ROCHESTER INSTITUTE OF TECHNOLOGY
MICROELECTRONIC ENGINEERING

INTRODUCTION TO ION IMPLANTATION

Dr. Lynn Fuller, Dr. Renan Turkman
Dr Robert Pearson
Webpage: http://people.rit.edu/lffeee
Rochester Institute of Technology
82 Lomb Memorial Drive
Rochester, NY 14623-5604
Tel (585) 475-2035
Fax (585) 475-5041
Email: Lynn.Fuller@rit.edu
Department webpage: http://www.microe.rit.edu

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VARIAN 400 & 120-10 ION IMPLANTERS

Varian 120-10

Varian 400

VARIAN 350 D ION IMPLANTER (4" AND 6" WAFERS)

OUTLINE

- Principles of Ion Implantation
  - Generate a focused beam of ions to be implanted (B^+, P^+ or As^+)
  - Accelerate the ions
  - Scan the ion beam over the wafer
  - Implant dose
- Ion Implantation Equipment
  - Plasma source and ion extraction
  - Ion selection
  - Accelerating column
  - End station
  - Low and high (beam) current implanters

OUTLINE

- **Implanted Dopant Profiles**
  - **Dopant ion-substrate interactions**
  - **Post implant anneal**
  - **Dopant concentration profiles Implanted Dopant Profiles (continued)**
  - **Channeling**
  - **Implanting through thin film layers (e.g. oxide)**
  - **Masking against ion implants**

INTRODUCTION

Ion implant is used to put specific amounts of n-type and p-type dopants (Dose) into a semiconductor. The dose is accurately measured during implantation giving outstanding control and repeatability.

Specific regions can be implanted using a variety of masking materials including photoresist. Ion implantation is basically a low temperature process.

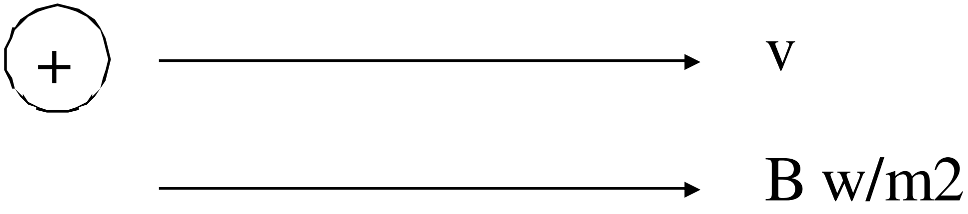
Ion implant can deliver lower doses than chemical doping (predeposit). Dose can be as low as 10^{11} /cm^2

In today's advanced integrated circuits ion implantation is used for all doping applications. (with a few exceptions)

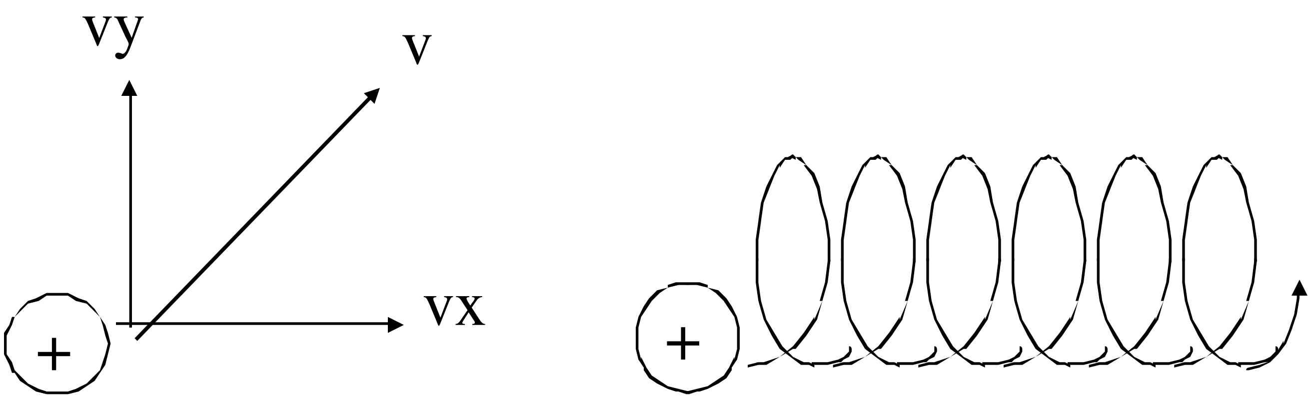
BASICS

$$\boxed{F = qE + q(v \times B)}$$

Example 1:



Example 2:



GENERATION OF A DOPANT GAS PLASMA

Source Gas Molecule + e $\longrightarrow$ Dopant Ion + (Other Atoms, Molecules and/or Radicals) + e + e

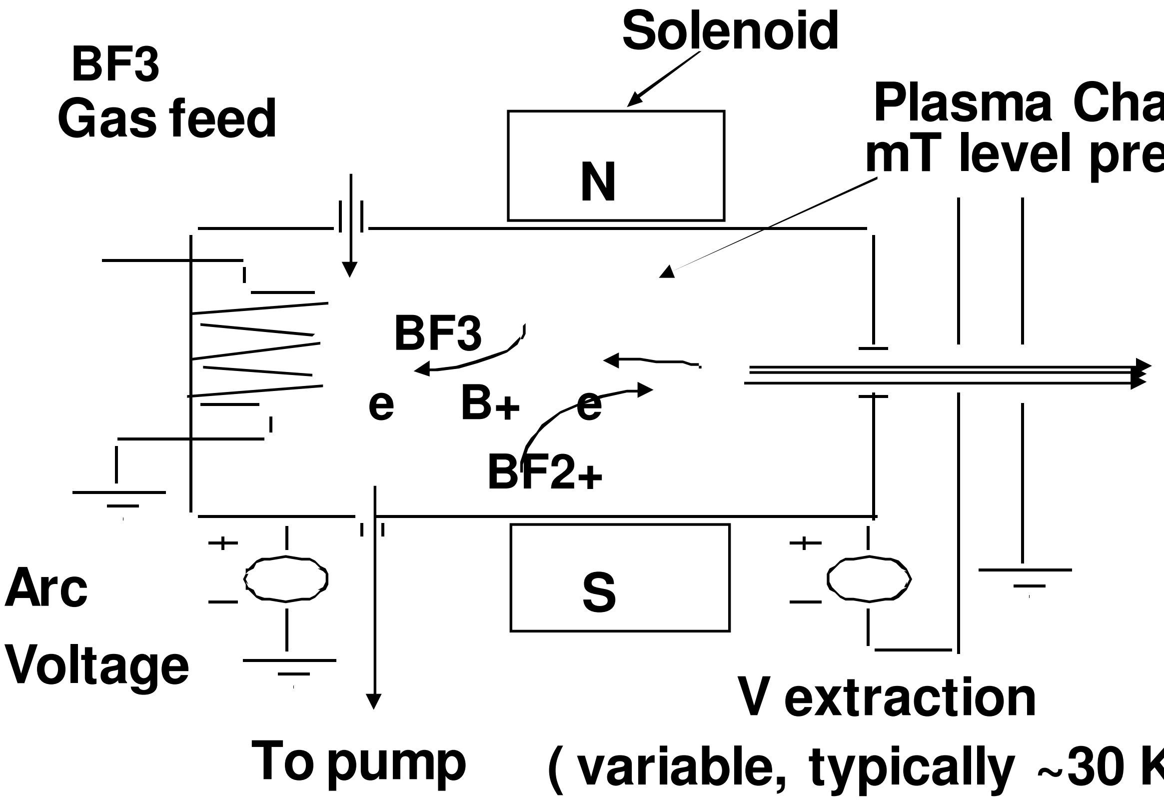
Example : Boron Trifluoride as B source

$BF_3 + e \longrightarrow B^+ + F_2 + F + e + e$

Other dissociative ionizations result in the generation of B^{10+},F^+, BF_2^+

The dopant ion sources commonly used in silicon processing are boron trifluoride BF_3, phosphine PH_3, arsenic pentafluoride AsF_5, arsine AsH_3 .

PLASMA SOURCE AND ION EXTRACTION



$$M v^2 / 2 = q V_{ext}$$

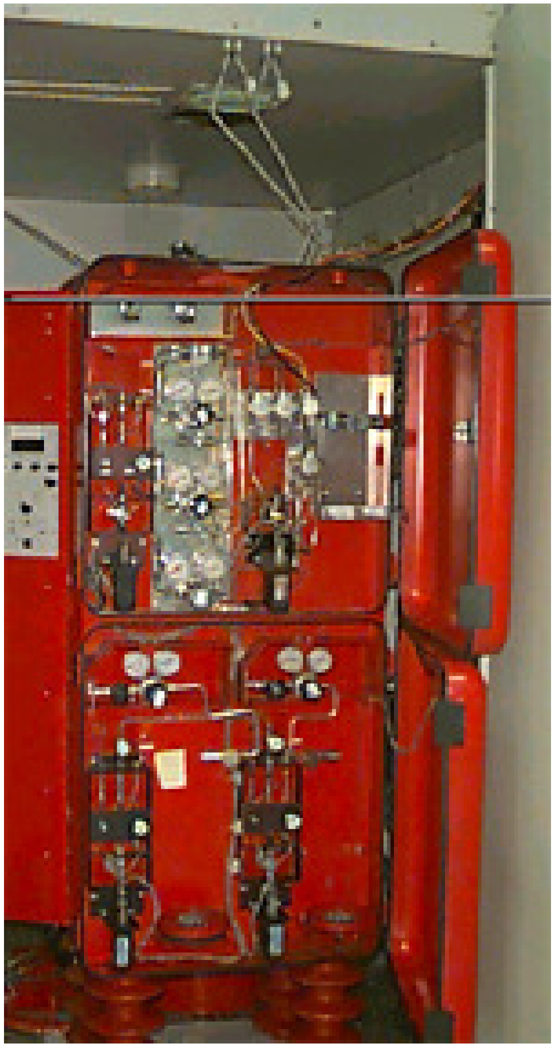
(positive) ions

$$v = \sqrt{\frac{2qV_{ext}}{m}}$$

$$v = \sqrt{\frac{(2)(1.6x10^{-19})(30{,}000)}{(11)(1.67x10^{-27})}} = 7.23x10^{5}\ m/s$$

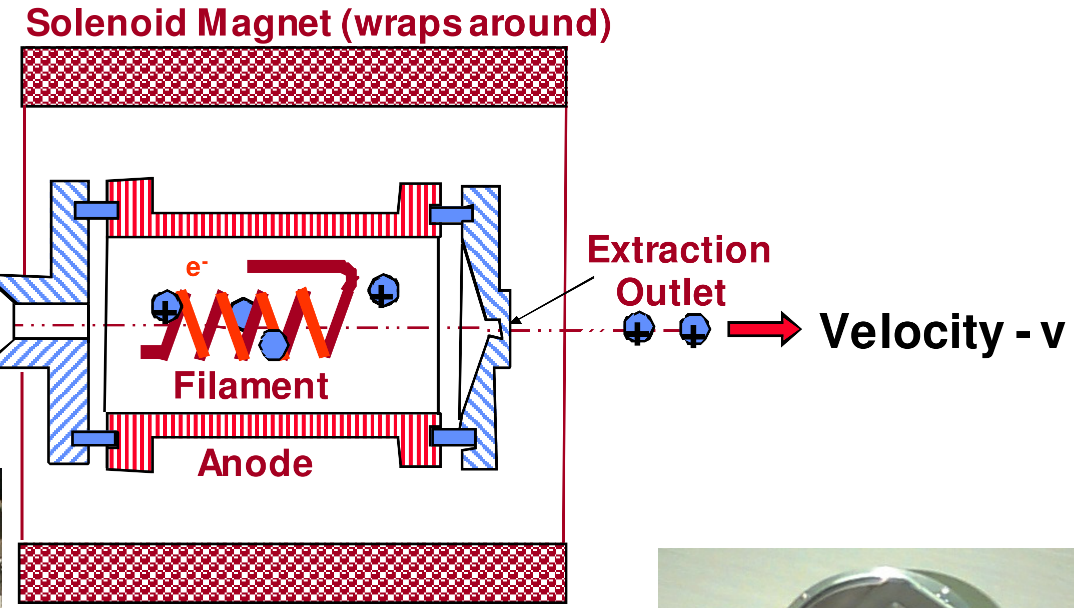
TYPICAL SOURCE SET UP

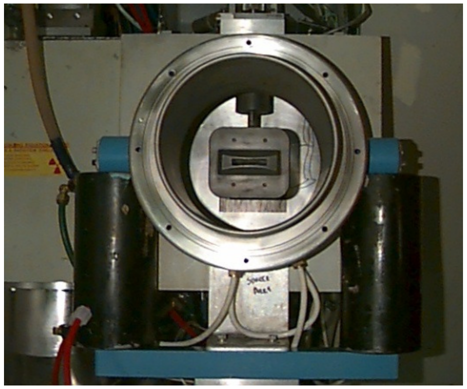
Pressure	30mT
Extraction Voltage	33 KV
Extraction Current	0.8 mA
Arc Voltage	2000 V
Arc Current	50 mA
Filament Current	150 A
Filament Voltage	20 V
Solenoid Current	3.0 A

