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
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

Materials for Integrated Optics

- Si/SiO₂
  - Si, porous, doped
  - Filters
  - Amplification ...
  - Electronic compatibility

Glassess
- Integrated optical circuits (iOC)
- Ionic exchange

Semiconductors
- III-V, nitrides ...
- Sources
- PBG

Organic Polymers
- PMMA, PPV,
- EO, NLO
- Photoluminescence
- Electroluminescence

Dielectrics
- LiNbO₃, KTP, Borates, Oxoborates ...
- EO, NLO, Passive

Integration – systems, hybrid integration
- "Engineering" the material at micro and nanometric scale

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

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


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

Magnetron sputtering principle

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

https://sites.google.com/site/vitalyslab/_/rsrc/14678988897251/home/magnetron%20sputtering.jpg?height=169&width=200
Techniques for Polymer Waveguides

Spin Coating

Process Trend Charts

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

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

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Techniques for Polymer Waveguides

Plasma Polymerization

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

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

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

### Some Advanced Materials for Polymer Waveguides

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


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

Sample preparation:
- Cleaning
- Metallic mask of (Al, Ta).

Emersion into an acid bath:
- Benzoic: C₆H₅COOH.
- Temperature: 120-250 °C
- Time: 15 - 90 min

Exchange of Li⁺ by H⁺: \( \text{Li}_1 \text{xH}_x \text{NbO}_3 \)

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

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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

Effects of implantation on the material refractive index

A. Boudrioua, “Photonic Waveguides”, J. Wiley & Sons, 2009
Ordinary and extraordinary index profiles of LiNbO₃-LiTaO₃ waveguide fabricated by He⁺ implantation

dose = 2×10¹⁶ ions/cm² and energy = 2 MeV

A. Boudrioua, "Photonic Waveguides", J. Wiley & Sons, 2009
Semiconductor Waveguides
Ga$_{1-x}$Al$_x$As System

Controlling Al concentration can engineer band-gap energy

$$E_g(x) = 1.439 + 1.042x + 0.468x^2 \text{ (eV)}$$

Semiconductor Waveguides
Ga$_x$In$_{1-x}$As$_y$P$_{1-y}$ System

$$E_g(y) = 1.35 - 0.775y + 0.149y^2 \text{ (eV)}$$

Lattice match
$$x = 0.1894y/(0.4184-0.013y)$$
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>
<thead>
<tr>
<th>Device</th>
<th>Epitaxial layer/substrate (wavelength, μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LED</strong></td>
<td>GaP/GaP</td>
</tr>
<tr>
<td></td>
<td>Al\textsubscript{x}Ga\textsubscript{1-x}As/GaAs</td>
</tr>
<tr>
<td></td>
<td>(0.565, 0.7)</td>
</tr>
<tr>
<td></td>
<td>Al\textsubscript{x}Ga\textsubscript{1-x}As/GaAs</td>
</tr>
<tr>
<td></td>
<td>(0.65–0.85)</td>
</tr>
<tr>
<td><strong>1970s</strong></td>
<td>Al\textsubscript{x}Ga\textsubscript{1-x}As/GaAs</td>
</tr>
<tr>
<td>Lasers</td>
<td>In\textsubscript{x}Ga\textsubscript{1-x}As\textsubscript{y}P\textsubscript{1-y}/InP</td>
</tr>
<tr>
<td></td>
<td>(1.0–1.65)</td>
</tr>
<tr>
<td></td>
<td>Sn\textsubscript{x}Pb\textsubscript{1-x}Te/PbTe</td>
</tr>
<tr>
<td></td>
<td>(6.6)</td>
</tr>
<tr>
<td></td>
<td>Cd\textsubscript{x}Hg\textsubscript{1-x}Te/CdTe</td>
</tr>
<tr>
<td></td>
<td>(&gt; 0.77)</td>
</tr>
<tr>
<td><strong>1980s</strong></td>
<td>In\textsubscript{x}Ga\textsubscript{1-x}As\textsubscript{y}P\textsubscript{1-y}/InP</td>
</tr>
<tr>
<td>LED</td>
<td>In\textsubscript{1-x}Ga\textsubscript{x}P/GaP\textsubscript{y}As\textsubscript{1-y}/GaAs</td>
</tr>
<tr>
<td></td>
<td>(1.0–1.65)</td>
</tr>
<tr>
<td></td>
<td>(0.59)</td>
</tr>
<tr>
<td><strong>Lasers</strong></td>
<td>Al\textsubscript{x}Ga\textsubscript{1-x}As\textsubscript{y}Sb\textsubscript{1-y}/GaSb</td>
</tr>
<tr>
<td></td>
<td>(1.2–1.7)</td>
</tr>
<tr>
<td></td>
<td>Al\textsubscript{x}Ga\textsubscript{y}In\textsubscript{1-x}As/InP</td>
</tr>
<tr>
<td></td>
<td>(0.87–1.6)</td>
</tr>
<tr>
<td><strong>Photodiodes</strong></td>
<td>In\textsubscript{x}Ga\textsubscript{1-x}As\textsubscript{y}Sb\textsubscript{1-y}/GaSb</td>
</tr>
<tr>
<td></td>
<td>(1.7–4.0)</td>
</tr>
<tr>
<td></td>
<td>In\textsubscript{1-x}Ga\textsubscript{x}As/InP</td>
</tr>
<tr>
<td></td>
<td>(1.5–2.4)</td>
</tr>
<tr>
<td></td>
<td>In\textsubscript{x}Ga\textsubscript{1-x}As\textsubscript{y}P\textsubscript{1-y}/GaAs</td>
</tr>
<tr>
<td></td>
<td>(0.67–0.88)</td>
</tr>
<tr>
<td><strong>1990s</strong></td>
<td>In\textsubscript{x}Ga\textsubscript{x}As thick crystals</td>
</tr>
<tr>
<td>High efficiency lasers</td>
<td>In\textsubscript{1-x}Ga\textsubscript{x}As\textsubscript{y}Sb\textsubscript{1-y}/GaSb</td>
</tr>
</tbody>
</table>

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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.
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) is an epitaxy 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).

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


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Waveguide Formation by Direct Writing
