INDEX CONTROL TECHNOLOGIES

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Integrated Photonics Course 377-2-5599

School of ECE

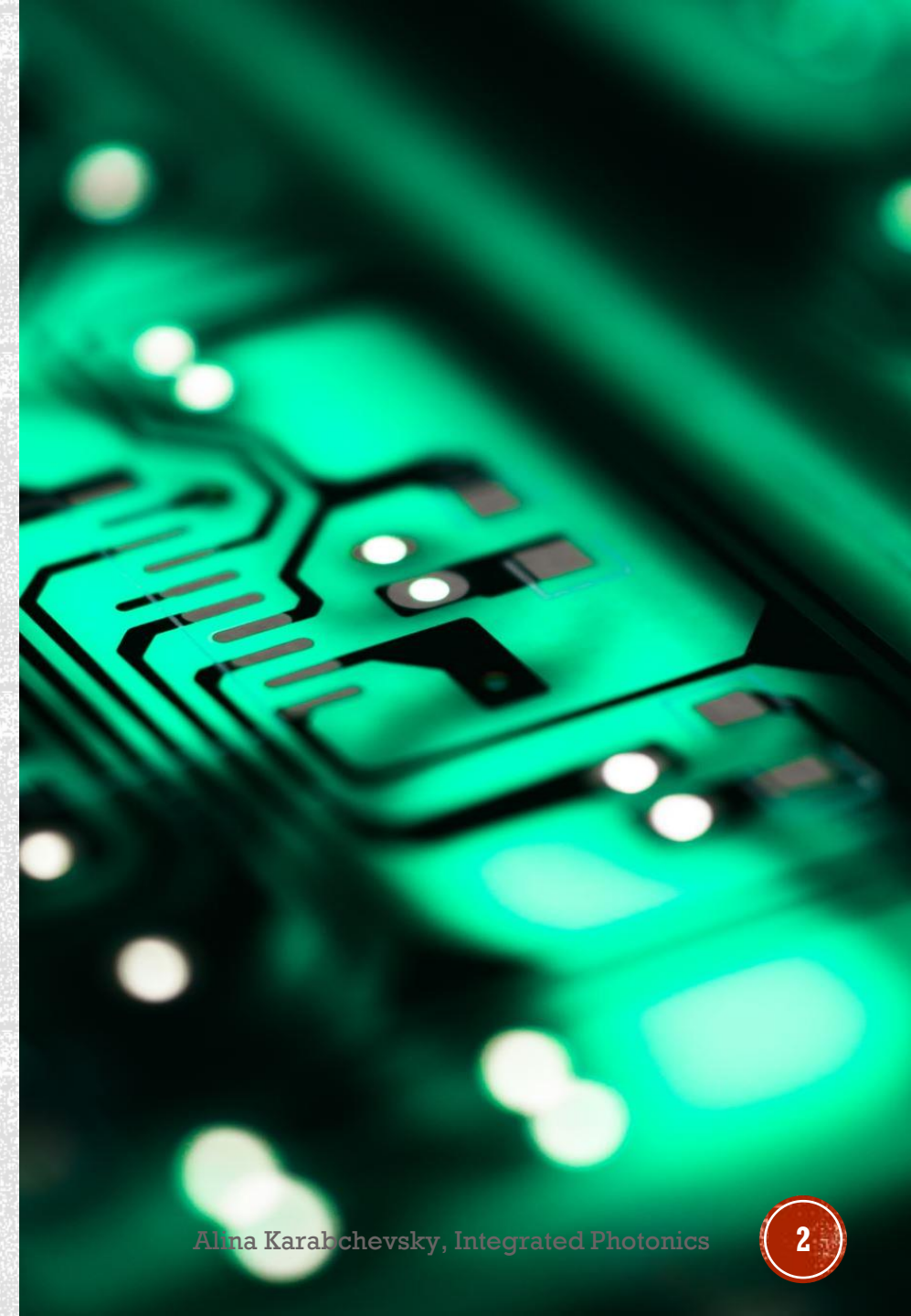Ben-Gurion University of the Negev, Israel

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OUTLINE

Index control methods

- Changing the free carriers in semiconductor
- Isotropic and anisotropic materials
- The electro-optic effect
- Electro-optic modulator

Waveguides fabrication

- Epitaxial growth
- Thin layer growth
- Laser induced index control
- Diffused waveguide

INDEX CONTROL

We will learn about methods in integrated photonics to control the refractive index of a material.

Why to change the refractive index?

Answer: the propagation characteristics dependent on the refractive index.

INDEX CONTROL METHODS

We will discuss three methods to control the refractive index:

1) **Changing the free carriers in a semiconductor** - the free carriers lower the refractive index and can prevent propagation of certain wavelengths. Decreasing the free carriers will cause the propagation for certain wavelengths.

2) **Using the electro-optic effect** - in this effect, the refractive index is dependent on the electric field applied on the material.

3) **Growing layer** in different methods:
   - Epitaxial growth - changing the molar concentration.
   - Growing thin-film.
   - Ion implantation.
   - Ion diffusion.

CHANGING THE FREE CARRIERS IN SEMICONDUCTOR

The relation between the dielectric constant and the refractive index:

- In semiconductor, the dielectric constant (resulting refractive index) depends on free carriers (electrons or holes).

- Free carriers influence the material by decreasing the refractive index.

- Decreasing the free carriers, locally, will increase the refractive index and allow for propagation.
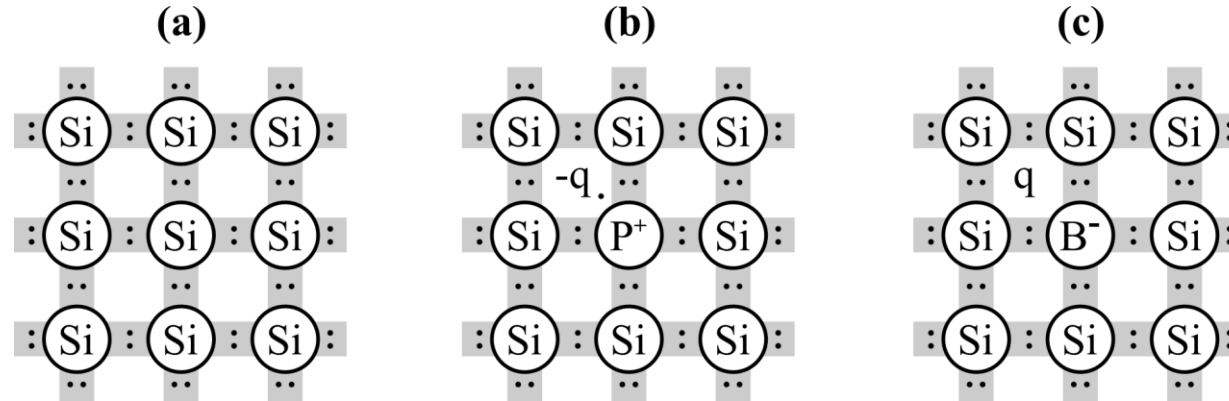
The complex refractive index is (n - real κ - imaginary):

$$n + j\kappa = \tilde{n} = \sqrt{\tilde{\varepsilon}} = \sqrt{\tilde{\varepsilon}_r + j\tilde{\varepsilon}_i}$$

Where $\tilde{\varepsilon}_r$ and $\tilde{\varepsilon}_i$ are the real and imaginary parts, respectively, of the dielectric constant (relative permittivity).
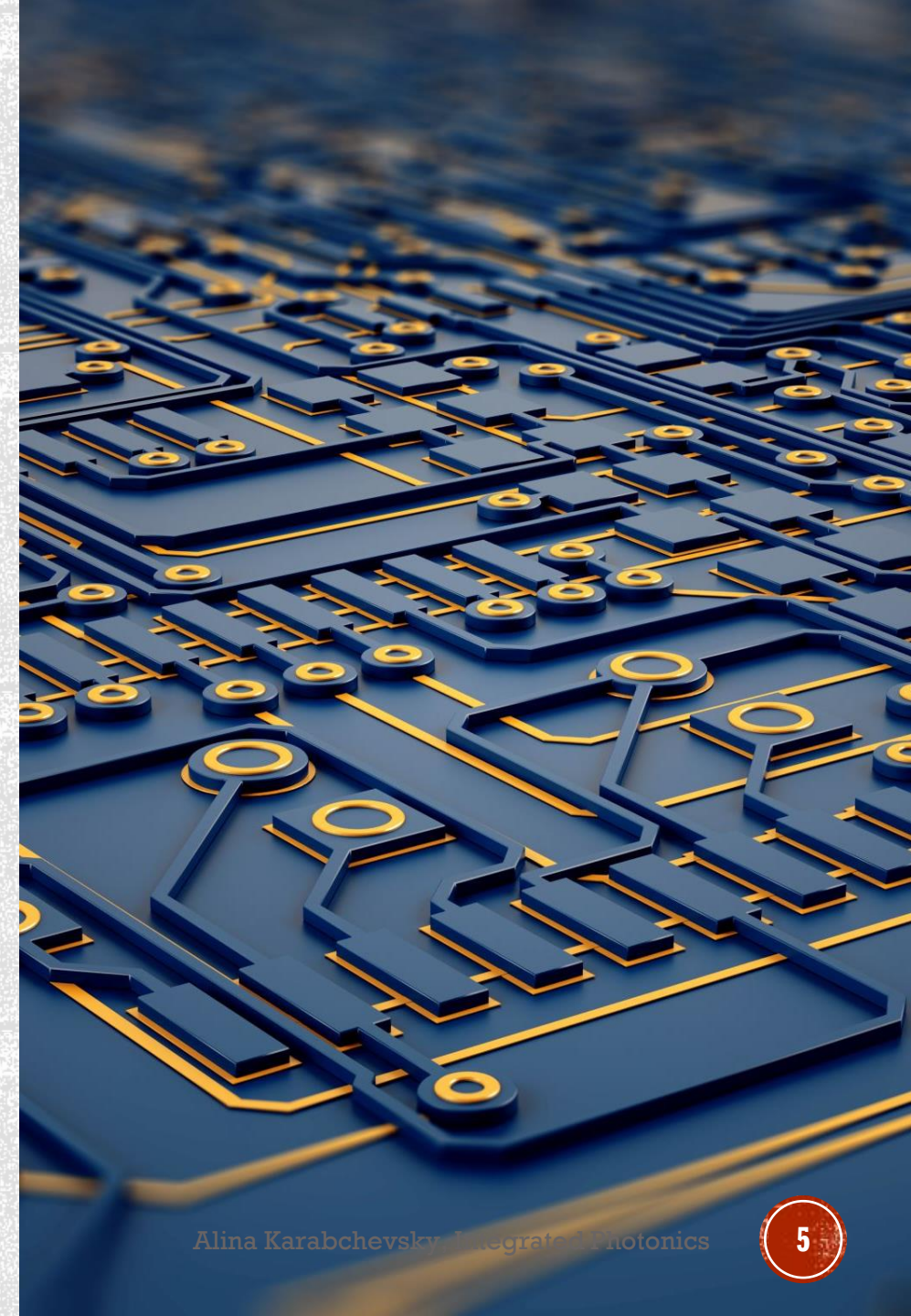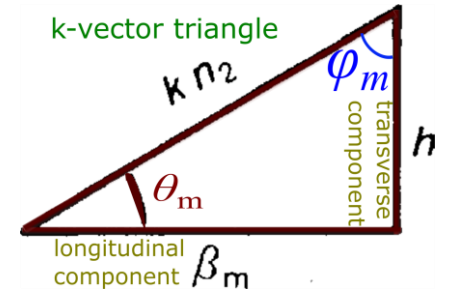
SEMICONDUCTOR DOPING - BASIC BONDS

(a) Intrinsic silicon. (b) Silicon n-type doped with phosphorus (P) - donor. (c) Silicon p-type doped with boron (B) - acceptor; The "column" number represents the number of valence electrons.

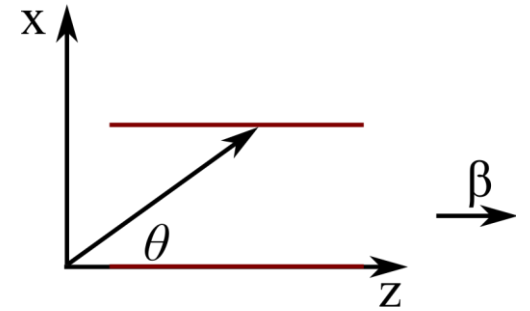| II	III	IV	V	VI
	B	C	N	O
	Al	Si	O	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sd	Te
Hg				

THE MEANING OF n AND κ

A wave propagates in slab waveguide defined by:

$$E(x, y, z) = \vec{E}_y(x)e^{j\beta_m z}$$

$$\beta_m = k\cos(\theta_m) = k_0 n \cos(\theta_m) \qquad k_0 = \frac{2\pi}{\lambda}$$

where β_m is the propagation constant in the z direction.

$$E(z) \propto e^{j\beta_m z} \implies E(z) \propto e^{j\beta_m \tilde{n} z} \implies E(z) \propto e^{j\beta_m (n+j\kappa)z} \implies$$

$$\implies E(z) \propto e^{j\beta_m n z} e^{-\beta_m \kappa z}$$

- The real part of the refractive index is related to the propagation of the wave and it is important for guiding.

- The imaginary part of the refractive index is related to the absorption – the attenuation of the light in the material.

