Waveguide Fabrication Techniques

Integrated Optics

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Optical Waveguides
Fabrication Techniques

General Methods

Deposition Techniques

- Deposit a higher index thin-film on a lower-index substrate

Substitution Techniques

- Create a higher index layer in a substrate by introducing new atoms

General Criteria for Technique Selection

- Thickness and Refractive Index of Thin Layer
- Losses of the Substrate
- Material Purity
- Stability of Process and Thin Film
- Reproducibility of the technique
- Cost

A. Boudrioua, "Photonic Waveguides", J. Wiley & Sons, 2009

Optical Waveguides
Fabrication Techniques

Planar (Slab) Waveguides

Dielectric Materials

Step-Index (deposition)

- Sputtered-film
- Polymer Film

Graded-Index (substitution)

- Ion Migration
- Proton Exchange
- Metal In-diffusion
- Ion Implantation

Semiconductor Materials

Step-Index (deposition)

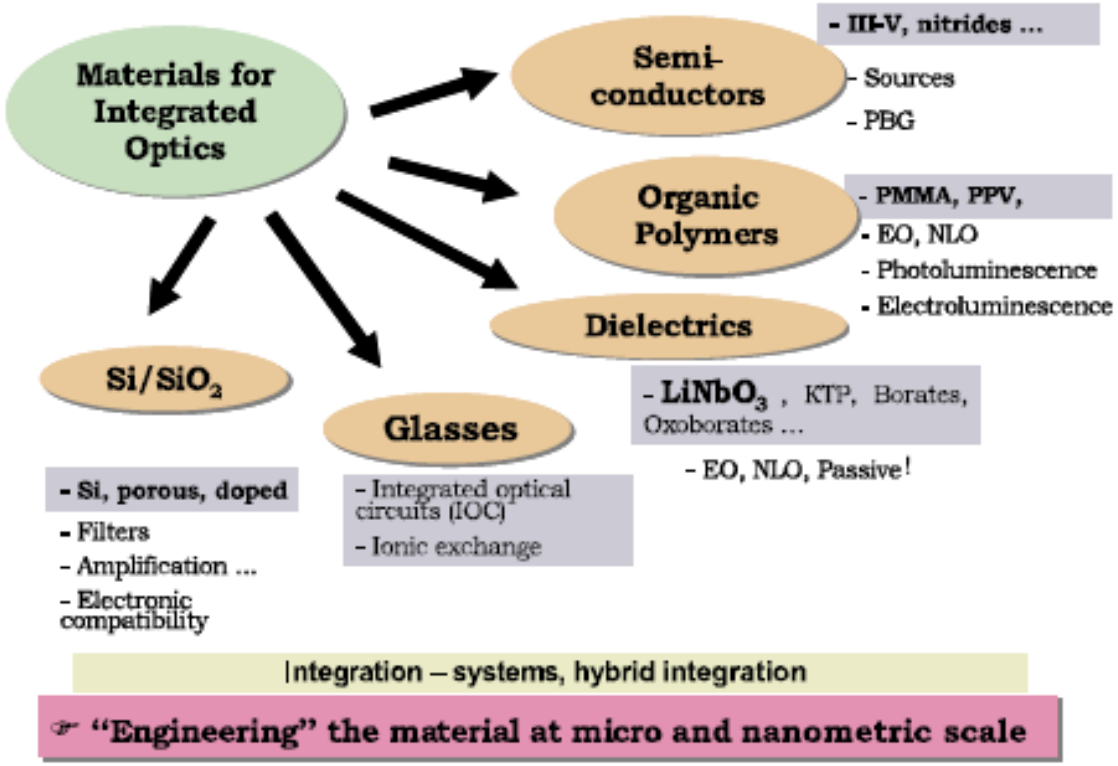
- Liquid-Phase Epitaxy (LPE)
- Vapor-Phase Epitaxy (VPE)
- Molecular Beam Epitaxy (MBE)

Graded-Index (substitution)

- N/A

D. L. Lee, "Electromagnetic Principles of Integrated Optics",J. Wiley & Sons, 1988

Schematic Presentation Of Different Types Of Optical Materials



A. Boudrioua, "Photonic Waveguides", J. Wiley & Sons, 2009

Deposition Processes

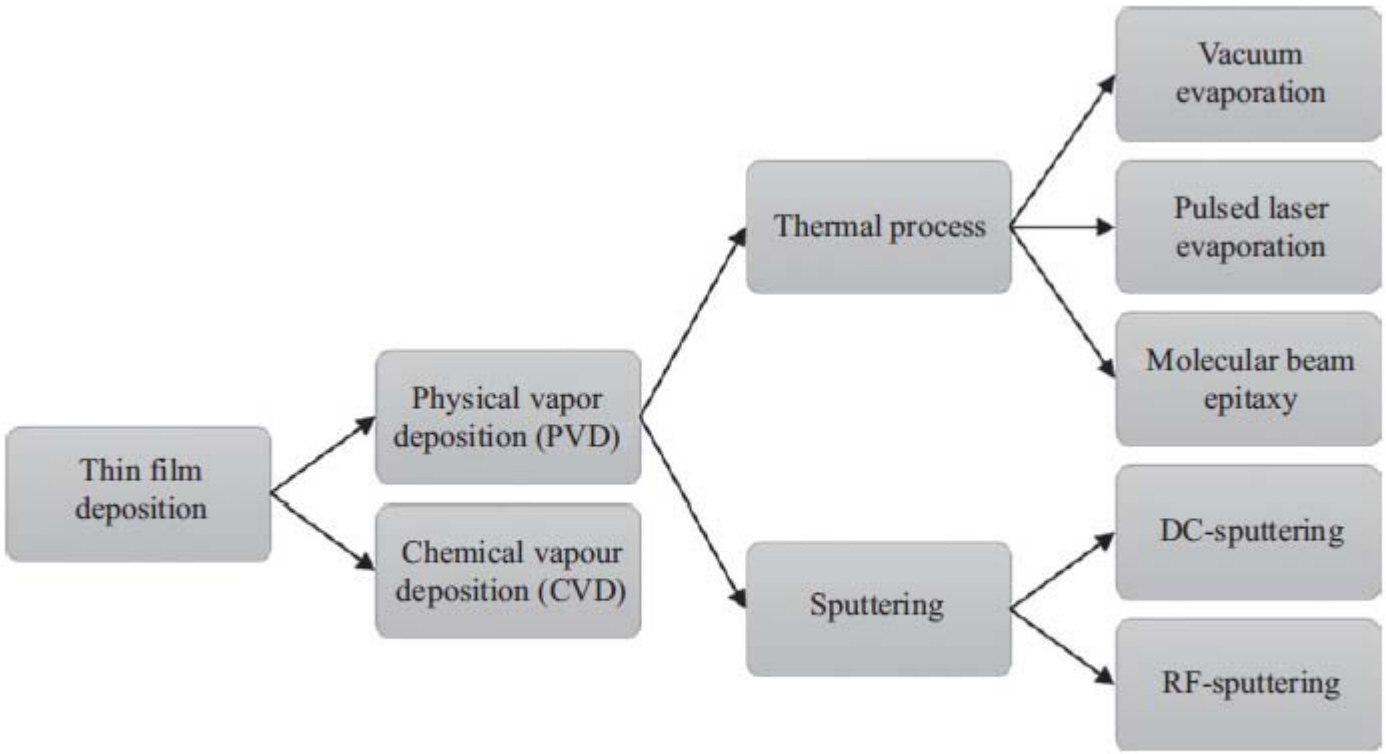
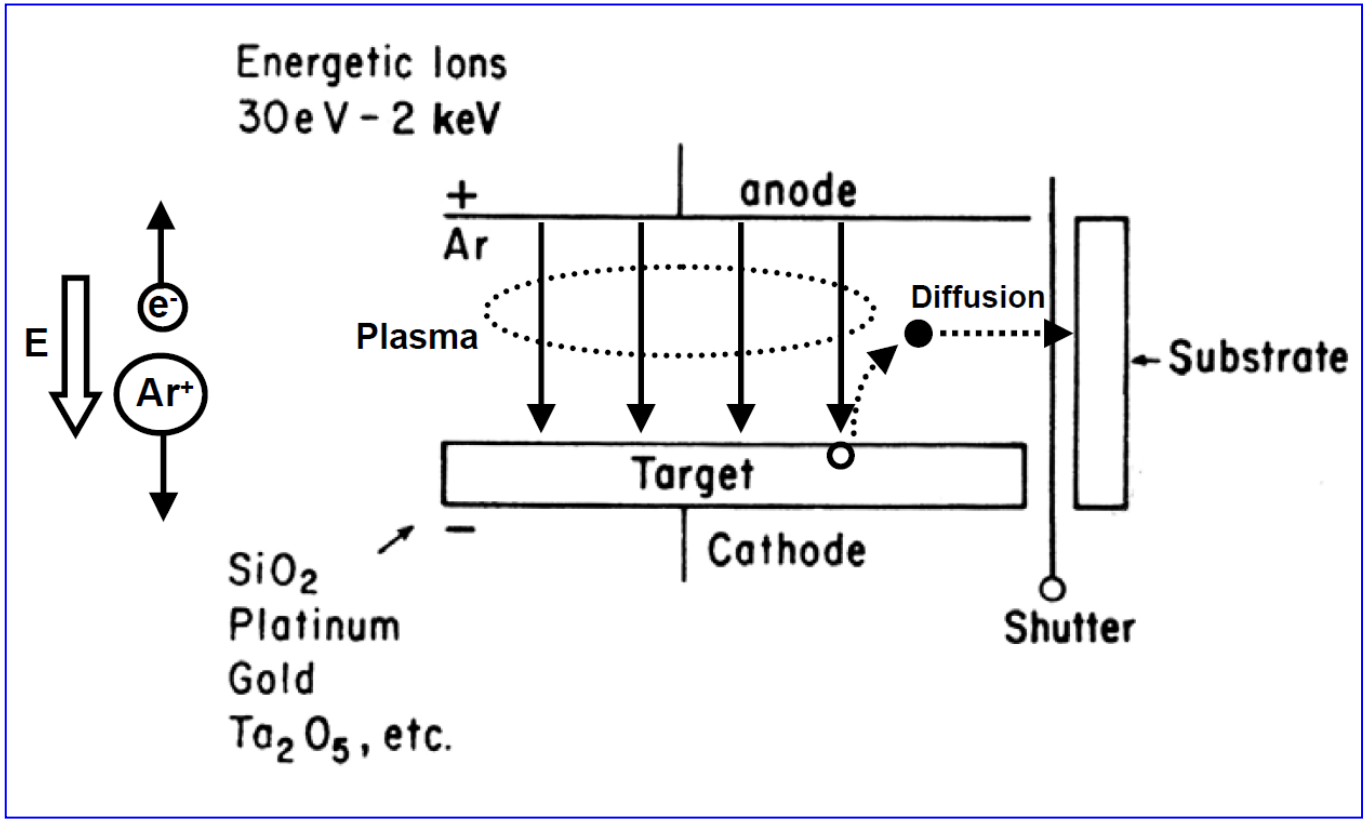


Figure 7.1 Thin-film deposition processes

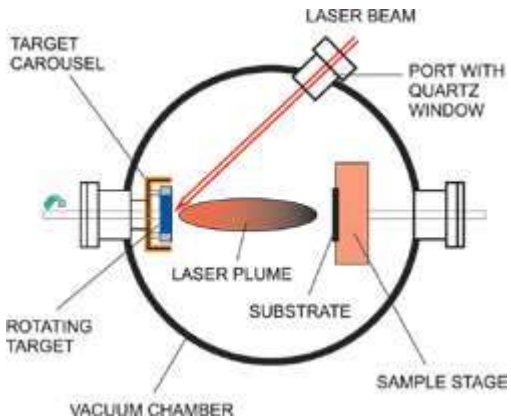
Righini and Ferrari, Eds., "Integrated Optics: Modeling, Platforms, Fabrication Techniques", vol. 1, IET series, 2021