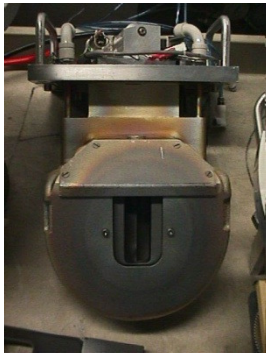


Source Cabinet for Varian 120-10

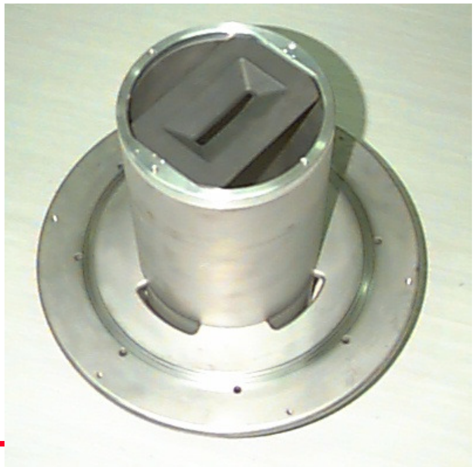
NIELSEN-TYPE GASEOUS SOURCE





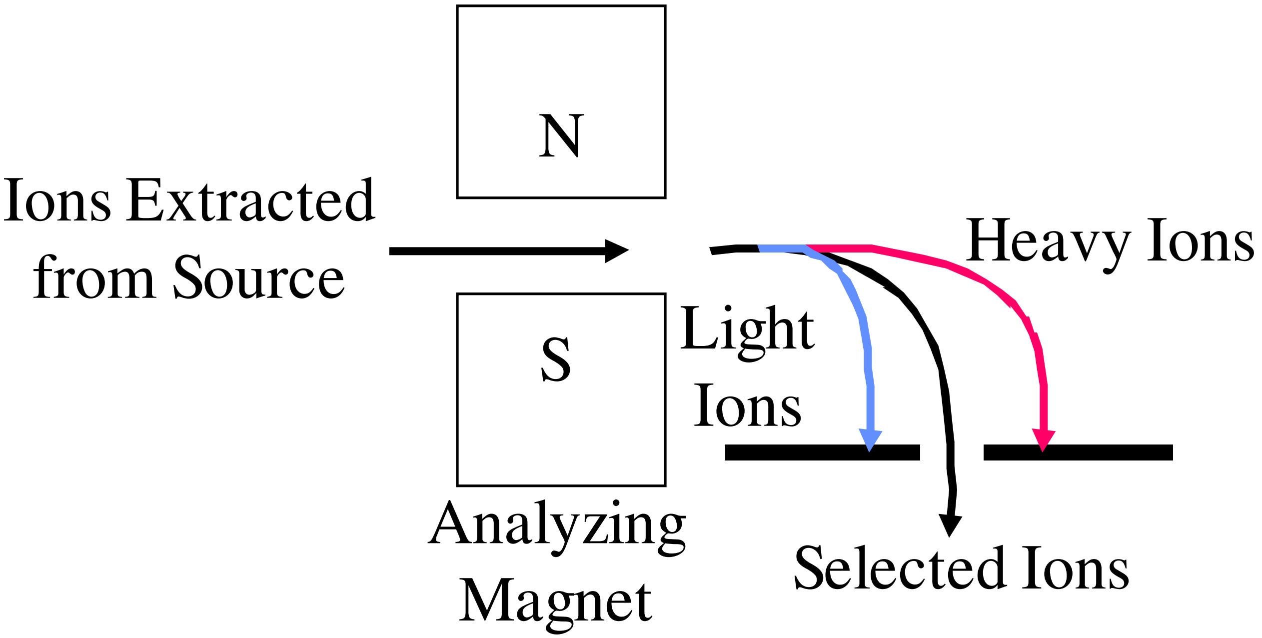


Electrons boil off the filament and ionize the gas. Solenoid make electrons follow a spiral path increasing ionization



SELECTION OF THE IONS TO BE IMPLANTED

The ions are extracted from the source and analyzed in a magnetic field. The Lorentz force makes the ions take a curved path with a radius of curvature that depends on the mass of each ionic species. By adjusting the magnetic field strength, only the selected ions will enter the accelerating column.



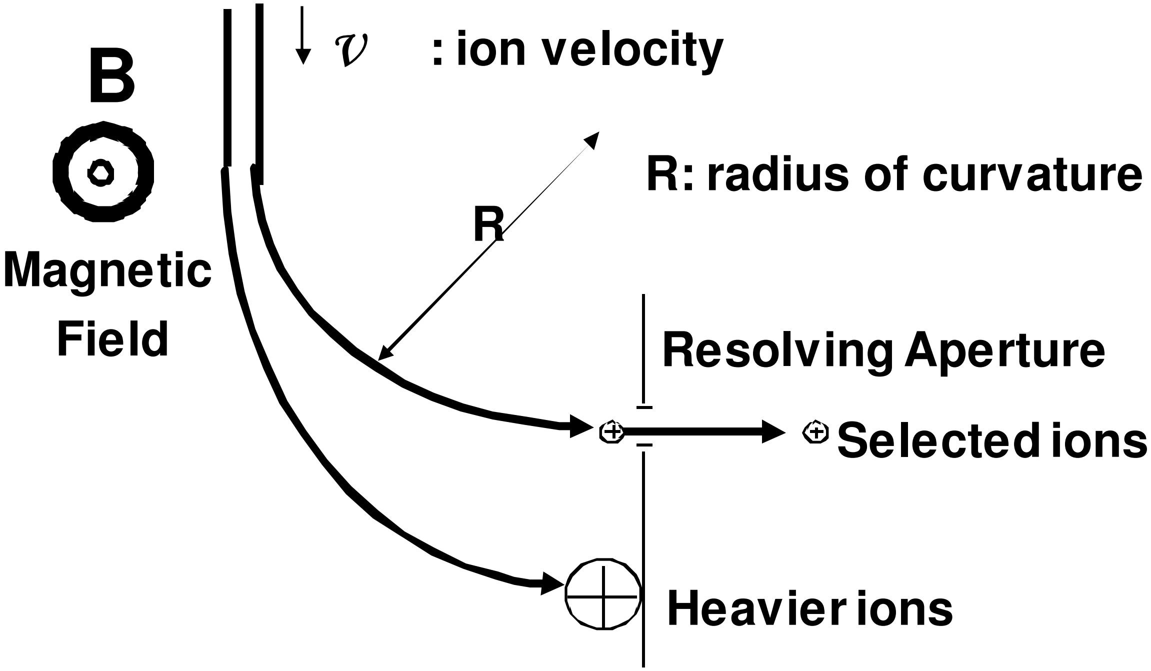
ION SELECTION - ANALYZING MAGNET

Lorentz Force = Centripetal force

$$q\,(\nu \times B) = M\,\nu^2 / R$$

$$R = M\,\nu / q\,B$$

$$\nu = \sqrt{\frac{2qV_{ext}}{m}}$$



Mass to charge ratio, M / q of the selected ions:

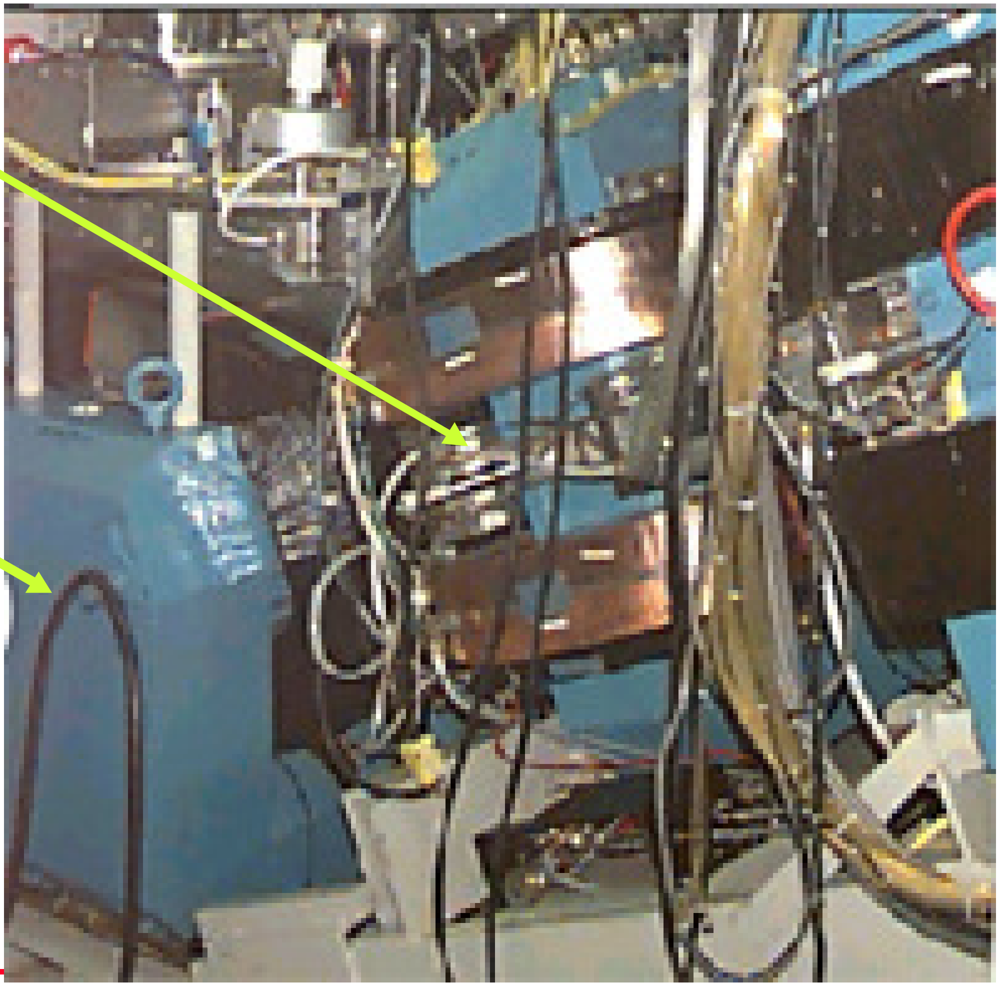
$$\boxed{M/q = R^2 B^2 / (2\,V_{ext})}$$

R is fixed, B and Vext are variable

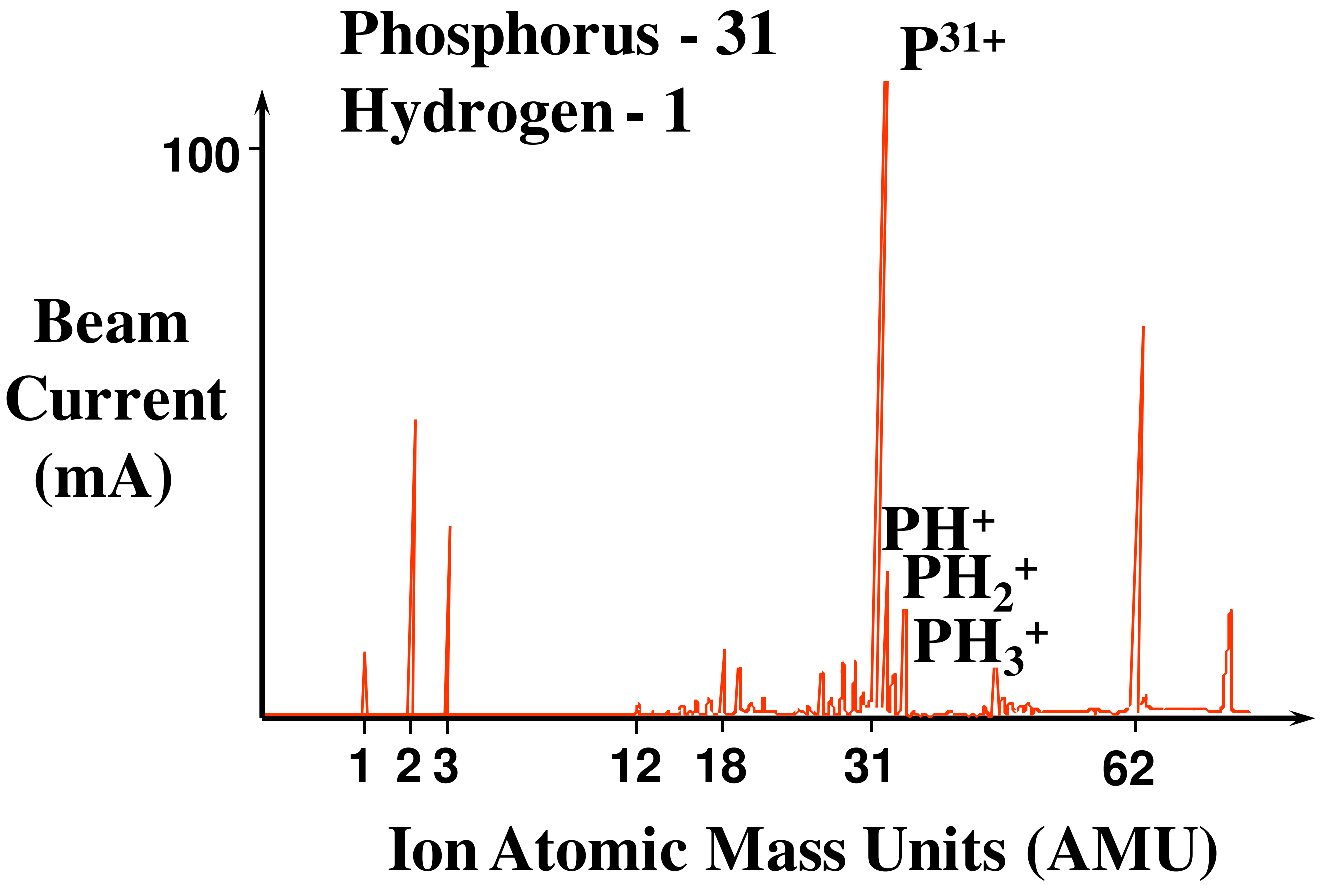
MAGNETIC SCAN COIL IN VARIAN 120-10

Scan Magnet to give X-scan

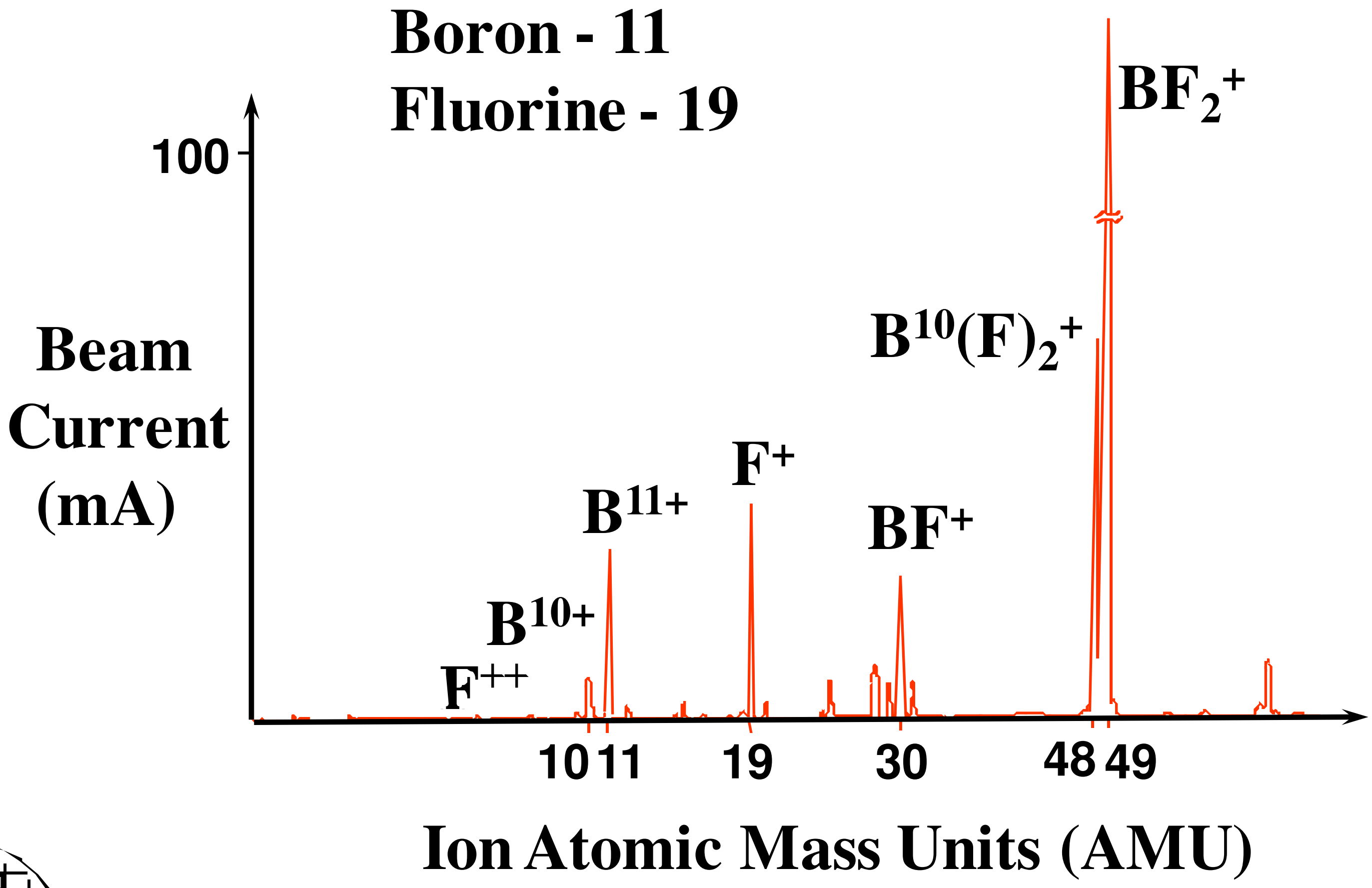
Analyzing Magnet for mass spectrometer (Ion Selection)



