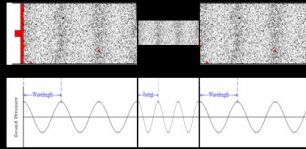
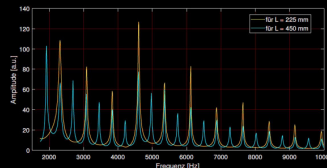
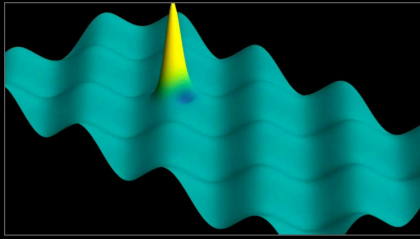


Quantenanalogie - Teil 2

PD Dr. Steffen Danzenbächer

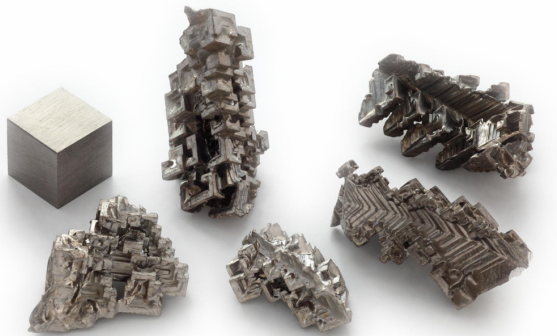


001

Die „kurze“ Geschichte von der Bandstruktur ...

oder:

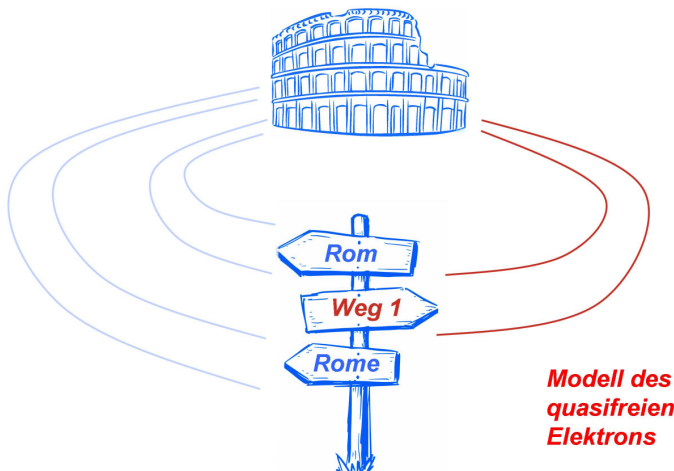
Wie funktioniert ein Festkörper ?



002

Die „kurze“ Geschichte von der Bandstruktur ...

„Alle Wege führen nach Rom ...“

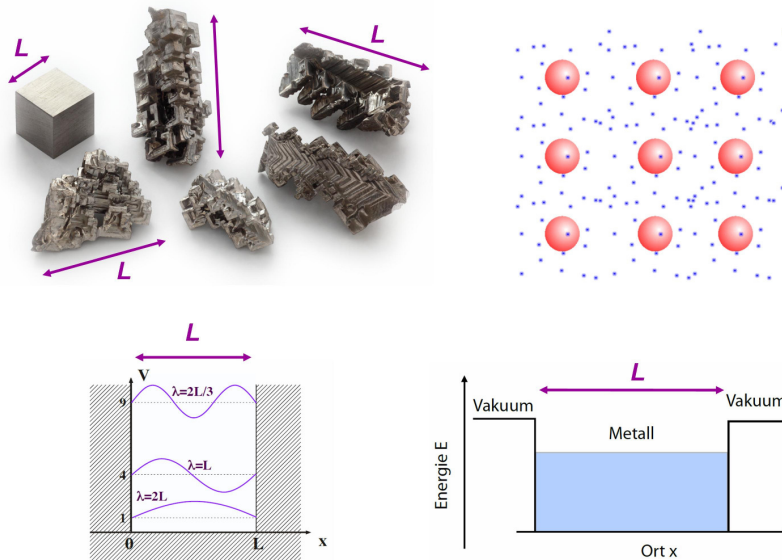


Modell des
quasifreien
Elektrons

003

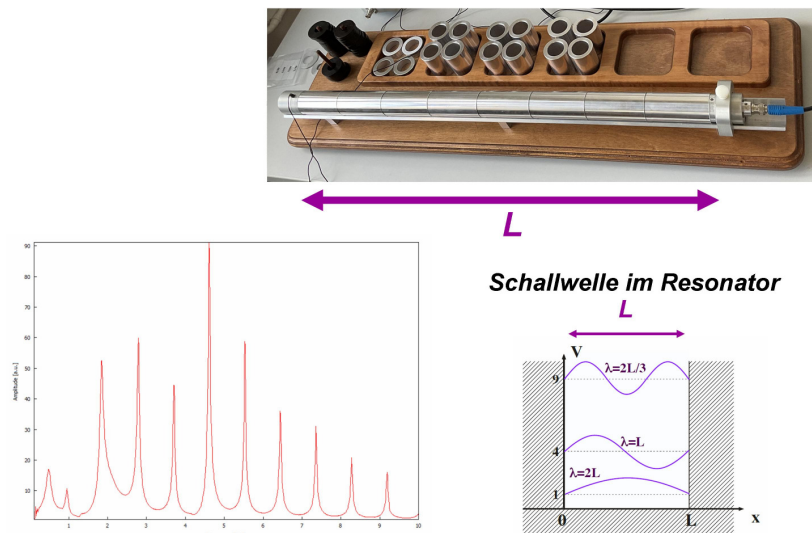
Die „kurze“ Geschichte von der Bandstruktur ...

004



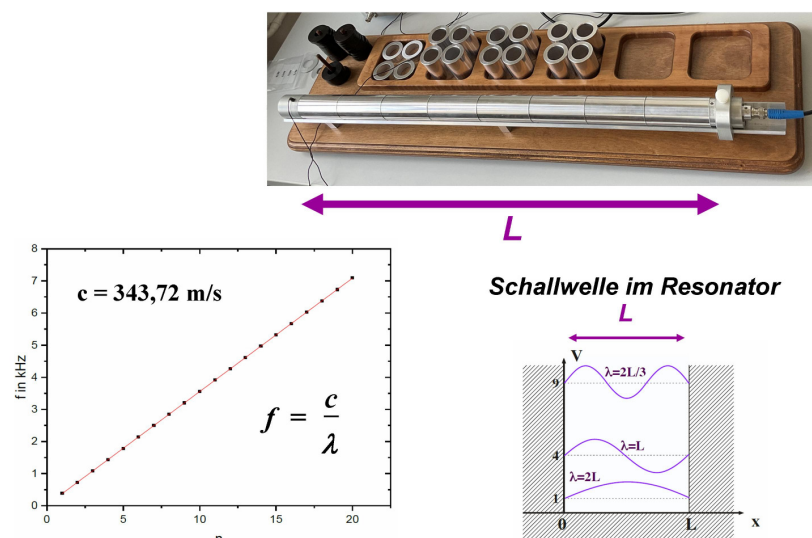
Die „kurze“ Geschichte von der Bandstruktur ...

005



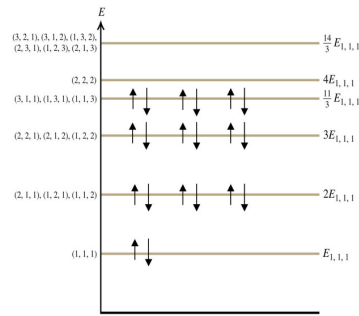
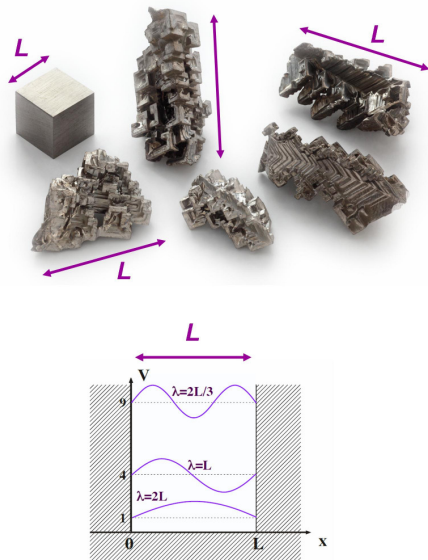
Die „kurze“ Geschichte von der Bandstruktur ...

006



Die „kurze“ Geschichte von der Bandstruktur ...

007



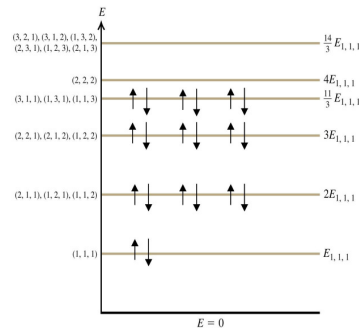
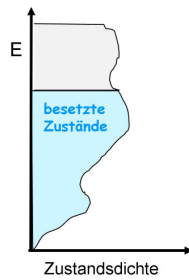
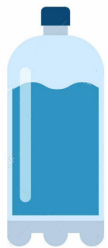
$$E_{ges} = \frac{\hbar^2 \pi^2}{2mL^2} \cdot (n_x^2 + n_y^2 + n_z^2)$$

Ein makroskopischen
Festkörper hat „große“
Ausdehnungen L



Die „kurze“ Geschichte von der Bandstruktur ...

008



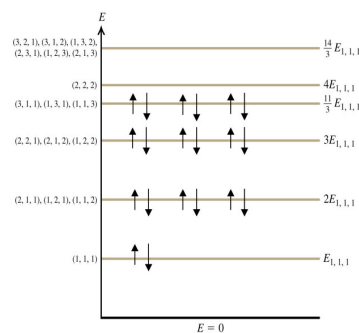
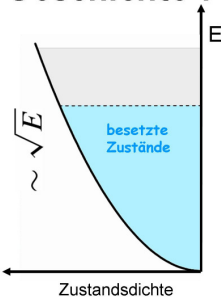
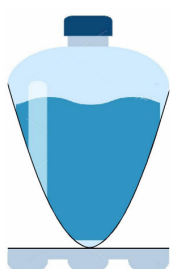
$$E_{ges} = \frac{\hbar^2 \pi^2}{2mL^2} \cdot (n_x^2 + n_y^2 + n_z^2)$$

Ein makroskopischen
Festkörper hat „große“
Ausdehnungen L



Die „kurze“ Geschichte von der Bandstruktur ...

009



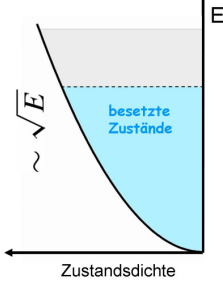
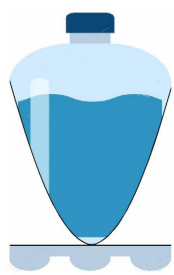
$$E_{ges} = \frac{\hbar^2 \pi^2}{2mL^2} \cdot (n_x^2 + n_y^2 + n_z^2)$$

Ein makroskopischen
Festkörper hat „große“
Ausdehnungen L

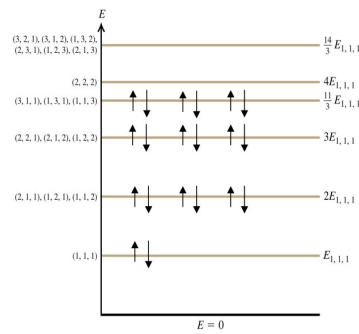
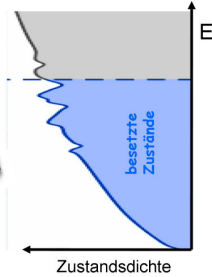


Die „kurze“ Geschichte von der Bandstruktur ...

010



Aluminium



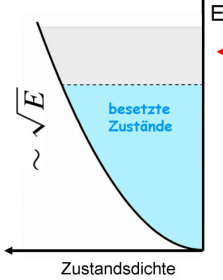
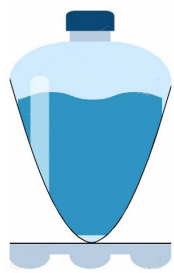
$$E_{ges} = \frac{\hbar^2 \pi^2}{2mL^2} \cdot (n_x^2 + n_y^2 + n_z^2)$$

Ein makroskopischen Festkörper hat „große“ Ausdehnungen L

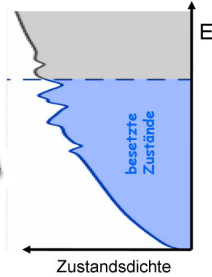


Die „kurze“ Geschichte von der Bandstruktur ...

011



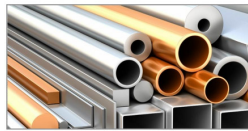
Aluminium



Im Modell quasi-freier Elektronen gibt es keine Bandlücken.

Bei allen Energie gibt es erlaubte Zustände.

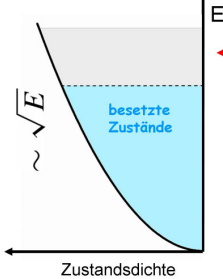
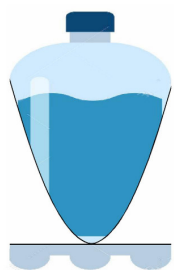
Halbleiter und Isolatoren lassen sich so nicht beschreiben.



Nur für Metalle geeignet !!!

Stromleitung in Metallen

012



Im Modell quasi-freier Elektronen gibt es keine Bandlücken.

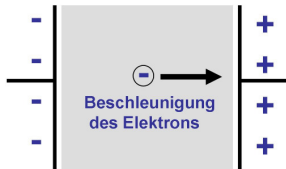
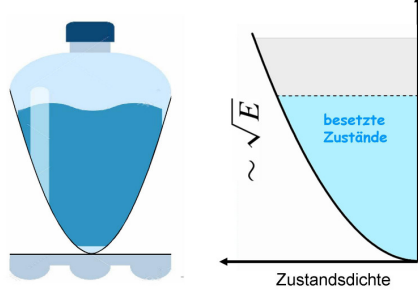
Bei allen Energie gibt es erlaubte Zustände.

