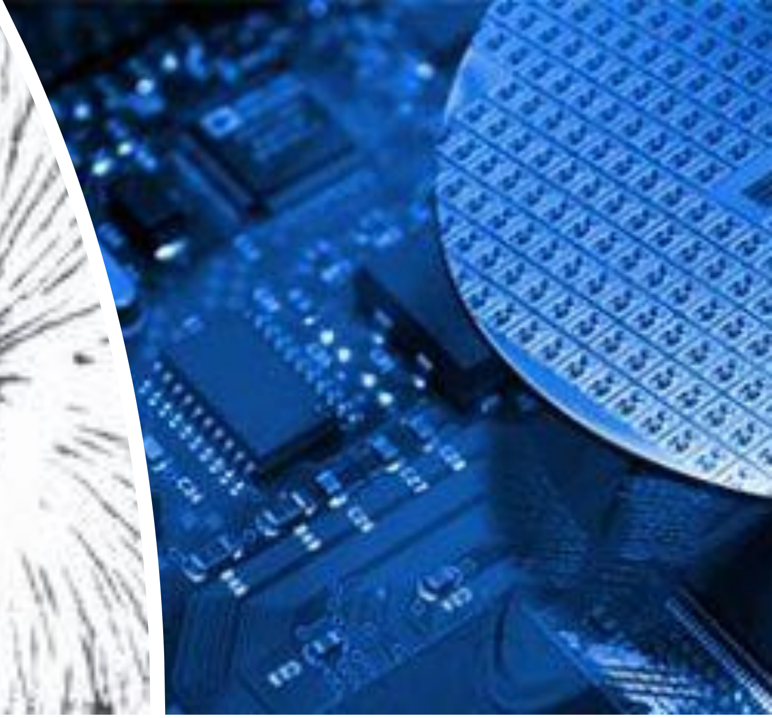
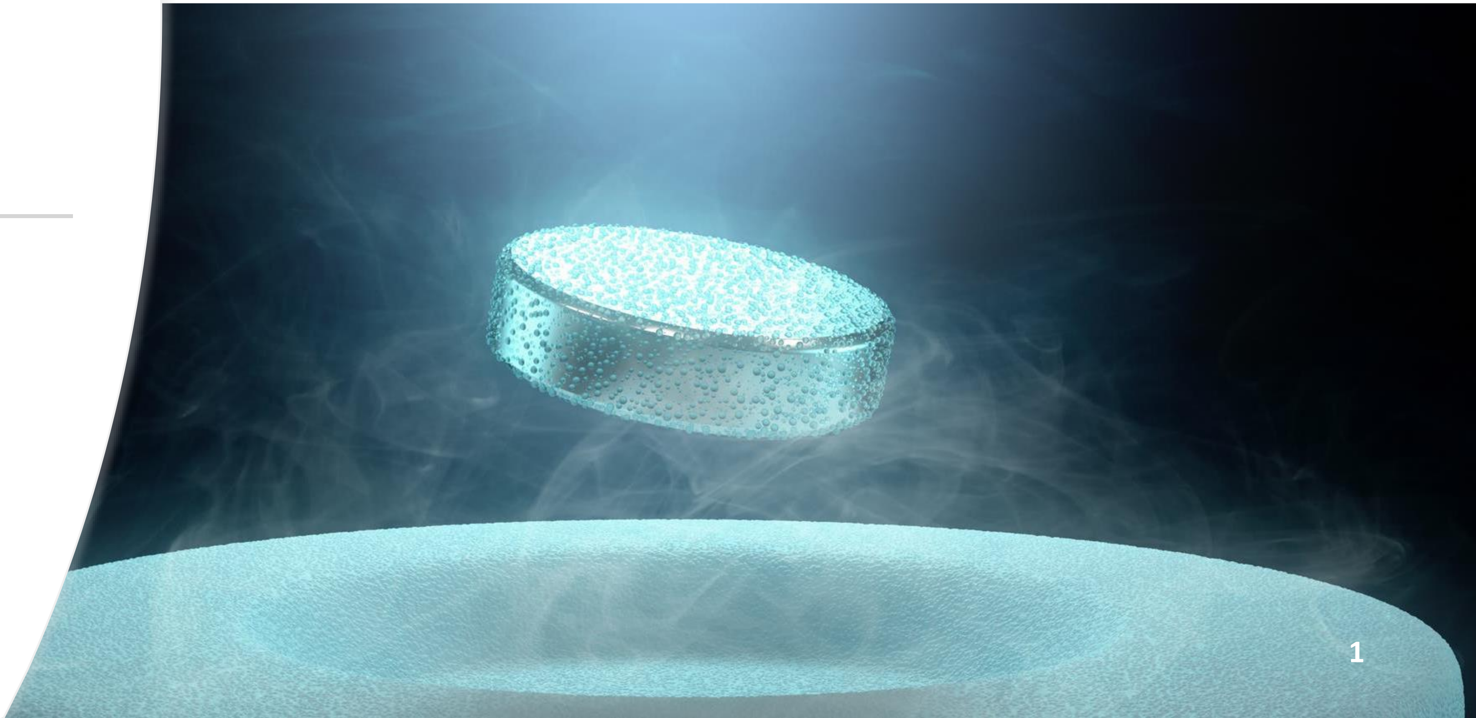
Moderne Experimentalphysik III
Experimentelle Festkörperphysik

