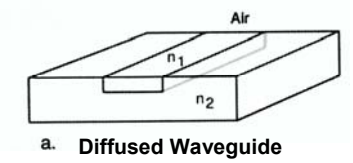
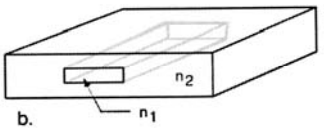
Waveguide Fabrication

Class: Integrated Photonic Devices
Time: Fri. 8:00am ~ 11:00am.
Classroom: 資電206
Lecturer: Prof. 李明昌(Ming-Chang Lee)

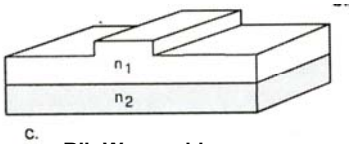
Types of Optical Waveguide



a. Diffused Waveguide



b. Channel Waveguide



c. Rib Waveguide

Principle of confinement

- **Index-confined**
- **Profile-confined**
- **Combined**

Materials

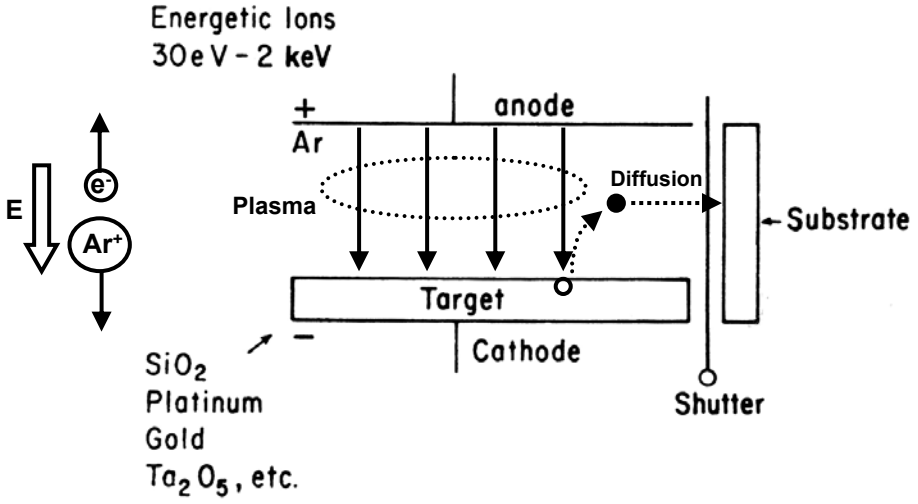
- **Silicon**
- **Silicon Dioxide**
- **LiNaO, LiTaO**
- **III-V (GaAs, …)**
- **Polymer**

Typical Process of Etched Waveguide

- **Thin Film Deposition**
  - Sputtering
  - Chemical Vapor Deposition (CVD)
  - Thermal Oxidation (SiO_2)
- **Photolithography**
- **Etching Process**

The waveguide dimension is usually controlled by thin film thickness and photolithography pattern.

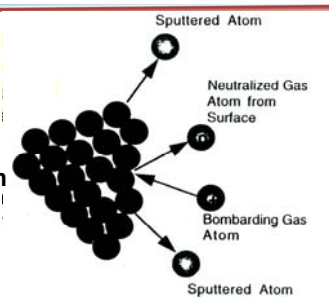
Sputtering

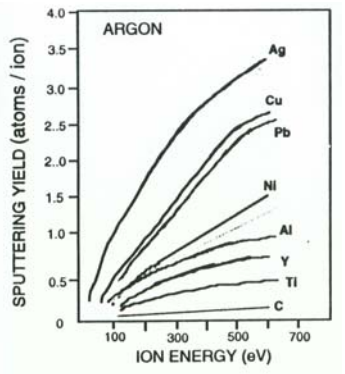


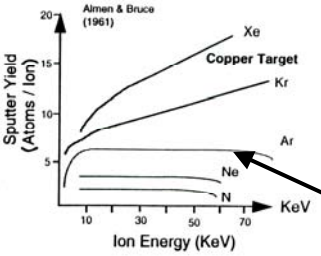
Physics of Sputtering

Energies of Bombarding Ions

- **< 5 eV: Ions are reflected or adsorbed**
- **5 – 10 eV: Ions cause surface damage**
- **10 eV - 10 keV: Ions cause sputtering**
- **> 10 keV: Ions primarily undergo implantation**



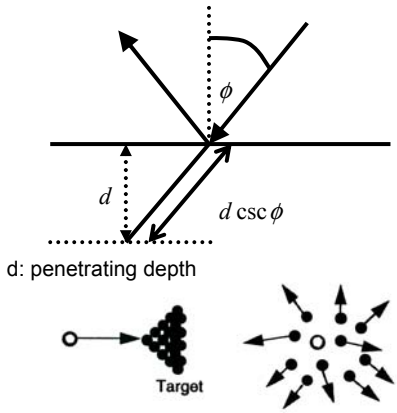


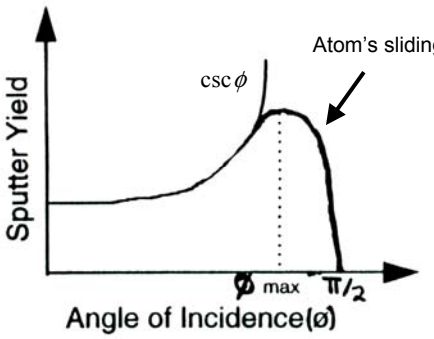


Sputter Yield:
The number of sputtered atoms per impinging ion

saturated

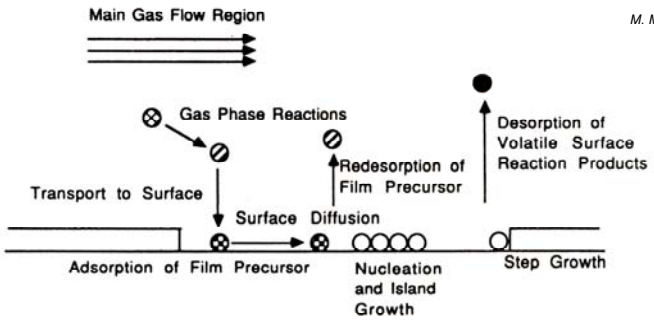
Sputtering Angle Effect





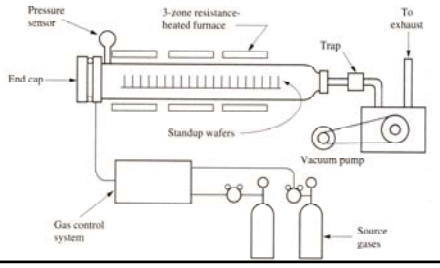
- **Sputter yield increase as sputtering angle**
- **As sputtering angle approximate 90˚, the sputtering yield reduces due to incident atom's sliding**

