Propagation of Light in Layered Materials

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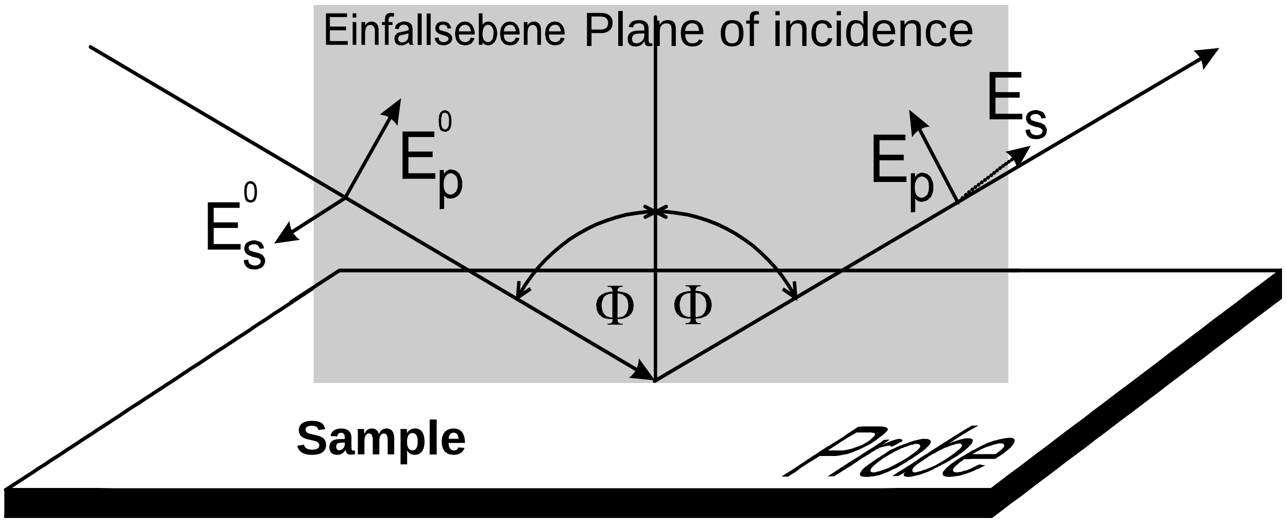
Contents

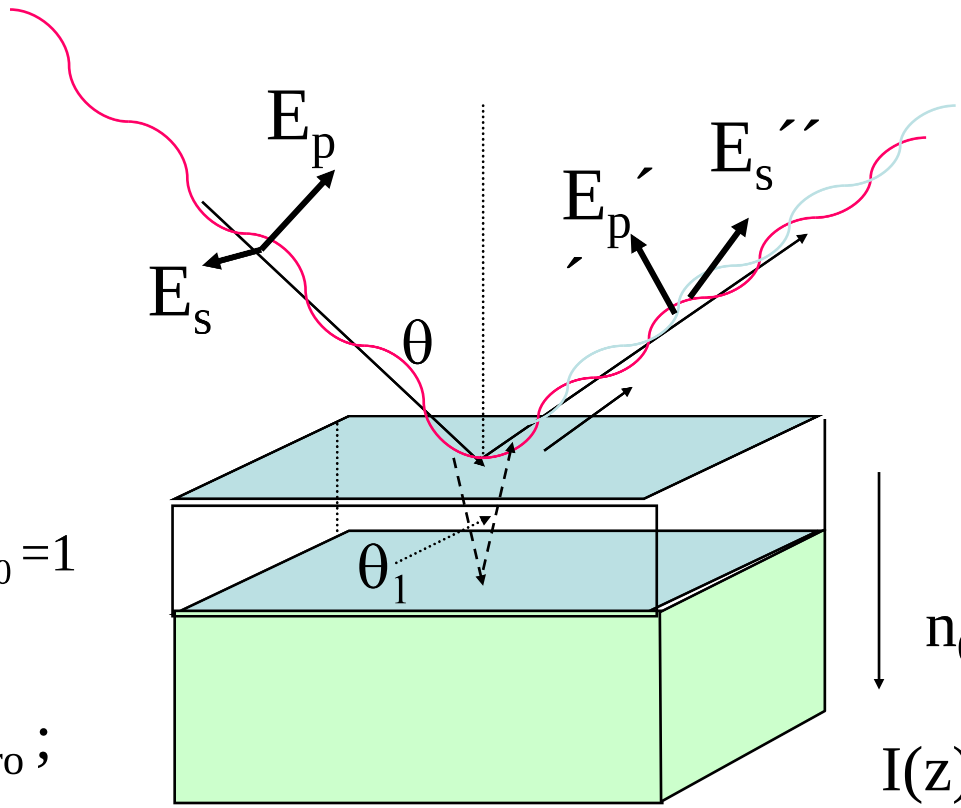
- **Recapitulation of Electrodynamics**
- **2 phase and 3- phase model**
- Transmission (scattering) matrix,
- Virtual interface model

Components of Polarization: ‘senkrecht’ ‘parallel’



Recap II: Polarization, Reflection, Refraction

3-phase model



$n_0 \; k_0 \, ; \, \varepsilon_{r0} = 1$

$n_1 \; k_1 \, ; \, \varepsilon_{ro} \, ;$

$n_s \; k_s \, ; \, \varepsilon_{rs}$

$n_0 \sin \phi_0 = n_1 \sin \phi_1$

$I(z) = I_0 \exp(-4\pi k_1 z/\lambda)$

Maxwell´s equations in vacuum and matter:

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \qquad \nabla \cdot \boldsymbol{E} = \frac{\rho}{\varepsilon_0}$$

microscopic fields

$$\nabla \times \boldsymbol{B} = \mu_0 \left(\boldsymbol{J} + \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} \right) \qquad \nabla \cdot \boldsymbol{B} = 0$$

