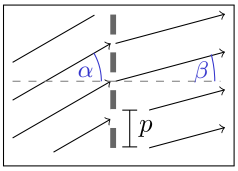
Typical elements: lenses, beam-shaping-surfaces, gratings [and combinations].

Very small elements → aperture-effect dominates! $\rightarrow U_- \boxed{\text{t}} U_+ \rightarrow$

Transmissionfunction of an optical element in the „thin element approximation“: $t(x,y) = \dfrac{U_+(x,y)}{U_-(x,y)}$.

Grating equation: $$\begin{cases} \sin(\alpha) + \sin(\beta) = \dfrac{m\lambda_n}{p} & \text{, in transmission} \\ -\sin(\alpha) + \sin(\beta) = \dfrac{m\lambda_n}{p} & \text{, in reflection} \end{cases} \quad , m \in \mathbb{N}, \text{ grating period } p.$$

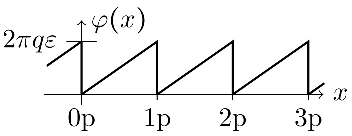


Diffraction efficiency: $\eta_m = \dfrac{P_m}{P_\text{in}}$, P_m power in the m-th diffraction order, P_in incident power .

For a blazed grating it is [$k = \frac{2\pi}{\lambda}$, $n, q \in \mathbb{N}$, $\varepsilon = \frac{\lambda_0}{\lambda}\frac{h}{h_0}$, $p = q\,p_\text{min}$, λ_0 design wavelength, h_0 design height]

$\tilde{t}(k) = p\,\text{sinc}(\pi[q\varepsilon - n])\,\text{e}^{\text{i}\,\pi[q\varepsilon - n]}\,\delta(k - n\frac{2\pi}{p})$ [$\Rightarrow \lambda = \frac{p}{n}$] and

$$t(x) = \sum_{n=-\infty}^{\infty} \text{e}^{\text{i}\,\frac{2\pi}{p}nx}\,\text{sinc}(\pi[q\varepsilon - n])\,\text{e}^{\text{i}\,\pi[q\varepsilon - n]} = \text{e}^{\text{i}\overbrace{2\pi q\varepsilon[\frac{x}{p} \mod 1]}^{\varphi(x)}} \quad ;$$



$$\Rightarrow \ \eta_m = \text{sinc}^2(\pi[\varepsilon q - m])$$

Layer deposition techniques: - Chemical Vapor Deposition [CVD]

[APCVD - athmospheric pressure CVD, LPCVD - low pressure CVD]

- Physical Vapor Deposition [PVD]

[sputtering, thermal evaporation [electric current, electron beam]]

mean free pathlength $\tilde{\lambda} = \frac{k_B T}{p\sqrt{2}\pi d^2} \gg l$, d - particle diameter, p pressure,

l - source-substrate distance

layer thickness on straight substrate $d_s(\alpha) = d_0 \cos^4(\alpha)$.

In reality $d_s(\alpha) = d_0 \cos^n(\alpha)$, $n = 3...4$.

Homogenity $\left|\frac{\Delta d_s}{d_s}\right| \approx \left|\dfrac{\frac{\text{d}\,d_s}{\text{d}\alpha}\Big|_{\alpha_\text{max}} \alpha_\text{max}}{d_s}\right| = n\tan(\alpha_\text{max})\alpha_\text{max}$

Layer deposition from the liquid phase:

- colloidal suspension of liquid and the solid, that is to be deposited
- wetting whole surface [no drops,. . .], evaporating solvent → solid layer remains
- e.g. dip coating [$d \propto \frac{1}{v_\text{out}}$], spray coating, spin coating [$d \approx c_0 \sqrt[3]{\frac{3k\eta}{2\rho\omega^2[1-c_0]}}$, c_0 solid concentration, k vaporization rate, ρ density, η viscosity], galvanic layer deposition [$m = \frac{ItM}{zF}$, m deposited mass, I current, t time, M molar mass, F Faraday constant, z charges per ion].

