IMM Istituto per la Microelettronica e Microsistemi

Consiglio Nazionale delle Ricerche

Deterministic doping: each atom counts!

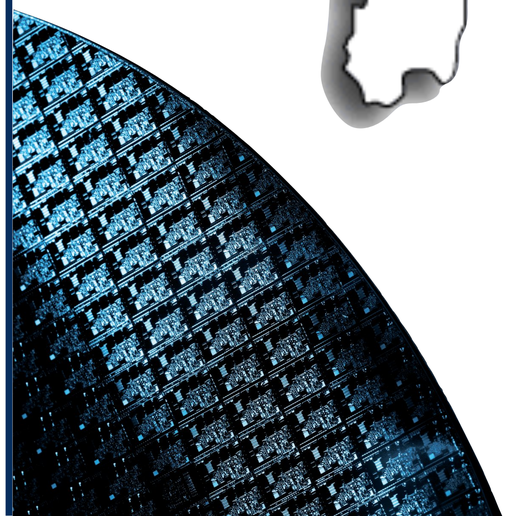
Michele Perego

CNR-IMM, Via Olivetti 2, Agrate Brianza, Italy

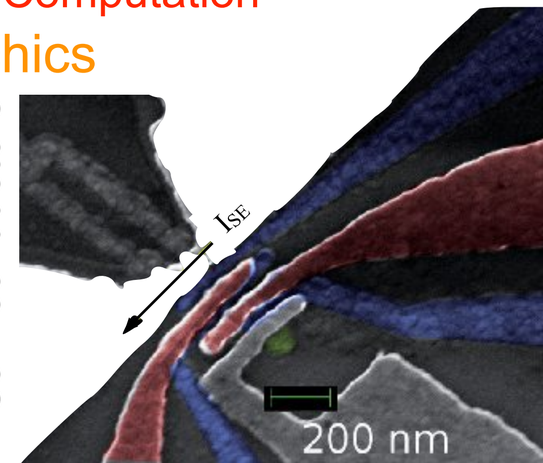
Advanced Manufacturing Open Stakeholder Meeting , Turin, October 24, 2023

The Laboratory

IMM activities extend from **basic research** (innovative materials and processes) to **technological concern** (prototyping and/or technological transfer to enterprises).

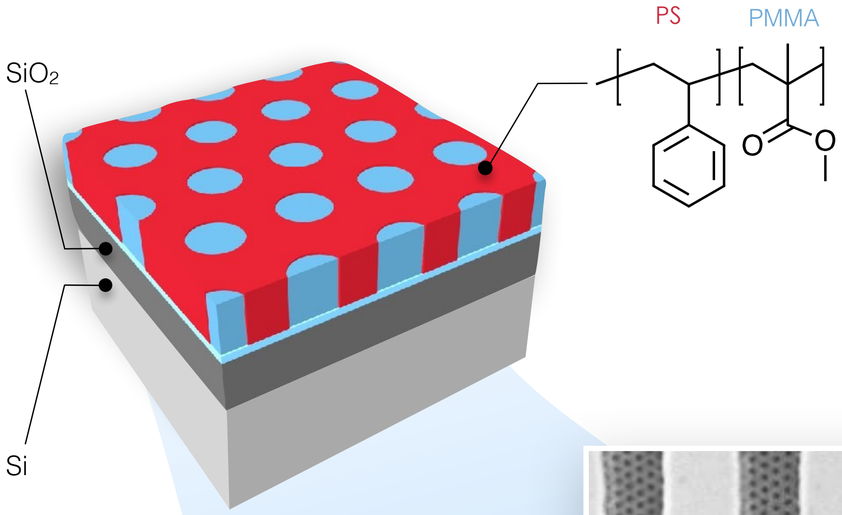


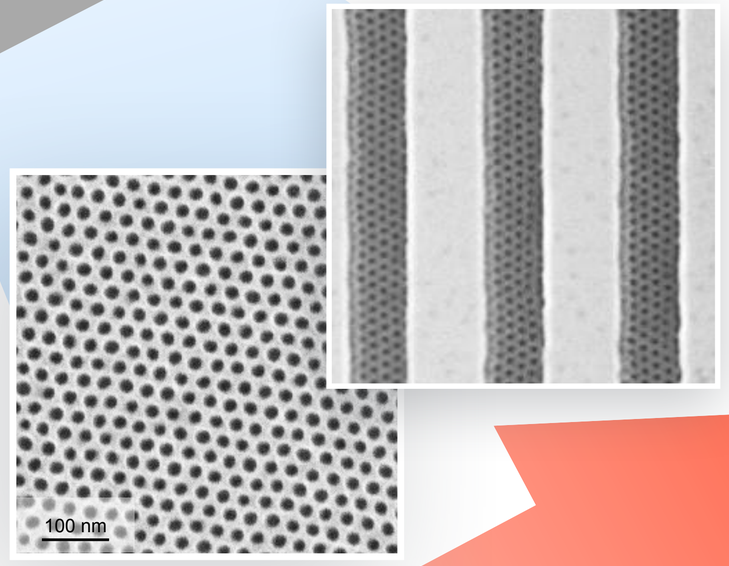
Spintronics
Memories
Memristors
Skyrmions
FIN-FET
Optoelctronics
Nanowires
DSA
Nanocrystals
Von Neuman Architecture
Lithography
Graphene
Transistors
CMOS
Single Atom Transistors
Phase Change Materials
Silicon
Silicene
Deterministic Doping
Microelectronics
Quantum Computation
Neuromorphics
Block-Copolymers
Self-Assembly
Spin Valves
Semiconductors

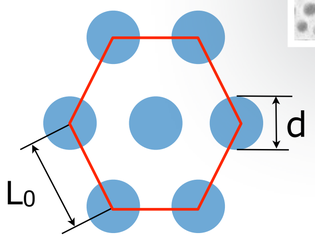


www.imm.cnr.it

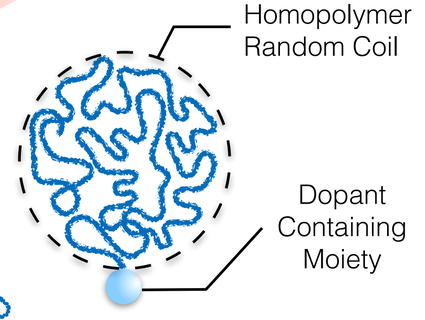
Research Activity

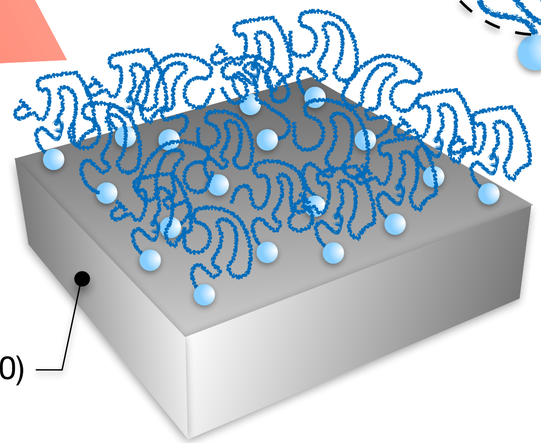






Top-Down





Bottom-Up

Introducing self-assembly materials into conventional manufacturing processes to increase our capability to control matter at the nanoscale.

Outline

1. Introduction

2. Deterministic Doping Strategies

2.1 Hydrogen-resist Lithography

2.2 Deterministic Ion Implantation

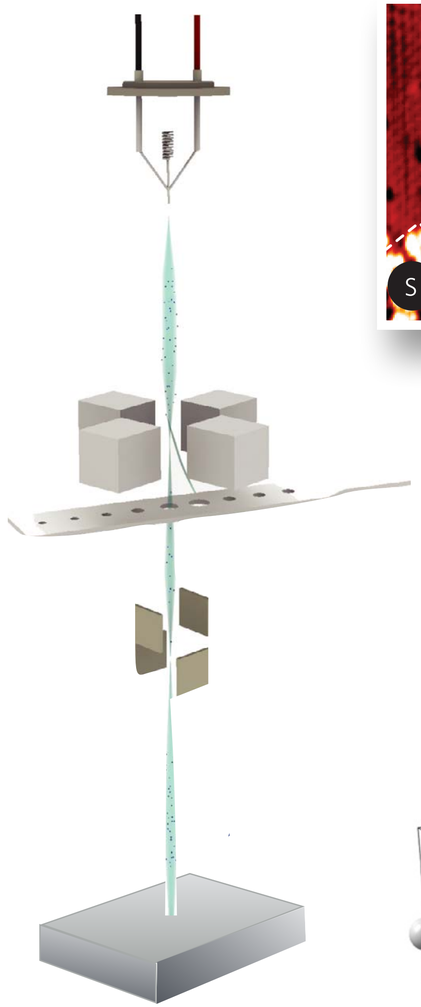
2.2 Alternative Doping Strategies

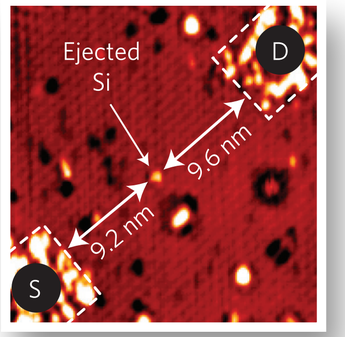
3. Detection of Isolated Impurities

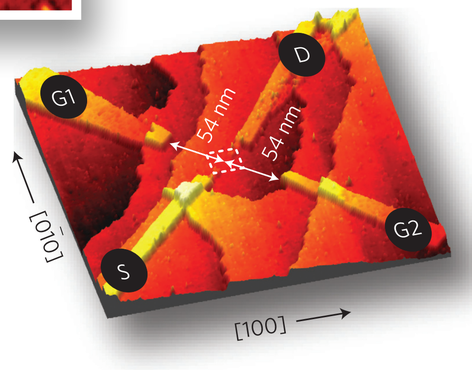
3.1 Scanning Probes

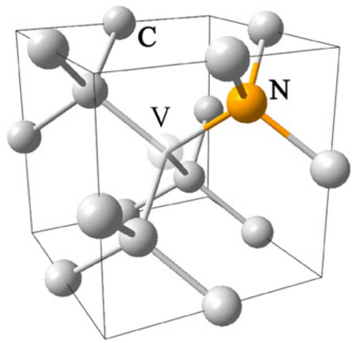
3.2 STEM Techniques

4. Conclusions





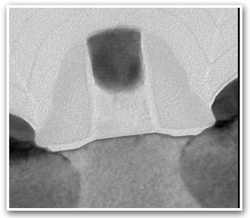




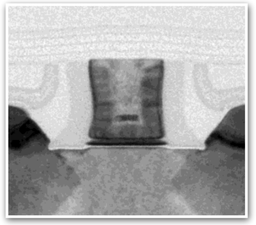
1. Introduction

In nanoscale transistors, the channel region contain few dopant atoms and the assumption of **uniform dopant distribution** is no longer feasible.

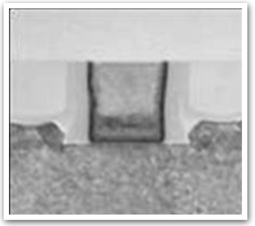
2006
65 nm



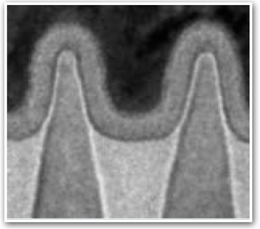
2008
45 nm



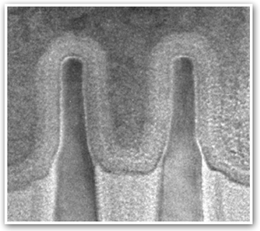
2010
32 nm



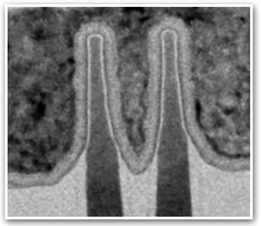
2012
22 nm



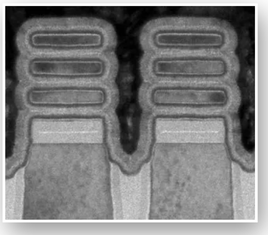
2014
14 nm



2016
10 nm



2024
3-2 nm

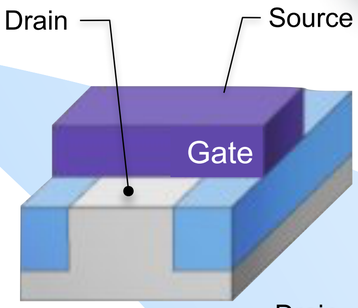


2006

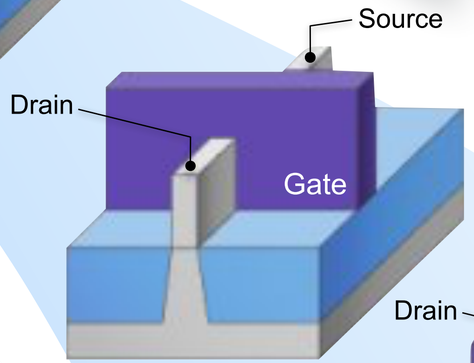
2010

2014

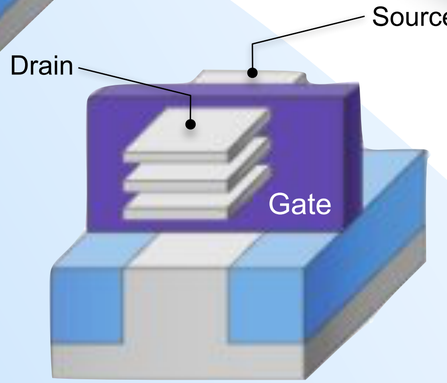
2018



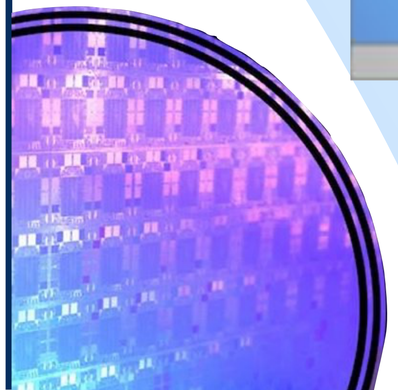
Planar FET



FinFET



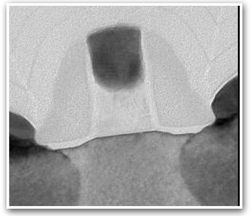
GAAFET



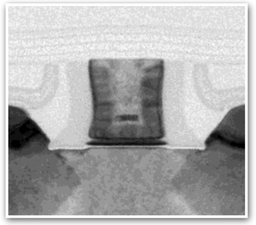
1. Introduction

Statistical fluctuation in dopant atom number into cthe channel causes serious fluctuation in the device's functioning

