Photonische Kristalle

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Festkörperphysik Oberseminar SS 2007
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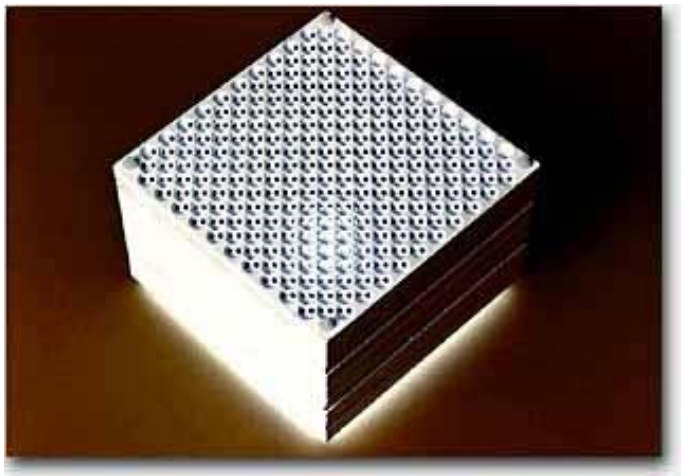
Christina Hilgers



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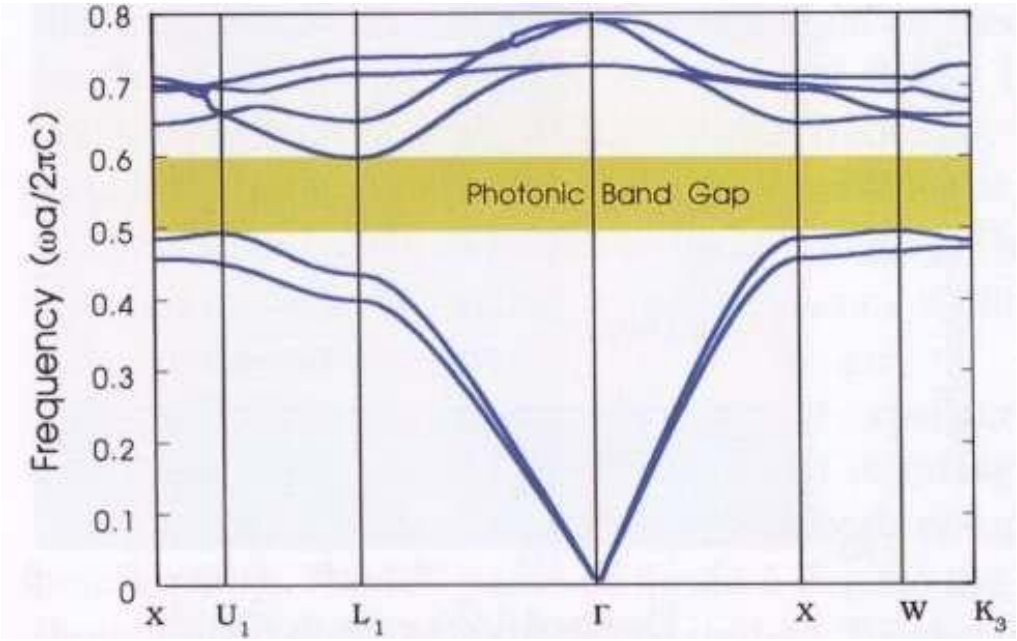
Was sind photonische Kristalle?

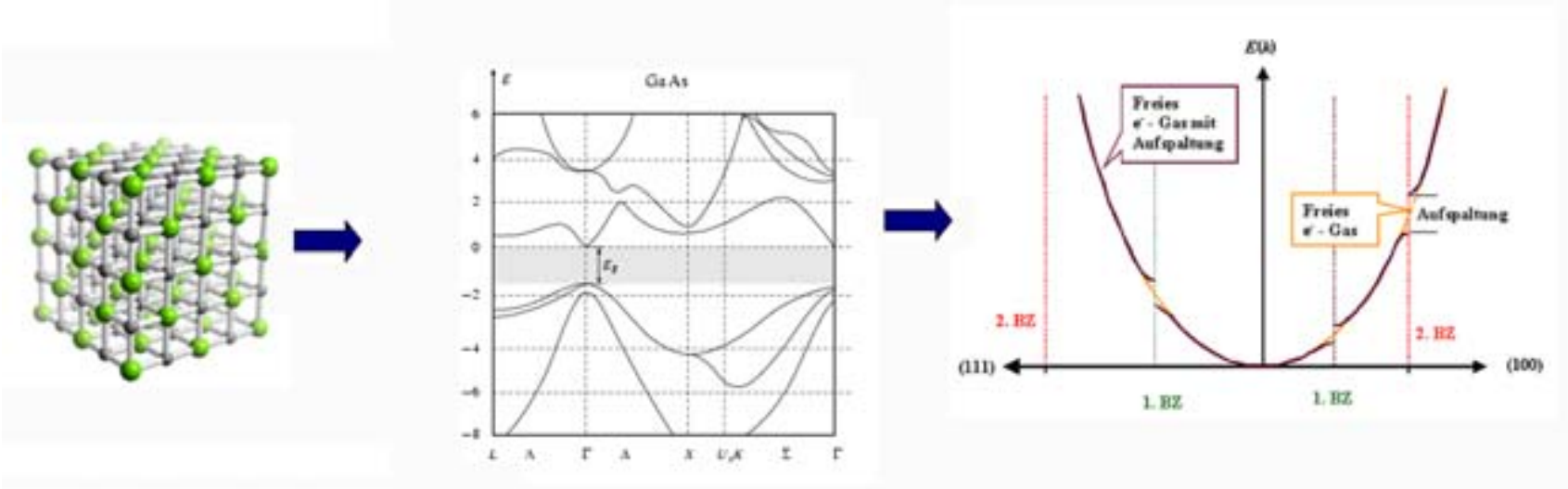
- Es sind **optische Halbleiter für Photonen**.
- Analog zur elektrischen Bandstruktur entsteht eine **photonische Bandstruktur**.



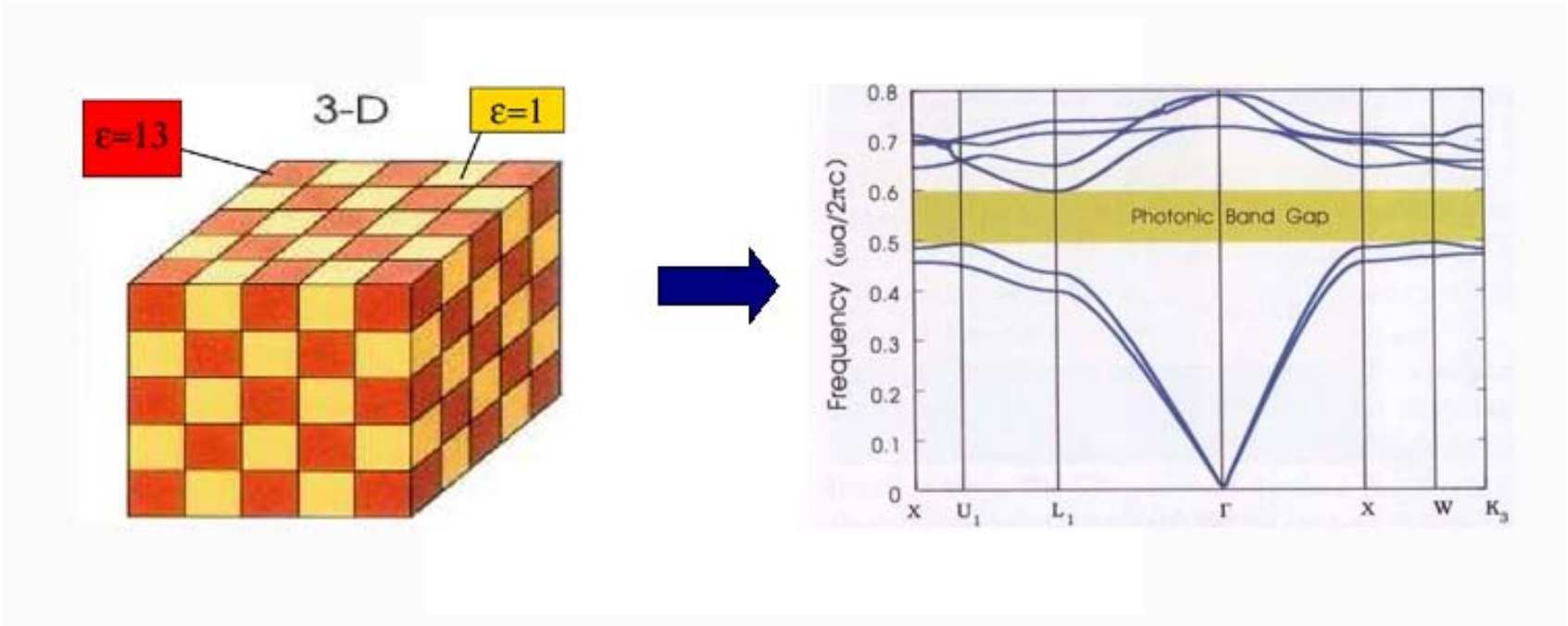
Motivation der photonischen Kristalle

- Eli Yablonovitch (Verbesserung von Telekommunikationslasern)
- Sajeev John (Grundlagenforschung)

Idee der photonischen Kristalle - Was kennen wir?

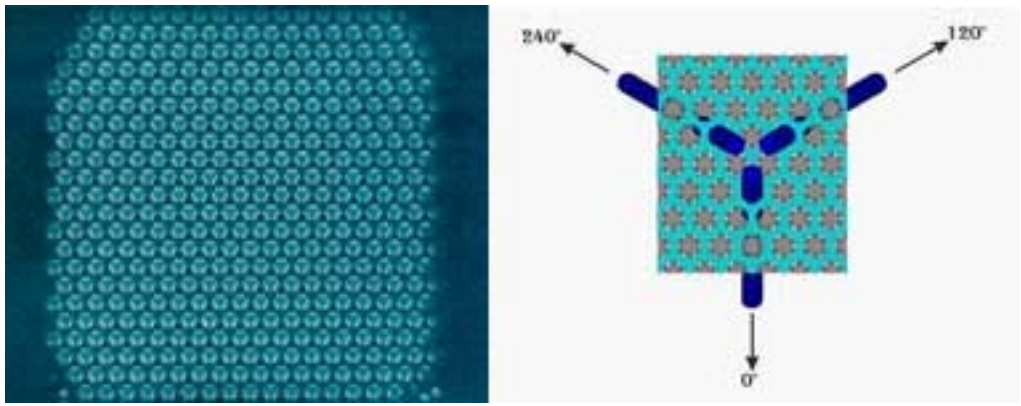


Idee der photonischen Kristalle - Geht das auch für Licht?



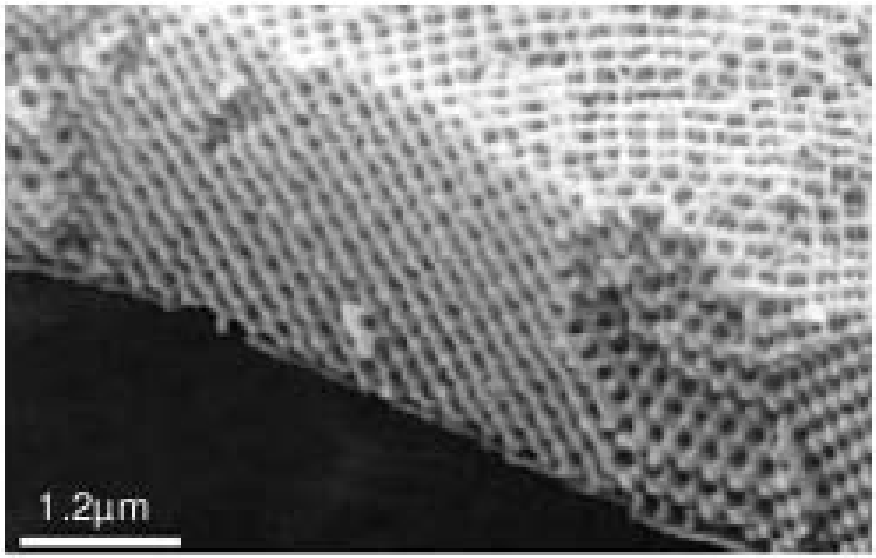
Periodizität in Größenordnung der Lichtwelle.

Photonischer Kristall ≠ Trivial



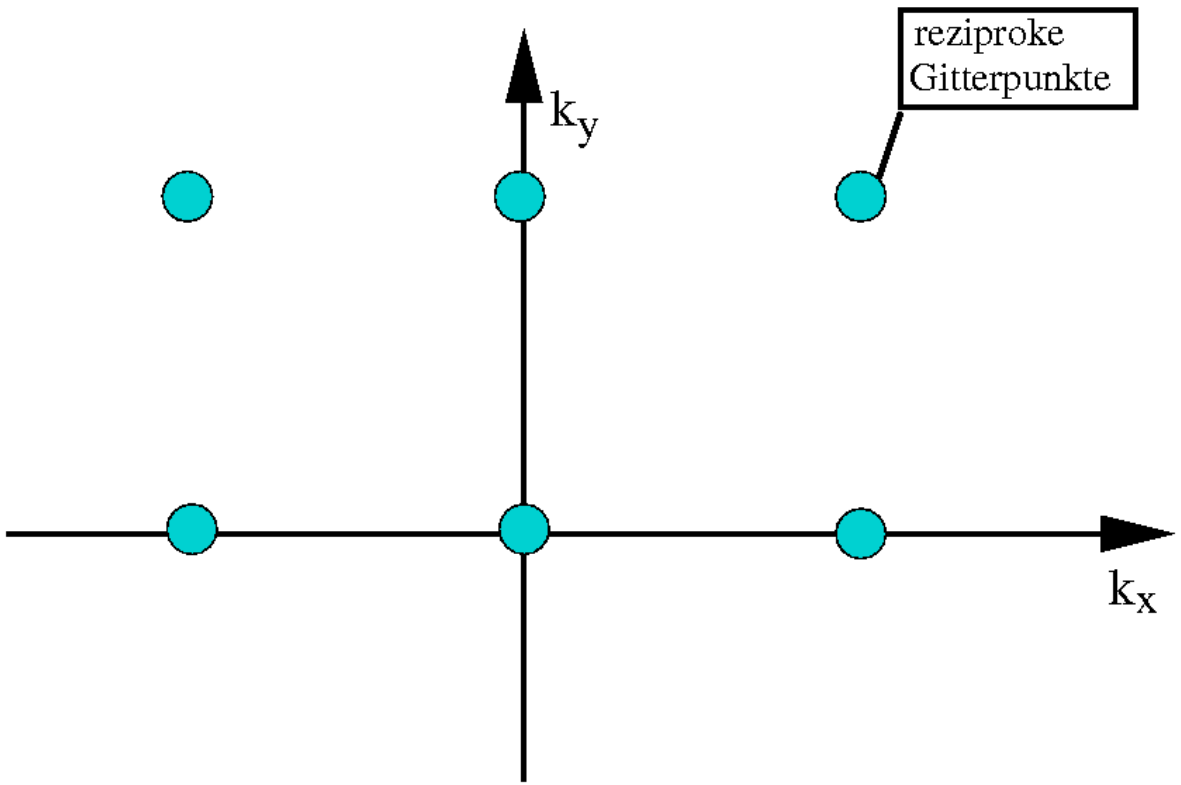
- **1987**: Yablonovitch und John haben unabhängig voneinander Idee zu PC
- **1991**: Yablonovitch fertigt 1. PC an mit Bandlücke im Bereich von **Zentimeterwellen** ("Schweizer Käse")
- **2001**: John stellt 1. PC mit Bandlücke von **1,5 Mikrometern** (=wichtiger Bereich für optische Telekommunikation) her.

