

**ΟΛΟΚΛΗΡΩΜΕΝΗ ΟΠΤΙΚΗ  
(INTEGRATED OPTICS)**

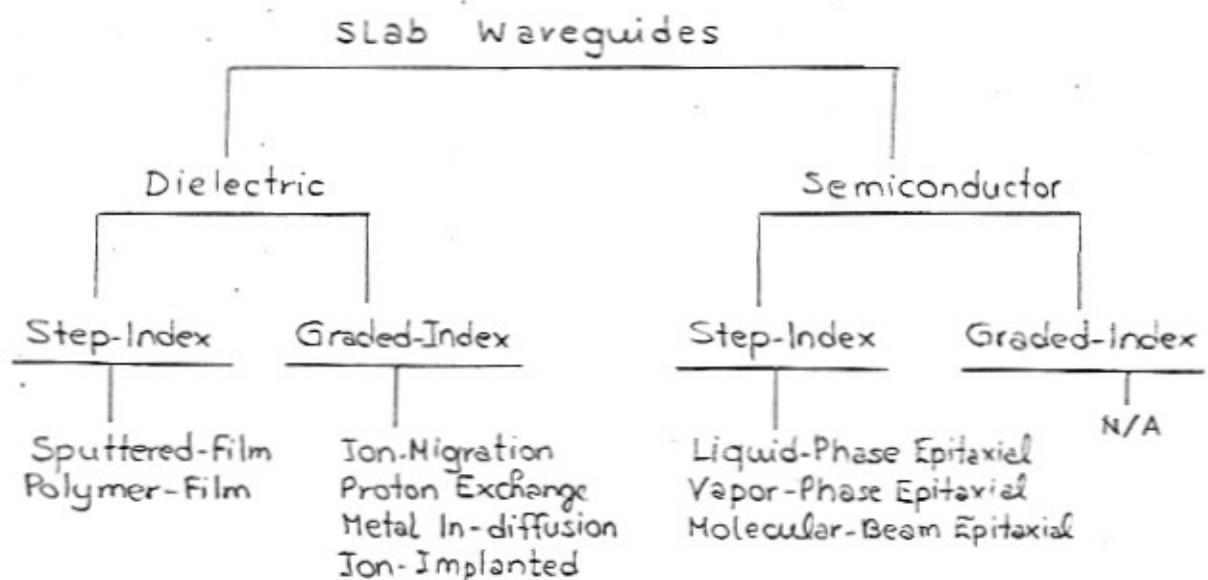
**ΜΕΘΟΔΟΙ ΚΑΤΑΣΚΕΥΗΣ  
ΟΠΤΙΚΩΝ ΚΥΜΑΤΟΔΗΓΩΝ  
(Optical Waveguides Fabrication Methods)**

Σημειώσεις

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## WAVEGUIDE FABRICATION: (from D.L. Lee)

The fabrication process for any given slab waveguide depends on the materials used and on the physical geometry (2D or 3D). The slab waveguides can be separated into 2 main categories: (a) the dielectric slab waveguides, and (b) the semiconductor slab waveguides. In each category we can distinguish 2 different types of waveguides: (1) the step-index and (2) the graded-index waveguides. Thus the slab waveguides and their corresponding fabrication processes can be summarized as follows:



A brief of each one of the above mentioned techniques will be discussed next.





## 2. Polymer - Film Waveguides:

In these step-index waveguides a polymer layer is deposited on the top of a substrate. In the solution deposit technique the substrate is covered by a polymer solution and the liquid layer is controlled by spinning the substrate at a rate of several thousand rpm in an axis perpendicular to its surface. Then, depending on the polymer used the films are dried and baked at temperatures in the range of  $60^{\circ}\text{C}$  to  $100^{\circ}\text{C}$  and for times of 5 min to 70 h. Low attenuation waveguides (0.1-0.3 dB/cm) can be fabricated with this method.

A second method involves a plasma polymerization process. An electric discharge in an environment of monomers causes fragmentation and rebonding of the monomers into polymers that are deposited on the substrate.