Chemical Vapor Deposition



M. Mardou, "Fundamentals of Microfabrication"

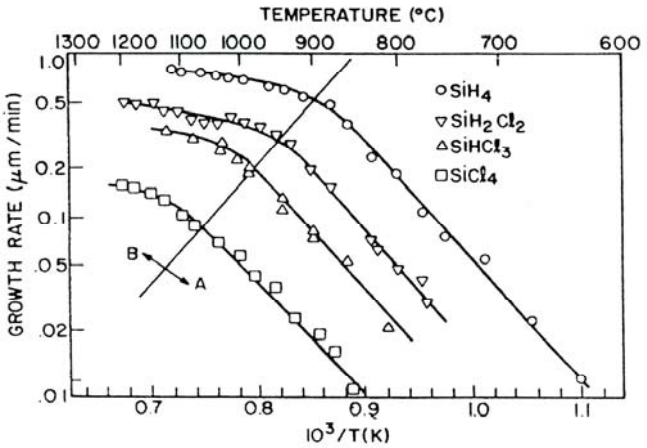
Types of CVD:
- LPCVD
- APCVD
- PECVD



The reaction rate depends on the slowest process

- **Reaction Limited Process**
- **Mass-Transfer Limited Process**

CVD Deposition Rate



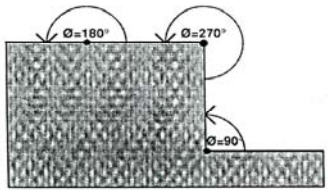
$$R = K_s \cdot N_{surface}$$

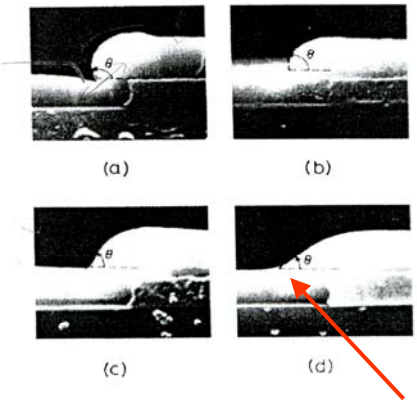
$$K_s = K_0 \exp(\frac{-E_a}{kT})$$

$$\log(\frac{K_s}{K_0}) = -\frac{E_a}{k}(\frac{1}{T})$$

- **A ~ Mass-Transfer Limited Process**
- **B ~ Reaction Limited Process**

Incident Angle





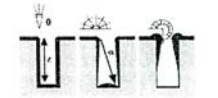
Reflow

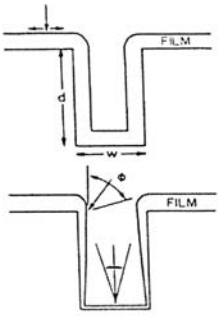
- Film is thicker in convex corners
- Film is thinner in concave corners

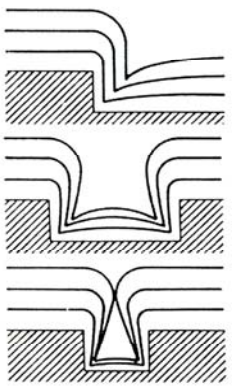
Gap Dependency

Large Gap

Small Gap





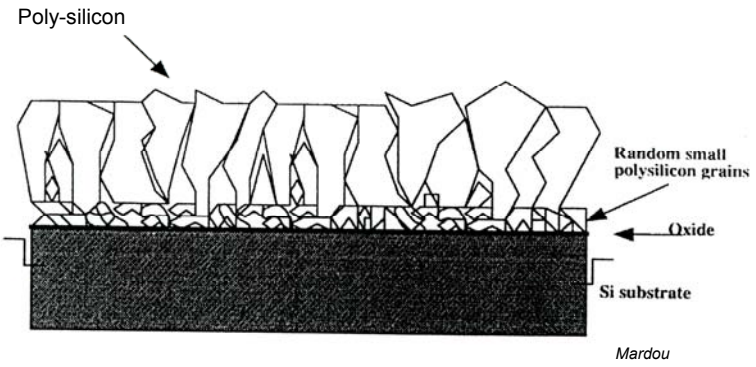


Pinch-off

Wolf and Tauber

- Mass-Transfer Limited Process --- Fast, but not conformal
- Reaction Limited Process --- Conformal, but slow

Poly Crystalline

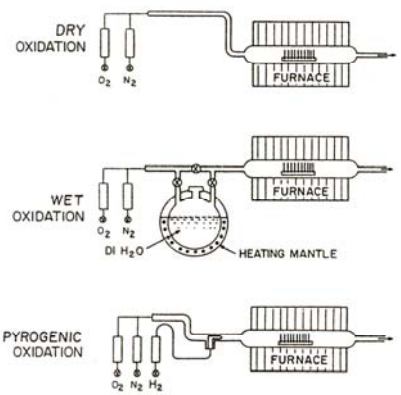


Mardou

- **Grain size depends on deposition temperature**
  - **Hotter deposition leads to larger grain structure**

Thermal Oxidation

Oxidation set-ups



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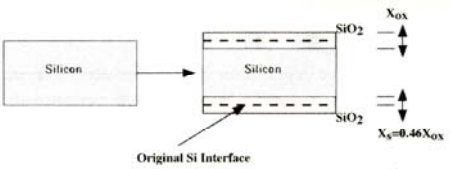
Silicon Thickness Converted

