COLDBEAMS2012
Wednesday October 3
11:50 to 12:10 am 20 min

CENTRE FOR QUANTUM COMPUTATION & COMMUNICATION TECHNOLOGY
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

Bypassing Liouville
Deterministic *single-ion-implanted* devices for reading atom quantum states

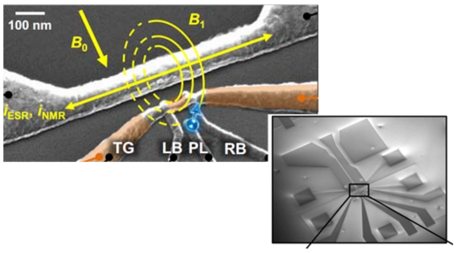
David N. Jamieson
ARC Centre for Quantum Computation and Communication Technology
School of Physics, University of Melbourne

Melbourne Royal Exhibition Buildings UNESCO world heritage site

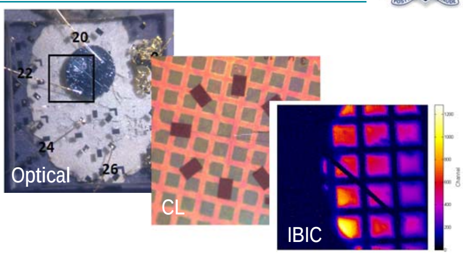
Wikkipedia

1

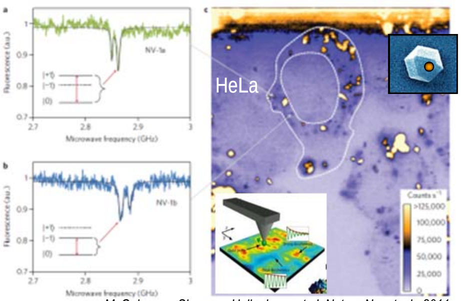
The Melbourne major projects



Quantum devices in Si:P

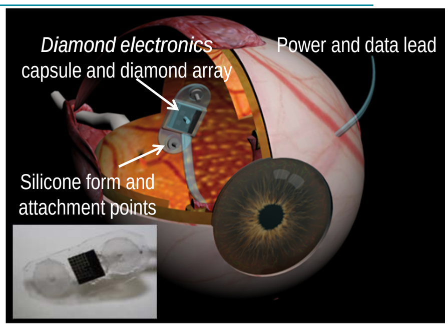


Diamond radiation dosimeter



McGuinness, Simpson, Hollenberg, et al, Nature Nanotech. 2011

N-V Nanodiamond decoherence probes



Bionic Eye

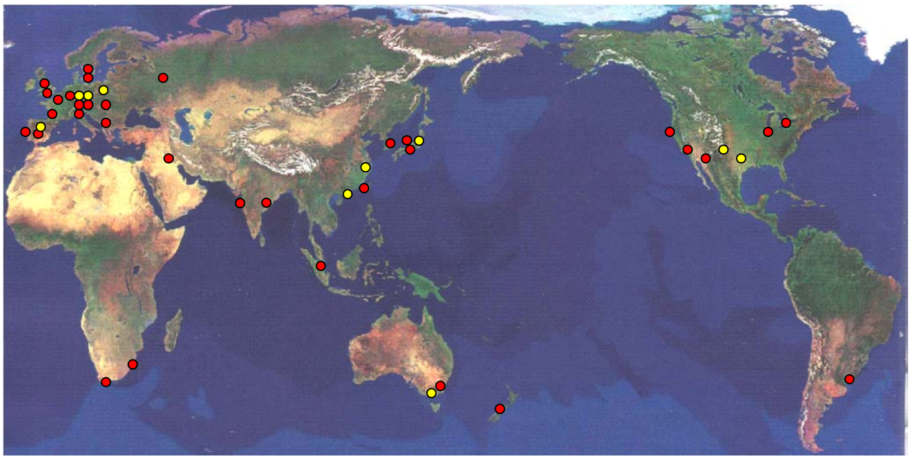
2

Part 1: Ion Beams In Melbourne

MeV ions, keV ions

Nuclear microprobe technology worldwide

The World's nuclear microprobe laboratories
Made by MARC



5

Joseph Liouville (1809 – 1882)

http://en.wikipedia.org/wiki/Joseph_Liouville

Born: 24 March 1809 (Ste Omer),
Died: 8 September 1882 (Paris)

Liouville's theorem (Hamiltonian): "the phase-space distribution function is constant along the trajectories of the system – that is that the density of system points in the vicinity of a given system point travelling through phase-space is constant with time."

$$x\theta\sqrt{E} = const$$

The Castellarius

Purity
Current
Brightness

High fidelity transport
Minimal leaks or aberrations
Technological elegance

Precise delivery
Amount on demand
High reliability

La fontaine d'Eure à Uzès

http://www.hydriad.com/

Pont du Gard

author

Castellum Divisorium

tripwow.tripadvisor.com

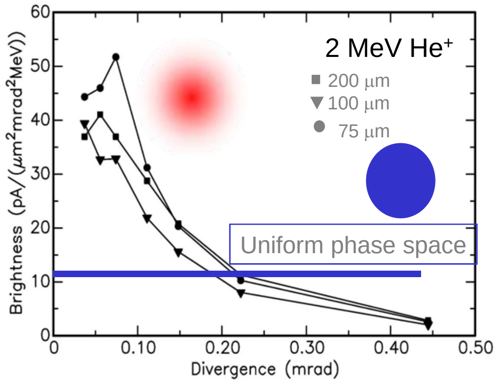
6

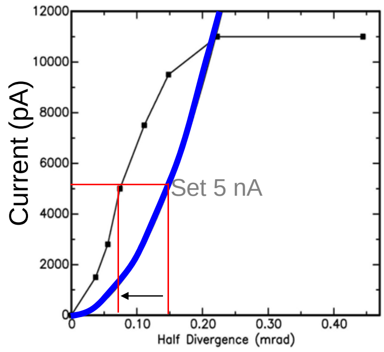
Ion Source Brightness: Flux Peaking

- Legge et al (1993) showed a *1 order of magnitude* decrease in probe size required a *5 orders of magnitude* increase in brightness for uniform model
- True situation more complicated: *1 order of magnitude* decrease in probe size requires *2 orders of magnitude* increase in brightness

For 5 nA divergence is 2.5 times less than uniform model so spherical aberration is reduced by a factor of 16

RF ion source on 5U Pelletron accelerator





7

Quest for brighter sources

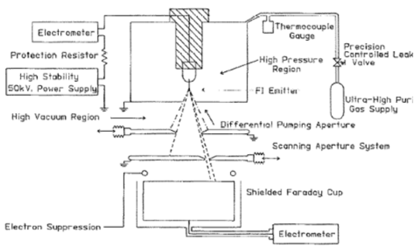
122 Nuclear Instruments and Methods in Physics Research B34 (1988) 122–126
North-Holland, Amsterdam

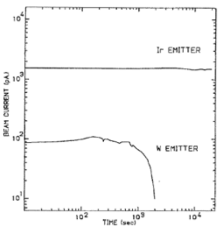
CHARACTERISTICS OF A HYDROGEN GAS FIELD ION SOURCE FOR MICROPROBE APPLICATION

G.L. ALLAN and G.J.F. LEGGE
Micro Analytical Research Centre, School of Physics, The University of Melbourne, Parkville, Victoria, 3052, Australia

J. ZHU
Shanghai Institute of Nuclear Research, Shanghai, PR China

Did not work – significant technical difficulties fitting into the terminal of a high energy particle accelerator