Photonische Kristalle in der Natur

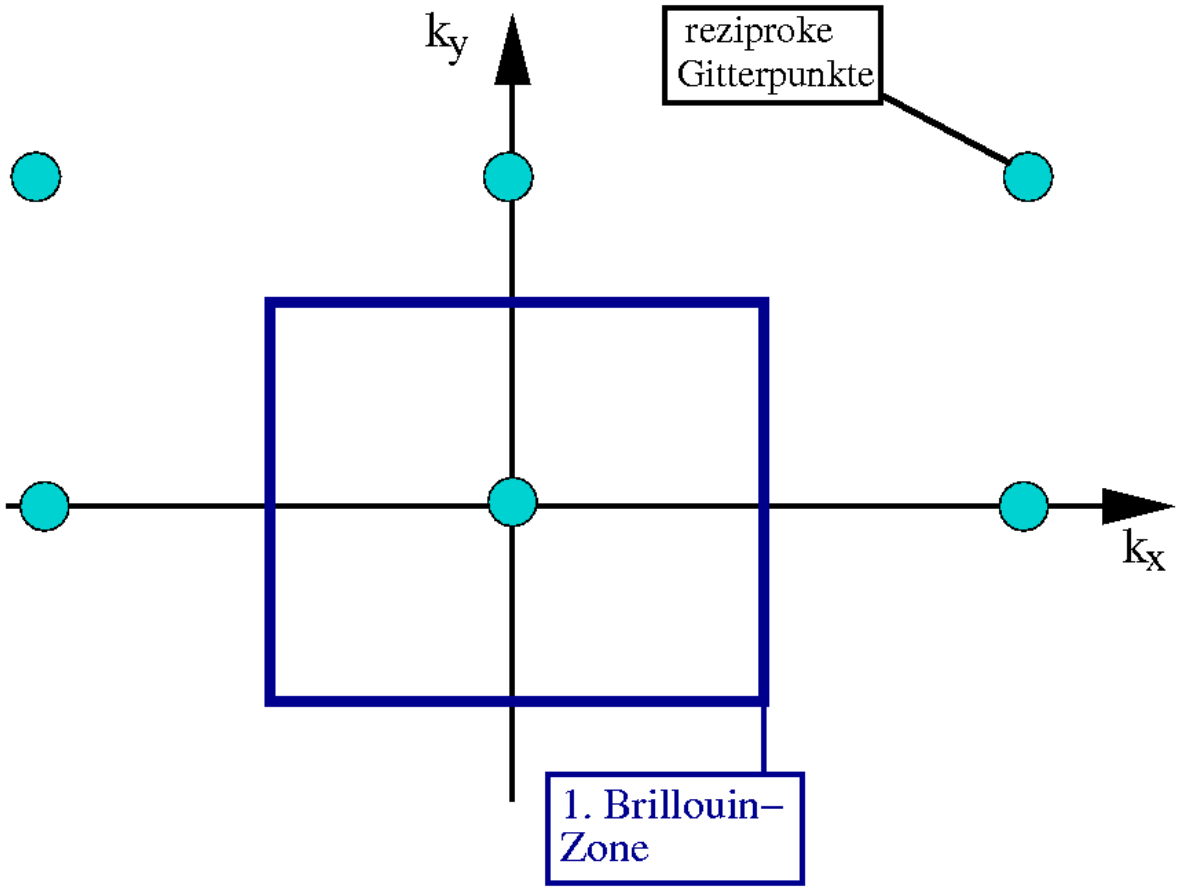


Erinnerung an Halbleiter

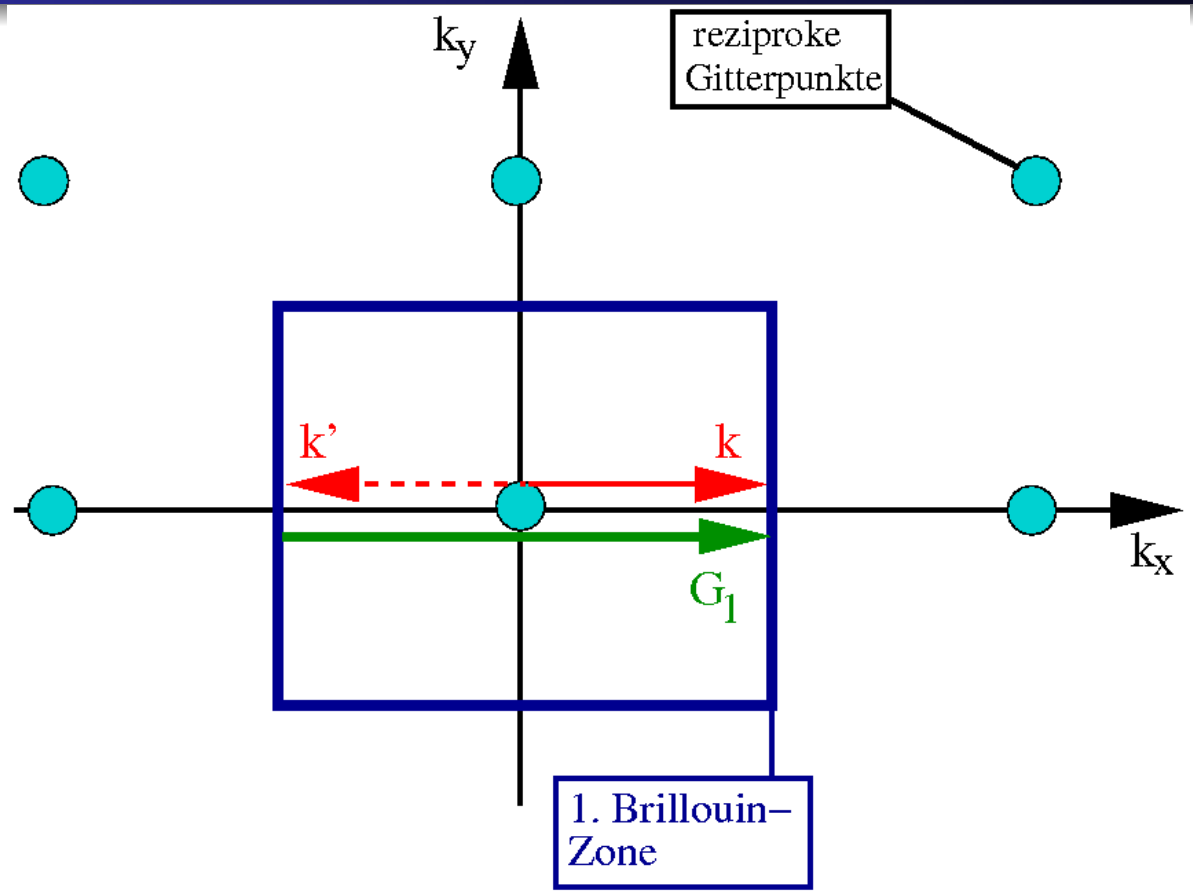
Reziproker Raum



Brillouin Zone



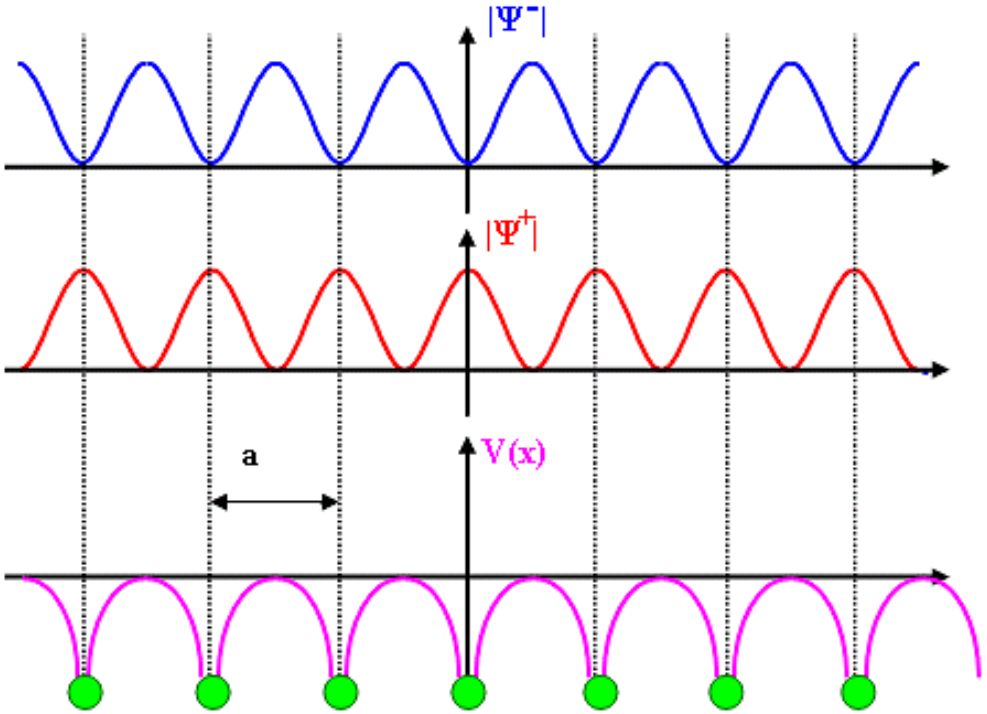
Brillouin Zone



Beugung $\Leftrightarrow k - k' = G$ (*Bragg-Bedingung*)

Aufenthaltswahrscheinlichkeiten

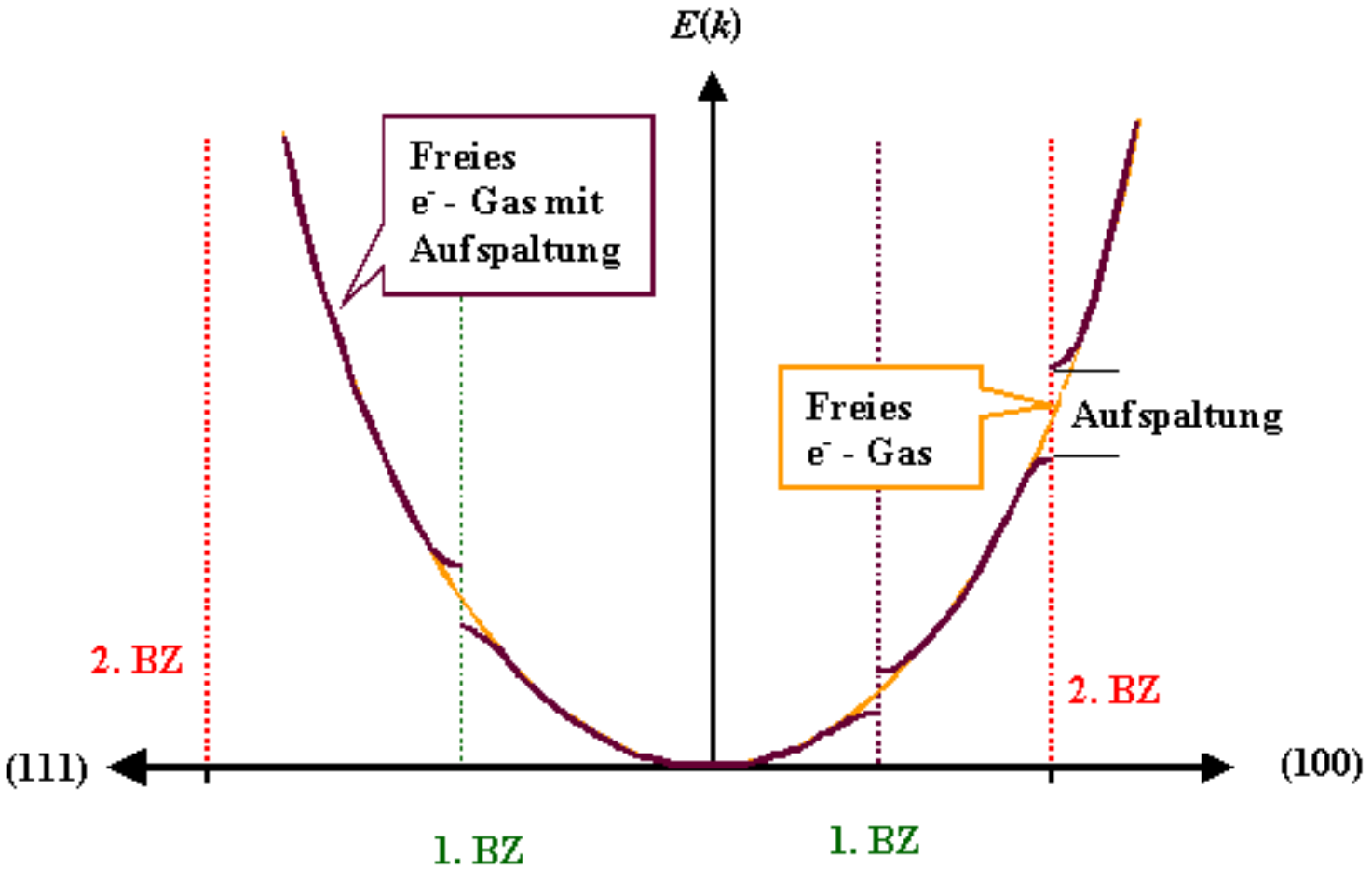
$$\psi^{\pm} = \exp(ikr) \pm \exp(ik'r) \qquad \text{mit} \quad k' = -k$$



$$|\psi^{+}|^2 \propto \cos^2\left(\frac{G}{2}\cdot x\right) \qquad (1)$$

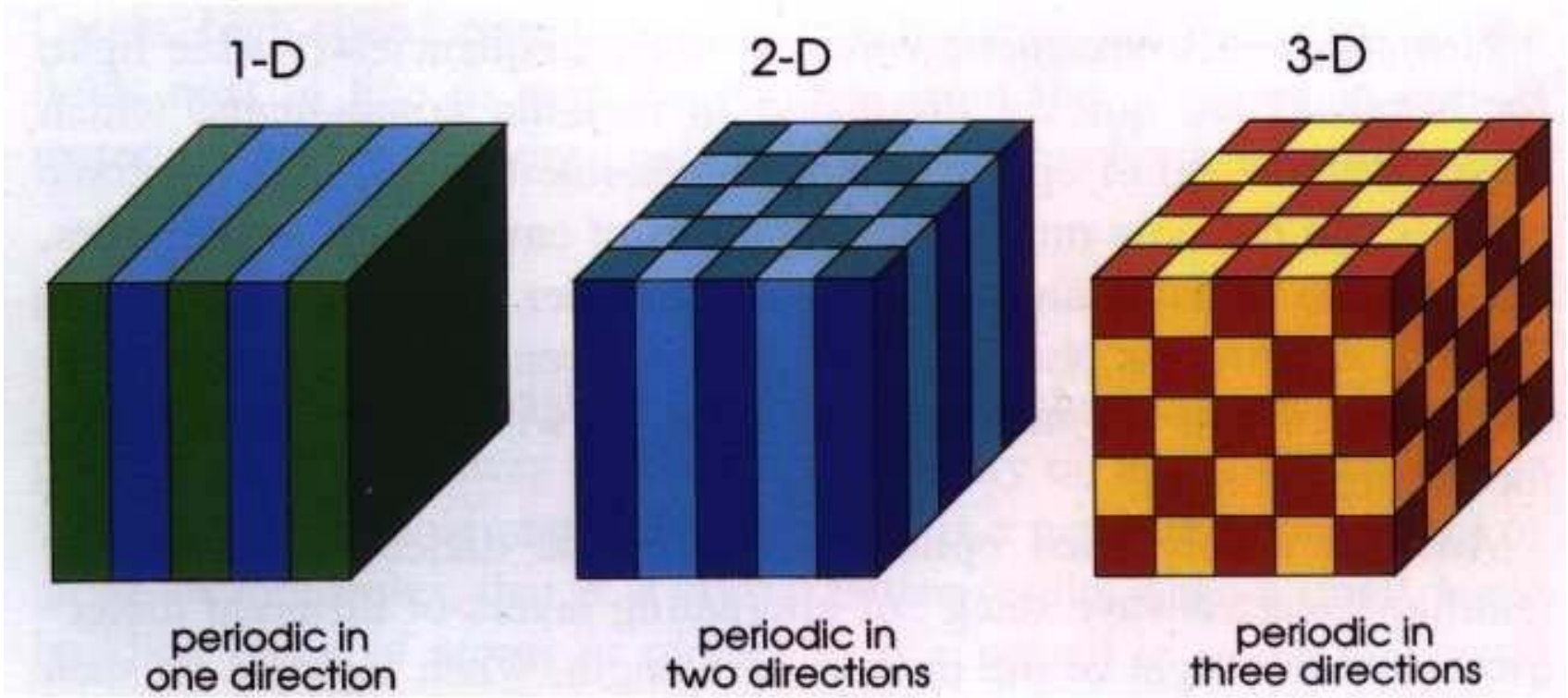
$$|\psi^{-}|^2 \propto \sin^2\left(\frac{G}{2}\cdot x\right) \qquad (2)$$

Dispersionskurve



Von Elektronenwellen zu Lichtwellen

Welche Strukturen erzeugen den denselben Effekt?