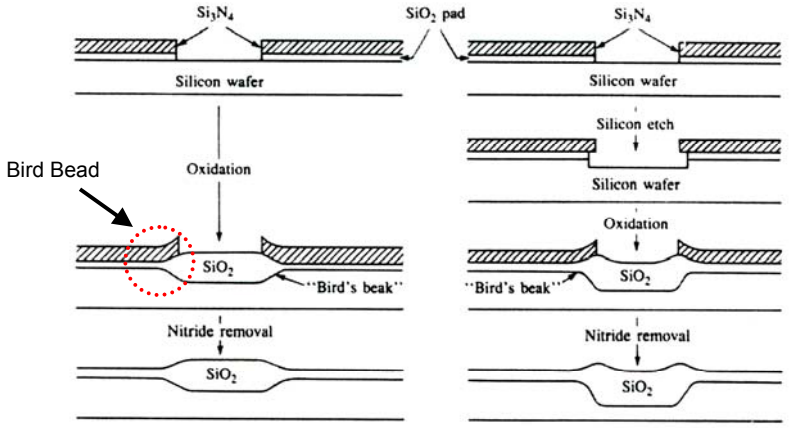


$Si + 2H_2O \rightarrow SiO_2 + H2$ (wet)

$Si + O_2 \rightarrow SiO_2$ (dry)

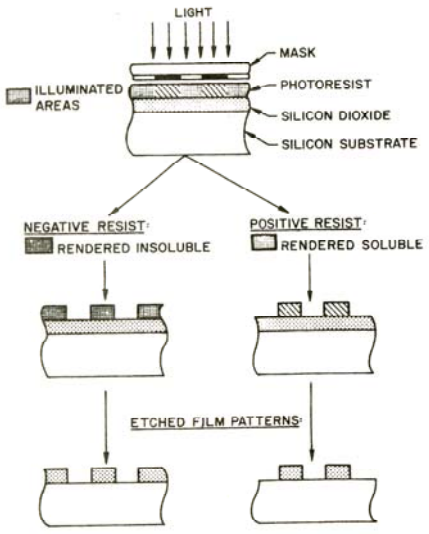
- **Thermal oxidation consume silicon**
- **Wet oxidation has faster reaction rate. However, dry oxidation has better thin film quality**

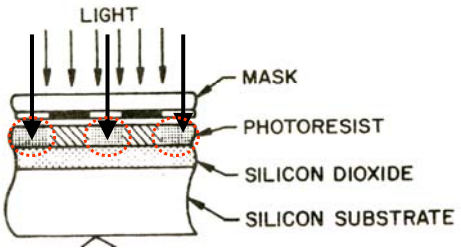
2D Profile Transformation



Symmetrical Expansion **Asymmetrical Expansion**

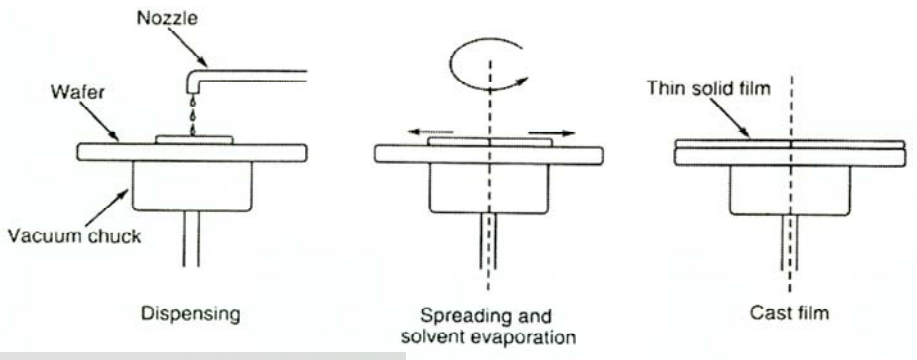
Photolithography and Etch





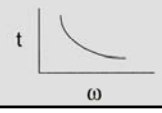
- **The exposed area is developed --- positive resist.**
- **The unexposed area is developed --- negative resist.**
- **The patterned photoresist protect the area from etching**

Spin Coating of Photoresist



$$t = K \cdot S \cdot \left(\frac{\nu}{\omega^2 \cdot R^2} \right)^{\frac{1}{3}}$$

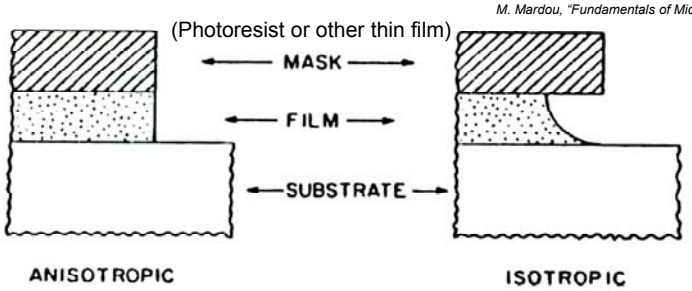
t = thickness
K = constant
S = fractions of solids
ν = viscosity
ω = angular velocity
R = radius