THE REAL AND THE IMAGINARY PARTS OF THE DIELECTRIC CONSTANT

The real and the imaginary parts of the dielectric constant are defined:

$$\tilde{\varepsilon} = \tilde{\varepsilon}_r + j\tilde{\varepsilon}_i \qquad \tilde{\varepsilon}_r = n_0^2 - \frac{\omega_p^2}{\omega^2 + \frac{1}{\tau^2}} \qquad \tilde{\varepsilon}_i = \frac{\omega_p^2}{\omega\tau\left(\omega^2 + \frac{1}{\tau^2}\right)}$$

Where:

ω - the angular frequency: $\omega = 2\pi f = 2\pi \frac{c}{\lambda} = kc$

ω_p - the angular frequency of the plasma: $\omega_p = \sqrt{\frac{Nq^2}{m^*\varepsilon_0}}$

q - the electron charge.

N - the concentration of the free carriers [cm^{-3}].

m^* - the relative mass of electron or hole.

n_0 - the refractive index in pure material. Theoretically only in 0K however in practice in GaAs when $N \leq 10^4$ cm^{-3}.

ε_0 - the permittivity of free space.

τ - the lifetime of free carriers (recombination time or relaxation time). $\tau \approx 10^{-6} - 10^{-11}$ sec.

THE REAL AND THE IMAGINARY PARTS OF THE DIELECTRIC CONSTANT

$\frac{1}{\tau^2}$ is negligible compared to $\omega : \omega \approx 10^{15} \gg \frac{1}{\tau}$

$$\tilde{\varepsilon}_i = \frac{\omega_p{}^2}{\omega\tau\left[\omega^2 + \dfrac{1}{\tau^2}\right]} \Rightarrow \tilde{\varepsilon}_i = \frac{\omega_p{}^2}{\omega^3 \cdot \tau}$$

$$\tilde{\varepsilon}_r = n_0{}^2 - \frac{\omega_p{}^2}{\omega^2 + \dfrac{1}{\tau^2}} \Rightarrow \tilde{\varepsilon}_r = n_0{}^2 - \frac{\omega_p{}^2}{\omega^2}$$

From the equations, we can see that the refractive index depends on ω_p, which in turn depends on N (the concentration of the free carriers).

Δn AS FUNCTION OF THE CONCENTRATION OF FREE CARRIERS N

- In semiconductor, in visible and near-infrared : $\tilde{\varepsilon}_r \gg \tilde{\varepsilon}_i$

- Using Taylor series (the first two terms):

$$\tilde{n} = \sqrt{\tilde{\varepsilon}_r + j\tilde{\varepsilon}_i} = \sqrt{\tilde{\varepsilon}_r} + j\frac{\tilde{\varepsilon}_i}{2\sqrt{\tilde{\varepsilon}_r}} \qquad \tilde{n} = n_r + jn_i = n + j\kappa$$

Therefore, the real and the imaginary parts of the refractive index are:

$$\boxed{n = \sqrt{\tilde{\varepsilon}_r}} \qquad \boxed{\kappa = \frac{\tilde{\varepsilon}_i}{2\sqrt{\tilde{\varepsilon}_r}}}$$

Homework:

1) For GaAs, show that $\tilde{\varepsilon}_r \gg \tilde{\varepsilon}_i$.

2) Show that the derivation in Taylor series is correct.

DECREASING THE CONCENTRATION OF THE FREE CARRIERS IN A WAVEGUIDE

We showed that the real part of the refractive index is related to the wave propagation. Therefore, we focus on the change of $\tilde{n}$ due to the changes in the concentration of the free carriers (N).

$$n_2^{\,2} - n_3^{\,2} = \Delta\varepsilon_r = -\frac{\Delta\left(\omega_p^{\,2}\right)}{\omega^2} = \frac{(N_3 - N_2)q^2}{m^*\varepsilon_0\omega^2}$$

$$\boxed{\Delta n = n_2 - n_3 = \frac{(N_3 - N_2)q^2}{(n_2 + n_3)m^*\varepsilon_0\omega^2}}$$

Since the change in refractive index is very small $n_2 \approx n_3$:

$$\boxed{\Delta n = n_2 - n_3 = \frac{(N_3 - N_2)q^2}{2n_2 m^*\varepsilon_0\omega^2}}$$

DECREASING OF THE CONCENTRATION OF THE FREE CARRIERS IN WAVEGUIDE

Example:

Doping a semiconductor in a non-uniform distribution. In the area where we want the light to propagate, the doping is high; in the substrate the doping is low. N and n distribution are:
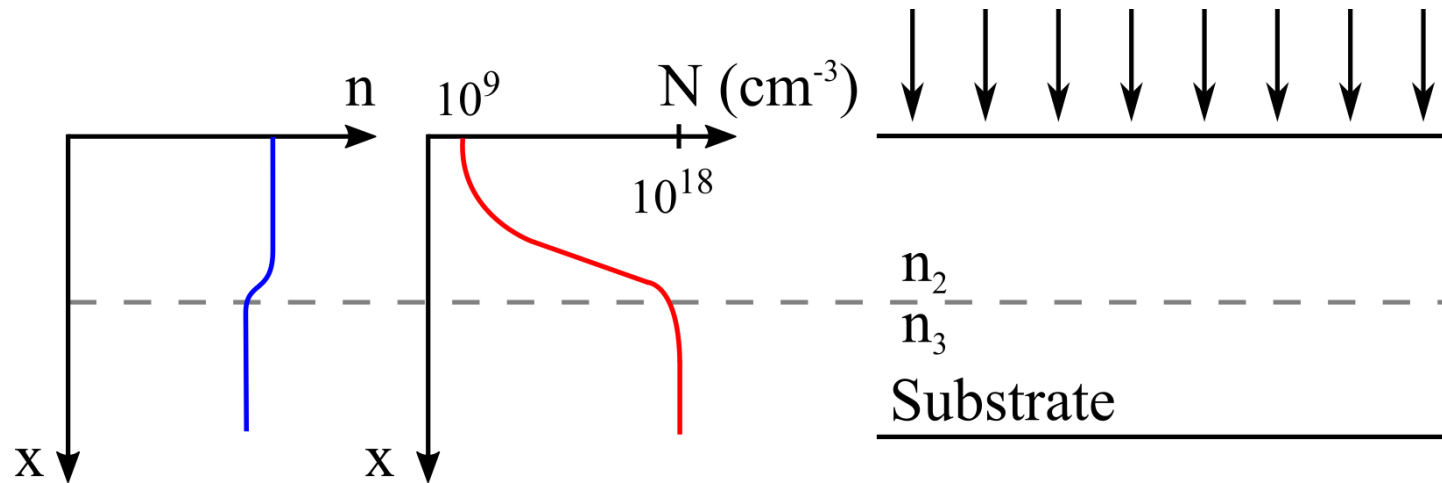
MILLER INDICES (HKL) IN CUBIC CRYSTALS

- Miller indices form a notation system in crystallography for planes in crystal lattices.

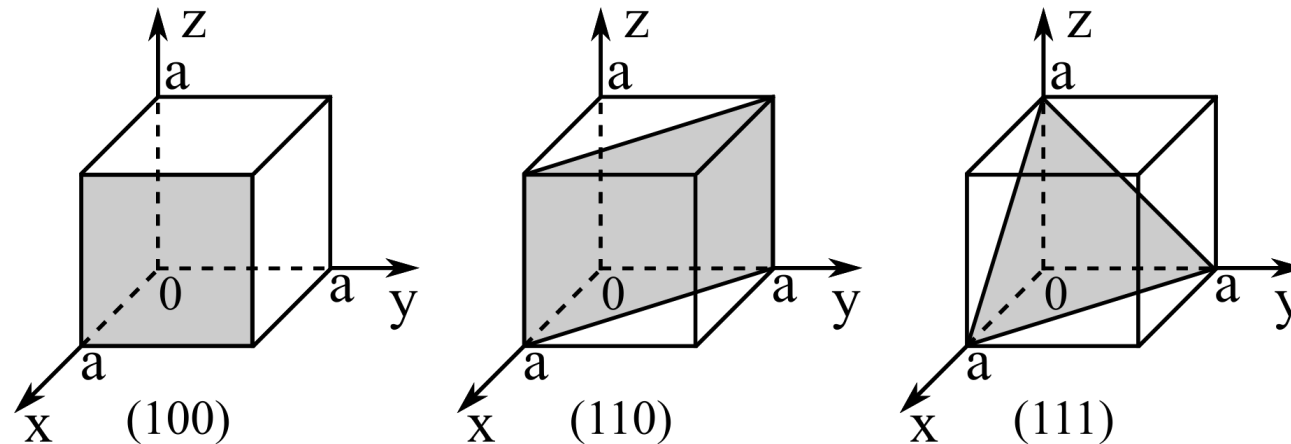- The values of the crystal are defined by the intercepts on the x, y and z axes.

Figure 1: Miller indices (hkl) in cubic crystals.

ISOTROPIC MATERIALS

Distinguish between two types for materials: isotropic and anisotropic materials.

Isotropic material - the electric displacement field $\vec{D}$ is proportional to the electric field $\vec{E}$ as:

$$\boxed{\vec{D} = \varepsilon \vec{E}}$$

where the permittivity is defined as: $\varepsilon = \varepsilon_0 \tilde{\varepsilon}$

- The refractive index is uniform and not dependent on the polarization of the wave or the electric field direction.

- Mostly exists in non-crystalline materials such as glass and liquids.

- Materials that are used in integrated photonics: glass, diamond, calcium fluoride - (CaF_2) and Gallium arsenide (GaAs).

ANISOTROPIC MATERIALS

Anisotropic material - due to the crystal orientation, the internal dipoles are constrained to lie in particular directions with respect to the underlying material.

The electric displacement vector $\vec{D}$ is not in the direction of the electric field $\vec{E}$:

$$\begin{bmatrix} D_x \\ D_y \\ D_z \end{bmatrix} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{31} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{23} & \varepsilon_{33} \end{bmatrix} \cdot \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}$$

$$\begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} = k_0 \begin{bmatrix} \chi_{11} & \chi_{12} & \chi_{31} \\ \chi_{21} & \chi_{22} & \chi_{23} \\ \chi_{31} & \chi_{23} & \chi_{33} \end{bmatrix} \cdot \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}$$

$$\vec{P} = P_i = k_0 \underline{\chi} \vec{E} = k_0 \chi_{ij} E_i$$

Therefore, the refractive index depends on the polarization of the wave or the electric field direction.

For example ($\lambda = 1.5 \ \mu m$):

SiO₂ (quartz crystal)	$n_o = 1.5284$	$n_e = 1.5369$
TiO₂	$n_o = 2.4547$	$n_e = 2.7112$
LiNbO₃	$n_o = 2.2128$	$n_e = 2.139$

ANISOTROPIC MATERIALS

- The refractive index depends on the polarization of the wave or the electric field direction.

- Usually, it is accepted to choose vertical directions - x, y and z in the crystal as the principal axes and three refractive indices - n_1, n_2 and n_3 for the polarization in the direction of the axes.

$$n_1 = n_x, \qquad n_2 = n_y, \qquad n_3 = n_z \ - \ \text{Principle refractive indices}$$

We distinguish a sub-group named 'uniaxial crystals'. In this crystal, $n_1 = n_2$ and the refractive index is ordinary (o) for $n_1 = n_2 = n_o$ and extraordinary (e) for $n_3 = n_e$.

THE ELECTRO-OPTIC EFFECT

Independent Nonvanishing Elements of $\chi^{(2)}(\omega = \omega_1 + \omega_2)$ for Crystals of Certain Symmetry Classes

Symmetry Class	Independent Nonvanishing Elements
Triclinic	
1	All elements are independent and nonzero
Monoclinic	
2	$xyz, xzy, xxy, xyx, yxx, yyy, yzz, yzx, yxz, zyz,$ zzy, zxy, zyx (two fold axis parallel to $\hat{y}$)
m	$xxx, xyy, xzz, xzx, xxz, yyz, yzy, yxy, yyx, zxx,$ zyy, zzz, zzx, zxz (mirror plane perpendicular to $\hat{y}$)
Orthorhombic	
222	$xyz, xzy, yzx, yxz, zxy, zyx$
$mm2$	$xzx, xxz, yyz, yzy, zxx, zyy, zzz$
Tetragonal	
4	$xyz = -yxz, xzy = -yzx, xzx = yzy, xxz = yyz,$ $zxx = zyy, zzz, zxy = -zyx$
$\bar{4}$	$xyz = yxz, xzy = yzx, xzx = -yzy, xxz = -yyz,$ $zxx = -zyy, zxy = zyx$
422	$xyz = -yxz, xzy = -yzx, zxy = -zyx$
$4mm$	$xzx = yzy, xxz = yyz, zxx = zyy, zzz$
$\overline{4}2m$	$xyz = yxz, xzy = yzx, zxy = zyx$
Cubic	
432	$xyz = -xzy = yzx = -yxz = zxy = -zyx$
$\overline{4}3m$	$xyz = xzy = yzx$
23	$= yxz = zxy = zyx$
Trigonal	
3	$xxx = -xyy = -yyz = -yxy, xyz = -yxz, xzy = -yzx,$ $xzx = yzy, xxz = yyz, yyy = -yxx = -xxy = -xyx,$ $zxx = zyy, zzz, zxy = -zyx$
32	$xxx = -xyy = -yyx = -yxy, xyz = -yxz, xzy = -yzx,$ $zxy = -zyx$
$3m$	$xzx = yzy, xxz = yyz, zxx = zyy, zzz, yyy = -yxx =$ $-xxy = -xyx$ (mirror plane perpendicular to $\hat{x}$)
Hexagonal	
6	$xyz = -yxz, xzy = -yzx, xzx = yxy, xxz = yyz,$ $zxx = zyy, zzz, zxy = -zyx$
$\bar{6}$	$xxx = -xyy = -yxy = -yyx, yyy = -yxx = -xyx =$ $-xxy$
622	$xyz = -yxz, xzy = -yxz, zxy = -zyx$
$6mm$	$xzx = yzy, xxz = yyz, zxx = zyy, zzz$
$\bar{6}m2$	$yyy = -yxx = -xxy = -xyx$

Physically, electrooptical effects result from both ionic or molecular movement and distortion of electronic cloud induced by the applied electric field. Even if the induced refractive index change is only around 10^{-5} (typical values of r_{ijk} are around 10^{-10} to 10^{-8} cm/v), a medium 1 cm long can already impose on a visible beam a phase retardation of more than $\pi/2$. Therefore, electrooptical effects have been widely used as optical modulators.