Angular Spectrum of Plane Waves

$\vec{E}(\vec{r},t) = \begin{pmatrix} u_x(\vec{r}) \\ u_y(\vec{r}) \\ u_z(\vec{r}) \end{pmatrix} \text{e}^{\text{i}[k_{n,z}z - \omega t]}$ be a plane wave with the main propagation direction z. The angular spectrum is then $A(f_x, f_y, z) = \iint_{\mathbb{R}^2} u(\vec{r})\,\text{e}^{-i\,2\pi[f_x x + f_y y]}\,\text{d}x\,\text{d}y$.

$$[\Rightarrow u(\vec{r}) = \iint_{\mathbb{R}^2} A(f_x, f_y, z)\,\text{e}^{i\,2\pi[f_x x + f_y y]}\,\text{d}f_x\,\text{d}f_y]$$

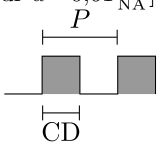
From the Helmholtz equation [$\Delta u + k_n^2 u = 0$] it follows: $u(x,y,z) = \text{FT}\left(\text{FT}^{-1}\left(u(x,y,z_0)\right)\text{e}^{\text{i}\,k_n\sqrt{1 - \lambda_n^2 f_x^2 - \lambda_n^2 f_y^2}[z - z_0]}\right)$.

For small f_x, f_y the Fresnel approximation is $u(x,y,z) = \dfrac{\text{e}^{\text{i}\,k_n z}}{\text{i}\,\lambda_n z}\,\text{e}^{\frac{\text{i}\,k_n}{2z}[x^2 + y^2]} \iint_{\mathbb{R}^2} u(\xi,\eta,0)\,\text{e}^{\text{i}\,\frac{k_n}{2z}[\xi^2 + \eta^2]}\,\text{e}^{-\text{i}\,\frac{k_n}{z}[x\xi + y\eta]}\,\text{d}\xi\,\text{d}\eta$
.

[follows from the Kirchhoff’sche Beugungsintegral]

Photolithography: [λιθος - stone, γράφειη - write → writing on stone]

- distance of mask and resist lead to diffraction effects [$\Delta x \propto \sqrt{d\lambda}$] → diffraction correcting optics.
  [Abbe: distance of two resolvable points at incoherent lightning with a circular apertur $d = 0{,}61\frac{\lambda}{\mathrm{NA}}$]
  Typically: resolution $P = k_1\frac{\lambda_n}{\mathrm{NA}}$ with $k_1 \approx 0{,}5$ and critical dimension $\mathrm{CD} = \frac{P}{2}$.

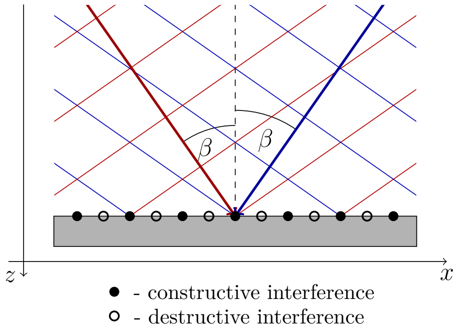


- structures are typically periodic → similarly to a grating diffraction orders.
  [$\left|\frac{m\lambda_n}{d}\right| = \left|\frac{mNA}{0{,}61}\right| = |\sin(\alpha)+\sin(\beta)| \le 2 \Rightarrow m \in \{-1,0,1\}$ maximally]
- Depth of focus [DOF]: $\mathrm{DOF} = k_2\frac{n\lambda_0}{\mathrm{NA}}$
  , for a gaussian beam [free space wavelength λ_0, beam waist radius w_0] $k_2 = \frac{2}{\pi}$, $\mathrm{NA} = n\sin(\alpha) \approx \frac{\lambda_0}{\pi w_0}$.
- The resist dissolution rate R during the development as a function of the exposure dose $D = I\,t$ [Intensity I, exposure time t] defines the contrast $\gamma = \left.\frac{\partial\ln(R)}{\partial\ln(D)}\right|_{\max}$.
- As a first order approximation it is $h = \frac{1}{\alpha}\ln\left(1+\alpha K D_0 t_d\right)$, with absorption coefficient α, exposure dose $D = \underbrace{I t_{\text{illuminate}}}_{D_0} e^{-\alpha z}$ [Lambert Beer], the development rate $R = KD$ [proportionality constant K], the developement time t_d and the structure height h.
- The final structure depends on the field distribution of the incident light as well as the contrast of the resist [→ response...]!
- In order of lowering the minimal structure size under the optical limit → double patterning.
- e.g. $\underbrace{\text{contact printing, proximity pr., projection pr.}}_{\text{with object mask}}$, $\underbrace{\text{laser lithography, holography, electron beam lithography}}_{\text{without object mask}}$