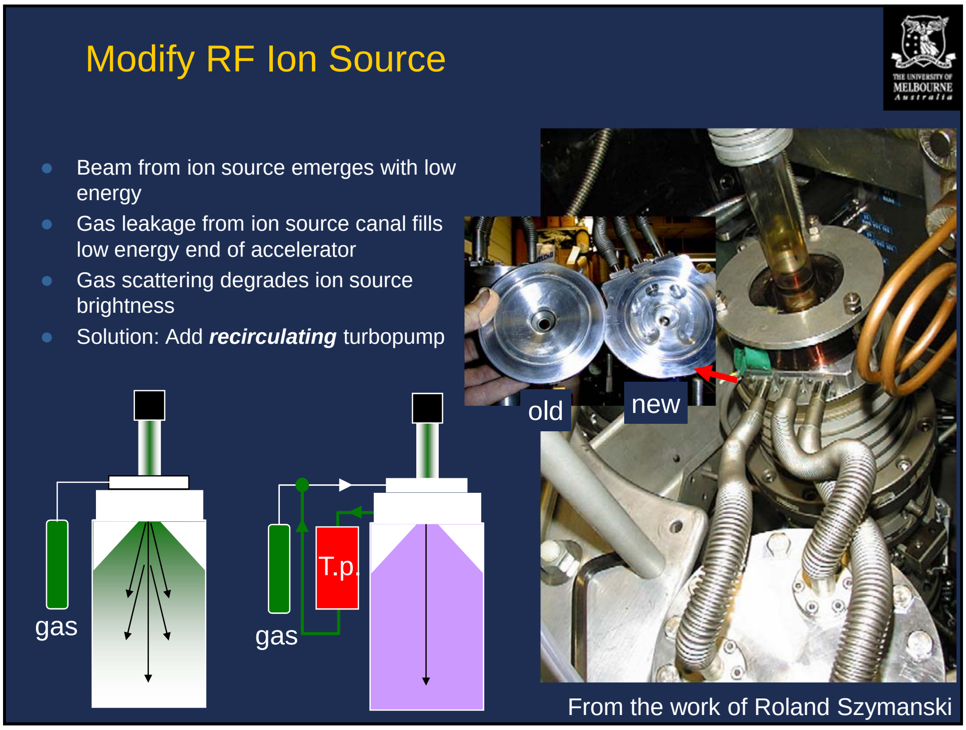


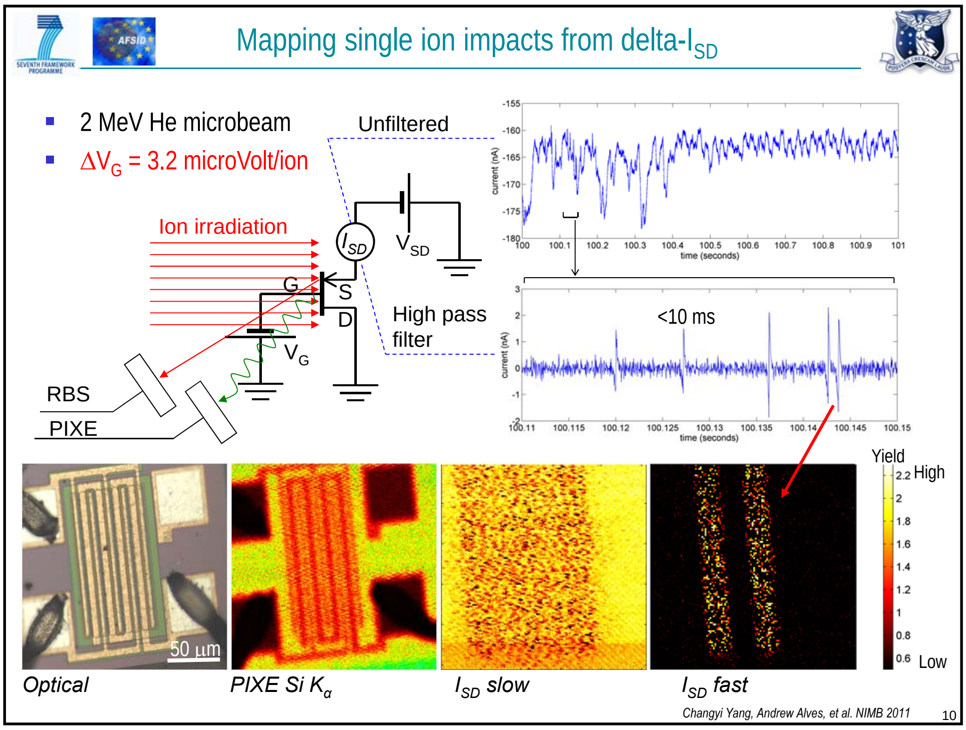
10^5 times brighter than RF source, but at cost of very large divergence

An analysis of the optics of a field ionization ion source for application with a scanning proton microprobe
R. A. Colman, G. L. Allan, and G. J. F. Legge

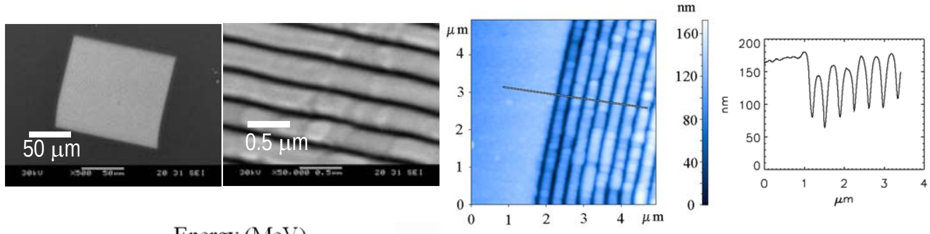
Citation: Rev. Sci. Instrum. **63**, 5653 (1992); doi: 10.1063/1.1143396

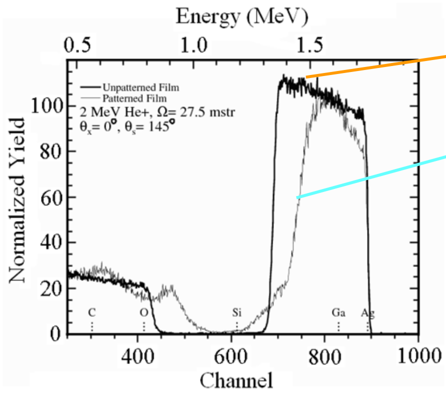
8

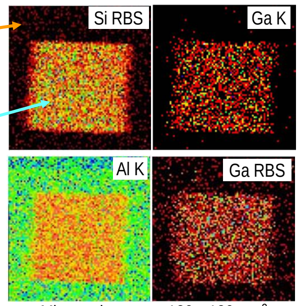

Modify RF Ion Source
THE UNIVERSITY OF MELBOURNE Australia
Beam from ion source emerges with low energy
Gas leakage from ion source canal fills low energy end of accelerator
Gas scattering degrades ion source brightness
Solution: Add recirculating turbopump
gas
T.p.
gas
old
new
From the work of Roland Szymanski


SEVENTH FRAMEWORK PROGRAMME
AFSID
Mapping single ion impacts from delta-I$_{SD}$
2 MeV He microbeam
ΔV_G = 3.2 microVolt/ion
Unfiltered
Ion irradiation
I_{SD}
V_{SD}
G
S
D
V_G
High pass filter
RBS
PIXE
current (nA)
time (seconds)
<10 ms
Yield
High
Low
50 µm
Optical
PIXE Si K_α
I_{SD} slow
I_{SD} fast
Changyi Yang, Andrew Alves, et al. NIMB 2011
10

Sub-microscopic structure photonic crystal made by FIB litography







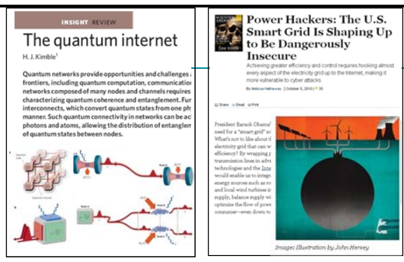
Microprobe maps: 180 ×180 µm^2

RBS/PIXE maps

(grating structure not resolved)

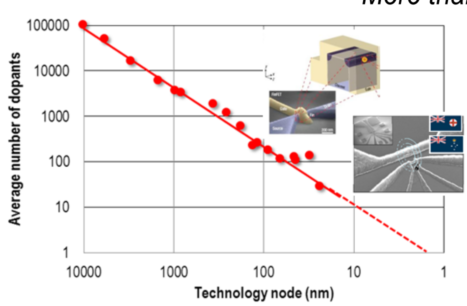
⇨ Ga residues and exposed Si

The work of Shannon Orbons and Patrick Reichart



Part 2: Deterministic Doping – Towards the quantum computer

"More than Moore"



International Technology Roadmap for Semiconductors
2011 Edition
Emerging Research Materials
Section 6: Single ion implantation

Isotope Considerations

- Isotopic abundances and nuclear spin of semiconductors and donors:

^{28}Si	92.2%	0^+
^{29}Si	4.7%	$½^+$
^{30}Si	3.08%	0^+
^{31}P	100%	$½^+$
^{75}As	100%	$3/2^-$
^{121}Sb	57%	5/2
^{123}Sb	43%	7/2
^{209}Bi	100%	9/2

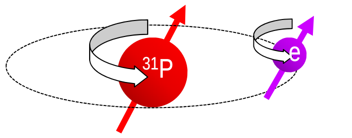
- Others:

^{69}Ga	60.1%	$3/2^-$
^{71}Ga	39.9%	$3/2^-$
^{12}C	98.3 %	0+
^{13}C	1.1 %	½ -
^{14}C	1e-10 %	0^+
^{14}N	99.6 %	1^+
^{15}N	0.36 %	$½^-$
^{10}B	19.9%	3^+
^{11}B	80.1 %	$3/2^-$