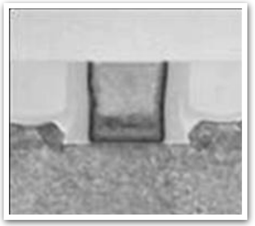
2006
65 nm



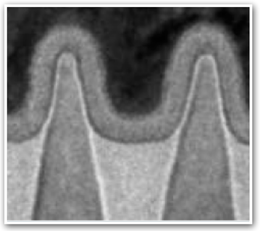
2008
45 nm



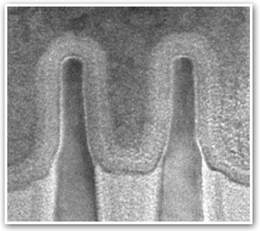
2010
32 nm



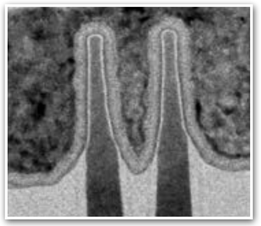
2012
22 nm



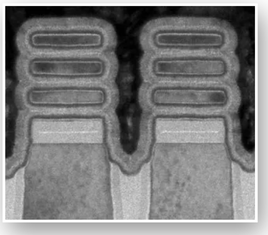
2014
14 nm



2016
10 nm



2024
3-2 nm



2006

2010

2014

2018

IBM

SAMSUNG

intel

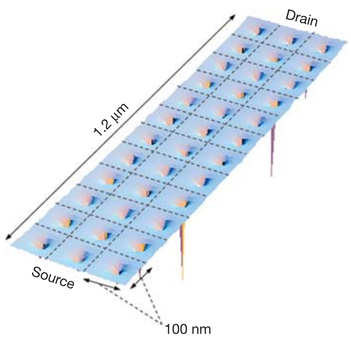
tsmc

LETTERS

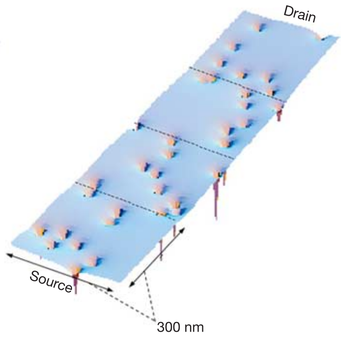
Enhancing semiconductor device performance using ordered dopant arrays

Takahiro Shinada[1], Shintaro Okamoto[2], Takahiro Kobayashi[2] & Iwao Ohdomari[1,2]

nature Vol 437|20 October 2005



Ordered Dopant Array



Random Dopant Distribution

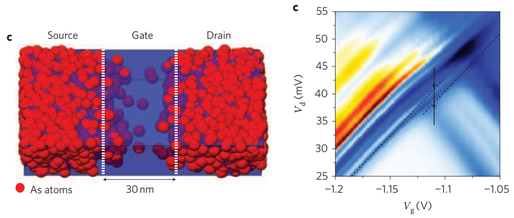
1. Introduction

Single atom devices have been successfully implemented, confirming the possibility to create **novel functional devices** exploiting **quantum phenomena** occurring at the atomic scale.

nature nanotechnology
LETTERS
PUBLISHED ONLINE: 6 DECEMBER 2009 | DOI: 10.1038/NNANO.2009.373

Single-donor ionization energies in a nanoscale CMOS channel

M. Pierre[1], R. Wacquez[1], X. Jehl[1], M. Sanquer[1]*, M. Vinet[2] and O. Cueto[2]



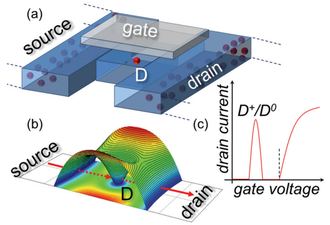
NATURE NANOTECHNOLOGY | VOL 5 | FEBRUARY 2010
135

2006

NANO REVIEW
Open Access

Atom devices based on single dopants in silicon nanostructures

Daniel Moraru[1], Arief Udhiarto[1], Miftahul Anwar[1], Roland Nowak[1,2], Ryszard Jablonski[2], Earfan Hamid[1], Juli Cha Tarido[1], Takeshi Mizuno[1] and Michiharu Tabe[1*]



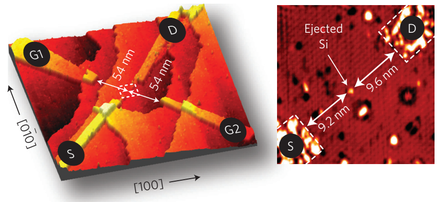
Moraru et al. Nanoscale Research Letters 2011, 6:479
http://www.nanoscalereslett.com/content/6/1/479
Nanoscale Research Letters
a SpringerOpen Journal

2010

LETTERS
PUBLISHED ONLINE: 19 FEBRUARY 2012 | DOI: 10.1038/NNANO.2012.21
nature nanotechnology

A single-atom transistor

Martin Fuechsle[1], Jill A. Miwa[1], Suddhasatta Mahapatra[1], Hoon Ryu[2], Sunhee Lee[2], Oliver Warschkow[4], Lloyd C. L. Hollenberg[2], Gerhard Klimeck[3] and Michelle Y. Simmons[1]*



NATURE NANOTECHNOLOGY | VOL 7 | APRIL 2012 |
242

2014

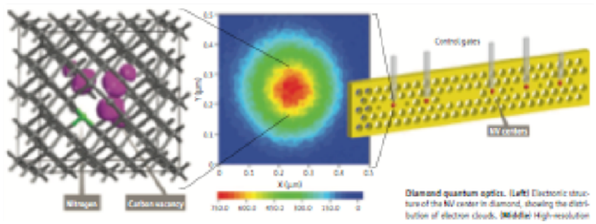
APPLIED PHYSICS

Diamond for Quantum Computing

Optically active defects in diamonds are promising candidates for the building blocks of quantum computers.

Steven Prawer and Andrew D. Greentree

www.sciencemag.org SCIENCE VOL 320 20 JUNE 2008

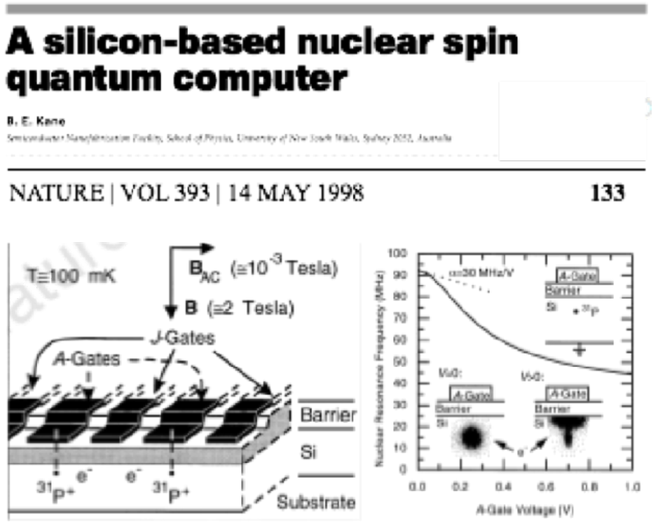


Diamond quantum optics. (Left) Electronic structure of the NV center in diamond, showing the distribution of electron clouds. (Middle) High-resolution

2018

1. Introduction

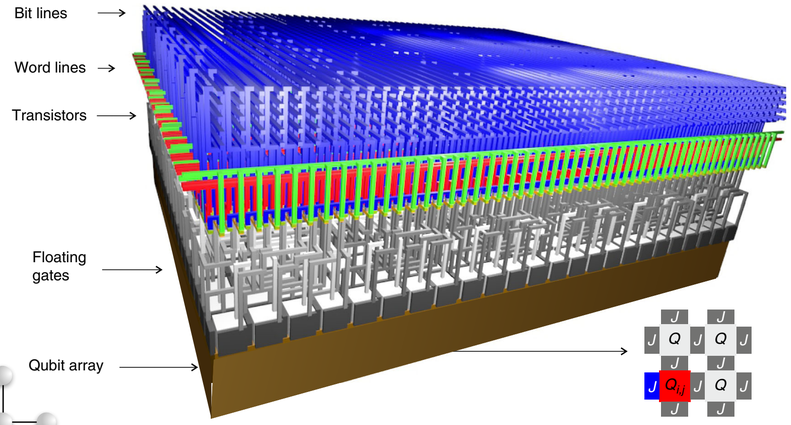
Fabrication of scalable **qubit arrays** constitutes one of the most stringent barriers in the field, even for the most promising platforms.


A silicon-based nuclear spin quantum computer

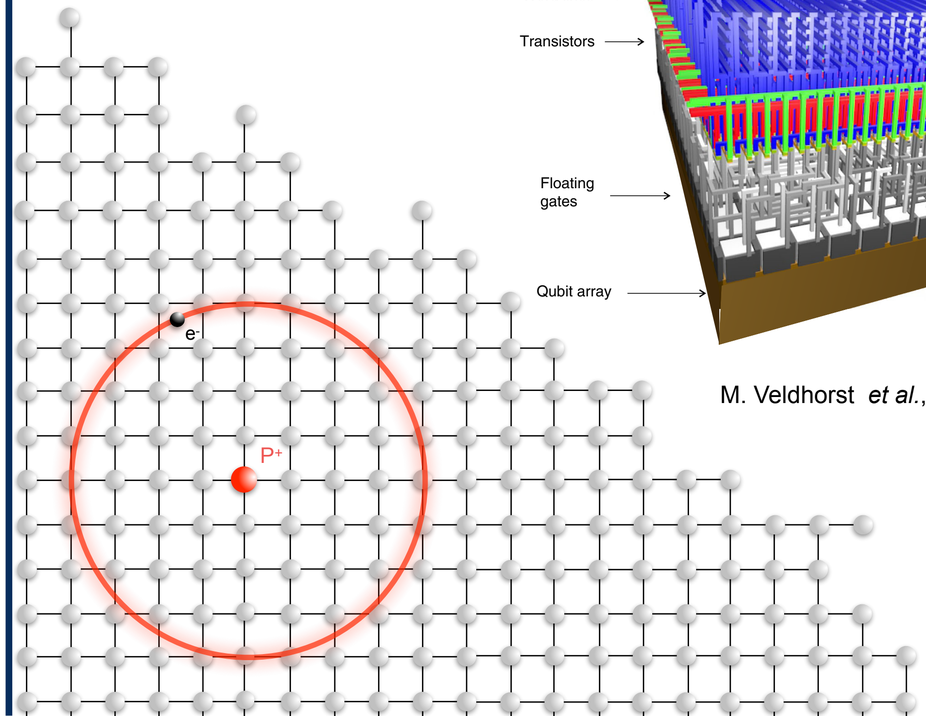
B. E. Kane

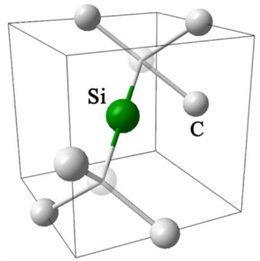
Semiconductor Nanofabrication Facility, School of Physics, University of New South Wales, Sydney 2052, Australia

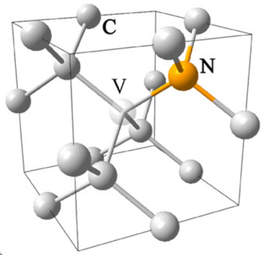
NATURE | VOL 393 | 14 MAY 1998 133

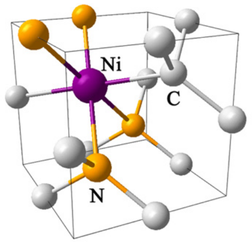


M. Veldhorst *et al.*, Nat. Comm. 8, 1766 (2017)

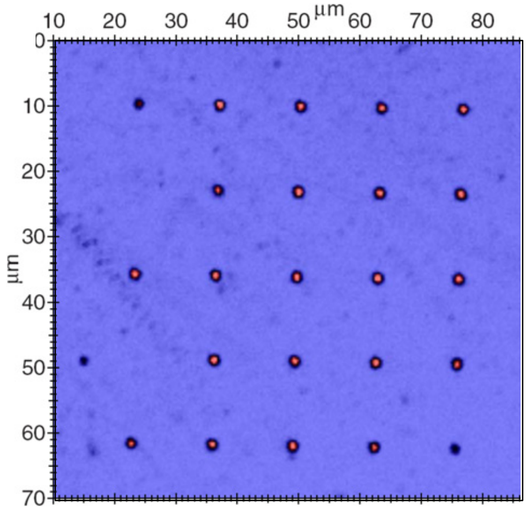








B. Naydenov *et al.*, *Appl. Phys. Lett.* **95** 3 (2009)



Single Photon Sources

Deterministic doping technology is required to effectively control matter at **the atomic scale**