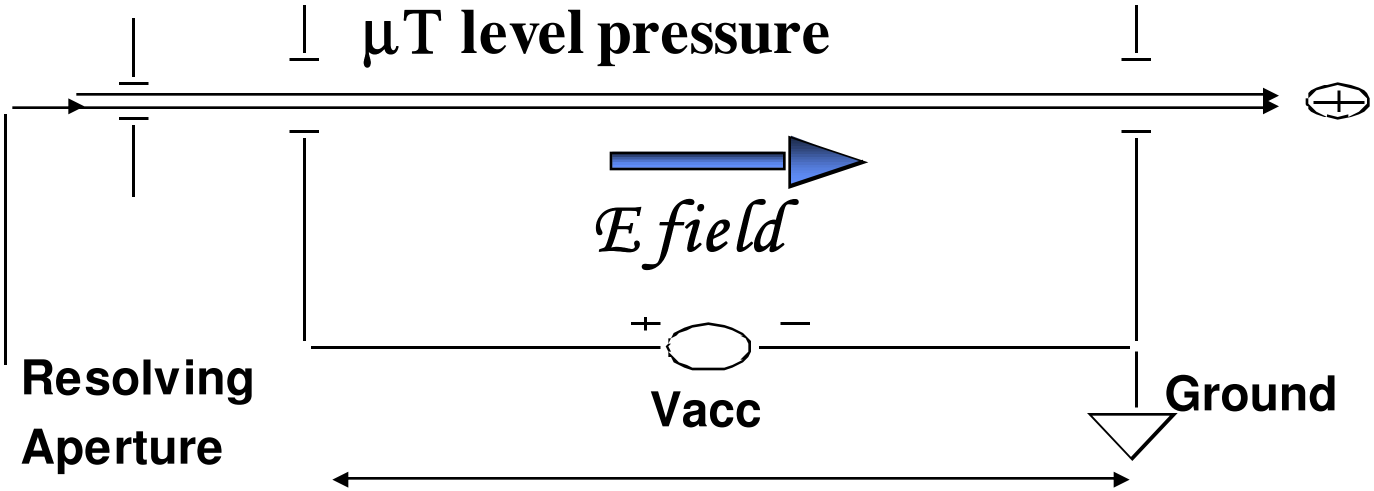
PH_3 GAS SPECTRUM



BF_3 GAS SPECTRUM



ACCELERATING COLUMN



Column length = 3 ‘

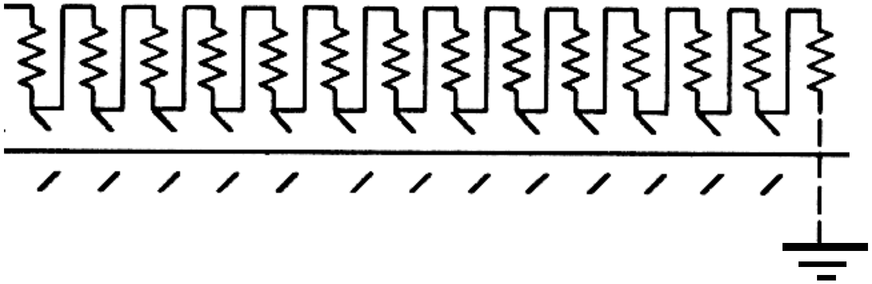
Final Kinetic Energy of the Ion = q (V_{ext} + V_{acc})

Example: V_{ext} = 30 KV V_{acc} = 70 KV

Energy of the Ion= E= 100 KeV

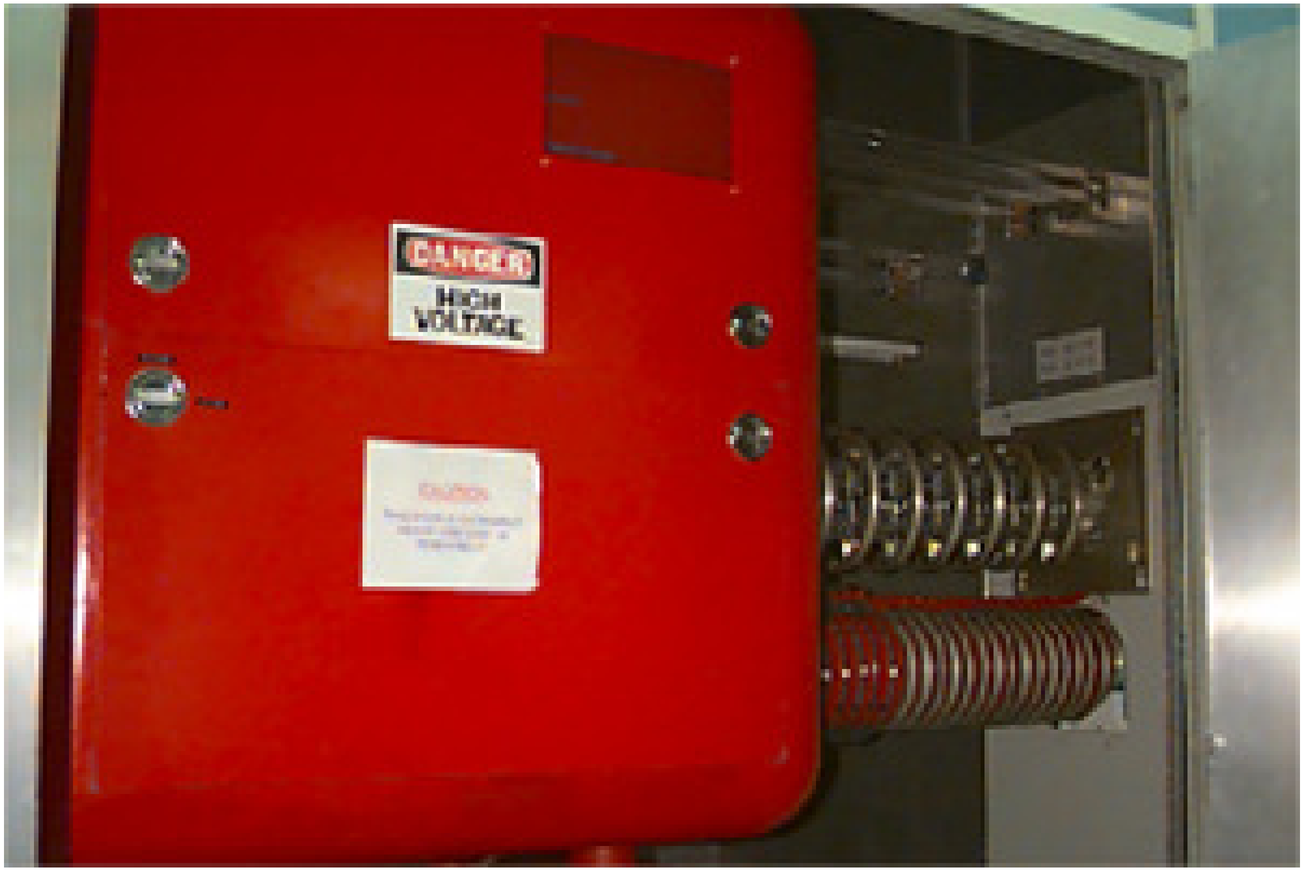
ACCELERATION OF THE IONS

An acceleration voltage is applied across the column giving the ions their final kinetic energy. This voltage should be adjustable.



This shows 14 equal acceleration plates. If the desired acceleration was 70KeV each section would contribute 5000 volts for example.

VARIAN 400 ACCELERATION HARDWARE



BF2 IMPLANTS

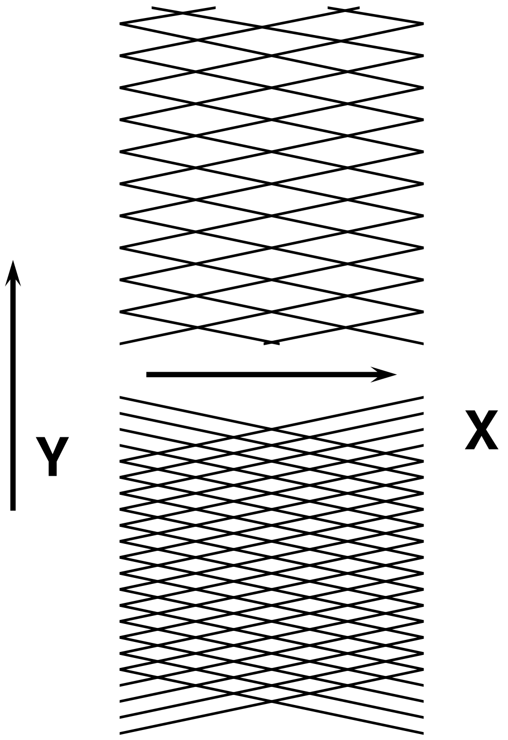
- Boron mass = 11
- Fluorine mass = 19
- BF2 mass = 49
- The energy divides by mass so 100 KeV BF2 is equivalent to 22.4 KeV B11 implant
- BF2 peak is larger than B11 peak giving more current and shorter time for large dose implants
- BF2 can give shallow implants
- BF2 reduces channeling (explained in following pages)

SCANNING THE BEAM

§ **Scanning of the beam**

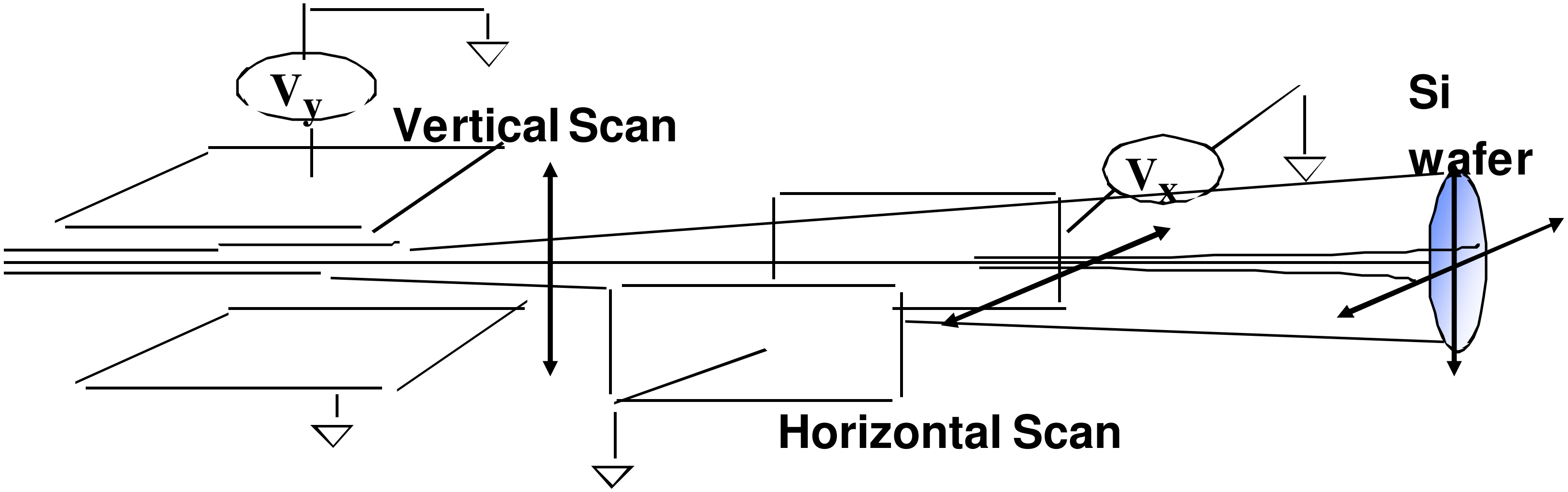
The focused ion beam is scanned over the wafer in a highly controlled manner in order to achieve uniform doping. Either the wafer or the beam could be stationary.

Scan Patterns



ELECTROSTATIC BEAM SCANNING

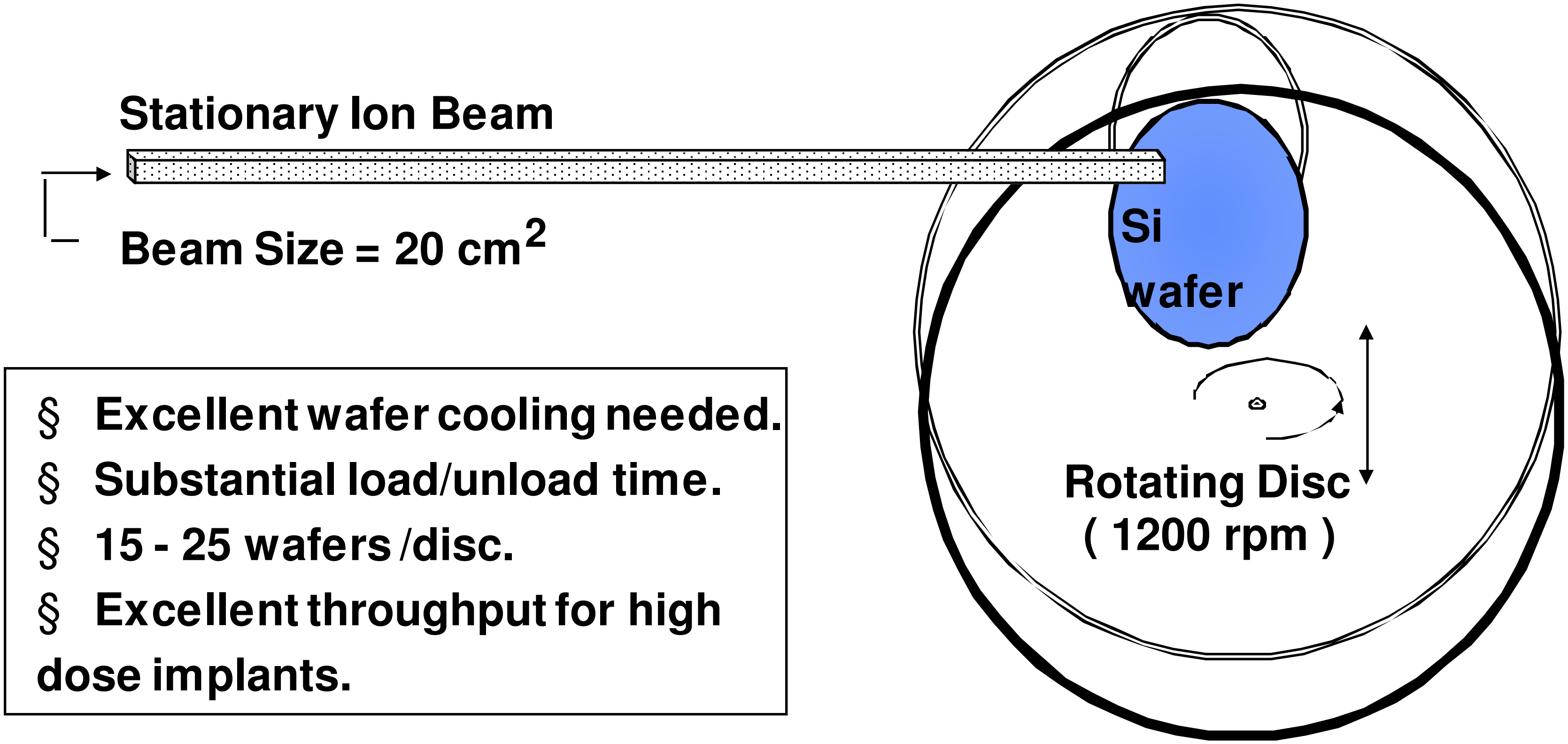
I) Electrostatic scanning (low/medium beam current implanters. I < 1mA)



This type of implanter is suitable for low dose implants. The beam current is adjusted to result in t=10 sec./wafer. With scan frequencies in the 100 Hz range, good implant uniformity is achieved with reasonable throughput.