The standard ^{28}Si kilogram

Spherical to 0.6 nm

http://www.acpo.csiro.au/avogadro.htm

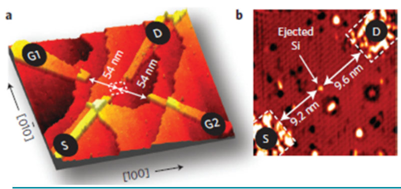


Approaches to "More than Moore"

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

A single-atom transistor

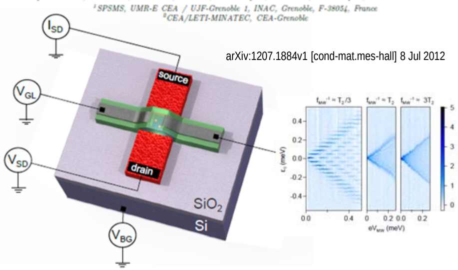
Martin Fuechsle[1], Jill A. Miwa[1], Suddhasatta Mahapatra[1], Hoon Ryu[2], Sunhee Lee[3], Oliver Warschkow[4], Lloyd C. L. Hollenberg[5], Gerhard Klimeck[3] and Michelle Y. Simmons[1]*



Coupling and coherent electrical control of two dopants in a silicon nanowire

E. Dupont-Ferrier,[1] B. Roche,[1] B. Voisin,[1] X. Jehl,[1] R. Wacquez,[2] M. Vinet,[2] M. Sanquer,[1] and S. De Franceschi[1]
[1] SPSMS, UMR-E CEA / UJF-Grenoble 1, INAC, Grenoble, F-38054, France
[2] CEA/LETI-MINATEC, CEA-Grenoble

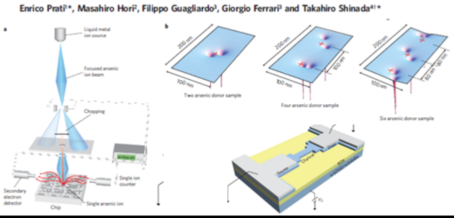
arXiv:1207.1884v1 [cond-mat.mes-hall] 8 Jul 2012



nature nanotechnology
LETTERS
PUBLISHED ONLINE: 1 JULY 2012 | DOI: 10.1038/NNANO.2012.94

Anderson–Mott transition in arrays of a few dopant atoms in a silicon transistor

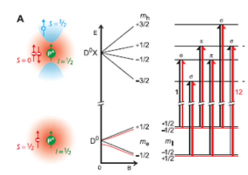
Enrico Prati[1]*, Masahiro Hori[2], Filippo Guagliardo[3], Giorgio Ferrari[3] and Takahiro Shinada[4]†*