Outline

1. Introduction

2. Deterministic Doping Strategies

2.1 Hydrogen-resist Lithography

2.2 Deterministic Ion Implantation

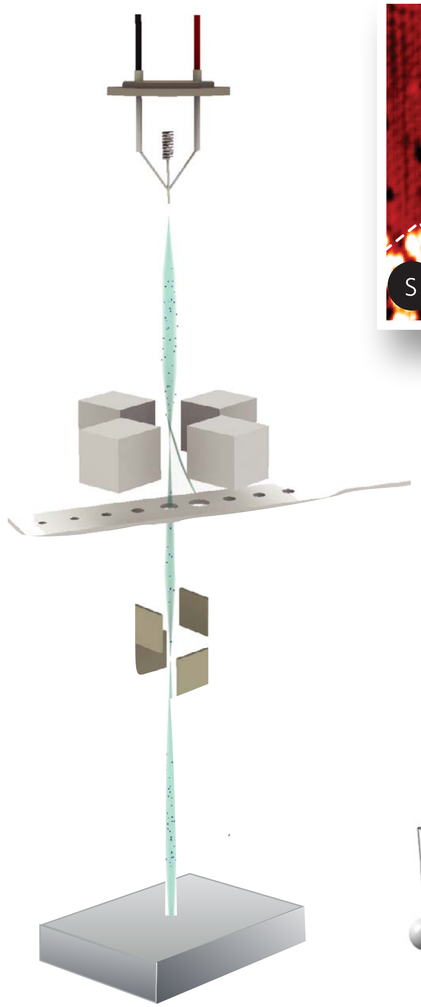
2.2 Alternative Doping Strategies

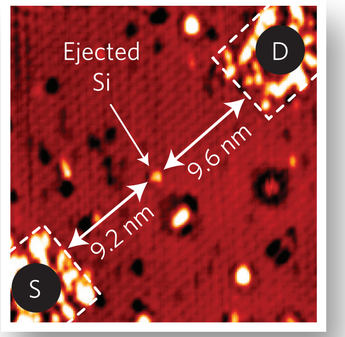
3. Detection of Isolated Impurities

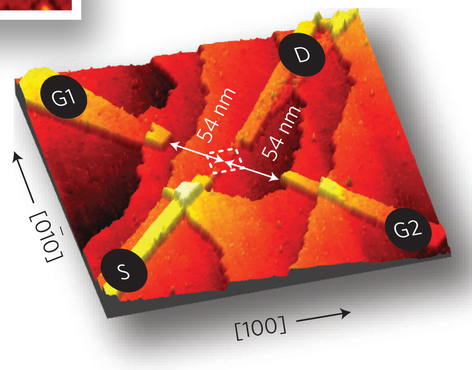
3.1 Scanning Probes

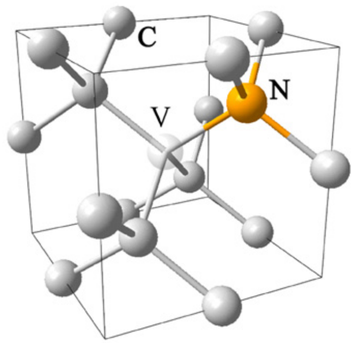
3.2 STEM Techniques

4. Conclusions









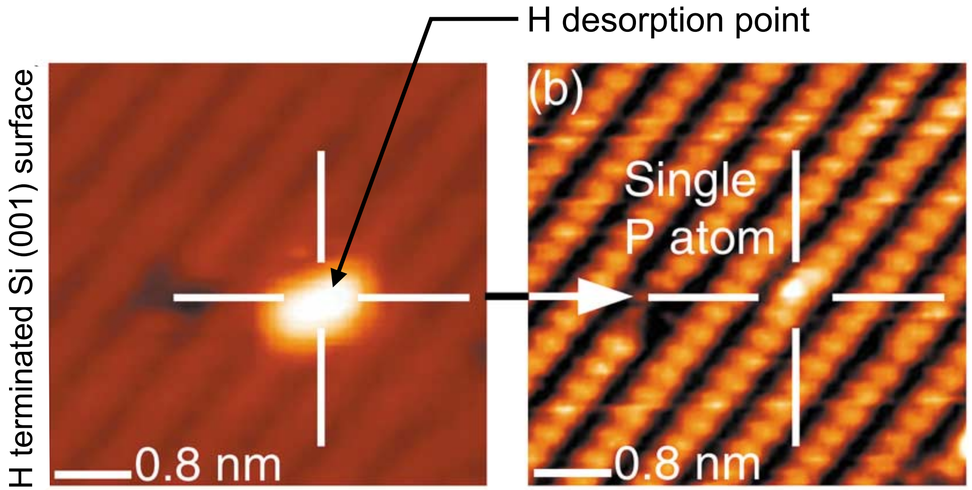
2.1 Hydrogen-Resist Lithograph

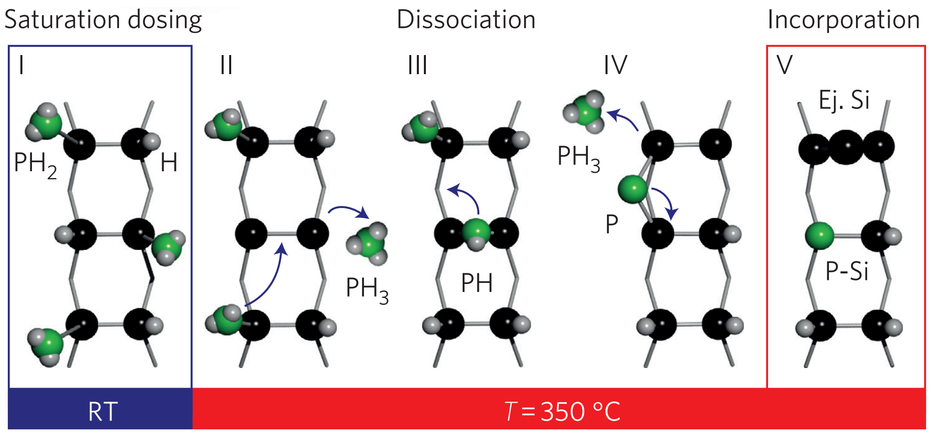
STM and hydrogen-resist lithography to deterministically place individual phosphorus dopant atom within an epitaxial silicon device architecture with a spatial accuracy of one lattice site

VOLUME 91, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2003

Atomically Precise Placement of Single Dopants in Si

S. R. Schofield,* N. J. Curson, M. Y. Simmons, F. J. Rueß, T. Hallam, L. Oberbeck, and R. G. Clark
Centre for Quantum Computer Technology, School of Physics, University of New South Wales, Sydney, NSW 2052, Australia
(Received 21 April 2003; published 25 September 2003)

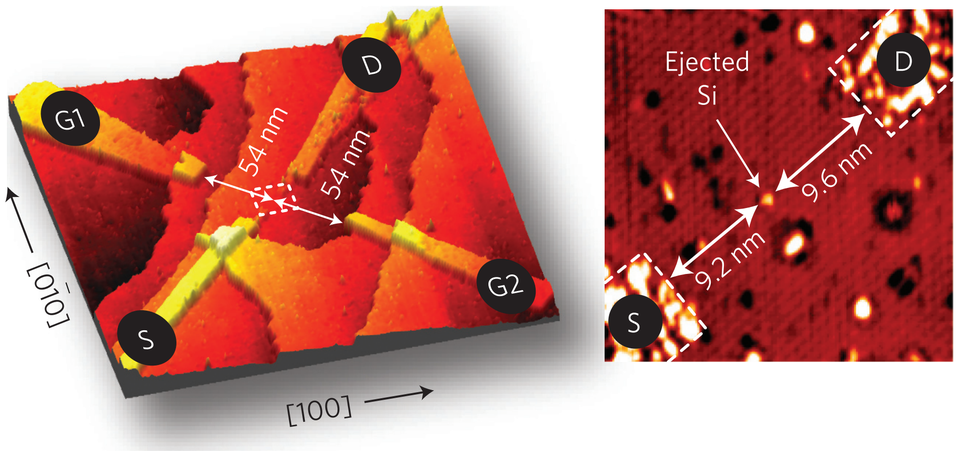




LETTERS
PUBLISHED ONLINE: 19 FEBRUARY 2012 | DOI: 10.1038/NNANO.2012.21
nature nanotechnology

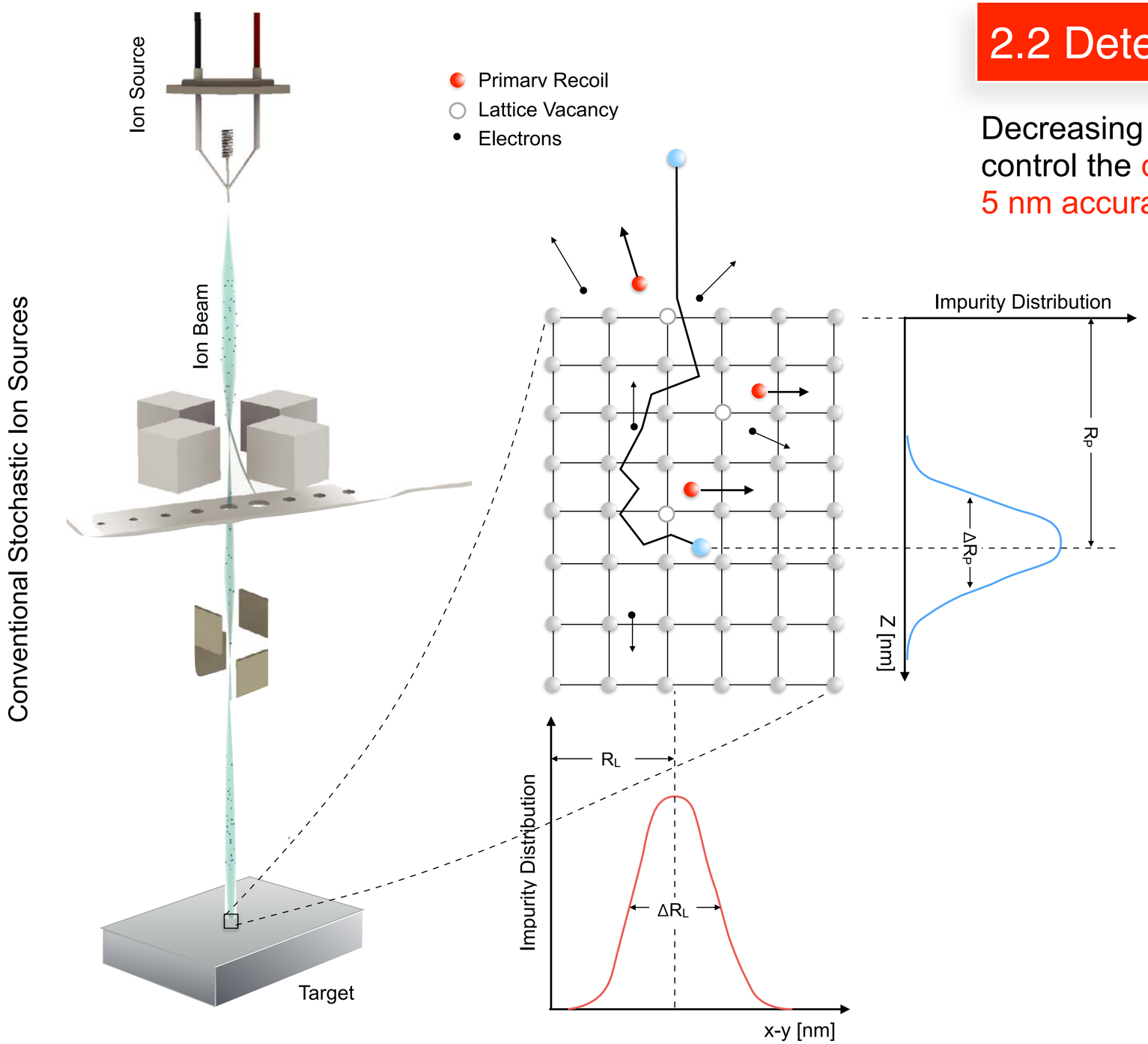
A single-atom transistor

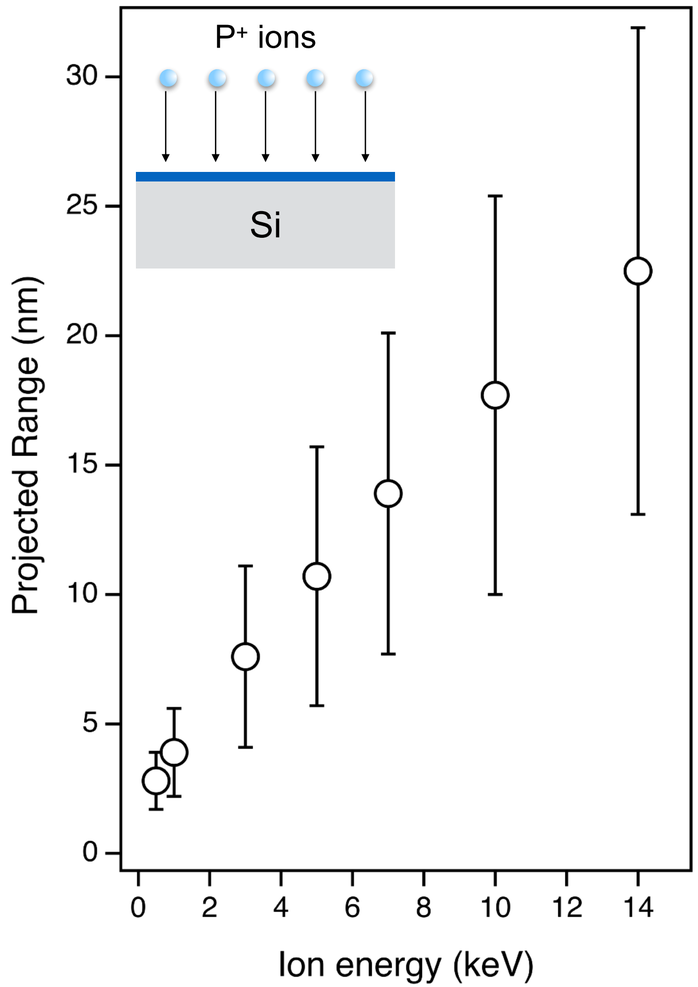
Martin Fuechsle[1], Jill A. Miwa[1], Suddhasatta Mahapatra[1], Hoon Ryu[2], Sunhee Lee[3], Oliver Warschkow[4], Lloyd C. L. Hollenberg[5], Gerhard Klimeck[3] and Michelle Y. Simmons[1]*