MECHANICAL BEAM SCANNING

Mechanical Scanning (high beam current implanters. I > 1 mA)



Stationary Ion Beam

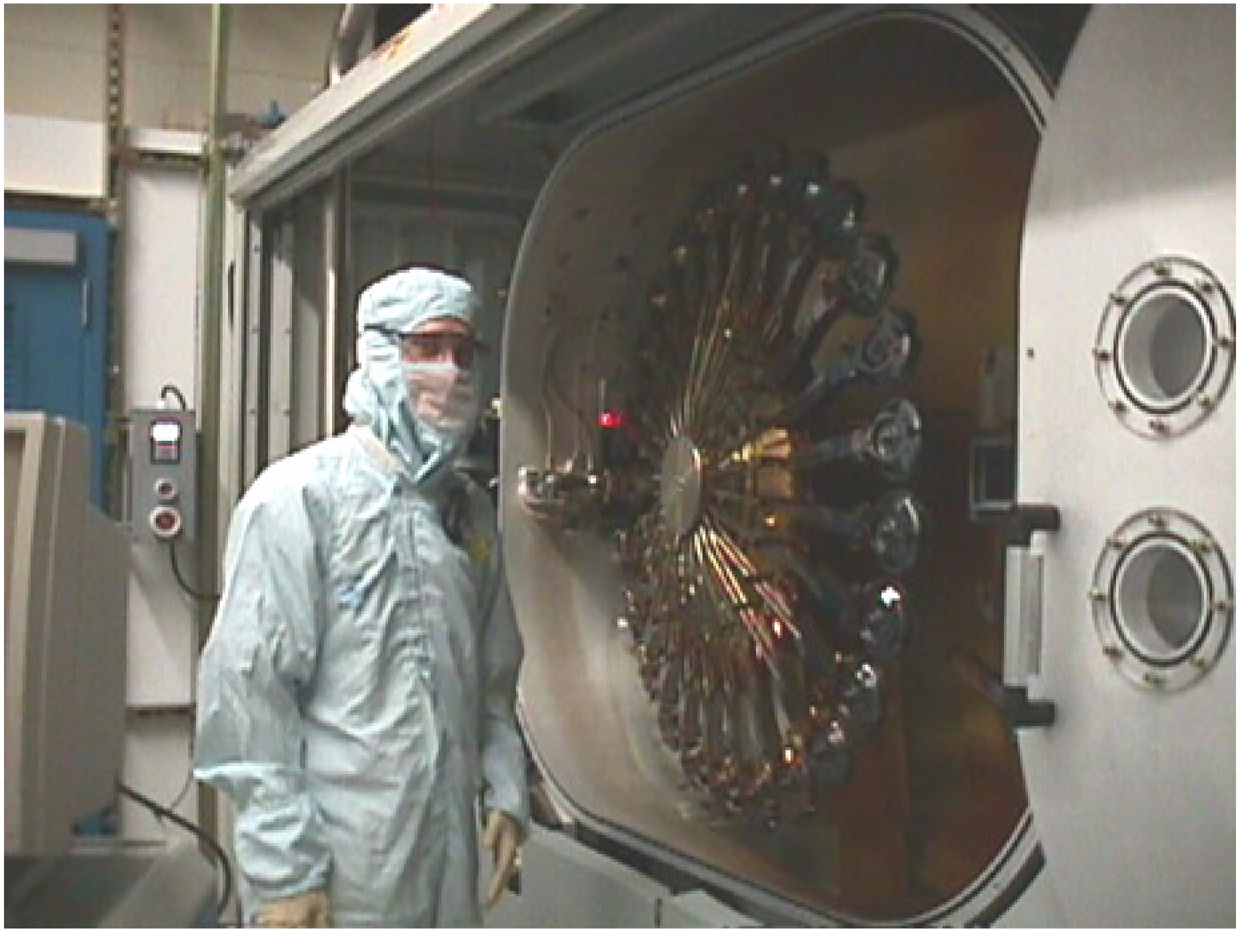
Beam Size = 20 cm^2

Si wafer

Rotating Disc (1200 rpm)

- **Excellent wafer cooling needed.**
- **Substantial load/unload time.**
- **15 - 25 wafers /disc.**
- **Excellent throughput for high dose implants.**

MECHANICAL SCAN END STATION



IMPLANT DOSE

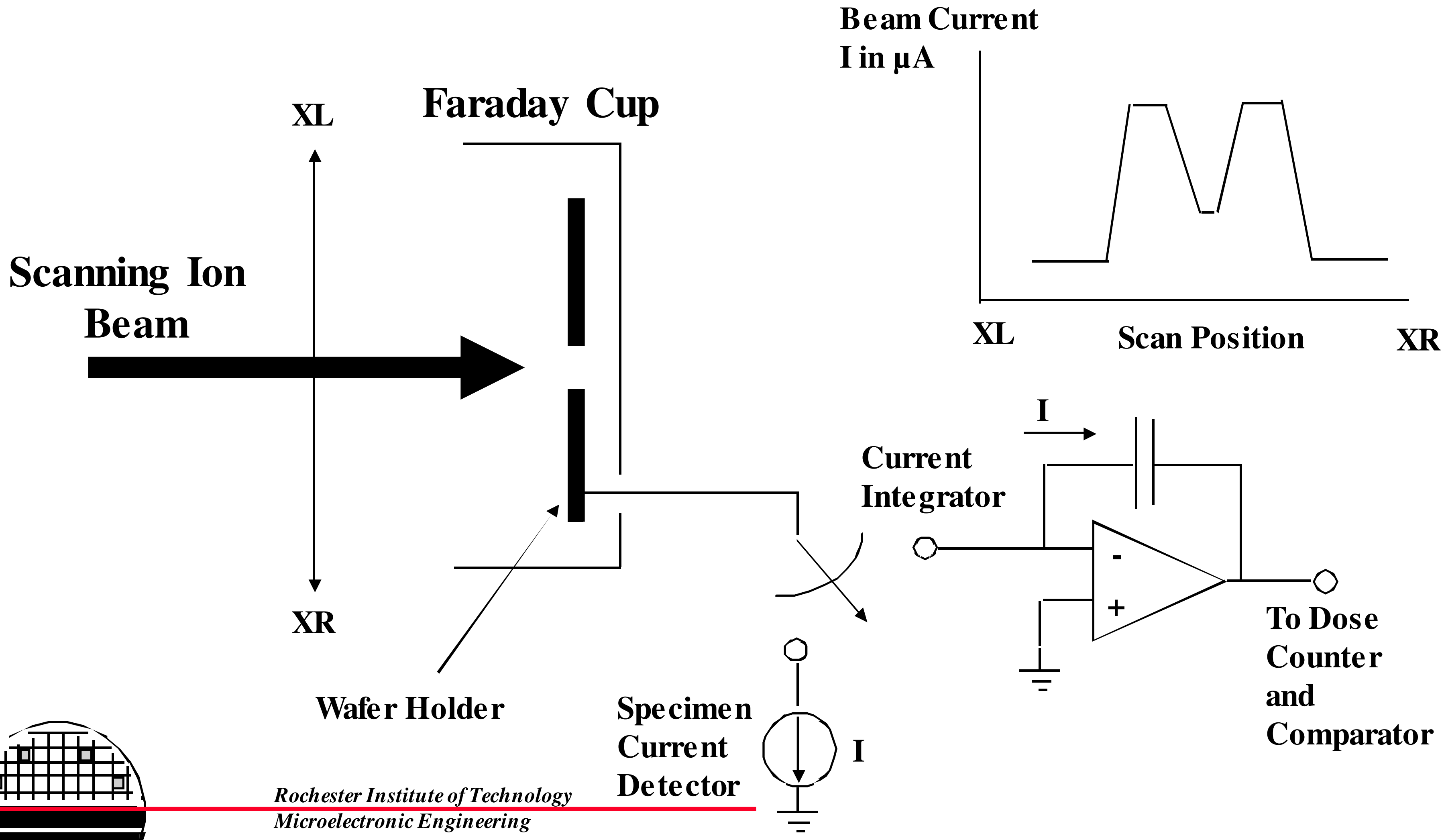
The implant dose ϕ is the number of ions implanted per unit area (cm2) of the wafer.

If a beam current I is scanned for a time t , the total implanted charge $Q = (I \times t)$.

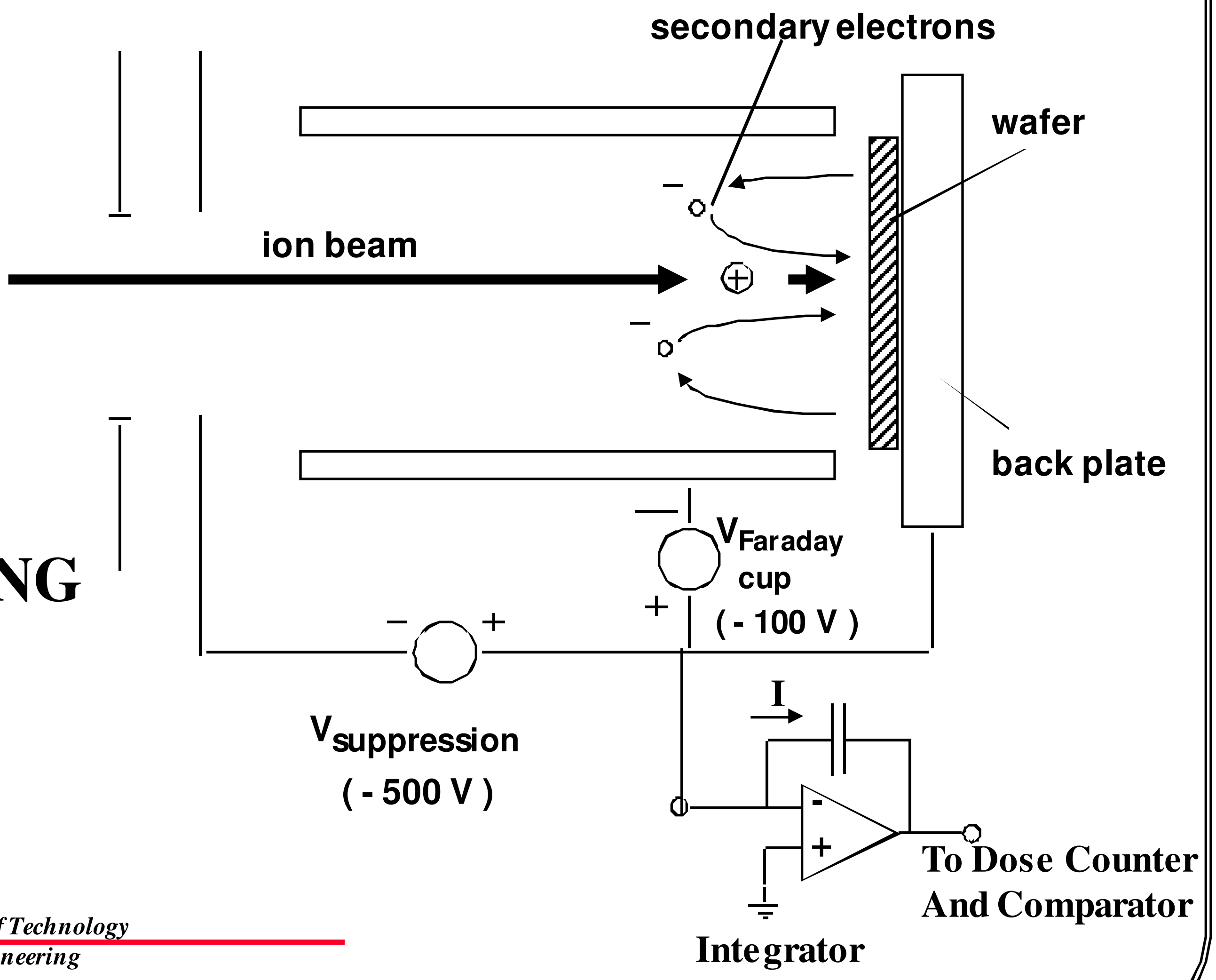
For a dose ϕ ,the total number of implanted ions is (Scan area $A_s \times \phi$). Since each ion is singly positively charged, this corresponds to a total charge of $(q \times A_s \times \phi)$.

$$Q = It = q\, A_s\, \phi \Rightarrow \boxed{\phi = \text{Dose} = I\, t / (q\, A_s)\ \text{ions/cm}^2}$$