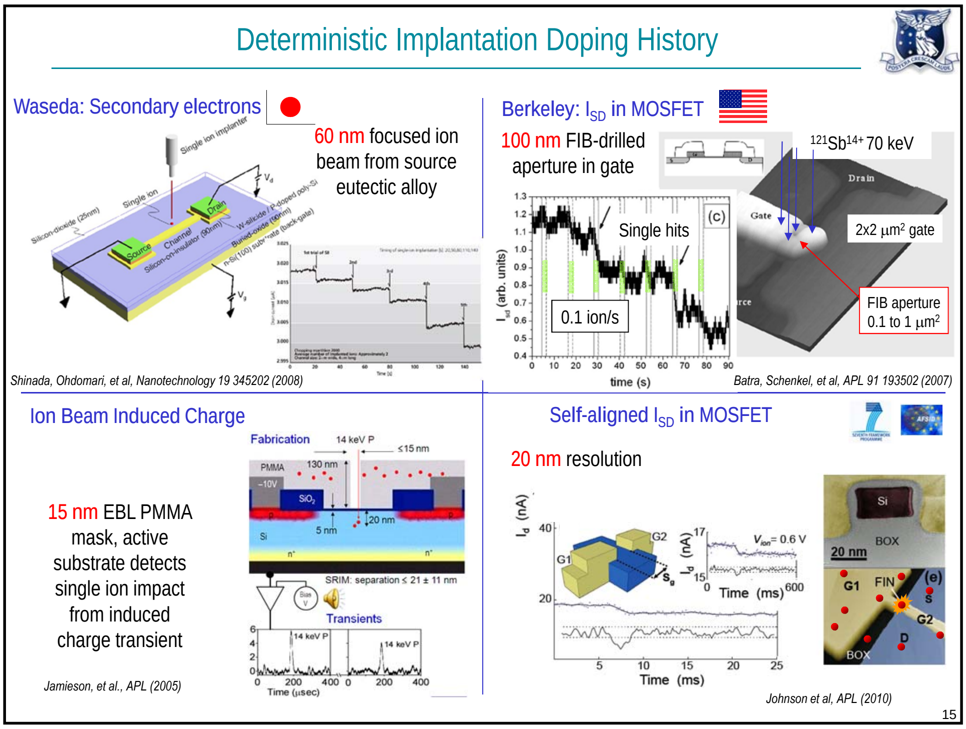


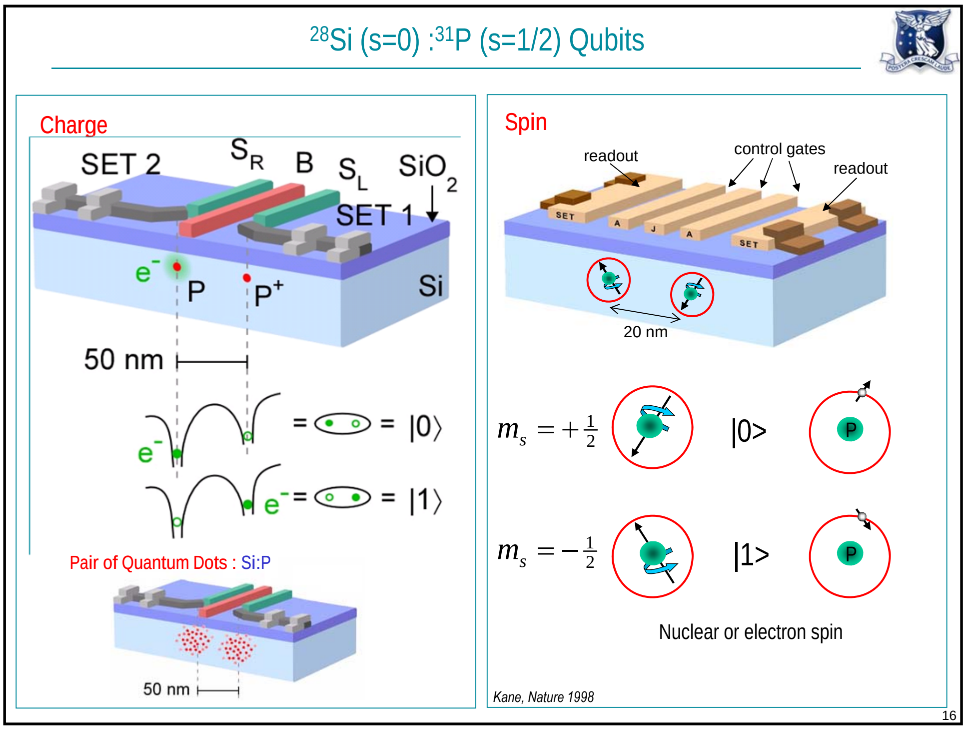
REPORTS
8 JUNE 2012 VOL 336 SCIENCE

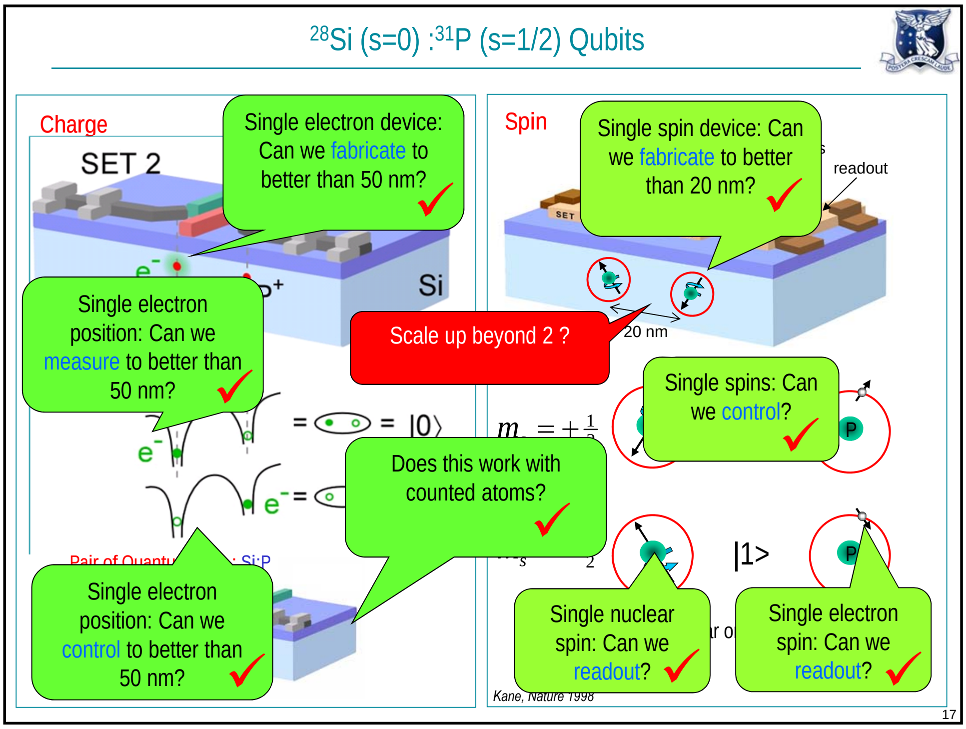
Quantum Information Storage for over 180 s Using Donor Spins in a ^{28}Si "Semiconductor Vacuum"

M. Steger,[1] K. Saeedi,[1] M. L. W. Thewalt,[1]* J. J. L. Morton,[2] H. Riemann,[3] N. V. Abrosimov,[3] P. Becker,[4] H.-J. Pohl[5]

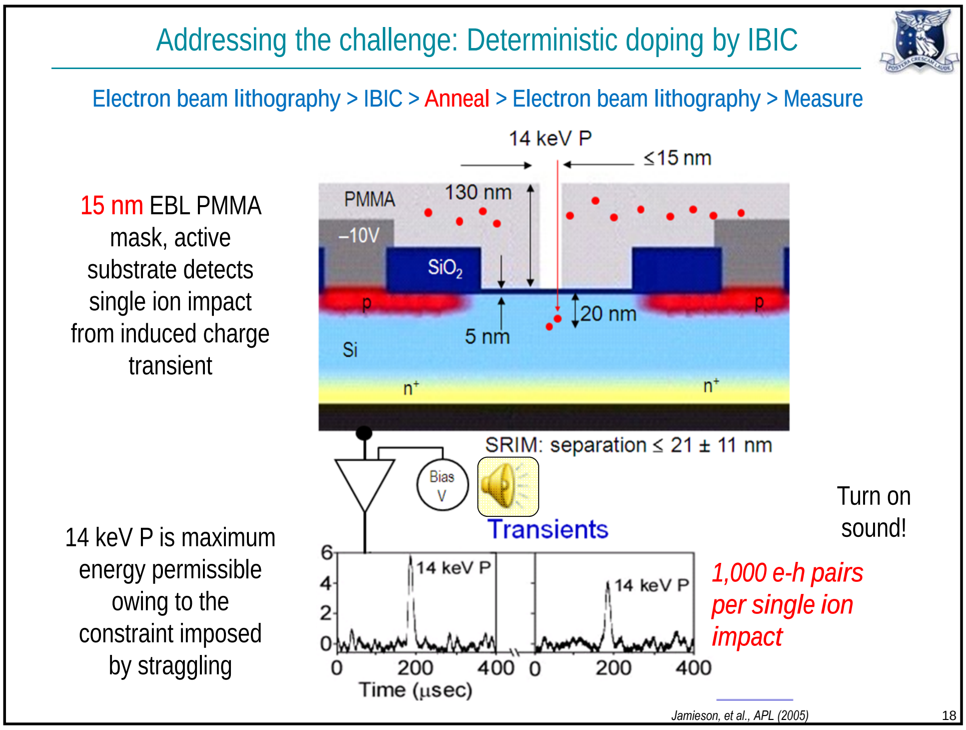



Deterministic Implantation Doping History
Waseda: Secondary electrons
60 nm focused ion beam from source eutectic alloy
Shinada, Ohdomari, et al, Nanotechnology 19 345202 (2008)
Berkeley: I_SD in MOSFET
100 nm FIB-drilled aperture in gate
121Sb14+ 70 keV
Single hits
0.1 ion/s
2x2 μm2 gate
FIB aperture 0.1 to 1 μm2
time (s)
Batra, Schenkel, et al, APL 91 193502 (2007)
Ion Beam Induced Charge
15 nm EBL PMMA mask, active substrate detects single ion impact from induced charge transient
Fabrication
14 keV P
Transients
Time (μsec)
Jamieson, et al., APL (2005)
Self-aligned I_SD in MOSFET
20 nm resolution
Time (ms)
Johnson et al, APL (2010)
15


28Si (s=0) :31P (s=1/2) Qubits
Charge
SET 2
S_R
B
S_L
SiO2
SET 1
e-
P
P+
Si
50 nm
= |0⟩
= |1⟩
Pair of Quantum Dots : Si:P
50 nm
Spin
readout
control gates
readout
20 nm
m_s = +1/2
|0>
m_s = −1/2
|1>
P
Nuclear or electron spin
Kane, Nature 1998
16

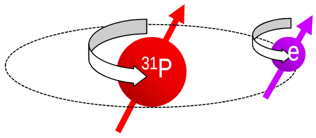


28Si (s=0) :31P (s=1/2) Qubits
Charge
SET 2
Si
Single electron device: Can we fabricate to better than 50 nm?
Single electron position: Can we measure to better than 50 nm?
Scale up beyond 2 ?
Does this work with counted atoms?
Single electron position: Can we control to better than 50 nm?
Spin
Single spin device: Can we fabricate to better than 20 nm?
readout
20 nm
Single spins: Can we control?
|1>
Single nuclear spin: Can we readout?
Single electron spin: Can we readout?
Kane, Nature 1998
17