Halbleiter und Isolatoren lassen sich so nicht beschreiben.



Nur für Metalle geeignet !!!

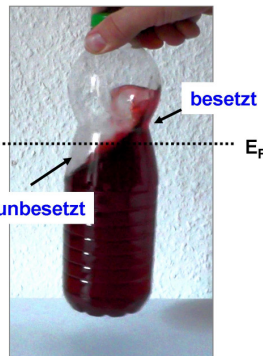
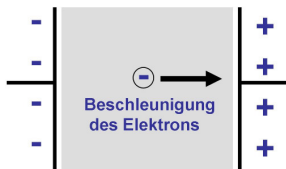
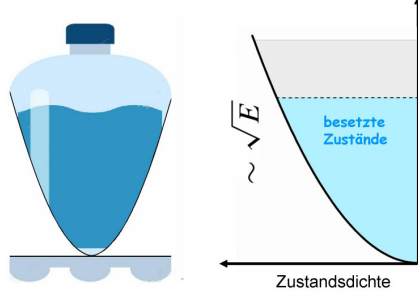
Stromleitung in Metallen



**Nur für Metalle
geeignet !!!**

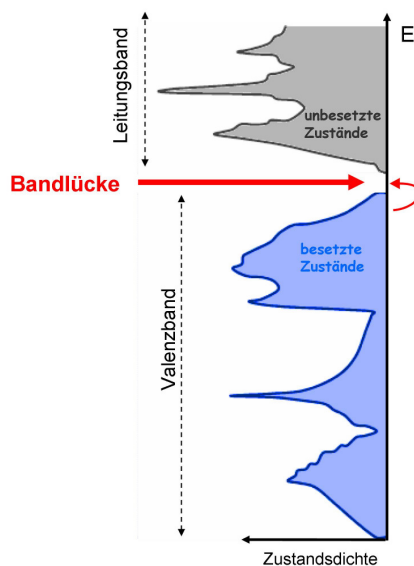
013

Stromleitung in Metallen



014

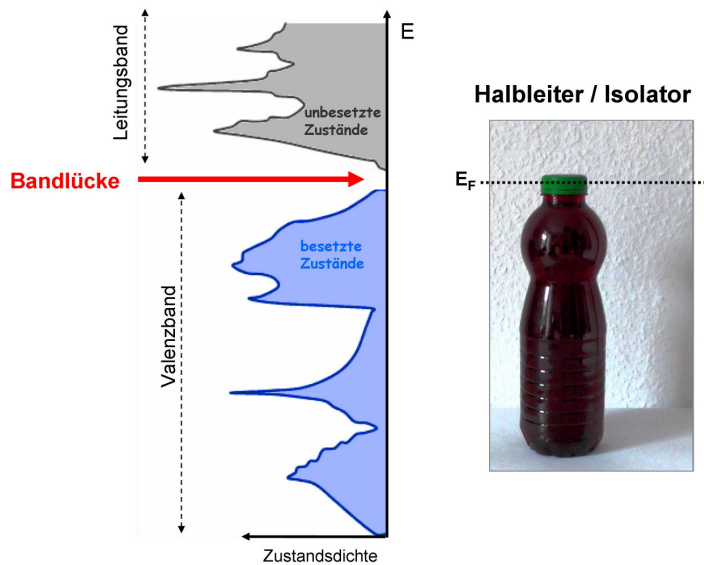
Beispiel: Germanium - Halbleiter



015

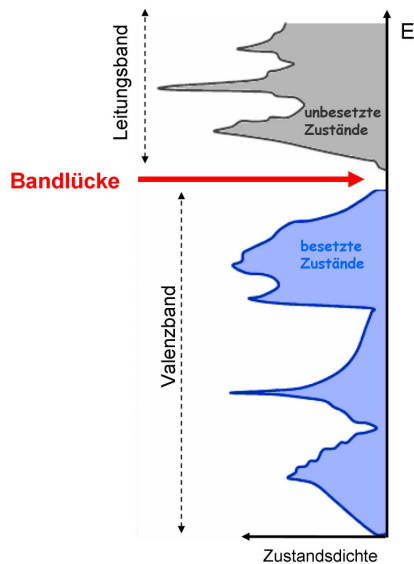
Beispiel: Germanium - Halbleiter

016



Beispiel: Germanium - Halbleiter

017



Frage:

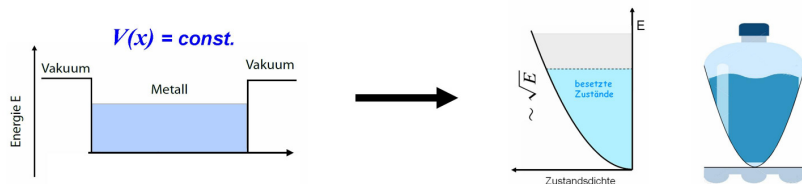
Wie komme ich nun zu einer Zustandsdichte mit einer Bandlücke ?

Antwort:

Über die Schrödinger-gleichung im periodischen Potential, also über die Bandstruktur !

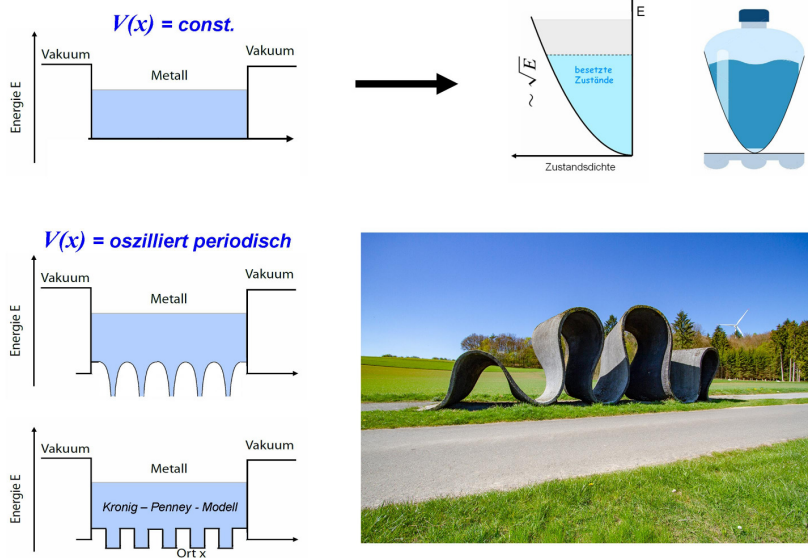
Schrödingergleichung für ein periodisches Potential ...

018



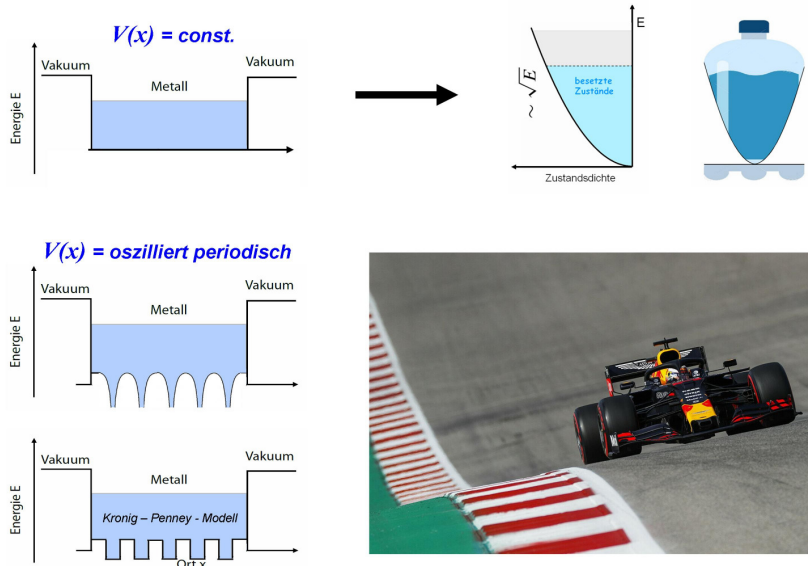
Schrödingergleichung für ein periodisches Potential ...

019



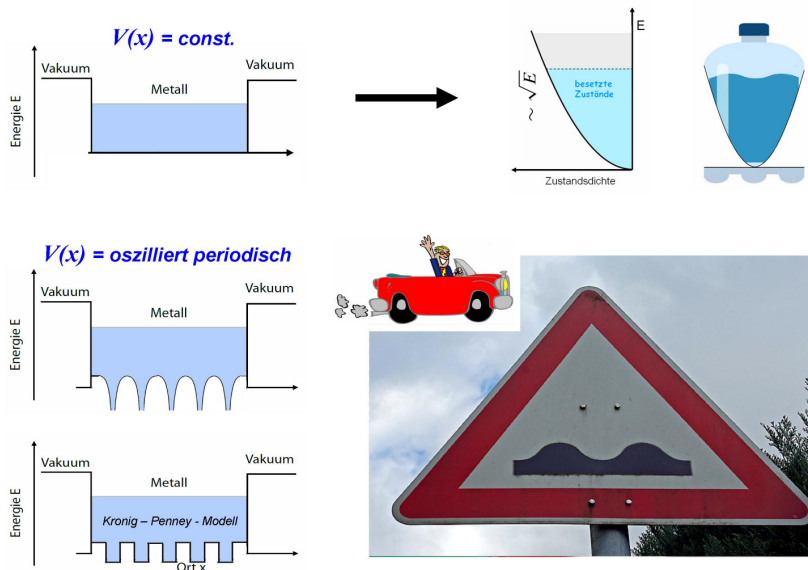
Schrödingergleichung für ein periodisches Potential ...

020



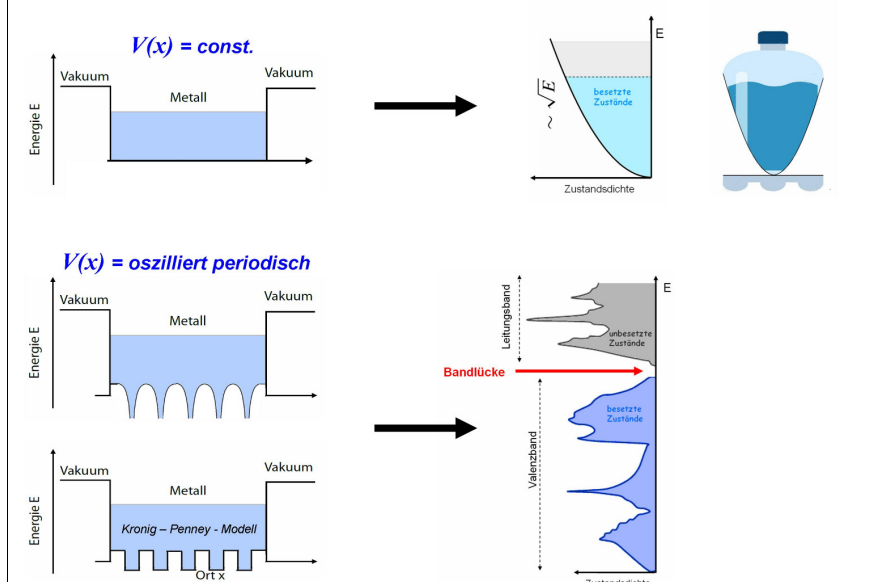
Schrödingergleichung für ein periodisches Potential ...

021



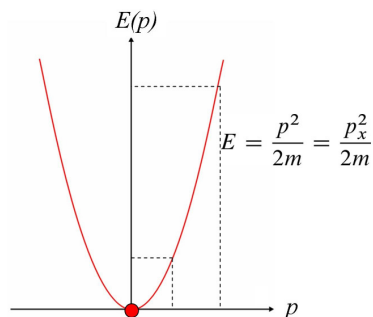
Schrödingergleichung für ein periodisches Potential ...

022



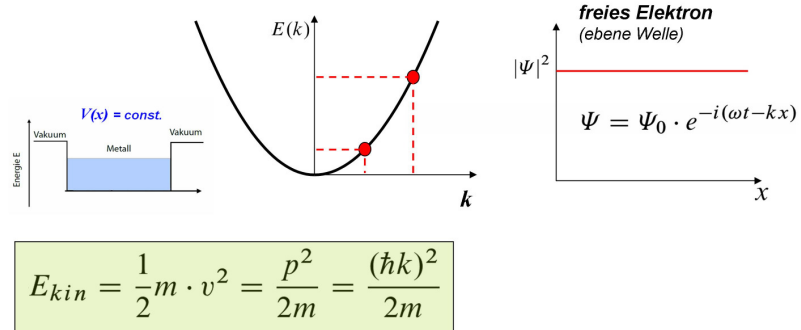
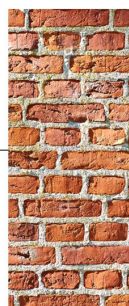
1-dimensionale Bandstruktur