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THE ELECTRO-OPTIC EFFECT

- In the electro-optic effect, the refractive index depends on the electric field applied on the material (refractive index tensor). The field influences the grating structure, resulting in change of the optical properties:

$$n' = n(E) \text{ when } E = 0 \Rightarrow n' = n$$

- Using Taylor series:
$$n(E) = n' = n + a_1 E + a_2 E^2 + \cdots$$

Where a_1 is **Pockels constant** and a_2 is **Kerr constant**.

- Changing n by a_1 is electro-optic effect of the first order named ''Pockels effect''.

- Changing n by a_2 is electro-optic effect of the second order named ''Kerr effect'': $\Delta n = a_2 E^2 = K\lambda E^2$ where K is **Kerr coefficient**. Usually negligible in integrated photonic materials.

POCKELS EFFECT - $\Delta n = a_1 E$

The electro-optical effect is defined though the index ellipsoid:

$$\Delta\left(\frac{1}{n^2}\right) = \frac{1}{n_{ij}^2(E_0)} = \left(\frac{1}{n_{ij}^2}\right)_0 + \sum_{j=1}^{3} r_{ij}\, E_j + \sum_{j=1}^{3} p_{ij,l}\, E_j E_l = \vec{r}\vec{E}$$

r_{ij} is linear electrooptical tensor and is tabulated in the literature for many crystals

$p_{\{i,j,l\}}$ is the quadratic electrooptical tensor

Where $i = 1, 2, 3, 4, 5, 6$

$$\frac{x^2}{n_{xx}^2} + \frac{y^2}{n_{yy}^2} + \frac{z^2}{n_{zz}^2} + \frac{2\,yz}{n_{yz}^2} + \frac{2\,zx}{n_{zx}^2} + \frac{2\,xy}{n_{xy}^2} = 1$$

$1 = (11) = (xx)$

$2 = (22) = (yy)$

$3 = (33) = (zz)$

with $n_{ii}^{-1} = (\varepsilon^{-1})_{ii}^{1/2}$ being the refractive index tensor.

$4 = (23) = (32) = (yz) = (zy)$

$5 = (13) = (31) = (xz) = (zx)$

$6 = (12) = (21) = (xy) = (yx)$

and $j = 1, 2, 3$ is x, y, z respectively.

POCKELS EFFECT

- $\Delta n = a_1 E$

$$\begin{bmatrix} \Delta(1/n^2)_1 \\ \Delta(1/n^2)_2 \\ \Delta(1/n^2)_3 \\ \Delta(1/n^2)_4 \\ \Delta(1/n^2)_5 \\ \Delta(1/n^2)_6 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \\ r_{41} & r_{42} & r_{43} \\ r_{51} & r_{52} & r_{53} \\ r_{61} & r_{62} & r_{63} \end{bmatrix} \cdot \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}$$

- The matrix is called the "electro-optic tensor".

- The r_{ij} are constant and known for each crystal.

POCKELS EFFECT - $\Delta n = a_1 E$

Linear Electro-optic Coefficients of Some Commonly Used Crystals

Substance	Symmetry	Wavelength λ (μm)	Electro-optic Coefficients r_{lk} (10^{-12} m/V)		Index of Refraction n_i		$n^3 r$ (10^{-12} m/V)	Dielectric Constant[a] $\varepsilon_i (\varepsilon_0)$
CdTe	$\bar{4}3m$	1.0	$(T)\ r_{41} = 4.5$		$n = 2.84$		103	$(S)\ \varepsilon = 9.4$
		3.39	$(T)\ r_{41} = 6.8$					
		10.6	$(T)\ r_{41} = 6.8$		$n = 2.60$		120	
		23.35	$(T)\ r_{41} = 5.47$		$n = 2.58$		94	
		27.95	$(T)\ r_{41} = 5.04$		$n = 2.53$		82	
GaAs	$\bar{4}3m$	0.9	$r_{41} = 1.1$		$n = 3.60$		51	$(S)\ \varepsilon = 13.2$
		1.15	$(T)\ r_{41} = 1.43$		$n = 3.43$		58	$(T)\ \varepsilon = 12.3$
		3.39	$(T)\ r_{41} = 1.24$		$n = 3.3$		45	
		10.6	$(T)\ r_{41} = 1.51$		$n = 3.3$		54	
GaP	$\bar{4}3m$	0.55–1.3	$(T)\ r_{41} = -1.0$		$n = 3.66{-}3.08$			$(S)\ \varepsilon = 10$
		0.633	$(S)\ r_{41} = -0.97$		$n = 3.32$		35	
		1.15	$(S)\ r_{41} = -1.10$		$n = 3.10$		33	
		3.39	$(S)\ r_{41} = -0.97$		$n = 3.02$		27	
LiNbO$_3$ ($T_c = 1230$ °C)	$3m$	0.633	$(T_4)\ r_{13} = 9.6$ $(T)\ r_{22} = 6.8$ $(T)\ r_{33} = 30.9$ $(T)\ r_{51} = 32.6$ $(T)\ r_c = 21.1$	$(S)\ r_{13} = 8.6$ $(S)\ r_{22} = 3.4$ $(S)\ r_{33} = 30.8$ $(T)\ r_{51} = 28$	$n_o = 2.286$ $n_e = 2.200$			$(T)\ \varepsilon_1 = \varepsilon_2 = 78$ $(T)\ \varepsilon_2 = 32$ $(S)\ \varepsilon_1 = \varepsilon_2 = 43$ $(S)\ \varepsilon_3 = 28$
		1.15	$(T)\ r_{22} = 5.4$ $(T)\ r_c = 19$		$n_o = 2.229$ $n_e = 2.150$			
		3.39	$(T)\ r_{22} = 3.1$ $(T)\ r_c = 18$	$(S)\ r_{33} = 28$ $(S)\ r_{22} = 3.1$ $(S)\ r_{13} = 6.5$ $(S)\ r_{51} = 23$	$n_o = 2.136$ $n_e = 2.073$			
KH$_2$PO$_4$ (KDP)	$\bar{4}2m$	0.546	$(T)\ r_{41} = 8.77$ $(T)\ r_{63} = 10.3$		$n_o = 1.5115$ $n_e = 1.4698$			$(T)\ \varepsilon_1 = \varepsilon_2 = 42$ $(T)\ \varepsilon_3 = 21$
		0.633	$(T)\ r_{41} = 8$ $(T)\ r_{63} = 11$		$n_o = 1.5074$ $n_e = 1.4669$			$(S)\ \varepsilon_1 = \varepsilon_2 = 44$ $(S)\ \varepsilon_3 = 21$
		3.39	$(T)\ r_{63} = 9.7$ $(T)\ n_o^3 r_{63} = 33$					

(T) = low frequency from dc through audio range; (S) = high frequency.

ELECTRO-OPTIC MODULATOR

- When the Schottky diode is in reverse bias V, the electric field causes a phase shift of the light wave in the guiding layer.

- For (100) crystal, the change of the refractive index is caused by TE polarized field (polarized along the y plane) wavelength of 1.15um:
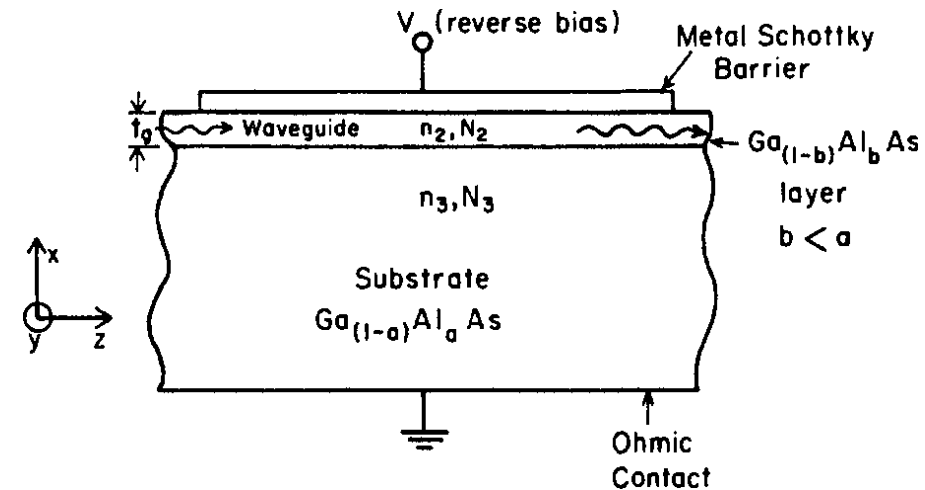
$$\Delta n = \Delta n_y = n^3 r_{41} \frac{V}{2t_g}$$
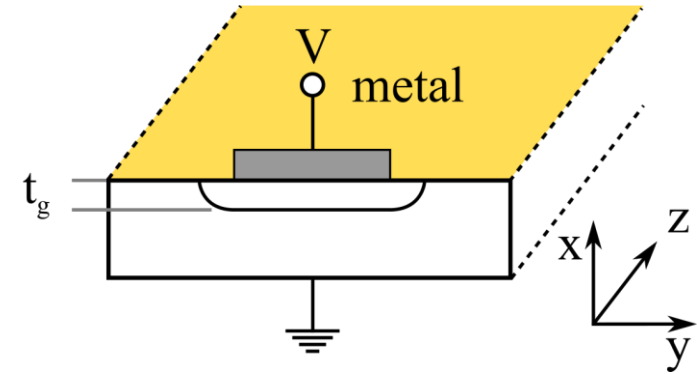
  where n is the refractive index without applied field.

- The phase shift caused by the field is:

$$\Delta\varphi_{\text{EO}} = \Delta\beta L = \frac{\pi}{\lambda_0} n_O{}^3 r_{41} \frac{VL}{t_g}$$

  where L is the length of the modulator.

EXAMPLES

Example 1: GaAs

For (100) crystal (the orthogonal vector is [1,0,0]) for TE polarized field with TE polarized field (E_y):

$$n_x = n_1' = n_o + \frac{1}{2}n_o{}^3 r_{41} E$$

$$n_y = n_2' = n_o - \frac{1}{2}n_o{}^3 r_{41} E$$

$$n_z = n_3' = n_o$$

The waveguide is made of Schottky diode. When the field is activated, a depletion region is created under the metal layer. In this area, there is a guiding layer - the refractive index depends on the field.

The wave propagates in the z direction and the field is in the y direction (TE). The change in the refractive index for (100) crystal in TE polarization:

$$\Delta n = n_o{}^3 r_{41} \frac{V}{2t_g}$$

EXAMPLES

For (100) GaAs or GaAlAs crystal in TE polarization:

$$\Delta n = {n_o}^3 r_{41} \frac{V}{2t_g}$$

n_o - the refractive index without field.

r_{41} - element (4,1) from the electro-optic tensor.

${n_o}^3 r_{41}$ - the electro-optic constant.

V - smaller than the breakout voltage V_{BR}.

V around 100 V is enough for creating depletion region with thickness of 1 μm.

Wavelength of 900 nm

$$\Delta n = 3.6^3 \cdot 1.1 \cdot 10^{-12} \frac{100}{2 \cdot 10^{-6}} = 3.5 \cdot 10^{-3}$$
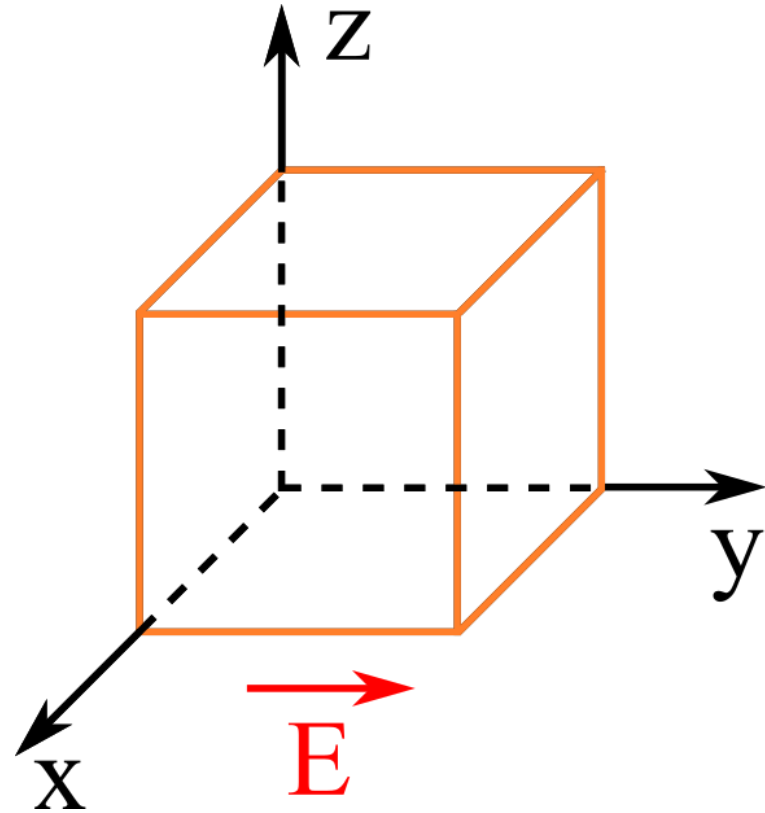
EXAMPLES

Example 2: Glass

Glass is not influenced by the electric field.