Using the solution technique it is rather difficult to control the uniformity and the thickness of the film. Using the vacuum discharge the growth rates are linear and typical rates are of the order of  $1000 \text{ \AA} / \text{min}$ . The table below summarizes some of the polymer waveguides

Film type	Refractive index	Attenuation (dB/cm)
Polystyrene	1.5860, TE modes 1.5888, TM modes	—
PMMA-SAN mixture	1.490-1.565	0.2
Polyurethane		
Type 9653-1	1.555	0.8
Type LX500	1.573	4
Epoxy	1.581	0.3
Photoresist (KPR)	1.615	7.0
VTMS-HMDS mixture	1.488-1.528	0.04-0.3

**Table 7.1** Composition and Optical Properties of a Number of Step-Index Dielectric Waveguides

Film Material	Film $n$	Substrate Material	Substrate $n$	Attenuation (dB/cm)
Barium silicate glass (a)	1.48–1.62 @ 0.63 $\mu\text{m}$	Fused quartz (a) Microscope slide (a)	1.512 @ 0.63 $\mu\text{m}$ —	1.2
Ta <sub>2</sub> O <sub>5</sub> (a)	2.2 @ 0.63 $\mu\text{m}$	Corning 7059 glass (a)	1.5285 @ 0.63 $\mu\text{m}$	0.9
SiO <sub>2</sub> -Ta <sub>2</sub> O <sub>5</sub> mixture (a)	1.46–2.08 @ 0.63 $\mu\text{m}$	Corning Vycor glass (a)	1.457 @ 0.63 $\mu\text{m}$	0.8
Nb <sub>2</sub> O <sub>5</sub> (a)	2.1–2.3 @ 0.63 $\mu\text{m}$	7059 glass (a)	1.5285 @ 0.63 $\mu\text{m}$	1.0–2.0
Ta <sub>2</sub> O <sub>5</sub> (a)	2.2 @ 0.63 $\mu\text{m}$	LiTaO <sub>3</sub> (x) with SiO <sub>2</sub> buffer layer	2.17, 2.18 (t)	1.0
ZnO (p)	—	Fused quartz (a)	1.512 @ 0.63 $\mu\text{m}$	—
GeO <sub>2</sub> (a)	1.6059 @ 0.55 $\mu\text{m}$	Microscope slide (a)	1.5158 @ 0.55 $\mu\text{m}$	0.7
Corning 7059 glass (a)	1.53–1.61 @ 0.63 $\mu\text{m}$	7059 glass (a)	1.5285 @ 0.63 $\mu\text{m}$	1.0

Notes. (a) Amorphous material; (p) polycrystalline material; (x) crystalline material; (t) refractive index depends on guided-mode polarization.

**Table 7.2** Optical Properties of a Number of Polymer Film Step-Index Waveguides

Film type	Refractive index	Attenuation (dB/cm)
Polystyrene	1.5860, TE modes 1.5888, TM modes	—
PMMA-SAN mixture	1.490–1.565	0.2
Polyurethane		
Type 9653-1	1.555	0.8
Type LX500	1.573	4
Epoxy	1.581	0.3
Photoresist (KPR)	1.615	7.0
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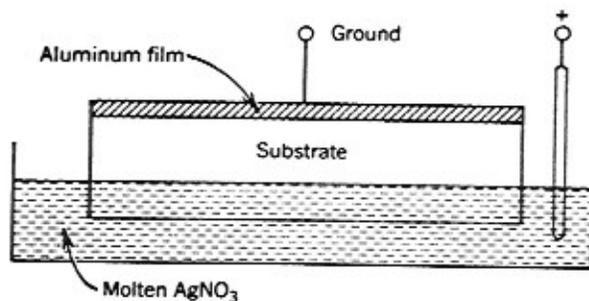
## B. Graded-Index Waveguides:

Graded-index waveguides are produced by the modification of the refractive index of the substrate near its surface by in-diffusion, or kinetic impact, or exchange of some atoms with others. The resulting refractive index profile in these cases has a continuous variation.