Photonic Crystals, Joannopoulos, Meade Winn, Princ. Univ. Press

Theoretischer Hintergrund - Annahmen

Lineare Optik

$$D(r) = \varepsilon_0 \varepsilon(r) E(r); \qquad B(r) = \mu\mu_0 H(r) = \mu_0 H(r) \quad \mu \approx 1 \tag{3}$$

Verlustfreies Medium, d.h. keine Absorption. Für ε gilt:

$$\varepsilon = \varepsilon_1 + i\varepsilon_2 \quad \text{mit} \quad \varepsilon_1 = n^2 - k^2 \quad \text{und} \quad \varepsilon_2 = 2nk \tag{4}$$

$$\text{Annahme: } k = 0 \Rightarrow \varepsilon_2 = 0; \quad \varepsilon_1 = n^2 \quad \Rightarrow \quad \varepsilon = \text{reell} \tag{5}$$

Annahme: $\varepsilon(r)$ frequenzunabhängig.

Theoretischer Hintergrund

Maxwell-Gleichungen

Annahme:

- Dielektrische Medien sind Ladungs- und Stromfrei: $\rho = j = 0$

$$\nabla \cdot H(r,t) = 0 \qquad \nabla \times E(r,t) + \mu_0 \frac{\partial H(r,t)}{\partial t} = 0 \tag{6}$$

$$\nabla \cdot \varepsilon(r)\, E(r,t) = 0 \qquad \nabla \times H(r,t) + \varepsilon_0 \varepsilon(r) \frac{\partial E(r,t)}{\partial t} = 0 \tag{7}$$

Maxwell-Gleichungen als Eigenwertproblem

Eigenwertgleichung für H(r) = Wellengleichung

$$\Theta H(r) = \nabla \times \left(\frac{1}{\varepsilon(r)} \nabla \times H(r) \right) = \left(\frac{\omega}{c} \right)^2 H(r) \tag{8}$$

$\neq$ Schrödinger-Gleichung, da $\varepsilon(r)$ periodische Funktion.

Lösungsansatz

Ansatz: Blochwellen $\Rightarrow H = H(r)e^{i\omega t}$ und

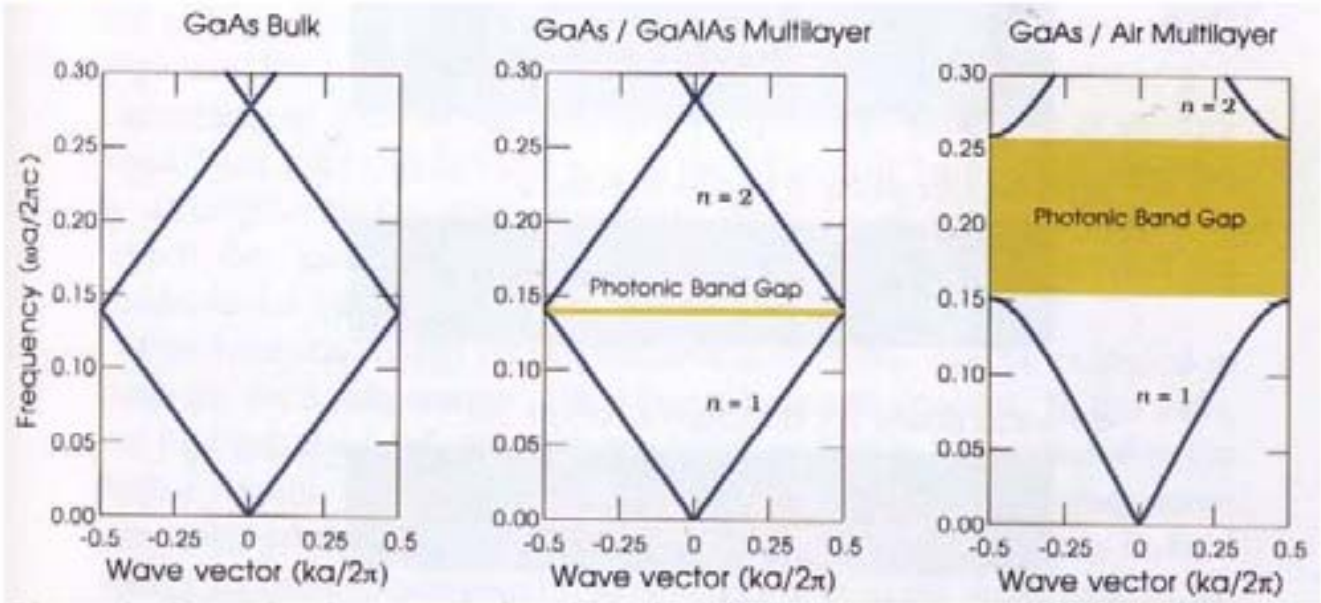
$$H_{k,n}(r) = e^{ikr} \cdot u_{k,n}(r); \qquad u_{k,n}(r) = u_{k,n}(r + R) \tag{9}$$

Maxwell-Gleichungen als Eigenwertproblem

Lösung für E(r) durch Einsetzen in MG

$$E(r) = \left(-\frac{ic}{\omega\varepsilon(r)}\right) \nabla \times H(r) \tag{10}$$

1-dimensionaler Kristall

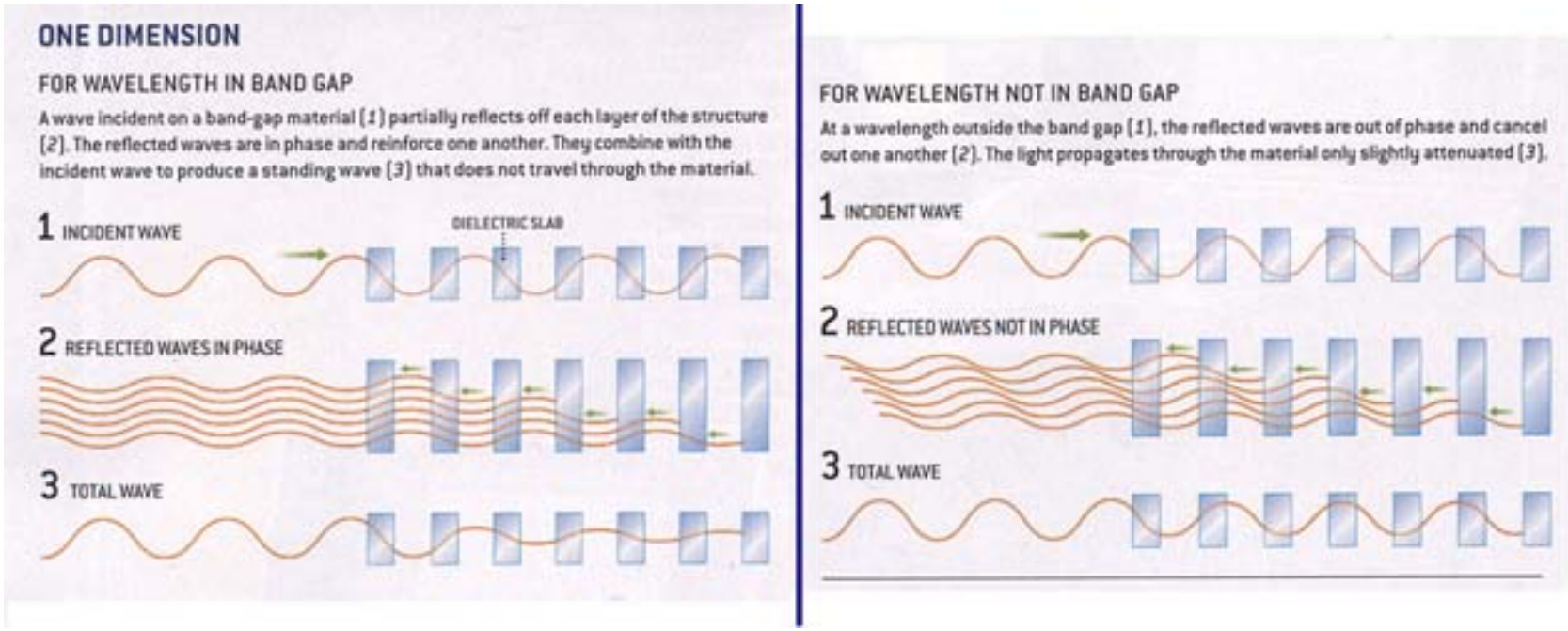


Photonic Crystals, Joannopoulos, Meade, Winn

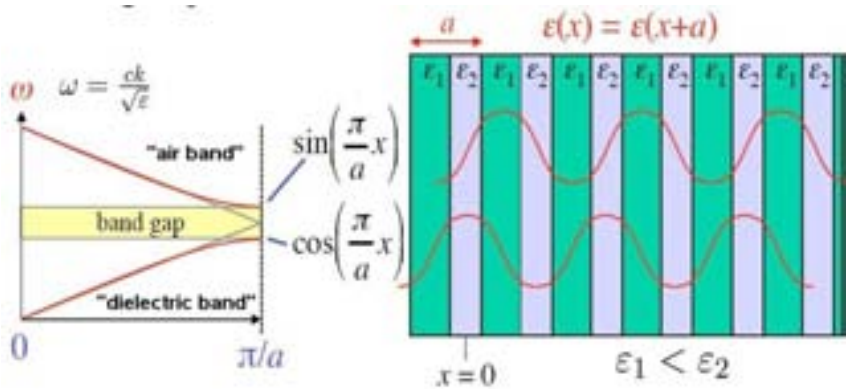
Dispersionsrelation: $\omega(k) = \frac{ck}{\sqrt{\varepsilon}}$

Links: $\varepsilon_1 = \varepsilon_2 = 13$; **Mitte:** $\frac{\varepsilon_1}{\varepsilon_2} = \frac{13}{12}$; **Rechts:** $\frac{\varepsilon_1}{\varepsilon_2} = \frac{13}{1}$

Physikalischer Hintergrund

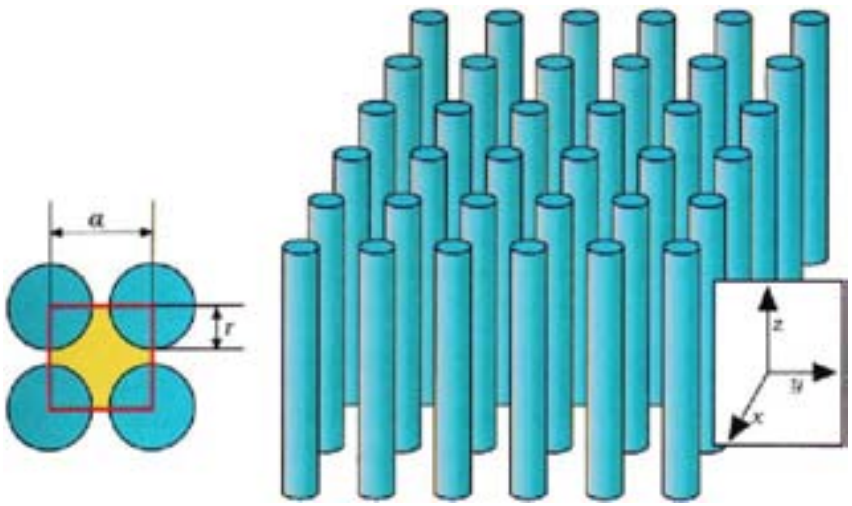


Ursprung der Bandlücke beim 1-d Kristall



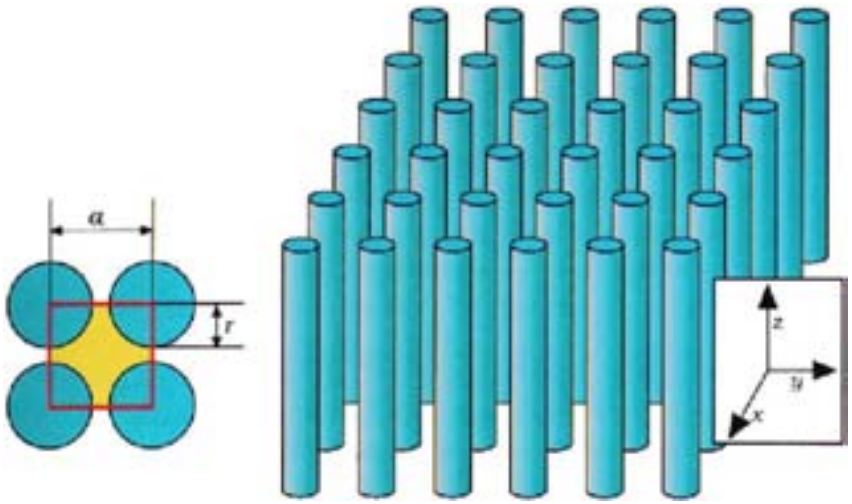
- $k = \pm\frac{\pi}{a}$
- Bildung stehender Wellen: $H_\pm \propto e^{i\frac{\pi}{a}x} \pm e^{-i\frac{\pi}{a}x}$
- Niederenergetische Mode hat hohe Aufenthaltswahrscheinlichkeit bei $\varepsilon_{\text{hoch}}$ und umgekehrt.

2-dimensionaler Kristall



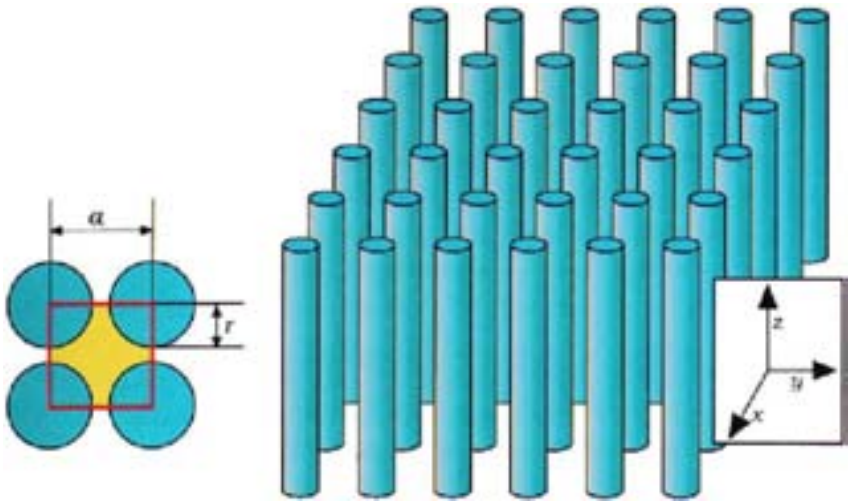
- In x-y-Ebene variiert ε, in z-Ebene ε homogen
- Idealer 2d-Kristall aus unendlich langen Stäben (dielektrische Säulen in Luft oder Luftsäulen in Dielektrikum)

Unterscheidung der Moden beim 2d-Kristall



- Ausbreitungsrichtung der Welle in x
- **TM-Moden**: **E** $\parallel$ **z**, $H \perp z$
- **TE-Moden**: **H** $\parallel$ **z**, $E \perp z$

Unterscheidung der Moden beim 2d-Kristall



- Ausbreitungsrichtung der Welle in x
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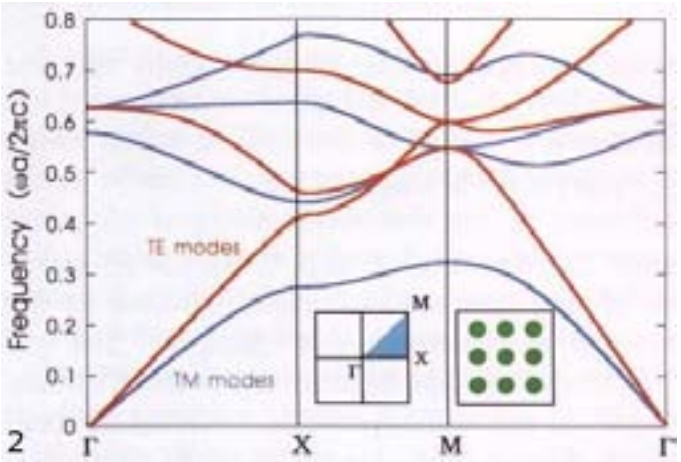
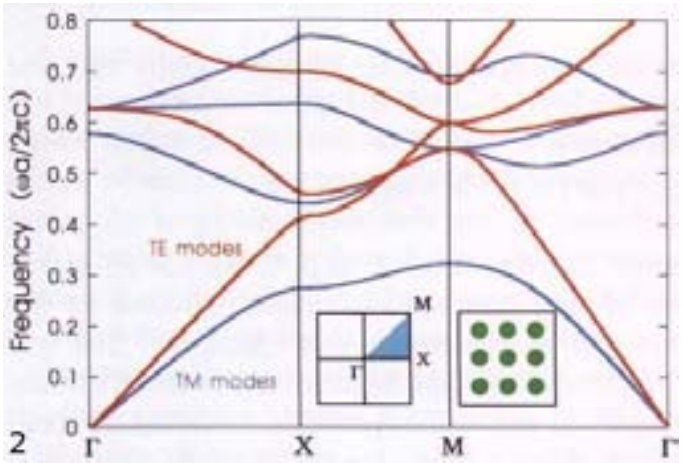
Komplette Bandlücke

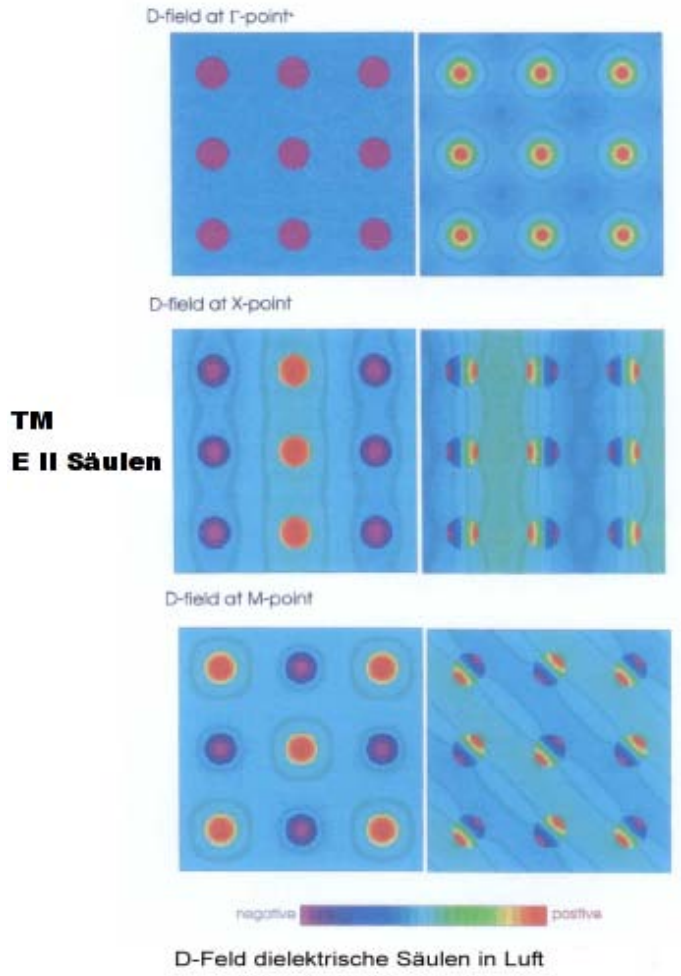
$\Longrightarrow$ Nur wenn in einem bestimmten spektralen Bereich kein Zustand für alle Raumrichtungen **und** beide Polarisationsrichtungen existiert.

