Confinement of Photons & Surface Science with Optics

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Outline

• Repeating Maxwell’s differential equations (last lecture Prof. Stelzer)
• Guided Light and Integrated Optics
• Confined (Handcuffed) Photons
• Optics and Surface Science: The Power of Polarized Light
• Current Interests: Nonlinear Interactions

1842: Daniel Colladon and Jacques Babinet

source: wikipedia.org
Maxwellgleichungen → Wellengleichung

(1) \( \text{rot} \ E = - \frac{\partial B}{\partial t} \)
(2) \( \text{rot} \ H = \frac{\partial D}{\partial t} + J \)
(3) \( \text{div} \ D = \rho \)
(4) \( \text{div} \ B = 0 \)
\( \nabla \times E = - \frac{\partial B}{\partial t} \)
\( \nabla \times H = \frac{\partial D}{\partial t} + J \)
\( \nabla \cdot D = \rho \)
\( \nabla \cdot B = 0 \)

Im Vakuum \( B = \mu_0 H \quad D = \varepsilon_0 E \quad J = 0 \quad \rho = 0 \)

\( \nabla \times (\nabla \times E) = - \nabla \times \left( \frac{\partial B}{\partial t} \right) = - \mu_0 \frac{\partial}{\partial t} \left( \nabla \times H \right) \)

\( \nabla \times (\nabla \times E) = - \mu_0 \frac{\partial}{\partial t} \left( \frac{\partial D}{\partial t} \right) = - \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2} \)
Solutions of Maxwell equations can be written as:

a) plane waves, b) the electric and magnetic fields are (usually) normal to the propagation direction and c) and propagate with speed of light.
Optical Communication

\[
\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} + \varepsilon_0 \varepsilon(x) \omega^2 \right) E_y(x, z) = 0
\]

\[
\varepsilon_0 = n^2
\]

Solution: 
\[
E_y(x, z) = E_y(x) \cos(\beta z - \omega t)
\]

Light wants to be in the medium with high refractive index, then energy is lower.

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source: wikipedia.org
Photonic Crystals WHY: Size Matters!

- Photonic Crystals:
- Bending radius 1µm

How and why can the photon be confined in the low index material?
Periodicity!

(a) E-field for mode at top of band 1

(b) E-field

(c) Local power in E-field, top of band 2

(d) Local power in E-field, bottom of band 2

TE Band Structure

Frequency (GHz) vs. Position
Is periodicity really important?
Circular photonic crystals

cT = 1.12

Contour Map of Ey

Power

Time [a/c]

Power in
Power out

cT = 1.47
Physics behind parabolic approximation:

For the worst case ($\Gamma - M$ direction) the field penetration depth is less than $0.75a$

$$\lambda_{\text{envelope}} = \sqrt{\frac{\alpha}{(\omega_c - \omega_0)}}$$

$$\alpha = \left. \frac{\partial^2 \omega}{\partial k^2} \right|_{k_c}$$

Univ. Leoben, Microwaves $\varepsilon_r=9.8$ (Al$_2$O$_3$)
Metamaterials - nanostructured metals

Perfect Lenses in the near field

Invisibility Cloaks

D. Schurig, J. B. Pendry, D. R. Smith, Science 2006

(A) the simulation of the cloak with the exact material properties,

(B) the simulation of the cloak with the reduced material properties,

(C) the experimental measurement of the bare conducting cylinder, and

(D) the experimental measurement of the cloaked conducting cylinder.

Appl. Phys. Lett. in press
Opt Exp. 2012 submitted

51 layer stack of Au and MgO
Negative n below 800 nm
\[ \lambda_0 = 600 \text{ nm} \]
$\lambda_0 = 800 \text{ nm}$
\[ \lambda_0 = 1300 \text{ nm} \]
“you can find meta-movements on youtube”

On May 16, 1983, during a televised tribute to Motown Records, pop star Michael Jackson performed a relatively unknown dance move.
What happens at a prism?