2.2 Deterministic Ion Implantation

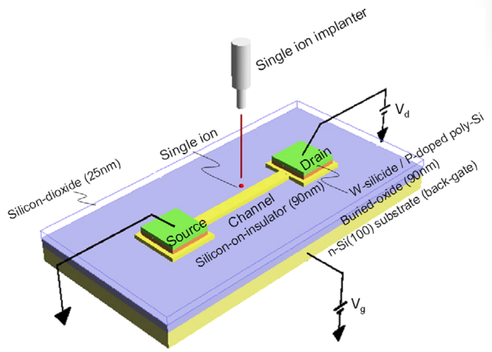
Decreasing the implantation energy it is possible to control the depth position of implanted impurities with sub 5 nm accuracy





2.2 Deterministic Ion Implantation

Control of lateral position of implanted impurities is possible using focused ion beams or broad beams through a focusing template



LETTERS

Enhancing semiconductor device performance using ordered dopant arrays

Takahiro Shinada[1], Shintaro Okamoto[2], Takahiro Kobayashi[2] & Iwao Ohdomari[1,2]

nature Vol 437|20 October 2005

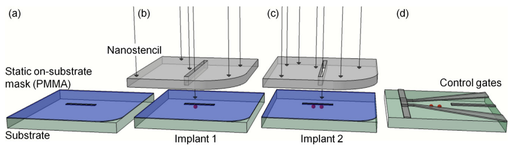
IOP PUBLISHING NANOTECHNOLOGY

Nanotechnology **24** (2013) 145304 (10pp) doi:10.1088/0957-4484/24/14/145304

Controlled deterministic implantation by nanostencil lithography at the limit of ion-aperture straggling

A D C Alves[1], J Newnham[1], J A van Donkelaar[1], S Rubanov[2], J C McCallum[1] and D N Jamieson[1]

P⁺ @ 14keV



Integration of Scanning Probes and Ion Beams

A. Persaud,* S. J. Park, J. A. Liddle, and T. Schenkel

E. O. Lawrence Berkeley National Laboratory, Berkeley, California 94720

J. Bokor

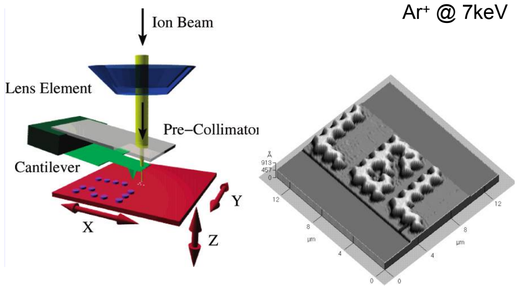
E. O. Lawrence Berkeley National Laboratory, Berkeley, California 94720 and Department of Electrical Engineering and Computer Science, University of California, Berkeley, California 94720

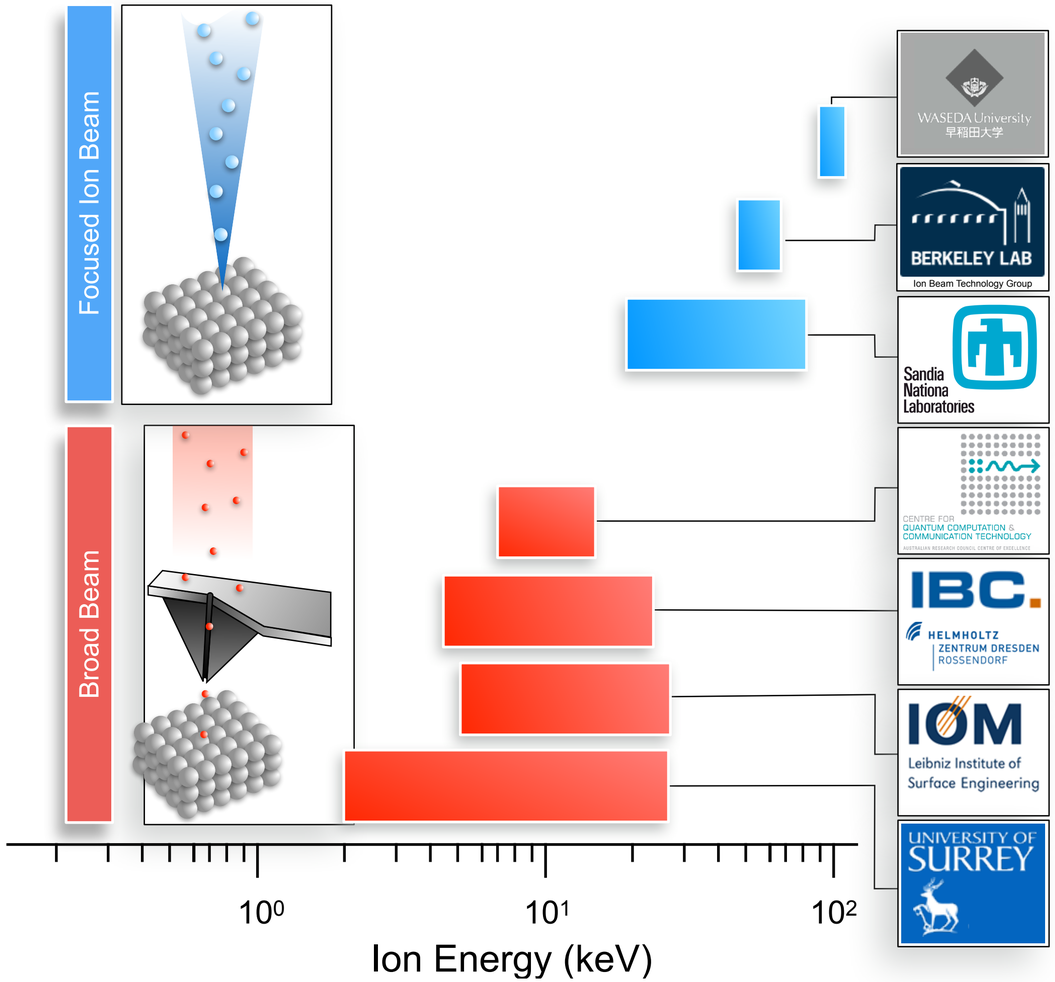
I. W. Rangelow

Institute of Microstructure Technologies and Analytics, University of Kassel, Germany

NANO LETTERS 2005 Vol. 5, No. 6 1087−1091

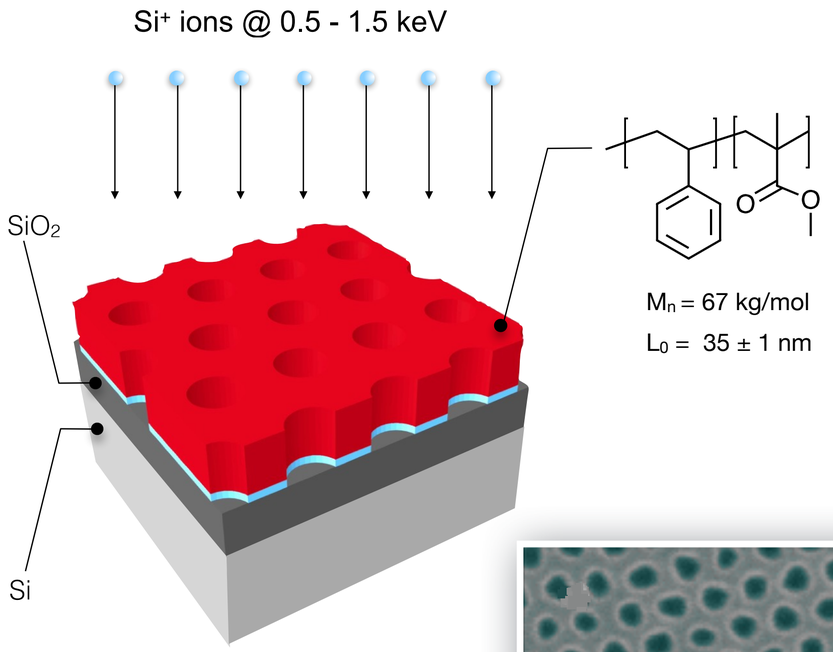
Ar⁺ @ 7keV

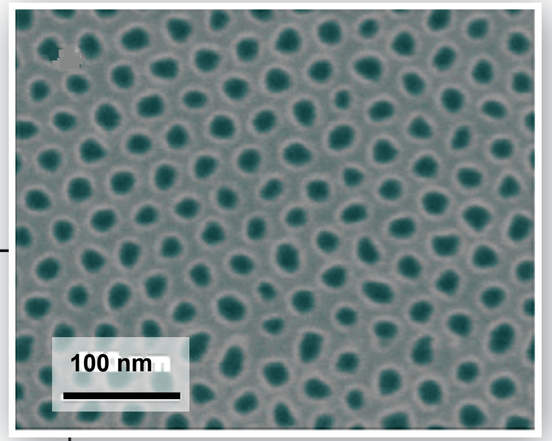


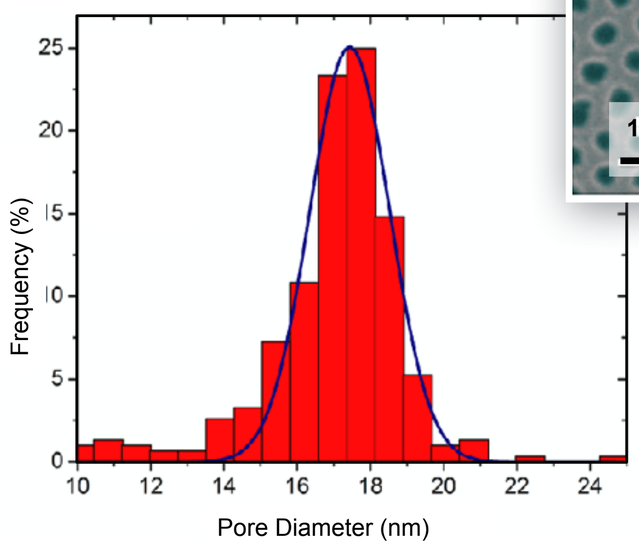


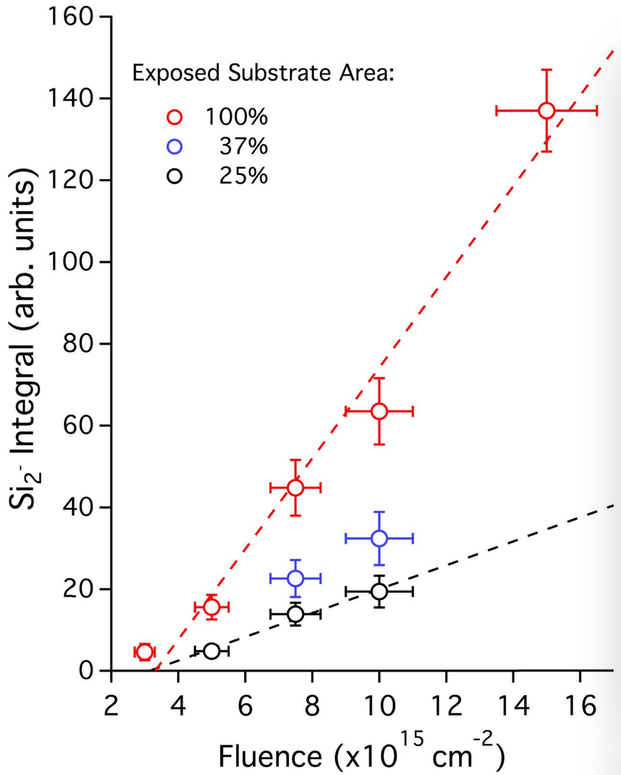
2.2 Deterministic Ion Implantation

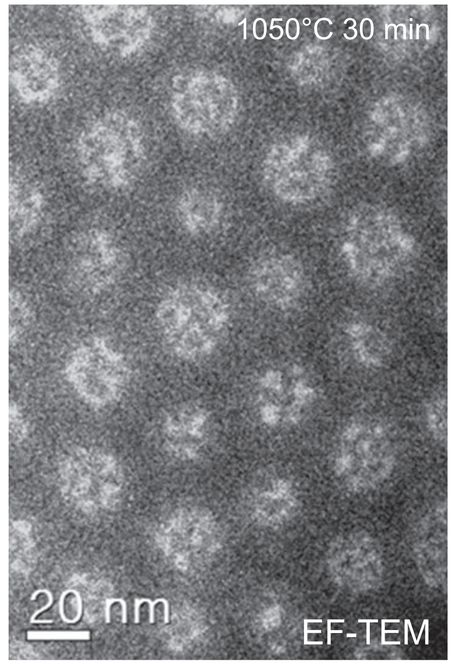
Effective confinement of silicon atoms in localized nano-volumes by implanting Si^+ ions at ULE in SiO_2 through a mesoporous polymeric template.