Dielektrische Säulen



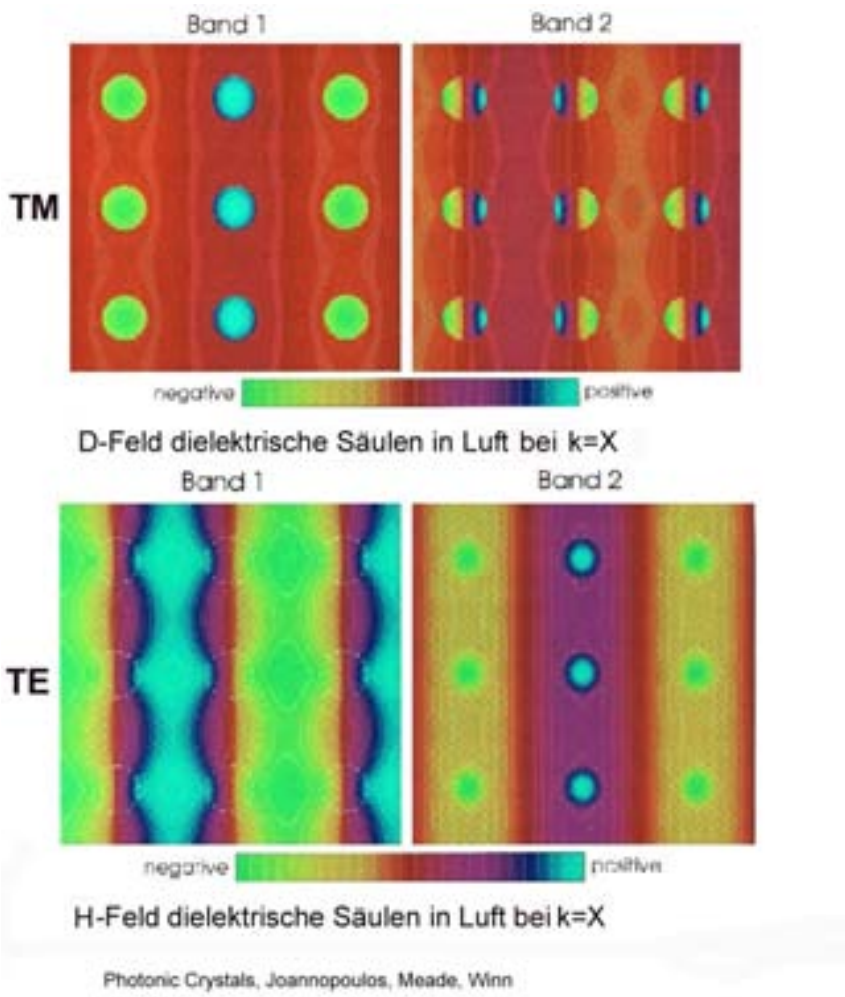
Dielektrische Säulen

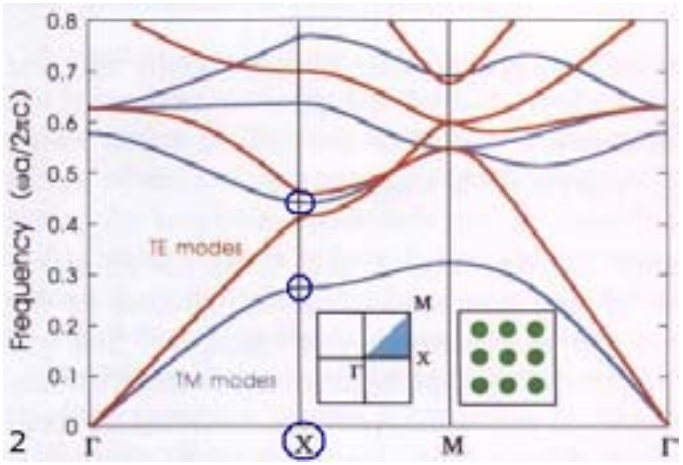




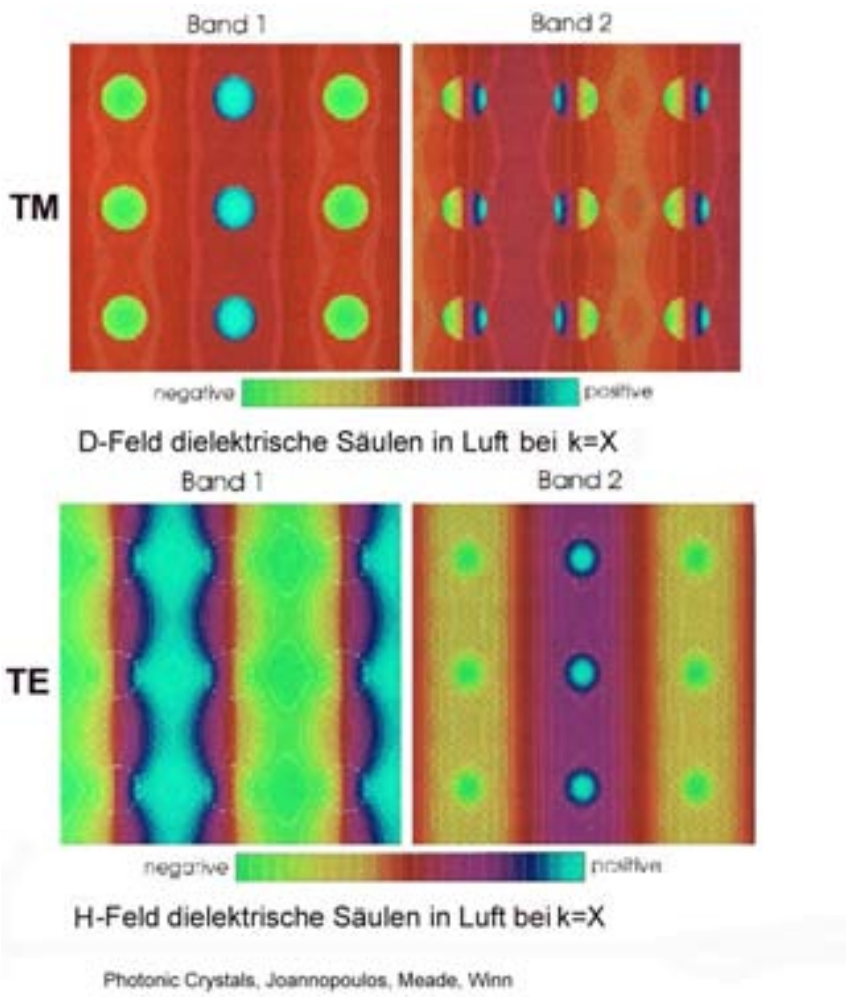
D-Feld dielektrische Säulen in Luft

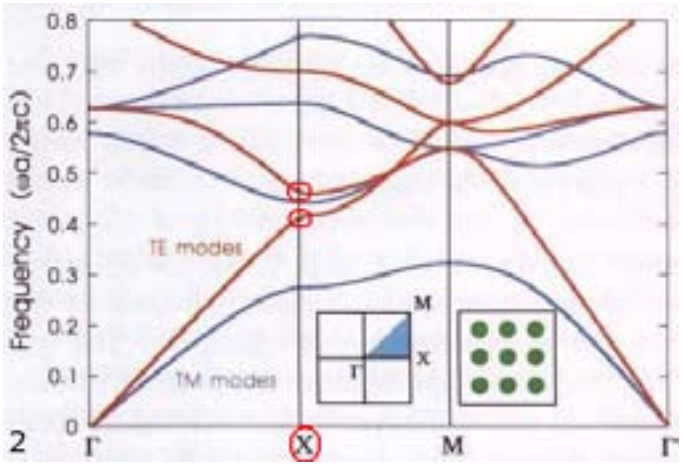
Dielektrische Säulen

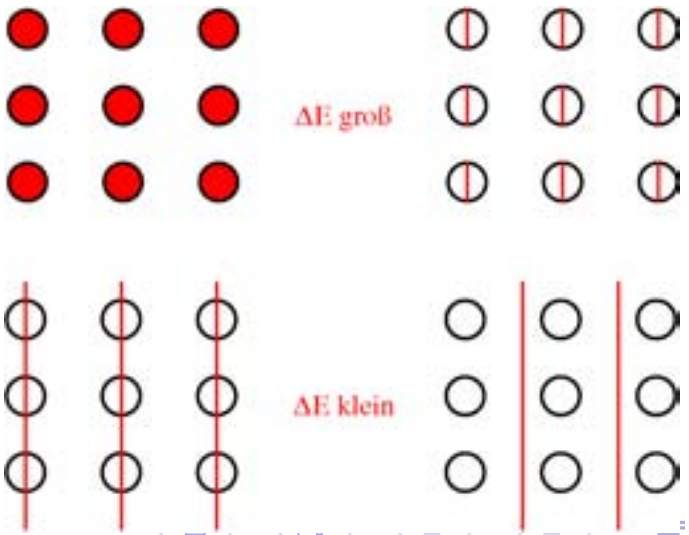




Dielektrische Säulen

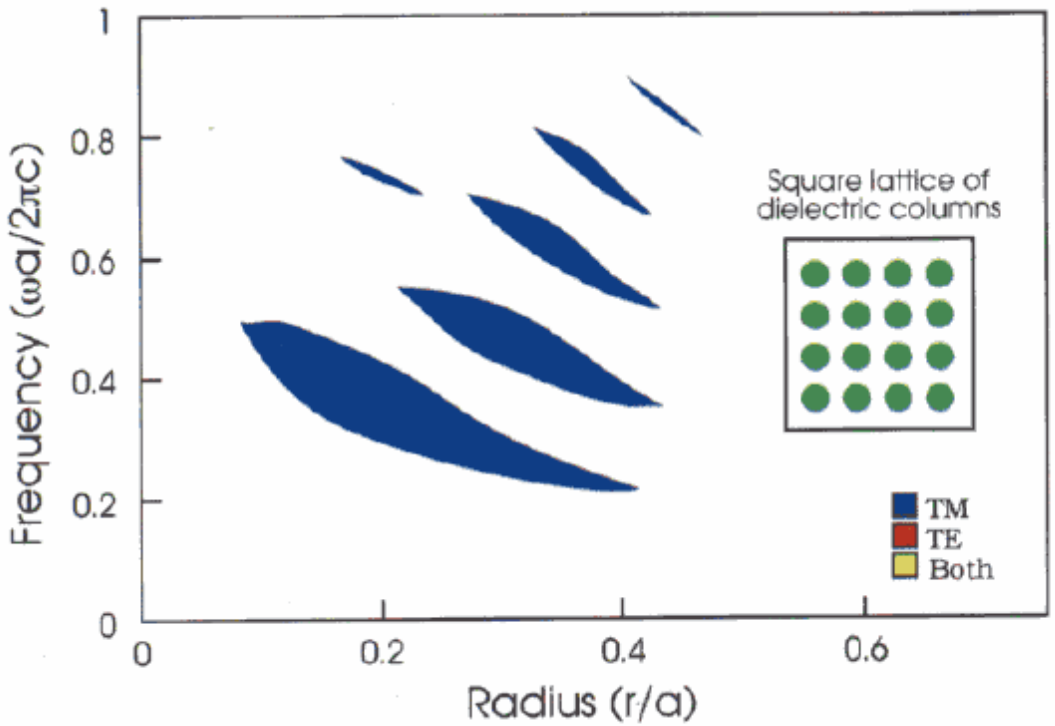




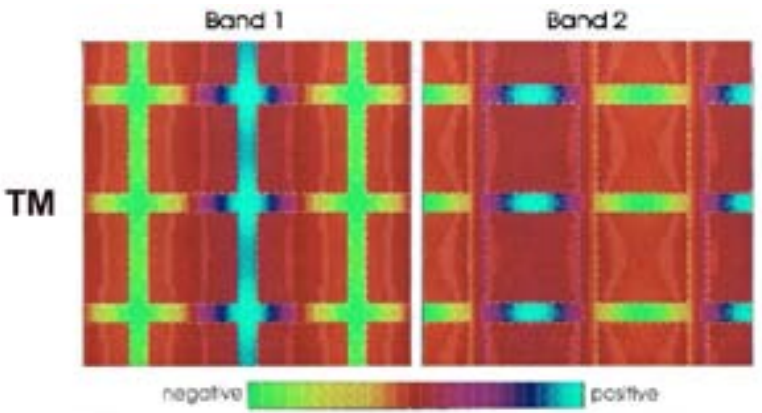


Gap map für dielektrische Säulen

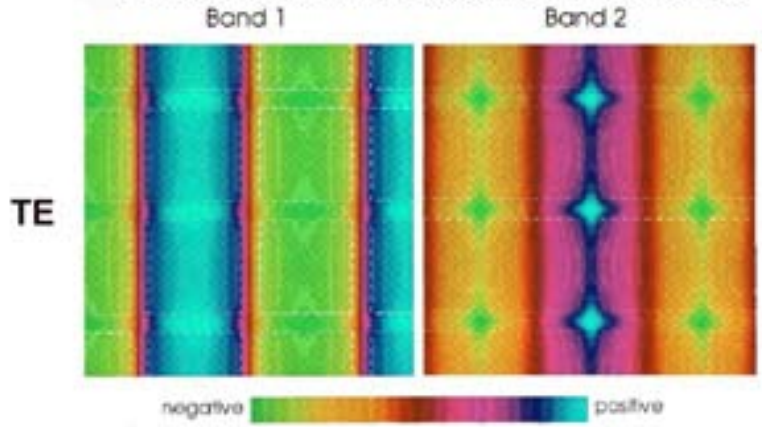
Gap map for 2D square-lattice of dielectric rods (Si)