- **The thickness is controlled by material viscosity and spin speed.**

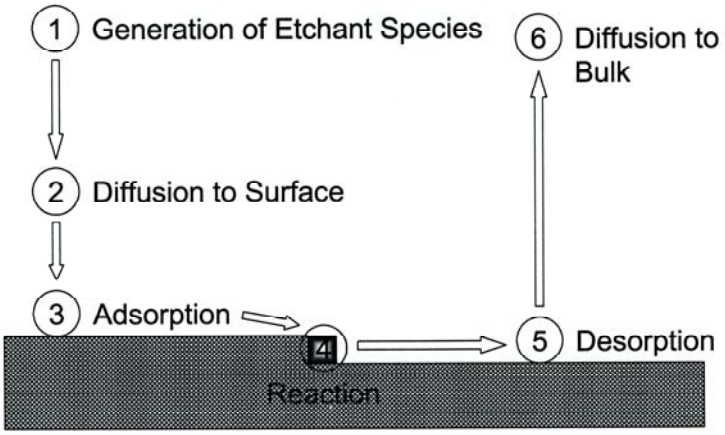
Types of Etching Process

M. Mardou, "Fundamentals of Microfabrication"



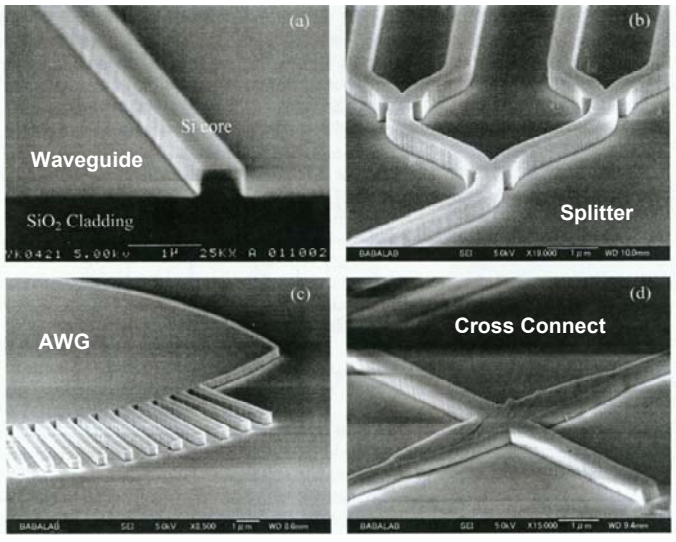
- **Anisotropic:**
  - **Best for making small gaps and vertical sidewalls**
  - **Typically more costly**
- **Isotropic:**
  - **Best to use with large geometries, when sidewall slope dons not matter, and to undercut the mask**
  - **Quick, easy, cheap**

Mechanics of the Etching Process



- **Slow process step dominate!**

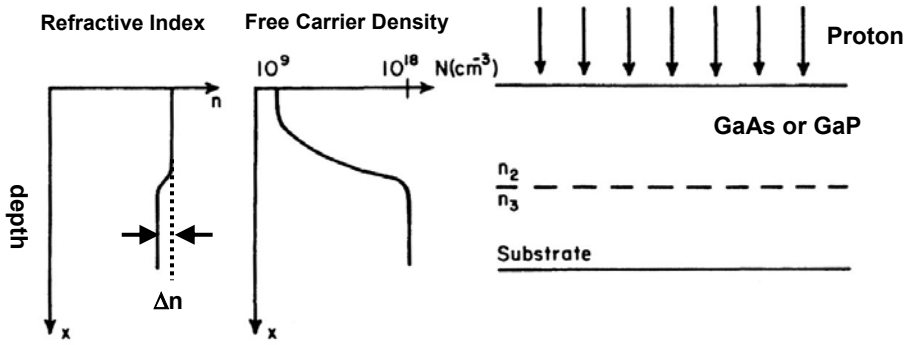
Examples of Etched Waveguides



Baba, 2002

- **Carrier-Concentration-Reduction Waveguides**

Proton Bombardment



- **Proton bombardment decreases the free carrier density due to the lattice defects (carrier traps).**
- **The free carrier density affect the refractive index.**
- **The index contrast is not proportional to the density contrast.**

Free-Carrier-Dependent Refractive Index

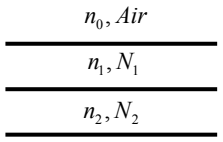
Recall $\Delta\left(\frac{\varepsilon}{\varepsilon_0}\right) = 2n\Delta n = -\frac{Ne^2}{\varepsilon_0 m^* \omega^2}$ (Discussed in free-carrier absorption loss)

$$\downarrow$$

$$n = n_0 - \frac{Ne^2}{2n\varepsilon_0 m^* \omega^2}$$

For two layers with different free carrier densities, the index contrast Δn:

$$\Delta n = n_1 - n_2 = \frac{(N_2 - N_1)e^2}{2n_1\varepsilon_0 m^* \omega^2}$$

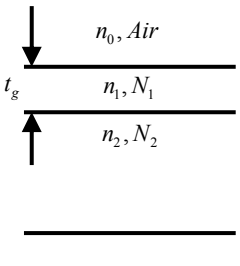


- **The index contrast is frequency-dependent. Higher frequency has lower index contrast.**

Cut-off Conditions for Free-Carrier Controlled Waveguides

Recall $M_{TE} = \left\langle \frac{2V}{\pi} - \frac{1}{\pi}\tan^{-1}\left(\sqrt{\frac{n_2^2 - n_0^2}{n_1^2 - n_2^2}}\right)\right\rangle_{\text{int}}$

For M = 0 $\rightarrow$ $\Delta n = (n_1 - n_2) \geq \frac{\lambda^2}{32 t_g^2 n_1}$



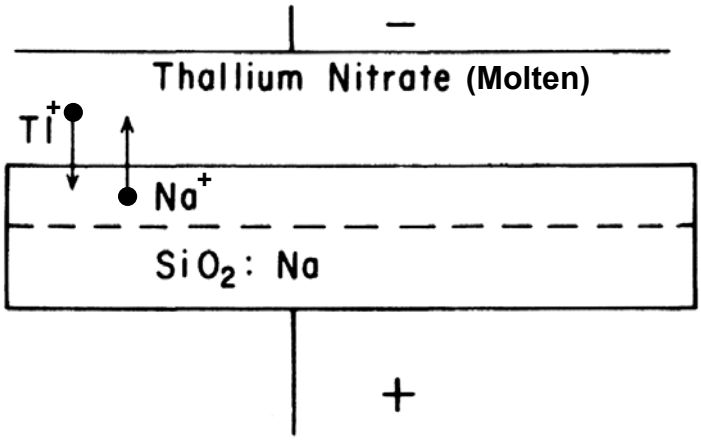
$$\frac{(N_2 - N_1)e^2}{2n_1\varepsilon_0 m^* \omega^2} \geq \frac{\lambda^2}{32 t_g^2 n_1}$$

$$\downarrow$$

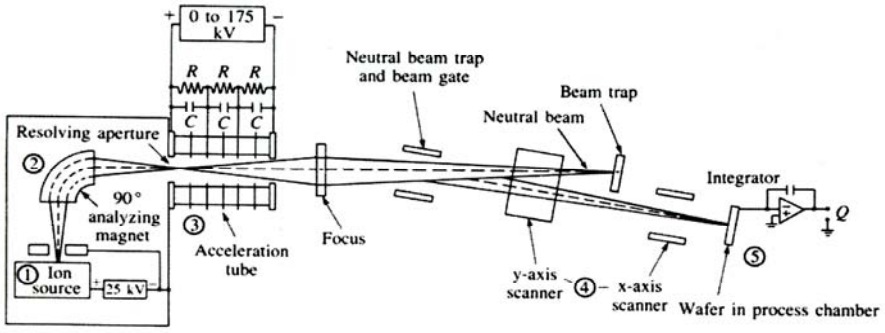
$$(N_2 - N_1) \geq \frac{\varepsilon_0 m^* \lambda^2 \omega^2}{16 t_g^2 e^2} \rightarrow (N_2 - N_1) \geq \frac{\varepsilon_0 m^* \pi^2 c^2}{4 t_g^2 e^2}$$