Sputtered-Film Waveguides

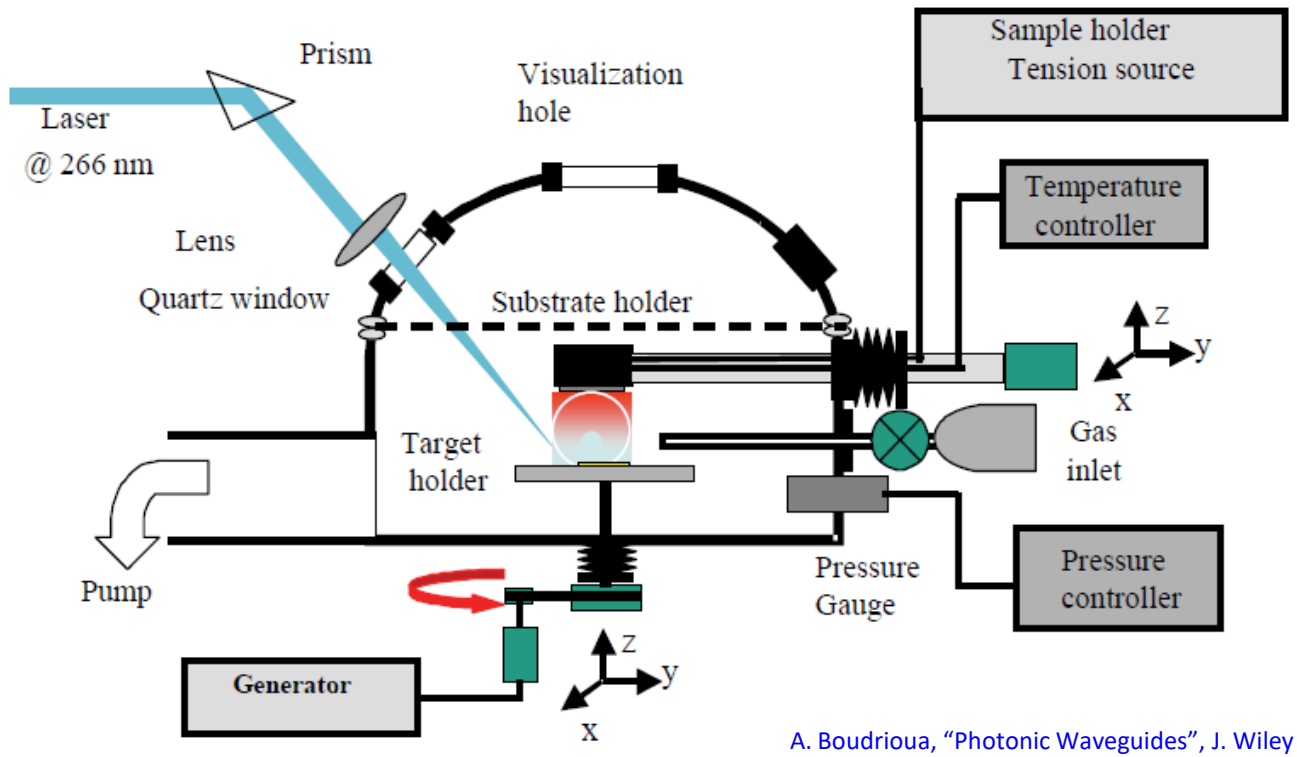


D. L. Lee, "Electromagnetic Principles of Integrated Optics",J. Wiley & Sons, 1988

Principle of thin film deposition by using pulsed laser deposition (PLD)



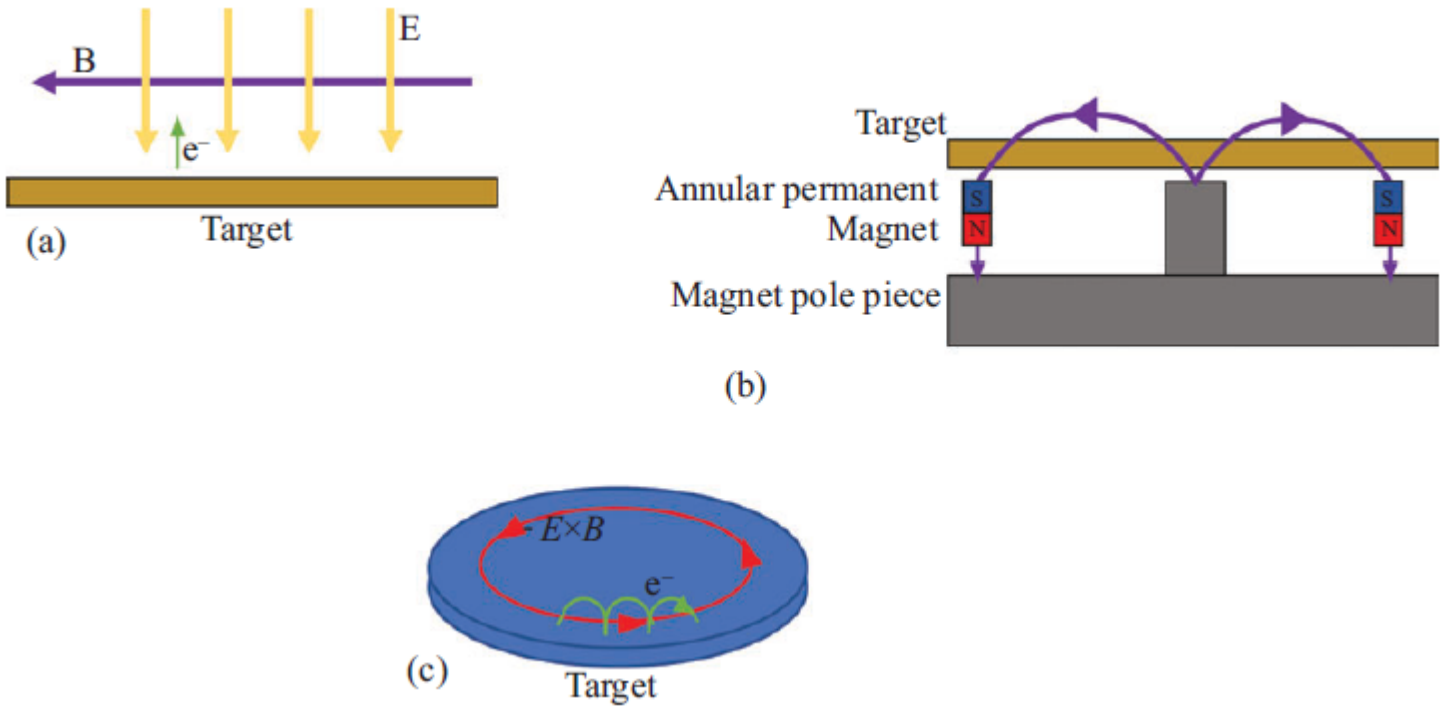
http://www.andor.com/learning-academy/pulsed-laser-deposition-an-introduction-to-pulsed-laser-deposition



A. Boudrioua, "Photonic Waveguides", J. Wiley & Sons, 2009

Sputtered-Film Waveguides

Magnetron sputtering principle

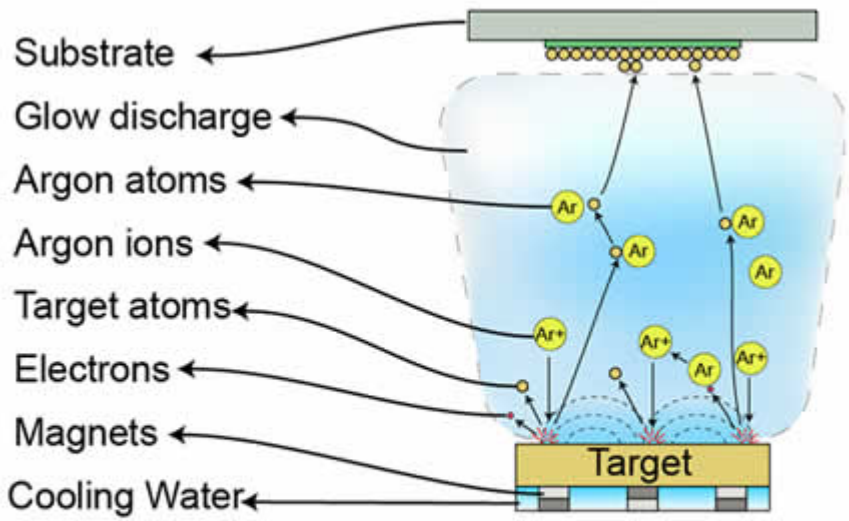


(a) Planar magnetron-sputtering arrangement: a static magnetic field is created parallel to the surface of the sputtering target to retain secondary electrons in that region; (b) annular design and (c) electrons drift in the $-\vec{\mathbf{E}} \times \vec{\mathbf{B}}$ *direction, actually executing a cycloidal path*

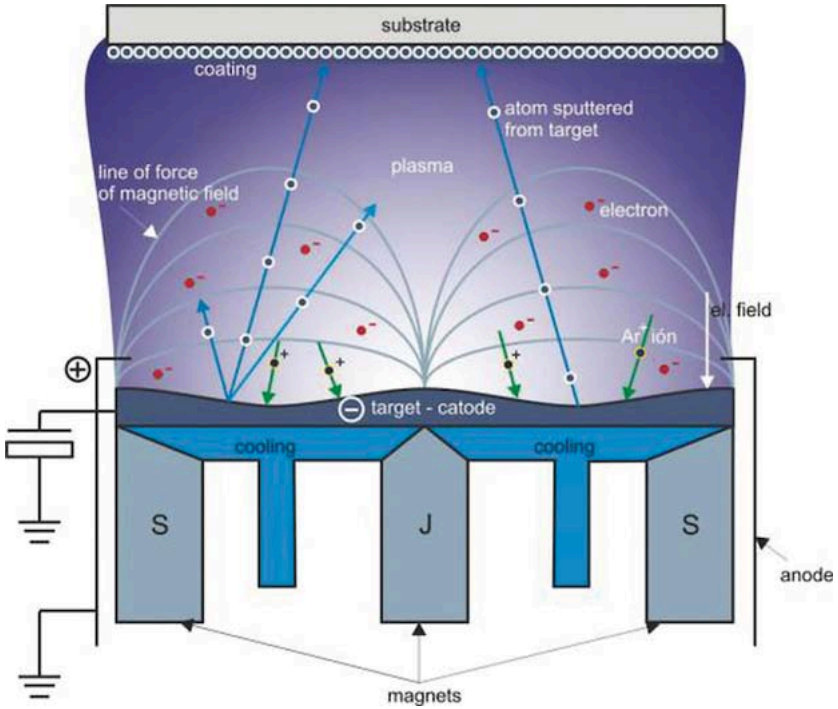
Righini and Ferrari, Eds., "Integrated Optics: Modeling, Platforms, Fabrication Techniques", vol. 1, IET series, 2021

Sputtered-Film Waveguides

Magnetron sputtering principle



The basic components of a magnetron sputtering system. Ionized Argon bombards a target, releasing atoms which form layers on a substrate. Electrons and Argon ions form a plasma, which is located near the target due to the magnetic field, resulting in greater efficiency and quality.