Dielektrische Verbindungen

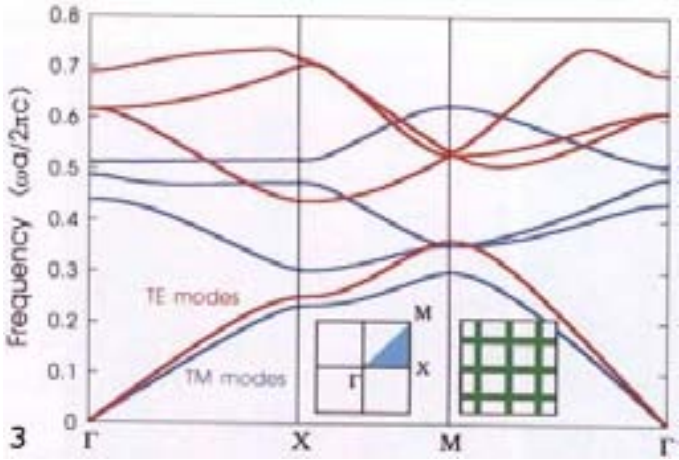


D-Feld dielektrische Verbindunden in Luft bei k=X

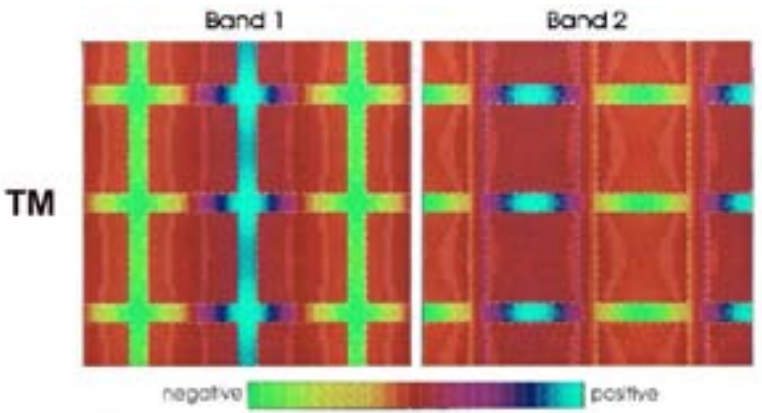


H-Feld dielektrische Verbindungen in Luft bei k=X

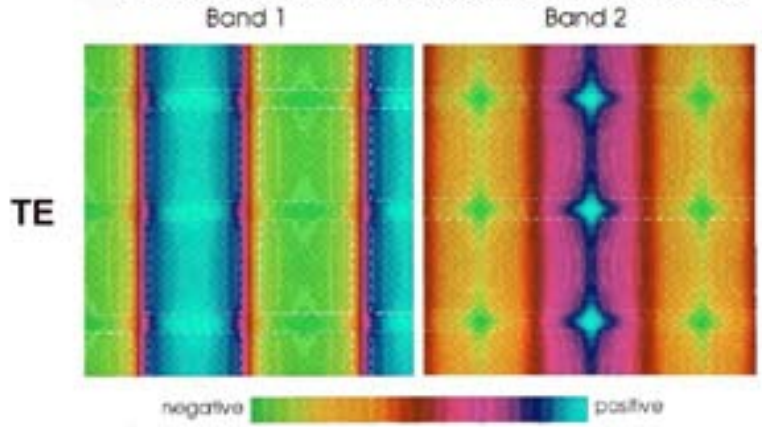
Photonic Crystals, Joannopoulos, Meade, Winn



Dielektrische Verbindungen



D-Feld dielektrische Verbindunden in Luft bei k=X



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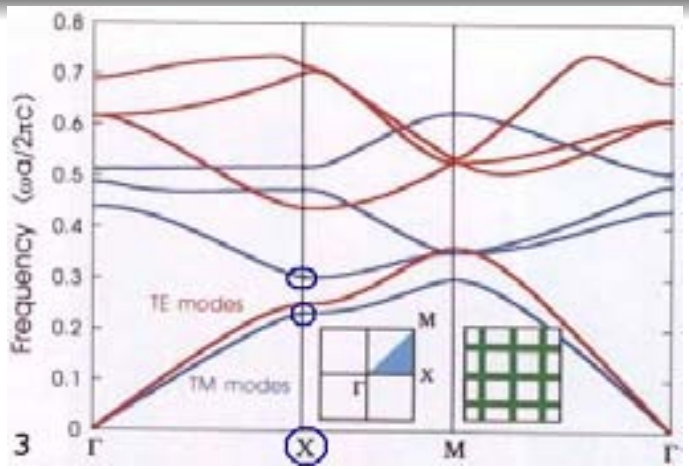
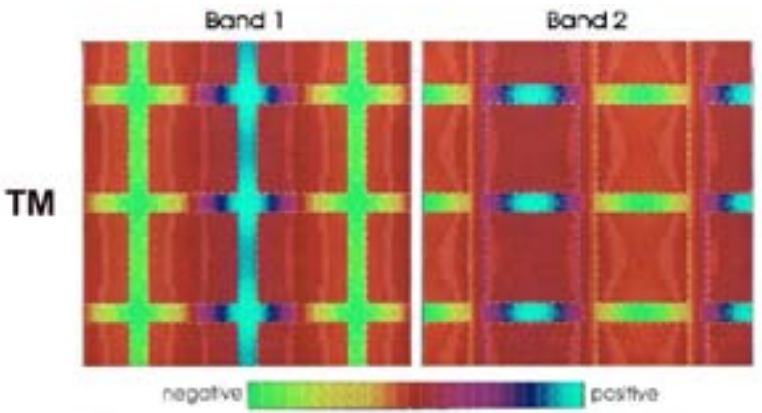


Dielektrische Verbindungen



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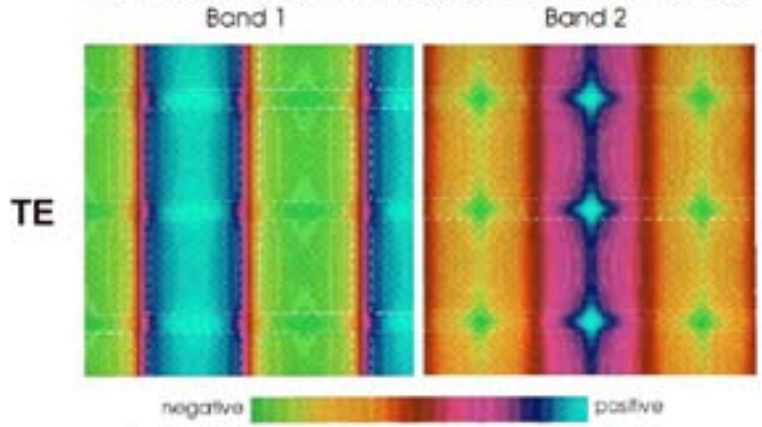

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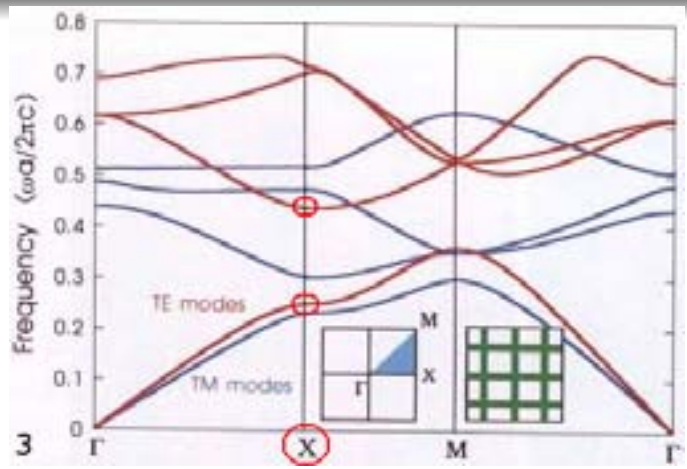
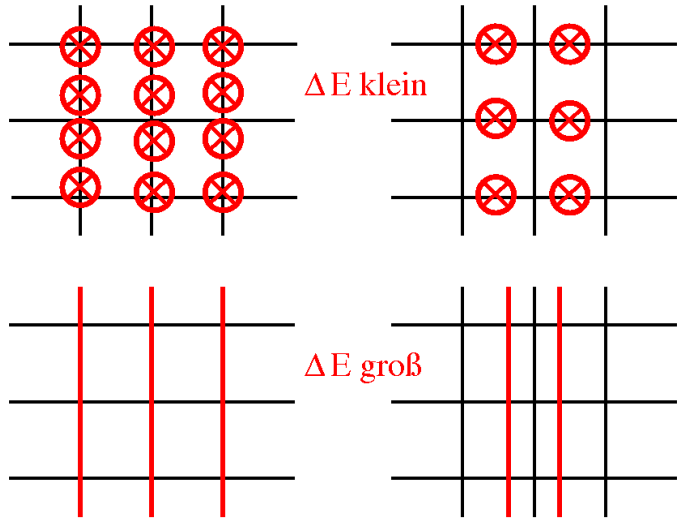
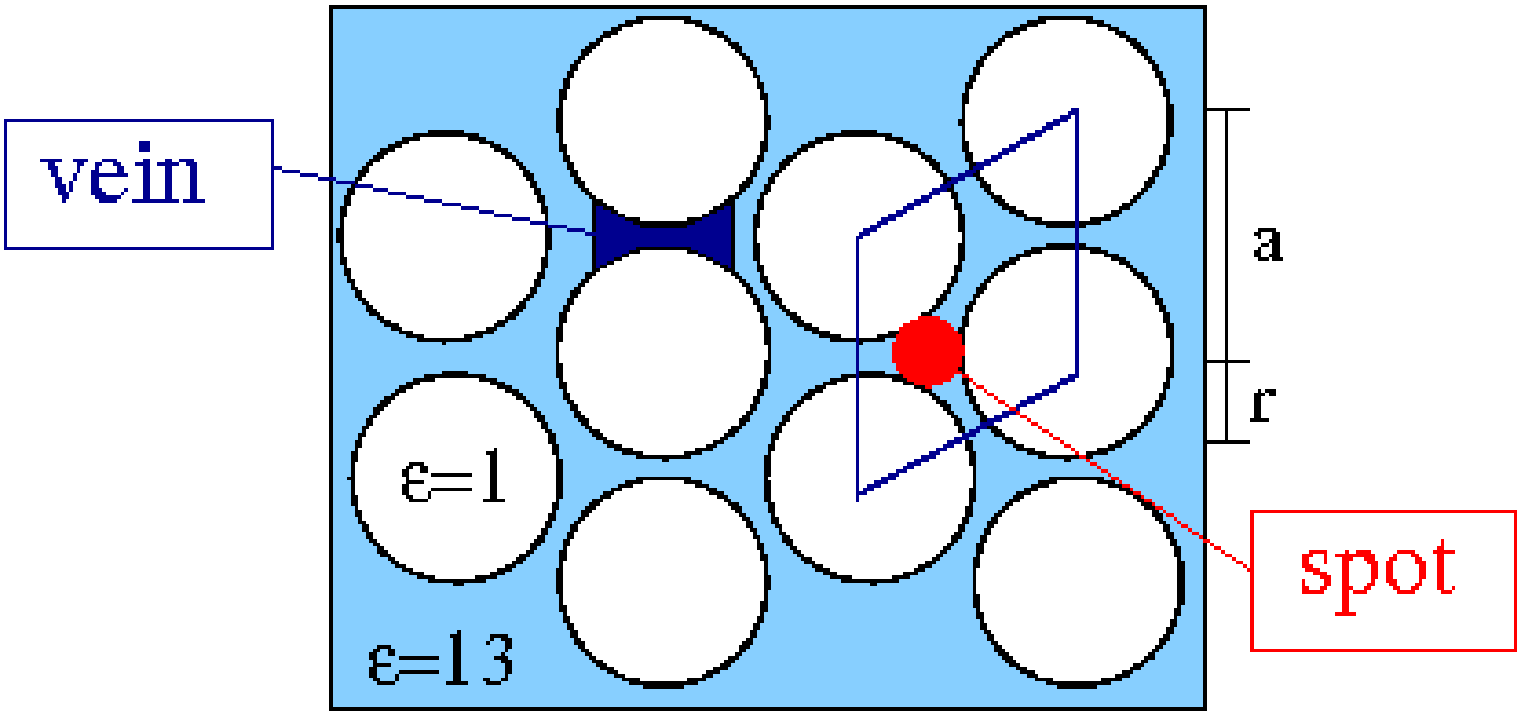
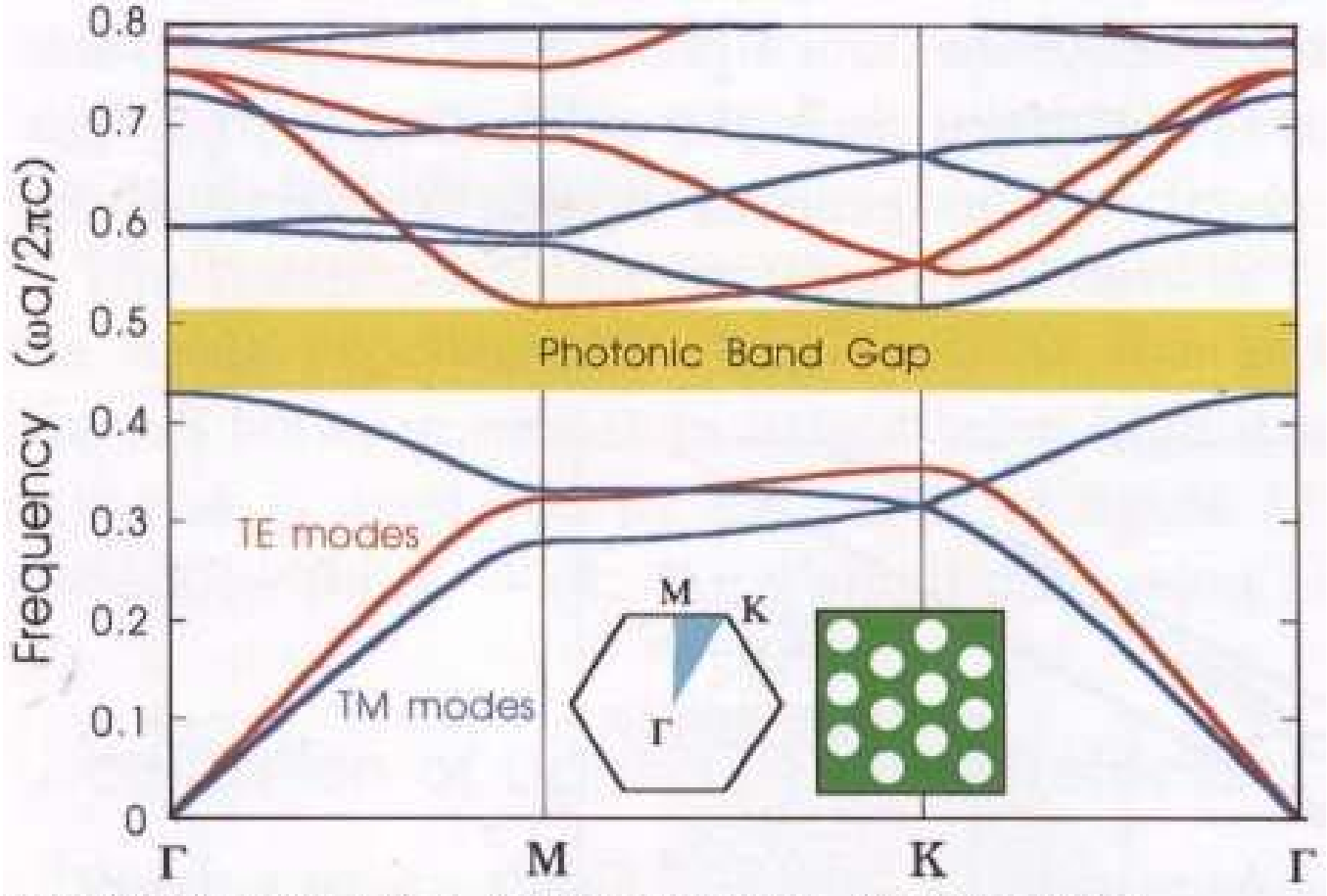