E and **H** are electric and magnetic field, **D** and **B** are displacement and magnetic induction fields; **E** and **B** are observable fields,
Bound charges and currents are put into the macroscopic fields **E** **B**

$$\nabla \cdot \underline{\boldsymbol{E}} = \frac{1}{\varepsilon_0}\left(\rho_f + \rho_b\right) = \frac{\rho_f}{\varepsilon_0} - \frac{\nabla \cdot \boldsymbol{P}}{\varepsilon_0} \quad \cdots \boldsymbol{P} = \frac{1}{\Delta V}\sum \boldsymbol{p}$$

$$\nabla \times \underline{\boldsymbol{B}} = \mu_0 \left(\boldsymbol{J}_f + \boldsymbol{J}_b + \varepsilon_0 \frac{\partial \underline{\boldsymbol{E}}}{\partial t} \right) = \mu_0 \left(\boldsymbol{J}_f + \frac{\partial \boldsymbol{P}}{\partial t} + \nabla \times \boldsymbol{M} + \varepsilon_0 \frac{\partial \underline{\boldsymbol{E}}}{\partial t} \right)$$

Linear Material properties

E all fields from now on macroscopic fields **<u>without</u>** underline,
most general linear approach

$$\boldsymbol{D}(\mathbf{r},t) = \varepsilon_0\ \vec{\vec{\varepsilon}}(\mathbf{r},t)\ \boldsymbol{E}(\mathbf{r},t) = \varepsilon_0\ \vec{\vec{\varepsilon}}(t)\ \boldsymbol{E}(\mathbf{r},t) = \varepsilon_0\ \boldsymbol{E}(\mathbf{r},t) + \boldsymbol{P}(\mathbf{r},t) = \varepsilon_0\ (1+\chi(\mathbf{r},t))\boldsymbol{E}(\mathbf{r},t)$$

$$\vec{\vec{\varepsilon}}(\mathbf{r},\omega) -> \vec{\vec{\varepsilon}}(\omega) -> \varepsilon(\omega)$$

$$\boldsymbol{B}(\mathbf{r},t) = \mu\ \boldsymbol{H}(\mathbf{r},t) = \mu_0(1+\chi_m)\boldsymbol{H}(\mathbf{r},t) \text{ for optical frequencies } \boldsymbol{B}(\mathbf{r},t) = \mu_0\ \boldsymbol{H}(\mathbf{r},t)$$

If ε tensor- see lecture on generalized ellipsometry, if ε is a function of **r**,
then solve a more complicated diff. equation, $\varepsilon(t)$ real => FT: $\varepsilon(\omega) = \varepsilon(-\omega)$

Redefine ME in macroscopic fields:

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \qquad \nabla \cdot \boldsymbol{D} = \rho_f$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}_f + \frac{\partial \boldsymbol{D}}{\partial t} \qquad \nabla \cdot \boldsymbol{B} = 0$$

$$\varepsilon = \varepsilon_0(1+\chi) \qquad \boldsymbol{D} = \varepsilon \boldsymbol{E}$$

$$\mu = \mu_0(1+\chi_m) \qquad \boldsymbol{B} = \mu \boldsymbol{H}$$

Dispersion relation and continuity at interfaces

No *free* charges or currents at optical frequencies:

$$\Delta \boldsymbol{E} - \mu\varepsilon \frac{\partial^2 \boldsymbol{E}}{\partial t^2} = 0 \qquad \boldsymbol{E} = \boldsymbol{E}_0 e^{i(\boldsymbol{k}\cdot\boldsymbol{r} - \omega t + \varphi_e)}$$

$$\tilde{n}^2 = (n - ik)^2 = \mu\varepsilon c^2 = \frac{\mu}{\mu_0}\frac{\varepsilon}{\varepsilon_0} \qquad k = \tilde{n}\frac{\omega}{c} \qquad \text{Dispersion relation: } \boldsymbol{k}^2 = \mu\varepsilon\omega^2$$

Normal component of ***D*** = ε ***E*** continous
Normal component of ***B*** continous
Tangential component of ***E*** continous
Tangential component of ***H=B/μ*** continous

$$\oiint_S \boldsymbol{D}\cdot\boldsymbol{n}\,dA = (\boldsymbol{D}_1 - \boldsymbol{D}_2)\cdot\boldsymbol{n}\,\Delta A = \varepsilon(\boldsymbol{E}_1 - \boldsymbol{E}_2)\cdot\boldsymbol{n}\,\Delta A = \rho = 0$$

$$(\boldsymbol{B}_1 - \boldsymbol{B}_2)\cdot\boldsymbol{n} = 0 \qquad \varepsilon(\boldsymbol{E}_1 - \boldsymbol{E}_2)\cdot\boldsymbol{n} = 0$$

$$\oint_C \boldsymbol{E}\,d\boldsymbol{l} = (\boldsymbol{t}\times\boldsymbol{n})(\boldsymbol{E}_2 - \boldsymbol{E}_1)\cdot\Delta\boldsymbol{l} = 0 = -\iint_{S'} \frac{\partial \boldsymbol{B}}{\partial t}\boldsymbol{n}\,dA$$

$$\boldsymbol{n}\times(\boldsymbol{E}_2 - \boldsymbol{E}_1) = 0 \qquad \boldsymbol{n}\times(\boldsymbol{H}_2 - \boldsymbol{H}_1) = 0$$