### 1. Ion-Migration Waveguides:

Many glass types contain mixtures of  $\text{SiO}_2$  with metal oxides such as  $\text{Li}_2\text{O}$ ,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$  and  $\text{Al}_2\text{O}_3$ . By diffusing ions such as  $\text{Ag}^+$ ,  $\text{Tl}^+$ , and  $\text{K}^+$  into the glass, the diffused region can be made to have higher refractive index than the undiffused glass.

An example of diffusing  $\text{Ag}^+$  is shown in the figure. The maxi-



imum increase of the index of refraction near the surface is 0.1. The diffusion process can be accelerated with the help of an applied electric field.

The waveguide losses with this method are of the order of a few tenths of  $\text{dB/cm}$ .

### 2. Proton-Exchange Waveguides:

$\text{LiNbO}_3$  and  $\text{LiTaO}_3$  have good electro-optic, acousto-optic, and piezoelectric properties. Thus, fabrication of waveguides using these crystalline materials is of great interest. Proton-exchange

is a technique similar to ion-migration. The difference is that instead of using other metal ions (like  $\text{Ag}^+$ ) hydrogen ions are used. Thus, metal ions from  $\text{LiNbO}_3$ ,  $\text{LiTaO}_3$  are replaced by hydrogen ions. The procedure involves the placing of the substrate in a solution of benzoic acid which is heated to  $\sim 200^\circ\text{C}$ . The  $\text{H}^+$  are created by dissociation of the acid:



The number of protons ( $\text{H}^+$ ) depends only on the temperature.

Then Li is replaced from  $\text{LiNbO}_3$  or  $\text{LiTaO}_3$ .

For these materials the proton exchange has significant effect only on the extraordinary index of refraction. The change of the extraordinary index is  $\sim 0.12$  (at  $\lambda_0 = 0.6328 \mu\text{m}$ ). The process is very rapid. The waveguide losses are as low as  $0.5 \text{ dB/cm}$ .

### 3. Metal In-Diffusion Waveguides:

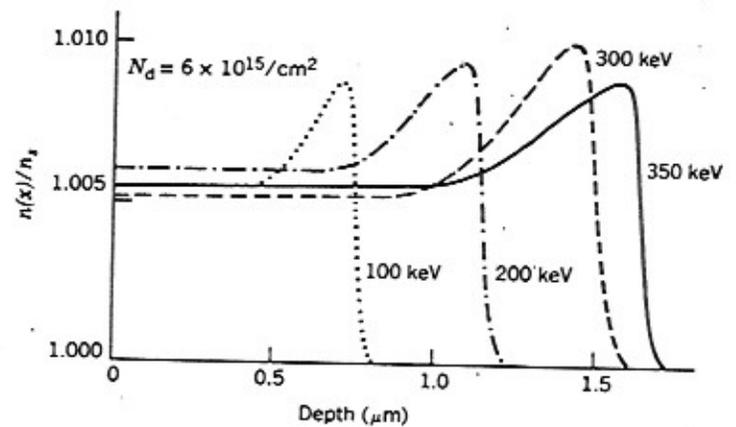
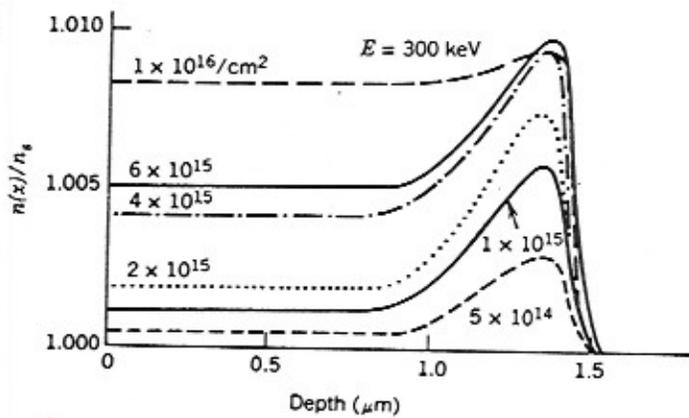
In this method a thin metallic film of thickness ranging from  $150 - 1500 \text{ \AA}$  is sputtered or evaporated on the top of the substrate. Then the substrate is heated in inert (or combinations of inert and oxygen) atmosphere at  $\sim 1000^\circ\text{C}$  for a period of several hours. Thus, the metal is diffused into the substrate creating the film layer. Usually, a Gaussian index distribution is produced. The method has been used on  $\text{LiNbO}_3$  &  $\text{LiTaO}_3$ . For  $\text{LiTaO}_3$  Nb was used while for  $\text{LiNbO}_3$  Ti was used for the metallic layer.