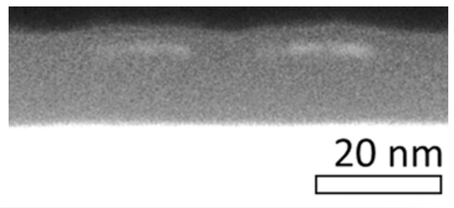












CEMES

C. Castro *et al.*, **Nanotechnology** 24, 075302 (2013)
C. Castro *et al.*, **Nanotechnology** 28, 014001 (2017)

ACS APPLIED MATERIALS & INTERFACES

www.acsami.org

Forum Article

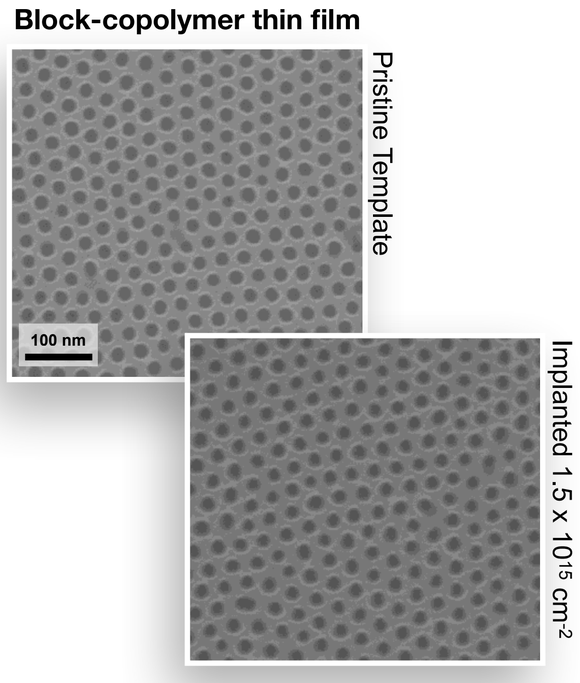
2.2 Deterministic Ion Implantation

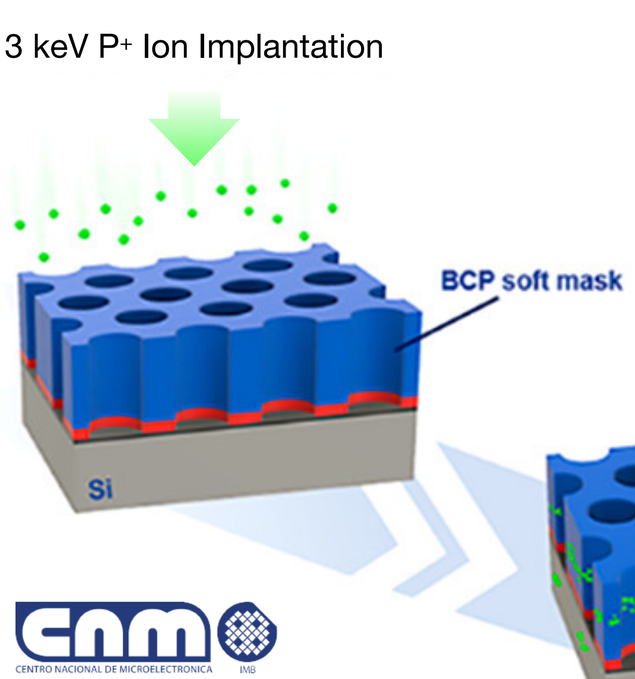
Periodic Arrays of Dopants in Silicon by Ultralow Energy Implantation of Phosphorus Ions through a Block Copolymer Thin Film

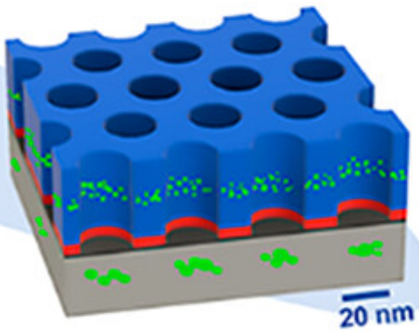
Stefano Kuschlan, Riccardo Chiarcos, Michele Laus, Francesc Pérez-Murano, Jordi Llobet, Marta Fernandez-Regulez, Caroline Bonafos, Michele Perego,* Gabriele Seguini, Marco De Michielis, and Graziella Tallarida

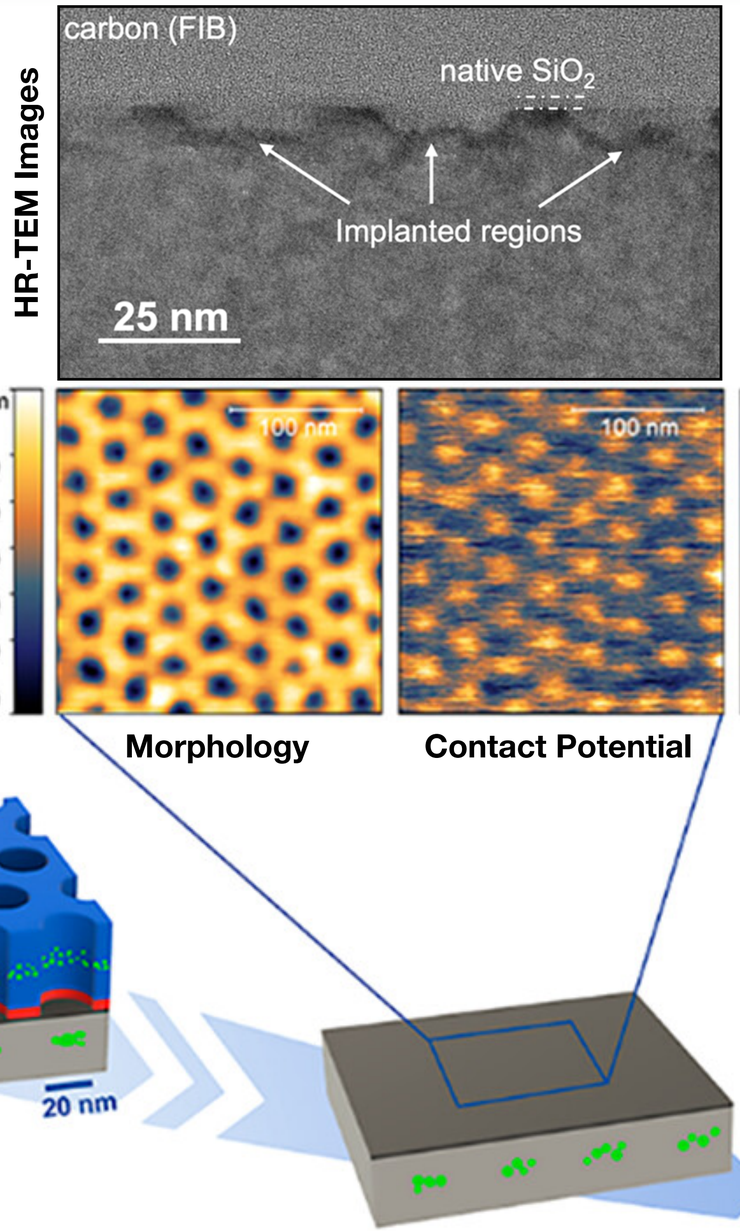
Cite This: https://doi.org/10.1021/acsami.3c03782

Read Online



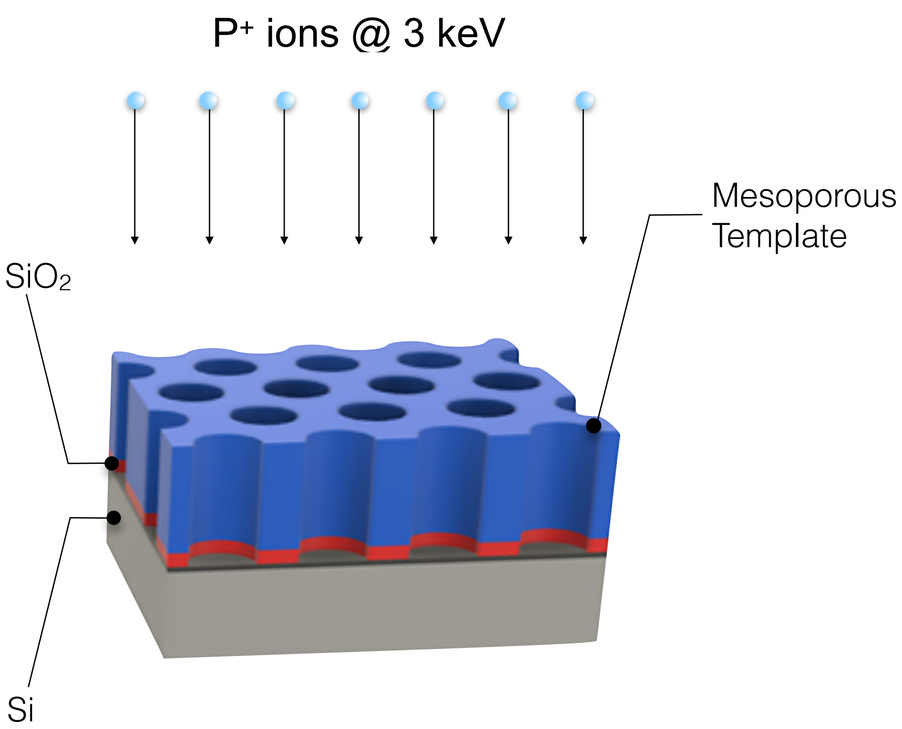






High fluency ion implantation at ultra low energy through a block-copolymer mask allows to control lateral distribution of dopants in silicon.

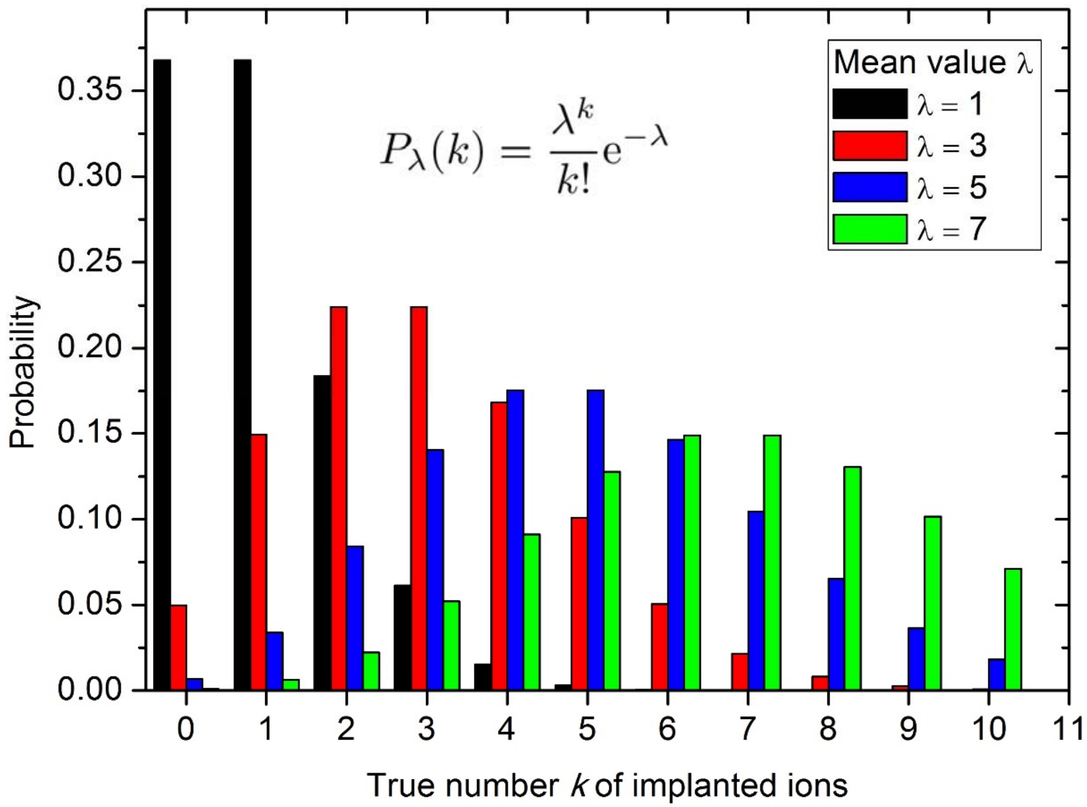
2.2 Deterministic Ion Implantation



Poisson's Tiranny

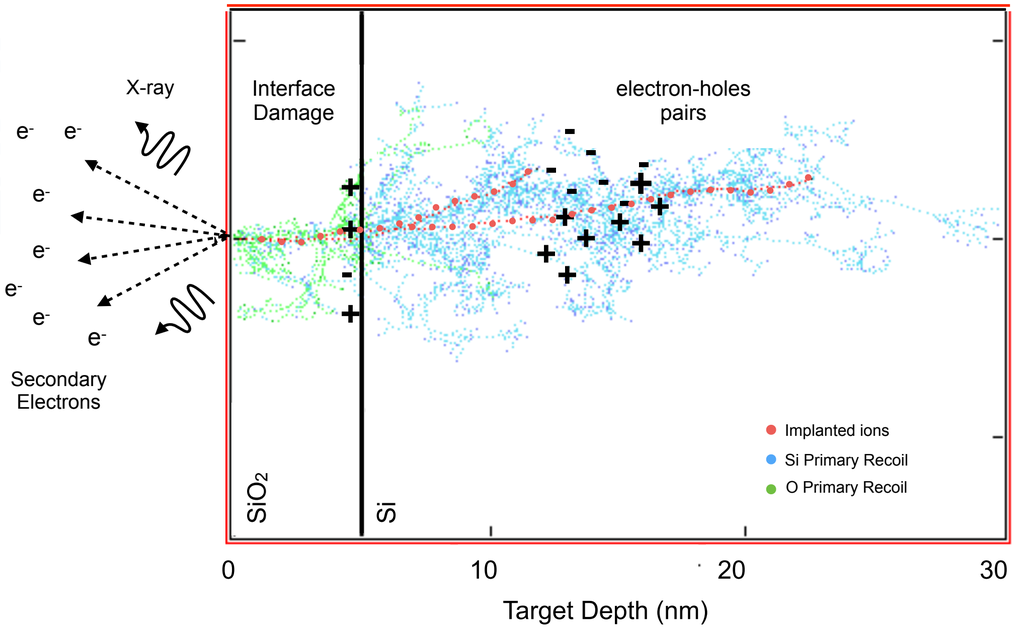
n	Probability
1	36.8%
2	13.5%
3	4.8%
5	0.66%
10	0.0045%