Kombination von TE und TM- Moden



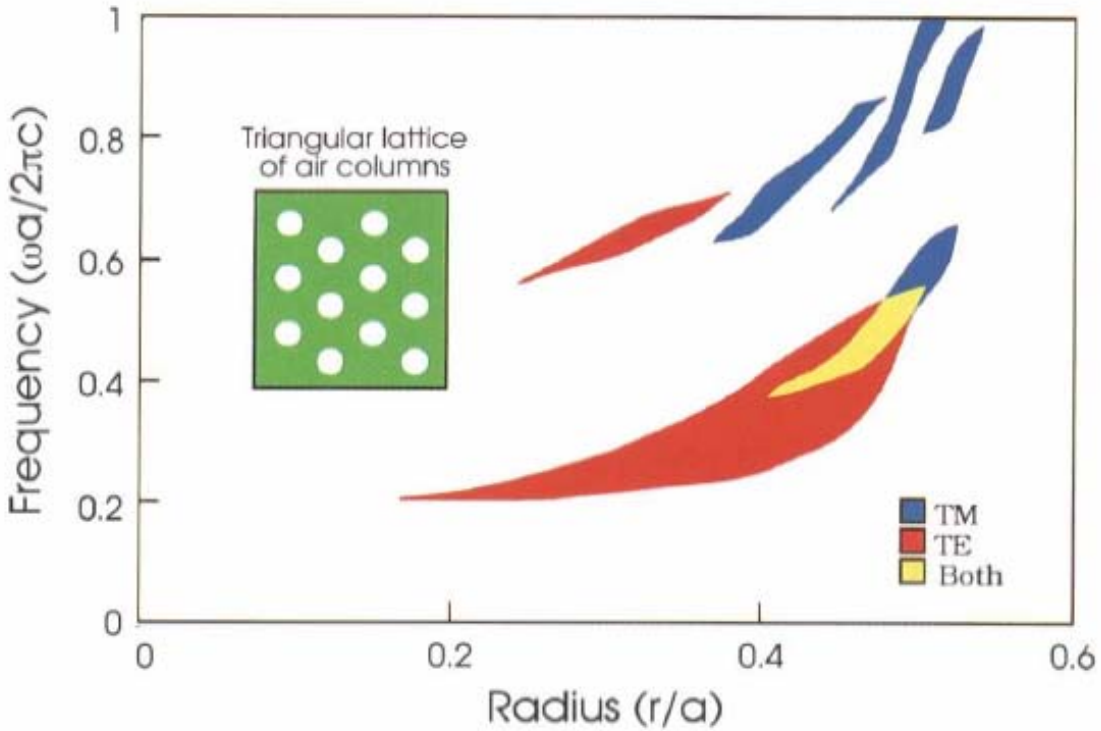
Bandlücke bei 2d-Kristall



Photonic Crystals, Joannopoulos, Meade Winn

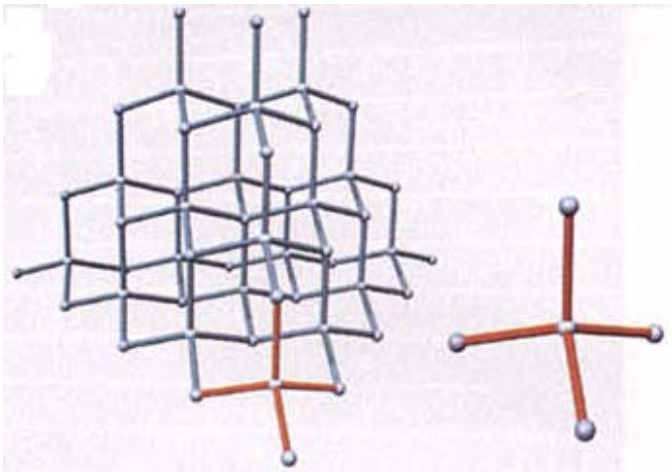
Gap map für dielektrische Säulen

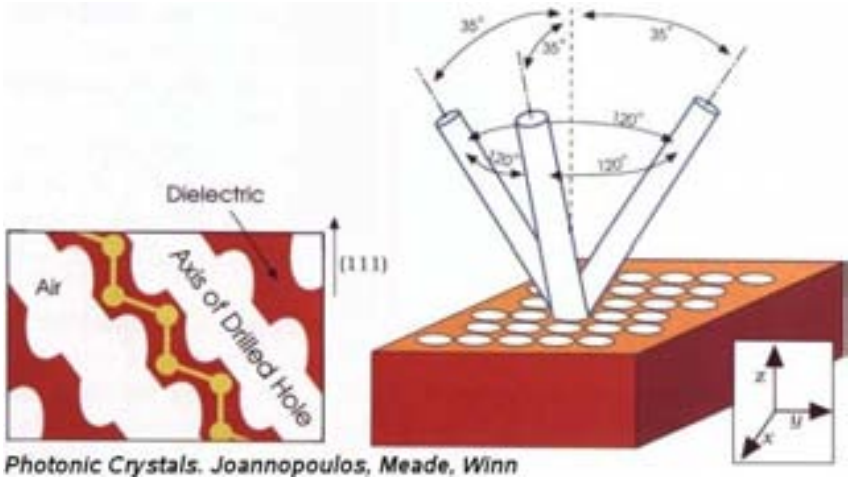
Gap map for 2D triangular-lattice of air cylinders in Si



3-dimensionaler Kristall - Yablonovite

- Diamantstruktur am besten geeignet (nach: Ho *et al.*, PRL65, 3152 (1990)):





Photonic Crystals. Joannopoulos, Meade, Winn

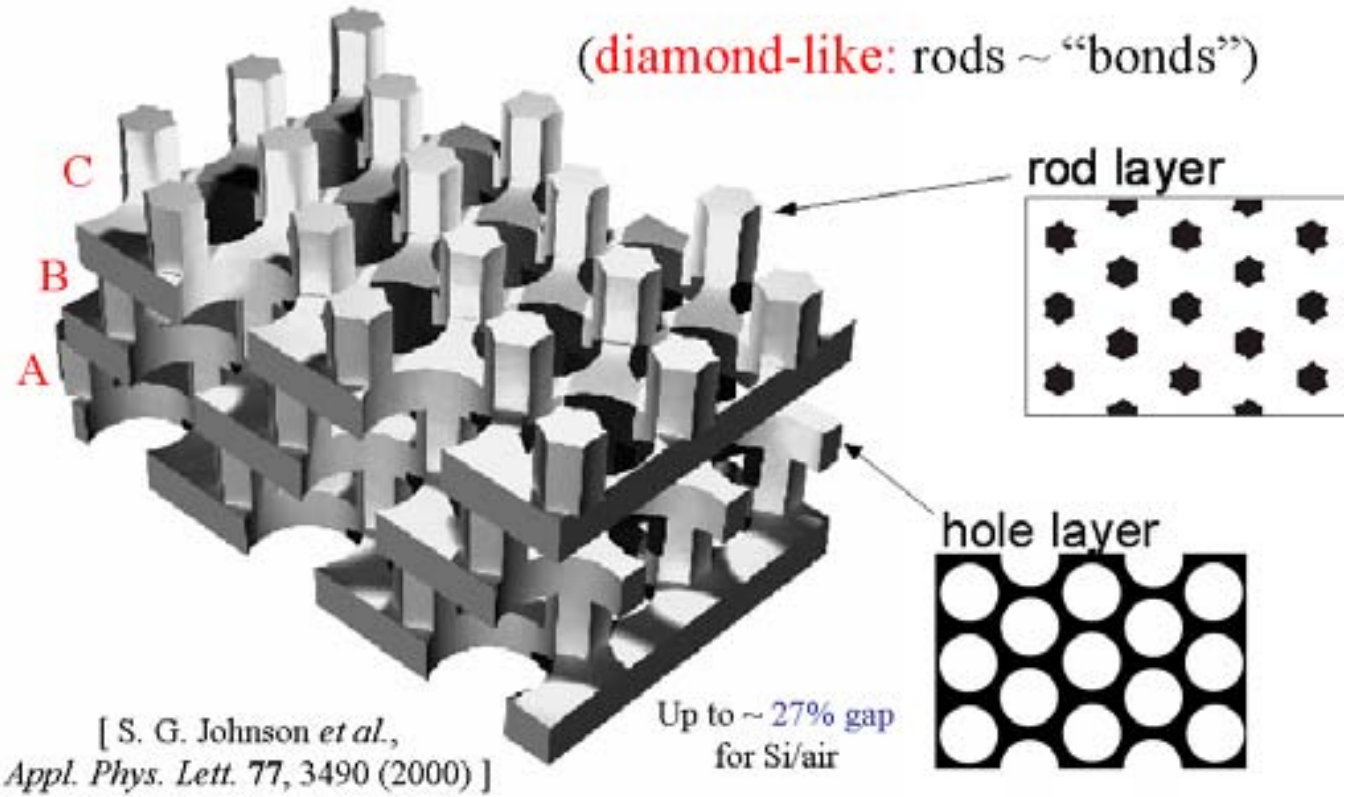
Yablonovite

Herstellung

3-dimensionaler Kristall

- Besteht aus Sequenz von planaren Schichten, die sich alle 3 Lagen wiederholen und so ein *fcc* Gitter bilden
- Schichten als abwechselnder Stapel von dielektrische Säulen in Luft und Luftsäulen im Dielektrikum
  $\Rightarrow$ 2d-Kristall in drei Dimensionen