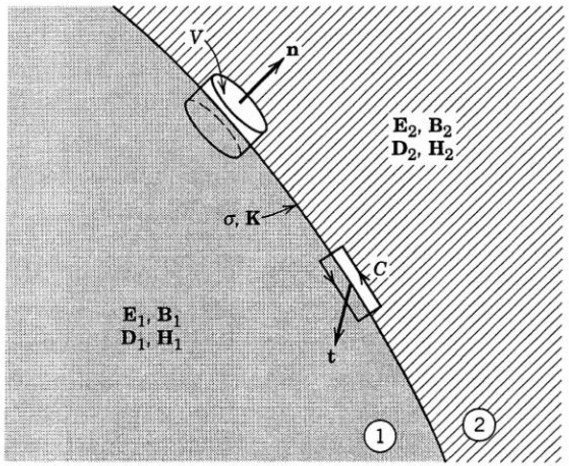
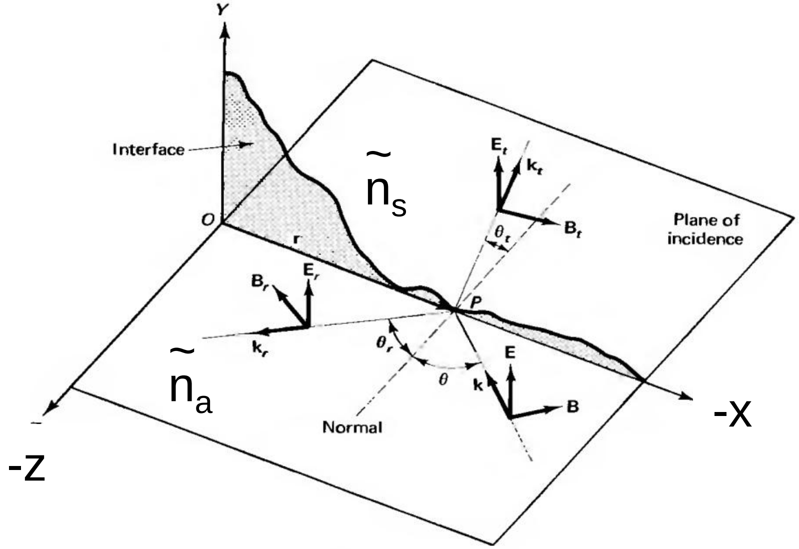


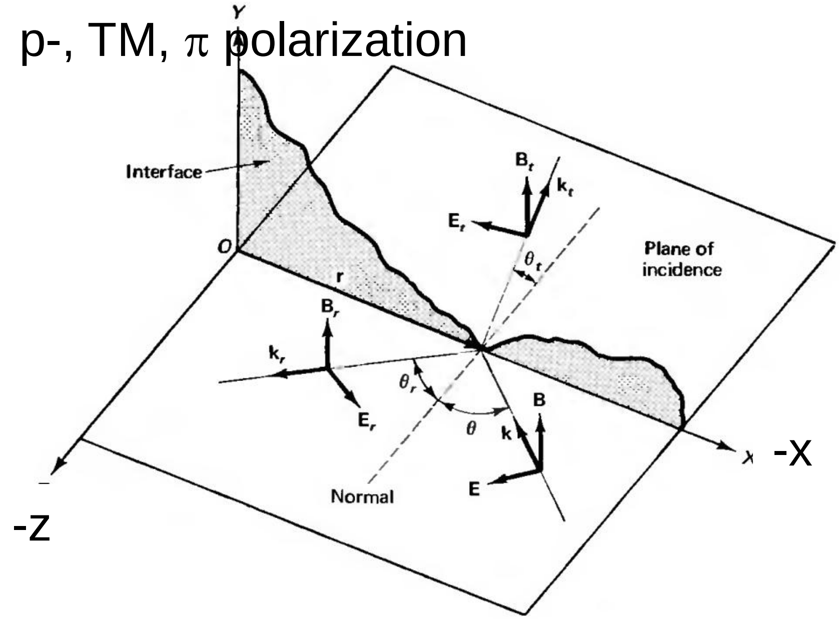
Figure I.4 Schematic diagram of boundary surface (heavy line) between different media. The boundary region is assumed to carry idealized surface charge and current densities σ and **K**. The volume V is a small pillbox, half in one medium and half in the other, with the normal **n** to its top pointing from medium 1 into medium 2. The rectangular contour C is partly in one medium and partly in the other and is oriented with its plane perpendicular to the surface so that its normal **t** is tangent to the surface.

Continuity II : waves from beneath

s-, TE, σ polarization



p-, TM, π polarization



$$\boldsymbol{k} = (k_x, 0, k_z) = \tilde{n}_a \frac{\omega}{c}(\sin\theta, 0, \cos\theta)$$

$$\boldsymbol{k}^r = (k^r{}_x, k^r{}_y, k^r{}_z) \quad k^r{}_x{}^2 + k^r{}_y{}^2 + k^r{}_z{}^2 = \left(\tilde{n}_a \frac{\omega}{c}\right)^2$$

$$\boldsymbol{k}^r = (k^t{}_x, k^t{}_y, k^t{}_z) \quad k^t{}_x{}^2 + k^t{}_y{}^2 + k^t{}_z{}^2 = \left(\tilde{n}_s \frac{\omega}{c}\right)^2$$

$$\boldsymbol{E}_{\tan g} e^{ixk_x} + \boldsymbol{E}^r{}_{\tan g} e^{i(xk^r{}_x + yk^r{}_y)} = \boldsymbol{E}^t{}_{\tan g} e^{i(xk^t{}_x + yk^t{}_y)}$$

$$\boldsymbol{H}_{\tan g} e^{ixk_x} + \boldsymbol{H}^r{}_{\tan g} e^{i(xk^r{}_x + yk^r{}_y)} = \boldsymbol{H}^t{}_{\tan g} e^{i(xk^t{}_x + yk^t{}_y)}$$

Phases have to be the same at z=0:

$$k^r{}_y = k^t{}_y = 0, \quad k^r{}_x = k_x \quad k^t{}_x = k_x$$

$$\boxed{\tilde{n} \sin\theta = \tilde{n}' \sin\theta'}$$

Fresnels formulas I : reflection for s-, TE, σ pol.