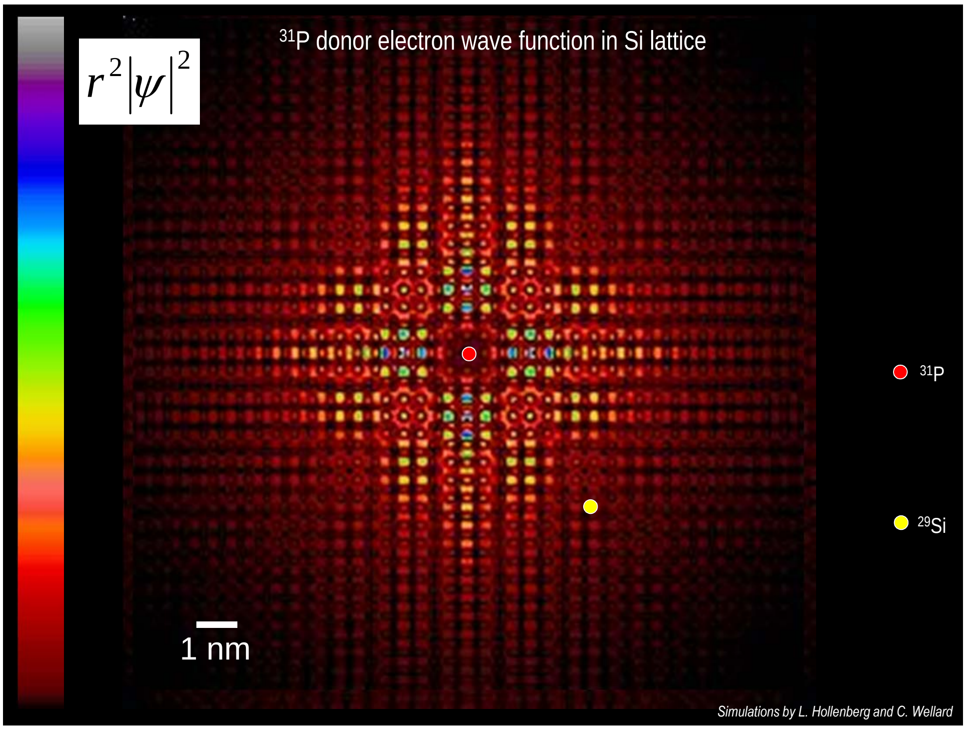


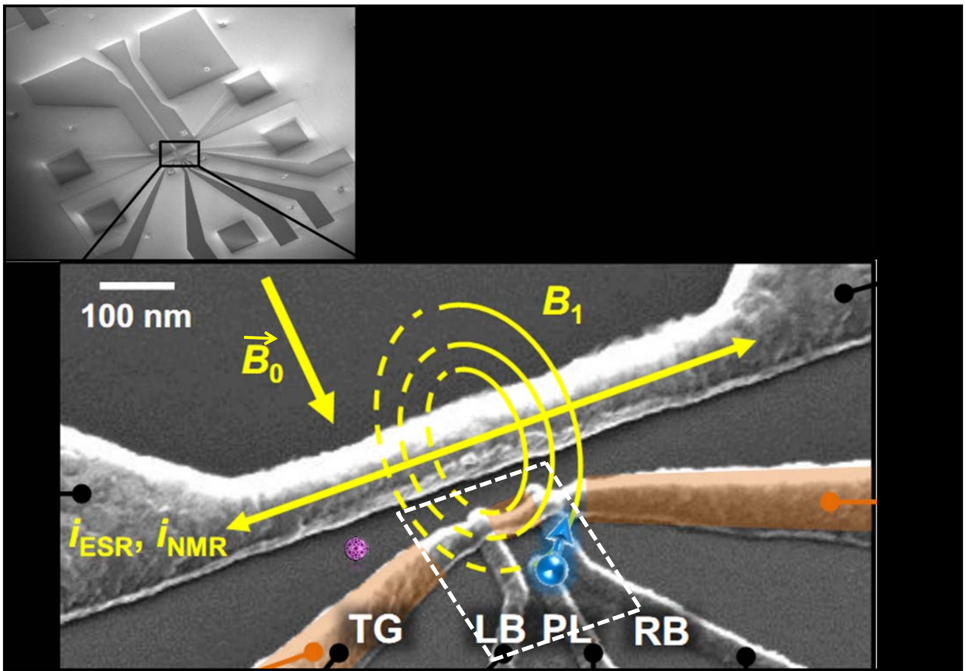
Addressing the challenge: Deterministic doping by IBIC
Electron beam lithography > IBIC > Anneal > Electron beam lithography > Measure
15 nm EBL PMMA mask, active substrate detects single ion impact from induced charge transient
14 keV P
≤15 nm
PMMA
130 nm
–10V
SiO2
20 nm
5 nm
Si
p
n+
SRIM: separation ≤ 21 ± 11 nm
Bias V
Transients
Turn on sound!
14 keV P is maximum energy permissible owing to the constraint imposed by straggling
14 keV P
Time (μsec)
1,000 e-h pairs per single ion impact
Jamieson, et al., APL (2005)
18