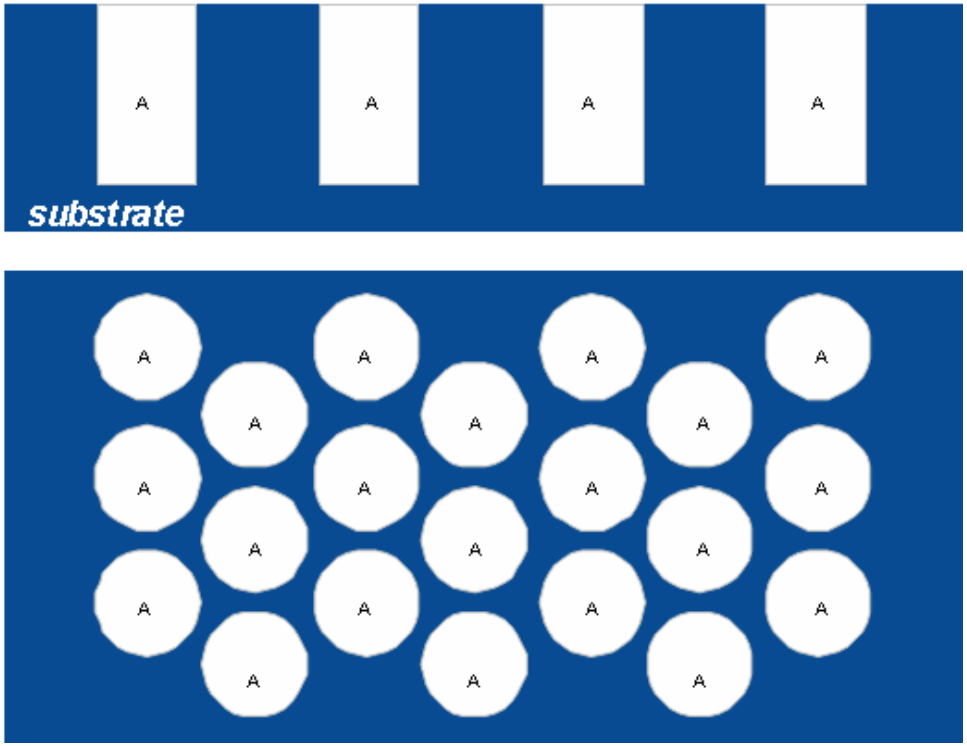
Herstellung eines 3d Kristalls



Herstellung eines 3d Kristalls

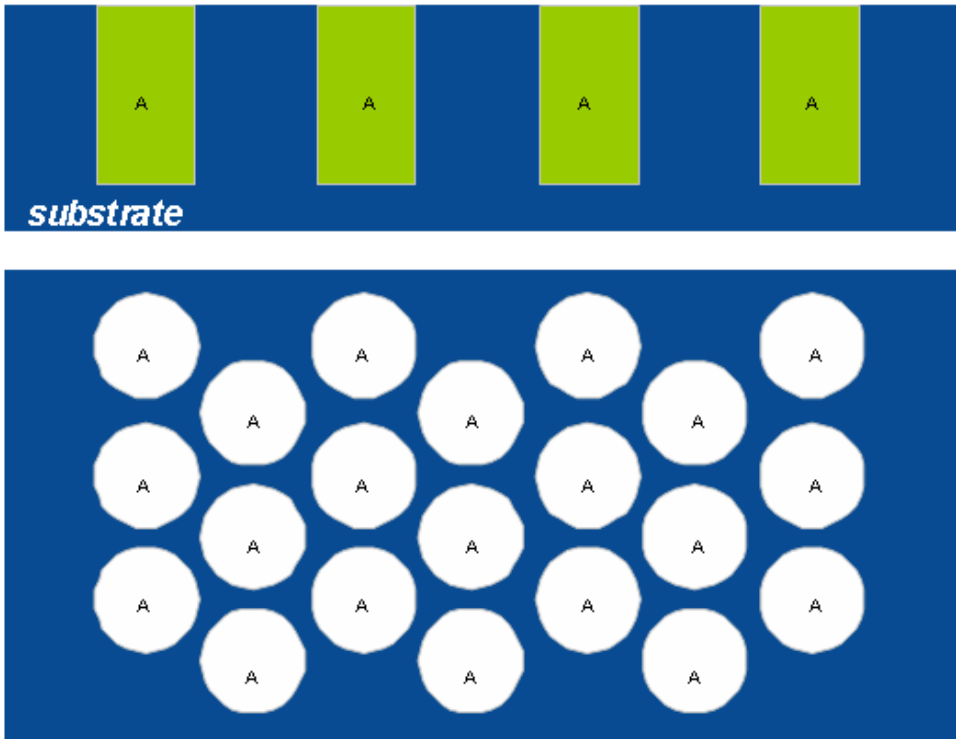
Herstellung eines 3d Kristalls

expose/etch holes



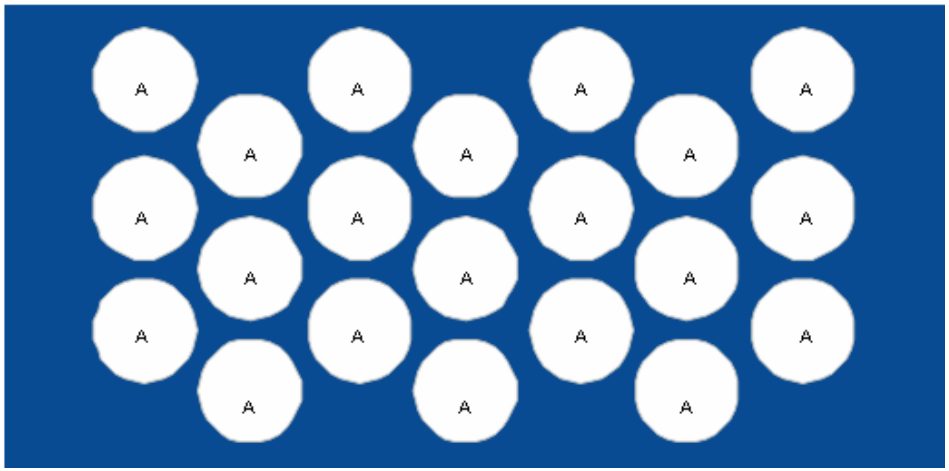
Herstellung eines 3d Kristalls

backfill with silica (SiO_2) & polish



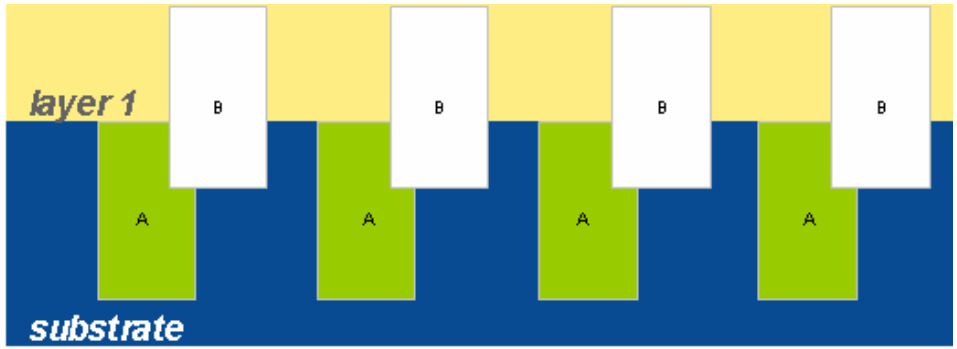
Herstellung eines 3d Kristalls

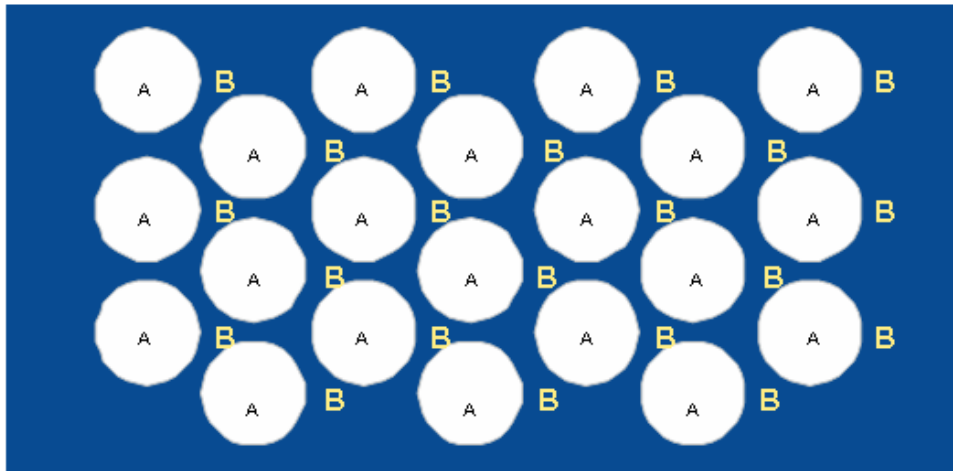
deposit another Si layer



Herstellung eines 3d Kristalls

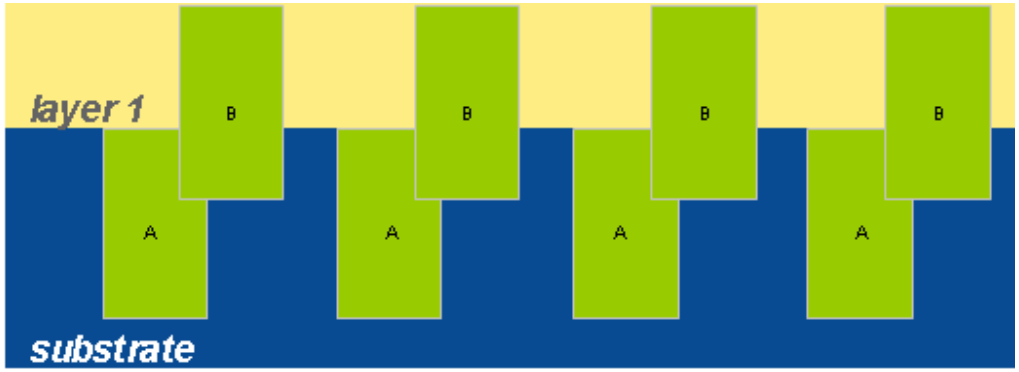
dig more holes
offset
& overlapping

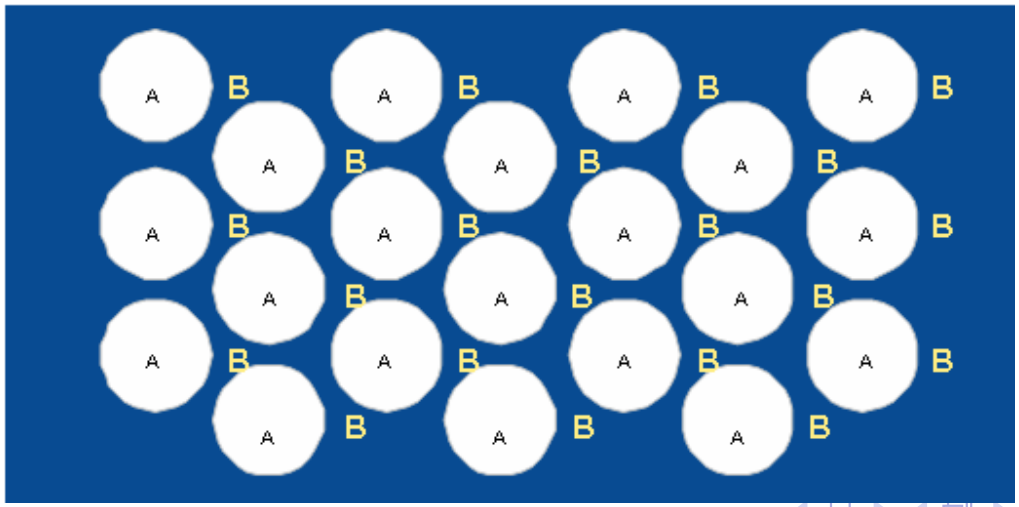




Herstellung eines 3d Kristalls

backfill

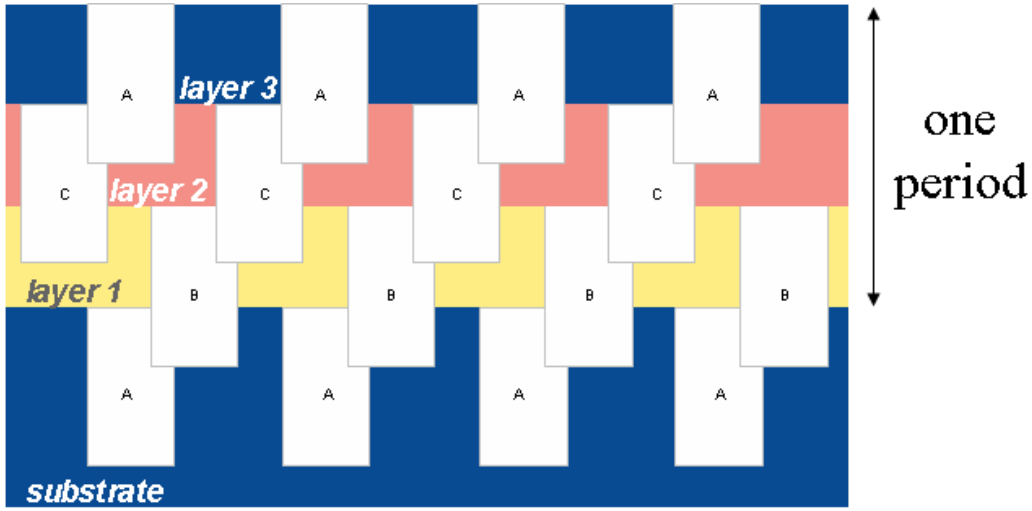


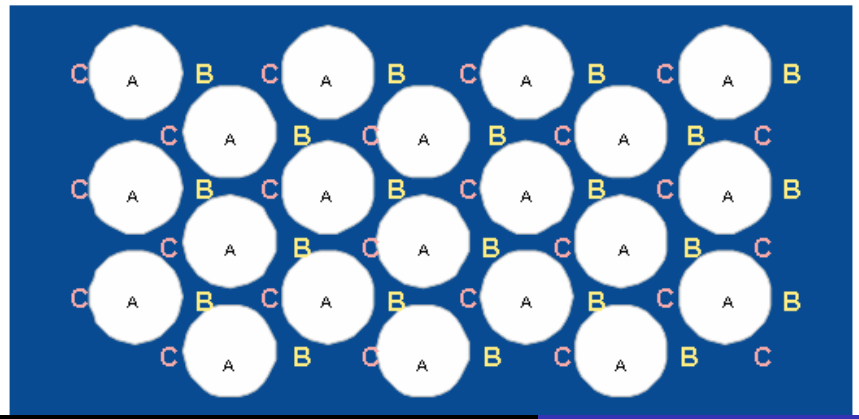


Herstellung eines 3d Kristalls

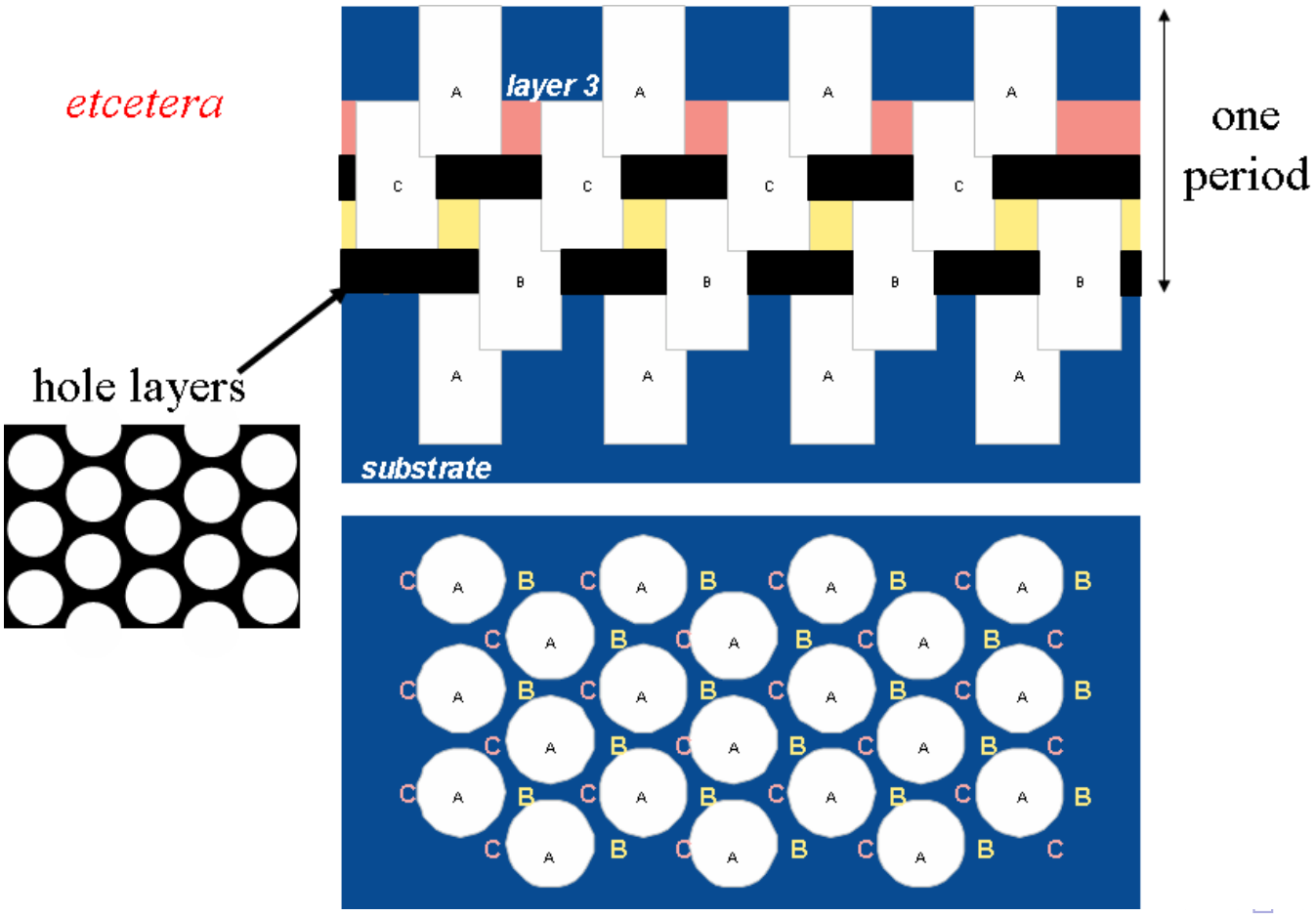
etcetera

(dissolve silica when done)