- **The cut-off condition is independent of wavelength (frequency).**

Ion Exchange and Migration



Ion Implantation



(1) **Ion source**
(2) **Mass spectrometer**
(3) **High-voltage accelerator**
(4) **X- and y-axis deflection system**
(5) **Target chamber**

$$Q = \int_0^T \frac{I}{n \cdot q \cdot A} dt$$

Q : *dorse*(*per unit area*)

I : *total current*

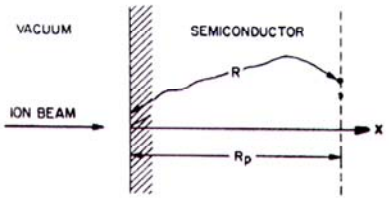
T: *time*

A: *area*

Ion Implantation

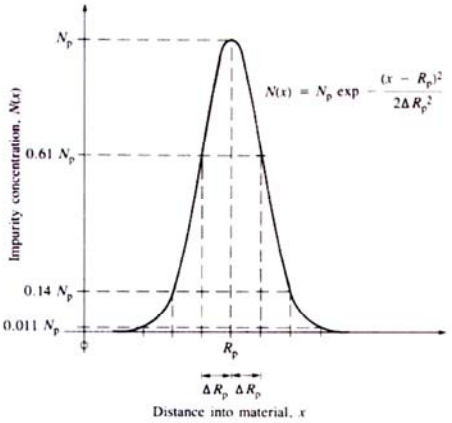
- **Electrostatically accelerate ions to velocities and energies that can deposit or implant dopants below the surface**
  - **Process performed at low temperature**
  - **Instant-on and instant-off control**
  - **Precise control of implanting current and charge allow for better control of the implanted dose**
  - **Increase implant energies can penetrate thin films of materials**
  - **The peak of implanted dopant profiles are always below the surface (buried)**

Implant Dopant Distribution (Planar Implantation)



- **Dopants follow a completely Gaussian distribution**
  - **Average depth (Projected Range) = R_p**
  - **Variance (Straggle) = $\pm\Delta R_p$**
  - **Asymmetry (Skewness)**

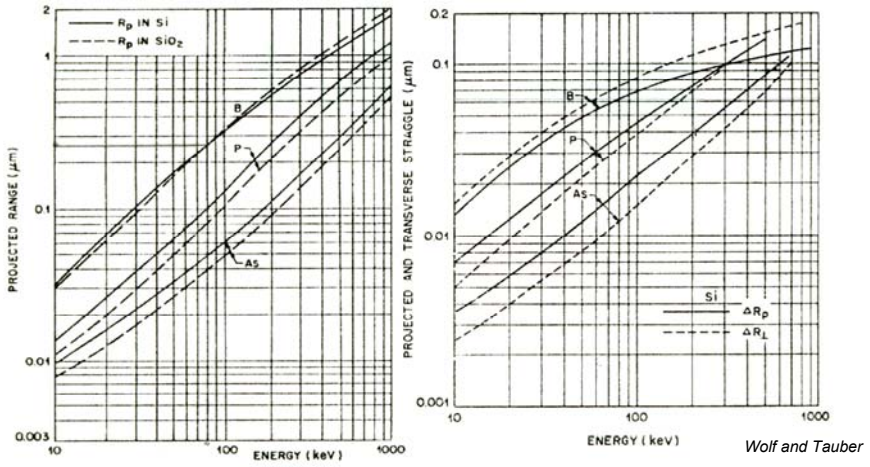
$$Q = \int_0^T \frac{I}{n \cdot q \cdot A} dt = A \cdot \int_0^\infty N(x) dx$$



$$Q = \sqrt{2\pi} \cdot N_p \cdot \Delta R_P$$

If profile is fully below surface

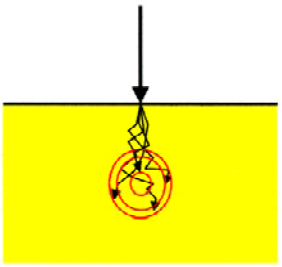
Implantation Parameter vs. Implantation Energy



Wolf and Tauber

- **Typical Implantation Energy ~ 10 to 200 keV**
- **Typical Depth of Implant ~ 0.05 μm to 1 μm**

3D Implantation (Point Source)



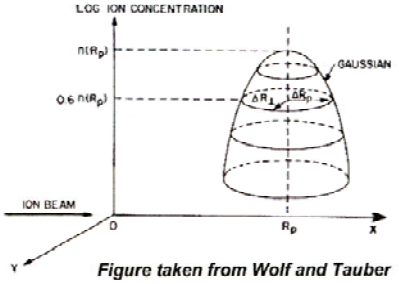
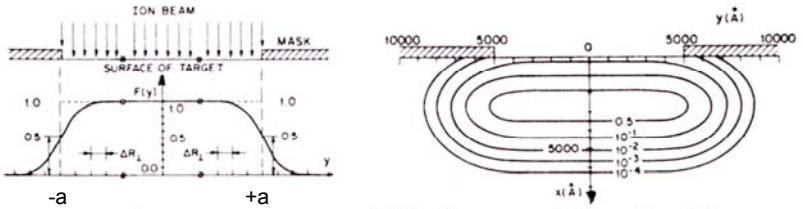


Figure taken from Wolf and Tauber

- **Gaussian distribution (lateral and vertical)**
  - **Vertical spread determined by the straggle** ΔR_p
  - **Lateral spread determined by the lateral straggle** $\Delta R_{p\perp}$

$$N_{implant}(x,y) = N_p \exp[-\left(\frac{x-R_p}{\Delta R_p\sqrt{2}}\right)^2] \cdot \exp[-\left(\frac{y}{\Delta R_{p\perp}\sqrt{2}}\right)^2]$$

3D Implantation (Plane Source)