M-PHYS-106295, SoSe 2024





TTProf. Dr. Philip Willke, Physikalisches Institut

Letzte Vorlesung

- Anmeldung für die Prüfung!!

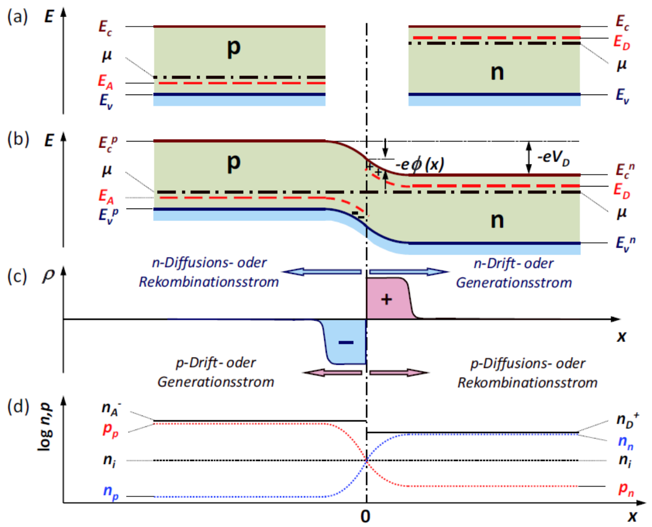
- Ab ca. 12:00 Uhr:

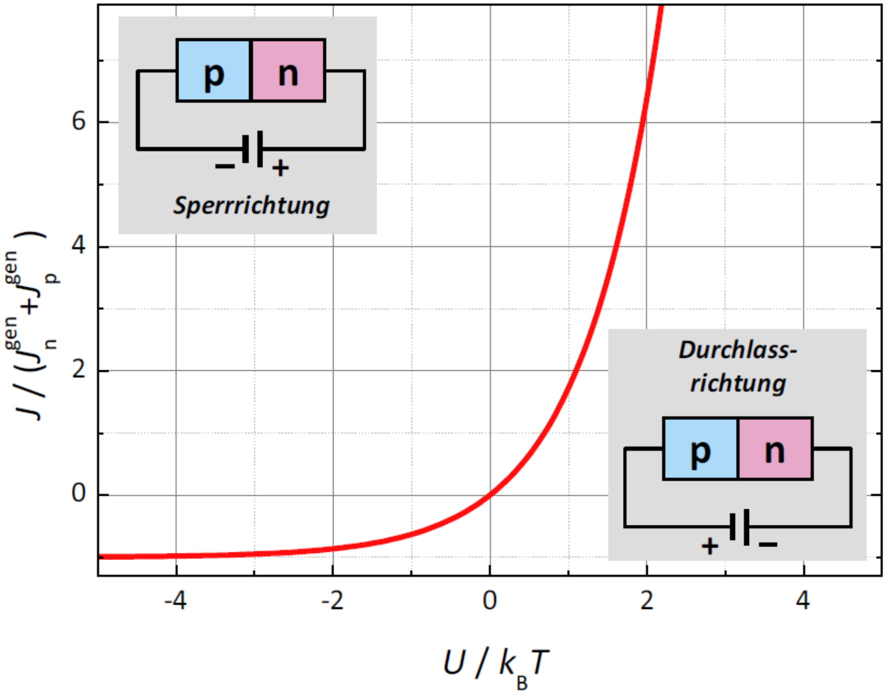
Wiederholung / Labortours

- Halbleiter-Spin Qubits (AG Wernsdorfer)
- SQUID lab (AG Wernsdorfer / AG Pop)
- Rastertunnelmikroskopie-Labor, Spins on Surfaces / Supraleiter (AG Willke)

