AGH University of Science and Technology

Neutron Transmutation Doping of Silicon

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Introduction

Disclaimer:

this short review is based on a quick literature survey and not on my personal research experience in this area

Motivation:

Growing demand for NTD (neutron transmutation doped) silicon from power electronics industry driven mainly by applications in hybrid electric cars, wind power and solar cell power plants

Remarks on radiation damage effects in semiconductor devices

Three categories of radiation effects:

Ionisation damage – characterised vs Total Ionising Dose (TID) up to 10 MGy (SiO_2)

Testing: gamma or X-ray source

Displacement damage – characterised vs 1 MeV eq. neutron fluence, up to 10^{16} cm^{-2}

Testing: almost any high energy neutron beam with known spectrum and preferably with low gamma background.

Single Event Effects – characterised by cross section vs lateral energy deposition

Testing: heavy ions (some tens of MeV, cyclotrons)

NTD - physical background

Neutron capture reaction to produce phosphorus (donors) dopands in silicon

$^{30}Si(n,\gamma)^{31}Si \rightarrow {}^{31}P + \beta^{-}$ (2.62h)

Composition of natural silicon

^{28}Si (abundance: 92.23%),

^{29}Si (abundance: 4.67%)

^{30}Si (abundance: 3.10%)

Absorption of fast neutrons lead to the direct or indirect production of Al (acceptor dopand) or Mg isotopes – a side effect should be suppressed.

Advantages and needs for NTD silicon

Advantage: NTD technique offers possibility of very uniform doping in large silicon volumes which cannot be achieved by commonly used Czochralski method of crystal growth.

Microelectronics industry is almost entirely based of Czochralski silicon (doping concentration may vary by an order of magnitude across large wafers)

Power electronics devices operate with very high currents (up to hundreds of Ampers) and voltages (up to thousands of Volts) pushed to the limits and require very uniformly doped silicon

Power electronics

Solid-state (silicon) devices used to the control and conversion of electrical power.

Conversion systems

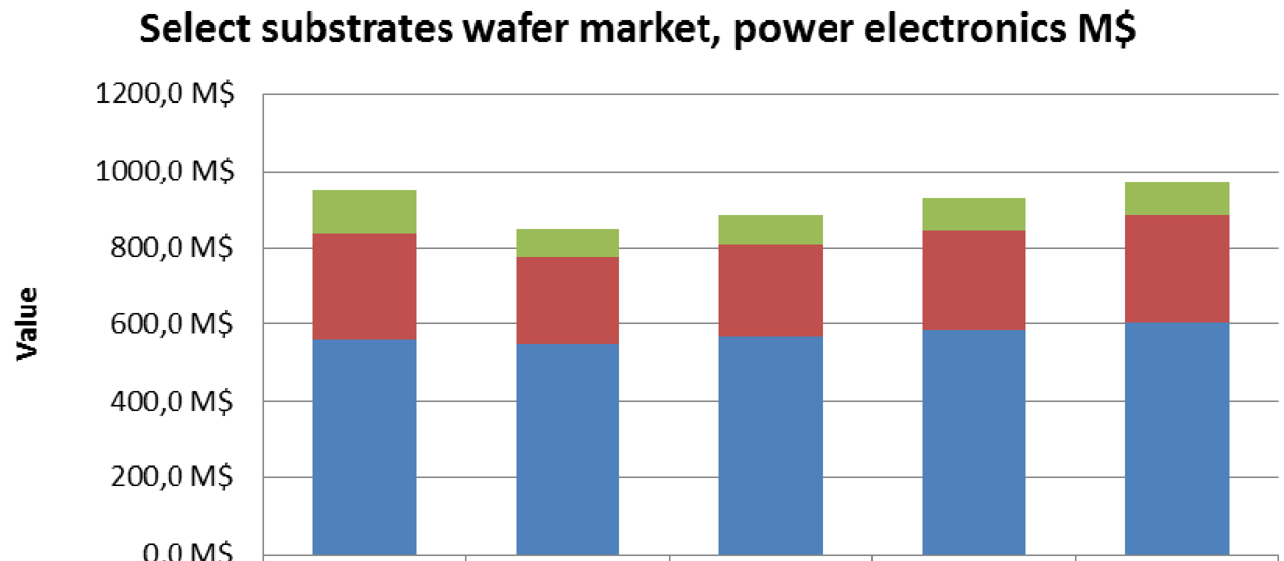
- AC to DC
- DC to AC
- DC to DC
- AC to AC

Devices

- Diodes
- SCR (Silicon Controlled Rectifiers)
- Thyristors
- BJT (Bipolar Junction Transitor)
- MOSFET (Metal-Oxide-Semiconductor Field Effect Transistor)
- IGBT (Insulated Gate Bipolar Transistor)

Demand for NTD silicon

Predictions for demand for NTD Si varied substantially over years depending on development of other alternative technologies, e.g. Magnetic Czochralski method



	2011	2012	2013	2014	2015
Si FZ NTD	113,2 M$	73,0 M$	77,2 M$	81,8 M$	87,0 M$
Si FZ PFZ	277,5 M$	228,0 M$	240,8 M$	260,1 M$	282,3 M$
Si CZ & CZ + Epi	558,0 M$	546,6 M$	568,5 M$	585,2 M$	602,3 M$

Source: http://www.topsil.com/media/

Demand for NTD silicon

Position of NTD Si in the power electronics industry.