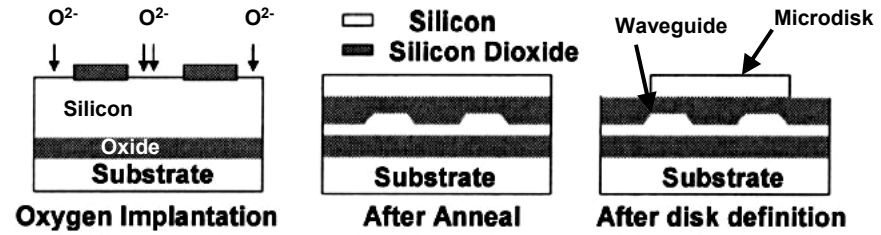
- **For a plane source one must take the convolution of a of the distribution from a point source of the region of interest:**

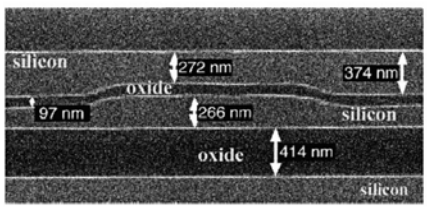
$$N_{implant}(x,y) \sim N_p \exp[-\left(\frac{x-R_p}{\Delta R_p\sqrt{2}}\right)^2] \cdot \int_{-a}^{+a} \exp[-\left(\frac{y-y'}{\Delta R_{p\perp}\sqrt{2}}\right)^2] dy'$$

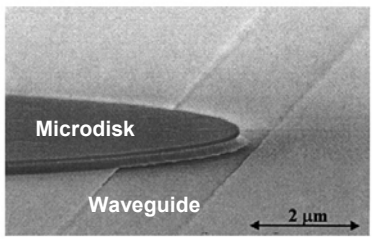
$$= N_p \exp[-\left(\frac{x-R_p}{\Delta R_p\sqrt{2}}\right)^2] \cdot \left[erfc\left(\frac{y-a}{\Delta R_{p\perp}\sqrt{2}}\right) - erfc\left(\frac{y+a}{\Delta R_{p\perp}\sqrt{2}}\right)\right]$$

Complementary error function

3D Sculpture by Ion Implantation

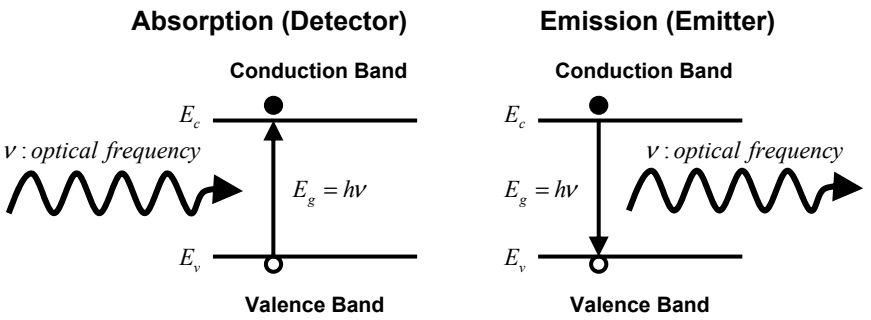






- **Epitaxial Growth Waveguides**

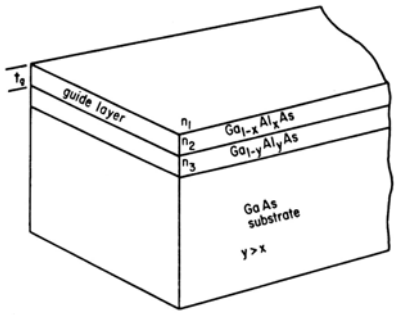
Issues of Monolithic Integrated Photonic Device



- **If the material can emit light, it can also absorb light.**
- **Can we have different band-gap energy in the same substrate?**

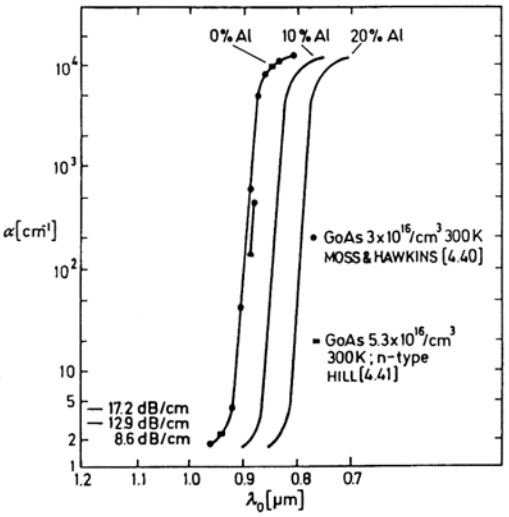
$$E_g \text{ (waveguide)} > E_g \text{ (emitter)} > E_g \text{ (detector)}$$

$Ga_{(1-x)}Al_xAs$ Waveguide



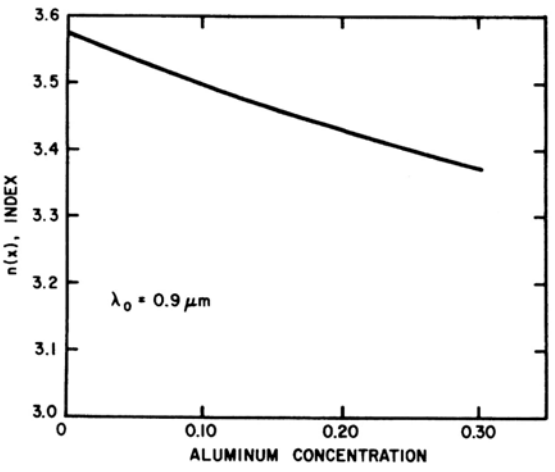
- **Controlling the Al concentration can engineer the band-gap energy.**

$$E_g(x) = 1.439 + 1.042x + 0.468x^2$$



Interband Absorption

Refractive Index Engineering of $Ga_{(1-x)}Al_xAs$



Sellmeier Equation

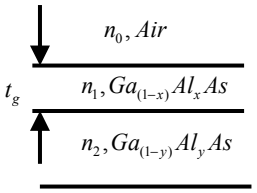
$$n(x) = A(x) + \frac{B}{\lambda^2 - C(x)} - D(x)\lambda^2$$

$$A(x) = 10.906 - 2.92x$$

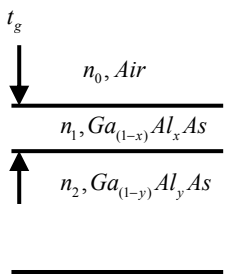
$$B = 0.97501$$

$$C(x) = \begin{cases} (0.52886 - 0.735x)^2 & \textbf{if } x \le 0.36 \\ (0.30386 - 0.105x)^2 & \textbf{if } x \ge 0.36 \end{cases}$$