Maximum changes of the refractive index is  $1\% - 3\%$  (at  $\lambda_0 = 0.6328 \mu\text{m}$ )

Propagation losses are less than  $1 \text{ dB/cm}$ .

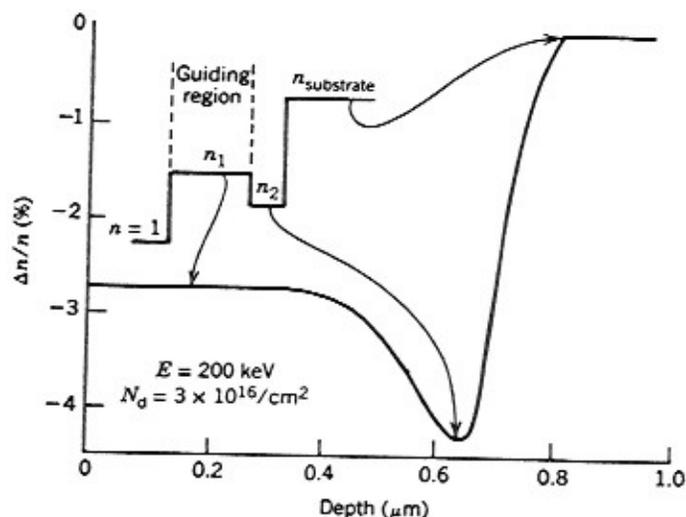
#### 4. Ion-Implanted Waveguides:

In this method energetic ions impinging on a substrate are used to cause the increase of the index of refraction. The ions release their kinetic energy through a series of collisions and finally come to rest inside the substrate. The kinetic energies of the accelerated ions are of the order of 10 - 500 keV. The resulting index profile depends on the ion flux and kinetic energy. Example profiles of  $\text{He}^+$  implants into fused  $\text{SiO}_2$  are shown in the following figures.



Ion-implanted waveguides in fused silica have been fabricated using a wide range of ions, including He, Li, C, P, Xe, and Te.

Ion-implantation using ions such as N, O, B, Ne, H, and He has also been used to create waveguides in  $\text{LiNbO}_3$  and  $\text{LiTaO}_3$ . For these materials however the implantation creates regions of lower permittivity. An example refractive index profile is shown in the next figure.



Losses in ion-implanted waveguides can vary from  $5 - 0.1$  dB/cm.

### B. Semiconductor Waveguides:

The procedures used to fabricate waveguides on semiconductor materials result in step-index waveguides.

By controlling the waveguide geometry and alloy compositions and doping we can tailor not only the permittivity but also important optoelectronics parameters such as band-gap, carrier confinement, carrier transport, and optical absorption.

Two primary semiconducting materials are used in integrated optics:  $Ga_{1-x}Al_xAs$  and  $Ga_{1-x}In_xAs_{1-y}P_y$  ( $x, y$  are mole fractions).

The most commonly used methods for fabricating waveguides in these semiconductor are summarized next.

#### 1. Liquid-Phase Epitaxial Film Waveguides:

Liquid-Phase epitaxy (LPE) is the technique by which an epitaxial crystalline layer is grown on a single-crystal substrate

by solidification of a molten solution that is saturated at the growth interface. LPE is extensively used for the fabrication of single-crystal layers of ternary alloys of GaAlAs on GaAs substrates and quaternary alloys of GaInAsP on InP substrates.