Holography:

$$I \propto |E_1+E_2|^2 = 2|E_1|^2\left[1+\cos\left(2\frac{2\pi}{\lambda_n}\sin(\beta)x\right)\right] \qquad [|E_1| = |E_2|]$$

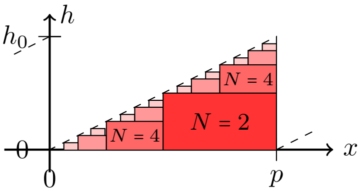
with a period of $p = \frac{\lambda_n}{2\sin(\beta)}$.



Electron beam lithography:

- minimal beam size limited by spherical aberrations, chromatic aberrations, source size, diffraction, …; typically smaller than for laser lithography.
- needs vacuum
- additional to primary electrons also back scattered electrons and X-ray radiation make the volume of interaction rather large [effects substrate! Higher e^- energies can make effected resist volume smaller]
- to prevent the effects of the e^- on the substrate [heating, ...], it exist chemically amplified resists [CAR]
- alternative exposure regimes:
  - variable dose exposure
  - multi level profile fabrication [due to misalignments it is not better, to use infinitly many levels... → find maximum]

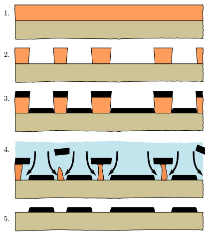
  [for optimal alignment the linear theory yields for N levels with a blazed grating for the fundamental wavelength λ_0 and $nh_0 = \lambda_0$ that the intensity scales with $I \propto \mathrm{sinc}^2(\frac{1}{\pi N})$]



Micro-lens-fabrication by resist reflow:

- for micro-optics the surface tension of droplets leads to nearly spherical profiles
- first one creates a binary cylinder, then it is melted [thermally] and a sphere forms [very smooth surface!]
- With the assumptions [diameter] $d_{\text{lens}} = d_{\text{cylinder}}$ and [volume] $V_{\text{lens}} = V_{\text{cylinder}}$ it is $h_{\text{cylinder}} = \frac{1}{2}h_{\text{lens}} + \frac{2}{3}\frac{h_{\text{lens}}^3}{d_{\text{lens}}^2}$.
- However restrictions for possible diameters, heights, minimal angles, fill factor, … when surface tension is dominated

by e.g. gravity or surface-forces from the substrate.



Transfer of the lithographically created pattern via:

- Lift-off-process
  - directed coating necessary
  - slight undercut of resist profile
  - applicable for all coatable materials
- Etching
  - photo-resists works as isolator; where there is none, the substrate is being modified
  - aspect ratio $\text{AR} = \dfrac{\text{depth}}{\text{width}}$
  - selectivity $= \dfrac{\text{etchrate of layer / substrate}}{\text{etchrate of mask / resist}}$
  - important property: isotropic [etching speed direction-independent] or anisotropic [etching speed direction-dependent]

  - wet etching
    - typically isotropic process
    - low AR
    - if however substrate [e.g. crystalline silicon] shows anisotropy, then also anisotropic process
  - dry etching [aka plasma etching]
    - sputter etching, ion-beam etching or ion-beam milling
    - accelerated plasma ions destroy bonds in material and deplete it
    - typically anisotropic process
    - addtitionally chemically active ions can be used [e.g. reactive ion etching [RIE] or reactive ion beam etching [RIBE]] → higher selectivity, higher AR possible

Characterization:

- exact 3D image of the structure surface needed; resolution should be at least 5× better than the smallest structure, which is to be characterized
- technical devices:
  - optical microscope
  - mechanical surface profiler
  - atomic force microscope [AFM]
  - scanning electron microscop [SEM]
  - confocal microscope
  - interference optical surface profiler