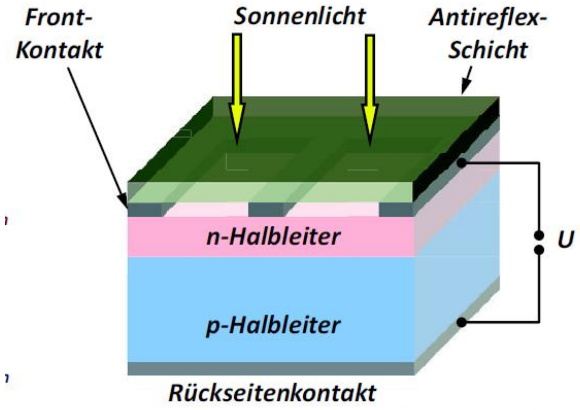
Wiederholung

- pn-Übergang





- Solarzelle



- Halbleiterheterostrukturen

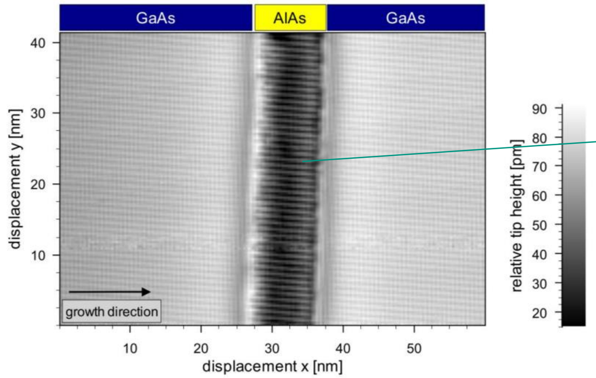
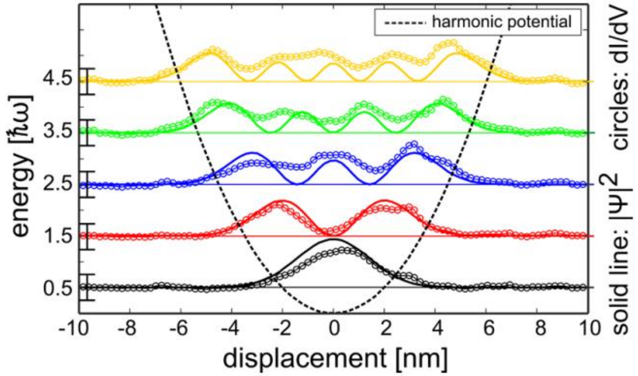


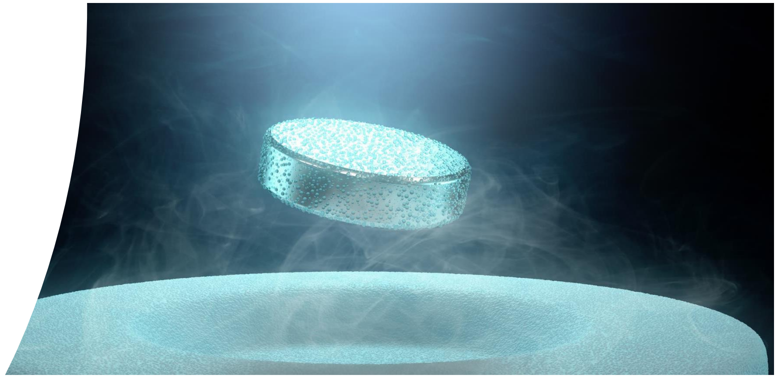
Figure 4.3: Constant current topography of the AlAs layer (marked yellow at the top of the image) embedded in GaAs (marked blue) taken at a setpoint of -2V and 0.1nA.