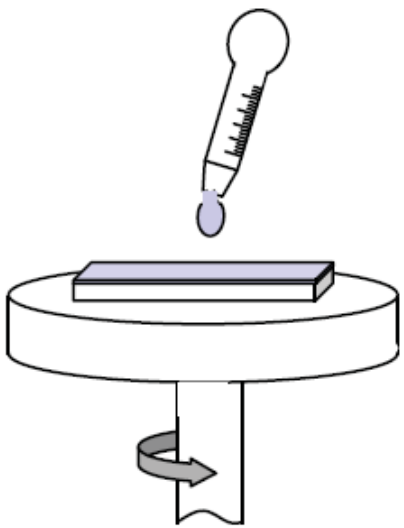


https://www.brown.edu/research/labs/xiao/magnetic-sputtering-technology-summary

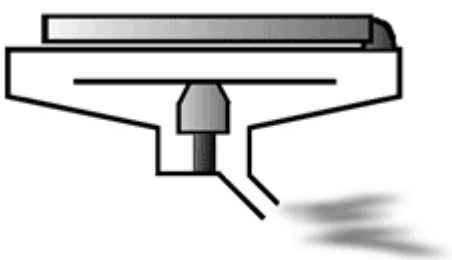
https://sites.google.com/site/vitalyslab/

Techniques for Polymer Waveguides

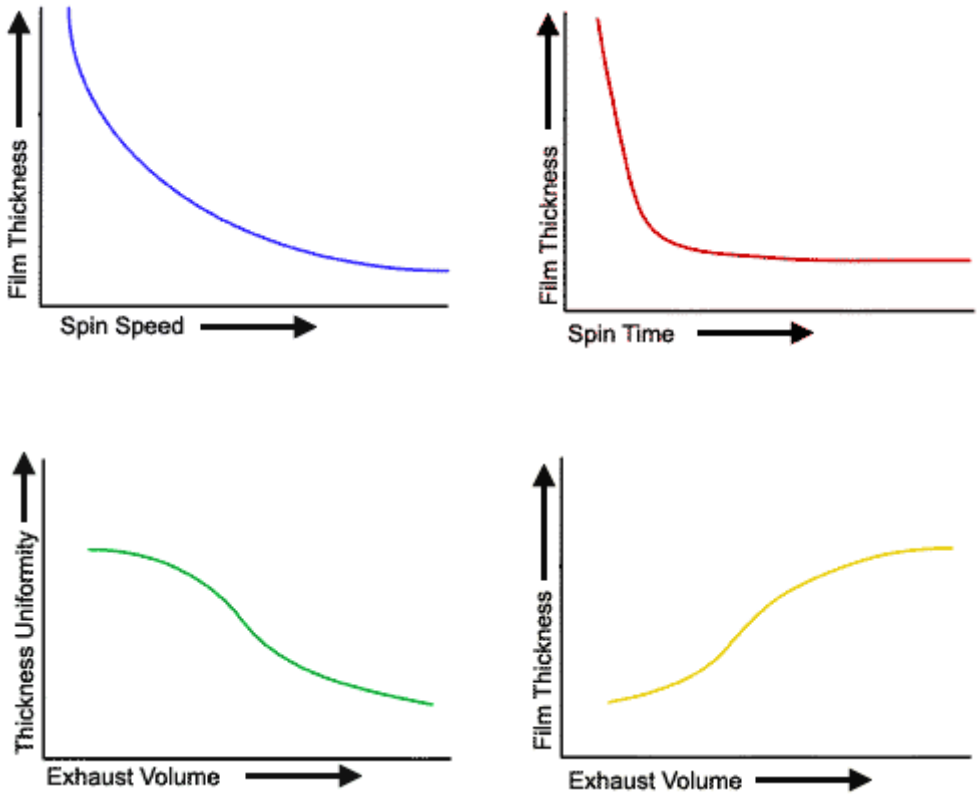
Spin Coating



A. Boudrioua, "Photonic Waveguides", J. Wiley & Sons, 2009



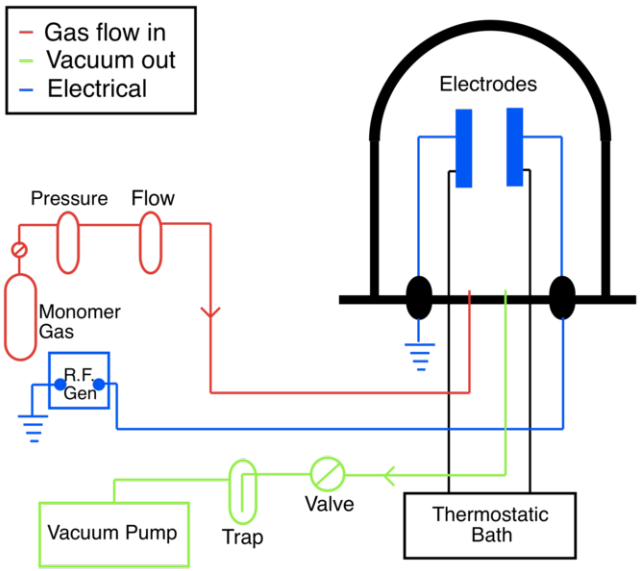
Process Trend Charts

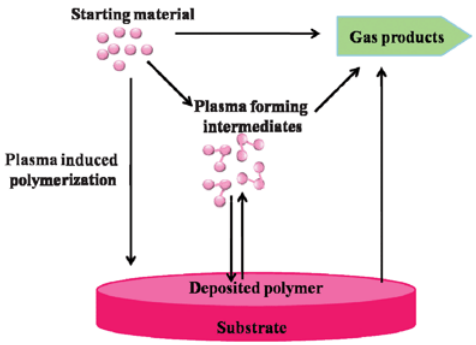


http://www.brewerscience.com/spin-coating-theory

Techniques for Polymer Waveguides

Plasma Polymerization





https://commons.wikimedia.org/wiki/File:Glow_Discharge_apparatus_color.png

Materials for Polymer Waveguides

Table 9.1 Properties of conventional optical polymers (Ma et al. 2002)

Material	Refractive index (n)	T_g (°C)	Loss (dB/cm)
PMMA	1.49	105	0.2 at 850 nm
PS	1.59	100	–
PC	1.58	145	–
PU	1.56	–	0.8 at 633 and 1,064 nm
Epoxy resin	1.58	–	0.3 at 633 nm; 0.8 at 1,064 nm

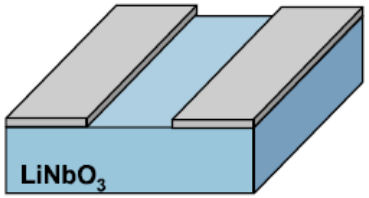
X. Colin Tong, "Advanced Materials for Integrated Optical Waveguides", Springer-Verlag, 2014

Some Advanced Materials for Polymer Waveguides

Polymer type	Patterning techniques	Propagation loss, single-mode waveguide (dB/cm) (wavelength, nm)	Other properties (wavelength, nm)
Acrylate (Polyguide)	Diffusion	0.18 (800) 0.2 (1,300) 0.6 (1,550)	Laminated sheets Excimer-laser machinable
Acrylate	Photoexposure/ wet etch, RIE, laser ablation	0.02 (840) 0.3 (1,300) 0.8 (1,550)	Birefringence: 0.0002 (1,550) Crosslinked, T_g: 25 °C Environmentally stable
Halogenated acrylate	Photoexposure/ wet etch, RIE, laser ablation	0.01 (840) 0.06 (1,300) 0.2 (1,550)	Birefringence: 0.000001 (1,550) Crosslinked, T_g: −50 °C Environmentally stable
Halogenated acrylate	RIE	0.02 (830) 0.07 (1,310) 1.7 (1,550)	Birefringence: 0.000006 (1,310) T_g: 110 °C
Deuterated polysiloxane	RIE	0.17 (1,310) 0.43 (1,550)	Environmentally stable
Fluorinated polyimide	RIE	TE: 0.3, TM: 0.7 (1,310)	PDL: 0.4 dB/cm (1,310) Environmentally stable
Fluorinated polyimide (Ultradel)	Photoexposure/ wet etch	0.4 (1,300) 1.0 (1,550)	Birefringence: 0.025, crosslinked, thermally stable
Polyetherimide (Ultem)	RIE, laser ablation	0.24 (830)	Thermally stable

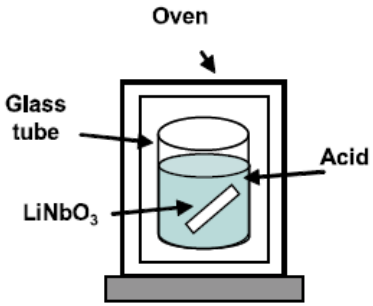
X. Colin Tong, “Advanced Materials for Integrated Optical Waveguides”, Springer-Verlag, 2014

Ion (Proton) Exchange (H+) in Lithium Niobate



Sample preparation:

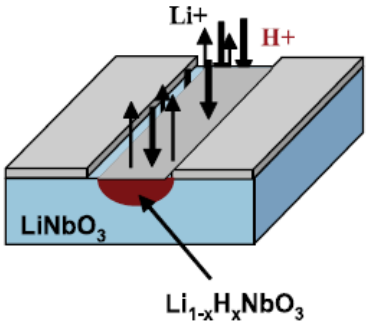
- ❑ Cleaning
- ❑ Metallic mask of (Al, Ta).



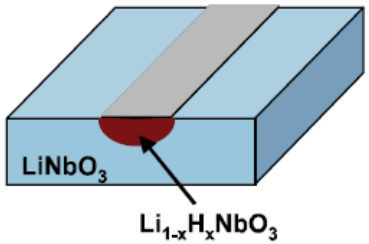
Emersion into an acid bath:

- ❑ Benzoic: C_6H_5COOH.

Temperature: 120-250 °C
Time: 15 -90 min



☞ **Exchange of Li+ by H+ : $Li_{1-x}H_xNbO_3$**



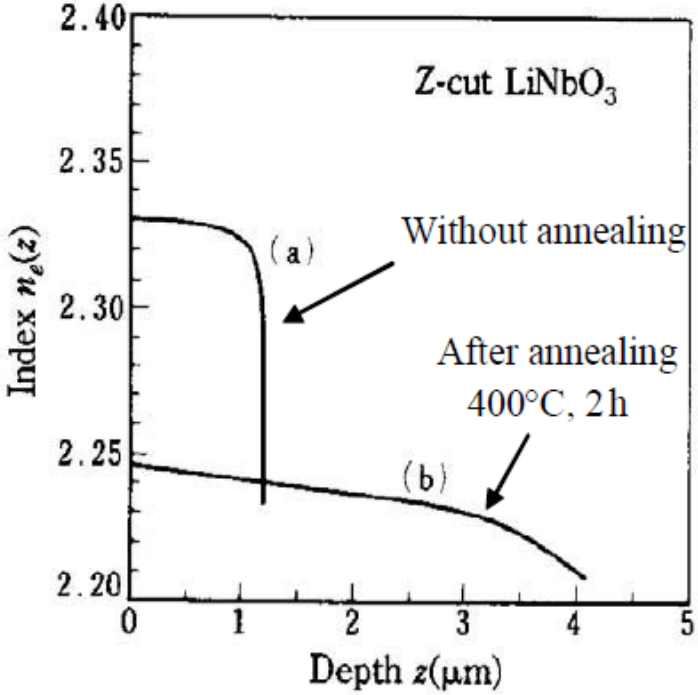
Thermal annealing:

- ❑ Temperature ~ 350 °C
- ❑ Time: several hours
- ❑ Atm.: air

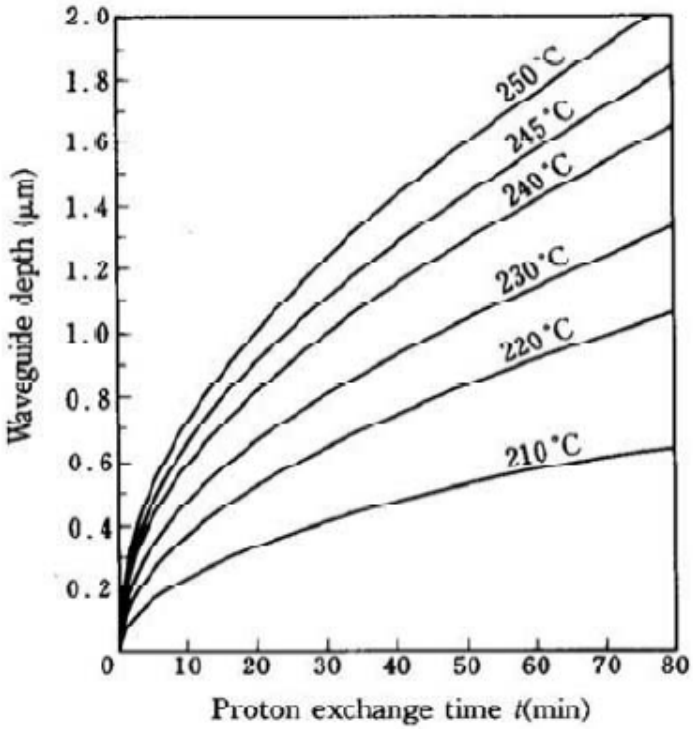
A. Boudrioua, "Photonic Waveguides", J. Wiley & Sons, 2009