The primary factors controlling the properties of LPE grown films are substrate orientation, melt and substrate temperatures, melt composition, cooling rate, and growth time. Accurate control of these parameters can produce repeatable films of precise composition and thickness.

## 2. Chemical Vapor Deposition Epitaxial Waveguides:

Chemical vapor deposition (CVD) (or vapor-phase epitaxy VPE) refers to the process of growing crystallographically oriented films on a substrate by the reaction of chemical vapors at high temperatures. This method is compatible with large-scale commercial processing. The two most widely used CVD procedures are:

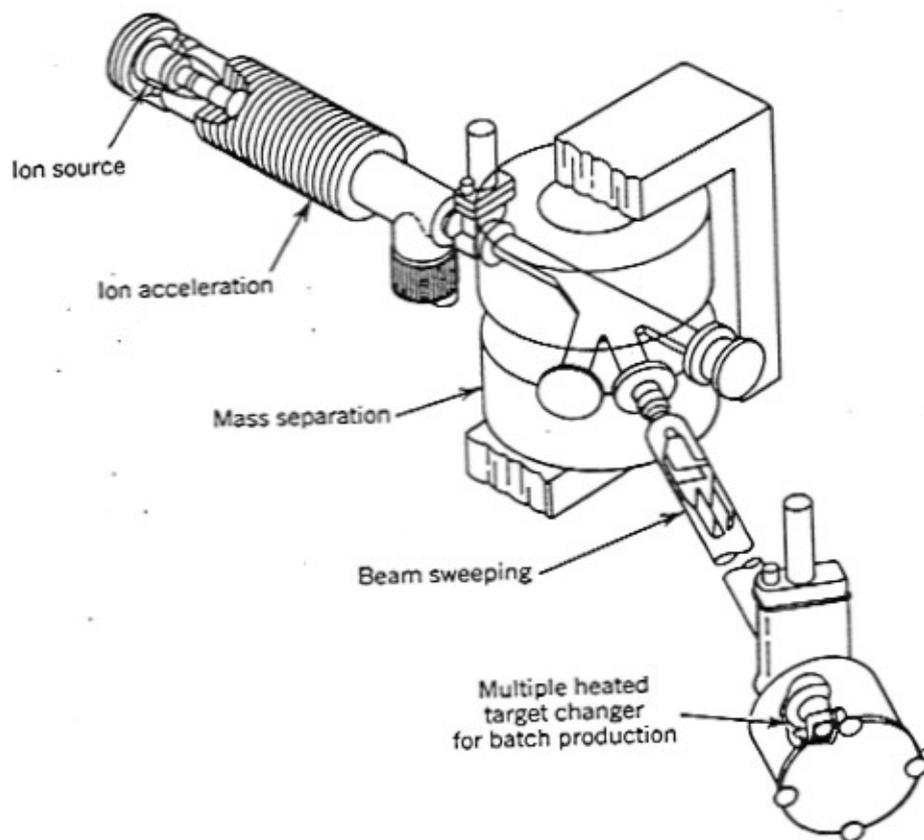
- a. Hydride / Chloride CVD for GaInAsP compounds
- b. Metal Organic CVD (MOCVD) for both GaInAsP and GaAlAs compounds.