Alternative technologies:

-Magnetic Czochralski Si

-SiC

-GaN

Source: http://www.topsil.com/media/

Major present NTD facilities

BR2 in Belgium

JRR-3M in Japan

HANARO reactor at the Korea

OPAL, a new reactor in Australia

South Africa’s SAFARI-1

FRM-II in Germany

Annual world wide capacity 150~180 tons NTD Si

Future demand for NTD wafers (Hybrid Electric Vehicles only)

Table IV: Number and size of IGBTs and FWDs in Toyota Prius II

Item	IGBTs			FWDs			Total number of 6 in. wafer
	Size [mm^2]	Number	Number of 6 in. wafer	Size [mm^2]	Number	Number of 6 in. wafer	
Motor inverter	13.7×9.7	12	0.111	6.4×6.4	12	0.031	0.142
Generator inverter	13.7×9.7	6	0.056	6.4×6.4	6	0.015	0.071
Buck/boost converter	15.0×15.0	6	0.103	13.0×9.0	6	0.048	0.151
Air-conditioning compressor inverter	4.7×4.7	4	0.005	3.0×3.0	4	0.002	0.007
Total			0.275			0.096	0.371

Table V: A rough prospect for HEV production and related need for 6 inch NTD-Si

Year	2010	2015	2020	2030
HEV production [in million vehicles]	1	3	10	50
Need for 6 inch NTD-Si ingot [tons]	16-51	47-153	157-510	786-2550

Source: Myong-Seop Kim, Sang-Jun Park and In-Cheol Lim
Power Electronics and Applications, 2009. EPE '09. 13th European Conference on

Requirements

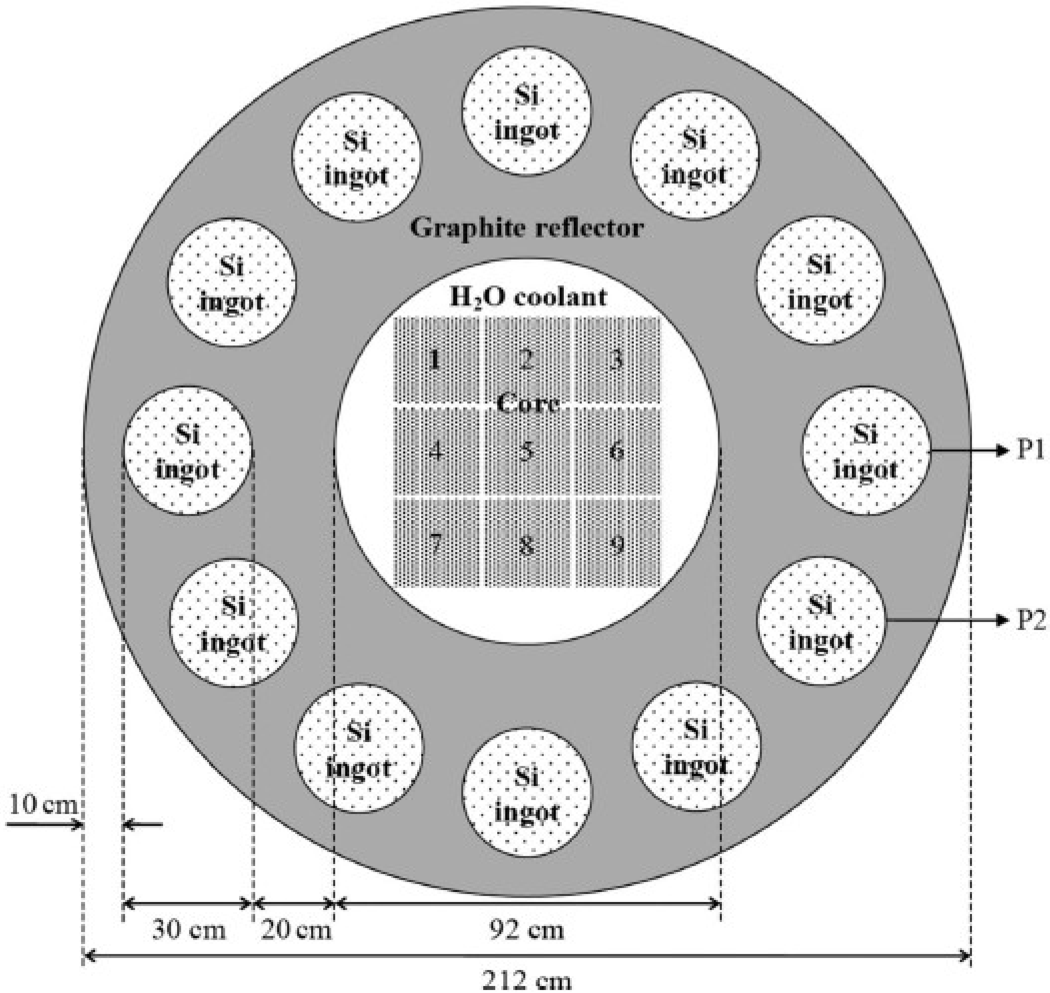
Sample size:
Ingots up to 1 m long of 8 inch (12 inch) diameter

Irradiation uniformity better then 5%

Neutron fluence

Resistivity (Ωcm)	Dopant conc. (10^{13} atoms/cm^3)	Ppba Phosphorus	Neutron dose (10^{16} cm^{-2})
30	14.5	2.9	86
100	4.3	0.85	24
200	2.1	0.42	10
300	1.4	0.28	7
500	0.85	0.17	4
1000	0.45	0.086	2

Dedicated irradiation facility – new ideas



Byambajav Munkhbat and Toru Obara

Conceptual design of a small nuclear reactor for large-diameter NTD-Si using short PWR fuel Assemblies

Journal of Nuclear Science and Technology, 2013
Volume 50, No. 1, 46–58,
http://dx.doi.org/10.1080/00223131.2013.750057

Question

Is it feasible to have a large volume of thermal neutrons outside the main irradiation volume ?