Source emits single frequency wave
Field snapshots taken every 10u
Simulation lasts 5000u
Metamaterials - metals - negative refraction

Material a

\[ \varepsilon_a = 1 \]

\[ \varepsilon_a \mathbf{E}_\perp = \varepsilon_b \mathbf{E}_\perp \]

\[ D_\perp = D_\perp \]

Material b

\[ \varepsilon_b = 2 \]

\[ \varepsilon_b = -2 \]

Resulting electric field in the material

\[ \mathbf{E}_\perp \]

\[ \mathbf{E}_\text{tang} \]

\[ \mathbf{E}_\text{tang} \]

\[ \mathbf{S} = \mathbf{E} \times \mathbf{H} \quad \mathbf{E}, \mathbf{D} \text{ antiparallel} \Rightarrow \mathbf{S}, \mathbf{k} \text{ antiparallel} \]

In homogeneous metals: P-polarization is refracted to left, S-polarization to the right despite material is homogeneous; this is only due to \( \mu = 1 \ (>0), \varepsilon < 0, \)
A 10% variation of the vacuum wavelength changes the wavelength $\lambda$, $(k)$ approximately a factor of 10!
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source: wikipedia.org
"God made solids, but surfaces were the work of the Devil." Wolfgang Pauli
Components of Polarization: ‘senkrecht’ ‘parallel’

Einfallsebene • Plane of incidence

Sample

Probe

$E_s^0$ $E_p^0$ $E_s$ $E_p$

$\Phi$ $\Phi$

$\theta$

$E_s$ $E_p$ $E_s''$ $E_p''$

$E_s$ $E_p$

$E_s''$ $E_p''$
Two Phase System can be solved analytically

\[\Psi, \Delta \text{ (ellipsometric angles)}\]

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

\[\frac{\varepsilon_s}{\varepsilon_a} = \sin^2(\theta) + \sin^2(\theta) \tan^2(\theta) \frac{(1 - \rho)^2}{(1 + \rho)^2}\]
Example: Silicon and (0, 1, 2, 3,) Å SiO$_2$
Paul Drude used for the 1st time ellipsometry in 1903 for determining the optical properties of silver.
Reversing the growth process: in situ - etching
Reversing the growth process: etching
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 (5 Å).
Closed Loop Control of Growth Ga$_{1-x}$Al$_x$As

Aspnes D.E. Journal Optical Society of America A10, No. 5, May 1993

JOSA, B26, 725, (2009)

Reflectance Difference Spectroscopy

Monitors Optical Anisotropy by measuring the difference in reflectances along two orthogonal directions - for the surface of just ONE material

\[ E_s \parallel <110> \]

\[ E_s \parallel \bar{<110>} \]

\[ \Delta \frac{r}{r} \]

Energy (eV)

Si (110)

HF

oxidised

Energy (eV)
Reflectance-Difference Spectroscopy (RDS)

Model: Dimer

Origin of Anisotropy:

- **Surface**: \[ \Delta \tilde{r} = \frac{4\pi i d}{\lambda} \frac{\Delta \varepsilon_0}{\varepsilon_s - 1} \]

- **Bulk**: \[ \frac{\Delta \tilde{r}}{\tilde{r}} = \frac{\Delta \varepsilon_s}{(\varepsilon_s - 1) \sqrt{\varepsilon_s}} \]
In Situ Arrangement (RDS)
Principle of Reflectance Difference Spectroscopy
RDS: In-situ kinetic data during ZnTe growth

![Graph representing in-situ kinetic data during ZnTe growth with time [s] on the x-axis and Δr/r on the y-axis, showing Zn shutter closed, Te shutter closed, Zn shutter opened, and Te shutter open events.]

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**Summary:**

The graph illustrates the in-situ kinetic data during ZnTe growth, with time [s] on the x-axis and Δr/r on the y-axis. It shows the cycles of Zn shutter opening and closing, as well as Te shutter opening and closing, affecting the growth process. The graph highlights the changes in Δr/r, which are indicative of the kinetic reactions occurring during the growth process.
In-situ RDS data:

“Te- history” at least 1.5 MLs

$E_1^\text{ZnTe}$

$E_1^\text{GaAs}$

$E_1 + \Delta_1^\text{ZnTe}$

Cd-termination

Te termination

$\Delta r/r$ vs. Energy (eV)
One layer strains the substrate!