$$\boldsymbol{E}_y + \boldsymbol{E}^r{}_y = \boldsymbol{E}^t{}_y \quad (1)$$

$$\left(\boldsymbol{B}_x + \boldsymbol{B}^r{}_x\right) = \frac{\mu_a}{\mu_s}\boldsymbol{B}^t{}_x \qquad \frac{1}{\omega}\left(\boldsymbol{k}\times\boldsymbol{E}_y\right)_x + \left(\boldsymbol{k}^r\times\boldsymbol{E}^r{}_y\right)_x = \frac{\mu_a}{\omega\mu_s}\left(\boldsymbol{k}^t\times\boldsymbol{E}^t{}_y\right)_x \;(2)$$

$$\left(\boldsymbol{k}_z\boldsymbol{E}_y\right) - \left(\boldsymbol{k}_z\boldsymbol{E}^r{}_y\right) = \frac{\mu_a}{\mu_s}\left(\boldsymbol{k}^t{}_z\boldsymbol{E}^t{}_y\right)(2a)$$

$$\boldsymbol{E}^t = \frac{2\,\boldsymbol{k}_z\mu_s}{\boldsymbol{k}_z\mu_s + \boldsymbol{k}^t{}_z\mu_a}\boldsymbol{E} = t_s\boldsymbol{E} \qquad \boldsymbol{E}^r = \frac{\boldsymbol{k}_z\mu_s - \boldsymbol{k}^t{}_z\mu_a}{\boldsymbol{k}_z\mu_s + \boldsymbol{k}^t{}_z\mu_a}\boldsymbol{E} = r_s\boldsymbol{E} \qquad \mu_s = \mu_a = 1$$

$$r_s = \frac{\tilde{n}_a\cos\theta - \tilde{n}_s\cos\theta_s}{\tilde{n}_a\cos\theta + \tilde{n}_s\cos\theta_s} = \frac{\sqrt{\varepsilon_a - \varepsilon_a\sin^2(\theta)} - \sqrt{\varepsilon_s - \varepsilon_a\sin^2(\theta)}}{\sqrt{\varepsilon_a - \varepsilon_a\sin^2(\theta)} + \sqrt{\varepsilon_s - \varepsilon_a\sin^2(\theta)}}$$

$$t_s = \frac{2\tilde{n}_a\cos\theta}{\tilde{n}_a\cos\theta + \tilde{n}_s\cos\theta_s} = \frac{2\sqrt{\varepsilon_a - \varepsilon_a\sin^2(\theta)}}{\sqrt{\varepsilon_a - \varepsilon_a\sin^2(\theta)} + \sqrt{\varepsilon_s - \varepsilon_a\sin^2(\theta)}}$$

Fresnels formulas II : reflection for p-, TM, π pol.

$$\boldsymbol{B}_y + \boldsymbol{B}^r{}_y = \frac{\mu_a}{\mu_s}\boldsymbol{B}^t{}_y \qquad (1)$$

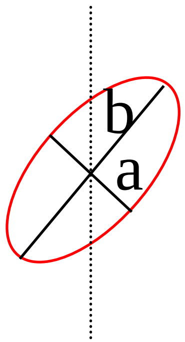
$$\boldsymbol{E}_x + \boldsymbol{E}^r{}_x = \boldsymbol{E}^t{}_x \qquad \frac{\boldsymbol{k}_z}{\mu_a\varepsilon_a\omega}\boldsymbol{B}_y - \frac{\boldsymbol{k}_z}{\mu_a\varepsilon_a\omega}\boldsymbol{B}^r{}_y = \frac{\boldsymbol{k}^t{}_z}{\mu_s\varepsilon_s\omega}\boldsymbol{B}^t{}_y \; (2)$$

$$\boldsymbol{B}^r = \frac{\varepsilon_s\boldsymbol{k}_z - \varepsilon_a\boldsymbol{k}^t{}_z}{\varepsilon_s\boldsymbol{k}_z + \varepsilon_a\boldsymbol{k}^t{}_z}\boldsymbol{E} = r_p\boldsymbol{B} \qquad \boldsymbol{B}^t = \frac{2\,\mu_s\varepsilon_s\boldsymbol{k}_z}{\mu_a\left(\varepsilon_s\boldsymbol{k}_z + \varepsilon_a\boldsymbol{k}^t{}_z\right)}\boldsymbol{B} = t^B{}_p\boldsymbol{B}$$

$$r_p = \frac{\tilde{n}_s\cos\theta - \tilde{n}_a\cos\theta_s}{\tilde{n}_s\cos\theta + \tilde{n}_a\cos\theta_s} = \frac{\varepsilon_s\sqrt{\varepsilon_a - \varepsilon_a\sin^2(\theta)} - \varepsilon_a\sqrt{\varepsilon_s - \varepsilon_a\sin^2(\theta)}}{\varepsilon_s\sqrt{\varepsilon_a - \varepsilon_a\sin^2(\theta)} + \varepsilon_a\sqrt{\varepsilon_s - \varepsilon_a\sin^2(\theta)}}$$

$$t_p = \frac{2\tilde{n}_a\cos\theta_s}{\tilde{n}_s\cos\theta + \tilde{n}_a\cos\theta_s} = \frac{2\,\varepsilon_a\sqrt{\varepsilon_s - \varepsilon_a\sin^2(\theta)}}{\varepsilon_s\sqrt{\varepsilon_a - \varepsilon_a\sin^2(\theta)} + \varepsilon_a\sqrt{\varepsilon_s - \varepsilon_a\sin^2(\theta)}}$$