023



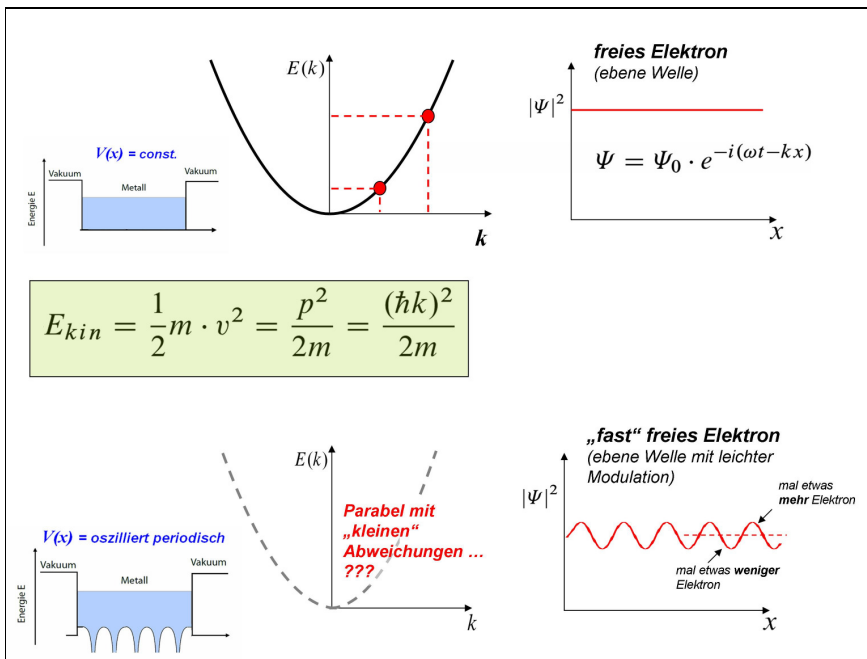
10 km/h

20 km/h

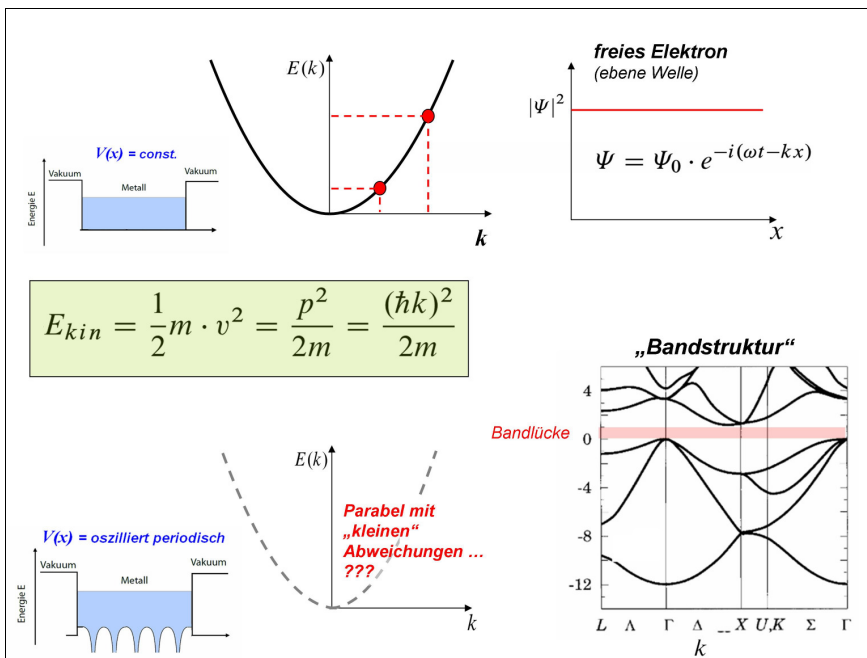


024

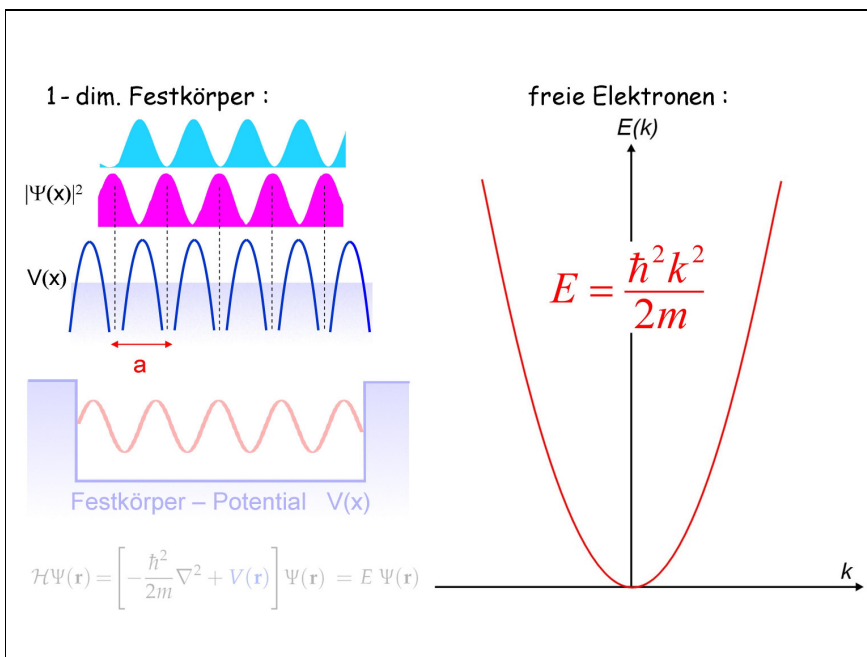




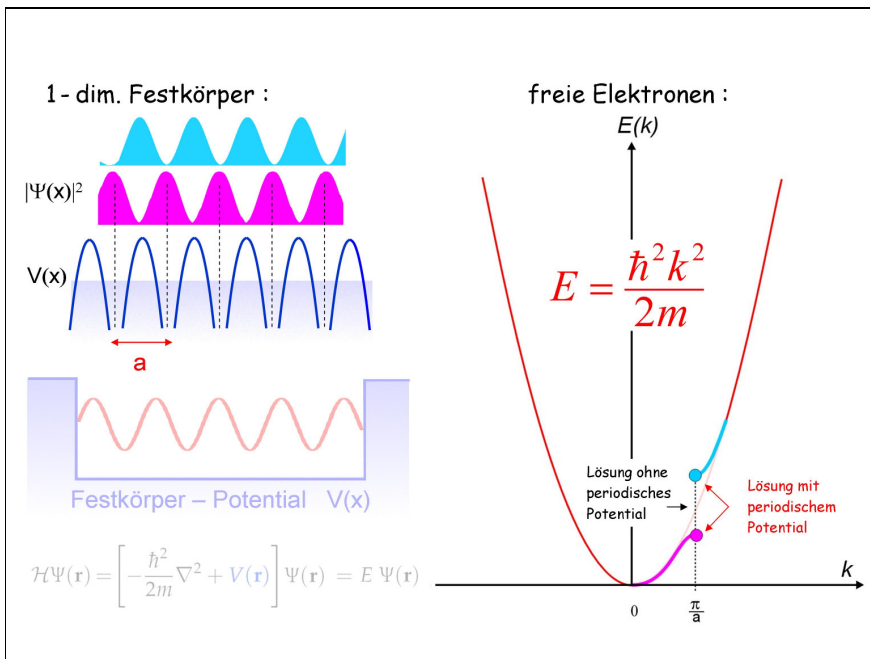
025



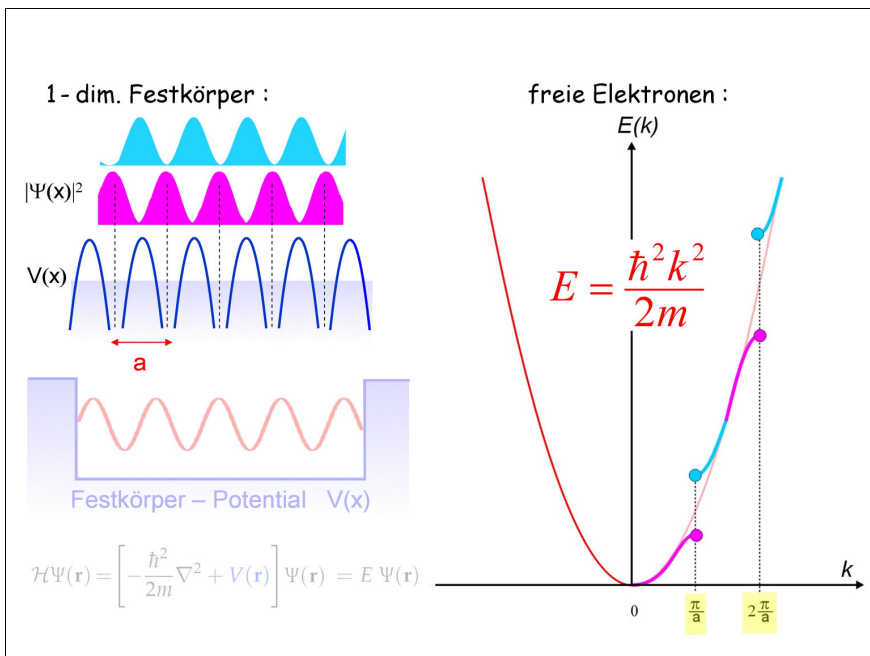
026



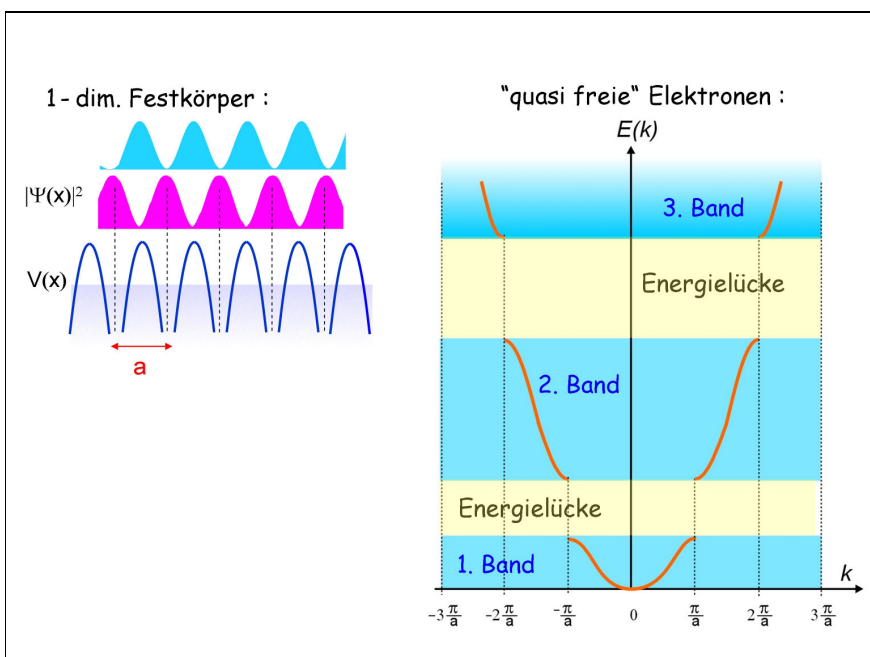
027



028

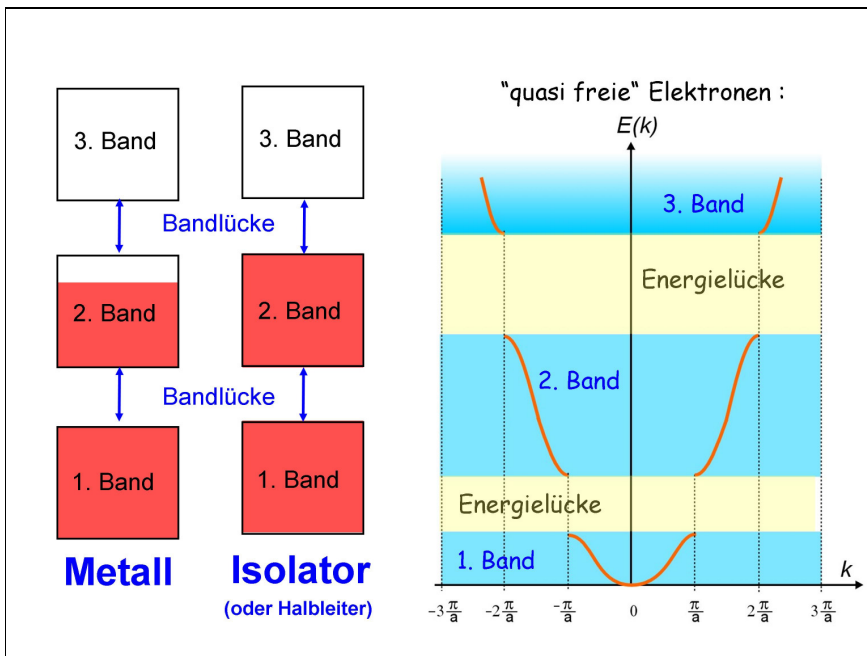


029



030

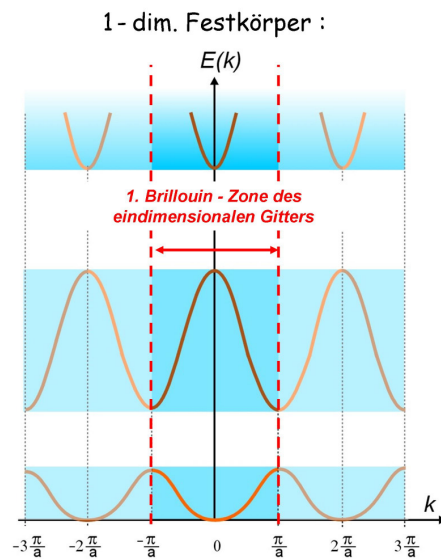
031



032

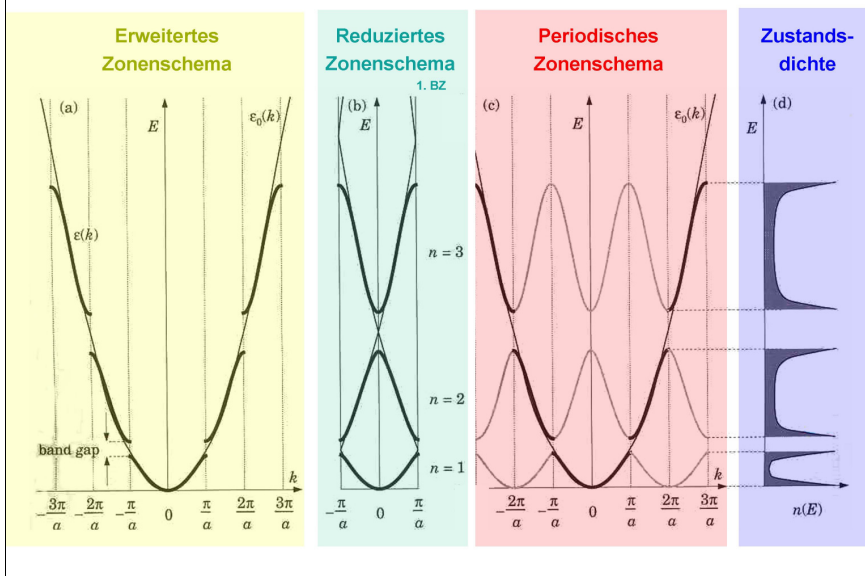
Aus der Vorlesung Festkörperphysik:

Die Funktion $E(k)$ ist im periodischen Festkörper auch eine periodische Funktion von k mit der Periodizität $2\pi/a$.