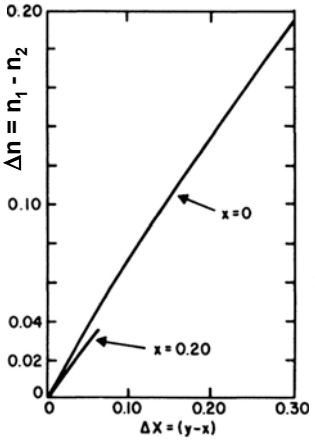
$$D(x) = 0.002467 - (1.41x + 1)$$



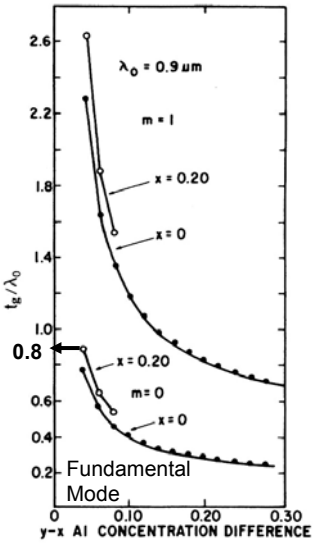
Cut-Off Condition for $Ga_{(1-x)}Al_xAs$



Index Contrast

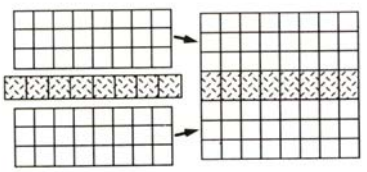


Cut-off Condition

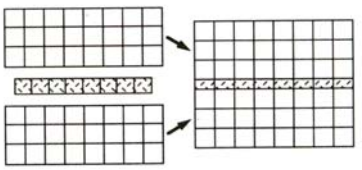


- **The cut-off condition is dependent on the ratio of wavelength (frequency) and thickness.**

Lattice strain



Compressive

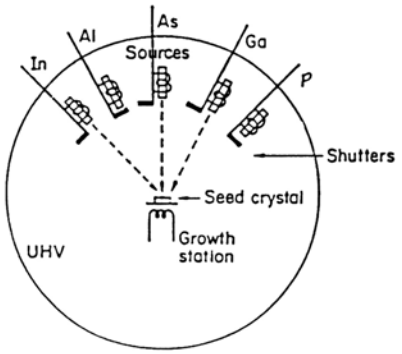


Tensile

- **Lattice constant mismatch results in lattice strain.**
- **Lattice strain can make the fabrication difficult (delaminating) and induce non-radiative recombination.**

Fabrication

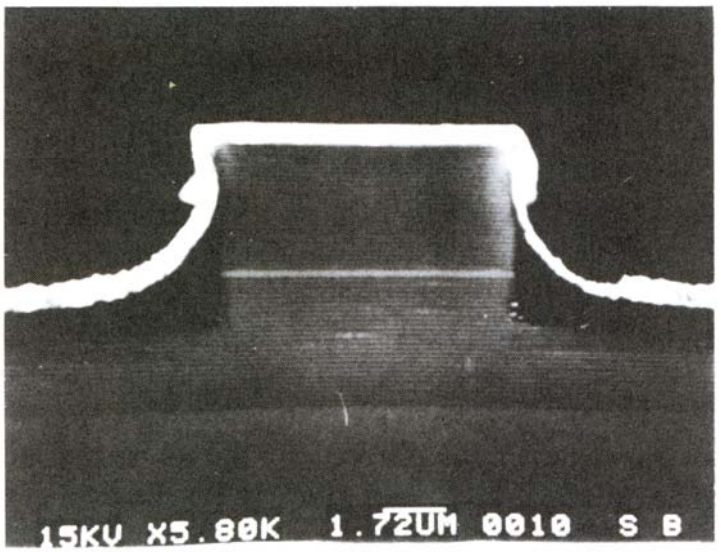
- Liquid Phase Epitaxy
- Vapor Phase Epitaxy
- Molecular Beam Epitaxy (MBE) and MOCVD



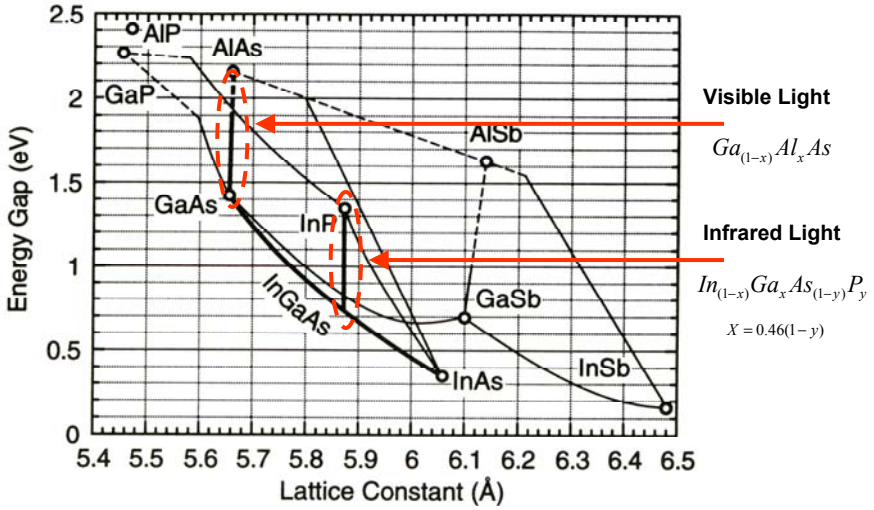
A schematic of an MBE growth system

- **Advantage**
  - Reduce the impurity
  - Well-controlled doping
  - Well-controlled thickness
- **Disadvantage**
  - Toxic