2 Phase System can be solved analytically



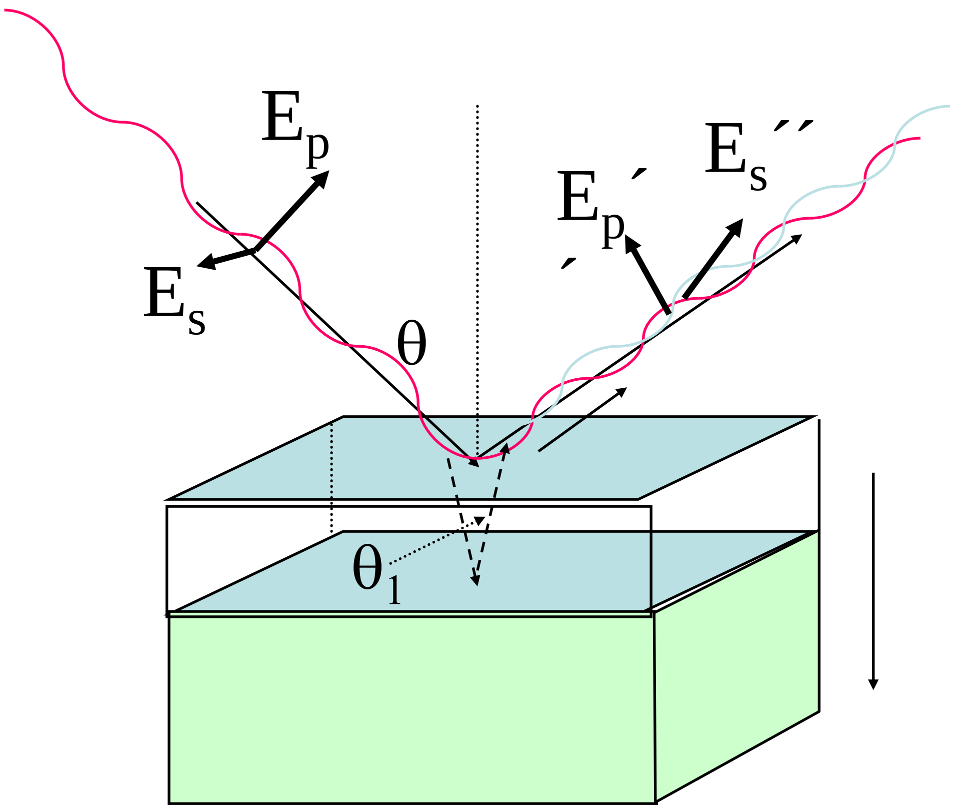
Ψ, Δ (ellipsometric angles)

$$\rho = \frac{r_p}{r_s} = \frac{\sin^2(\theta) - \cos(\theta)\sqrt{\frac{\varepsilon_s}{\varepsilon_a} - \sin^2(\theta)}}{\sin^2(\theta) + \cos(\theta)\sqrt{\frac{\varepsilon_s}{\varepsilon_a} - \sin^2(\theta)}} =: \tan\psi \, e^{i\Delta}$$

$$\frac{\varepsilon_s}{\varepsilon_a} = \sin^2(\theta) + \sin^2(\theta) \tan^2(\theta) \frac{(1-\rho)^2}{(1+\rho)^2}$$

3 Phase System cannot be solved analytically

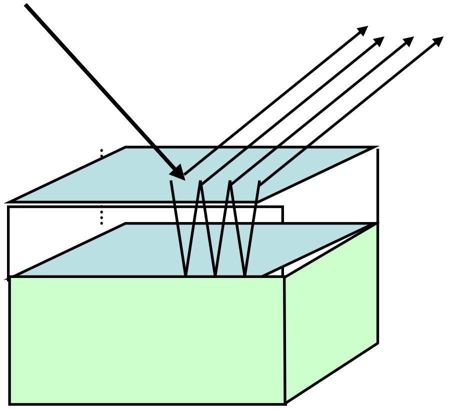
However, ε_a, ε_o, ε_s, and d_o by simulation respectively / fitting is always possible and highly accurate (multiple solutions).



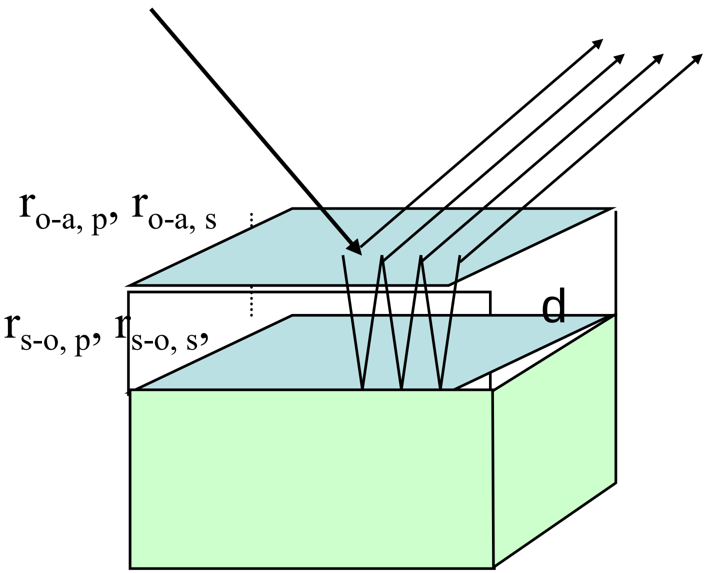
The measured value is still ρ!

Techniques:

- 3 Phase system (extension to more layers by contiunous fractions)
- Scattering Matrix (S-matrix)
- T-matrix



3 Phase System



For both polarizations it can be shown:

$$r_{o-a} = -r_{a-o}$$

$$t_{o-a} = (1 - r_{a-o}{}^2) / t_{a-o}$$

The phase acquired by passing the overlayer back and forth:

$$Z = e^{i 4\pi (d_o/\lambda)\tilde{n}_o \cos\theta_o} = e^{2 i (\omega/c)\sqrt{\varepsilon_s - \varepsilon_a \sin^2(\theta)}}$$

For s- and p-pol therefore:

$$r_{all} = r_{a-o} + t_{a-o} t_{o-a} r_{o-s} Z + t_{a-o} t_{o-a} r_{o-a} r^2{}_{o-s} Z^2 + t_{a-o} t_{o-a} r^2{}_{o-a} r^3{}_{o-s} Z^3 + \ldots$$

$$r_{all} = r_{a-o} + \frac{t_{a-o} t_{o-a} r_{o-s} Z}{1 - r_{o-a} r_{o-s} Z} = \frac{r_{a-o} + r_{o-s} Z}{1 + r_{a-o} r_{o-s} Z}$$