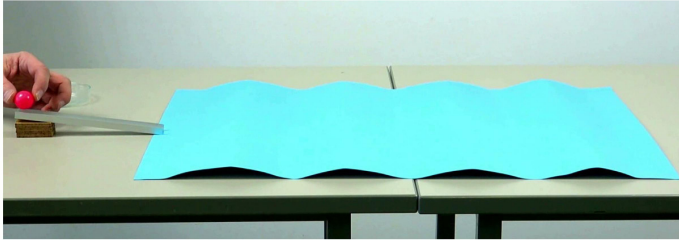


033

Bezeichnungen für Bandstrukturen

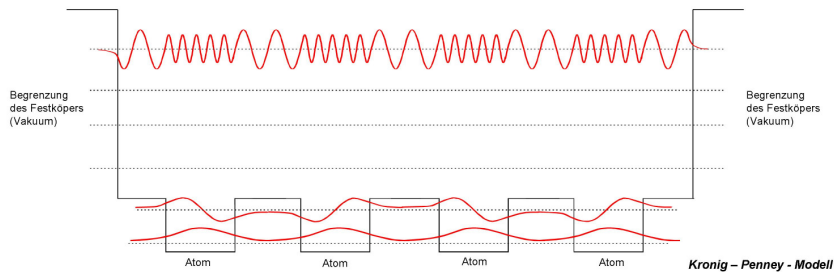


037



$$\lambda = \frac{h}{p}$$

periodische Potentialtöpfe mit beidseitiger Begrenzung (eindimensionaler Festkörper)

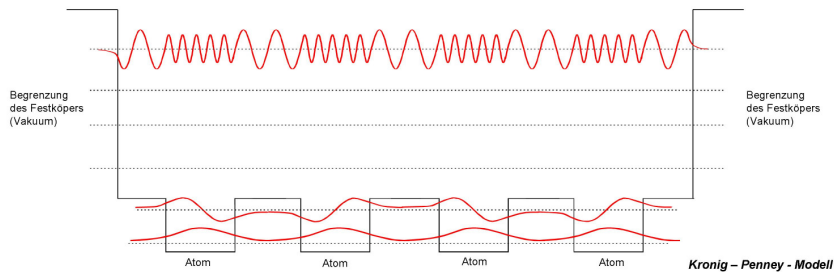


038

mechanisches Analogon zum 1-dim Festkörper ...

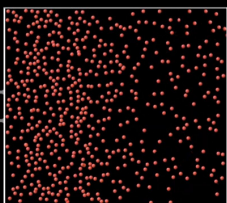


periodische Potentialtöpfe mit beidseitiger Begrenzung (eindimensionaler Festkörper)



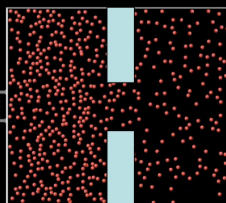
039

Schallausbreitung und Schallgeschwindigkeit



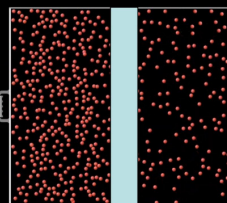
Schallausbreitung
mit normaler
Schallgeschwindigkeit

$$C = C_{Schall}$$



Druckausgleich wird
Behindert und
Schallausbreitung
verlangsamt

$$C < C_{Schall}$$

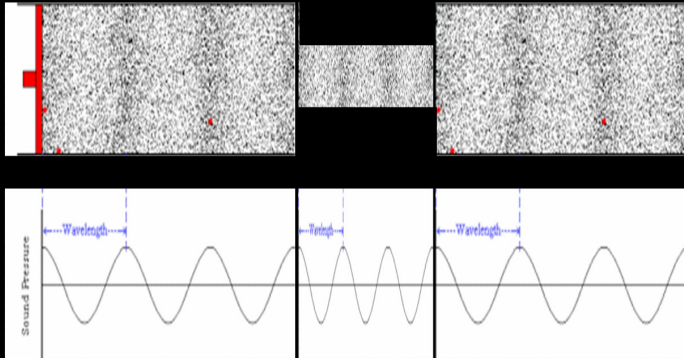


Druckausgleich nicht
mehr möglich,
Schallausbreitung
gestoppt

$$C = 0$$

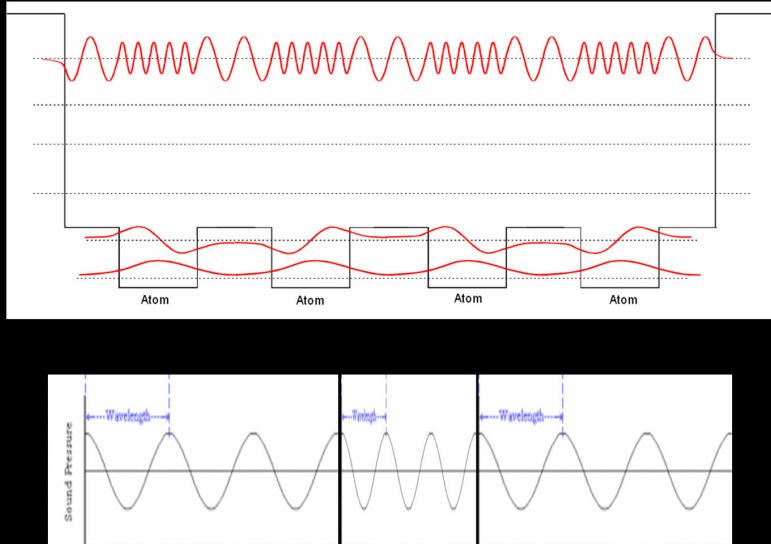
$$f = \text{const.}$$

$$\lambda = \frac{c}{f}$$



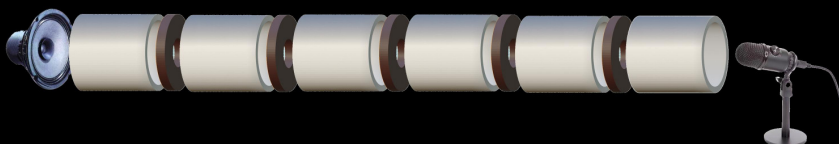
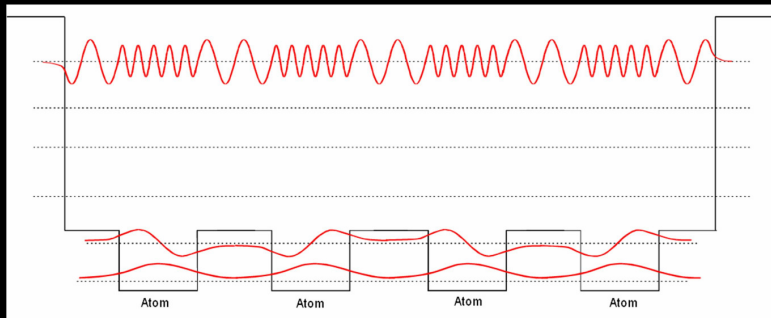
040

periodische Potentialtöpfe mit beidseitiger Begrenzung (eindimensionaler Festkörper)



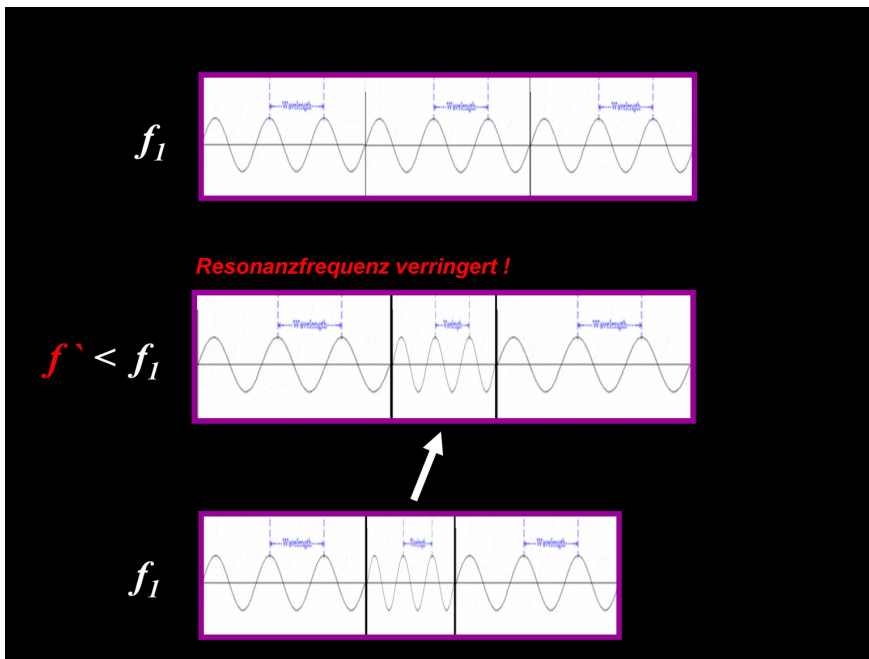
041

periodische Potentialtöpfe mit beidseitiger Begrenzung (eindimensionaler Festkörper)