According to Poisson statistic, maximum probability of success in implanting one single ion (n = 1) per pore is 36.8%



Chains or arrays formed by *n* single implanted atoms can only be produced via deterministic implantation of counted single ions

J. van Donkelaar *et al.*, J. Phys. Condens. Matter 27, 154024 (2051)



electrons

REVIEW OF SCIENTIFIC INSTRUMENTS **88**, 123301 (2017)

Ion implantation for deterministic single atom devices

J. L. Pacheco, M. Singh, D. L. Perry, J. R. Wendt, G. Ten Eyck, R. P. Manginell, T. Pluym, D. R. Luhman, M. P. Lilly, M. S. Carroll, and E. Bielejec
Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

Interface Damage

IOP Publishing NANOTECHNOLOGY
Nanotechnology **19** (2008) 345202 (4pp) doi:10.1088/0957-4484/19/34/345202

A reliable method for the counting and control of single ions for single-dopant controlled devices

T Shinada[1], T Kurosawa[2], H Nakayama[2], Y Zhu[2], M Hori[2] and

e-h pairs

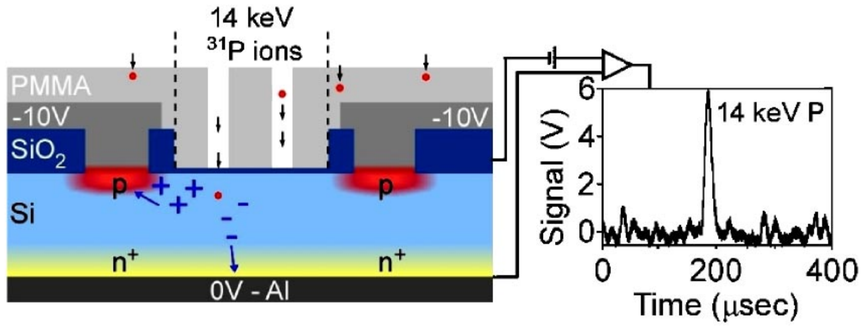
IOP Publishing Journal of Physics: Condensed Matter
J. Phys.: Condens. Matter **27** (2015) 154204 (9pp) doi:10.1088/0953-8984/27/15/154204

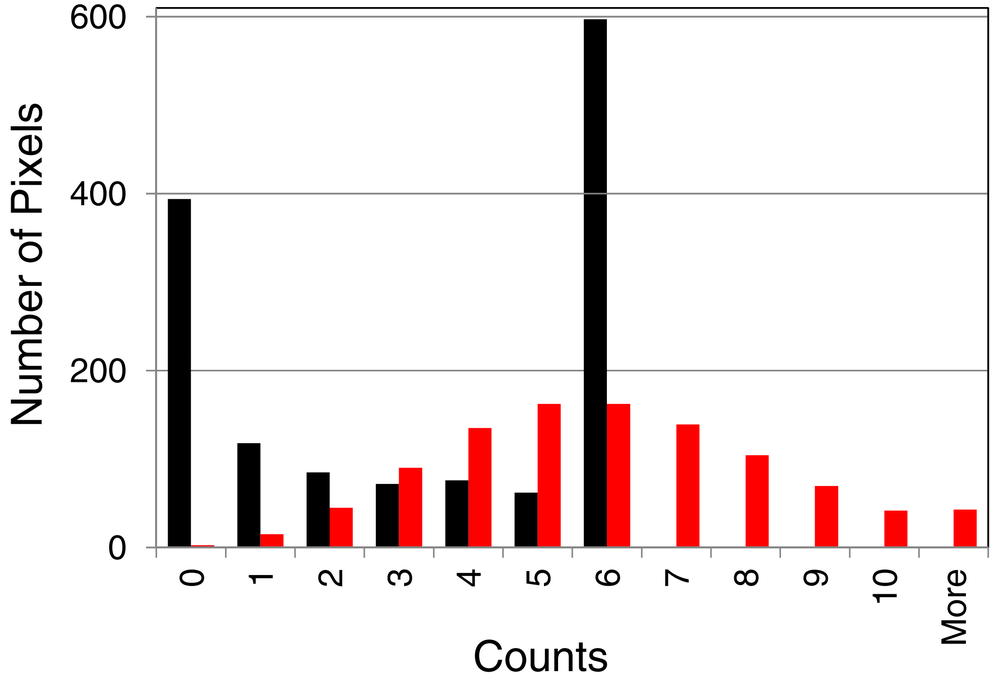
Single atom devices by ion implantation

Jessica van Donkelaar[1], C Yang[1], A D C Alves[1,3], J C McCallum[1], C Hougaard[1], B C Johnson[1], F E Hudson[2], A S Dzurak[2], A Morello[2], D Spemann[1] and D N Jamieson[1]

2.2 Deterministic Ion Implantation

Data demonstrate the successful creation of a **non-Poisson distribution** imposed by the ion detection system,





2.3 Alternative Doping Strategies

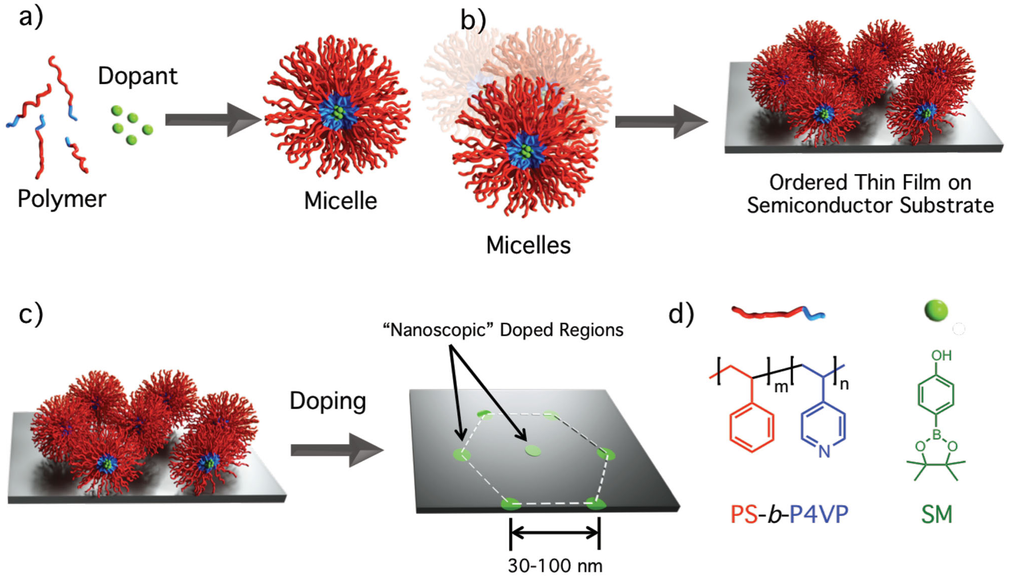
Materials Views
www.MaterialsViews.com

ADVANCED MATERIALS INTERFACES
www.advmatinterfaces.de

Large-Area, Nanometer-Scale Discrete Doping of Semiconductors via Block Copolymer Self-Assembly

*Bhooshan C. Popere, Boris Russ, Andrew T. Heitsch, Peter Trefonas, and Rachel A. Segalman**

Adv. Mater. Interfaces **2015**, *2*, 1500421



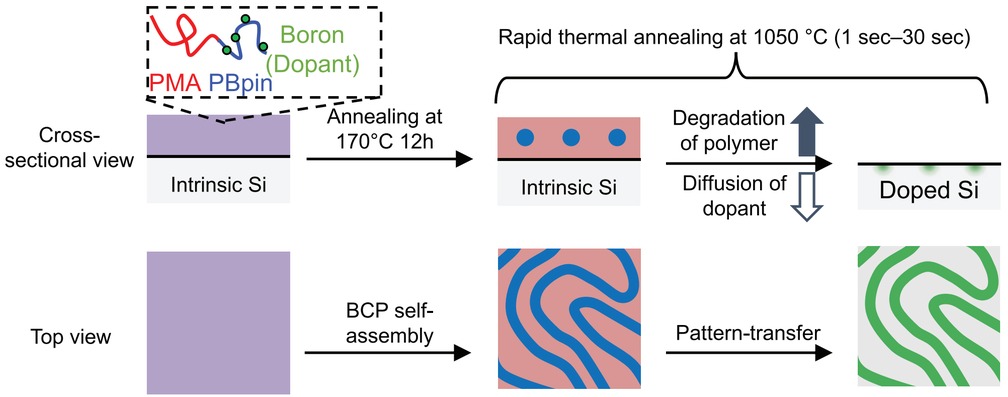
RESEARCH ARTICLE

Macromolecular Materials and Engineering
www.mame-journal.de

Discrete, Shallow Doping of Semiconductors via Cylinder-Forming Block Copolymer Self-Assembly

Yuanyi Zhang, Scott P. O. Danielsen, Bhooshan C. Popere, Andrew T. Heitsch, Mingqi Li, Peter Trefonas, Rachel A. Segalman, and Reika Katsumata**

Macromol. Mater. Eng. **2022**, 2200155



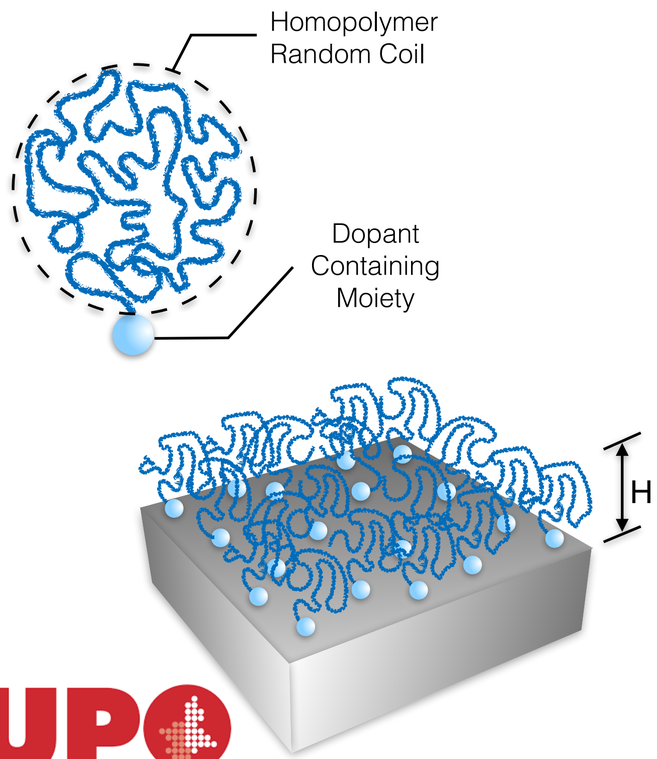
ACS NANO
Cite This: ACS Nano 2018, 12, 178−186
www.acsnano.org

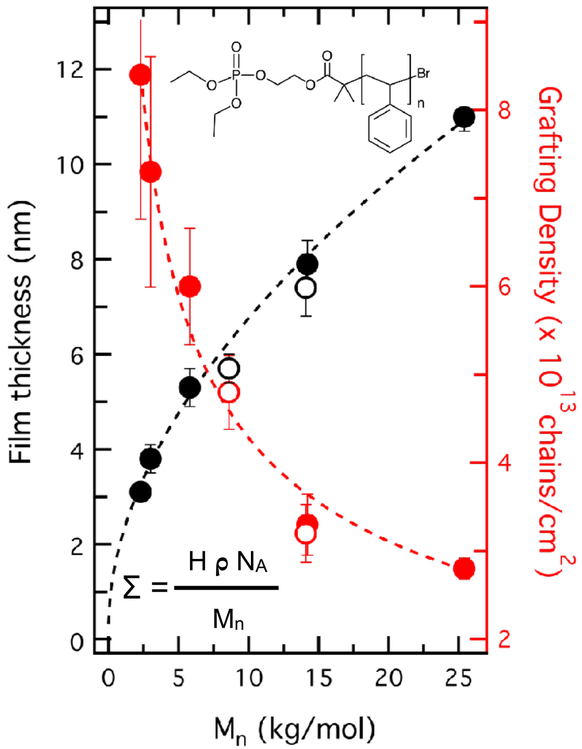
2.3 Alternative Doping Strategies

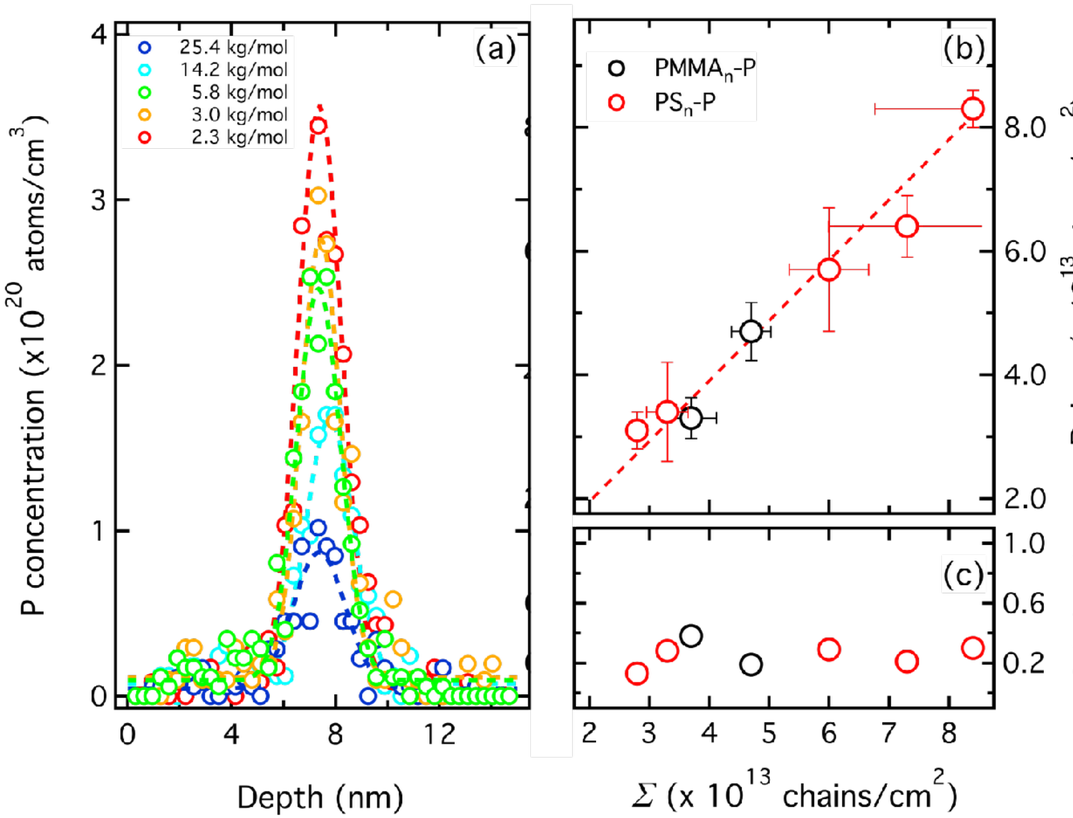
Control of Doping Level in Semiconductors *via* Self-Limited Grafting of Phosphorus End-Terminated Polymers