Proton Exchange (H+) in Lithium Niobate

Typical index profile of a H+:LiNbO3 (z-cut) waveguide

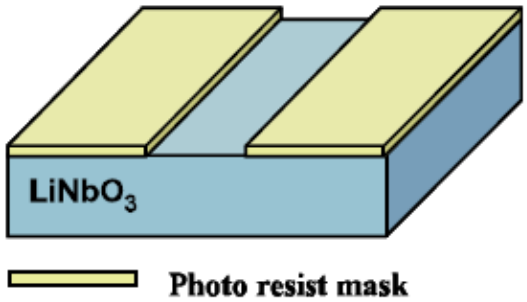


H+:LiNbO3 (z-cut) thickness variation versus proton exchange duration for different temperature values

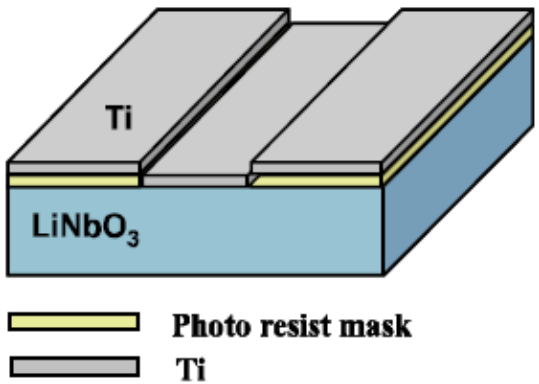


A. Boudrioua, "Photonic Waveguides", J. Wiley & Sons, 2009

Ti-Indiffusion in Lithium Niobate



Sample preparation:
- ❑ Cleaning
- ❑ Mask deposition in cleaning room

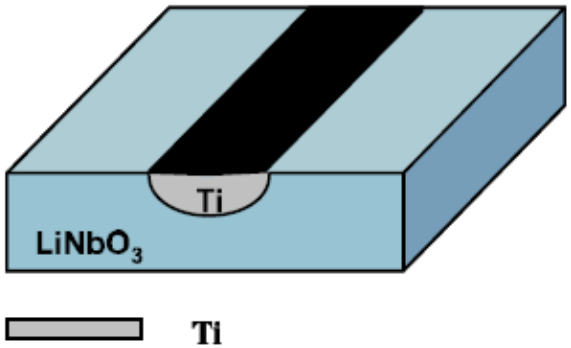


Deposition of Ti:
- ❑ By electron bombardment
- ❑ By RF sputtering
  - ~ 240 Å/min in Argon gas
  - 3-4 Å/min makes it possible to control the guide thickness

Melting of Ti = 1,725°C.

The sample is heated

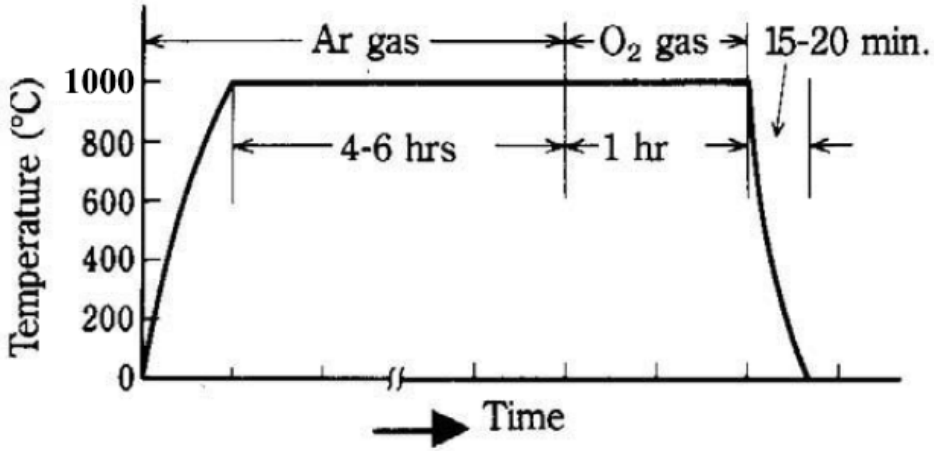
The photo resist is removed by using a solvent



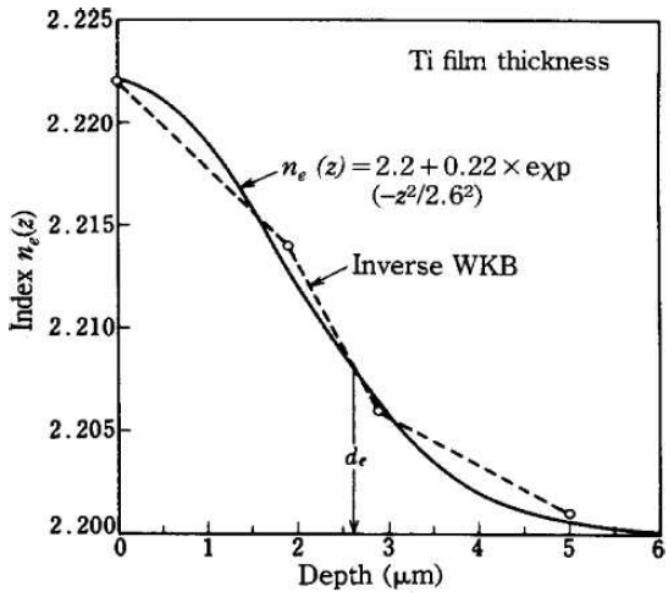
Thermal diffusion:
- ❑ Diffusion of Ti into the substrate by using annealing procedure at 1,000°C.

A. Boudrioua, "Photonic Waveguides", J. Wiley & Sons, 2009

Ti-Indiffusion in Lithium Niobate



Typical temperature profile for titanium diffusion

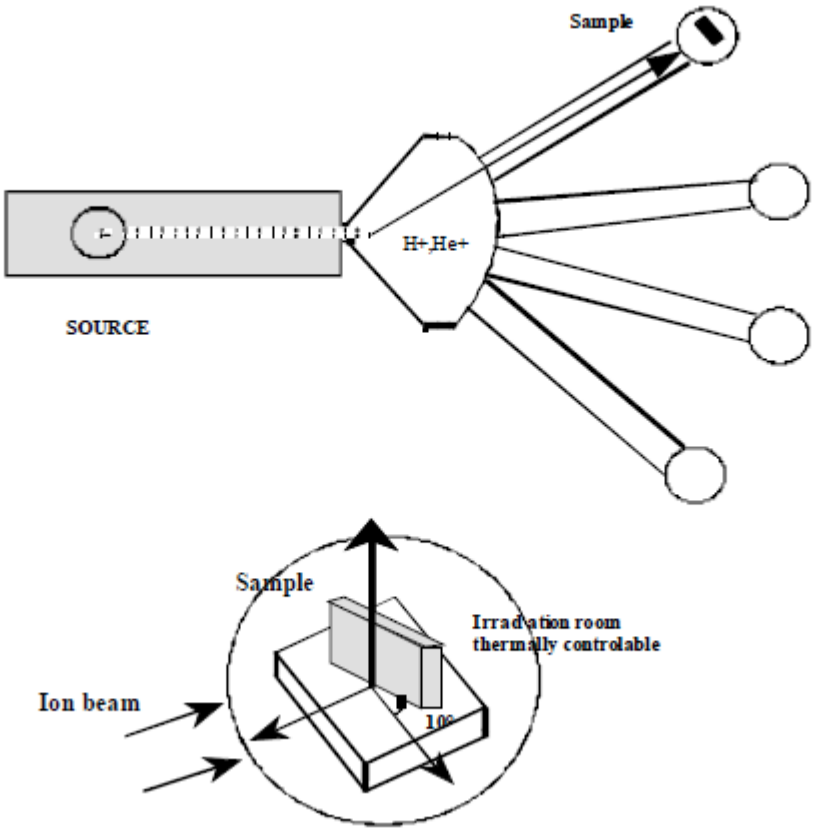


index profile of a titanium diffusion guide

A. Boudrioua, "Photonic Waveguides", J. Wiley & Sons, 2009

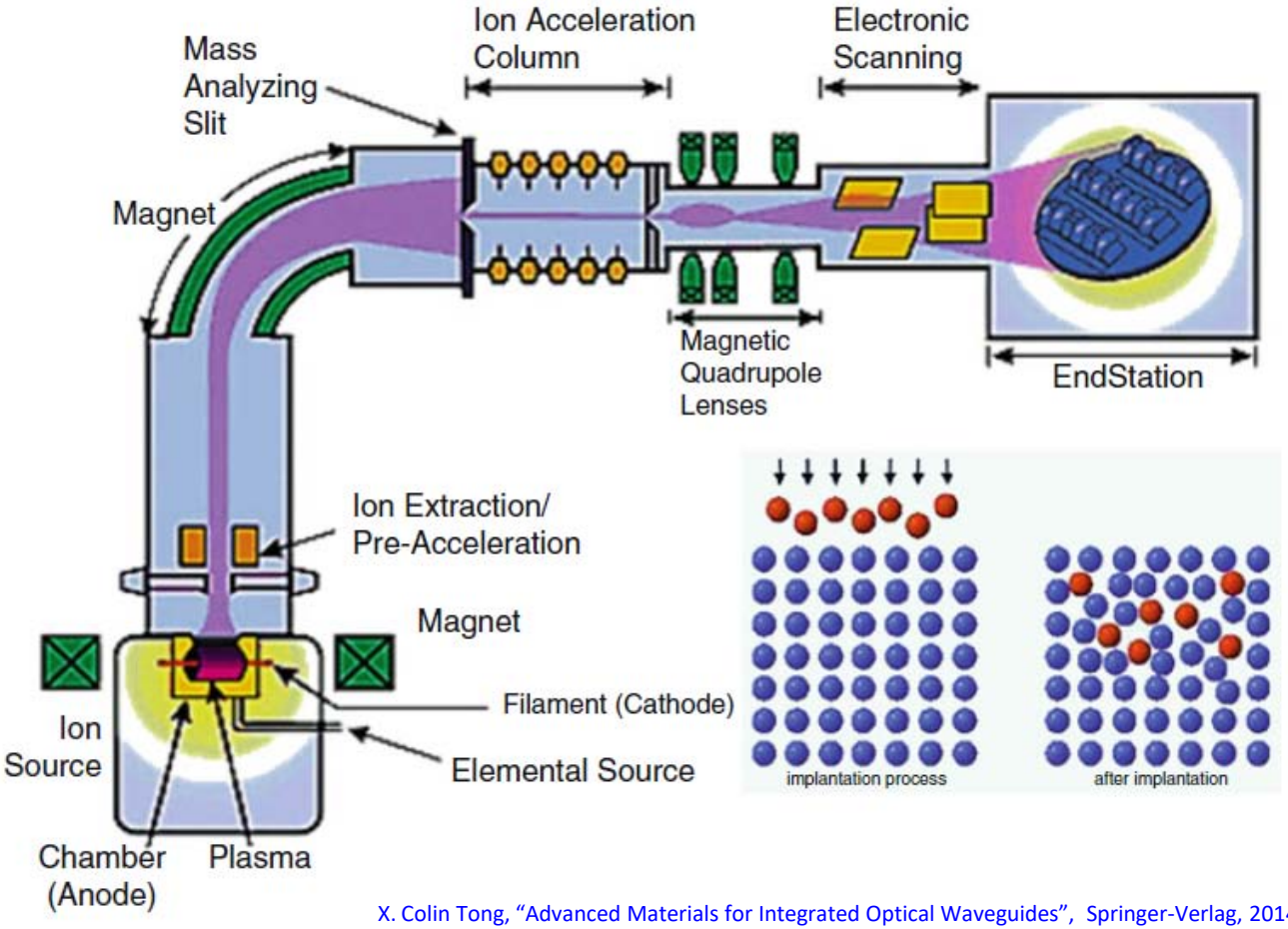
Ion Implantation

Scheme of the Van de Graaff accelerator (300 KeV – 2.2 MeV)