Part 3: Spin Qubit 101



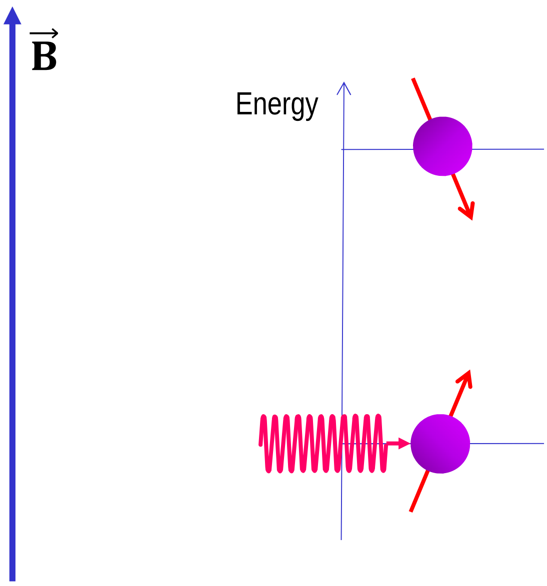
19





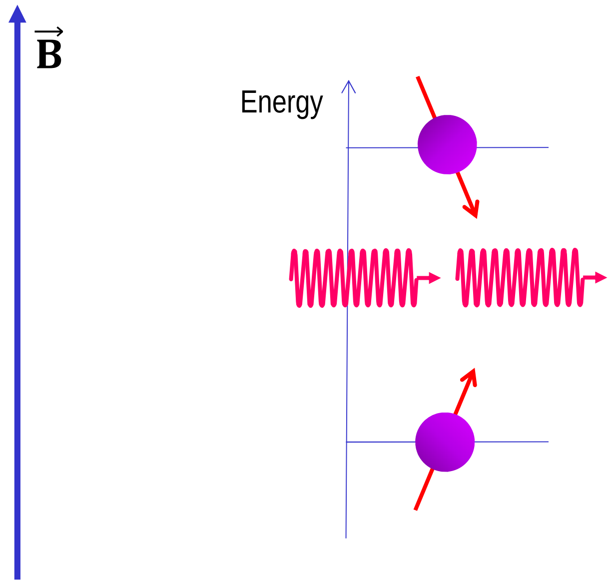
10,000,000 times actual size

Superposition



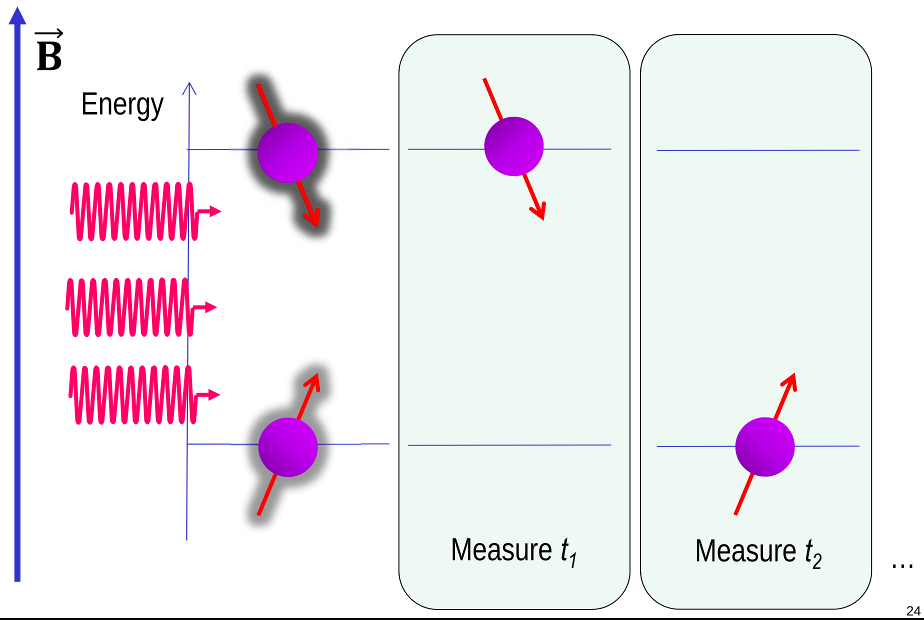
22

Superposition

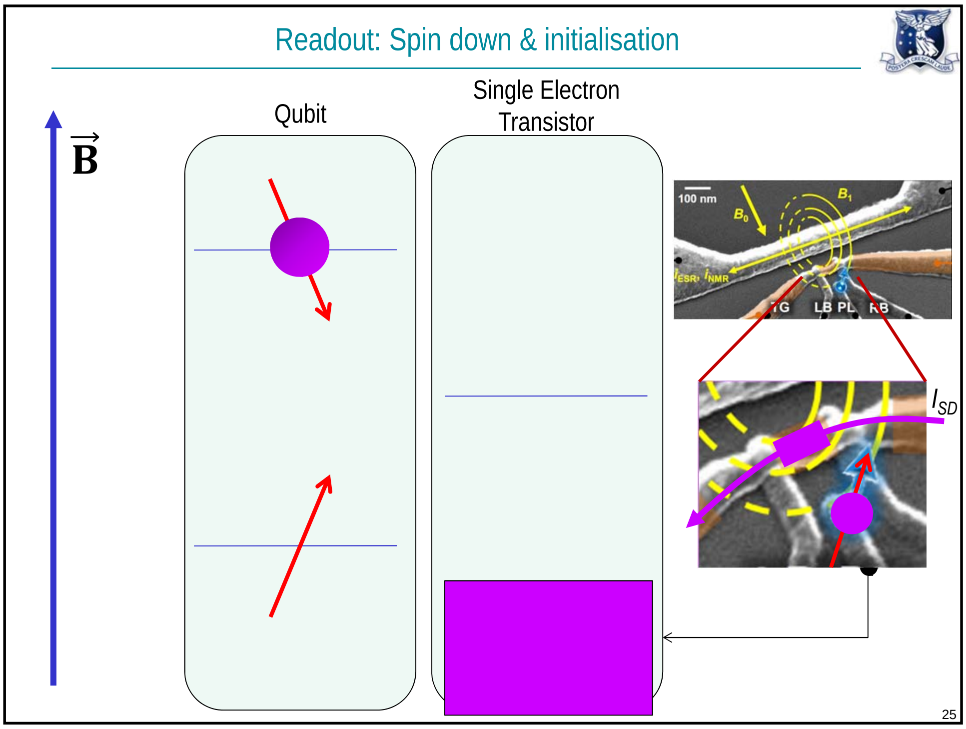


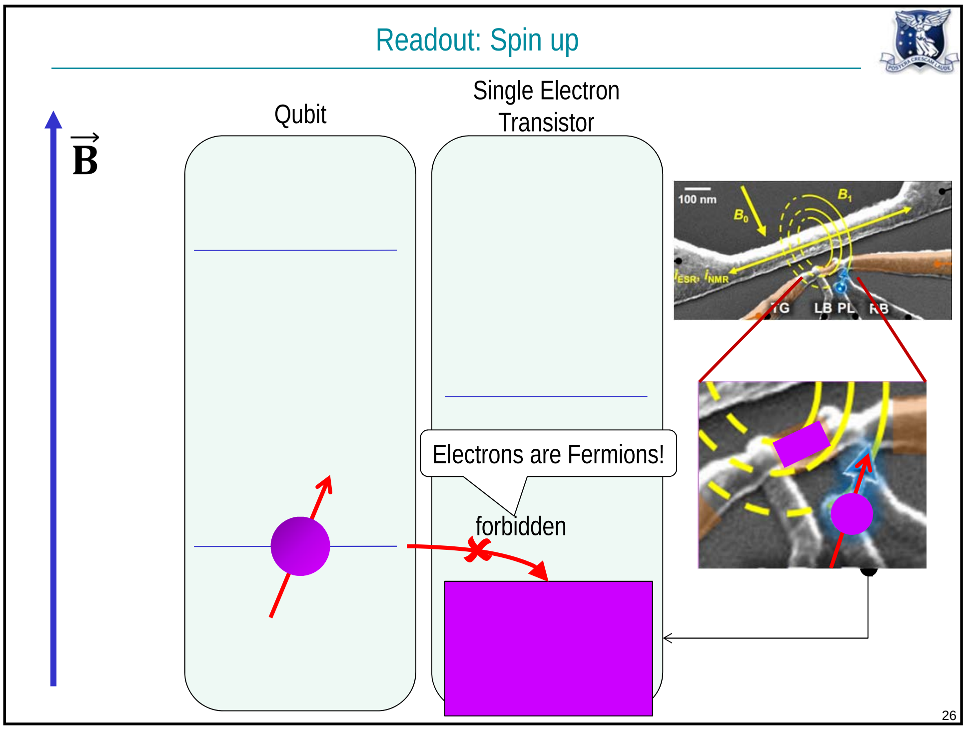
23

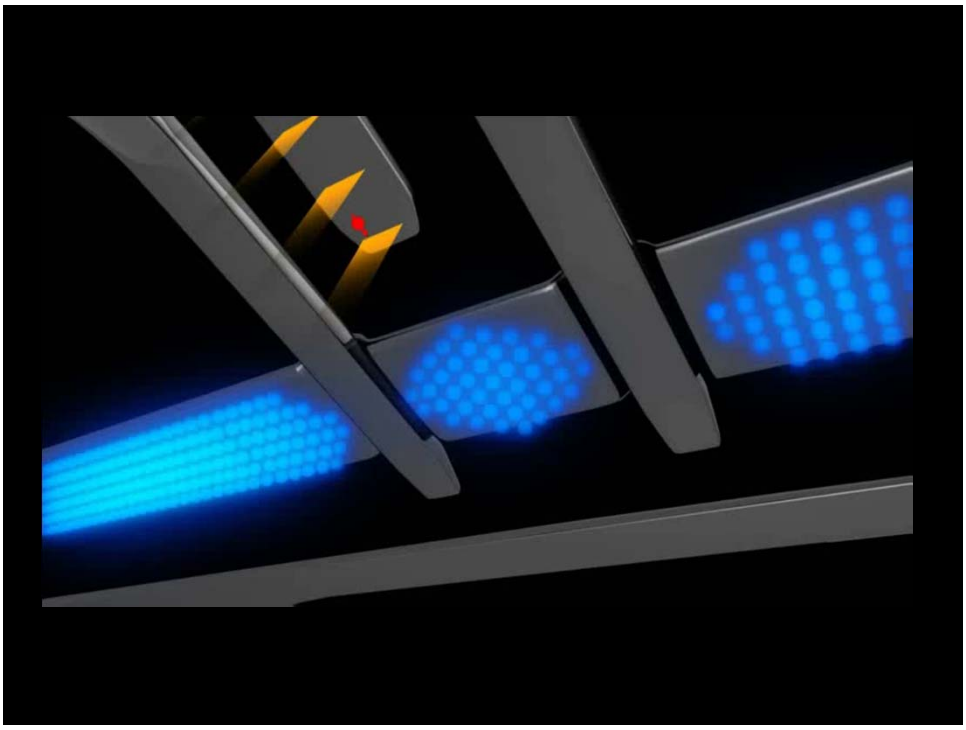
Superposition

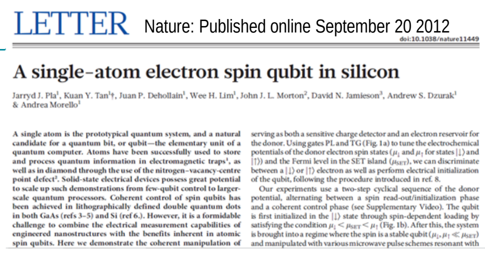


24


Readout: Spin down & initialisation
Qubit
Single Electron Transistor
B
100 nm
B_0
B_1
I_{ESR}, I_{NMR}
TG
LB PL RB
I_{SD}
25


Readout: Spin up
Qubit
Single Electron Transistor
B
100 nm
B_0
B_1
I_{ESR}, I_{NMR}
TG
LB PL RB
Electrons are Fermions!
forbidden
26





LETTER Nature: Published online September 20 2012

doi:10.1038/nature11449

A single-atom electron spin qubit in silicon

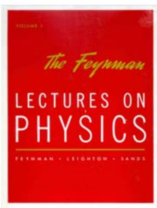
Jarryd J. Pla[1], Kuan Y. Tan[1]†, Juan P. Dehollain[1], Wee H. Lim[1], John J. L. Morton[2], David N. Jamieson[3], Andrew S. Dzurak[1] & Andrea Morello[1]

A single atom is the prototypical quantum system, and a natural candidate for a quantum bit, or qubit—the elementary unit of a quantum computer. Atoms have been successfully used to store and process quantum information in electromagnetic traps[1], as well as in diamond through the use of the nitrogen-vacancy-centre point defect[2]. Solid-state electrical devices possess great potential to scale up such demonstrations from few-qubit control to larger-scale quantum processors. Coherent control of spin qubits has been achieved in lithographically defined double quantum dots in both GaAs (refs 3–5) and Si (ref 6.). However, it is a formidable challenge to combine the electrical measurement capabilities of engineered nanostructures with the benefits inherent in atomic spin qubits. Here we demonstrate the coherent manipulation of

serving as both a sensitive charge detector and an electron reservoir for the donor. Using gates PL and TG (Fig. 1a) to tune the electrochemical potentials of the donor electron spin states ($\mu_\downarrow$ and $\mu_\uparrow$ for states $|\downarrow\rangle$ and $|\uparrow\rangle$) and the Fermi level in the SET island (μ_{SET}), we can discriminate between a $|\downarrow\rangle$ or $|\uparrow\rangle$ electron as well as perform electrical initialization of the qubit, following the procedure introduced in ref. 8.