ION IMPLANT BEAM CURRENT SET UP



END STATION DOSE MEASUREMENT



$$\int I dt = q = A_s\, q\, \phi$$

DOSE MONITORING

Rochester Institute of Technology
Microelectronic Engineering

VARIAN 120-10 END STATION

COMPLETE SYSTEM

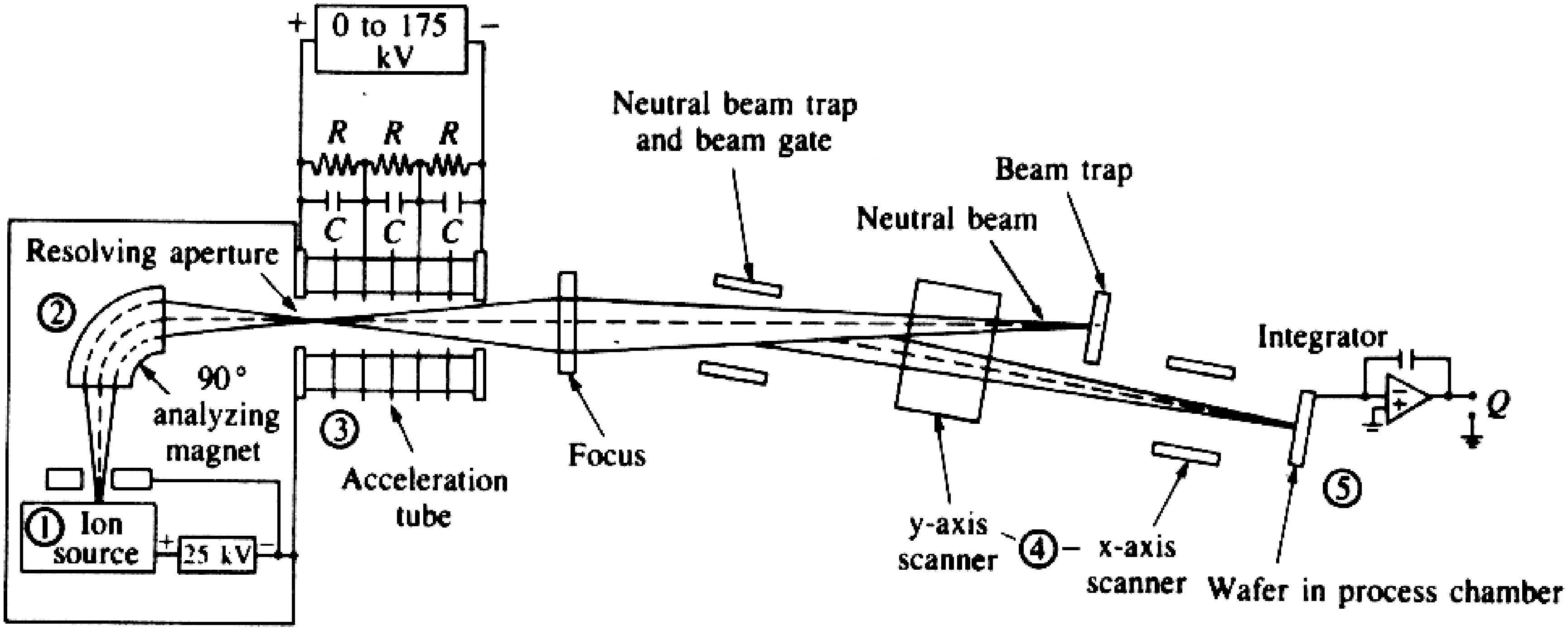


Fig. 5.1 Schematic drawing of a typical ion implanter showing (1) ion source, (2) mass spectrometer, (3) high-voltage accelerator column, (4) *x*- and *y*-axis deflection system, and (5) target chamber.

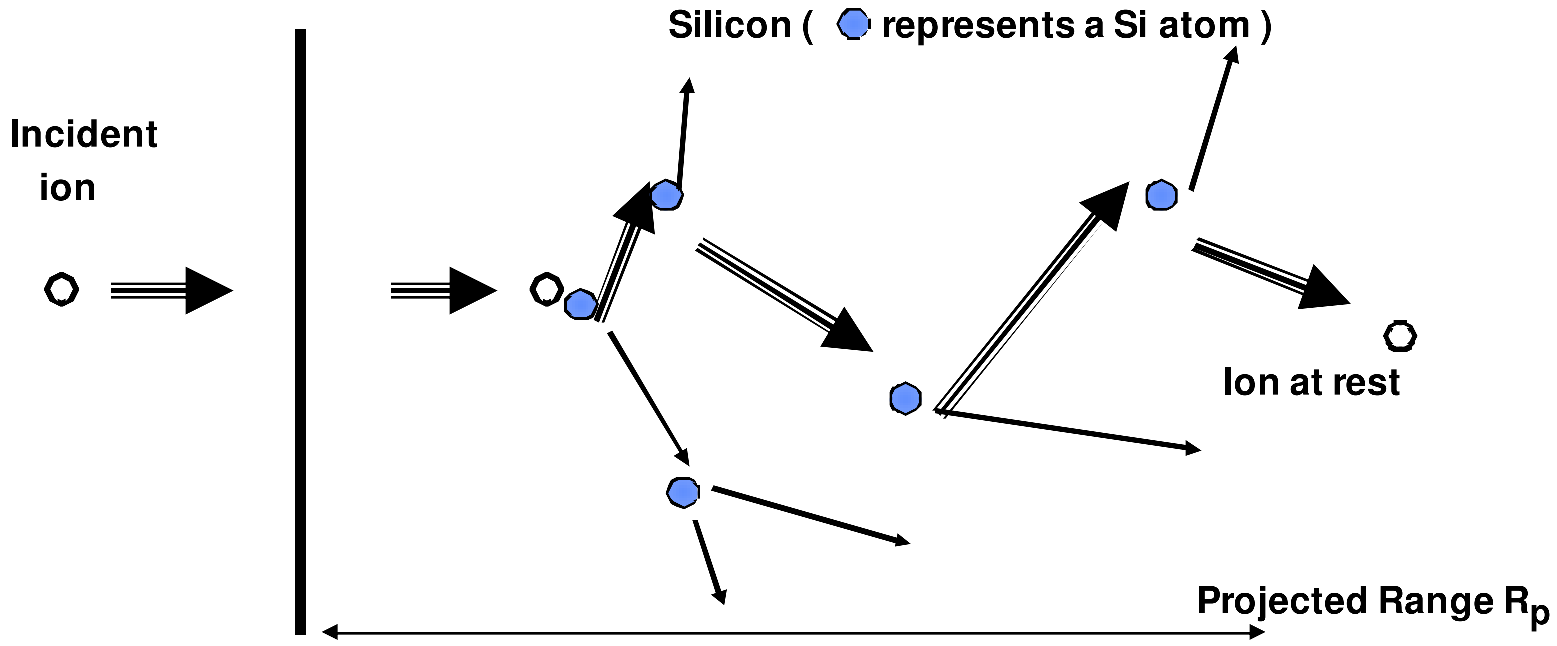
DOPANT ION-SUBSTRATE INTERACTIONS

Upon entering the substrate, the ion slows down due to **nuclear** and **electronic** stopping.

Nuclear stopping :

Nuclear stopping is due to the energy transfer from the ion to Si nuclei. The interaction may be strong enough to displace the Si atom from its site (only 15 eV needed to displace one Si atom). The displaced Si atom may even have enough kinetic energy to displace several other Si atoms. Arsenic and Phosphorous ions lose their energy mostly by nuclear stopping. They cause substantial Si crystal damage when the implant dose exceeds 5E13/cm^2.

DOPANT ION-SUBSTRATE INTERACTIONS



Electronic stopping is due to the energy transfer from the ion to the electrons of the host Si crystal. Boron ions lose their energy mostly by electronic stopping. Electronic stopping does not cause crystal damage.

POST IMPLANT ANNEAL

The **damaged crystal needs to be restored**. This is typically achieved by 900 C, 30 min. furnace anneals or 1150 C, 30 sec. rapid thermal anneals.

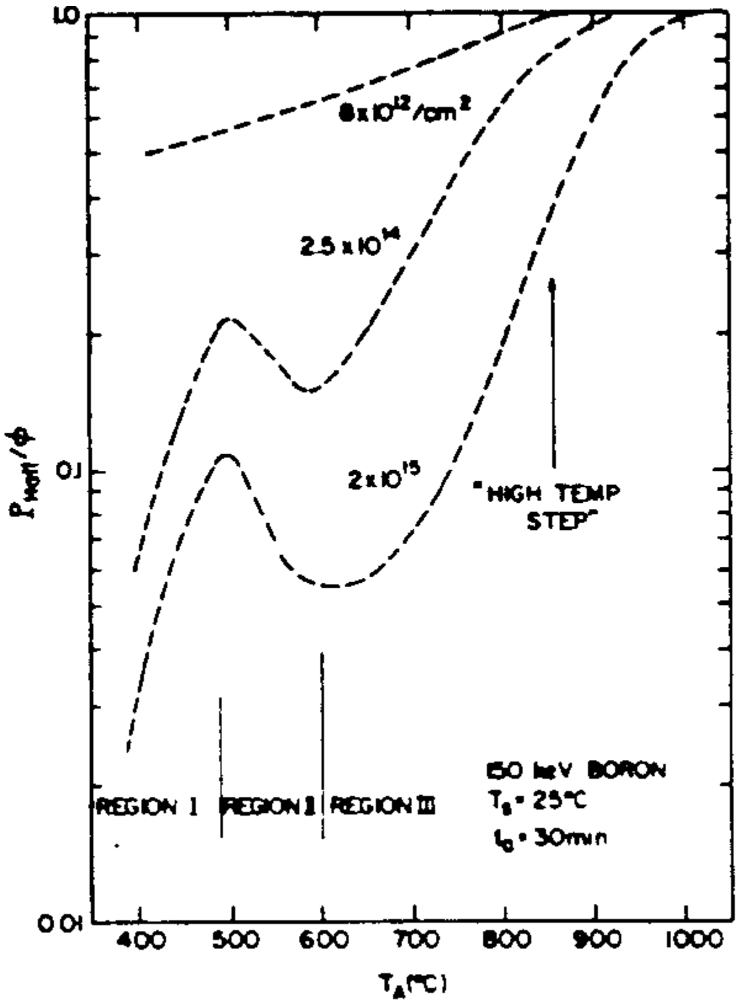
The interstitial dopant ions become substitutional, thus donating carriers. The interstitial (displaced) silicon atoms become substitutional ,thus removing the defects that trap carriers and/or affect their mobility.

During the post implant anneal, dopant ions diffuse deeper into silicon. This must be minimized to maintain shallow junctions.

ISOCHRONAL ANNEALING OF BORON

P_{Hall}

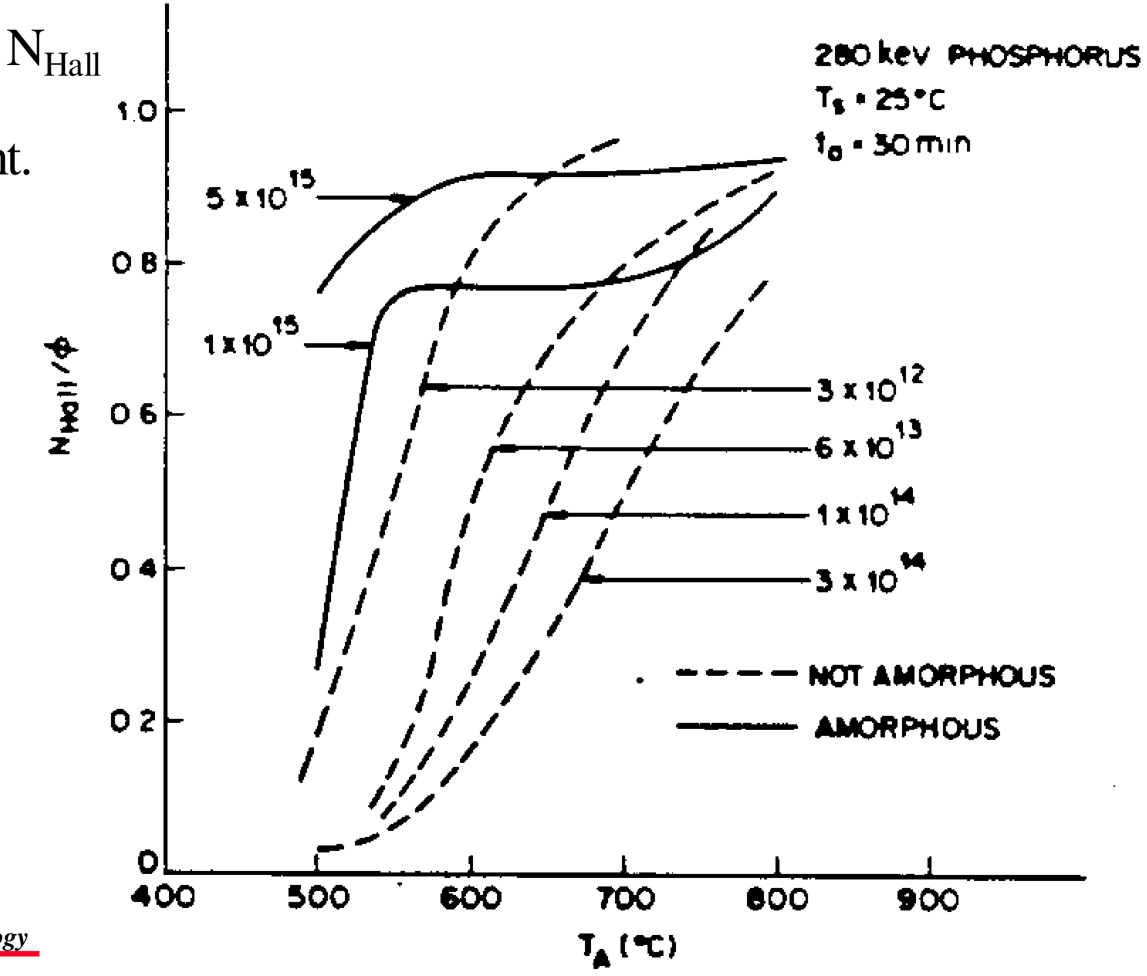
P_{hall} is the free hole content (holes/cm2) determined by Hall measurements



Trend: higher the dose, the more disorder, thus the higher the final temperature required for full activation

ISOCHRONAL ANNEALING OF PHOSPHOROUS

N_{Hall} is the free electron content. Note that heavy dose Phosphorous implants can be annealed easier than the lesser dose implants



ION IMPLANT EQUATIONS

Gaussian Implant Profile

$$N(x) = \frac{N'}{\sqrt{2\pi}\;\Delta Rp} \exp\left[\frac{-(X-Rp)^2}{2\Delta Rp^2}\right]$$

$$\left.\begin{array}{l} Rp = \text{Range} \\ \Delta Rp = \text{Straggle} \end{array}\right\} \text{From Curves}$$