Example 3: LiNbO$_3$

We choose z as main optical axis:

$n_1 = n_2 = n_o$ $\qquad n_1 = n_x$ $\qquad n_2 = n_y$ $\qquad n_3$
$= n_z = n_e$

First case: Activating external field in y direction

$n_x = n_1' = n_o + \frac{1}{2}n_o{}^3 r_{22}E$

$n_z = n_3' = n_e - \frac{1}{2}n_e{}^3 r_{51}E$

Where:

$r_{22} = 3.45 \times 10^{-12} \ (m/V)$

$r_{51} = 28 \times 10^{-12} \ (m/V)$

$n_o = 2.272 \qquad n_e = 2.187$
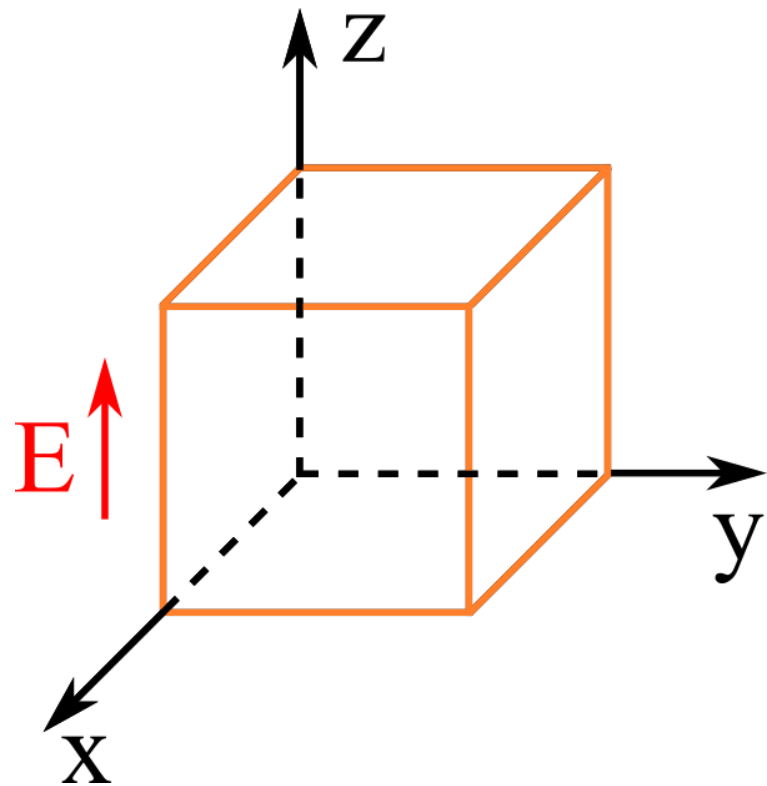
EXAMPLE: LINBO$_3$

Second case: Activating external field in z direction

$$n_x = n_1' = n_y = n_2' = n_o - \frac{1}{2}n_o{}^3 r_{13} E$$

$$n_z = n_3' = n_e - \frac{1}{2}n_e{}^3 r_{33} E$$

Where:

$$r_{13} = 8.6 \times 10^{-12} \; (m/V)$$

$$r_{33} = 30.8 \times 10^{-12} \; (m/V)$$

$$n_o = 2.272 \quad n_e = 2.187$$

FABRICATION OF A WAVEGUIDE

Methods of fabricating waveguides for optical integrated circuits:

1) Deposited thin films (glass, nitrides, oxides, organic polymers).

2) Photo resist films.

3) Ion bombarded glass.

4) Diffused dopant atoms.

5) Heteroepitaxial layer growth.

6) Electro-optic effect.

7) Metal film stripline.

8) Ion migration.

9) Reduced carrier concentration in a semiconductor.
   - Epitaxial layer growth.
   - Diffusion.
   - Ion implantation.

EPITAXIAL GROWTH - CHANGING THE MOLAR CONCENTRATION

- In integrated optics on monolithic circuit made of semiconductor, epitaxial growth is a widely used method for fabricating waveguides.

- This method allows changing the chemical composition of the layer growth to fit the needed molar concentration and wavelength.

- With this method, we fabricate the common waveguide made of a layer of $Ga_{1-x}Al_xAs$ on substrate of GaAs.
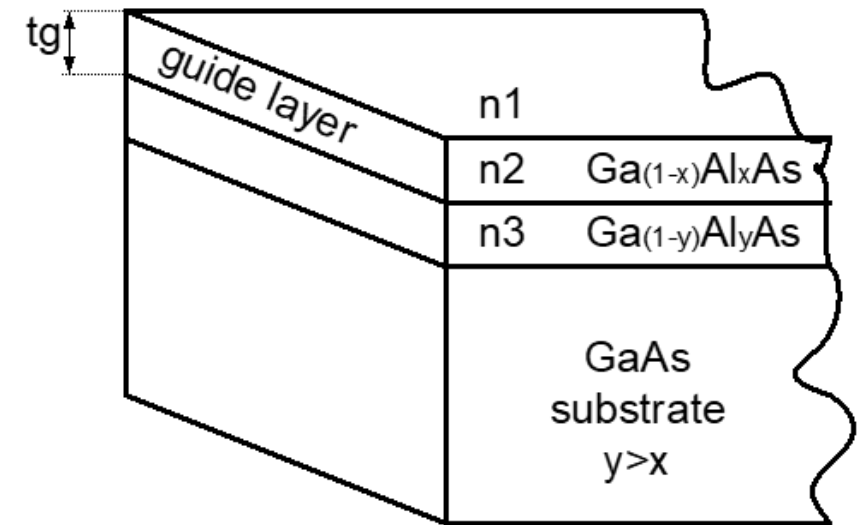
EPITAXIAL GROWTH - CHANGING THE MOLAR CONCENTRATION

For $Ga_{1-x}Al_xAs$, the refractive index depends on the molar concentration of the aluminum (x). It allows waveguide fabrication by only changing x. As x is getting bigger, the refractive index n is getting smaller as shown in the graph below.
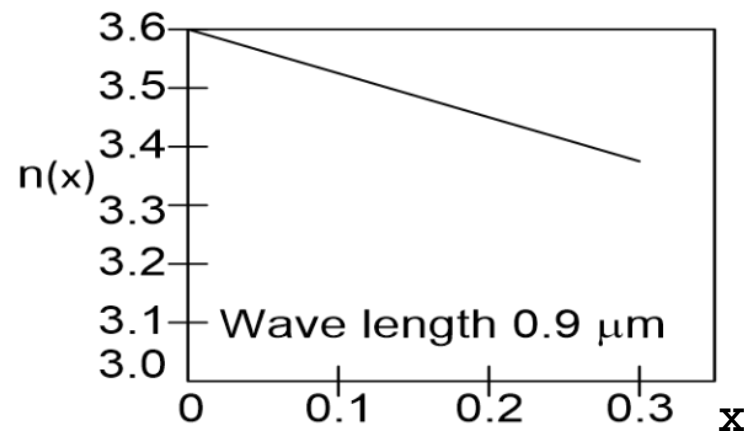
Figure 2: Refractive index of $Ga_{1-x}Al_xAs$ as function of x for wavelength of 0.9 μm.

EPITAXIAL GROWTH - CHANGING THE MOLAR CONCENTRATION

The difference in the refractive indices as a function of the difference in the Al concentration between two layers of $Ga_{1-x}Al_xAs$.
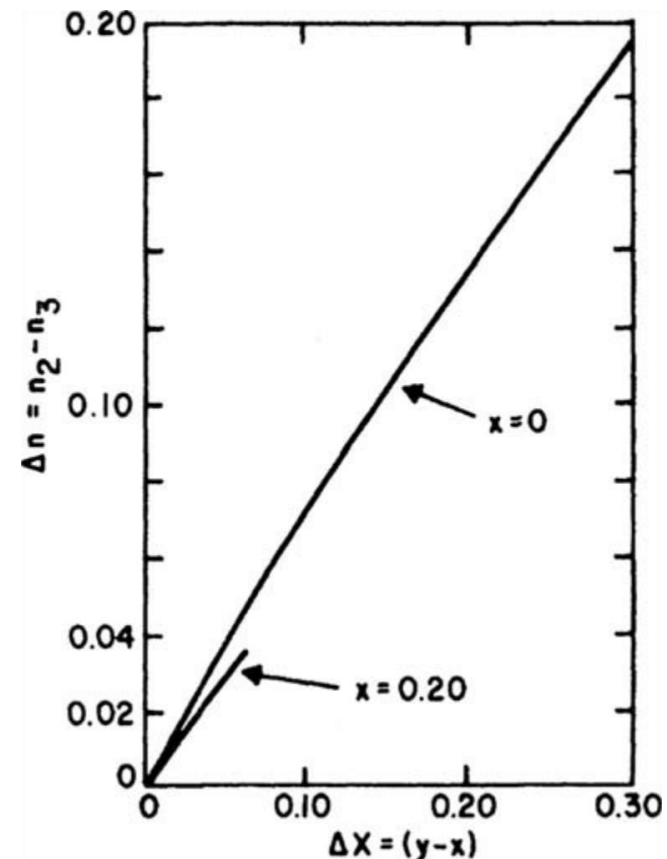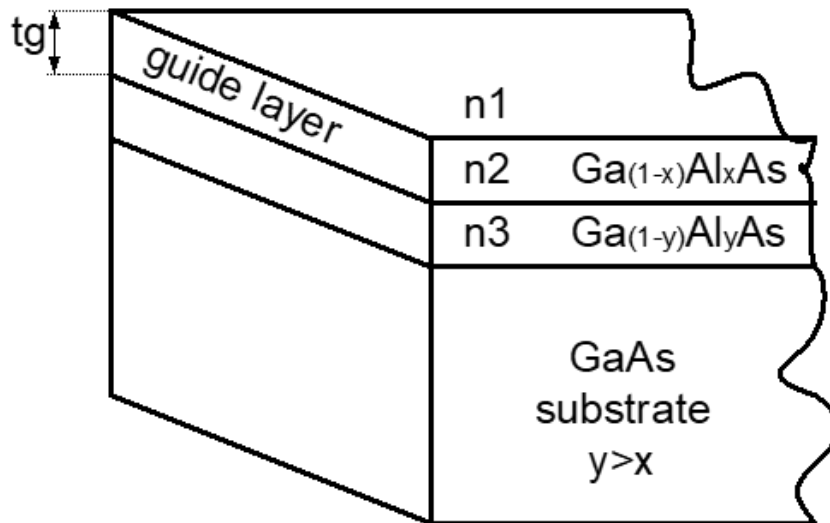
EPITAXIAL GROWTH - CHANGING THE MOLAR CONCENTRATION

The ratio between the refractive indices and wavelength as a function of the difference in the Al concentration between two layers of $Ga_{1-x}Al_xAs$.
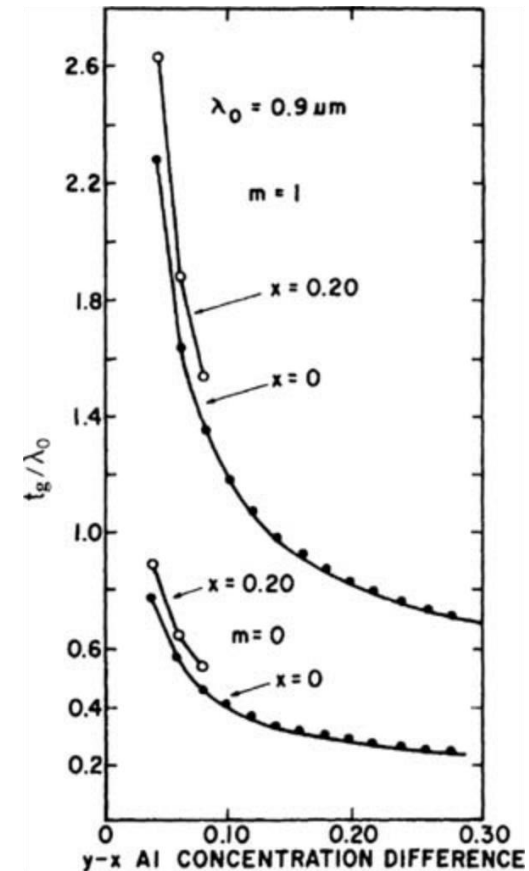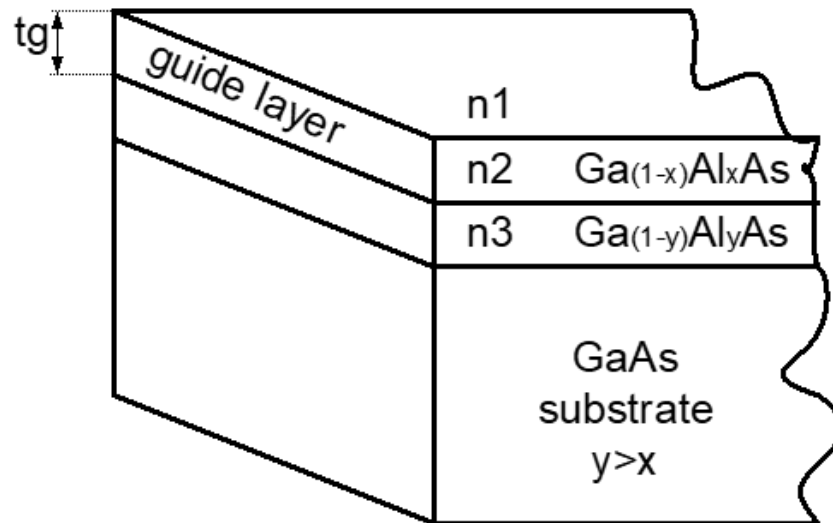
EPITAXIAL GROWTH - CHANGING THE MOLAR CONCENTRATION

The distance between the atoms in GaAs and AlAs is very close:

- Allows preventing defects in the material.