Michele Perego,*[,†] Gabriele Seguini,[†] Elisa Arduca,[†,‡] Andrea Nomellini,[‡] Katia Sparnacci,*[,§] Diego Antonioli,[§] Valentina Gianotti,[§] and Michele Laus[§]

[†]Laboratorio MDM, IMM-CNR, Via C. Olivetti 2, I-20864 Agrate Brianza, Italy
[‡]Università degli Studi di Milano, Via G. Celoria 16, I-20133 Milano, Italy
[§]Università del Piemonte Orientale "A. Avogadro", Viale T. Michel 11, I-15121 Alessandria, Italy



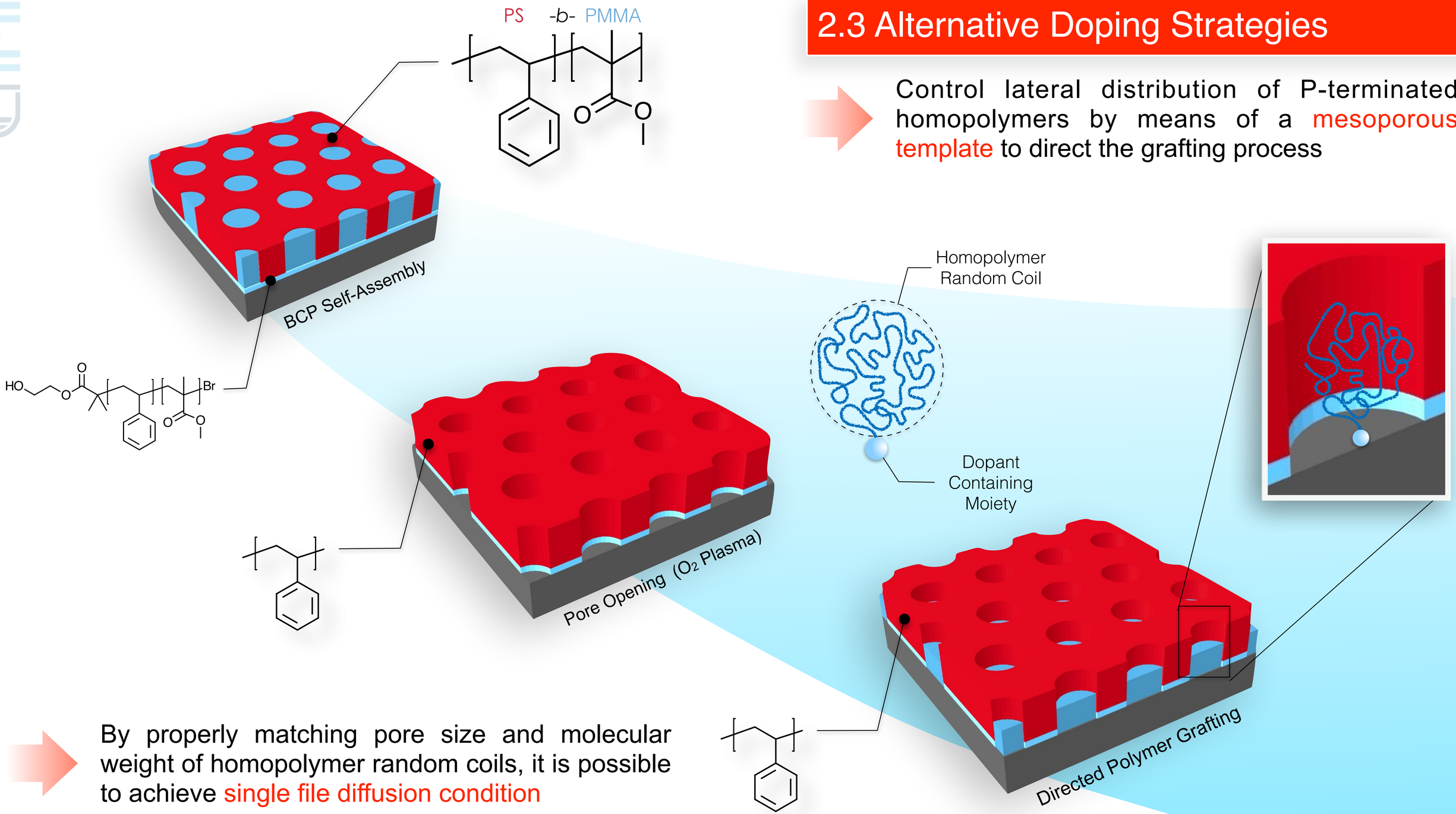




- Polymeric chains are sacrificial elements acting as spacers to tune the grafting density of the dopant containing moieties
- Dopant containing moieties serve as dopant carriers to effectively deliver dopant atoms onto silicon surfaces

2.3 Alternative Doping Strategies

Control lateral distribution of P-terminated homopolymers by means of a mesoporous template to direct the grafting process



By properly matching pore size and molecular weight of homopolymer random coils, it is possible to achieve single file diffusion condition

Outline

1. Introduction

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2.1 Hydrogen-resist Lithography

2.2 Deterministic Ion Implantation

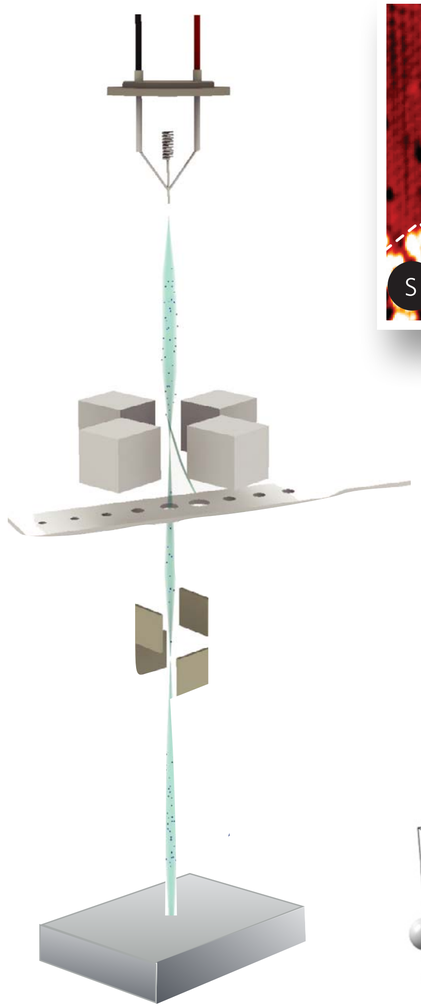
2.2 Alternative Doping Strategies

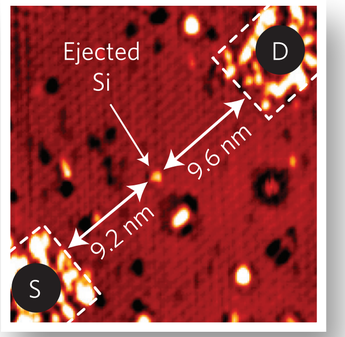
3. Detection of Isolated Impurities

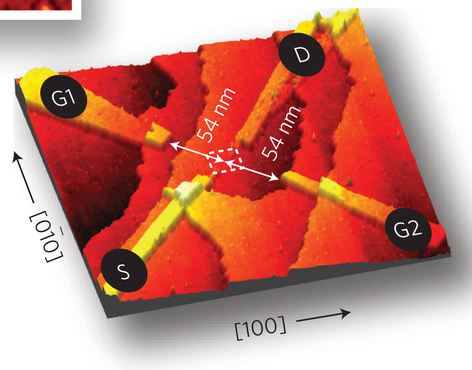
3.1 Scanning Probes

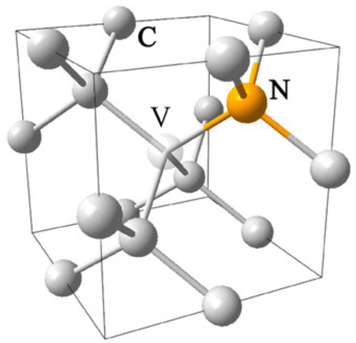
3.2 STEM Techniques

4. Conclusions





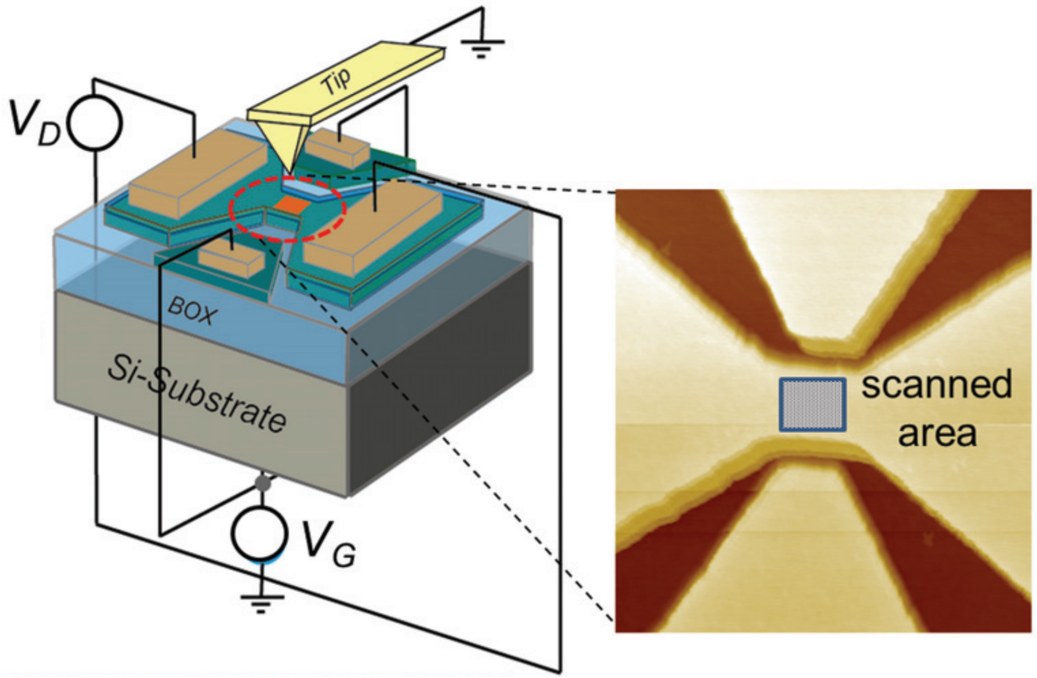




NANO REVIEW Open Access

Atom devices based on single dopants in silicon nanostructures

Daniel Moraru[1], Arief Udhiarto[1], Miftahul Anwar[1], Roland Nowak[1,2], Ryszard Jablonski[2], Earfan Hamid[1], Juli Cha Tarido[1], Takeshi Mizuno[1] and Michiharu Tabe[1*]