3 layer: ambient / overlayer /substrate

$$\rho_{all} = \frac{r_{all,p}}{r_{all.s}} = \tan\psi\ e^{i\Delta} = \frac{r_{a-o,p} + r_{o-s,p}Z}{1 + r_{a-o,p}r_{o-s,p}Z} \Big/ \frac{r_{a-o,s} + r_{o-s,s}Z}{1 + r_{a-o,s}r_{o-s,s}Z}$$

Thin layer expansion:

$$r_{all,p} = r_{a-s,p}\left(1 + \frac{d\, 4\pi i(\grave{o}_o - \grave{o}_s)\cos\theta\sqrt{\grave{o}_a}\left(\grave{o}_a(\grave{o}_o + \grave{o}_s)\sin^2(\theta) - \grave{o}_o\grave{o}_s\right)}{\lambda_0\grave{o}_o\left(\grave{o}_s{}^2\cos^2(\theta) + \grave{o}_a\left(\grave{o}_a\sin^2(\theta) - \grave{o}_s\right)\right)}\right)$$

$$r_{all,s} = r_{a-s,s}\left(1 - \frac{d\, 4\pi i(\grave{o}_o - \grave{o}_s)\cos(\theta)\sqrt{\grave{o}_a}}{\lambda_0\left(\grave{o}_s - \grave{o}_a\right)}\right)$$

$$\langle\varepsilon\rangle = \frac{\varepsilon_s}{\varepsilon_a} + d\frac{4\pi i\sqrt{\varepsilon_a}}{\lambda}\frac{\varepsilon_s\left(\varepsilon_s - \varepsilon_o\right)\left(\varepsilon_o - \varepsilon_a\right)}{\varepsilon_o\left(\varepsilon_s - \varepsilon_a\right)}\sqrt{\frac{\varepsilon_s}{\varepsilon_a} - \sin^2\varphi_a}$$

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- Recapitulation of Electrodynamics
- 2 phase and 3- phase model
- **Transmission (scattering) matrix,**
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Transmission and Scattering matrices:

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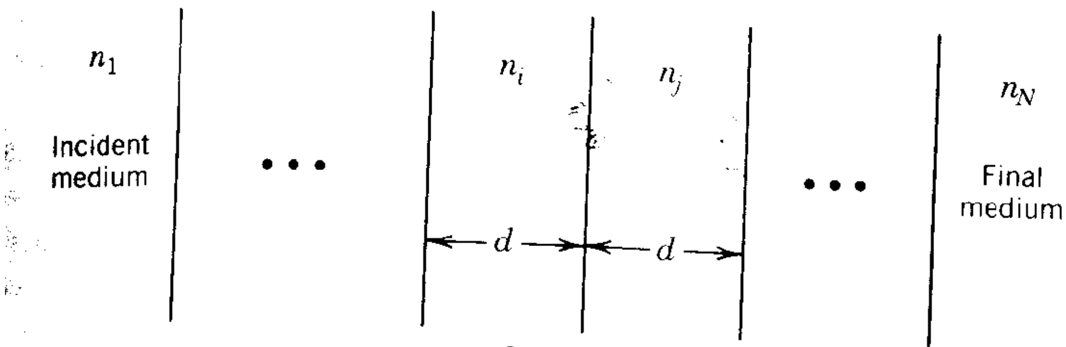
4 layers: recursive fractions: $\dfrac{r_{a-o,p} + r_{o-s,p} Z}{1 + r_{a-o,p} r_{o-s,p} Z}$



For s- as well as for p- polarization:

$$E_{rj} = E'_{ri} t_{ij} + E_{lj} r_{ji}$$

$$E'_{li} = E_{lj} t_{ji} + E'_{ri} r_{ij}$$

Using the realtions for the Fresnel coefficients:

Instead: use linear relationship, including the phases: Light is impinging on the structure with N layers from the left. The ith layer is the one left of the jth. Fields on the left side of each layer are unprimed, on the right side are primed:

E_{rj} is the rightward propagating field on the left side of the jth layer (but on the right side of the interface), E'_{lj} is the leftward propagating field in the jth layer.

Transmission and Scattering matrices II:

$$E'_{li} = \frac{1}{t_{ij}}\left(E_{lj} + r_{ij}E_{rj}\right)$$

$$E'_{ri} = \frac{1}{t_{ij}}\left(r_{ij}E_{lj} + E_{rj}\right)$$

$$\mathbf{E'_i} = \begin{pmatrix} E'_{li} \\ E'_{ri} \end{pmatrix}, \mathbf{E}_j = \begin{pmatrix} E_{lj} \\ E_{rj} \end{pmatrix}, \quad \mathbf{H_{ij}} = \frac{1}{t_{ij}}\begin{pmatrix} 1 & r_{ij} \\ r_{ij} & 1 \end{pmatrix}$$

Propagation within one layer:

$$E'_{rj} = E_{rj}e^{i\beta_j} = E_{rj}e^{2\,i\,(\omega/c)\sqrt{\varepsilon_s - \varepsilon_a \sin^2(\theta)}}$$

$$E_{lj} = E'_{lj}e^{i\beta_j} = E'_{lj}e^{2\,i\,(\omega/c)\sqrt{\varepsilon_s - \varepsilon_a \sin^2(\theta)}}$$

$$\mathbf{L_j} = \begin{pmatrix} e^{i\beta_j} & 0 \\ 0 & e^{i\beta_j} \end{pmatrix}$$