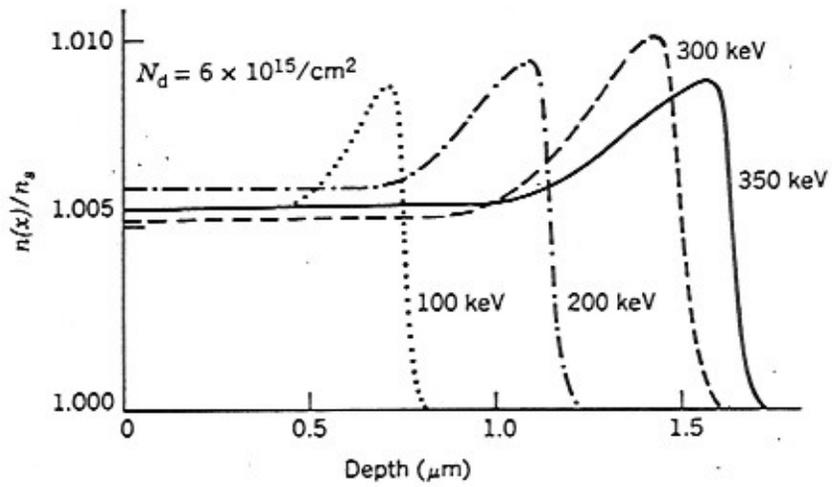
Typical film growth rates are of the order of  $3000 \text{ \AA} / \text{min}$ .

## 3. Molecular-Beam Epitaxial Waveguides:

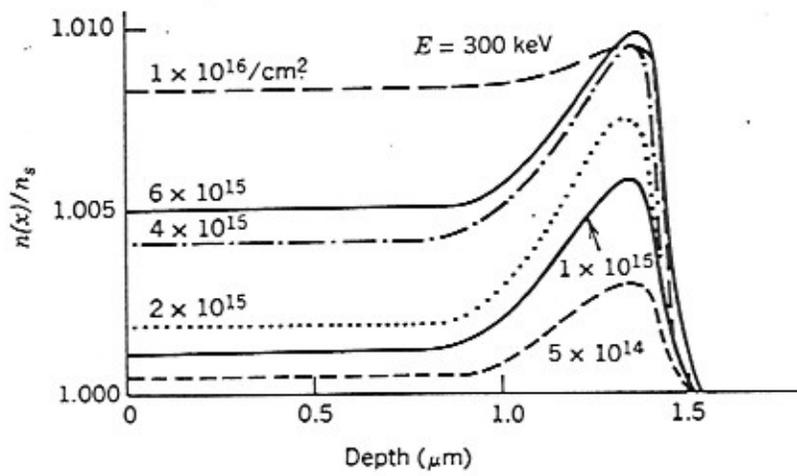
Molecular-beam epitaxy (MBE) is the process by which epitaxial films are grown from beams of atoms or molecules by their reaction with a crystalline surface under ultrahigh vacuum conditions.





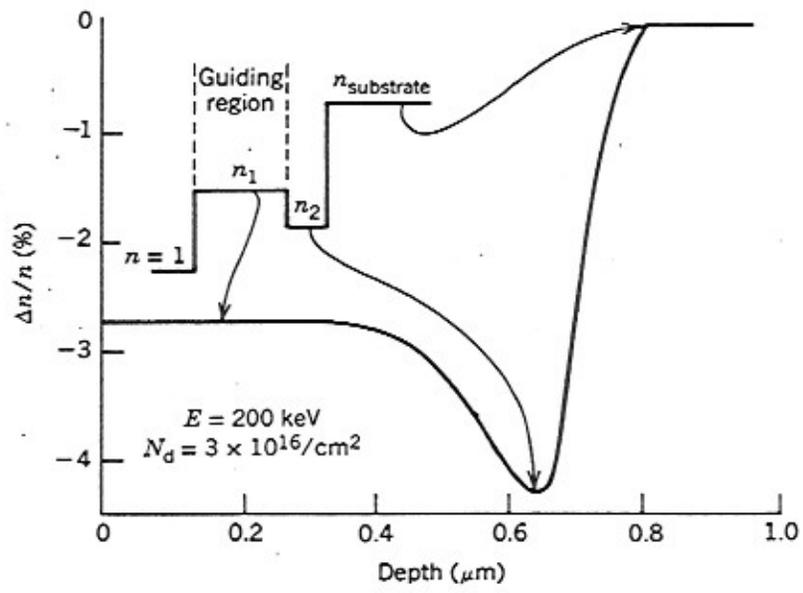


(a)



(b)

Fused silica (He<sup>+</sup> implants)



$\text{He}^+$  implant on  $\text{LiTaO}_3$