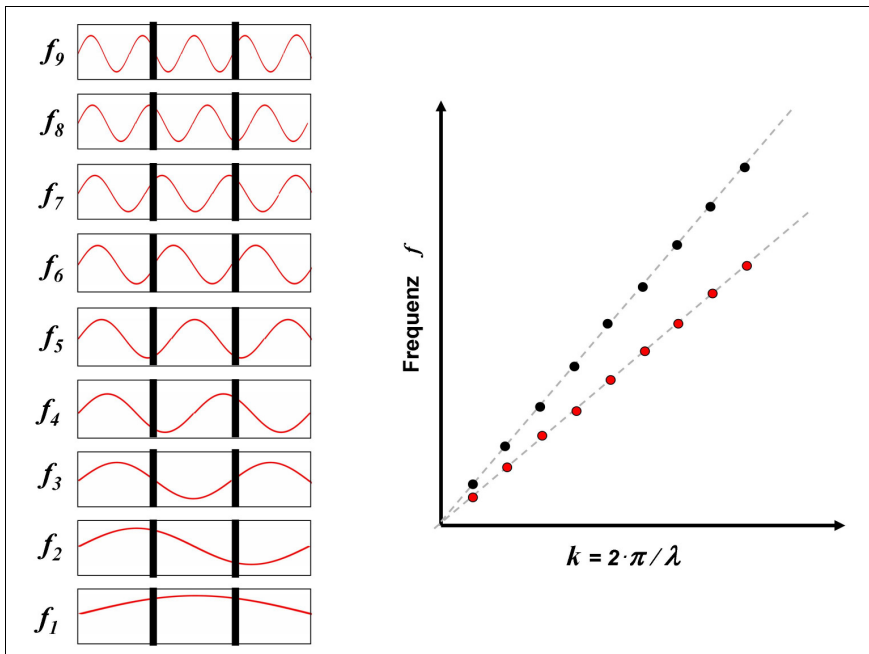


042

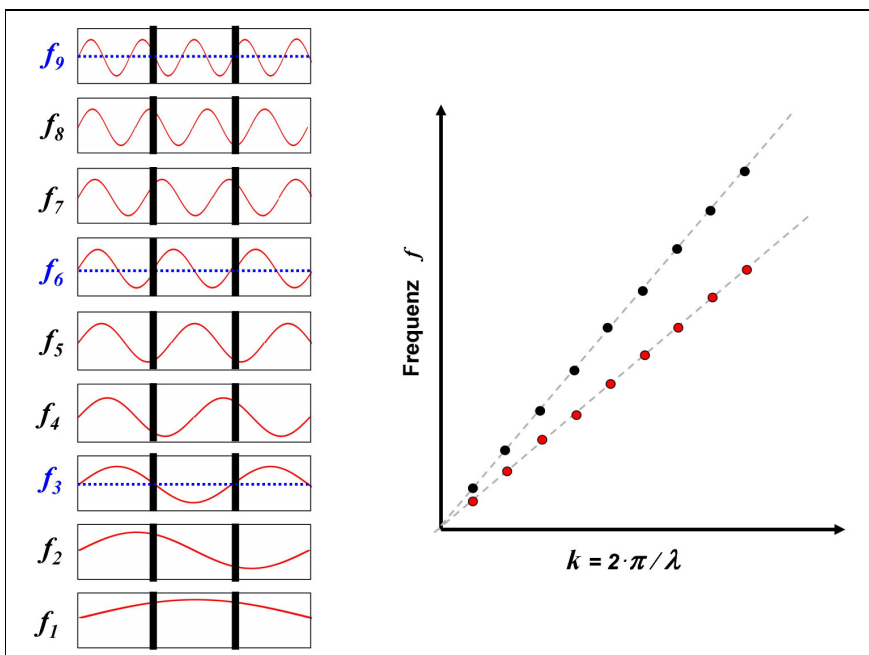
043

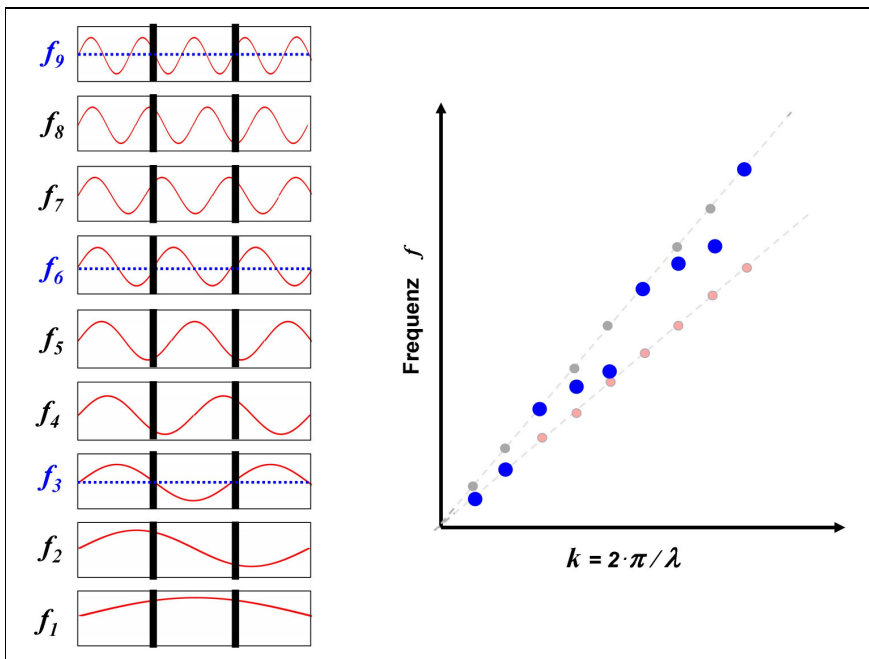


044

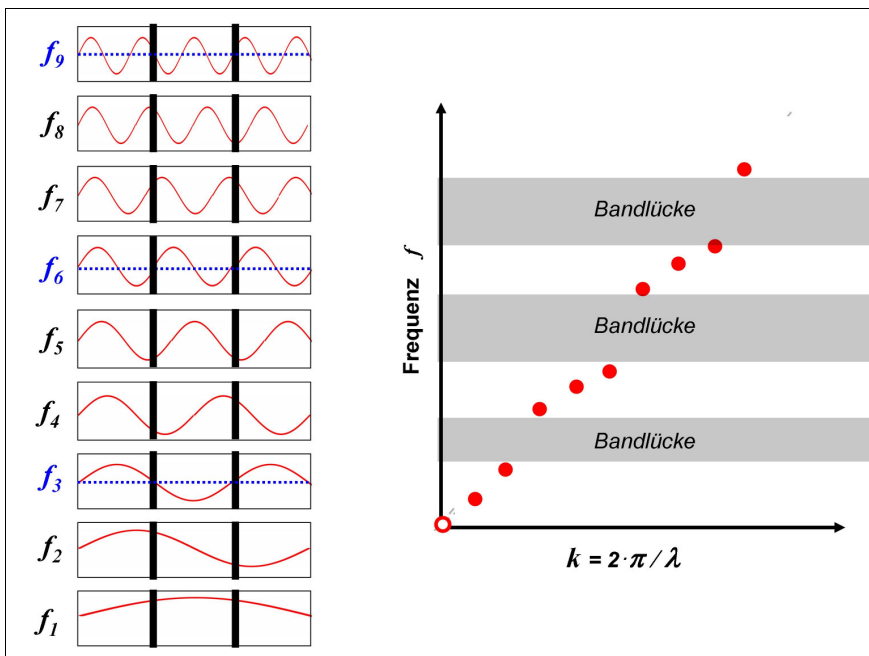


045

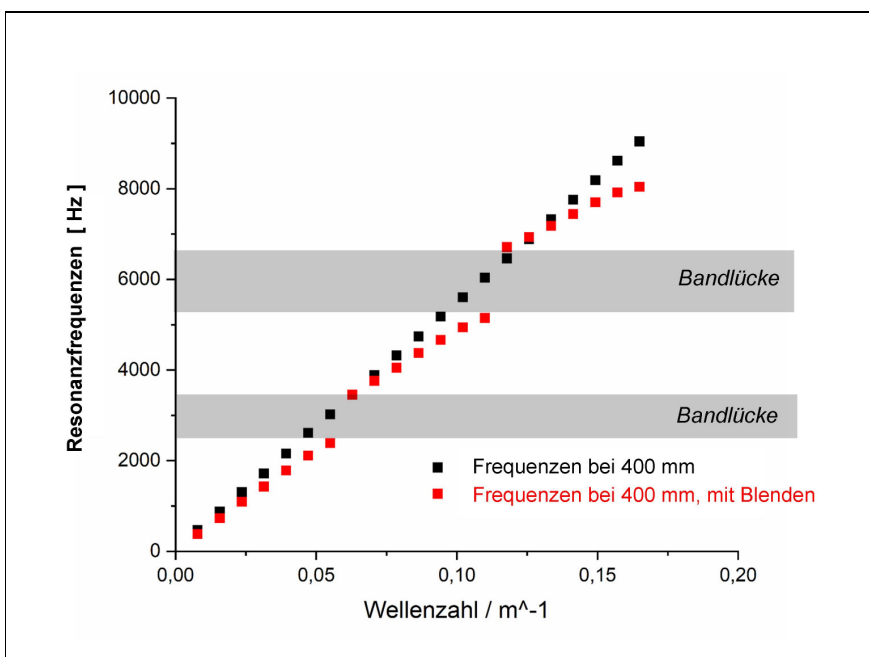




046

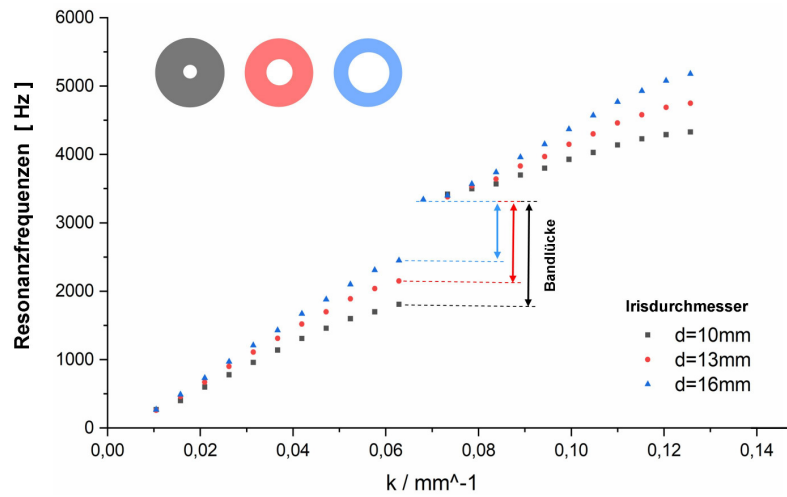


047

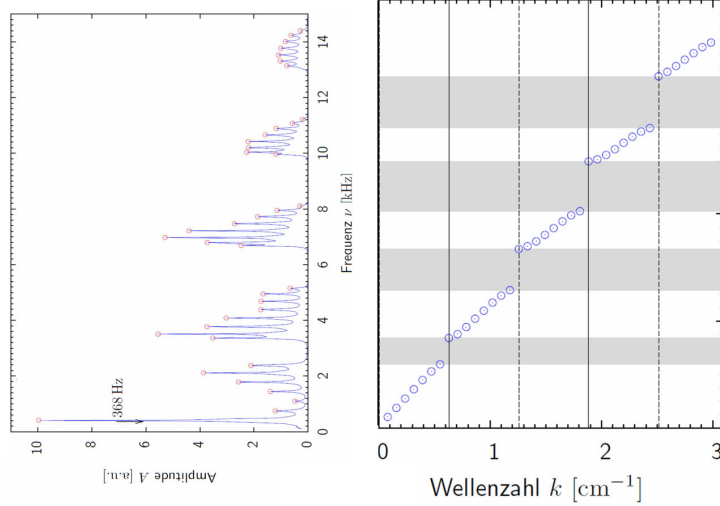


048

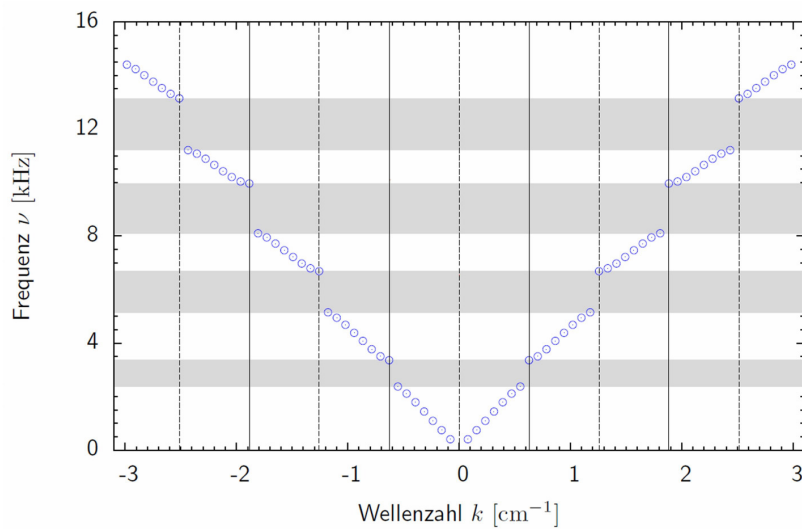
Variation der Kopplungsstärke (Irisdurchmesser)



049

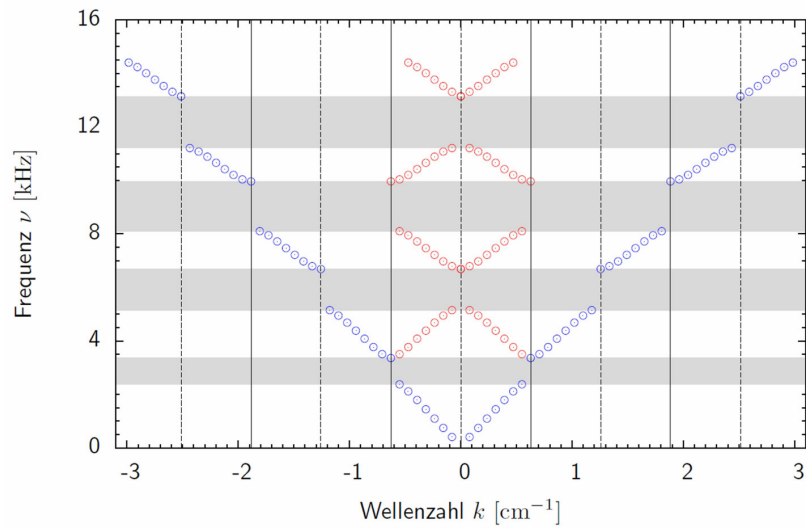


050

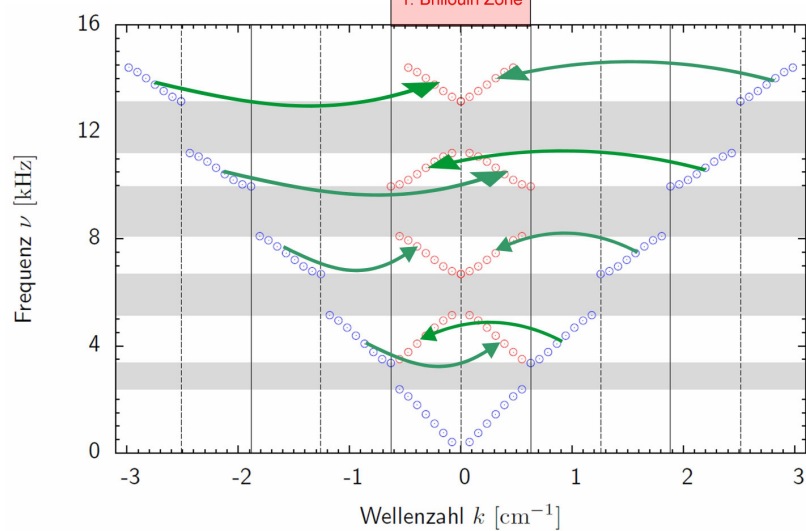


Dispersionsrelation mit Gitterkonstante $a = 5.0 \text{ cm}$ im [erweiterten Zonenschema](#).
Die Ränder der Brillouin-Zonen sind mit durchgezogenen Linien markiert.

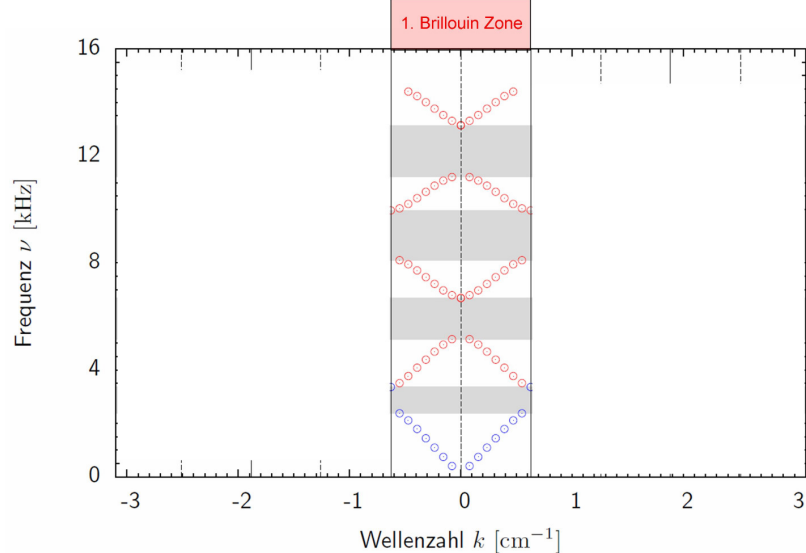
051



052

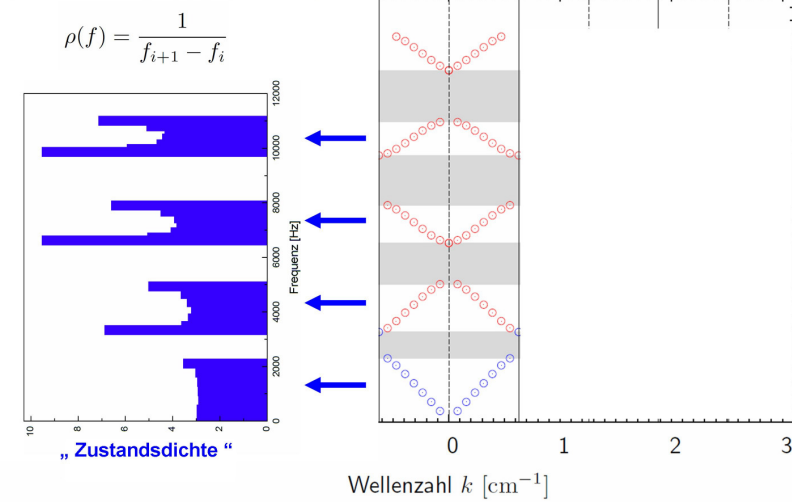


053



054

Reziproker Frequenzabstand:



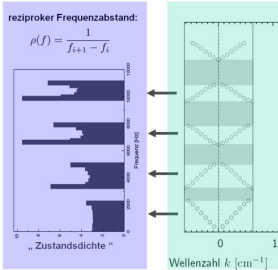
055

mechanisches Analogon zum 1-dim Festkörper ...