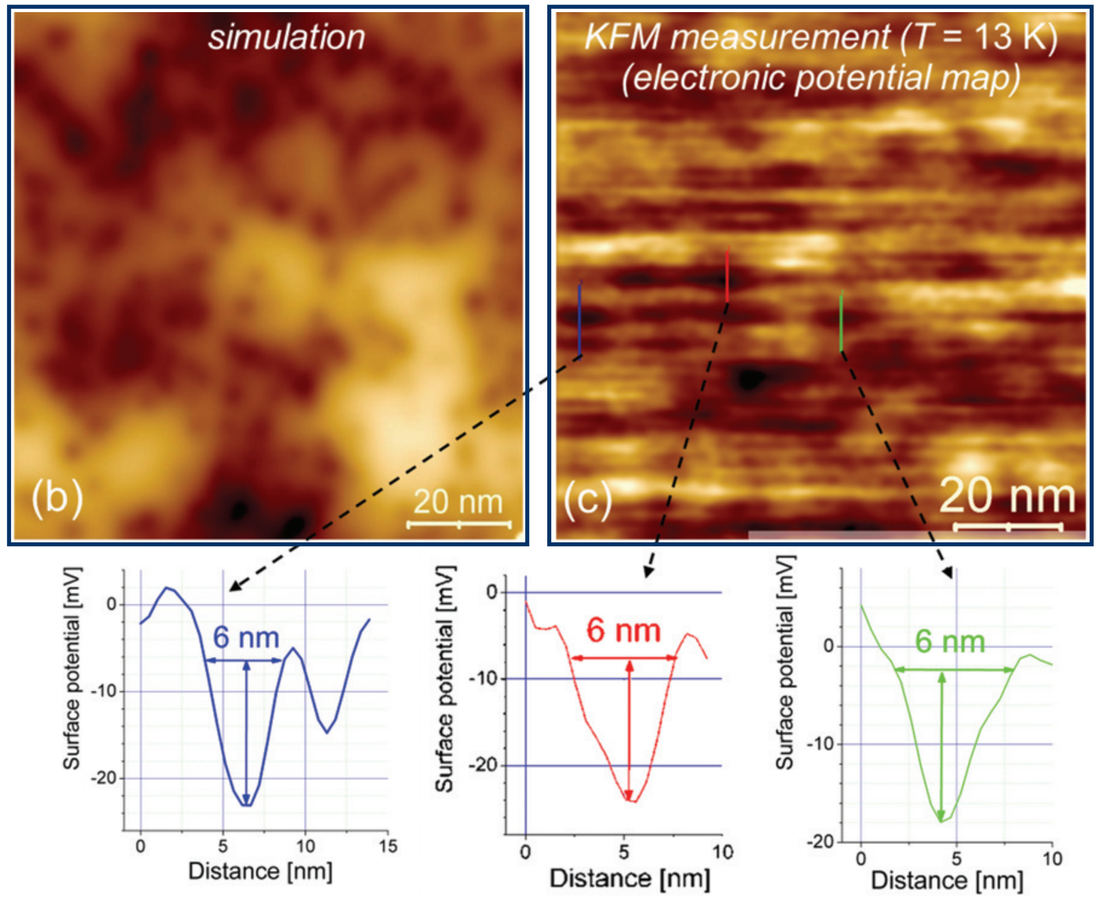
M. Ligowski *et al.*, Appl Phys Lett 93,142101 (2008)

M. Tabe *et al.*, Thin Solid Films 518, S38-S43 (2010)

D. Moraru *et al.*, Nanoscale Research Letters 6, 479 (2011)

3.1 Scanning Probes

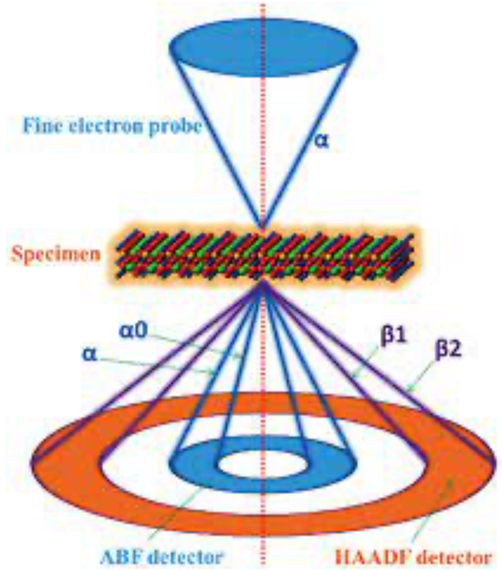
Using our low-temperature (LT)-KFM technique, the discrete distribution of P donors in the channel of thin SOI-FETs is observed as electronic potential maps

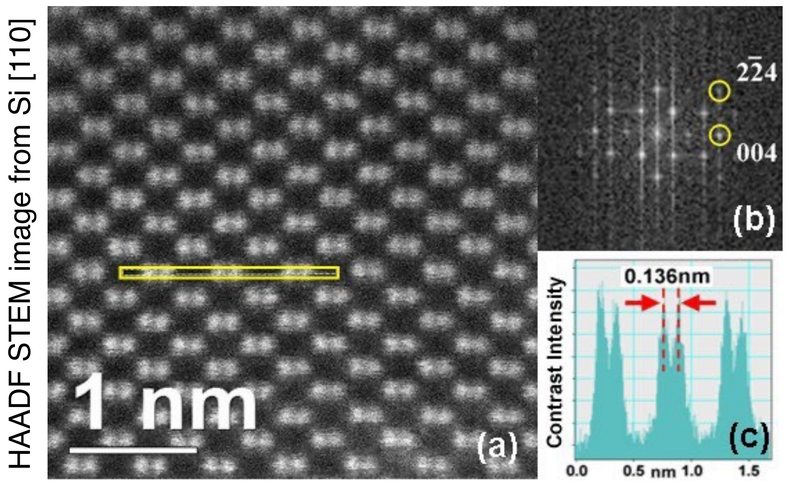


3.2 STEM Techniques

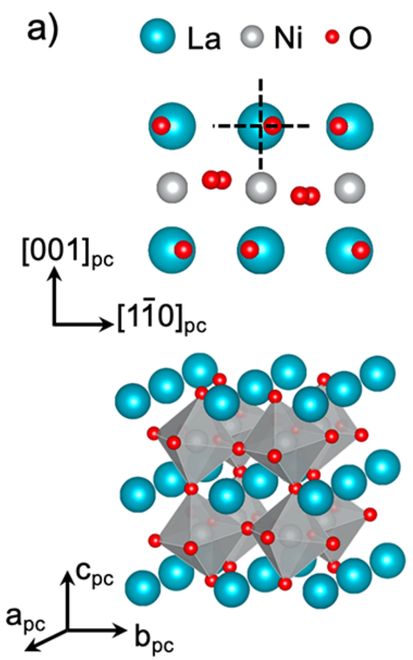
Aberration corrected STEM techniques achieved elemental compositional maps and profiles with atomic-column resolution

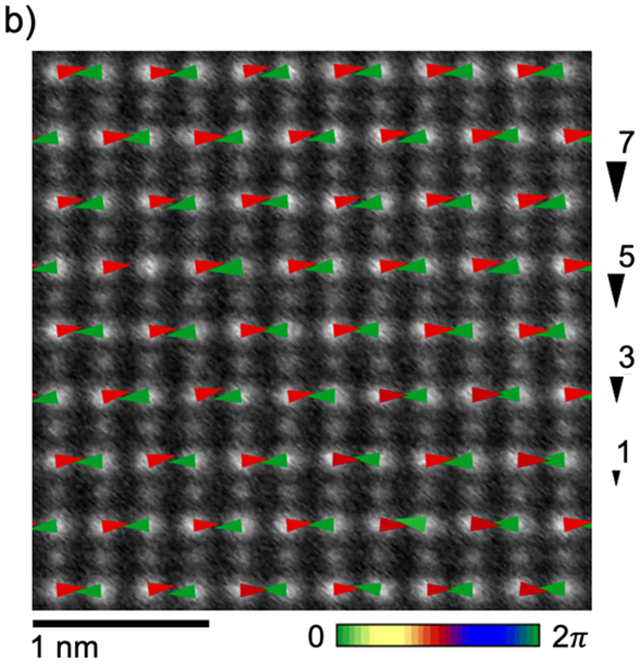
D.Hernández-Maldonado et al., Microscopy and Microanalysis, 17 (4), 578–581, (2011)





I.M Ross *et al.*, Journal of Physics: Conference Series 371 (2012) 012013





Michelle A. Smeaton et al., *Nano Lett.* 2023, 23, 6393–6398

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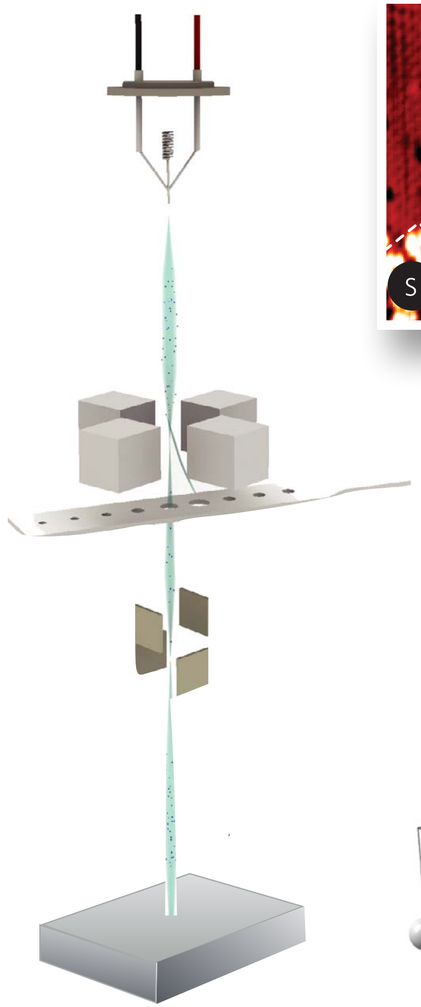
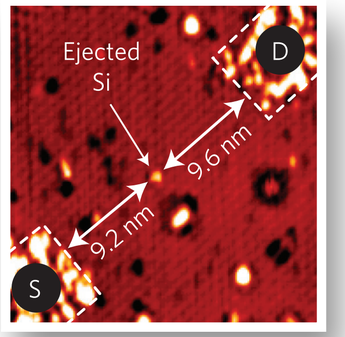
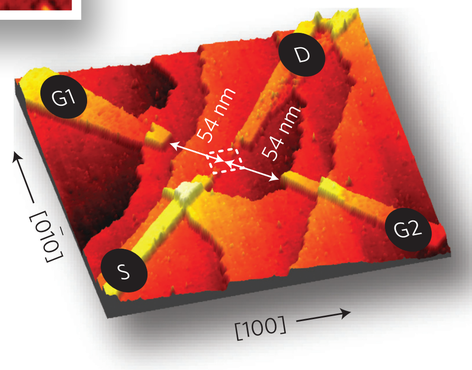
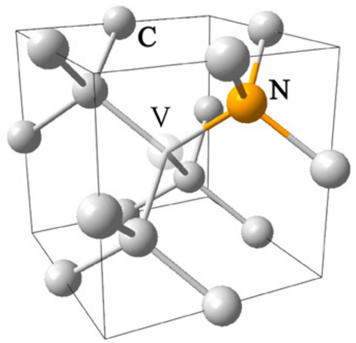
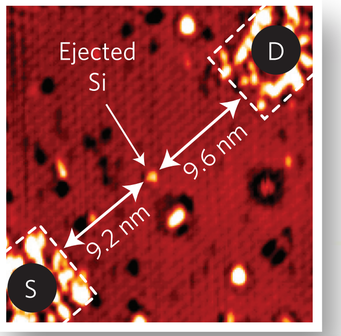
4. Conclusions

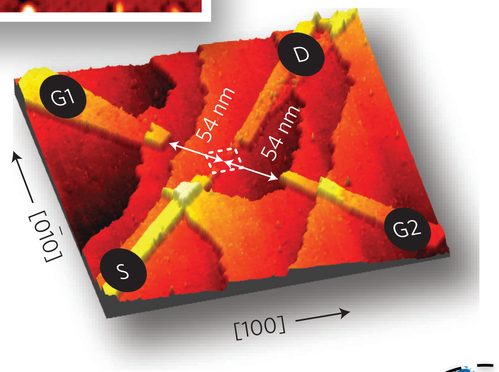


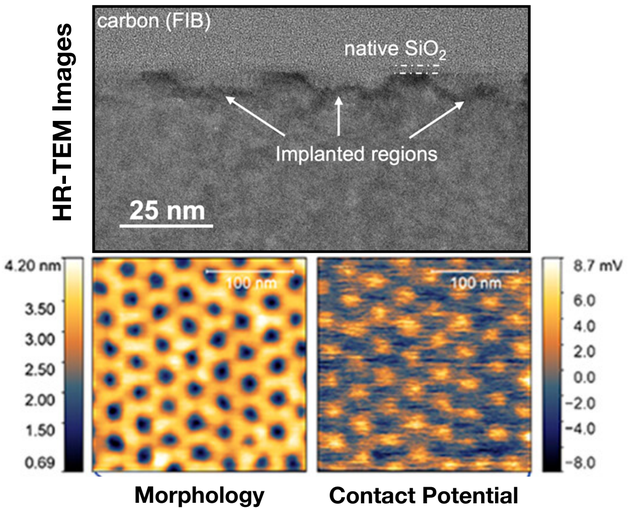


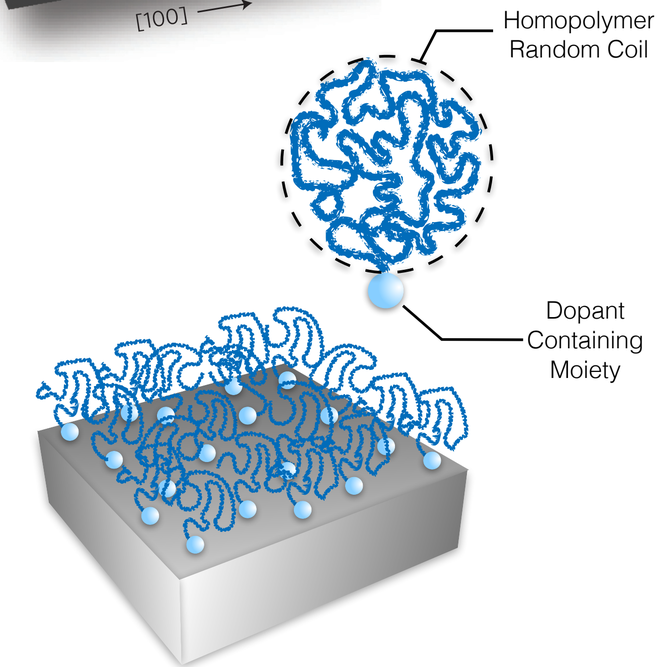












4. Conclusions

Deterministic Doping Strategies

The development of deterministic doping techniques represents a big chance for material scientists and engineers to develop a new generation of atomic scale devices

Scanning tunneling lithography and single ion implantation technologies have been demonstrated to guarantee control of dopant position

New doping strategies based on self-assembling materials have been proposed as an alternative approach to achieve deterministic doping

Metrology Challenge

Detection of impurity atoms within a semiconductor with atomic resolution represents a formidable challenge for metrology