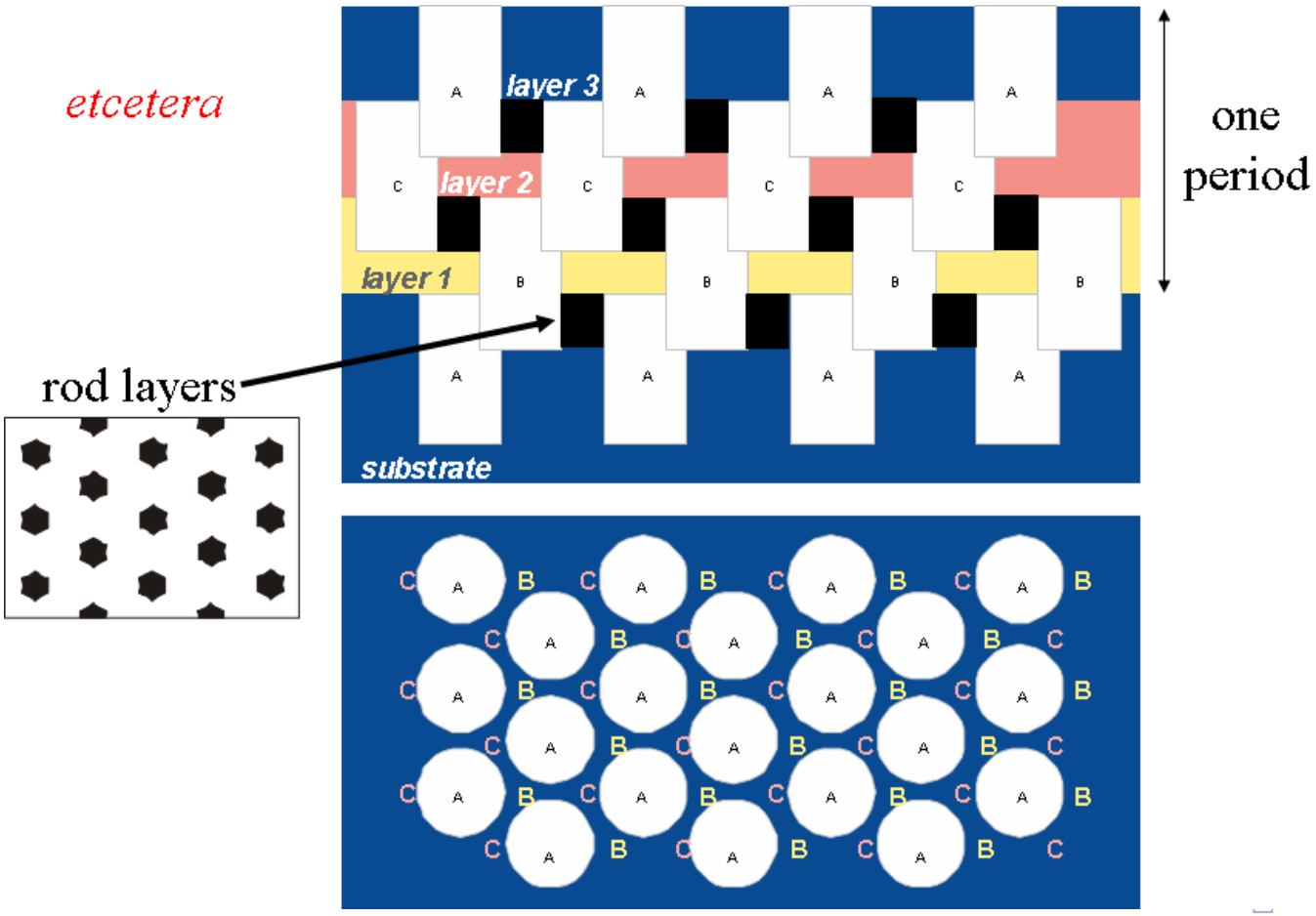




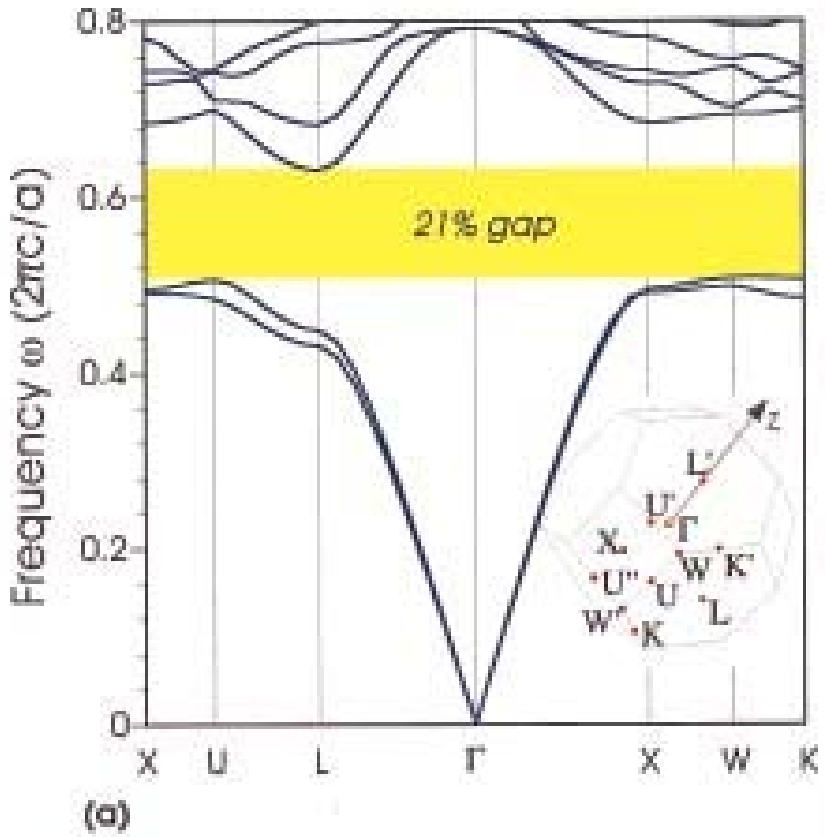
Herstellung eines 3d Kristalls



Herstellung eines 3d Kristalls



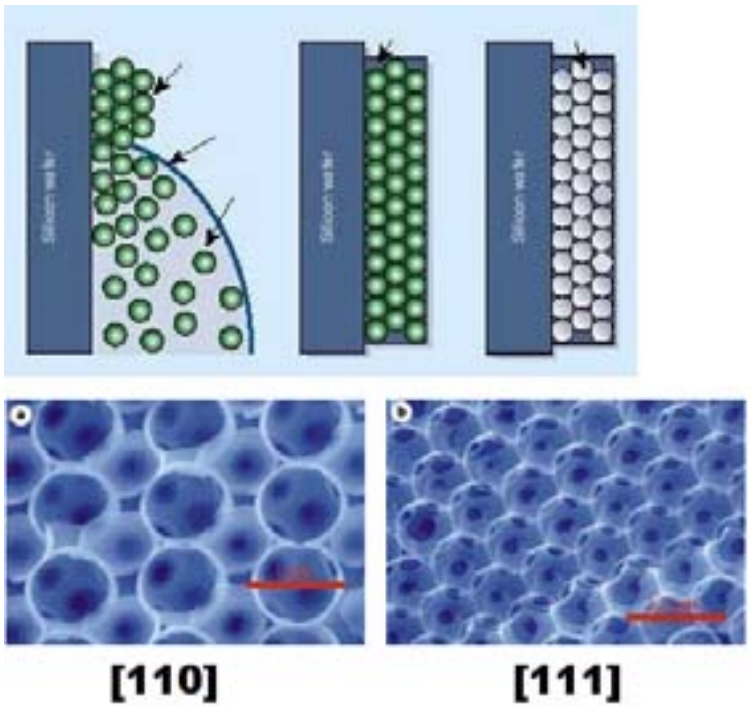
Banddiagramm



$$\frac{\Delta\omega}{\omega_0} = 0,21$$

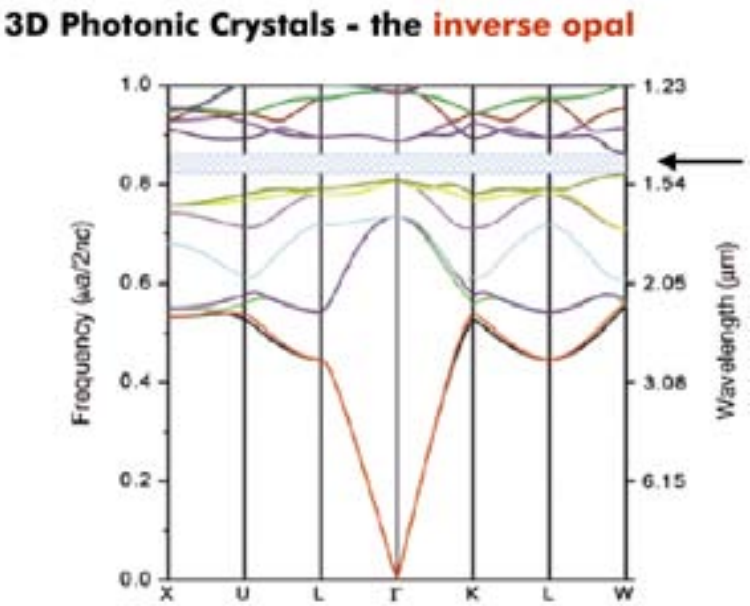
mit ω_0= Frequenz in der Mitte der Lücke

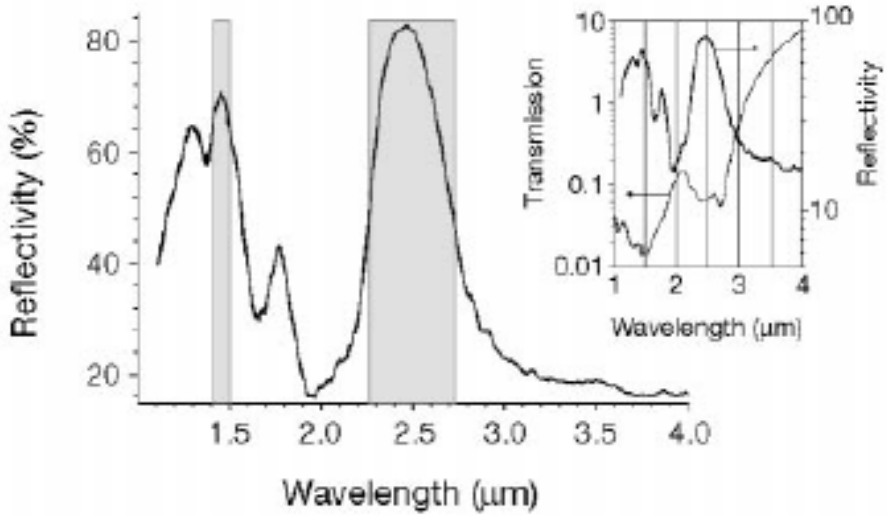
Inverse Opal



- Herstellung von Künstlichen Opal:
  Verdampfen einer Kolloidlösung
  $\Rightarrow$ Quarz ordnet selbstständig in *fcc*-Gitter an
- Durch Sintern werden Kugeln zusammengebacken.
- Einströmen von Si
- Wegätzen von Silikat
  $\Rightarrow$ **Invertierter Opal**

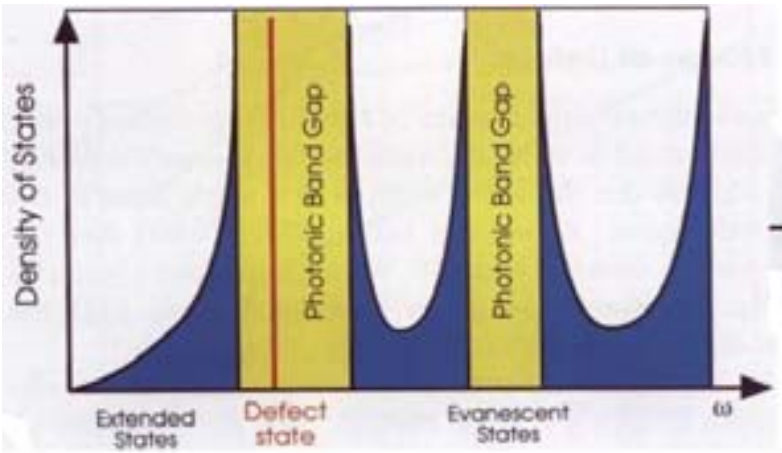
Inverse Opal





Anwendungen

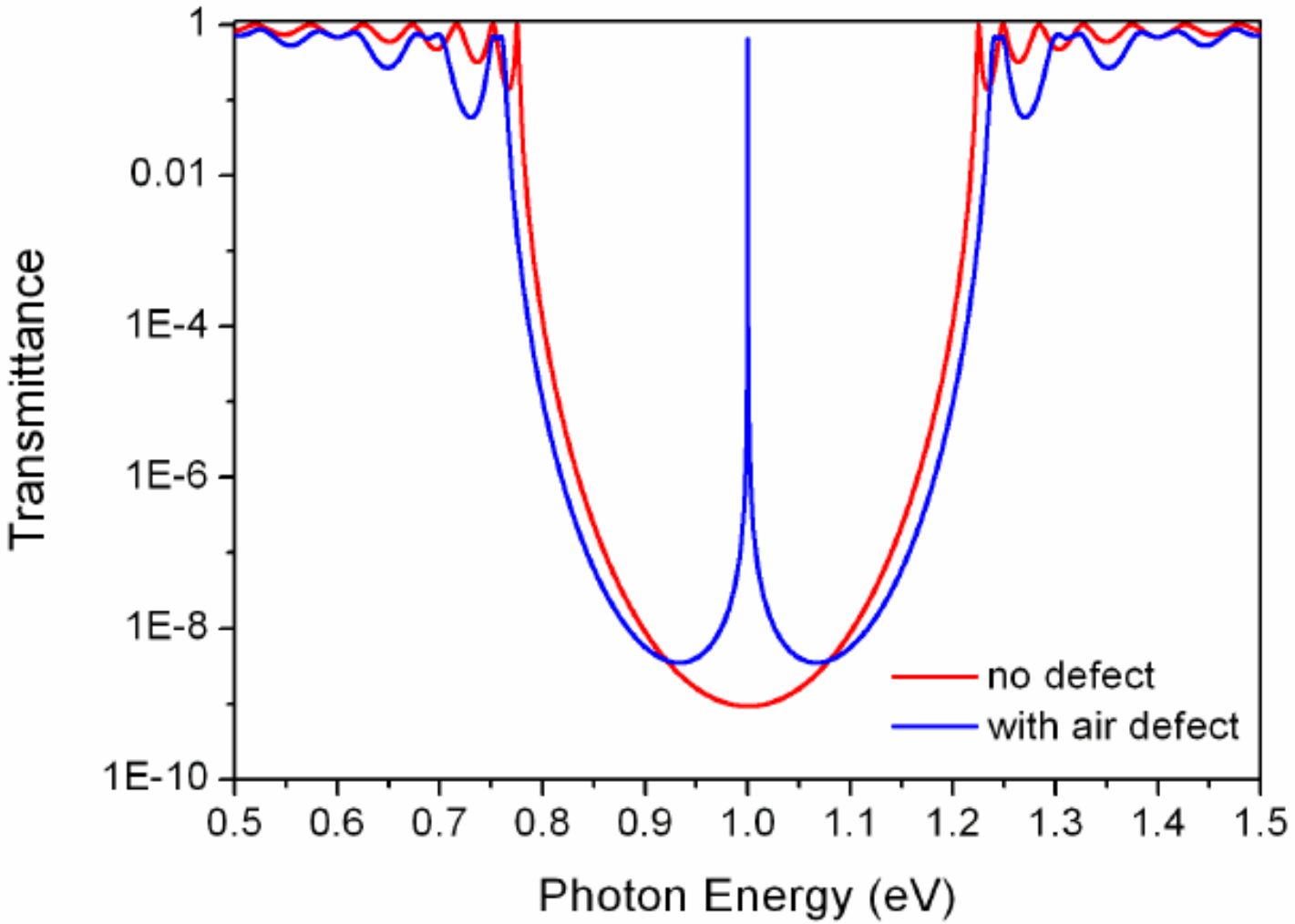
Defekte im Kristall



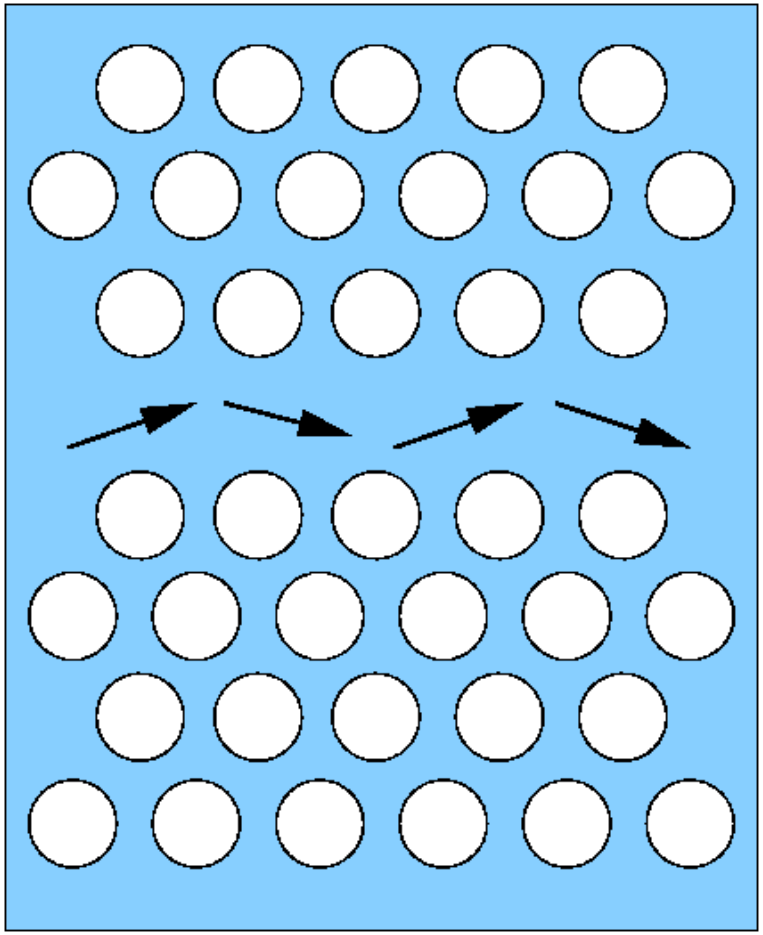
Photonic Crystals, Joannopoulos, Meade, Winn

- Defekt = Störungen der Periodizität von $\varepsilon(r)$
- Erlauben Lokalisation von Defektmoden
- Anwendungen:
  - Scharfe Filter
  - Kleine Laser

Defekte im Kristall

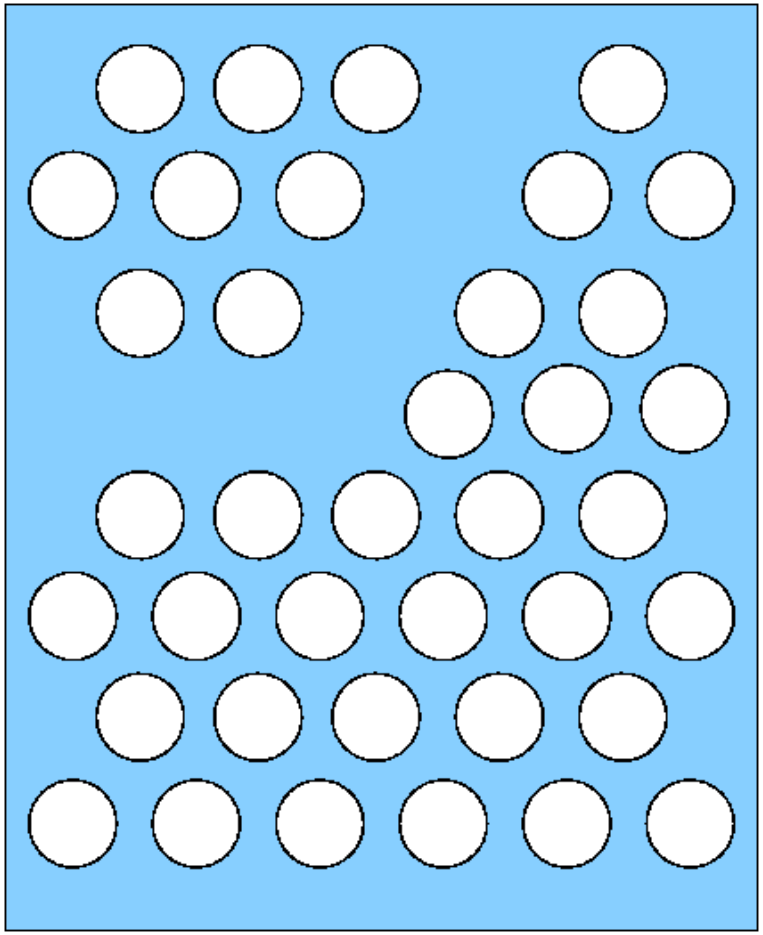


Liniendefekte



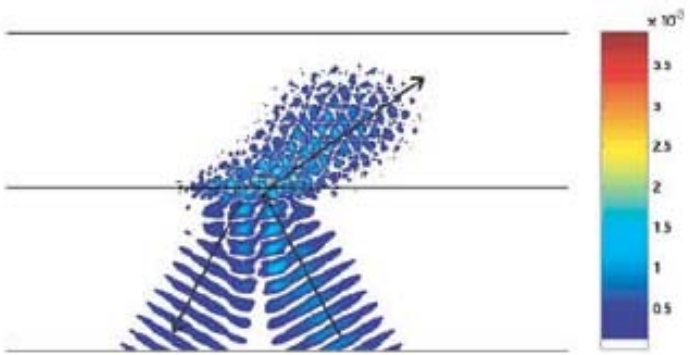
- Liniendefekt entsteht durch Auslassen von Luftlöchern
- Licht mit ν innerhalb der Bandlücke ist umgeben von Material, in das es nicht eindringen kann
  $\Rightarrow$ "folgt" dem Liniendefekt

Liniendefekte



- Wellenleiter-Krümmung mit extrem kleinen Krümmungsradien möglich
  $\Rightarrow$ Das Licht "geht" um die Ecke.

Linksbrechende Materialien



- Mithilfe von Photonischen Kristallen Herstellung von Materialien mit negativen Brechungsindex im sichtbaren Bereich.
- Zum genaueren Verständnis Vortrag in 2 Wochen!

Zusammenfassung

Zusammenfassung und Ausblick

- Photonische Kristalle sind die "Halbleiter der Optik".
- Sie können uns die Kontrolle über das Licht geben.
- Sie werden Einsatz in der Telekommunikationbranche und Computerindustrie finden.