Our experiments use a two-step cyclical sequence of the donor potential, alternating between a spin read-out/initialization phase and a coherent control phase (see Supplementary Video). The qubit is first initialized in the $|\downarrow\rangle$ state through spin-dependent loading by satisfying the condition $\mu_\downarrow < \mu_{SET} < \mu_\uparrow$ (Fig. 1b). After this, the system is brought into a regime where the spin is a stable qubit ($\mu_\downarrow, \mu_\uparrow \ll \mu_{SET}$) and manipulated with various microwave pulse schemes resonant with

Part 4: Results



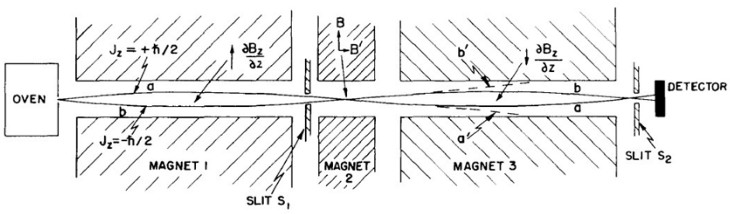


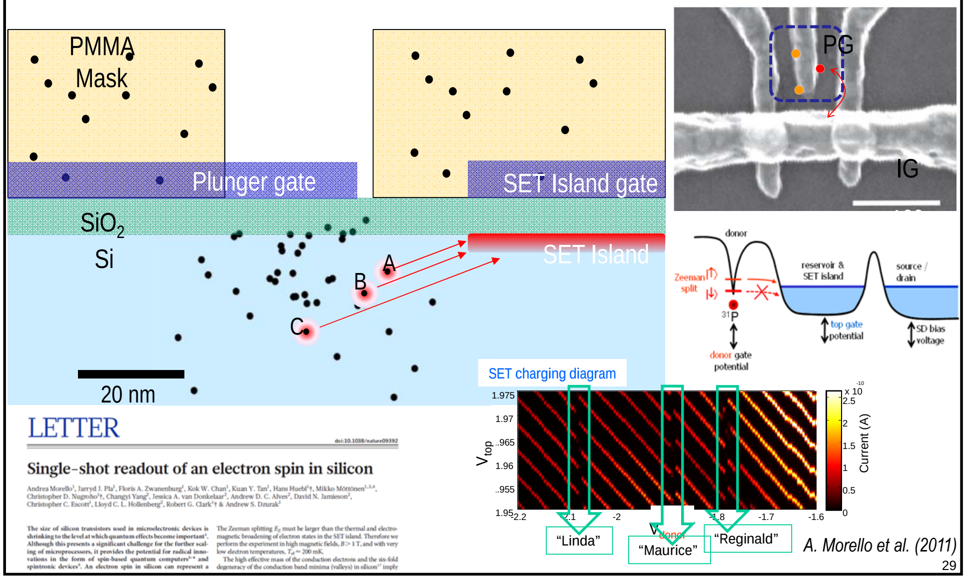
Fig. 35–5. The Rabi molecular-beam apparatus.

35–5

28

Post-implant donor selection: Nuclear and Electron spin readout

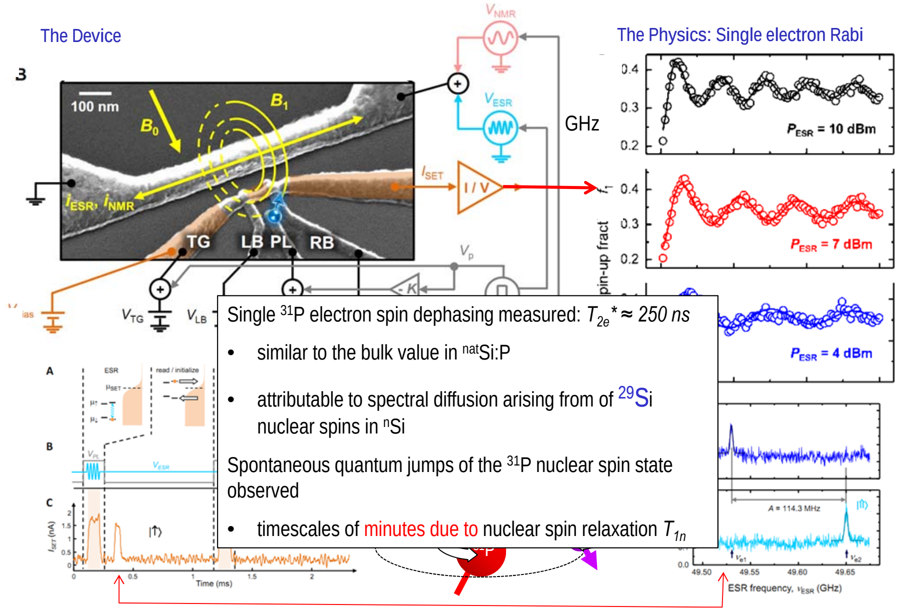
- 14 keV P^+ Implant, 30 atoms into EBL mask + Spin dependent electron readout
- But nuclear spin is coupled to the electron spin via spin-orbit….



A. Morello et al. (2011)

Single Electron Spin Rabi Oscillations

http://www.beyonddiscovery.org/content/view.article.asp?a=129



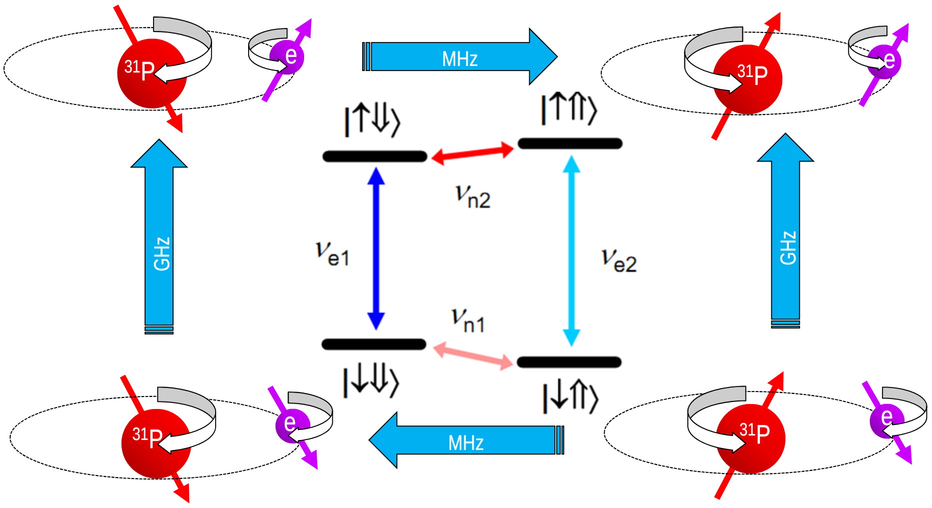
Single ^{31}P electron spin dephasing measured: $T_{2e}^* \approx 250$ ns

- similar to the bulk value in ^{nat}Si:P
- attributable to spectral diffusion arising from of ^{29}Si nuclear spins in ^{n}Si

Spontaneous quantum jumps of the ^{31}P nuclear spin state observed

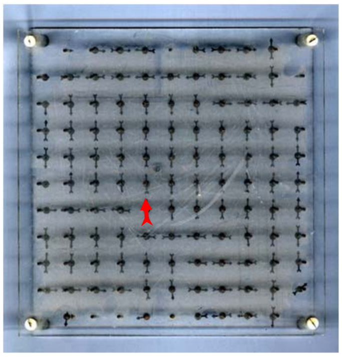
- timescales of minutes due to nuclear spin relaxation T_{1n}

The work of Jarryd Pla, Andrea Morello, Andrew Dzurak, et al



31

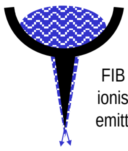
Part 5: Beyond single ions



32

^{31}P ion beam for Melbourne FIB

Waseda P eutectic



- P alloy: CuPtP
- Must use P^{++} to avoid interference with P^{+} / Cu++
- Not commercially available
- Japanese supplier no longer working on these materials

Dresden P eutectics

NiP alloy:

- Attacks Pt / W / Ir tips
- Short lifetime

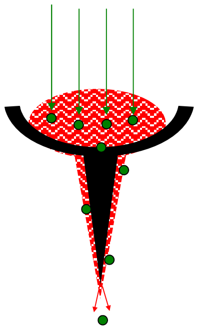
Alternatives:

- GaP – high melting point
- InP – high melting point

Exotics:

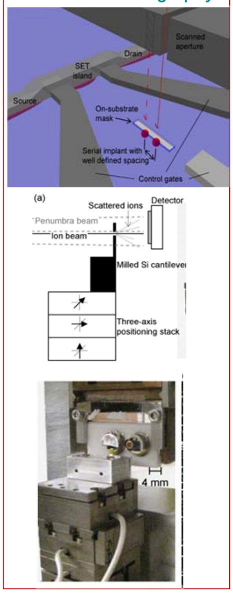
- Pt-P-Sb (Hitachi)

UM P implant



- Use standard Ga source (off the shelf)
- Implant with $1x10^{17}$ P/cm^2 in Colutron
- Use ExB filter to select P ion beam
- Aim for 100 P/s