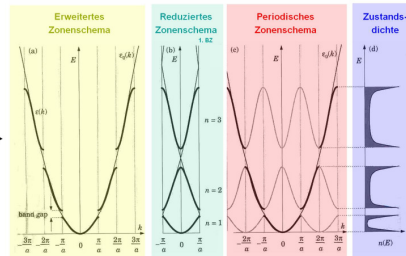


056

Schallwelle im Resonator



Elektron als Materiewelle

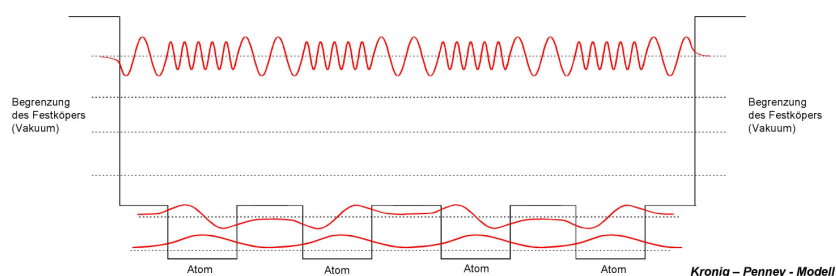


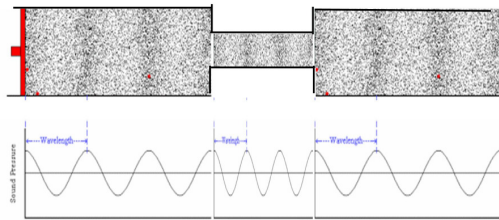
mechanisches Analogon zum 1-dim Festkörper ...



057

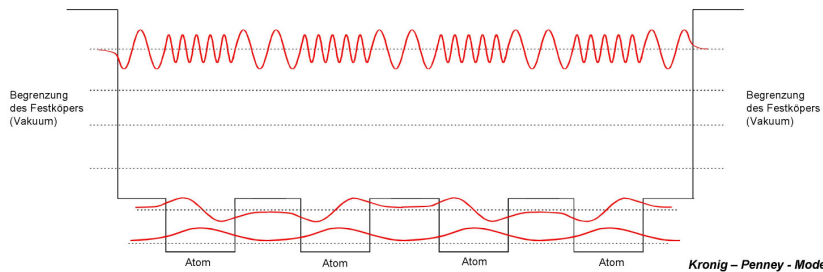
periodische Potentialtöpfe mit beidseitiger Begrenzung (eindimensionaler Festkörper)





058

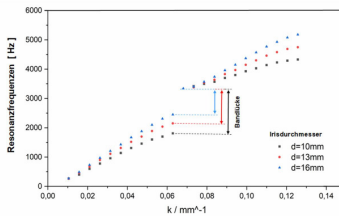
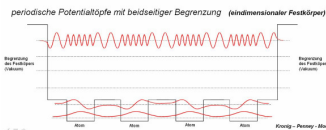
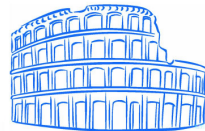
periodische Potentialtöpfe mit beidseitiger Begrenzung (eindimensionaler Festkörper)



Kronig - Penney - Modell

Die „kurze“ Geschichte von der Bandstruktur ...

„Alle Wege führen nach Rom ...“

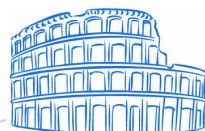


Modell des
quasifreien
Elektrons

059

Die „kurze“ Geschichte von der Bandstruktur ...

„Alle Wege führen nach Rom ...“

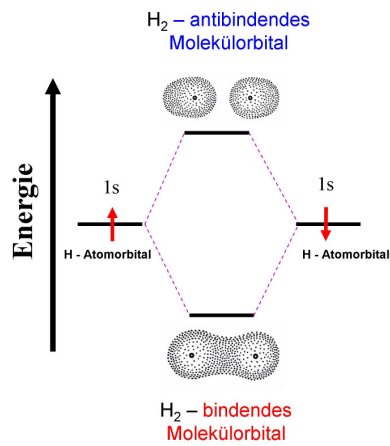


Methode der
starken
Kopplung

(Tight-Binding-Methode)

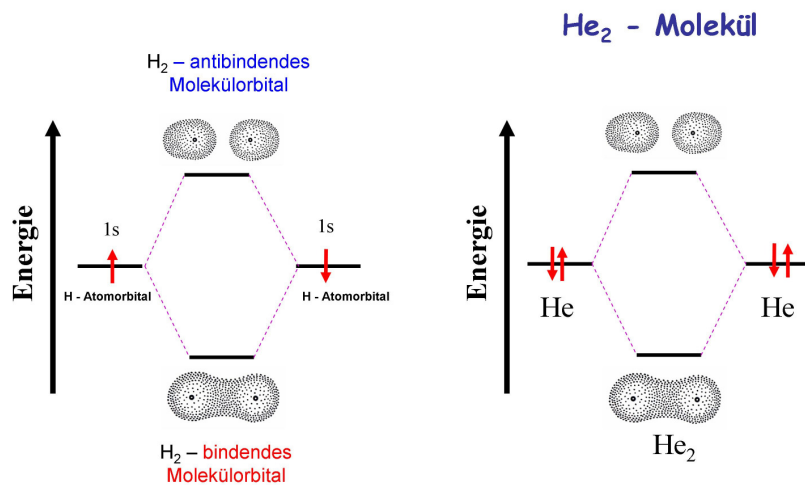
060

Molekülorbitalschema:



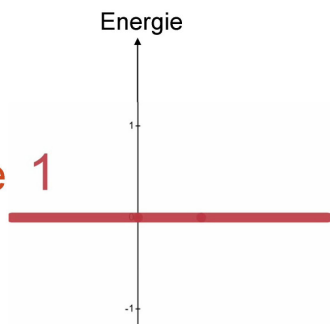
061

Molekülorbitalschema:



062

Atome 1



Reziproker Frequenzabstand

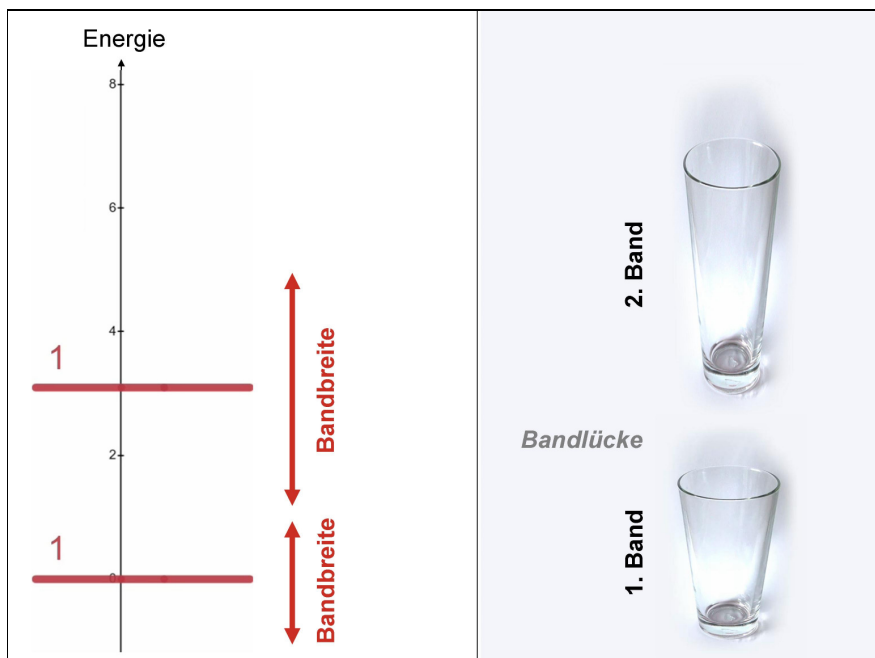
$$\rho(f) = \frac{1}{f_{i+1} - f_i}$$

Zustandsdichte

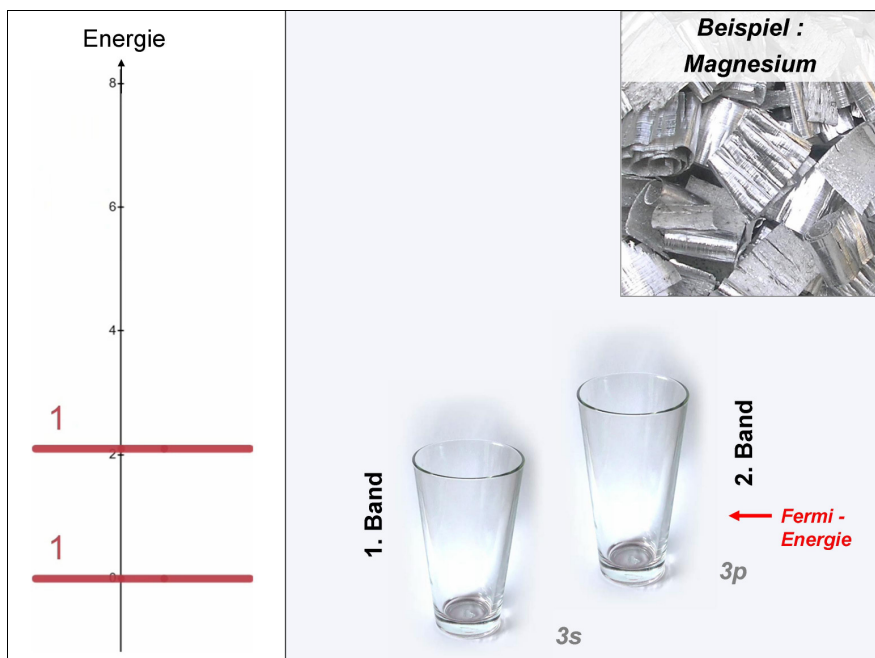


$$E_k = E_0 + \frac{E_B}{2} \cdot \cos\left(\frac{k \cdot \pi}{N+1}\right)$$

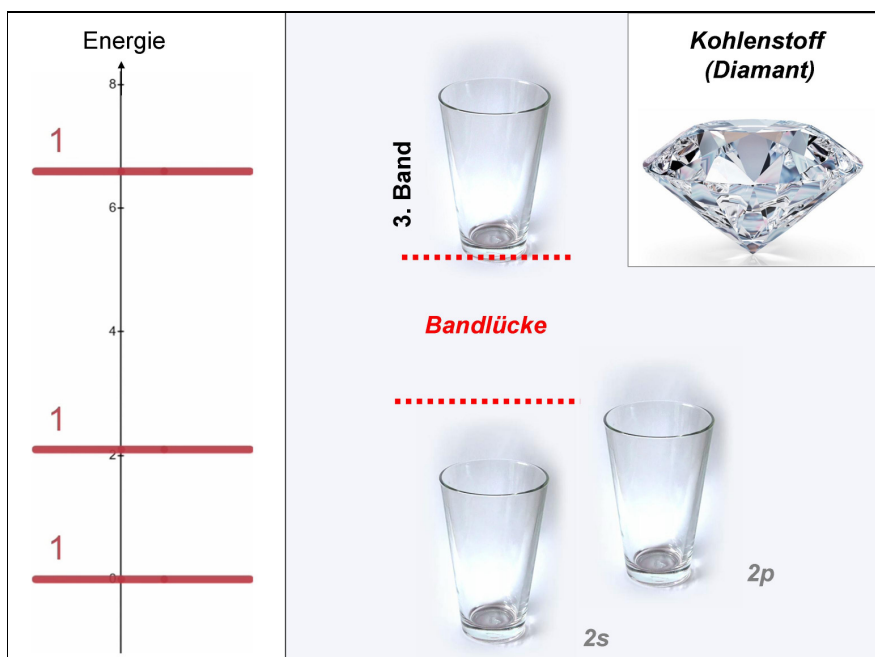
063



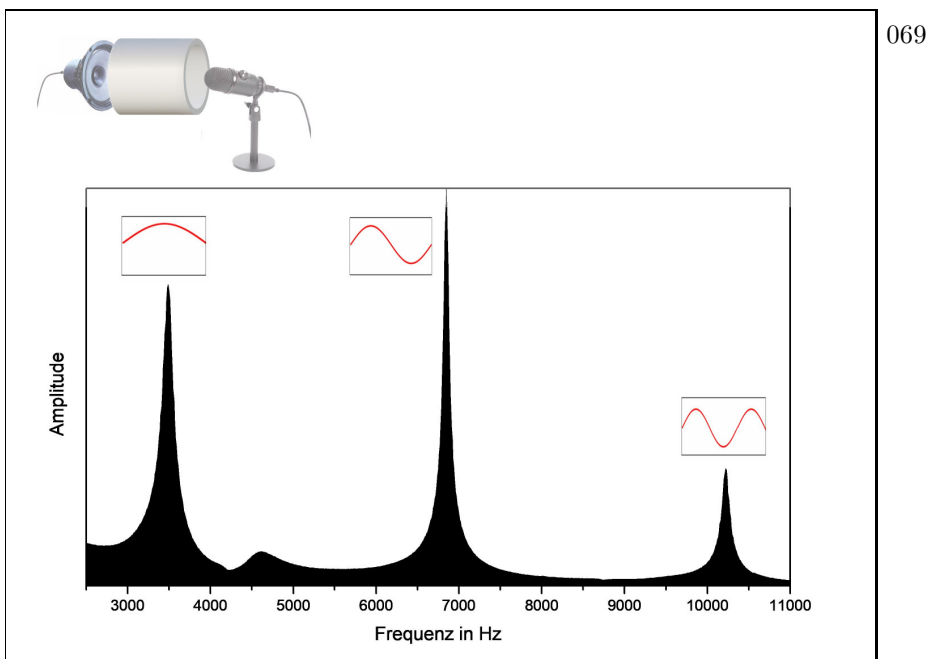
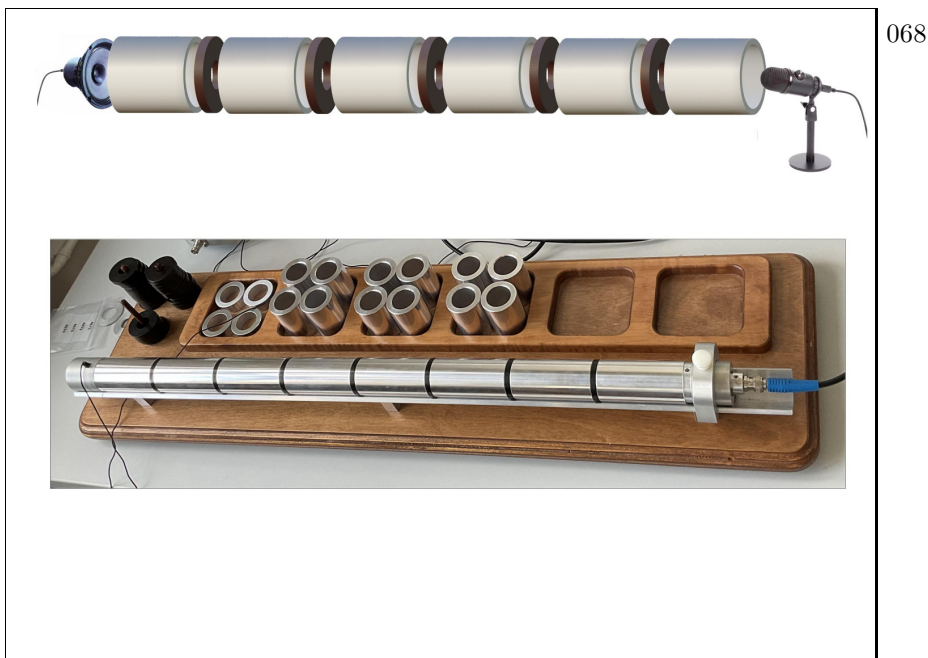
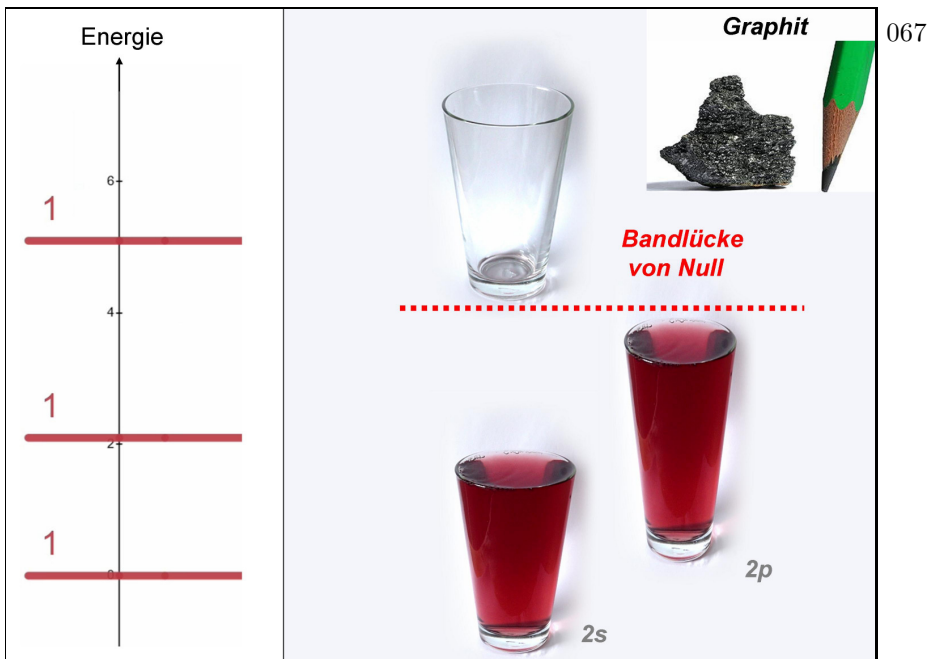
064