J.P. Silveira*, F. Briones, Journal of Crystal Growth 201/202 (1999), 113

1 A $\rightarrow$ 1000000 A

[Diagram of RHEED setup with labels: CELL, SPLIT PHOTODIODES, REFERENCE SIGNAL, HEATED WINDOW, MIRROR, BEAM-SPLITTER, LASER]

[Graphs showing RHEED intensity and [1-10] deflection over time]
Surface states as well as bulk anisotropy contributions (coop. W. P. Zeppenfeld)


L. Sun et al, PRL. 96, 016105 (2006)

FIG. 1. Real part of the RDS spectra recorded at 12 K from the clean Cu(110) surface (circles) and after adsorption of 2 L of CO at 12 K (squares). The inset shows the evolution of the RDS feature around 2.1 eV after CO exposures of 0, 0.007, 0.012, 0.018, 0.028, 0.038, 0.059, 0.111, 0.205, 0.375, 0.505, 0.805, 1.305, 1.805, and 2.305 L of CO (from top to bottom).

FIG. 2. (a) RDS signal recorded during adsorption of CO at 12 K at a photon energy of 2.13 eV. (b) Normalized specular He intensity monitored during adsorption of CO at 50 K. The inset in (a) shows a zoom-in of the initial decay of the RDS signal (circles) and the He intensity (triangles). Lines are fits to the data based on the cross section overlap model [Eq. (2)] as described in the text.
In situ Observation of Deposition Processes

**Spectroscopic Ellipsometry**
- Thickness of Overlayers
- Growth Rate of the TOP surface (5 Angstrom!)
- Composition of a ternary Semiconductor $\text{Al}_x\text{Ga}_{1-x}\text{As}$
  - $x$ determined $x \pm 0.001$
- Roughness
- Overlayers
- Etching

**Reflectance Difference (Anisotropy) Spectroscopy**
- Thickness; Monolayer Oscillations
- Surface Fingerprints; Dimers in MOCVD environment
- Doping Monitoring
- Anisotropic Strain and dislocations
- Piezoelectric effects
- Kerr Rotation (MOKE)
- Quantum Dots
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Second Harmonic Generation: the ultimate technique?

An immediate consequence of (2.32) is that $\chi^{(2)} = 0$ in the electric dipole approximation for a medium with inversion symmetry: with $S$ being the inversion operation, $S \cdot \hat{\varepsilon} = -\hat{\varepsilon}$, (2.32) yields $\chi^{(2)}_{ijk} = -\chi^{(2)}_{ijk} = 0$. This explains that second-order nonlinear optical interactions can occur only in noncentrosymmetric crystals, that is, in crystals that do not display inversion symmetry. Since liquids, gases, amorphous solids (such as glass), and
Effect of spatial dispersion for Si(111): field varies with depth

\[ C_{(1)} = \left( \text{Re} \left[ e^{i k_{\omega} z} \right] \right)^2 e^{-\alpha_{\omega} z} \text{Re} \left[ e^{i k_{2 \omega} z} \right] e^{-\alpha_{2 \omega} z/2} \]

\[ C_{(2)} = \left( \text{Re} \left[ e^{i k_{\omega} (z+\Delta)} \right] \right)^2 e^{-\alpha_{\omega} (z+\Delta)} \text{Re} \left[ e^{i k_{2 \omega} (z+\Delta)} \right] e^{-\alpha_{2 \omega} (z+\Delta)/2} \]

\[ \vec{B}_{\text{rad,2}\omega}^{\text{slab}} = \frac{1}{V} \sum_j \beta_2 (C_{(1)} - C_{(2)}) \vec{b}_j \vec{b}_j \cdot \vec{E}_0 \vec{E}_0 \]

Finite bulk contribution of the same size than the surface!

\[ \beta_2 \sum_{n=1}^{\infty} (C_{(1,n)} - C_{(2,n)}) \equiv \frac{\beta_2 (1 - e^{-\Delta (\alpha_{2 \omega}/2 + \alpha)})}{e^d (\alpha_{2 \omega}/2 + \alpha) - 1} \approx \beta_2 / 4 \]
Thanks!

First and most important:
Iris, Veronika, Javad, Michael, Tayebeh, Hamed, Ahmed, Uli, Martin, Klaus, David T.
Amir, Babak, Klaus, Doddy, Gholam, Sajjad, Mohammad, Harald, Reyhaneh

ZONA: Erika, David, Günter, Klaus, Christoph & Central Workshop Members

Semiconductor & Solid State Physics for support & hospitality during APART and CDL

Physics Faculty (especially my teachers W. Macke, H. Heinrich and D. Aspnes) for discussion time and coining the way of thinking & critisizing discussing physics!