Nanostencil lithography

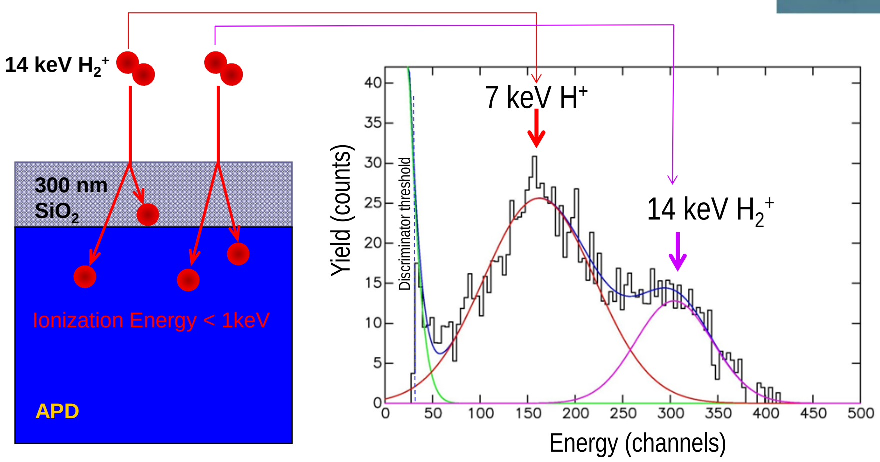


33

Fast 2 atom prototype: P_2 molecular ions into APD

- Linear mode Hammamatsu APD
- Charge gain: ~ 100
- Detection limit: less than 1 keV ionization energy

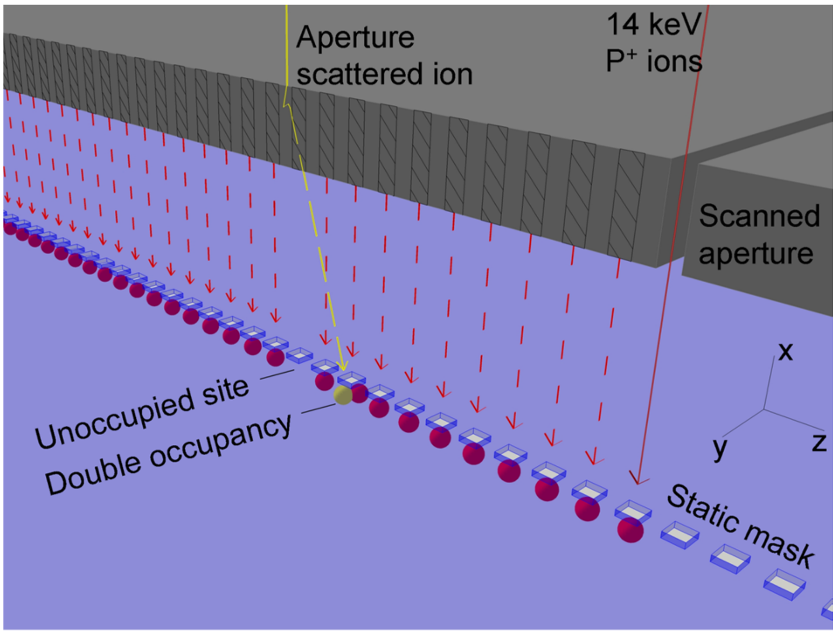
http://sales.hamamatsu.com/index.php?id=13166473



34

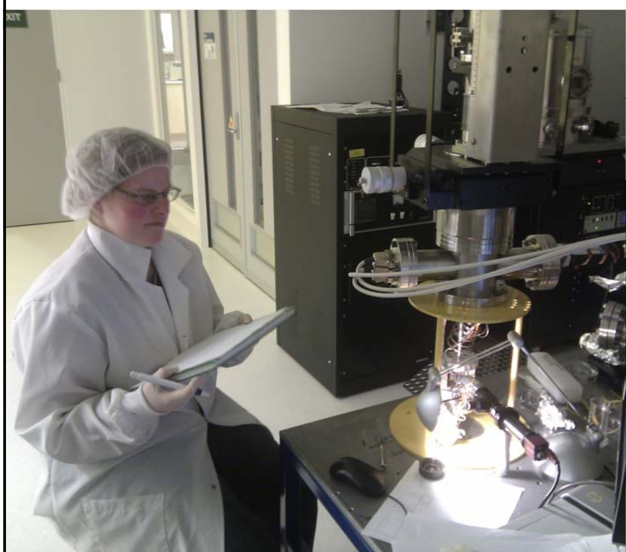
David Jamieson et al.

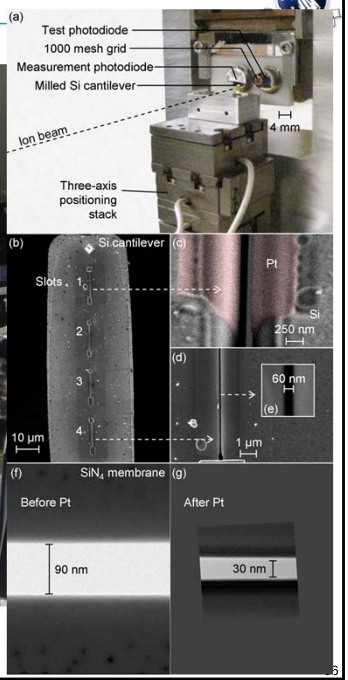
More than *one deterministic* atom?



35

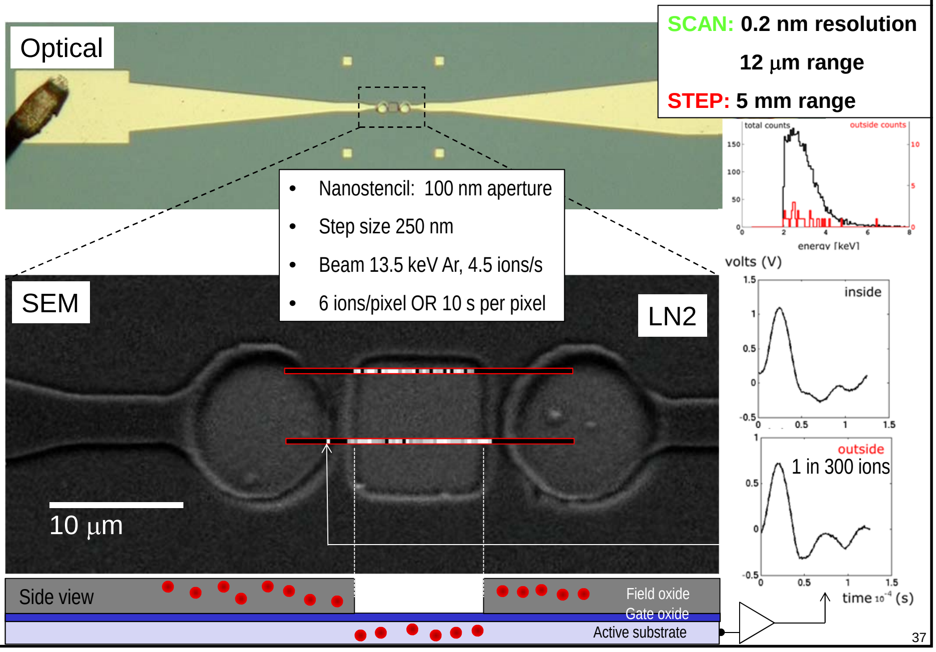
The reality: Scanned nanostencils





PhD thesis of Jessica van Donkelaar

Scale-up: Deterministic Heavy Ion Doping – *First device!*



37

Conclusions: What we want

All to be consistent with the device fabrication process flow!

In order to have the best possible workshop, I would also stress that in complement to present your work the purpose of the conference is to give your vision for the field, your needs and desires for future products and applications, research, etc ...
Daniel Comparat, September 2012

Realistic:

- Sub-10 nm P^+ ion beam; 100 ions/s; sub-10 nm positioning accuracy
  - For the production of large arrays of single donors in Si
- Ion Impact Detector Performance:
  - PIN: 1.5 keV noise threshold demonstrated (14 keV P), 0.5 keV in near future?
  - APD: 1000 gain demonstrated in commercial device
- Remaining issues
  - Gate oxide: have 5 to 8 nm, move to 2 nm desirable
  - Geiger mode/APD advanced development (7 keV P)

Si Quantum devices are REAL!
Long lived quantum spin states in Si demonstrated

Dream:

- PH_4^+ molecular ions
  - H bystander ions create greater ionisation leading to better deterministic doping signals
- PSi_4^+ molecular ions
  - Even better: Si bystander ions amorphise surface layer and supress channeling and allow shallow donors with less straggling – follows industry-standard B implant approach
- ^{28}Si island formation by ion deposition on ^{n}Si wafers

Thank you Castellaria!

& Andrew Dzurak, Andrea Morello group @ UNSW

CENTRE FOR QUANTUM COMPUTATION & COMMUNICATION TECHNOLOGY
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

38