- Allows using material that contains two different x.

Two grating structures are common in semiconductors when every central atom is equidistant to four atoms.
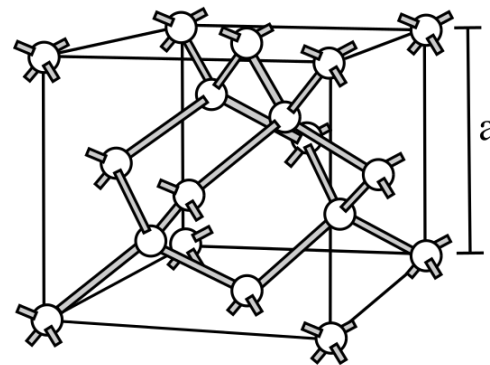
Diamond
(C, Ge, Si, etc)
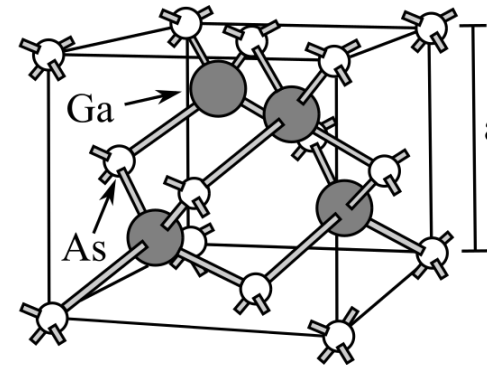
Zincblende
(GaAs, GaP, etc)

EPITAXIAL GROWTH - SELLMEIER EQUATION

The Sellmeier equation defines the refractive index as function of the wavelength:

$$n(\lambda[\mu m])^2 = 1 + \sum_i \frac{A_i \lambda^2}{\lambda^2 - B_i}$$

Where A_i and B_i are Sellmeier coefficients and λ is the vacuum wavelength in micrometers.

EPITAXIAL GROWTH - SELLMEIER EQUATION

Sellmeier equation that fits the GaAs and $Ga_{1-x}Al_xAs$ is:

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

where A, B, C and D depend on x as:

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	$(0.52886 - 0.735x)^2$ $x \leq 0.36$ $(0.30386 - 0.105x)^2$ $x \geq 0.36$	$(0.002467)(1.41x + 1)$

MBE - MOLECULAR BEAM EPITAXY

- Certain atoms are delivered to the substrate during the growth by accelerated molecules (or atoms).

- The crystal is placed in an Ultra-High-Vacuum (UHV) chamber. Each cell contains different material which can be heated and emits atoms beam. It allows growing material with the needed doping.

The advantages of this method:

1. Control of doping.

2. Control of the thickness.
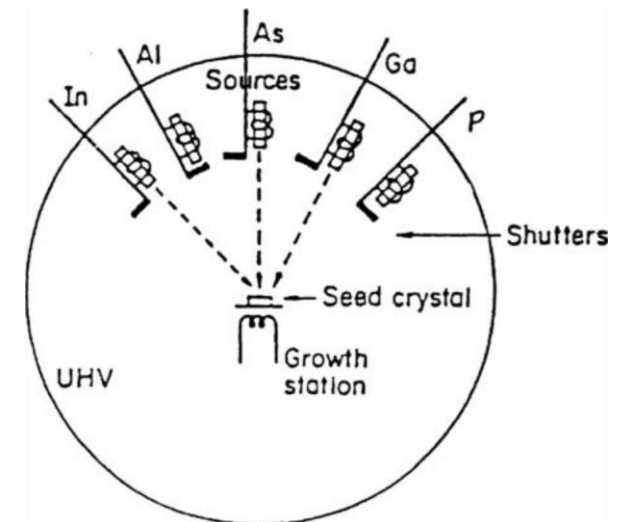
THERMAL EVAPORATION

- High current flows in a metal filament (e.g. tungsten, molybdenum).

- A solid target material inside a high vacuum chamber, typically 3×10^{-4} Torr, is heated by the filament.

- The material in the target is heated up until it evaporates.

- The vacuum allows evaporation of the metal on the substrate and creation of the metal layer (non-uniform layer).
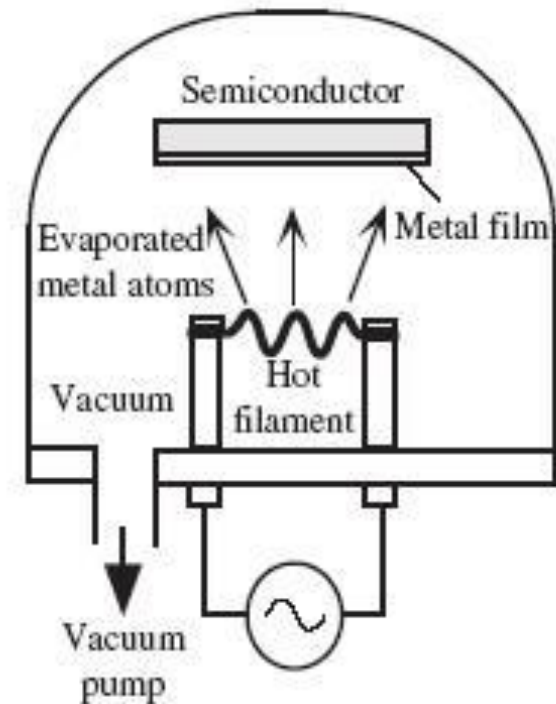
E-BEAM EVAPORATION

- Instead of wire, there is an electron gun [1,2].

- The electrons hit the target and evaporate it.

- The atoms hit the substrate and create a metal layer (non-uniform layer).
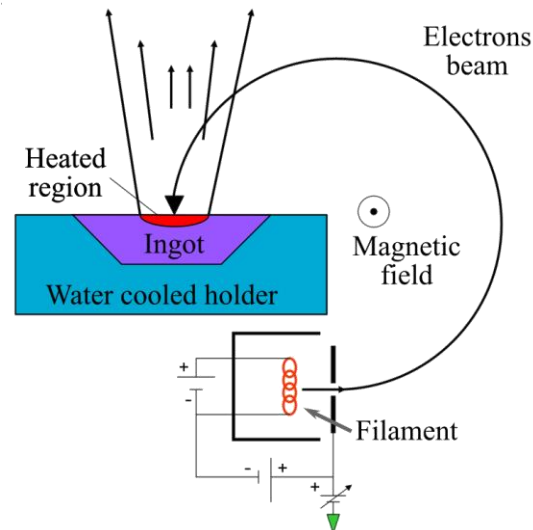
SPUTTERED DIELECTRIC FILMS

- Thermally stimulated vacuum-evaporation for AR coatings is not good for waveguide fabrication - lossy films with 10 dB/cm due to inclusion of contaminant atoms that act as absorption and scattering centers.

- **Sputtering** is the process in which atoms or molecules are removed from the surface of a source (target) material, in vacuum, by bombardment with ions having energies in excess of about 30 eV to about 2 keV - kinetically distributed atoms over the surface with losses on the order of 1 dB/cm.

SPUTTERING SYSTEM

- Atoms or molecules are removed from the source (target) material bombardment with ions, with energies about 30 eV - 2 keV, in vacuum.

- The atoms (or molecules) are deposited on the surface of a substrate, forming a thin film layer.

- This process produces a very uniform layer because the deposited atoms are kinetically distributed over the surface.

PLASMA DISCHARGE SYSTEM

- The target and substrate are placed in a vacuum system and a gas is let in at a pressure of $(2 - 20) \times 10^{-3}$ torr.

- A high voltage bias is applied between anode and cathode.

- Ions generated in the plasma discharge are accelerated toward the cathode.

- The atoms near the surface of the target material, which are thereby sputtered off, and then deposited on the substrate.

Energetic Ions
30 eV - 2 keV

Ar

anode

+

Substrate

Target

SiO₂
Platinum
Gold
Ta₂O₅, etc.

Cathode

Shutter
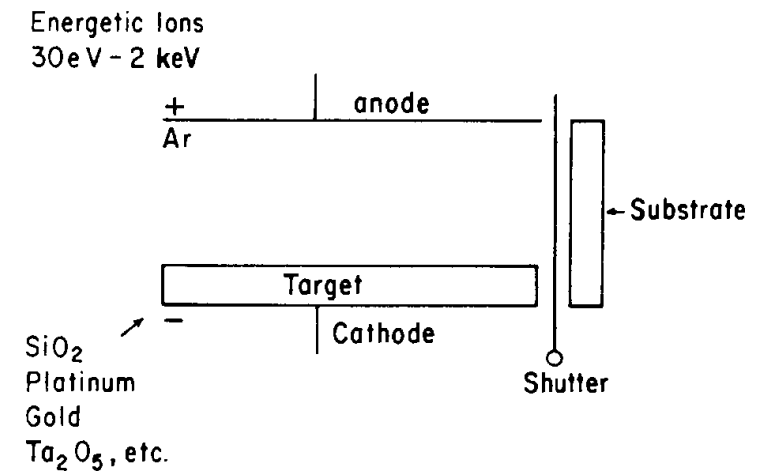
ION BEAM SPUTTER DEPOSITION SYSTEM

- Collimated beam of ions, produced by an ion gun, hit the target.

- The advantages is that the deposition can be done in a high vacuum $< 10^{-6}$ torr, and that the focused ion beam strikes only the target. No contaminant atoms are sputtered off the walls of the chamber.

- Since the focused ion beam is often smaller than the target, the beam is usually electrically scanned in a raster pattern over the target to ensure uniform sputtering.
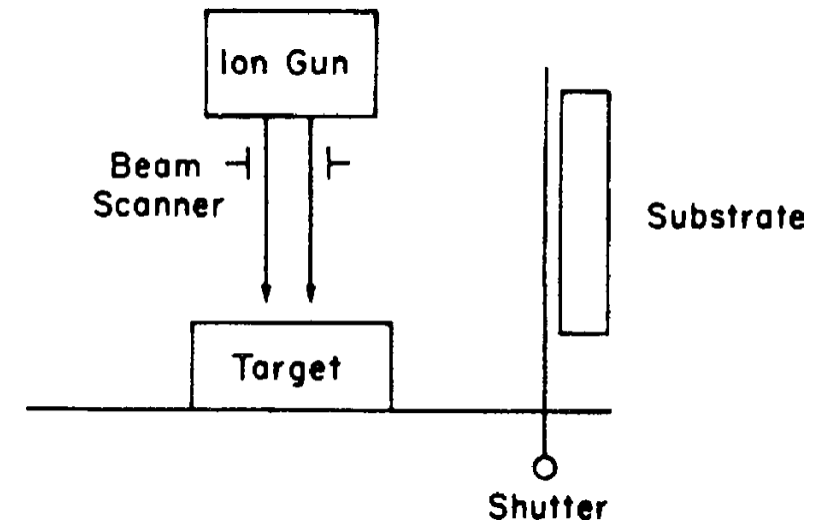
SPIN-COATING FROM SOLUTIONS

- Spin coating is a procedure used to deposit a uniform thin film onto a flat substrate. A small amount of coating material is applied on the center of the substrate. The substrate is then rotated at high speed in order to spread the coating material by centrifugal force.

- The advantages of spin coating are the simplicity and relative ease.

(i) Deposition

(ii) Spin up

(iii) Spin off

(iv) Evaporation
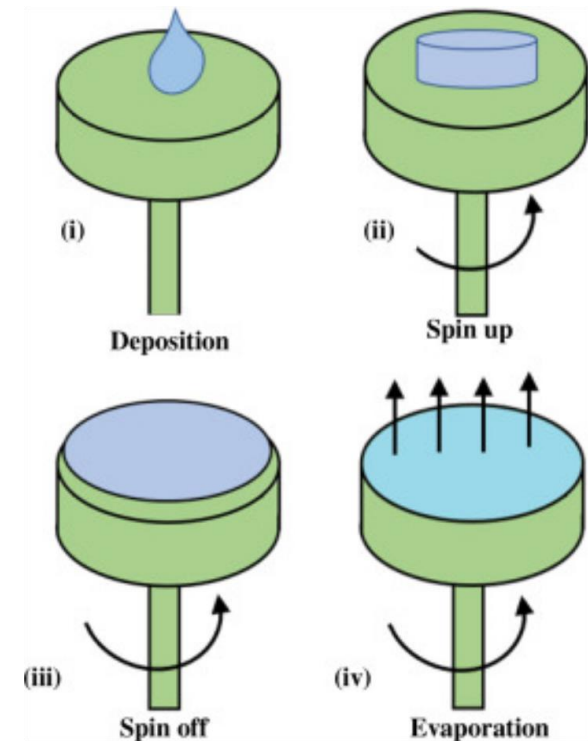
SPIN-COATING FROM SOLUTIONS

- Spin-coating of PMMA with 0.3 dB/cm loss at 1300 nm.

- Polyimide channel waveguides fabricated by direct laser writing.

Waveguide materials applied by spinning and dipping

Material	Solvent
Photoresist	Acetone
Epoxy	Proprietary Compounds
Polymethylmethacrylate	Chloroform, Toluene
Polyurethane	Xylene
Polyimide	
Spun-on glass (SOG)	

POLYMER WAVEGUIDES

- Polymers such as halogenated acrylate, fluorinated polyimide, and deuterated polymethylmethacrylate (PMMA) have been used.