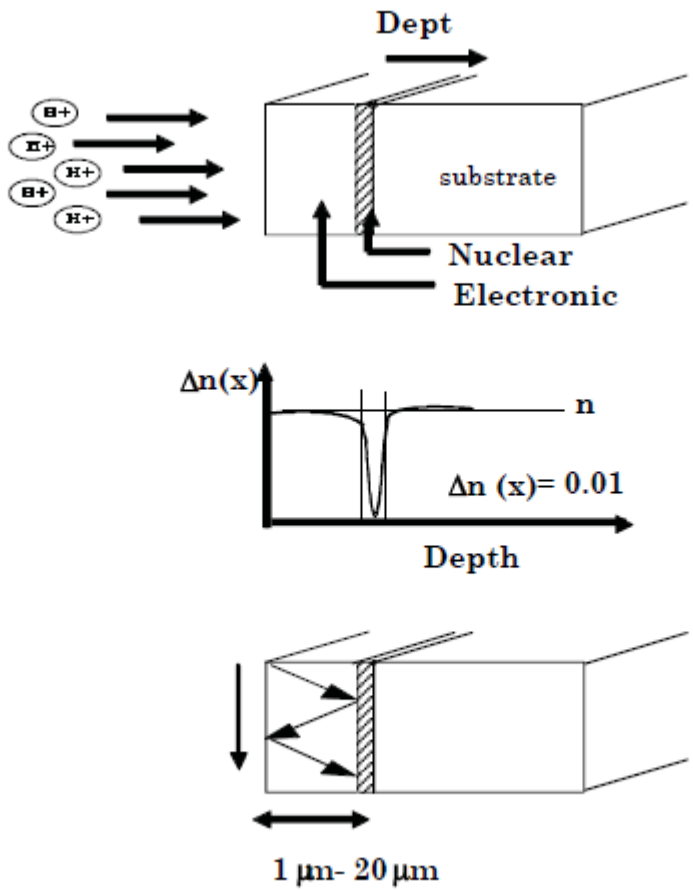
A. Boudrioua, “Photonic Waveguides”, J. Wiley & Sons, 2009

Ion Implantation Waveguide Fabrication Process



X. Colin Tong, "Advanced Materials for Integrated Optical Waveguides", Springer-Verlag, 2014

Effects of implantation on the material refractive index

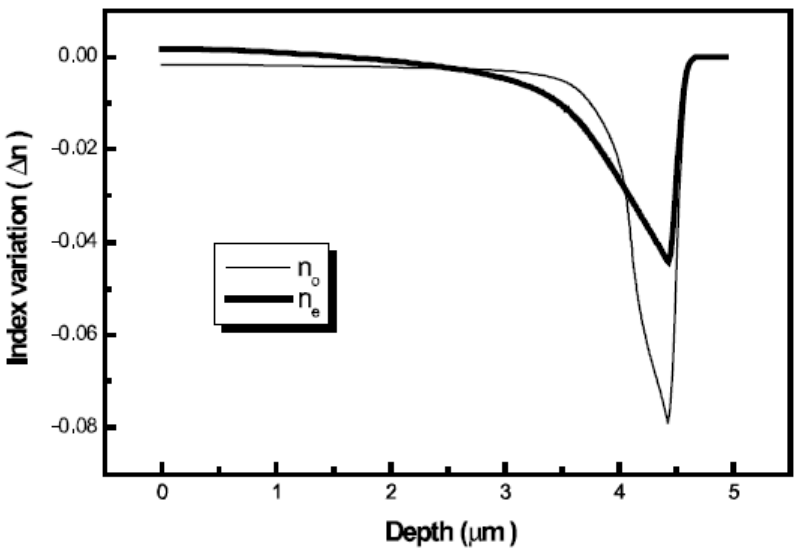


A. Boudrioua, "Photonic Waveguides", J. Wiley & Sons, 2009

Ordinary and extraordinary index profiles of $LiNbO_3$ -$LiTaO_3$ waveguide fabricated by He+ implantation

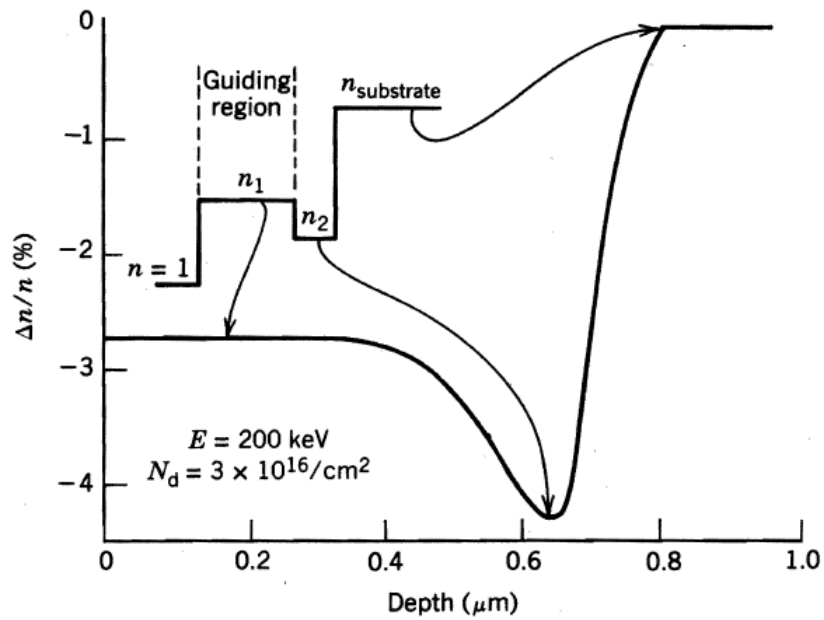
$LiNbO_3$

dose = 2×10^{16} ions/cm^2 and energy = 2 MeV



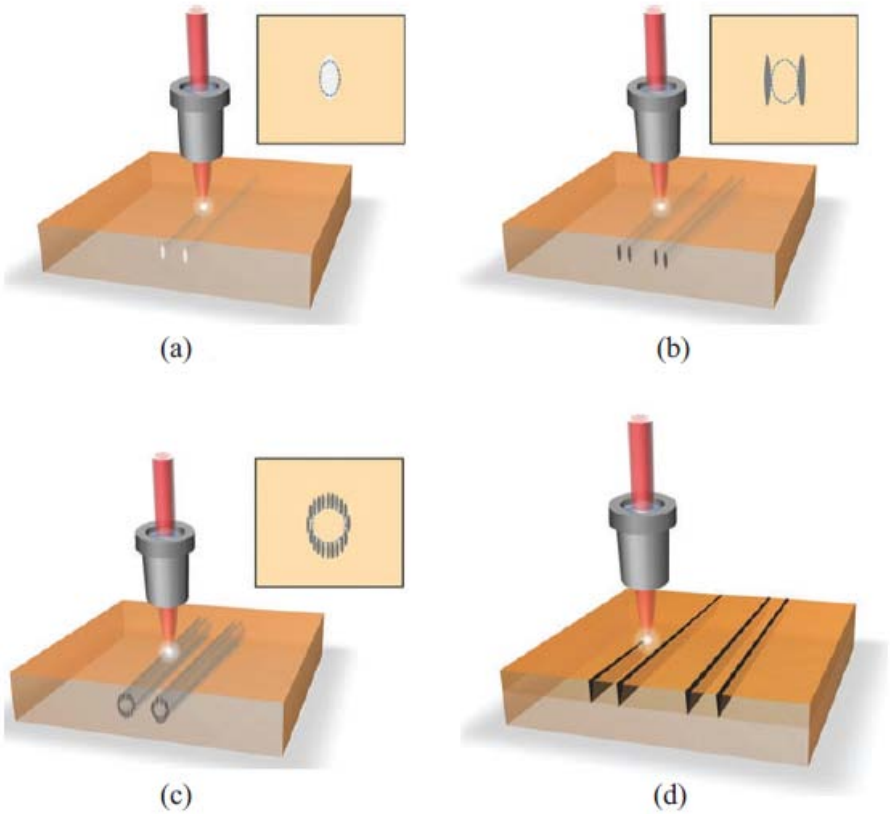
A. Boudrioua, "Photonic Waveguides", J. Wiley & Sons, 2009

$LiTaO_3$



D. L. Lee, "Electromagnetic Principles of Integrated Optics",J. Wiley & Sons, 1988

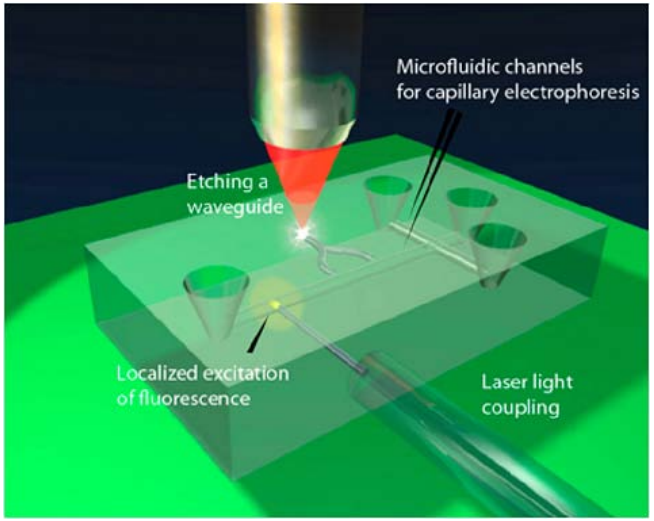
Waveguides by Laser Writing



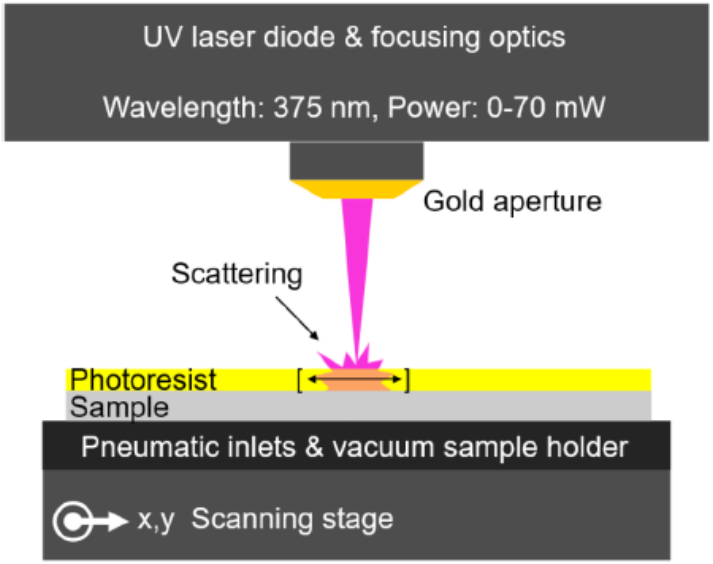
Fabrication procedure of fs-laser micromachined waveguides in crystals: (a) type I, (b) type II, (c) type III and (d) type IV configurations. The shadows represent the fs-laser-induced tracks and the dashed lines indicate the spatial locations of the waveguide cores. © 2014 John Wiley and Sons. Reprinted, with permission, from Reference [21]