Transmission and Scattering matrices III:

$$\mathbf{E}_j = \mathbf{L}_j \mathbf{E}'_j \quad \mathbf{E}_N = \begin{pmatrix} 0 \\ E_{rN} \end{pmatrix}$$

$$\mathbf{E}_{N-1} = \mathbf{L}_{N-1} \mathbf{H}_{N-1,N} \mathbf{E}_N$$

$$\mathbf{E}'_1 = \left(\mathbf{H}_{1,2} \mathbf{L}_{2\ldots\ldots} \mathbf{L}_{N-1} \mathbf{H}_{N-1,N} \right) \mathbf{E}_N$$

$$\mathbf{E}'_1 = \mathbf{S}_{1,N} \mathbf{E}_N$$

Matrix S contains all combined effects of arbitrary many layers including multiple reflections. Per definition, it is related to the total reflection and transmission coefficient

$$\begin{pmatrix} E'_{l1} \\ E'_{r1} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} 0 \\ E_{rN} \end{pmatrix}$$

$$= \begin{pmatrix} S_{12} E_{rN} \\ S_{22} E_{rN} \end{pmatrix}$$

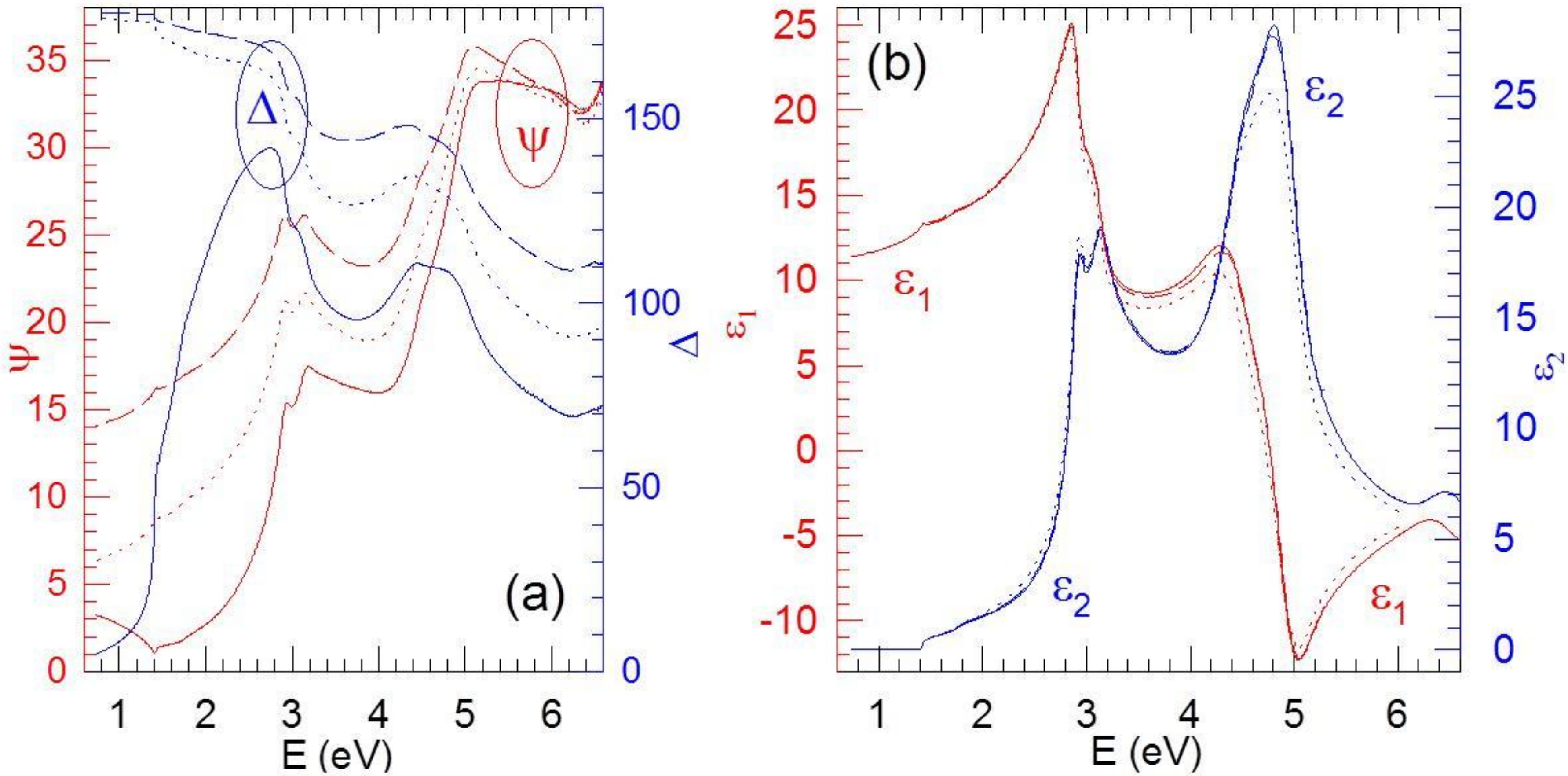
$$r_{1N} = \frac{E'_{l1}}{E'_{r1}} = \frac{S_{12}}{S_{22}}$$

$$t_{1N} = \frac{E_{rN}}{E'_{r1}} = \frac{1}{S_{22}}$$

Example: Optical Constants of GaAs:

- Below the band gap (0.04 to 1.4 eV):
  - Absorption coefficient from transmission measurements (bulk)
  - Refractive index from prism refraction measurements
  - Both are very accurate, see Blakemore (JAP **53**, R123, 1982).
- Near gap (1.2 to 1.8 eV):
  - n from reflection measurements of bulk samples
  - k from transmission measurements through thin films
  - Good accuracy, see Sell (1974) and Sturge (1962)
- Above the band gap (2 to 6 eV):
  - Kramers-Kronig transform of reflectance data is not accurate.
  - Spectroscopic Ellipsometry: Aspnes and Studna (1984): Rotating-analyzer ellipsometer
  - Rotating- compensator ellipsometer