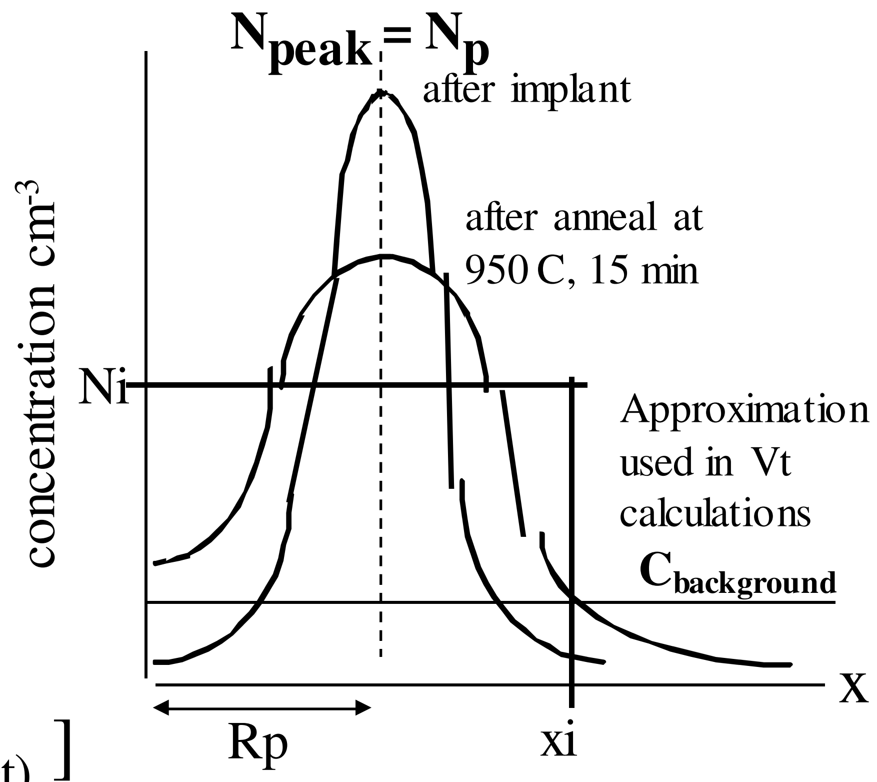
$$N' = \text{Dose} = \int \frac{I}{mqA}\,dt$$

After Anneal

$$N(x) = \frac{N'}{\sqrt{2\pi}\;\sqrt{\Delta Rp^2 + 2Dt}} \exp\left[\frac{-(X-Rp)^2}{2(\Delta Rp^2+Dt)}\right]$$

where D is diffusion constant at the anneal temperature

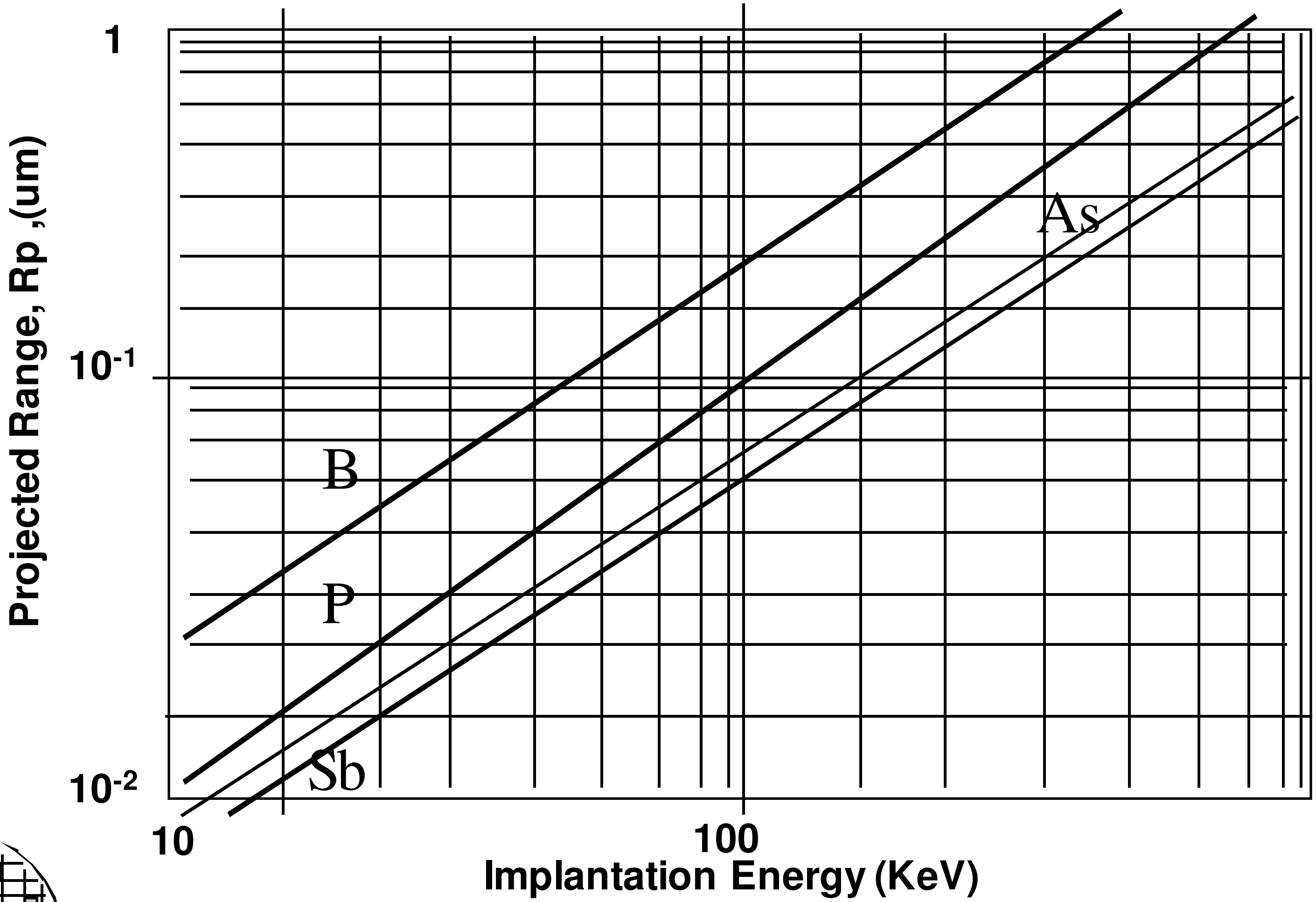
t is time of anneal



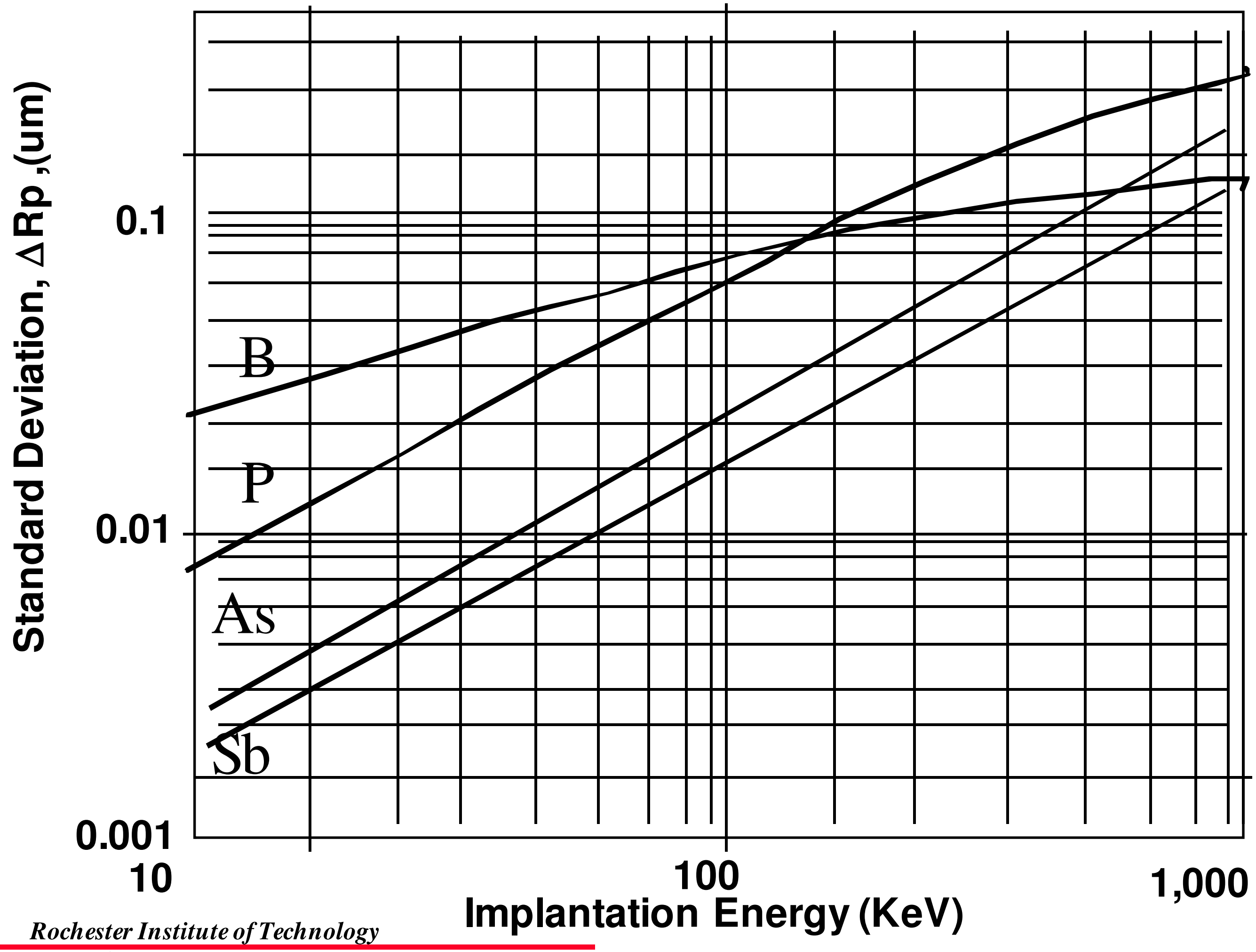
Approximation

$N' = Ni\ xi$

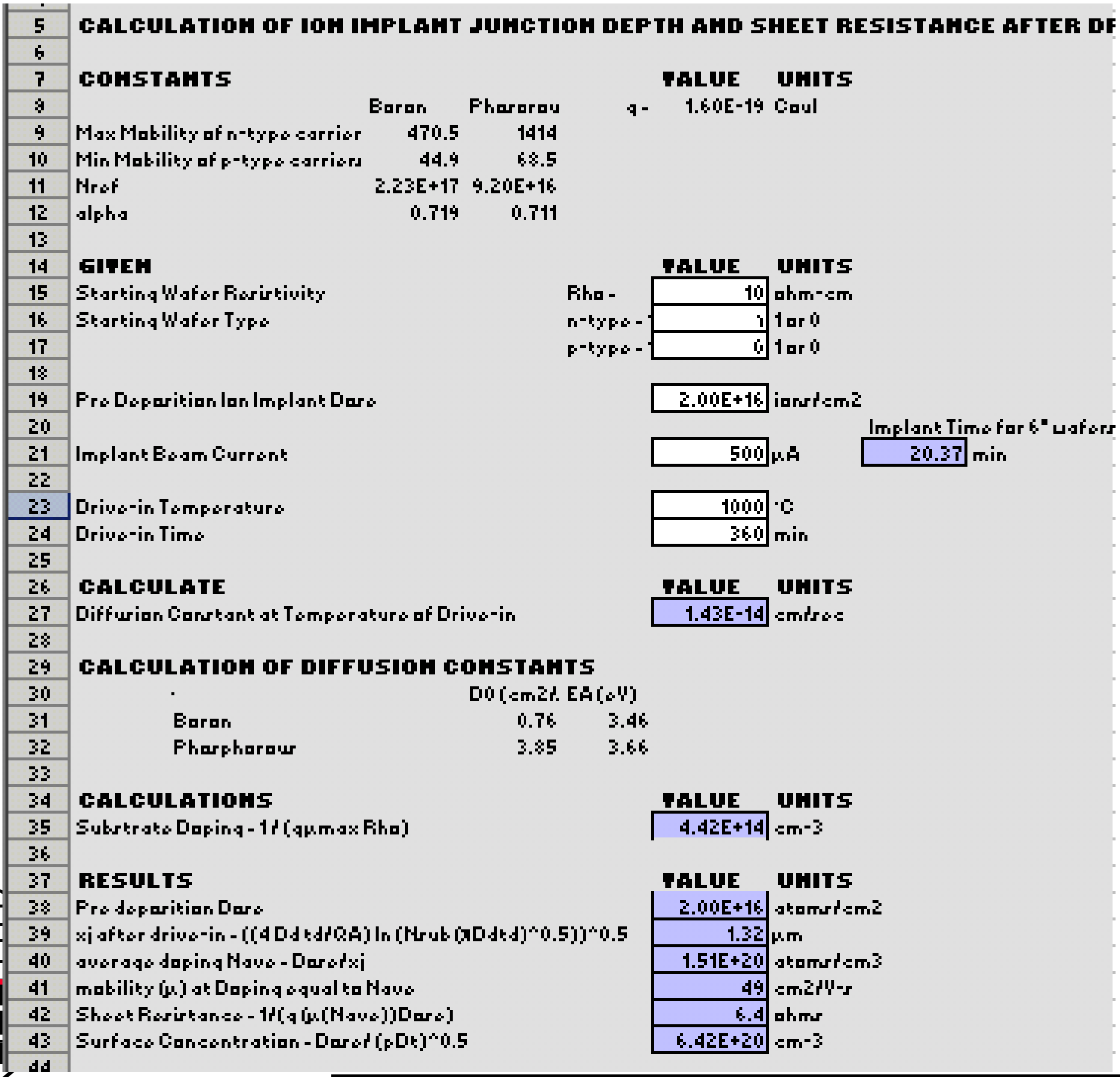
ION IMPLANT RANGE



ION IMPLANT STANDARD DEVIATION



CALCULATIONS



5	**CALCULATION OF ION IMPLANT JUNCTION DEPTH AND SHEET RESISTANCE AFTER D**						
6							
7	**CONSTANTS**				**VALUE**	**UNITS**	
8		Boron	Phosphorus	q =	1.60E-19	Coul	
9	Max Mobility of n-type carrier	470.5	1414				
10	Min Mobility of p-type carriers	44.9	68.5				
11	Nref	2.23E+17	9.20E+16				
12	alpha	0.719	0.711				
13							
14	**GIVEN**				**VALUE**	**UNITS**	
15	Starting Wafer Resistivity			Rho =	10	ohm-cm	
16	Starting Wafer Type			n-type = 1	1	1 or 0	
17				p-type = 1	0	1 or 0	
18							
19	Pre Deposition Ion Implant Dose				2.00E+16	ions/cm2	
20							Implant Time for 6" wafers
21	Implant Beam Current				500	µA	20.37 min
22							
23	Drive-in Temperature				1000	°C	
24	Drive-in Time				360	min	
25							
26	**CALCULATE**				**VALUE**	**UNITS**	
27	Diffusion Constant at Temperature of Drive-in				1.43E-14	cm/sec	
28							
29	**CALCULATION OF DIFFUSION CONSTANTS**						
30	.		D0 (cm2/	EA (eV)			
31	Boron		0.76	3.46			
32	Phosphorous		3.85	3.66			
33							
34	**CALCULATIONS**				**VALUE**	**UNITS**	
35	Substrate Doping = 1/(qµmax Rho)				4.42E+14	cm-3	
36							
37	**RESULTS**				**VALUE**	**UNITS**	
38	Pre deposition Dose				2.00E+16	atoms/cm2	
39	xj after drive-in = ((4 Dd td/QA) ln (Nsub (πDdtd)^0.5))^0.5				1.32	µm	
40	average doping Nave = Dose/xj				1.51E+20	atoms/cm3	
41	mobility (µ) at Doping equal to Nave				49	cm2/V-s	
42	Sheet Resistance = 1/(q (µ(Nave))Dose)				6.4	ohms	
43	Surface Concentration = Dose/ (pDt)^0.5				6.42E+20	cm-3	
44							