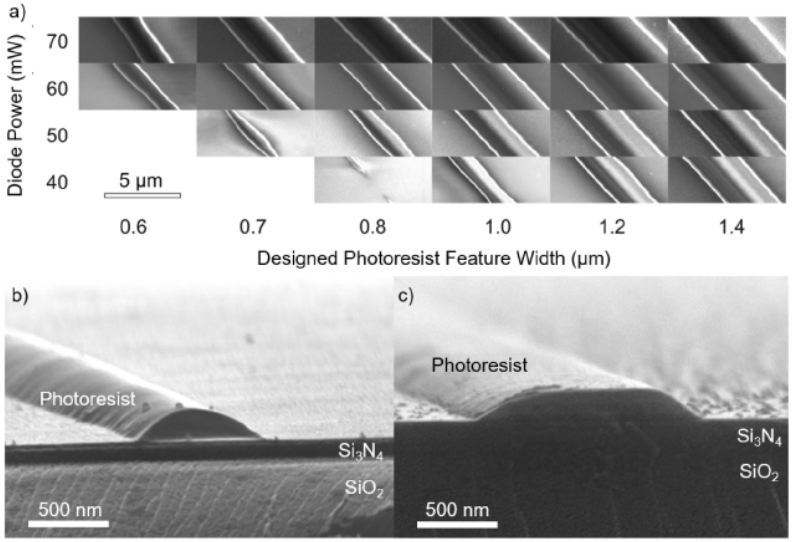
Righini and Ferrari, Eds., "Integrated Optics: Modeling, Platforms, Fabrication Techniques", vol. 1, IET series, 2021

Waveguide Formation by Direct Writing



G.C. Righini & A. Chiappini, "Glass Optical Waveguides: A Review of Fabrication Techniques", Opt. Eng., 53(7) 0171819 (July 2014)

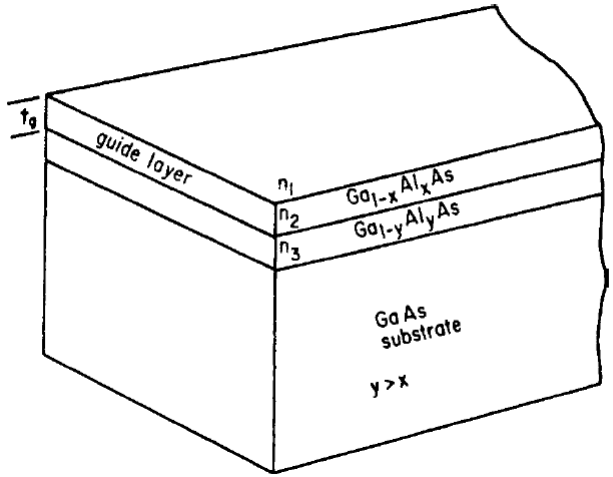


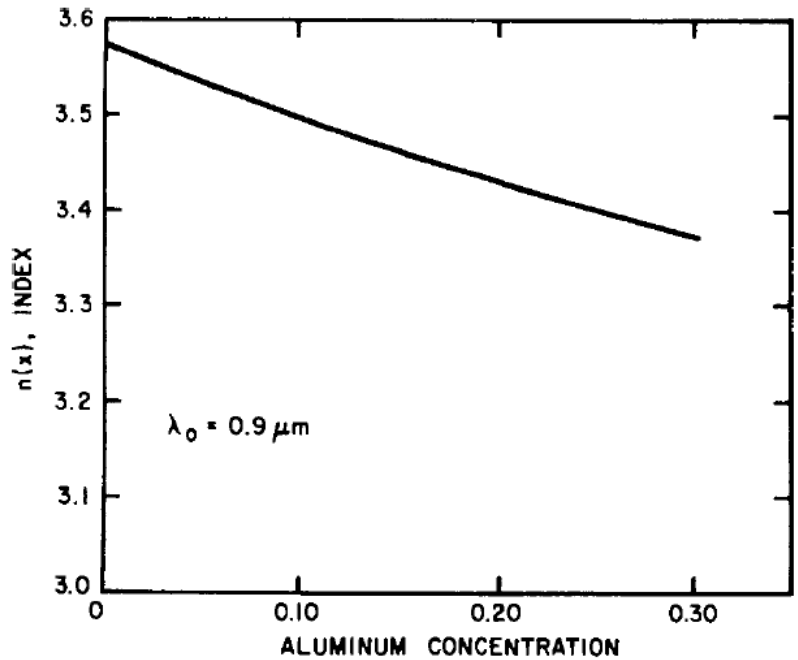


D. B. Bonneville et al., "Flexible and low-cost fabrication of optical waveguides by UV laser resist-mask writing", Opt. Material Express., 9(4) (Apr. 2019)

Semiconductor Waveguides

$Ga_{1-x}Al_xAs$ System





Controlling Al concentration can engineer band-gap energy

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

$$n^2 = A(x) + \frac{B}{\lambda_0^2 - C(x)} - D(x)\lambda_0^2,$$

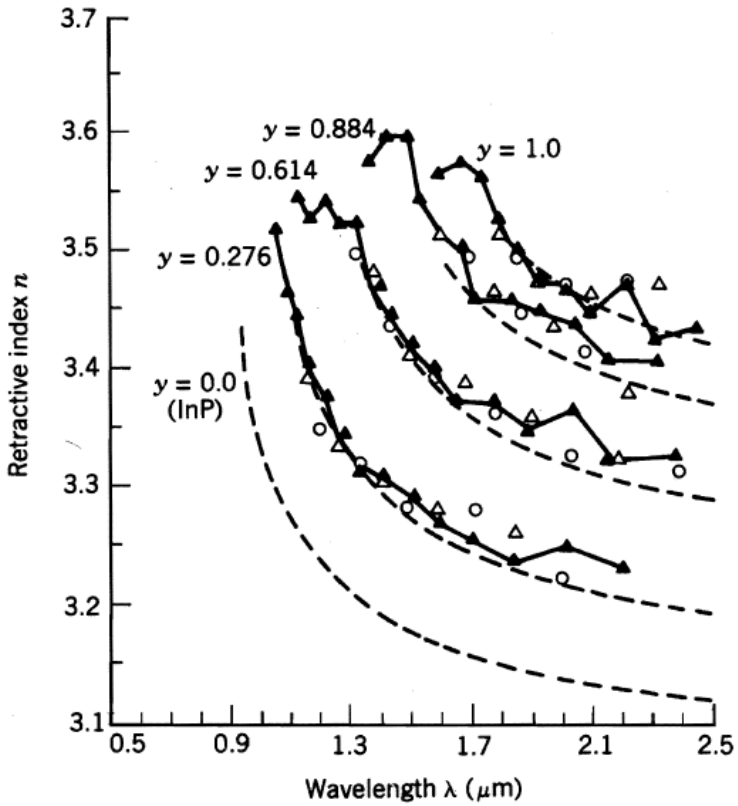
Table 4.2 Sellmeier equation coefficients (for λ_0 in μm)

Material	A	B	C	D
GaAs	10.906	0.97501	0.27969	0.002467
$Ga_{(1-x)}Al_xAs$	$10.906 - 2.92x$	0.97501	$(0.52886 - 0.735x)^2$ $x \leq 0.36$ $(0.30386 - 0.105x)^2$ $x \geq 0.36$	$(0.002467)(1.41x + 1)$

R. G. Hunsperger, "Integrated Optics", 6th Ed., Springer-Verlag, 2009

Semiconductor Waveguides

$Ga_xIn_{1-x}As_yP_{1-y}$ System



Lattice matched to InP

x=0.47y

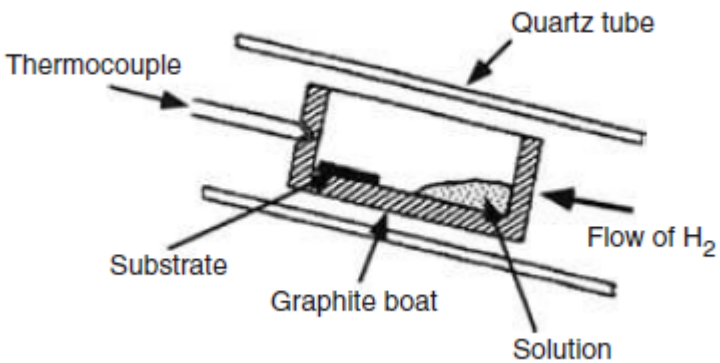
$E_g(y) = 1.35 - 0.72y + 0.12y^2$ (eV)

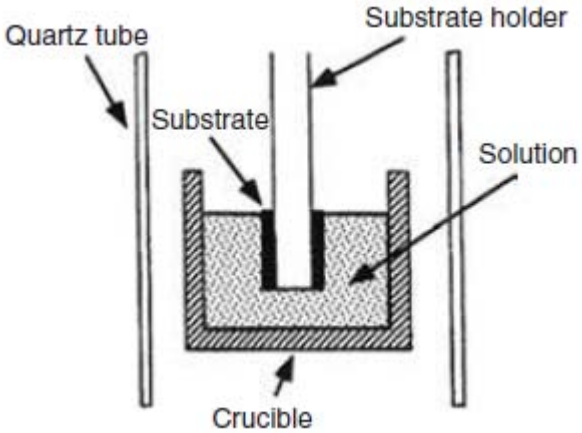
$$n(y) = 3.205 + 0.34y + 0.21y^2, \quad \text{at } \lambda = 1.3\ \mu\text{m for } 0 \le y \le 0.6,$$
$$n(y) = 3.166 + 0.26y + 0.09y^2, \quad \text{at } \lambda = 1.55\ \mu\text{m for } 0 \le y \le 0.9.$$

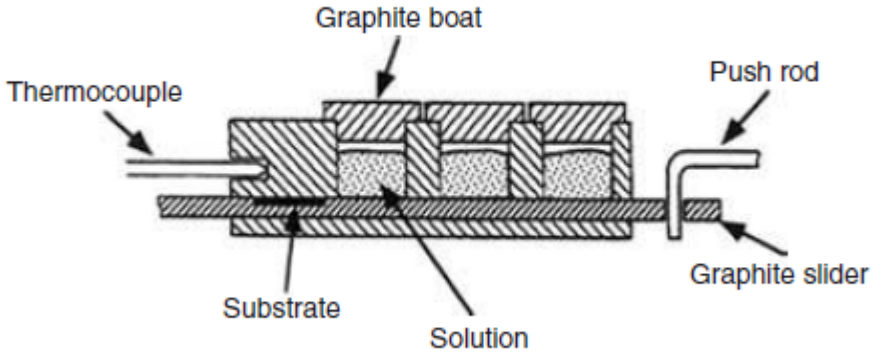
Jia-Ming Liu, "Photonic Devices", Cambridge, Univeristy Press, 2005

Liquid Phase Epitaxy (LPE)

LPE involves the precipitation of a crystalline film from a supersaturated melt onto a substrate that serves as both the template for epitaxy and the physical support for the heterostructure.







https://www.sciencedirect.com/topics/chemistry/liquid-phase-epitaxy

P. Capper & M. Mauk ,"Liquid Phase Epitaxy", J. Wiley & Sons, 2007

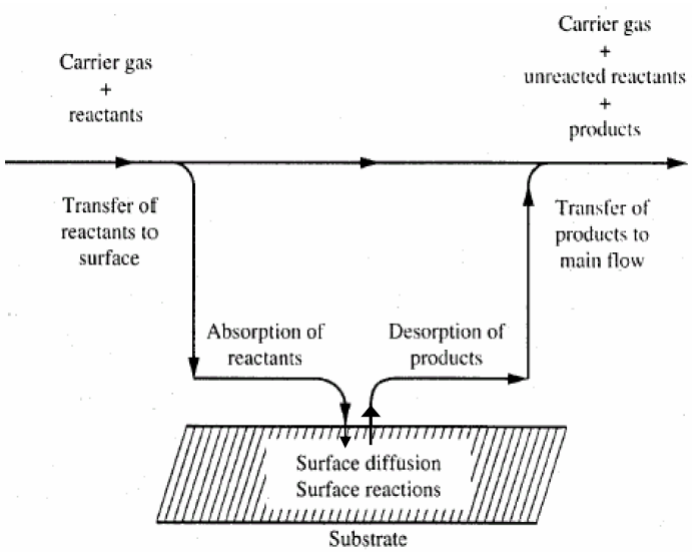
Liquid Phase Epitaxy (LPE)