- Polymer films can be fabricated on top of Si, glass, quartz, or plastic through spin coating.

- Photoresist layer on top used for reactive ion etching of the core layer through a photomask.
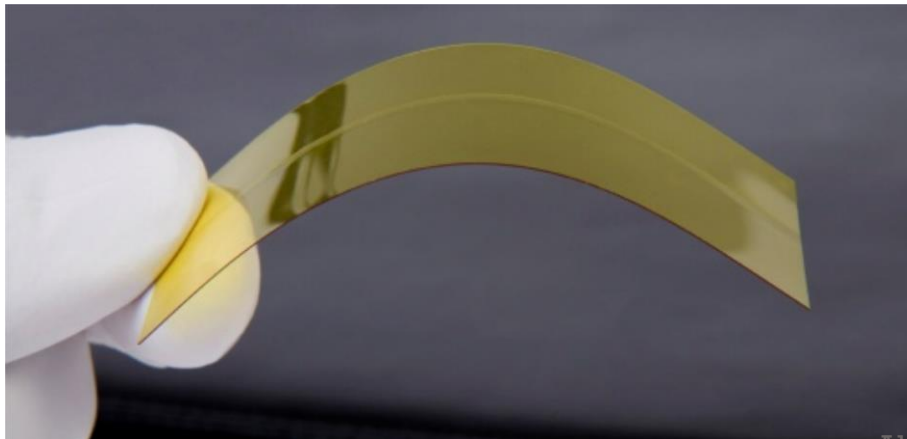
LASER-WRITTEN WAVEGUIDES
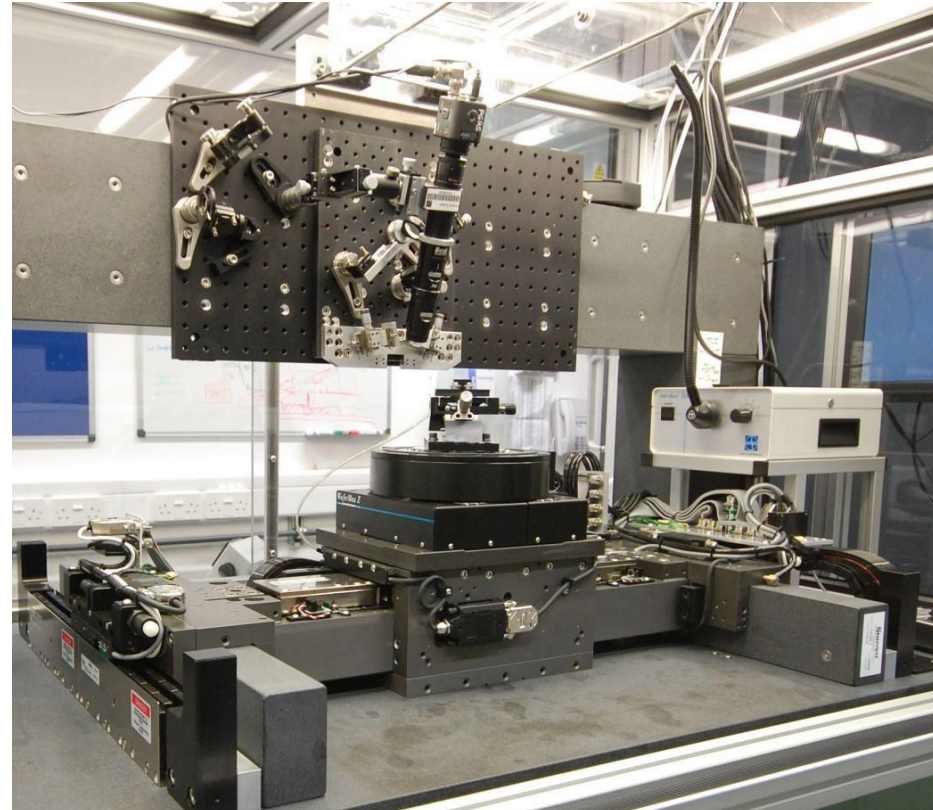
Figure 4: Set-up of UV written waveguides, Peter Smith lab, ORC, UoS.
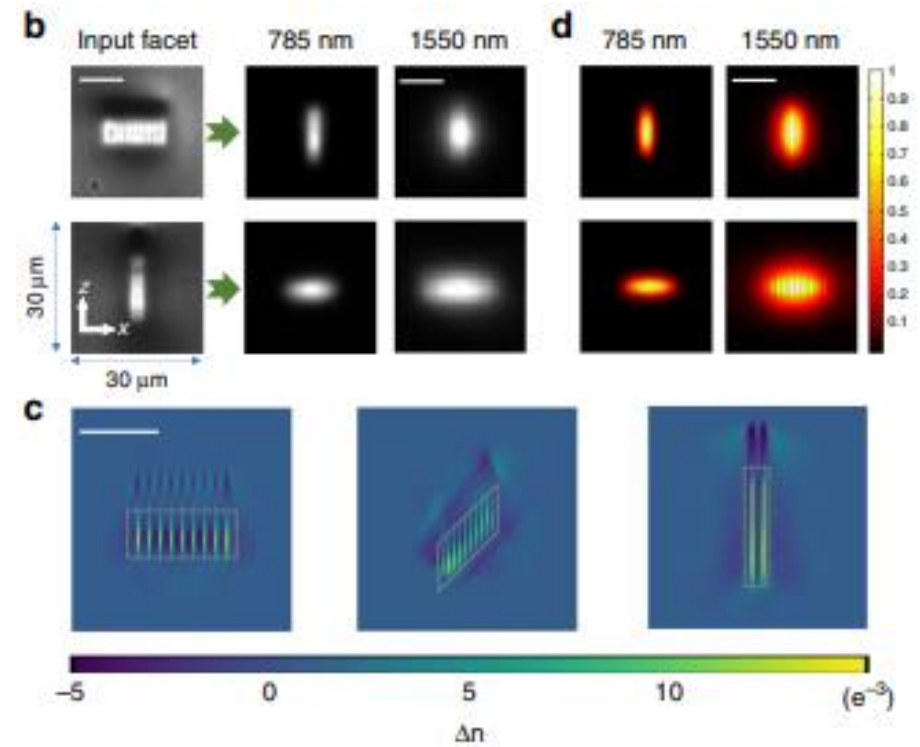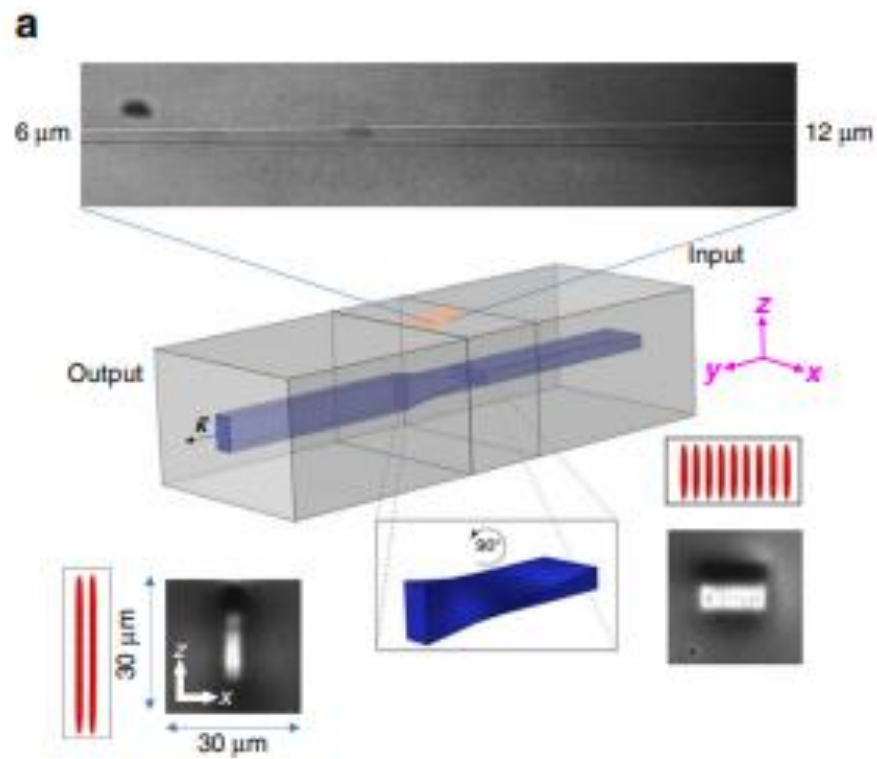
LASER-WRITTEN WAVEGUIDES

Sun, B., Morozko, F. , Salter, P. S., Moser, S., Pong, Z., Patel, R. B., Walmsley, I. A., Wang, M., Hazan, A., Barré, N., Jesacher, A., Fells, J., He, C., Katiyi, A., Tian, Z. H., Karabchevsky, A. and Booth, M. J., 'On-chip beam rotators, adiabatic mode converters, and waveplates through low-loss waveguides with variable cross-sections'. Light: Science & Applications, 11(1), 1-15 (2022).

LASER-WRITTEN WAVEGUIDES

- CW or pulsed light from a laser used for writing waveguides in silica and other glasses.

- Photosensitivity of germanium-doped silica exploited to enhance refractive index in the region exposed to a UV laser.

- Absorption of 244 nm light from a krypton fluoride (KrF) laser changes refractive index by $\sim 10^{-4}$ only in the region exposed to UV light.

- Index changes $> 10^{-3}$ can be realized with a 193-nm Argon fluoride (ArF) laser. This laser is used also in eye surgery, micro-machining.

- A planar waveguide formed first through CVD, but core layer is doped with germania.

- An UV beam focused to ~ 1 mm is scanned slowly to enhance n selectively. UV-written sample is then annealed at 80C.

LASER-WRITTEN WAVEGUIDES

- Femtosecond pulses from a Ti:sapphire laser can be used to write waveguides in bulk glasses.

- Intense pulses modify the structure of silica through multiphoton absorption.

- Refractive-index changes $\sim 10^{-2}$ are possible.
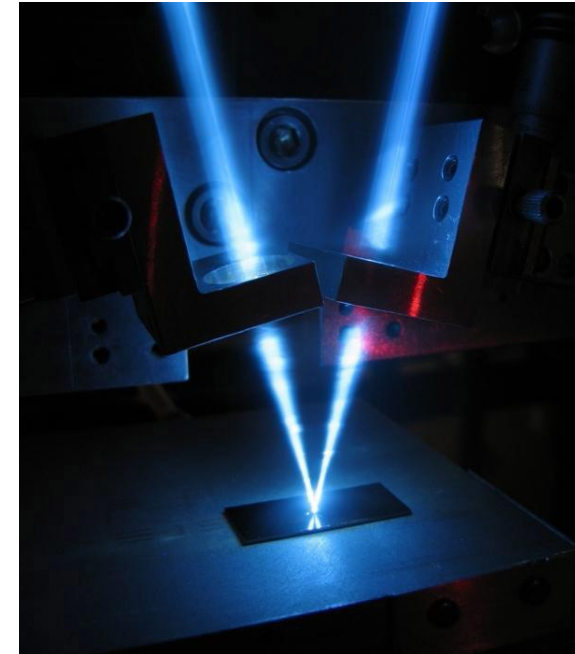
Figure 5: UV written waveguides from Peter Smith lab, ORC, UoS.

ION IMPLANTATION
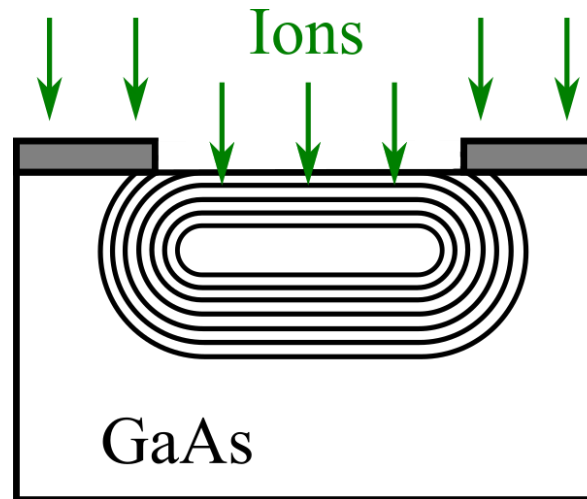
- Accelerating ions in high energy that fits to ion penetration to the substrate.

- The penetrating ions' distribution is gaussian (as function of the penetration depth). The penetration depth R_p and the width of the gaussian depends on concentration and mass of the ions.

- The drawback of this method is that defects are created in the substrate which can be solved by relaxation using heat.