Using the equations on the previous pages:

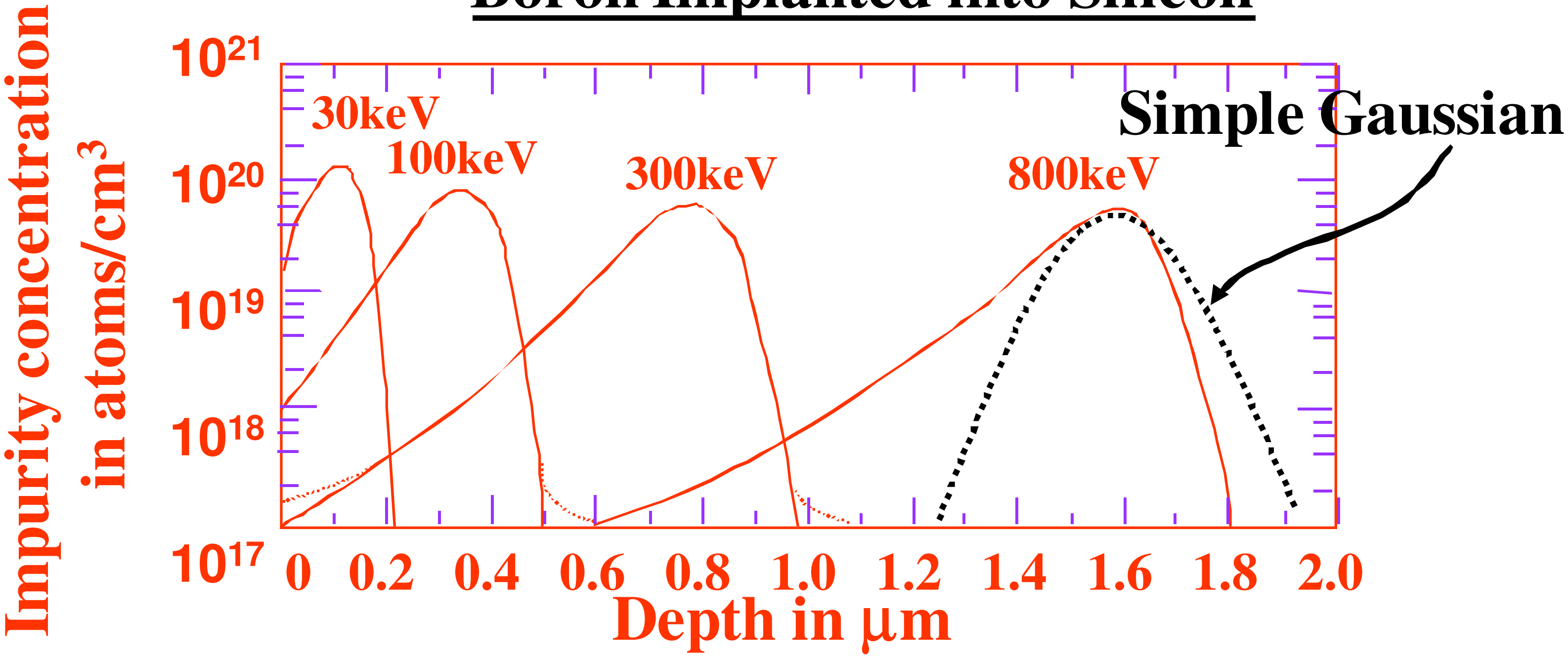
Find:

- Xj
- sheet Rho
- implant time
- surface conc.
- average doping

ACTUAL PROFILES ARE NOT GAUSSIAN

- **Light ions such as boron, are more effectively scattered backwards**
  - ❖ **more ions to come to rest on the surface-side of Rp**
- **Heavy Ions, such as Arsenic, scatter more in forward direction**
  - ❖ **the amount of dopant on the deeper side will be higher.**

Boron Implanted into Silicon



VT ADJUST IMPLANT

Assume that the total implant is shallow (within W_{dmax})

$$\boxed{+/- \Delta Vt = q\ Dose^*/Cox'}$$

where Dose* is the dose that is added to the Si

Cox' is gate oxide capacitance/cm^2

$Cox' = \varepsilon o \varepsilon r / Xox$

Boron gives + shift

Phosphorous gives - shift

Example: To shift +1.0 volts implant Boron through 1000 Å kooi oxide at an energy to place the peak of the implant at the oxide/silicon interface. Let Xox= 200 Å. Dose = ΔVt Cox'/q

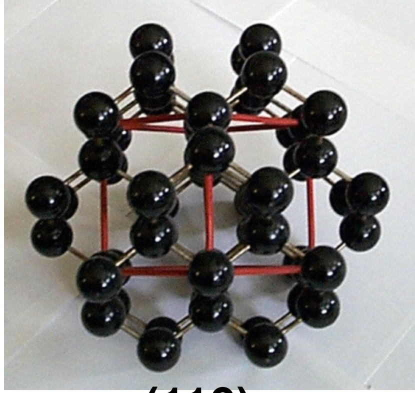
$$=(1.0)(3.9)(8.85E-14)/(1.6E-19)(200E-8)=1.08E12\ ions/cm^2$$

but multiply by 2 since ½ goes into silicon and ½ in Kooi oxide

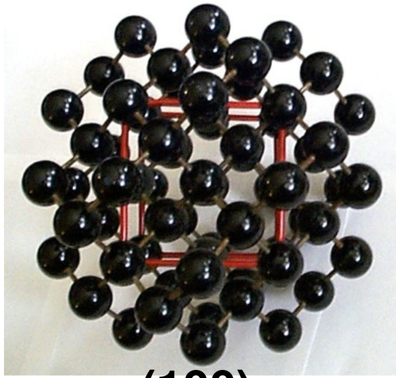
so dose setting on the implanter is 2.16E12 ions/cm^2

CHANNELING

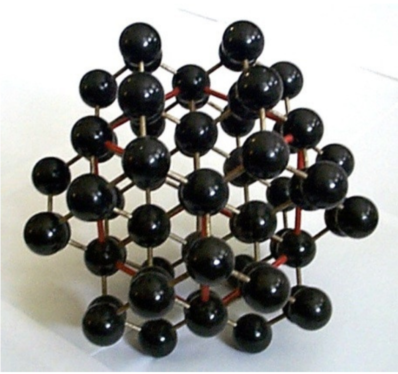
§ Origin : the crystalline nature of the host substrate



(110)

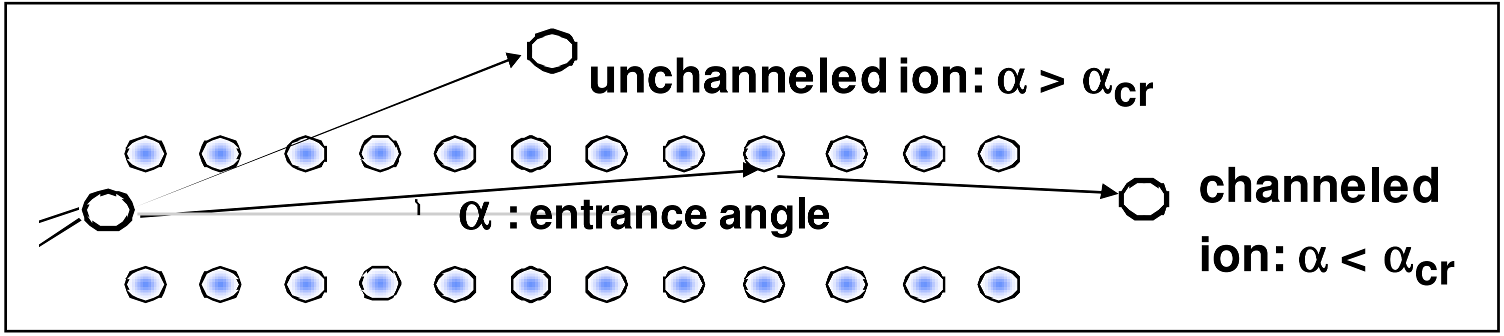


(100)



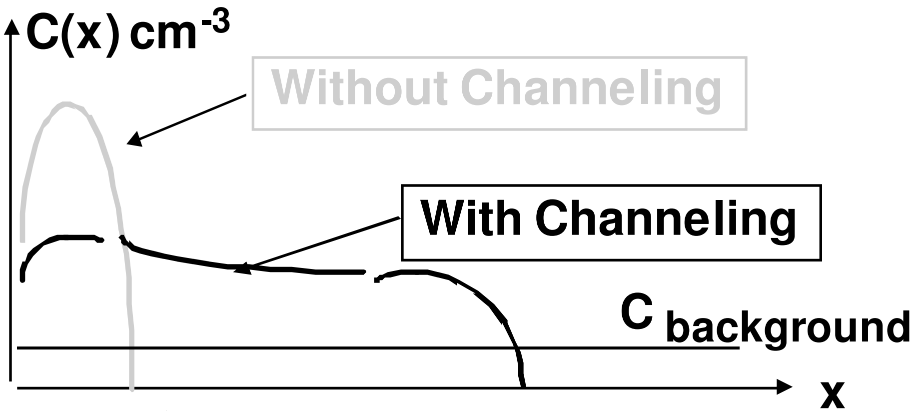
(111)

Relative degree of openness of the silicon crystal for ions moving in <111>, <100> and <110> directions



Channeling process

CHANNELING ION PROFILES



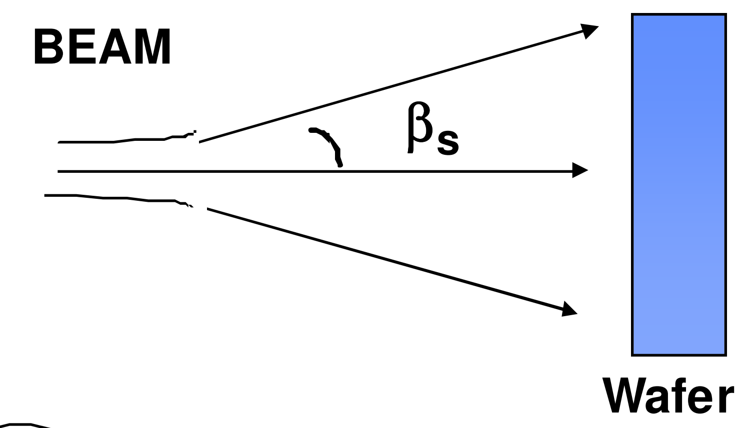
The implanted dose $\int C(x)\,dx$ is about the same with or without channeling. But μ along the channeled profile is higher than μ along the unchanneled profile. Since the sheet resistance R_s is defined as:

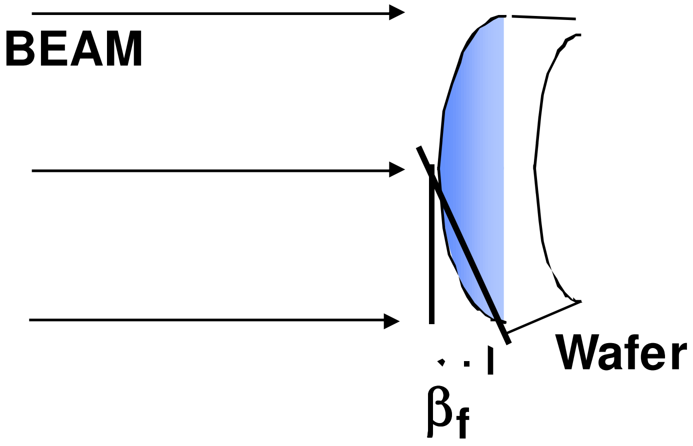
$$R_s = [\int q\,\mu(x)\,C(x)dx\,]^{-1} = [q\,\mu \int C(x)dx]^{-1}$$

(where μ is the average effective mobility) R_s is smaller in regions where channeling occurs.

CHANNELING IS NON UNIFORM ACROSS THE WAFER

Due to beam scan angle β_s and/or the wafer flex angle β_f, the entrance angle of ions varies across the wafer. The resulting channeling variations cause the sheet resistance to vary across the wafer. These R_s variations can be as much as 25 % across a wafer. As the extent of **local channeling is difficult to control, channeling must be prevented**.





PREVENTING CHANNELING

Channeling does not occur if there is significant implant damage that turns the implanted layer into an amorphous one. **Heavy ions like P^{31} and As^{75} at large doses do not show channeling.**

Light ions and/or low dose implants are prone to channeling. In such instances, channeling can be prevented by:

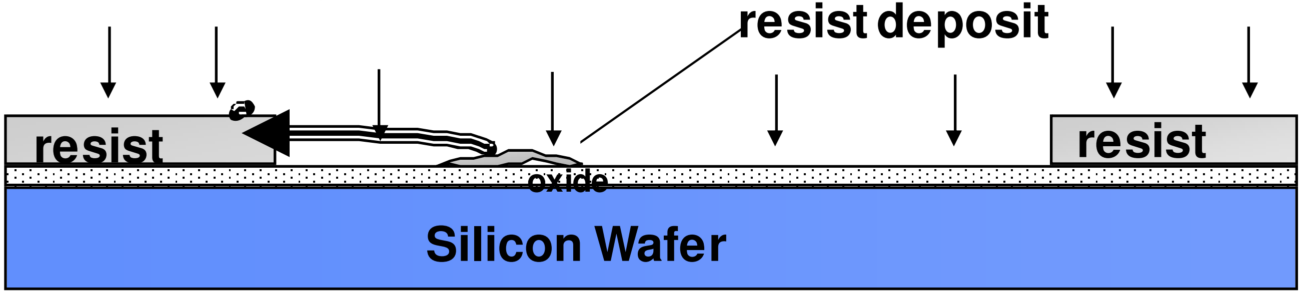
1) **Implanting through a thin amorphous layer (e.g. oxide).**
2) Tilting and twisting the wafer to close crystal openness as seen by the ion beam.
3) Implanting heavy, but electrically inactive species like Si or Ar prior to the actual dopant implant. The pre-implant implant turns the wafer surface into an amorphous layer.