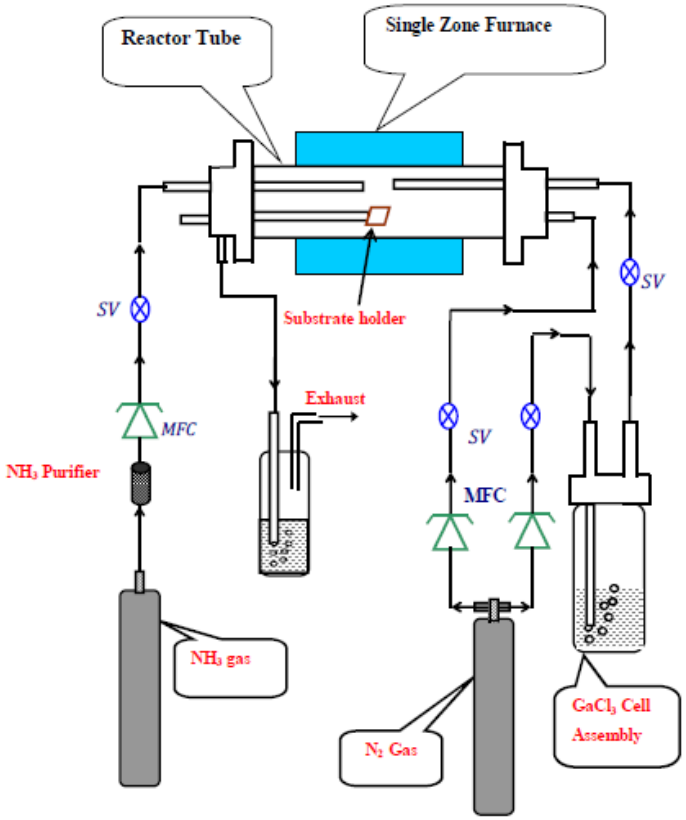
Table 3.1 III-V materials grown by LPE

	Device	Epitaxial layer/substrate (wavelength, μm)	
1970s	LED	GaP/GaP	(0.565, 0.7)
		$Al_xGa_{1-x}As$/GaAs	(0.65–0.85)
	Lasers	$Al_xGa_{1-x}As$/GaAs	(0.65–0.85)
		$In_xGa_{1-x}As_yP_{1-y}$/InP	(1.0–1.65)
		$Sn_xPb_{1-x}Te$/PbTe	(6.6)
		$Cd_xHg_{1-x}Te$/CdTe	(> 0.77)
1980s	LED	$In_xGa_{1-x}As_yP_{1-y}$/InP	(1.0–1.65)
		$In_{1-x}Ga_xP/GaP_yAs_{1-y}$/GaAs	(0.59)
	Lasers	$In_xGa_{1-x}As_yP_{1-y}$/InP	(1.0–1.65)
		$Al_xGa_{1-x}As_ySb_{1-y}$/GaSb	(1.2–1.7)
		$Al_xGa_yIn_{1-x-y}As$/InP	(0.87–1.6)
	Photodiodes	$In_{1-x}Ga_xAs_ySb_{1-y}$/GaSb	(1.7–4.0)
		$InP_xAs_ySb_{1-x-y}$/GaSb	(1.5–2.4)
		$In_xGa_{1-x}As_yP_{1-y}$/GaAs	(0.67–0.88)
		$In_{1-x}Ga_xAs$/InP	(1.65)
1990s	High efficiency lasers	$In_{1-x}Ga_xAs$ thick crystals	
	TPV	$In_{1-x}Ga_xAs_ySb_{1-y}$/GaSb	

Hydride/Chloride Vapor Phase Epitaxy

Hydride vapour phase epitaxy (**HVPE**) is an epitaxial growth technique often employed to produce semiconductors such as GaN, GaAs, InP and their related compounds, in which hydrogen chloride is reacted at elevated temperature with the group-III metals to produce gaseous metal chlorides, which then react with ammonia to produce the group-III nitrides. Carrier gasses commonly used include ammonia, hydrogen and various chlorides.

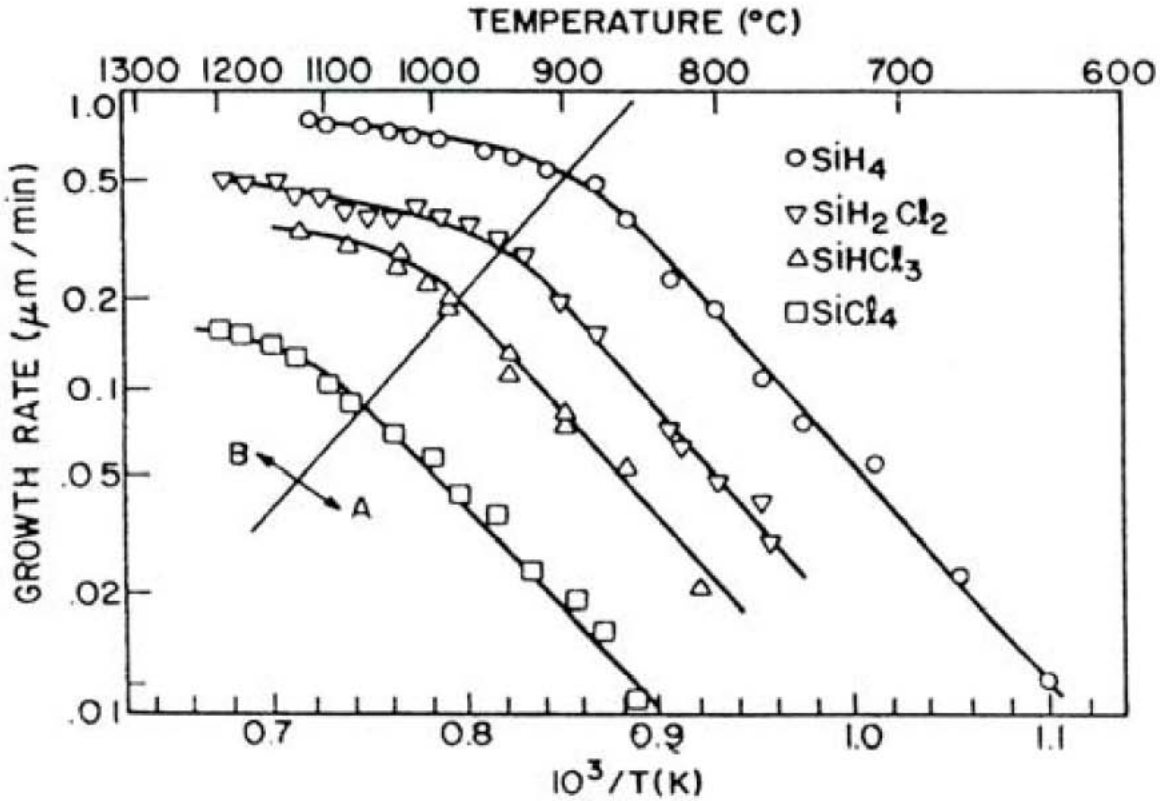




NH_3 – Ammonia, SV – Solenoid Value, MFC- Mass Flow Controller, N_2 – Nitrogen, $GaCl_3$ – Gallium Tri Chloride

https://en.wikipedia.org/wiki/Hydride_vapour_phase_epitaxy#:~:text=Hydride%20vapour%20phase%20epitaxy%20(HVPE,then%20react%20with%20ammonia%20to

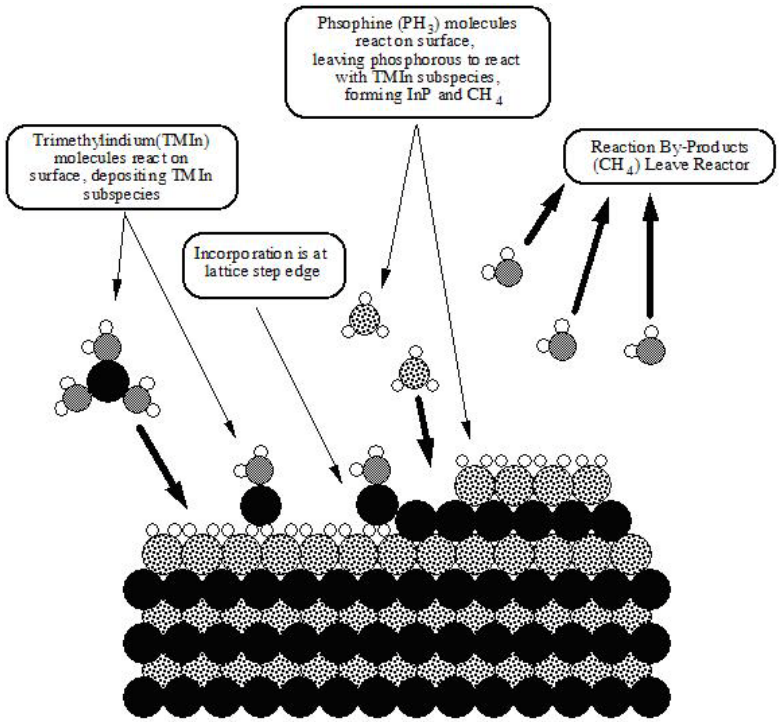
Hydride/Chloride Vapor Phase Epitaxy

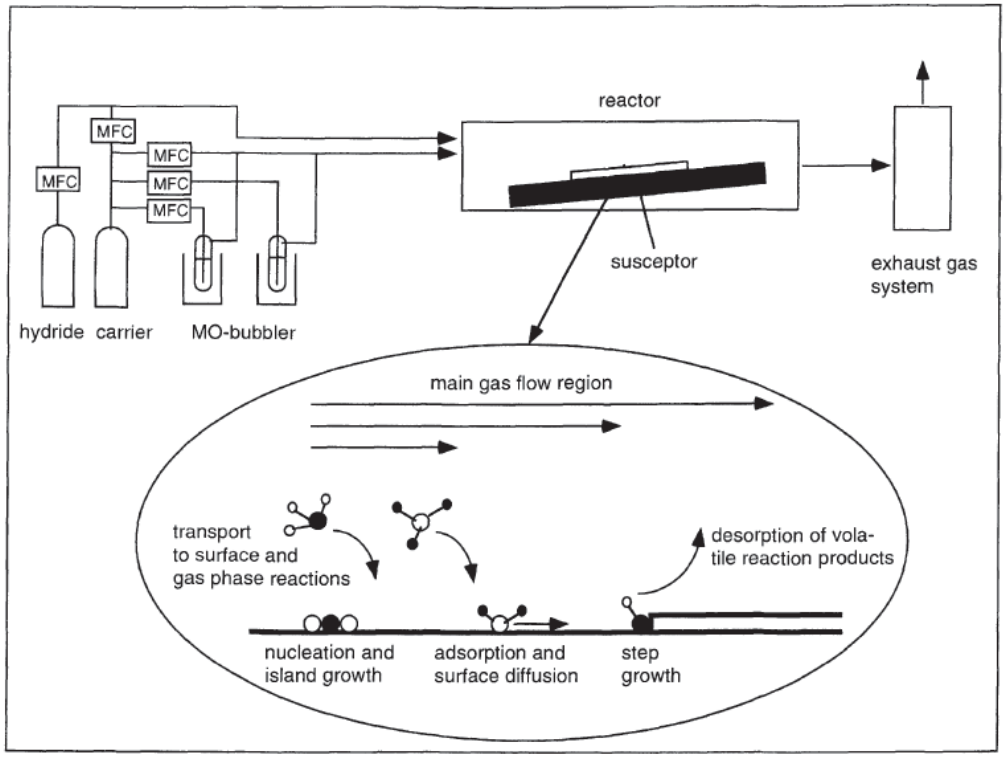


- A ~ Mass-Transfer Limited Process
- B ~ Reaction Limited Process

Metal-Organic Vapor Phase Epitaxy (MOVPE)
Metal Organic Chemical Vapor Deposition (MOCVD)

Metal-organic vapor-phase epitaxy (MOVPE), also known as metalorganic chemical vapor deposition (MOCVD), is a chemical vapor deposition method used to produce single or polycrystalline thin films. It is a process for growing crystalline layers to create complex semiconductor multilayer structures.