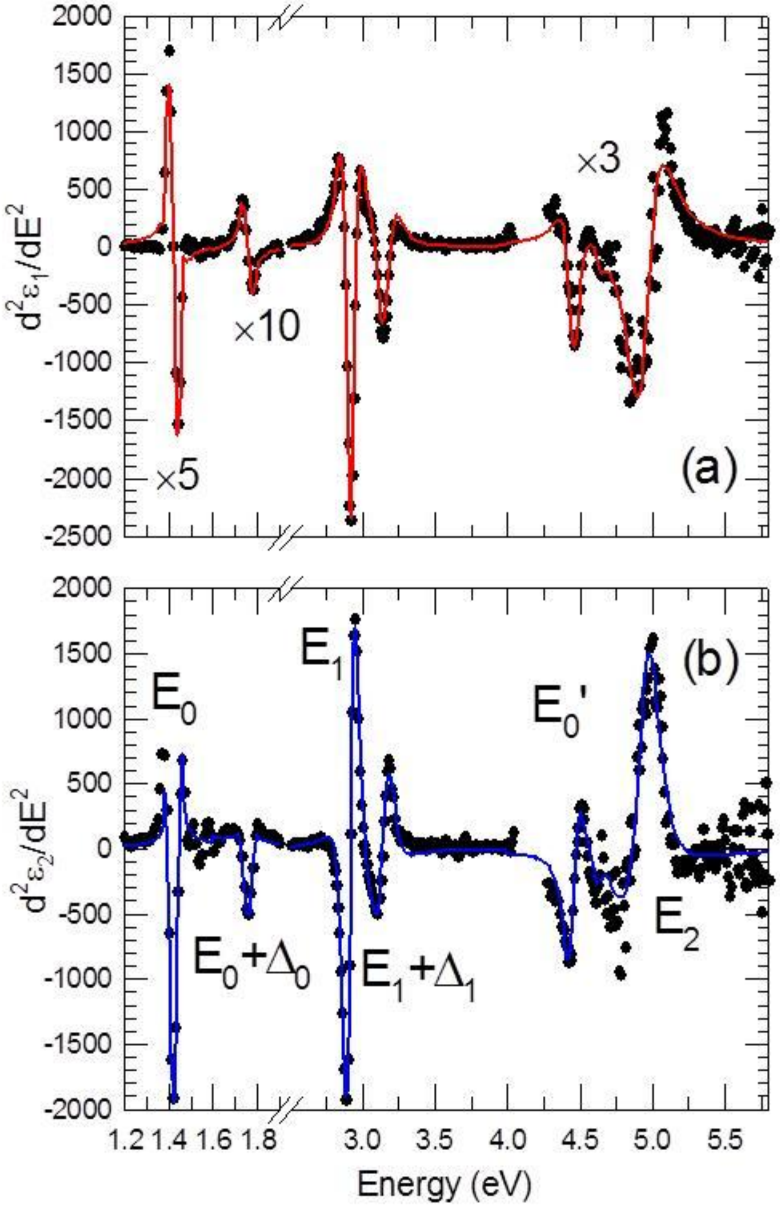
Dielectric Function of Bulk GaAs at 300 K



(a) Ellipsometric angles at three angles of incidence (65, 70, 75 degrees).

(b) Differences between solid and dotted: oxide coverage (5A).

Critical-point parameters of Bulk GaAs at 300 K



- Derivatives related to band structure and critical points (CPs)
- Critical-point parameters:
  A: amplitude
  E: transition energy
  Γ: broadening
  ϕ: phase angle
  n: dimension of CP
- Solid lines show fit to data using analytical lineshapes.
- Good agreement with Lautenschlager *et al*. (1987).

$$\varepsilon(\hbar\omega) = A(\hbar\omega)^{-2}\exp(i\phi)(\hbar\omega - E + i\Gamma)^{n}$$

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Virtual Interface Model:Thin layer expansion

During growth /etching we have a time dependent signal: either $r_{all}(t)$ or <ε>(t);

Is it possible –assuming we know the growth rate- to determine the dielectric function of the currently growing layer with dielectric function ε_o for any „***virtual***“ substrate? Answer … Dave Aspnes 1992, 1993, JOSA 10(5), 974

Exact:

$$r_{all,s} = r_{a-s,s}\left(1-\frac{d\,4\pi i(\grave{o}_o-\grave{o}_s)\cos(\theta)\sqrt{\grave{o}_a}}{\lambda_0(\grave{o}_s-\grave{o}_a)}\right) \Rightarrow \grave{o}_o=\grave{o}_s-\frac{i\Delta r_s(\grave{o}_a-\grave{o}_s)\lambda_0}{4\pi\sqrt{\grave{o}_a}\cos(\theta)}$$

Approximation:

$$\langle\varepsilon\rangle = \frac{\varepsilon_s}{\varepsilon_a}+d\frac{4\pi i\sqrt{\varepsilon_a}}{\lambda}\frac{\varepsilon_s(\varepsilon_s-\varepsilon_o)(\varepsilon_o-\varepsilon_a)}{\varepsilon_o(\varepsilon_s-\varepsilon_a)}\sqrt{\frac{\varepsilon_s}{\varepsilon_a}-\sin^2\varphi_a}$$

$$\epsilon_o = \xi \pm (\xi^2 - \langle\epsilon\rangle\epsilon_a)^{1/2},$$

$$\xi = \frac{1}{2}(\langle\epsilon\rangle + \epsilon_a) + \frac{i\lambda(\langle\epsilon\rangle - \epsilon_a)\langle\epsilon\rangle'}{8\pi\langle n_z\rangle\langle\epsilon\rangle}.$$

The Role of Surfaces and Interfaces

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"God made solids, but surfaces were the work of the Devil." Wolfgang Pauli

- Material Science: Function strongly dependent on the surface/ interface properties: for sensors, semiconductor devices, etc.
- Broken symmetry -> dimers, image charges, modification of bulk properties, surface stress and surface strain!
- Intrinsic effects: band bending, surface phonons, surface plasmons,
- "Dirt effects:" roughness, diffusion, steps, Quantum dots
- When you can´t avoid it; HOW can you control/monitor it?