CHANNELING

Implanting Through Thin Films

In addition to channeling prevention, implanting through a thin film layer (e.g. few 100 A of SiO_2) offers the following advantages:

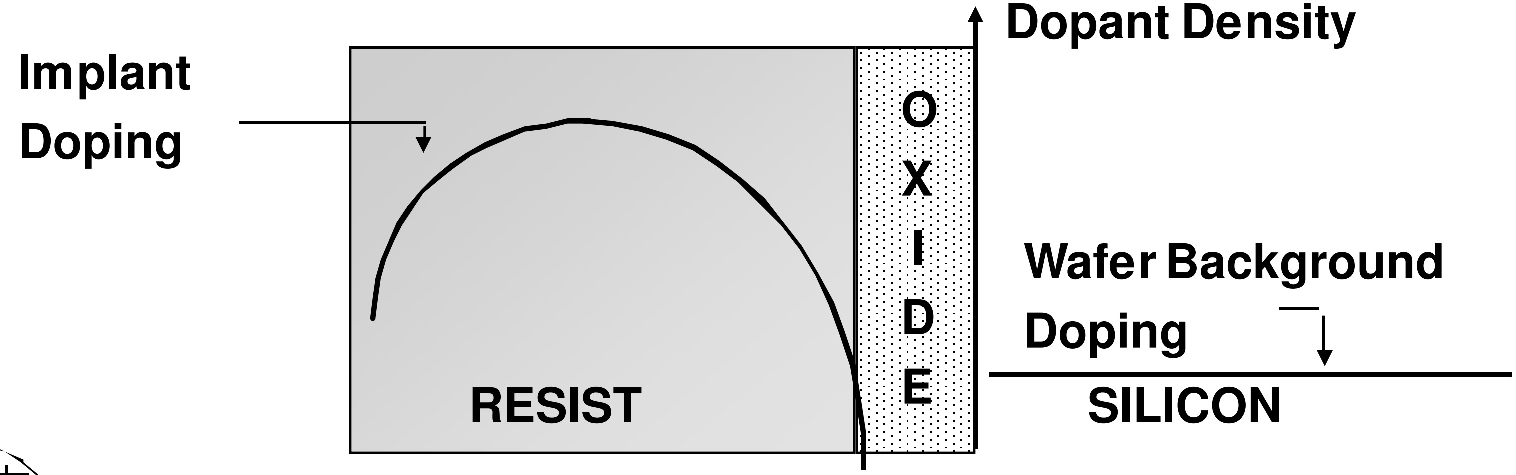
1) It prevents photoresist residues/deposits from reaching the silicon surface. The resist residues deposited on the thin film can subsequently be etched away with that film (e.g. SiO_2 dipped in B.O.E.)



2) It prevents excessive evaporation (out-gassing) of volatile species (e.g. As) during implant damage anneals.

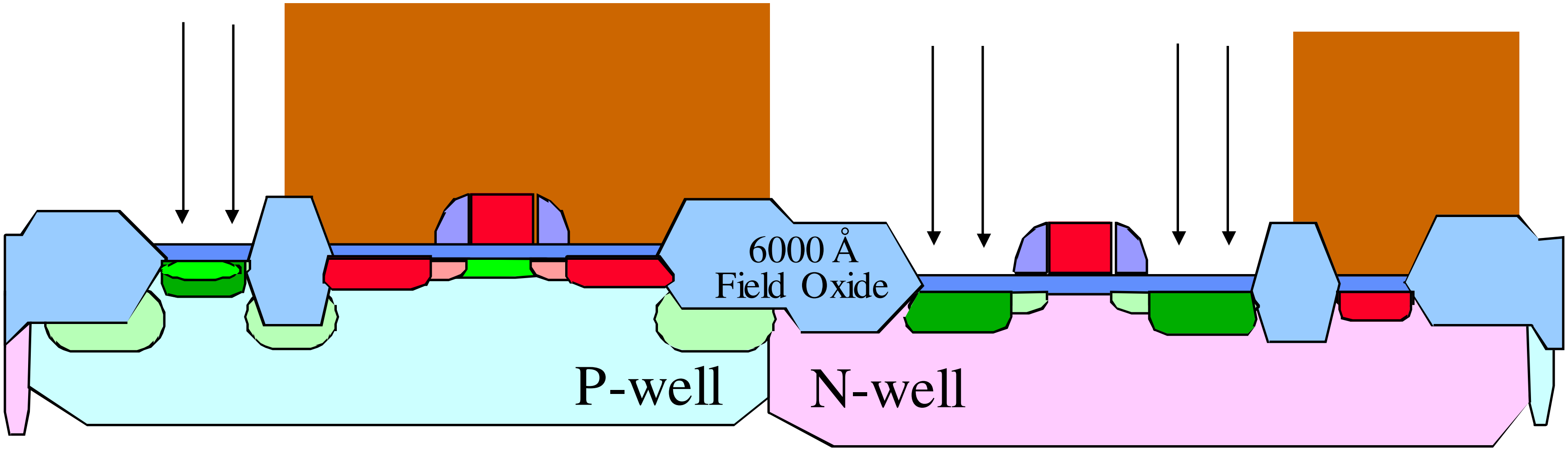
MASKING AGAINST ION IMPLANTS

Various thin films can be used to mask against ion implants : resist, oxide, nitride, polysilicon, etc. The most widely used combination is resist over the oxide. 1 to 1.5 µm thick resist blocks most of the ion implants encountered in silicon processing.Silicon dioxide slows down the ions at about the same rate as silicon does. Silicon nitride is a much stronger barrier to ions than silicon.



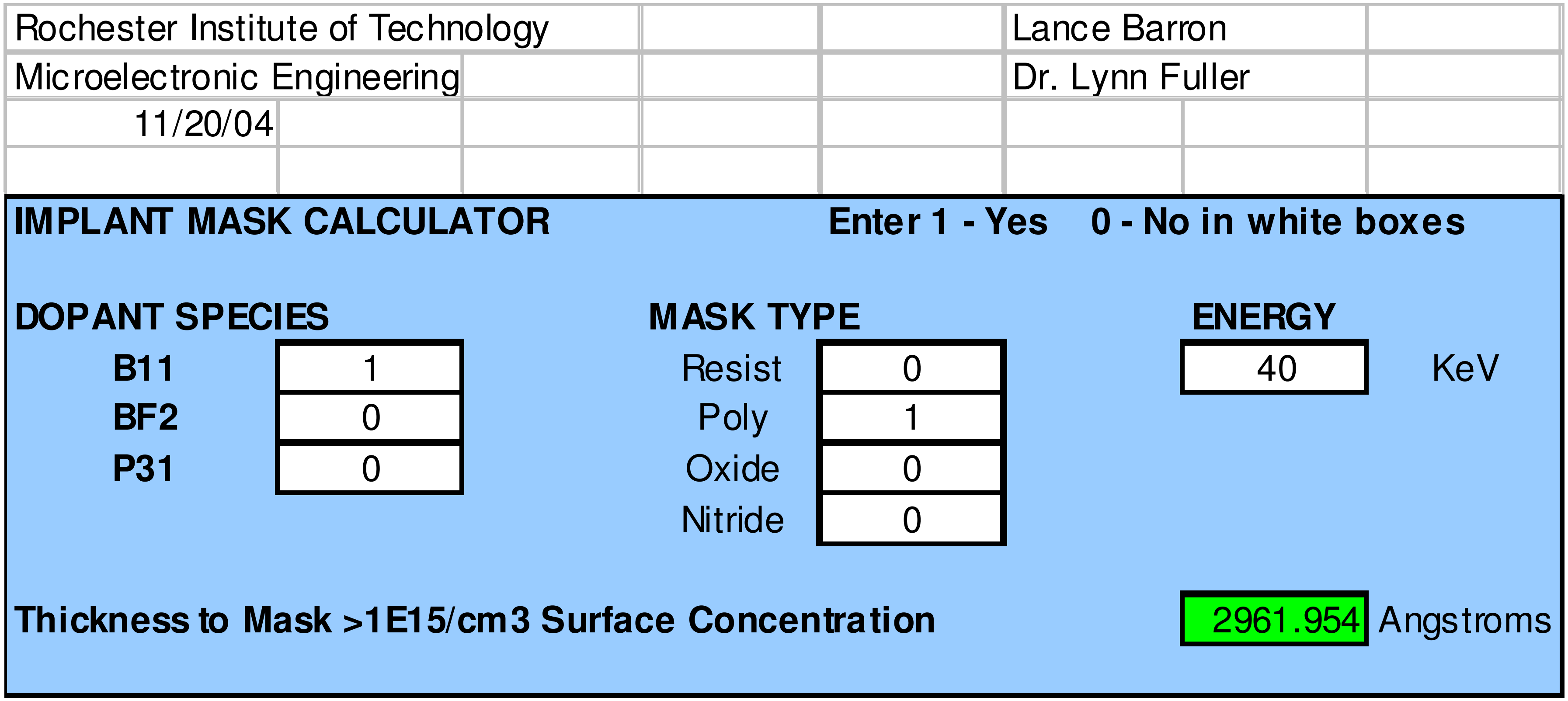
MASKING WITH PHOTORESIST, POLY, AND OXIDE

B11, Dose = 2 E15, E = 50 KeV



N-type Substrate 10 ohm-cm

IMPLANT MASKING THICKNESS CALCULATOR



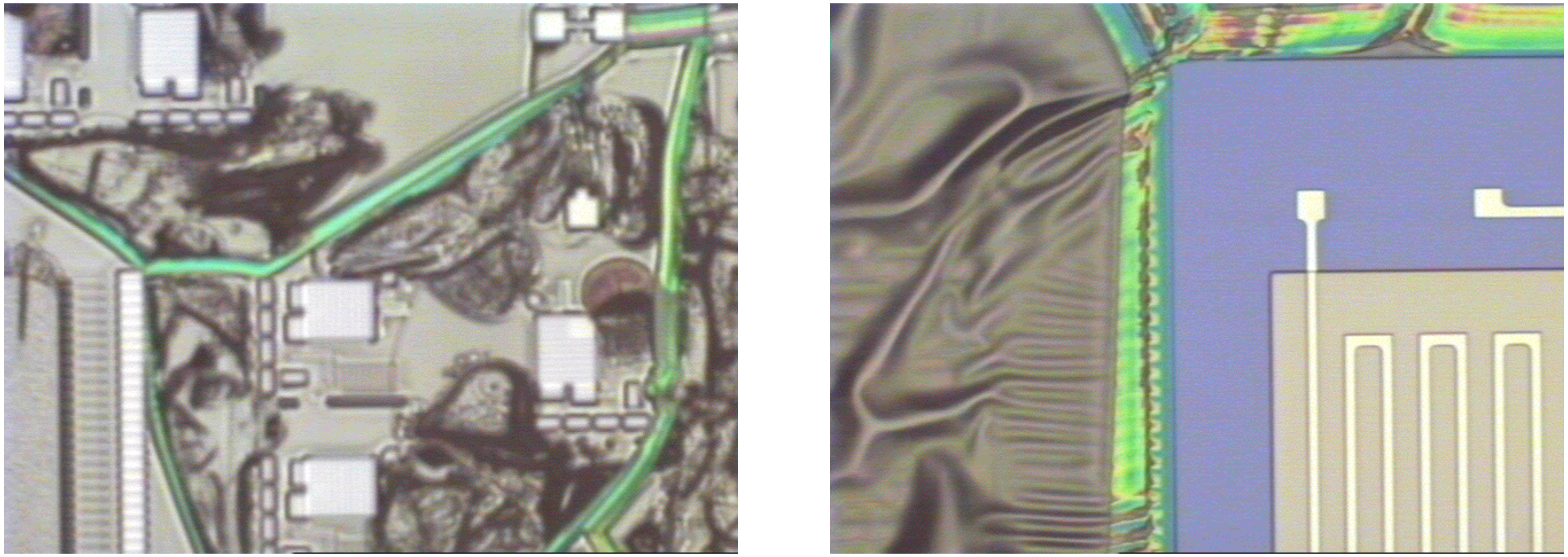
Rochester Institute of Technology	Lance Barron
Microelectronic Engineering	Dr. Lynn Fuller
11/20/04	

IMPLANT MASK CALCULATOR **Enter 1 - Yes 0 - No in white boxes**

DOPANT SPECIES		**MASK TYPE**		**ENERGY**	
B11	1	Resist	0	40	KeV
BF2	0	Poly	1		
P31	0	Oxide	0		
		Nitride	0		

Thickness to Mask >1E15/cm3 Surface Concentration 2961.954 Angstroms

RESIST DAMAGE AT HIGH IMPLANT CURRENTS



BF2 Implant at 80 µA in Varian 400 ***without a water cooled chuck***

Note: Varian 350D can do implants up to 300 µA with no photoresist damage because of wafer cooling

ION IMPLANT VS. CHEMICAL SOURCE PREDEPOSIT

Advantages of Ion Implant

Low dose introduction of dopants is possible. In chemical source predeposits dose values less than 5E13/cm^2 are not achievable. Ion implant dose control is possible down to 1E11/cm^2.

High dose introduction is not limited to solid solubility limit values.

Dose control is very precise at all levels.

Excellent doping uniformity is achieved across the wafer and from wafer to wafer.

Done in high vacuum, it is a very clean process step (except for out gassing resist particulates due to excessive local power input).

Drawbacks of Ion Implant

It requires very expensive equipment ($1M or more).

At high dose values, implant throughput is less than in the case of chemical source predep.

LECTURE REVIEW

- **Principles of Ion Implantation**
  - **The implant depth controlled by the energy E of the ions**
  - **Dopant density primarily controlled by the implant dose**
- **Ion Implantation equipment**
  - **Low current implanters**
  - **High current implanters**
- **Implanted Dopant Profiles**
  - **Nuclear stopping and implant damage**
  - **Post implant anneal**
  - **Gaussian doping profiles**
  - **Channeling and its prevention**
  - **Thin film coverage of the wafer surface**
- **Advantages and Drawbacks of Ion Implantation**

REFERENCES

1. Silicon Processing for the VLSI Era Volume I, S. Wolf and R.N. Tauber, Lattic Press, Sunset Beach, CA, 1986.
2. The Science and Engineering of Microelectronic Fabrication, S.A. Campbell, Oxford University Press, New York, NY, 1996.
3. VLSI Technology, Edited by S.M. Sze, McGraw-Hill Book Company, 1983.

HOMEWORK – ION IMPLANT

1: The implant depth is controlled by the
a) beam size b) acceleration voltage c) beam current d) implant time
2: The volume density of implanted dopants is controlled by the
a) plasma density b) beam size and implant time c) implant time only d) beam current and implant time
3: In using low current implanters that process one wafer at a time, the optimal implant time per wafer (i.e. best uniformity / throughput compromise) a) 1 s b) 10 s c) 50 s d) 100 s
4: True or false? “Channeling is a serious problem when implanting AS^{75} ions at a dose $\Phi = 5x10^{15}/cm^2$”.
5: In CMOS processing, threshold adjust doping can be made by
a) chemical source predep only b) ion implant only c) either chemical source predep or ion implant.
6: Calculate the implant dose and energy needed to make the pmos Vt of -1 volt for the following device parameters. N+ Poly gate, 250 Å gate oxide, 2E16 cm-3 substrate doping, Nss=3.4E11.