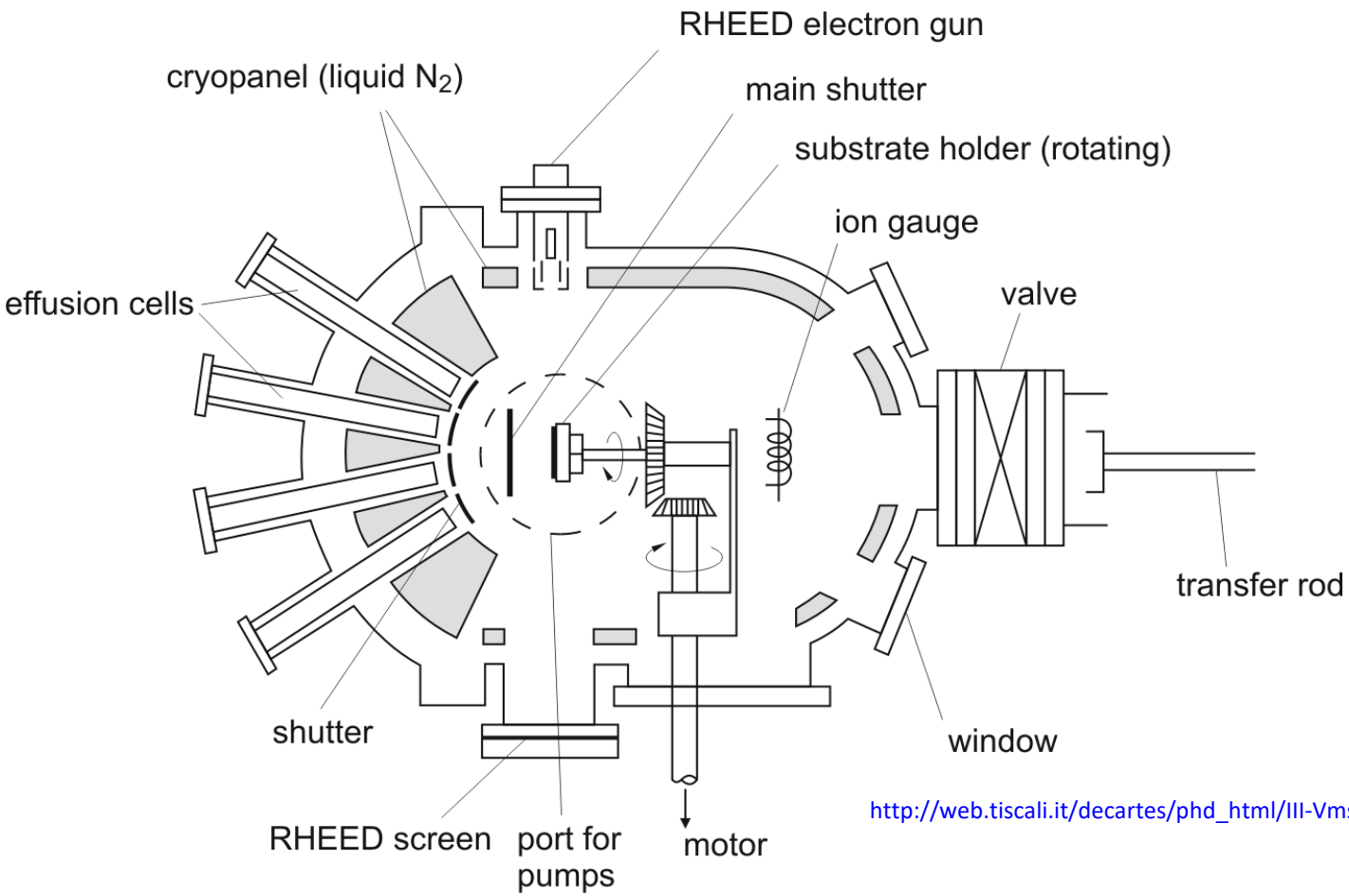




https://en.wikipedia.org/wiki/Metalorganic_vapour-phase_epitaxy

Molecular Beam Epitaxy (MBE)

Molecular-beam epitaxy (**MBE**) is an epitaxial method for thin-film deposition of single crystals. MBE is widely used in the manufacture of semiconductor devices and it is considered one of the fundamental tools for the development of nanotechnologies. Molecular-beam epitaxy takes place in high vacuum or ultra-high vacuum (10^{-8}–10^{-12} Torr).

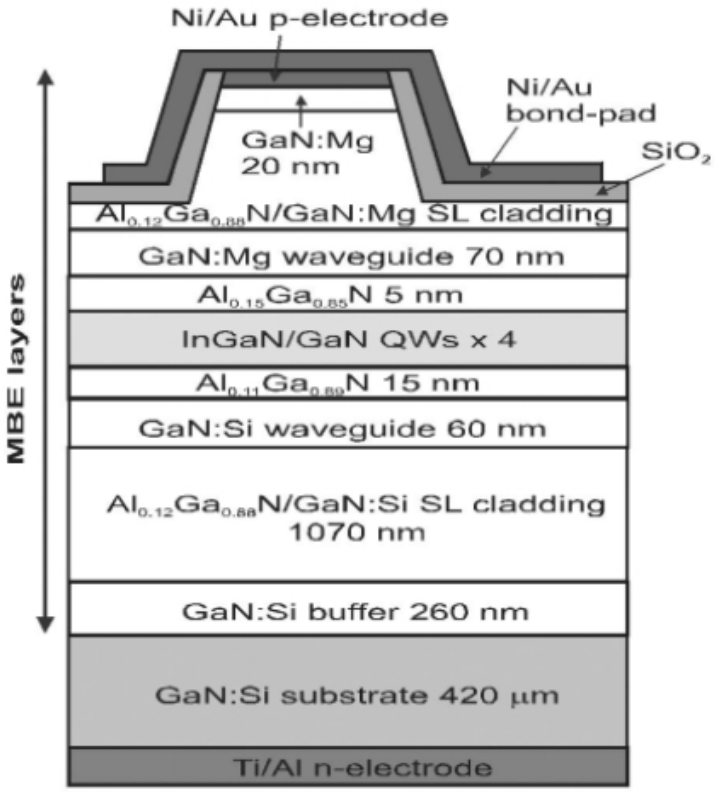


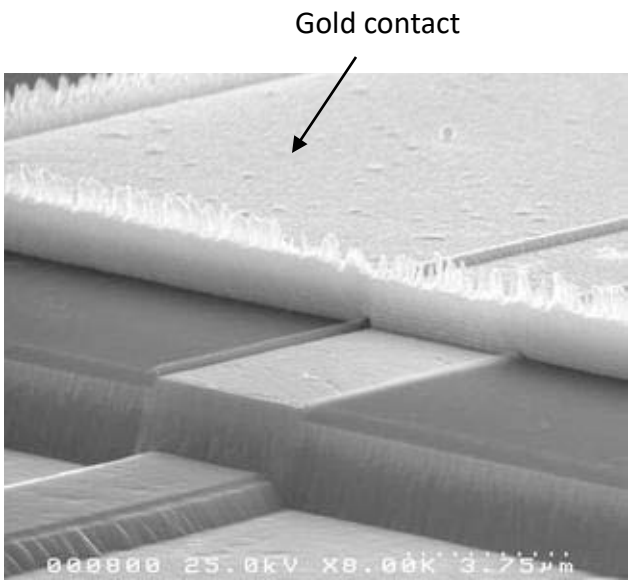
http://web.tiscali.it/decartes/phd_html/III-Vms-mbe.png

https://en.wikipedia.org/wiki/Molecular-beam_epitaxy#:~:text=Molecular%2Dbeam%20epitaxy%20(MBE),for%20the%20development%20of%20nanotechnologies.

Epitaxial Growth Example

Blue laser diodes grown by MBE





SEM image showing fabricated laser.

M. Kauer et al. "InGaN laser diodes fabricated by molecular beam epitaxy"

Epitaxial Growth Example

Violet Laser Diodes Grown by MBE

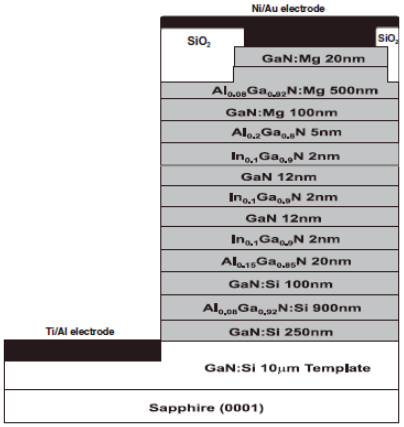


Fig. 1 (online colour at: www.pss-a.com) Schematic of InGaN laser diode structure.

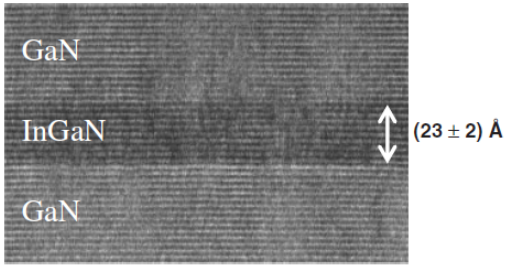
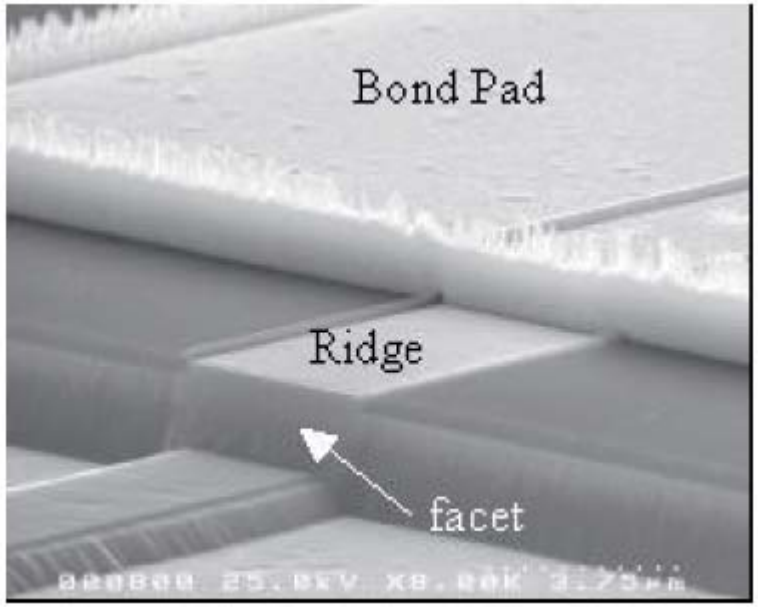


Fig. 2 HR-TEM image of single InGaN quantum well grown by MBE.



F. Heffermann et al, Phys. Stat. Sol. (a) 201, No. 12, 2688–2671 (2004) / DOI 10.1002/pssa.200405034