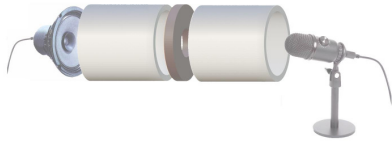


065

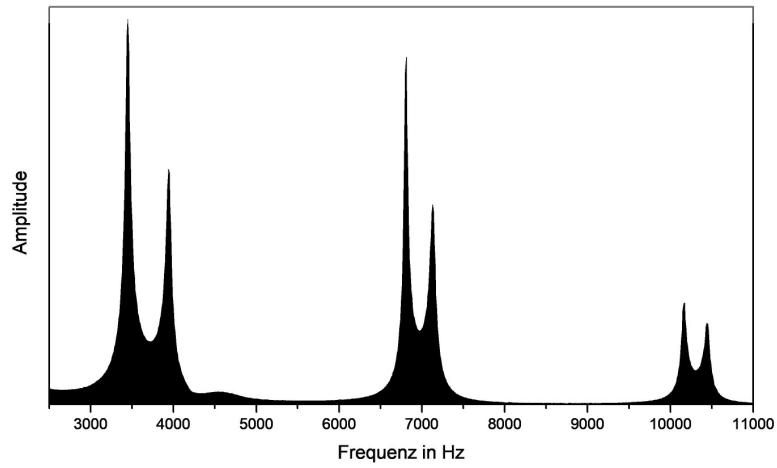


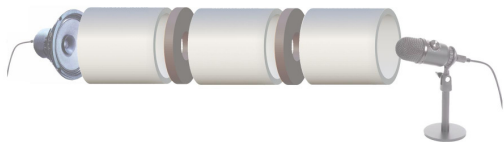
066



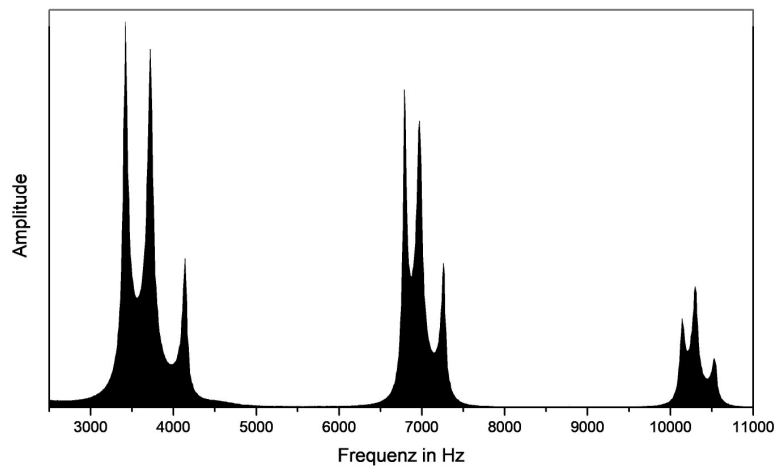


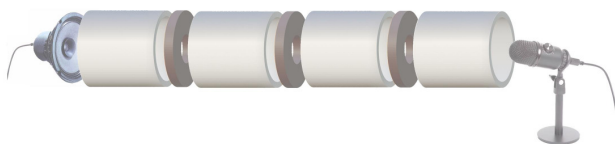
070



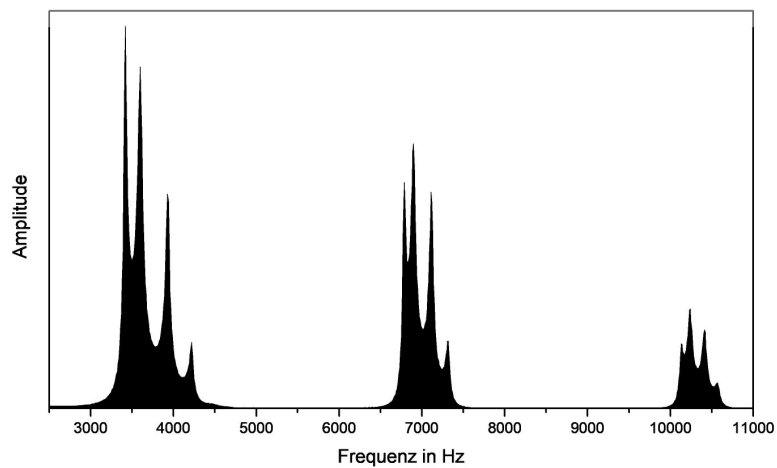


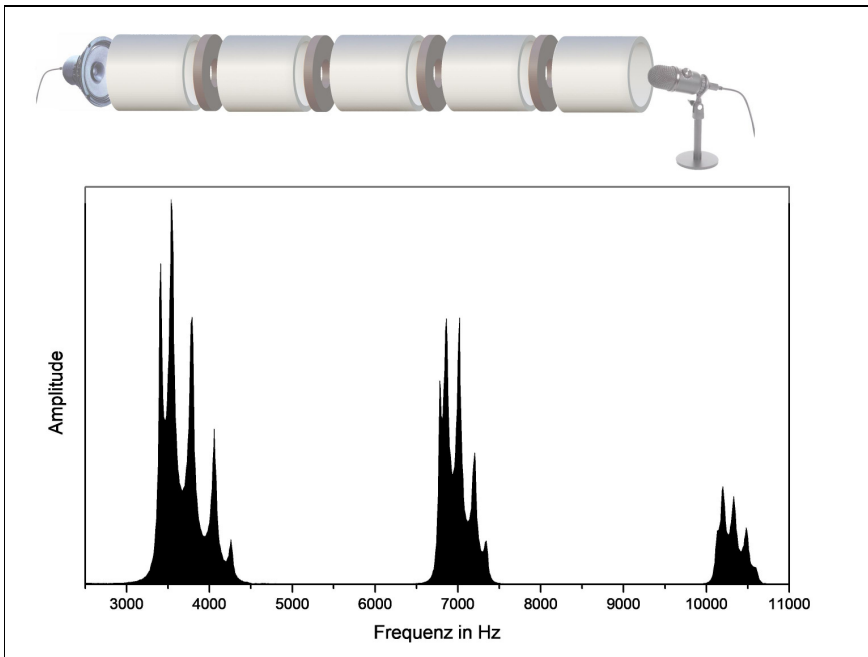
071



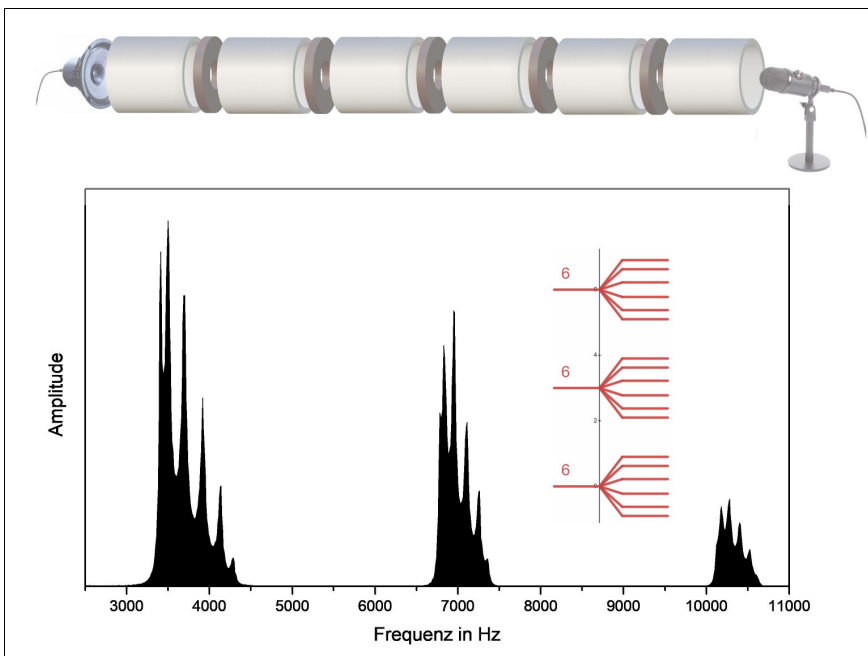


072

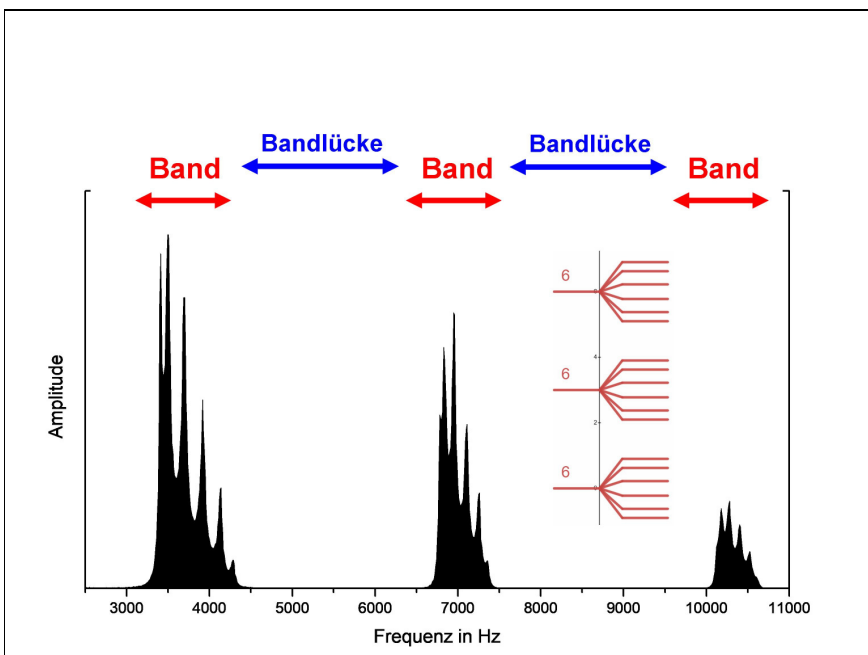




073



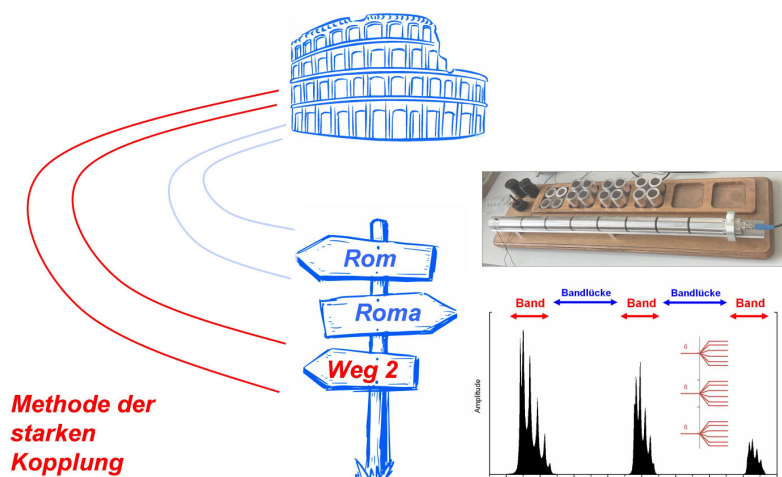
074



075

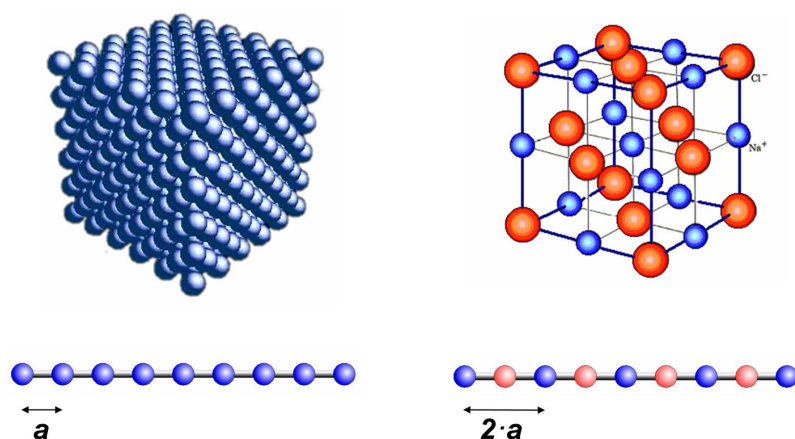
Die „kurze“ Geschichte von der Bandstruktur ...

„Alle Wege führen nach Rom ...“



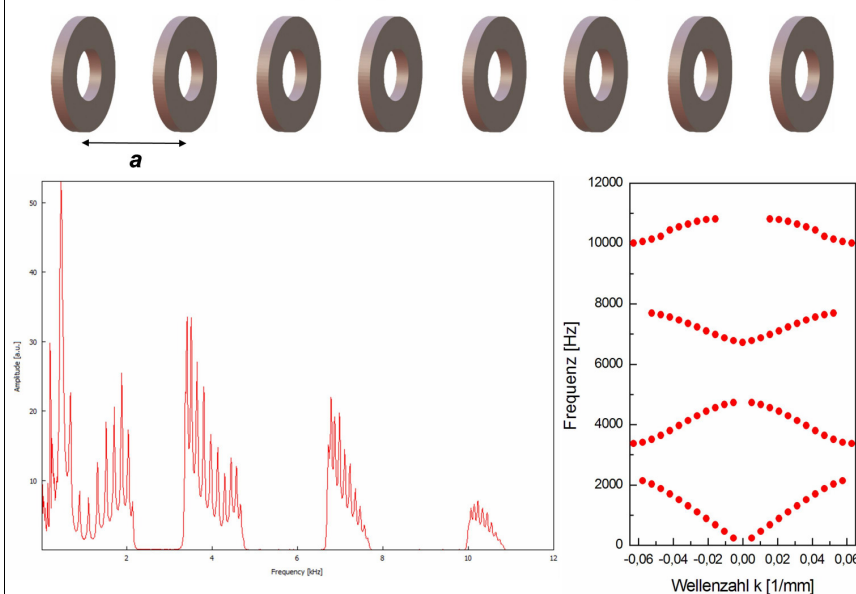
076

Back-Folding ...



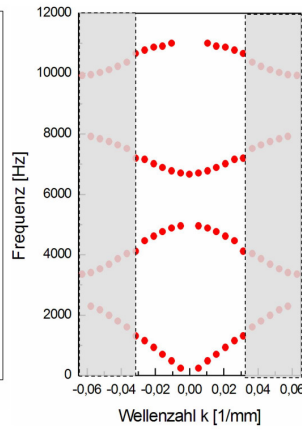
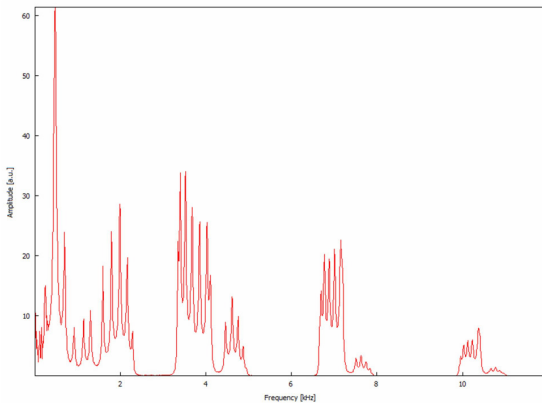
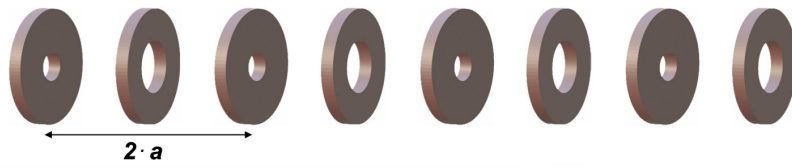
077

Einheitliche Irisdurchmesser



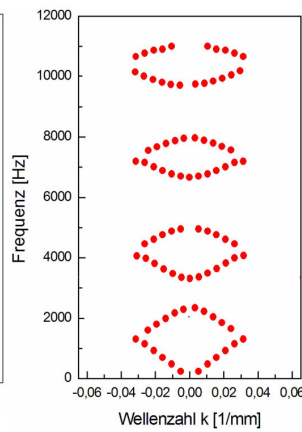
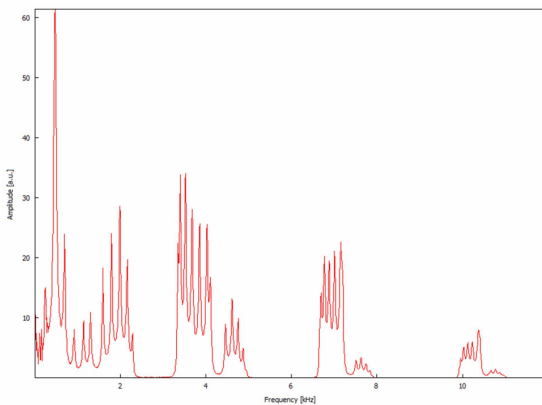
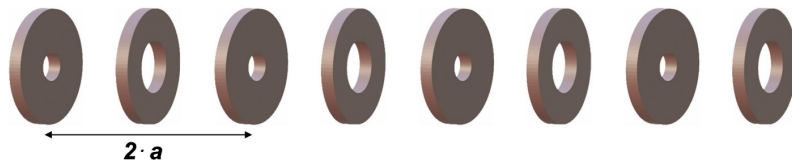
078

Alternierender Irisdurchmesser



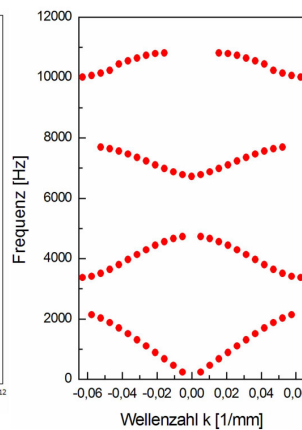
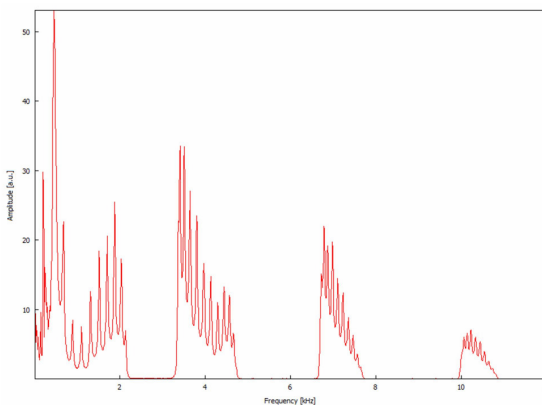
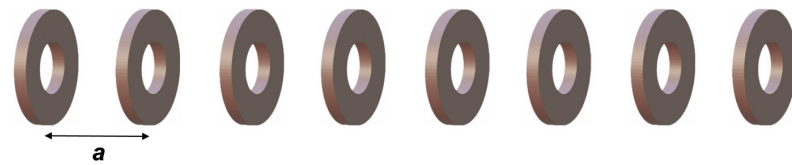
079

Alternierender Irisdurchmesser



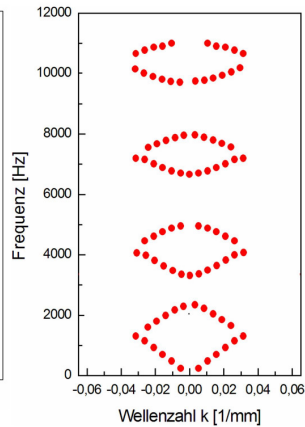
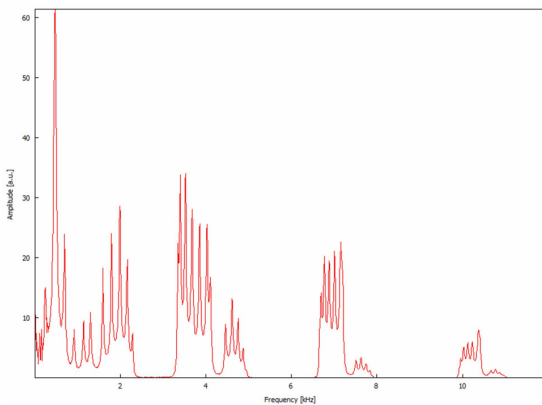
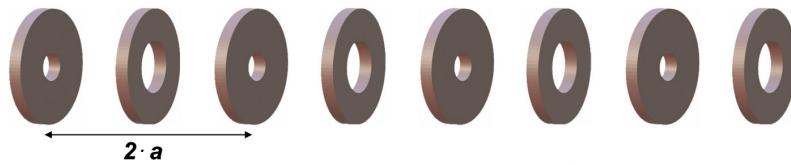
080

Einheitliche Irisdurchmesser



081

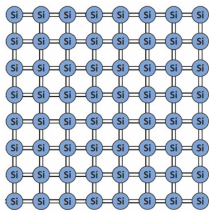
Alternierender Irisdurchmesser



082

Dotierte Halbleiter ...

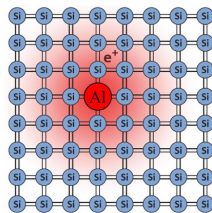
intrinsischer Halbleiter



Elektronenkonfiguration:

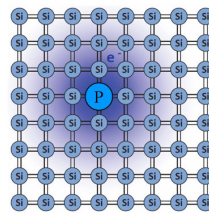
Si: $[\text{Ne}] 3s^2 3p^2$

dotierter Halbleiter



Si: $[\text{Ne}] 3s^2 3p^2$

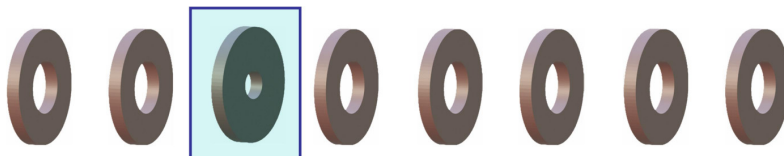
Al: $[\text{Ne}] 3s^2 3p^1$



Si: $[\text{Ne}] 3s^2 3p^2$

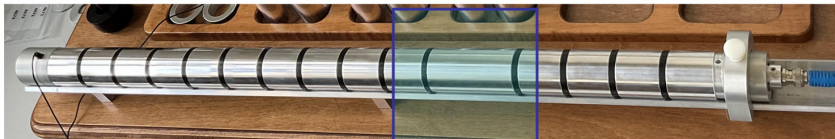
P: $[\text{Ne}] 3s^2 3p^3$

083



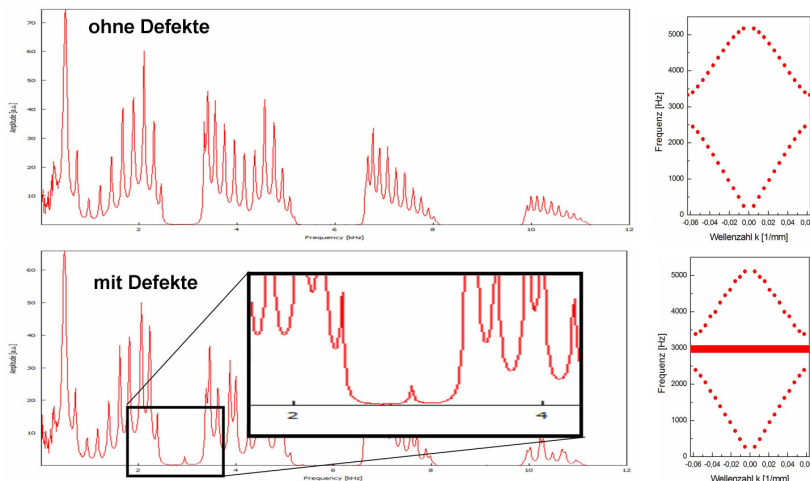
Defekt

084



↑
Defekt

085



086