Vertical-Cavity Semiconductor Lasers

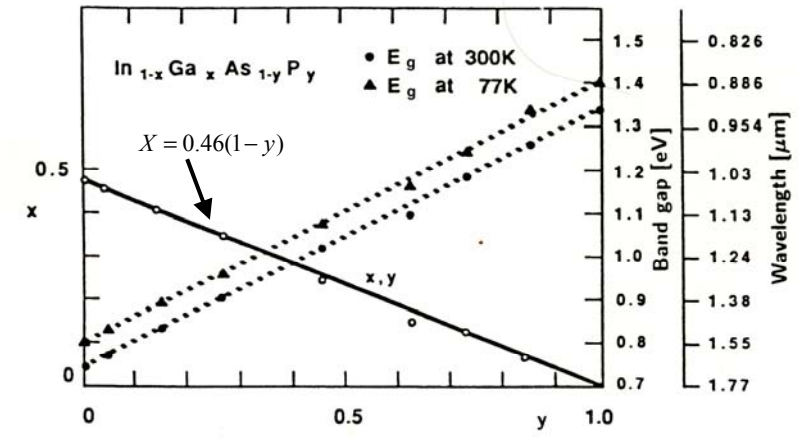


Other III-V Semiconductor



- **In addition to band-gap energy, the lattice constant have to be considered.**

Measured Band gaps and lattice matching



1. **Determine the wavelength (band gap)**
2. **Determine the concentration of phosphorous Y**
3. **Determine the concentration of Ga (lattice match)**

- **Polymer Waveguide**

Key Properties of Optical Polymers

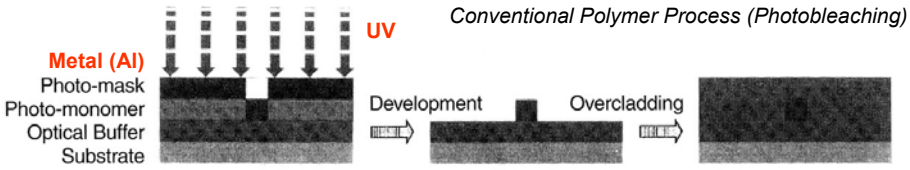
Table 5.1. Key properties of optical polymers developed worldwide [5.2] ©2000 IEEE

Manufacturer	Polymer Type [Trade Name]	Patterning Techniques	Optical Loss, dB/cm [at wavelength, nm]	Other Properties [at wavelength, nm]
Allied Signal	Acrylate	Photoexposure/wet etch, RIE, laser ablation	0.02 [840] 0.2 [1300] 0.5 [1550]	Birefringence: 0.0002 [1550] Crosslinked, T_g: 25 °C Environmentally stable
	Halogenated Acrylate	Photoexposure/wet etch, RIE, laser ablation	< 0.01 [840] 0.03 [1300] 0.07 [1550]	Birefringence: < 0.000001 [1550] Crosslinked, T_g: −50 °C Environmentally stable
Amoco	Fluorinated Polyimide [Ultradel™]	Photoexposure/wet etch	0.4 [1300] 1.0 [1550]	Birefringence: 0.025 Crosslinked, Thermally stable
Dow Chemical	Benzocyclobutene [Cyclotene™]	RIE	0.8 [1300] 1.5 [1550]	T_g: > 350 °C
	Perfluorocyclobutene [XU 35121]	Photoexposure/wet etch	0.25 [1300] 0.25 [1550]	T_g : 400 °C
DuPont	Acrylate [Polyguide™]	Photolocking	0.18 [800] 0.2 [1300] 0.6 [1550]	Laminated sheets Excimer laser machinable
General Electric	Polyetherimide [Ultem™]	RIE, laser ablation	0.24 [830]	Thermally stable
Hoechst Celanese	PMMA copolymer [P2ANS]	Photobleaching	1.0 [1300]	NLO polymer
JDS Uniphase Photonics (form. Akzo Nobel Photonics)	[BeamBox™]	RIE	0.6 [1550]	Thermally stable
NTT	Halogenated Acrylate	RIE	0.02 [830] 0.07 [1310] 1.7 [1550]	Birefringence: 0.000006 [1310] T_g: 110 °C
	Deuterated Polysiloxane	RIE	0.17 [1310] 0.43 [1550]	Environmentally stable
	Fluorinated Polyimide	RIE	TE: 0.3, TM: 0.7 [1310]	Environmentally stable

Polymer Waveguide Devices

Table 5.4. Polymer waveguide devices

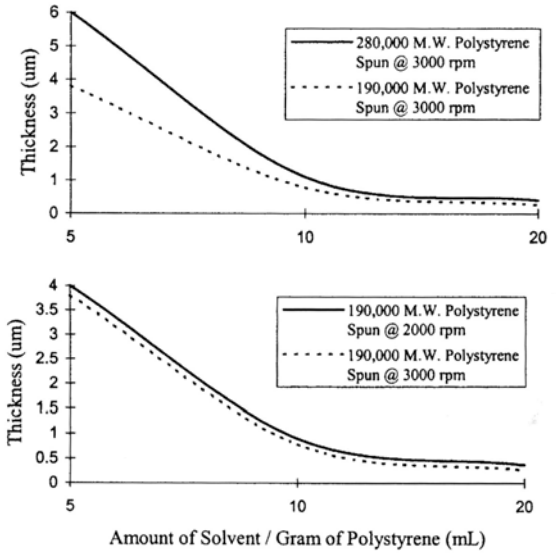
(Passive)	(Active)
Coupler/splitter	Light emitter
Grating/filter	LASER
Delay line	Light detector
Mode converter	Optical modulator/switch
Attenuator	Accelerometer
Array waveguide (AWG)	Chemical detector



Conventional Polymer Process (Photobleaching)

- **Some polymer is similar to negative photoresist which is easy to be fabricated**

Thickness vs. Dilution (Spin Coating)



Process of Polymide

Polymides are polymers with excellent thermal stability, solvent resistance and electrical properties.

Table 5.3. Process for polyimide channel waveguide fabrication [5.7]

1.	Clean substrate with acetone, methanol and isopropyl alcohol.
2.	Spin coat polyimide, typically 10 seconds at 500 rpm.
3.	Soft bake at 120 °C 20 or 30 minutes.
4.	Apply photoresist by spinning on.
5.	Bake at 90 °C for 10 minutes.
6.	Expose photoresist using mask aligner.
7.	Develop photoresist (If the photoresist contains an alkali the polyimide will also be etched in this step.)
8.	Etch polyimide. (Use either an alkali wet etch or a sputter dry-etching process.)

Require Etching Process

- **Optical Fiber Waveguide Device**

Fiber Bragg Grating Fabrication