ION IMPLANTATION SETUP
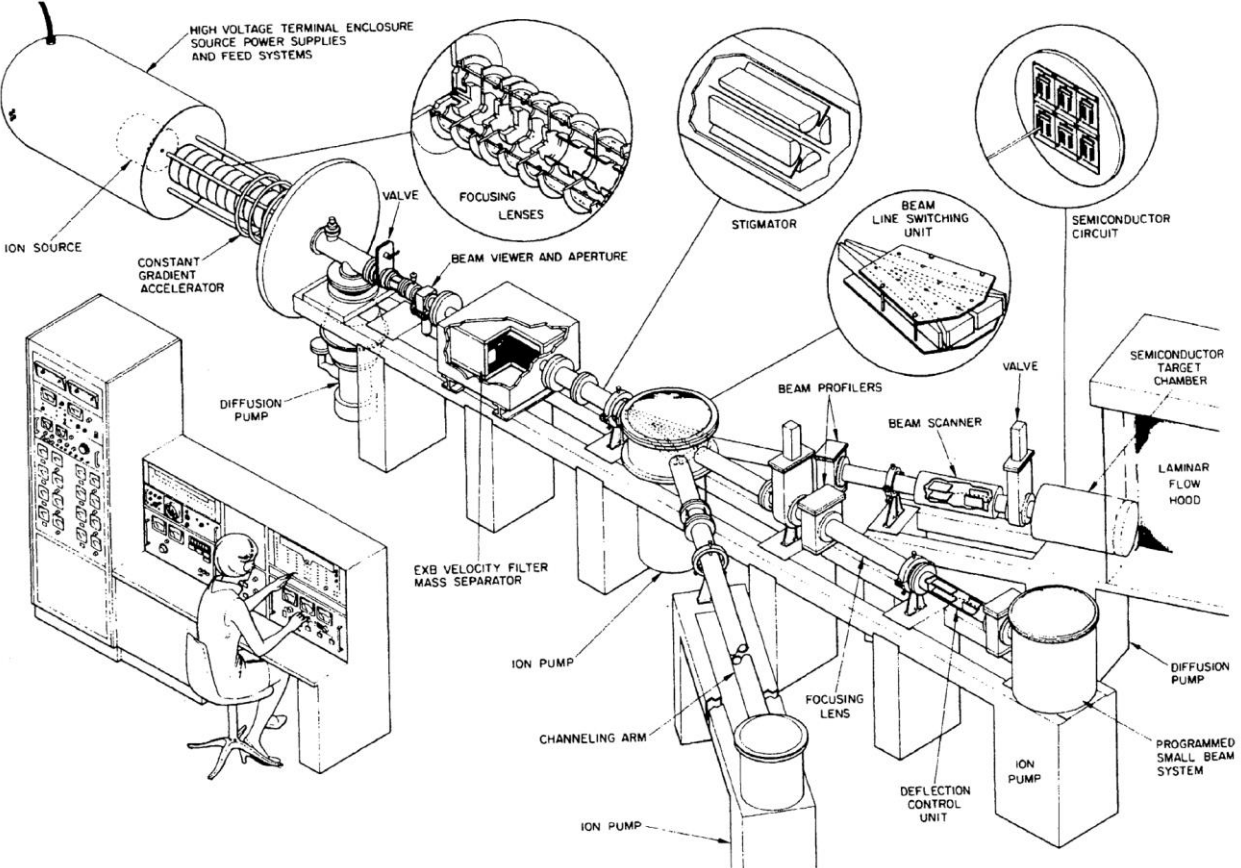
Figure 6: Drawing of a 300-kV ion-implantation system.

ION-EXCHANGE FABRICATION PROCEDURE

- The process involves ion-exchange between the salt and glass which increases the refractive index.

- The substrate layer of a diffused-channel waveguide is made of materials such as soda lime glass, Pyrex, Corning 3-71, or borosilicate (BK7).

- A mask is placed on the substrate and the substrate is baked with the salt.

- The main advantage of an ion-exchange waveguide is its low propagation losses, although its structure is an optically weak ($\Delta = 0.5\%$ in BK7, using KNO_3).

ION-EXCHANGE FABRICATION PROCEDURE

- Conventional photolithography

- SM

- < 8dB coupling efficiency;

0.2 dB/cm prop. loss
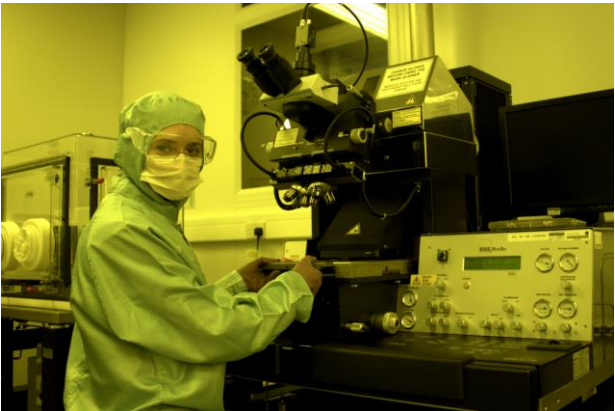
1. Cleaning

2. Al mask e-beam deposition

Al 250nm
bk7

3. Positive photolithography

hard mask

UV exposure

S1813
250nm Al
bk7

4. Resist removal

S1813
Al
bk7

5. Al etch

Al 250nm
bk7
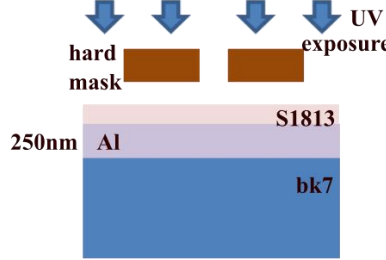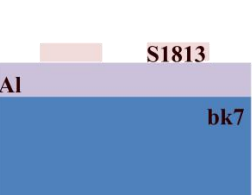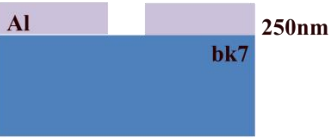
6. Immersion in KNO_3 @395C for 11hr

Molten

Al 250nm
bk7
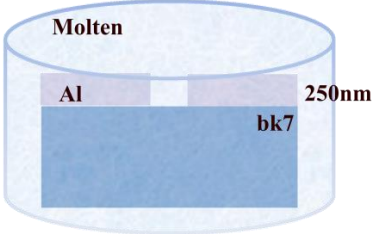
6. Sawing/Lapping/Polishing

holding jig

5mm from each side
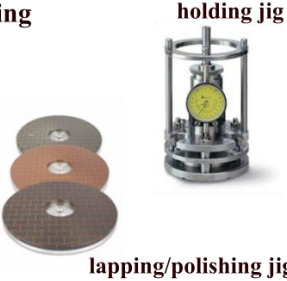
lapping/polishing jig

SPATIAL DISTRIBUTION OF REFRACTIVE INDEX
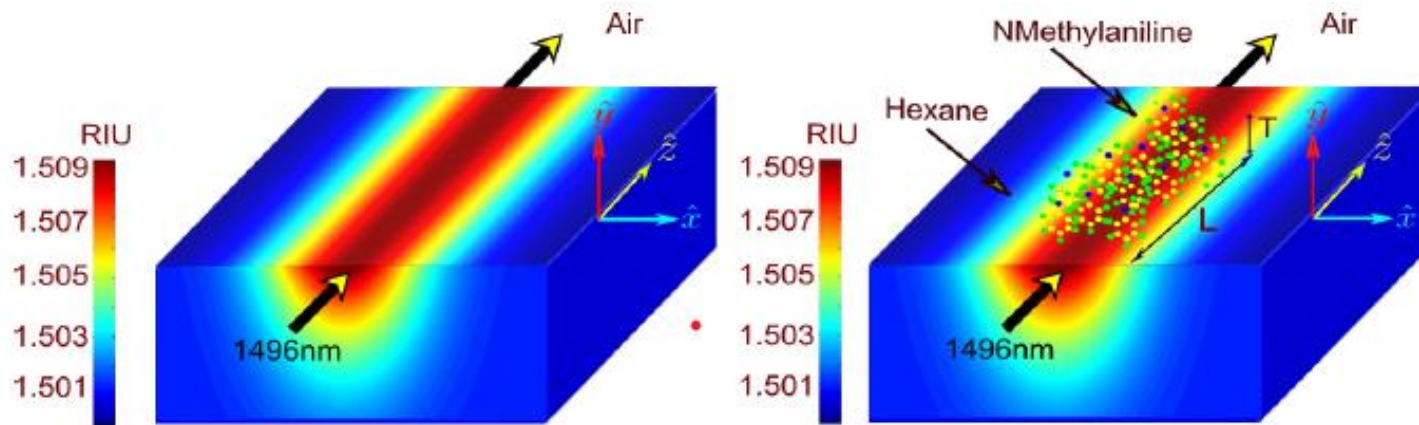
$$n(x, y) = n_s + \Delta n \cdot \text{erfc}\left(\frac{y}{dy}\right) \exp\left(\frac{-x^2}{dx^2}\right)$$

$n_s = 1.50127$

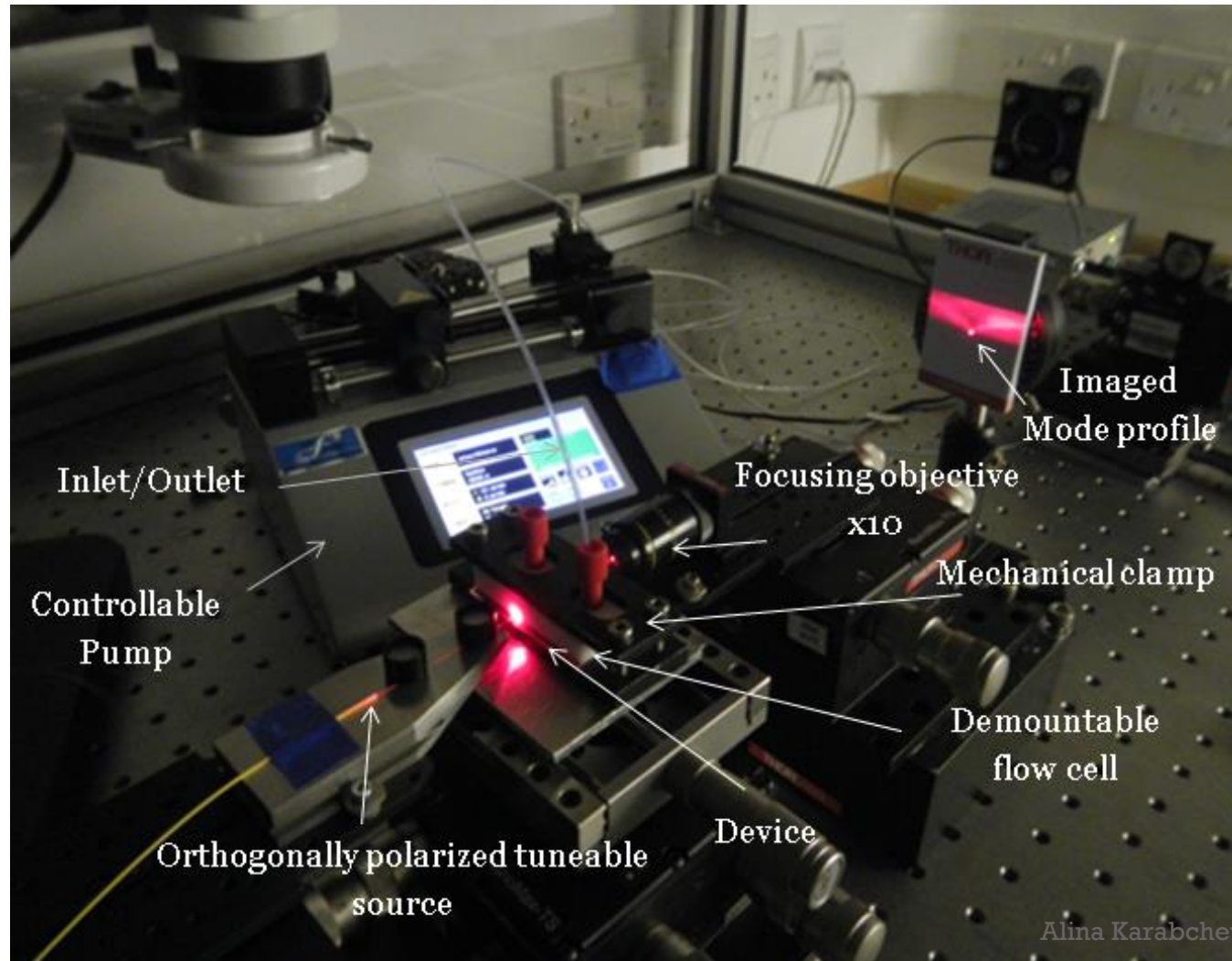Δn increases in refractive index at the surface

