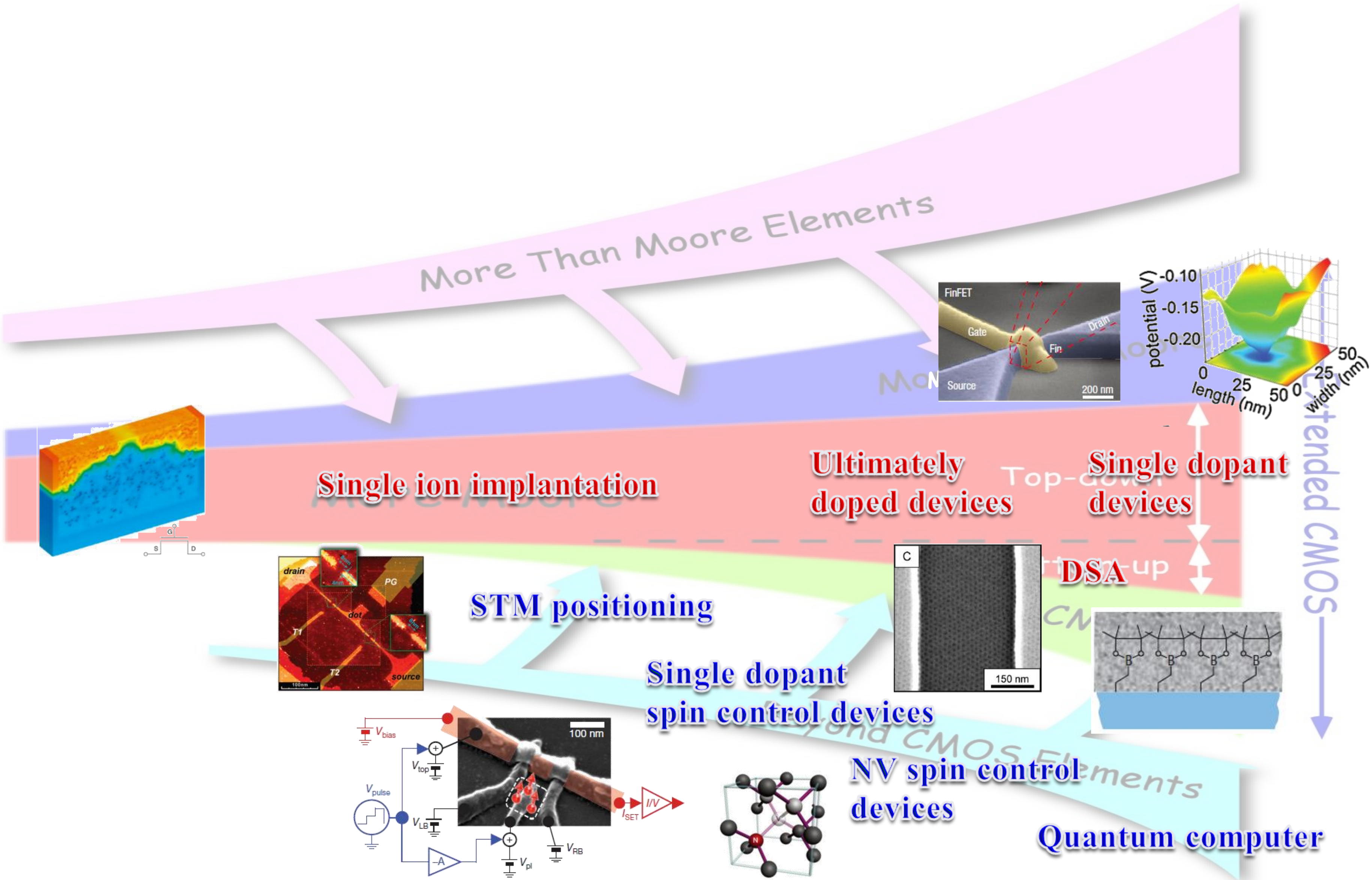
Low temperature process for nanoscale CMOS and new materials

Evolution of Extended CMOS



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

Concept of deterministic doping



Trends in device technologies

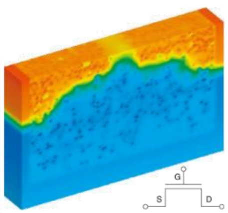
2010 hp45 — **2012** hp32 — **2015** hp21 — **2020** — **2030**

Doped channel

Random dopant fluctuation

Ultimate doped channel
(Limit of traditional transistors)

Bulk silicon MOSFET



Single dopant control

Single dopant devices

Single spin devices

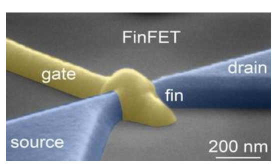
Single NV diamond devices

Work function control

Nondoped channel

FD SOI MOSFET

Ultimate non-doped channel
(All metal transistors?)

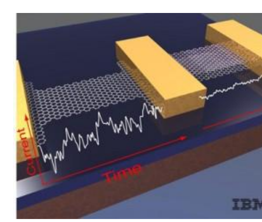


FD Multi gate devices

Nanowire FETs

III-V & Ge FETs

Graphene FETs



Target of deterministic doping

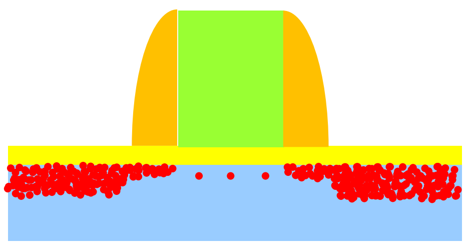
2010	2012	2015	2020	2030
hp45	hp32	hp21		

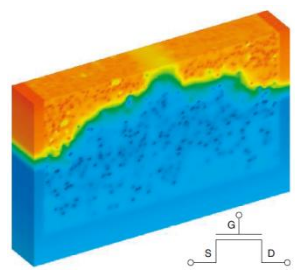
Deterministic doping for:

(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
Cryo ion implantation
Co-implantation
Molecular implantation
Plasma doping
DSA doping

Laser anneal
Flash anneal
Microwave anneal

SSRM
Atom probe tomography
Kelvin Force Microscopy

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