Fall 2008 EE 410/510:
Microfabrication and Semiconductor Processes
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EB 239 Engineering Bldg.

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Tables and Charts taken from Cambell, Science and Engineering of Microelectronic Fabrication, Oxford 2001
Implantation images taken from Axcelis Corporation.
Ion Implantation

Penn State Graphical Description of Ion Implantation: http://courses.ee.psu.edu/ruzyllo/ionimplant/

Online chapter of ion implantation process parameters: http://www.iue.tuwien.ac.at/phd/hoessinger/node20.html


Freeware for 1-D implant predictions: http://www.gs68.de/software/simplant/index.html
Arc Chamber

- Ion source: Arc Chamber
  - Feed gas of implant species using mass flow controllers
    - $\text{BF}_3$, $\text{AsH}_3$, $\text{PH}_3$ for Si
    - $\text{SiH}_4$ and $\text{H}_2$ for GaAs
  - Solid sources can be heated to vapor form and controlled via a shutter if needed
  - Molecules flow past a hot charged filament in a magnetic field to produce ionization.
  - Positive ions are accelerated and exit the chamber through a slit, resulting in an ion beam a few mm by 1 cm across
Ion Separation

- Ions are separated by atomic mass using a large magnetic field.
- The field bends the ion beam by an angle $\phi$ which does NOT have to be $90^\circ$.
- In fact, it is possible to conceive of an implanter with multiple exit slits allowing for mass production of devices implanted with different atomic masses.

As ions enter the analyzer magnet,

$$\frac{Mv^2}{r} = qvB$$

$$v = \sqrt{\frac{2E}{M}} = \sqrt{\frac{2qV_{ext}}{M}}$$

$$r = \frac{Mv}{qB} = \frac{1}{B} \sqrt{\frac{2M}{q} V_{ext}}$$

$$D = \frac{1}{2} r \frac{\delta M}{M} \left[ 1 - \cos \phi + \frac{L}{r} \sin \phi \right]$$
Beam Steering

- After separation
- Ions are accelerated by RF bias fields
- Magnetic lenses can be used to focus the beam
- Electronic biasing plates are used to steer and scan the beam over a limited range
- Beam exits through a window and implants high energy ions onto substrate
- Substrate can also be scanned across the beam as needed
Ion Penetration

Where $S_e$ and $S_n$ are the energy losses due to electronic and nuclear stopping potentials

Electronic stopping potential due to scattering of ions from electron within the lattice

$$S_e = \left. \frac{dE}{dx} \right|_e = \sqrt{\frac{Z_i Z_t}{M_i^3 M_t}} \frac{(M_i + M_t)^{3/2}}{(Z_i^{2/3} + Z_t^{2/3})^{3/2}} \sqrt{E}$$

Nuclear stopping potential due to scattering from nuclei in the lattice

$$S_n^o \approx 2.8 \times 10^{-15} \text{ eV/cm}^2 \times \frac{Z_i Z_t}{Z^{1/3}} \frac{M_i}{M_i + M_t}$$

$$Z = \left( Z_i^{2/3} + Z_t^{2/3} \right)^{3/2}$$

$E$ = energy of the implanted ions (eV)
$Z$ = charge number of protons in the atom
$M$ = atomic mass
$i$ = incident ion
$t$ = target material
Implantation Range

- Penetration is estimated using range and standard deviation equations

\[ R_p = \int_0^{R_p} dx = \int_{E_0}^0 \frac{dE}{dE/dx} = \int_{E_0}^0 \frac{dE}{S_n + S_e} \]

\[ \Delta R_p \approx \frac{2}{3} R_p \left[ \sqrt{\frac{M_l M_m}{M_l + M_m}} \right] \]

- Impurity concentration as a function of depth is

\[ N(x) = \frac{\phi}{\sqrt{2\pi\Delta R_p}} e^{-\frac{(x-R_p)^2}{2\Delta R_p^2}} \]
Figure 5-9 Projected range (left axis) and standard deviation (right axis) for (a) n-type, (b) p-type, and (c) other species into a silicon substrate, and (d) n-type and (e) p-type dopants into a GaAs substrate, and several implants into (f) SiO₂ and (g) AZ111 photoresist (data from Gibbons et al.).
Implantation Range
Channeling Effects

- Channeling is a lack of scattering due to geometrical orientation of the target material with respect to the incident beam.
- Occurs when ion velocity is parallel to a major crystal orientation.
- Once in a channel, the ion will continue in that direction making many glancing internal collisions that are early elastic until coming to rest or de-channels due to a crystal defect or impurity.
- Effect is characterized by a critical angle.

\[ \Psi = 9.73^\circ \sqrt{\frac{Z_i Z_t}{E_o d}} \]
Implantation Applications

Medium Dose Applications
- Buried channel doping
- 0.5 keV to 750 keV
- 35-65 nm ULSI

High Dose Applications
- 0.2 keV to 80 keV

The Ultra delivers effective contamination control below 1.0% in all cases, for maximum on-wafer product yield.

http://www.axcelis.com/
Implantation Applications

High Energy Applications

10 keV to 4 MeV
Channel Engineering and Transistor isolation

http://www.axcelis.com/
Quantum Computing with Single Atom Implantation

- Single atom ion implantation can be used to produce quantum computers
- Doping of one atom creates a single electron that exist in either one or two different quantum states (double well)
- The quantum information packet is called a (q-bit)
- Surface electrodes S and B control the state
- Single electron transistors (SETs) detect charge transfer between the two donors

Buried Dielectrics

- SOI wafers formed by ion implantation of O2 into Silicon followed by annealing
- 150 – 300 keV O+ does to about 2*10^{18} cm^{-2}
- Very long implantation time
- Often done on axis to take advantage of channeling effects
- Generates a nearly amorphous layer of 30% Si / 60% O_2
- To reduce damage, wafers must be heated to at least 400°C during implant
- Anneals are performed at 1300-1400°C for several hours under an deposited oxide cap
- Implanters designed for SIMOX operate at 100mA with metallic contamination held below 10^{11} cm^{-2} and pinhole density less than 0.2 cm^{-2}. Thickness uniformity is approx. 50 Ang over 6 in

Rapid Thermal Annealing

- Method for annealing materials at temperatures up to 1200°C for very short periods of time
- Typical ramp rates are 30 sec
- Process times range from 2-600 sec
- Advantages
  - Extremely fast technique
  - Single wafer processing produces best uniformity
  - Minimizes redistribution of dopants
  - Cold walls allow multiple processes to occur without contamination
  - Photochemistry can be exploited
- Disadvantages
  - Absolute temperatures are almost never known
  - Nonthermal-equilibrium process makes modeling and predicting difficult
  - Uniform heating is more critical than traditional thermal processing
    - Ramp rates
    - Internal stresses

FIG. 1. Temperature sensor signal vs time for four RTA methods. A, arc lamp; I, incandescent lamp; F, bell-jar furnace; S, susceptor furnace. Preheat region below 600 °C varies among methods. Origin of time is start of heating cycle in each case.
Rapid Thermal Annealing

- Types of RTP
  - Adiabatic: excimer laser heats surface
  - Thermal Flux: rastered electron beam
  - Isothermal: Optical illumination
- Measurement Devices
  - Pyrometry: measures thermal light intensity
  - Acoustic: measures velocity of sound in the chamber as a linear function of temperature
  - Thermocouples imbedded in SiC, Si, or Graphite susceptor plate

![Diagram](image)

**FIG. 4.** Configuration of sapphire light guide sensors for a ripple technique in an oven with AC-powered incandescent lamps and quartz isolation tube (after Ref. 22)