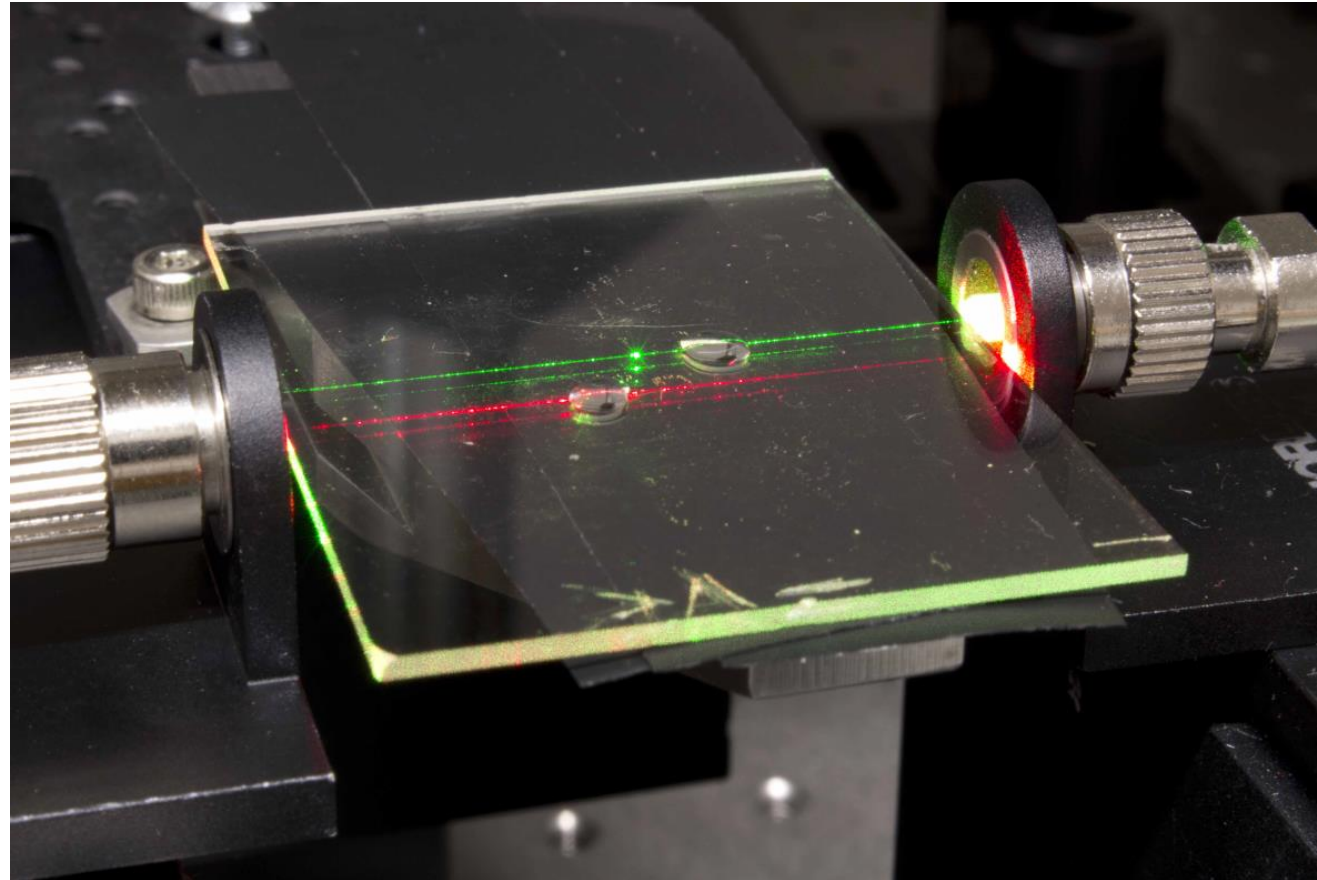$\Delta n_{\text{TM}} = 0.0092$ and $\Delta n_{\text{TE}} = 0.008$

dy - refractive index profile depth
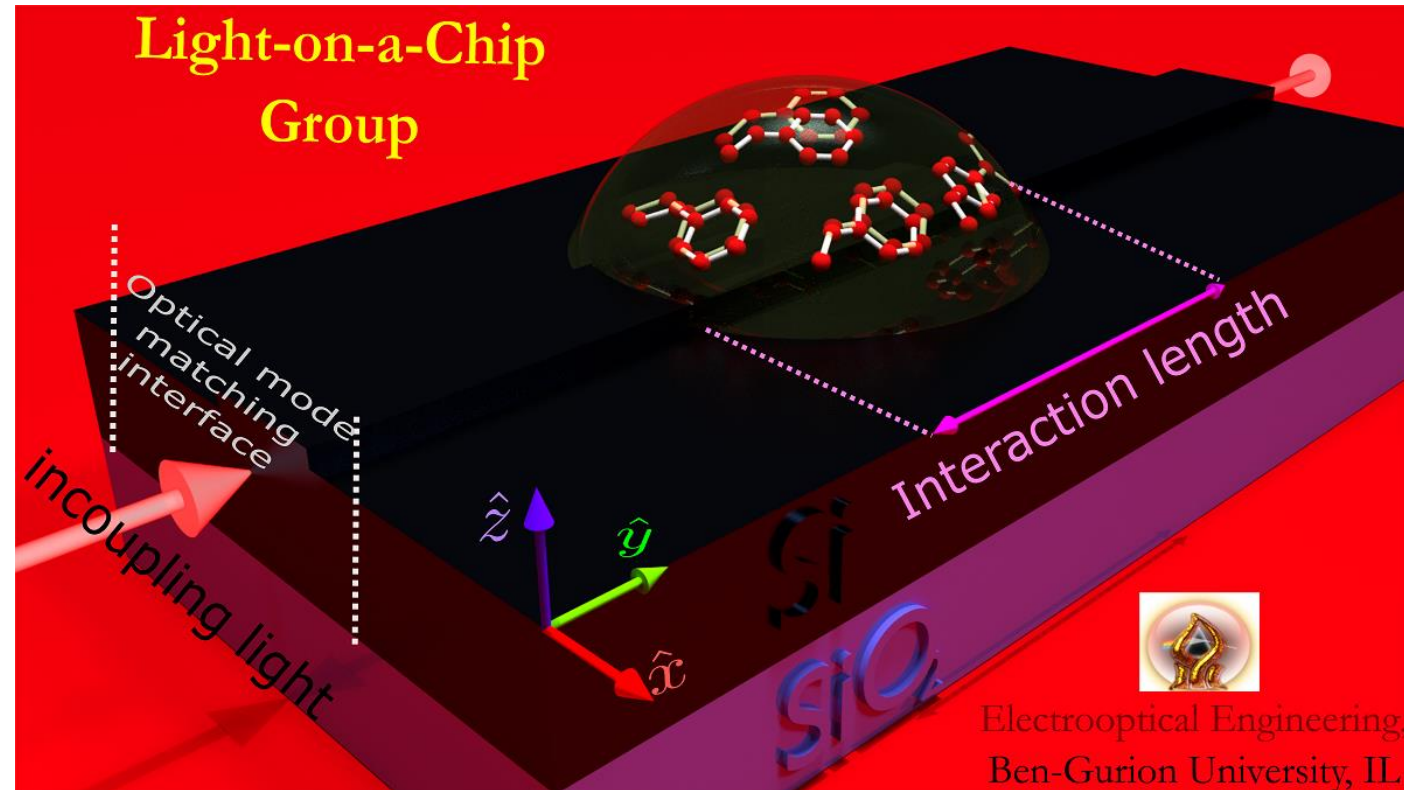
dx - refractive index profile half-width

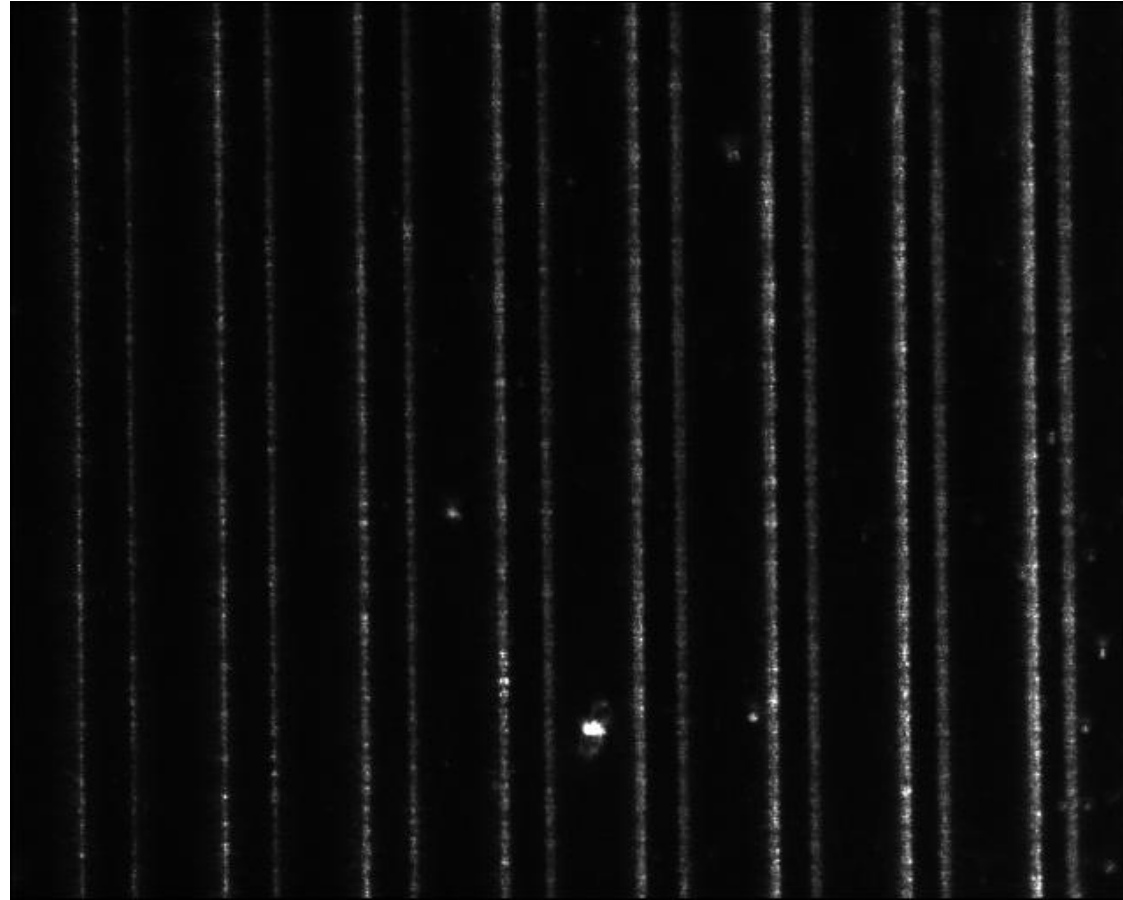# HOW TO CHARACTERIZE WAVEGUIDES
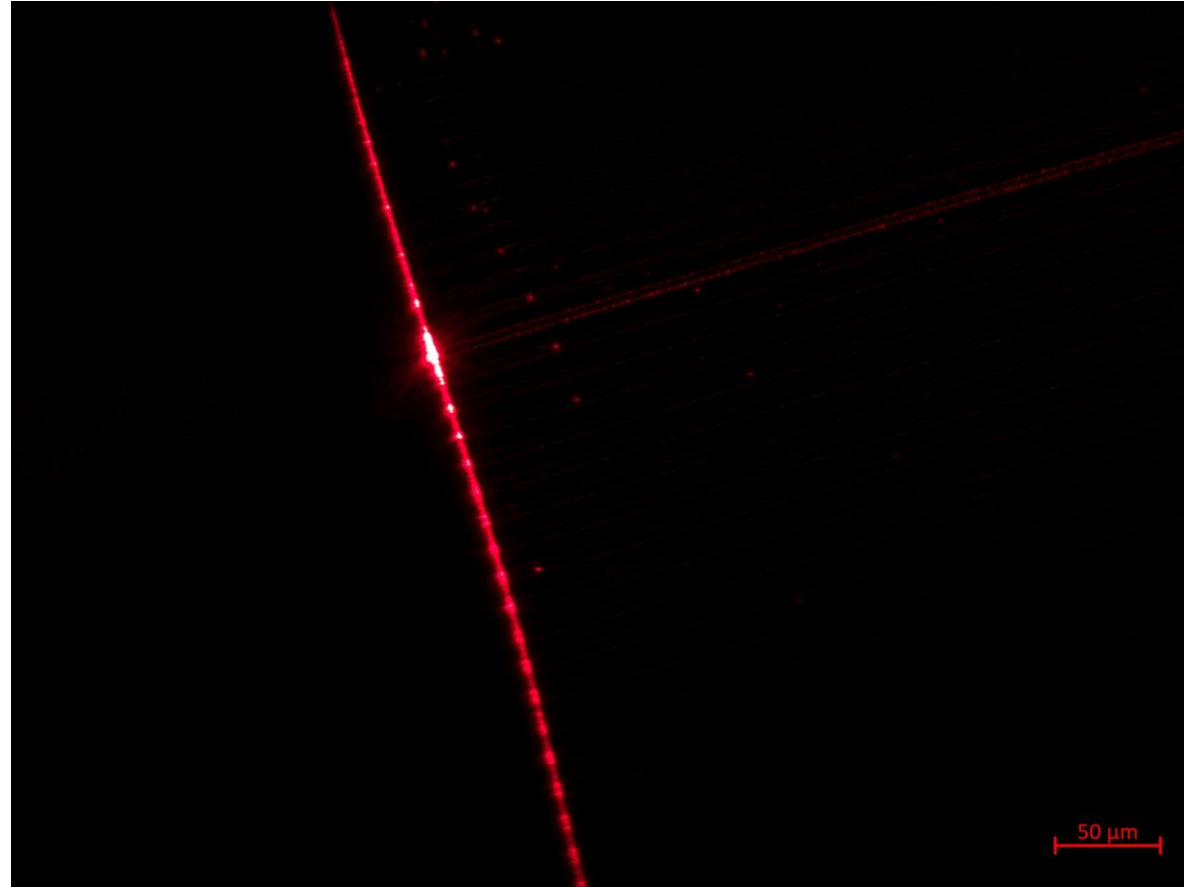
ION EXCHANGE OPTICAL WAVEGUIDES

THE STRUCTURE

Figure 7: From A. Katiyi and A. Karabchevsky, ACS Sensors 3(3) 618-623 (2018)

SCATTERING FROM THE EDGES

SCATTERING FROM THE EDGES

50 µm

H.W.1

1) List and explain other coupling in and out techniques.

2) What are the pits and falls of each coupling technique.

3) Mathematically express the coupling between two guides.

4) Define coupling efficiency.

5) Explain the multiphoton absorption effect: physics and mechanism of observation.

6) Explain the mechanism of annealing.

7) Explain the mechanism of RIE (reactive ion etching).

BIBLIOGRAPHY

[1] http://www.oxford-vacuum.com/background/thin film/evaporation.htm

[2] https://en.wikipedia.org/wiki/Electron-beam physical vapor deposition

[3] Karabchevsky, A. and Kavokin, A. V. Giant absorption of light by molecular vibrations on a chip. Sci. Reports, 6:1-7 9 (2016).