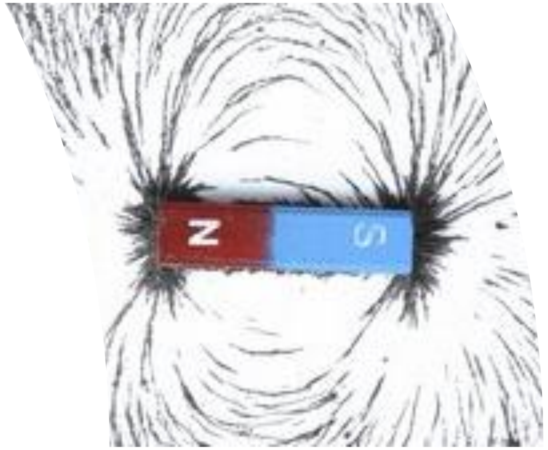


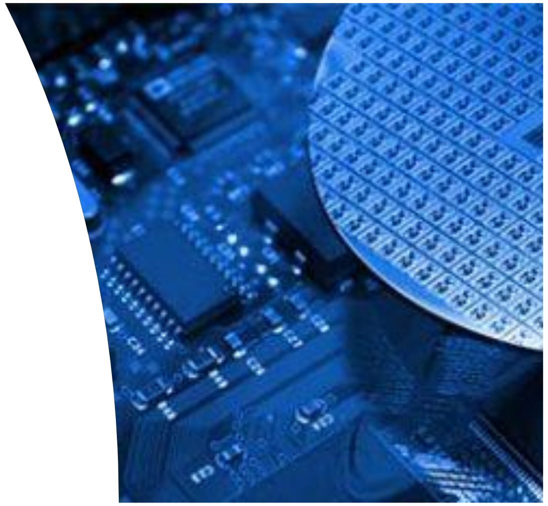
Inhalt

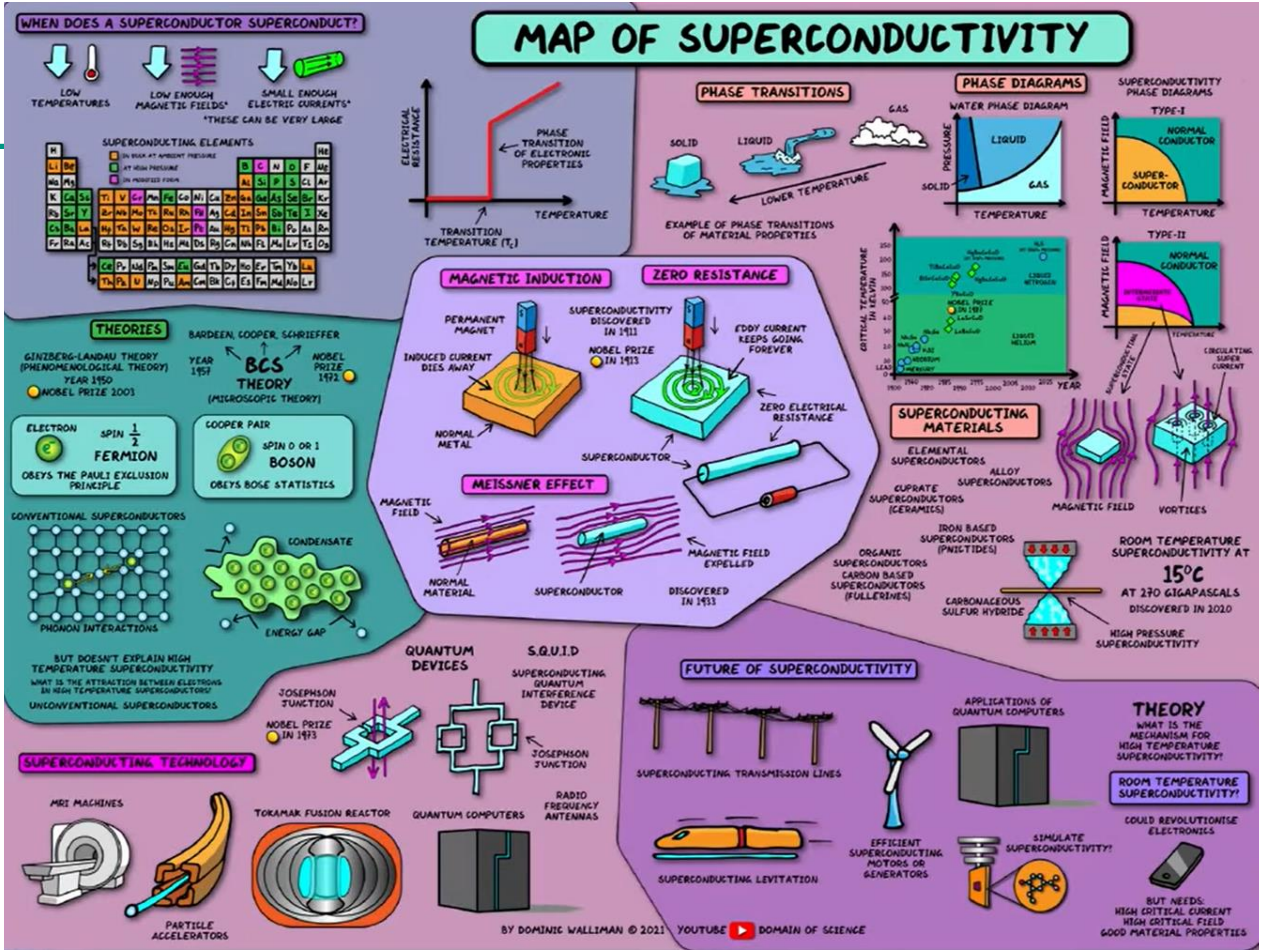
- Dielektrische Eigenschaften von Isolatoren
- Halbleiter
- p-n-Übergang
- Niedrigdimensionale Elektronensysteme
- 1D- und 2D-Elektronengas
- Quanten-Hall Effekt
- Magnetische Eigenschaften
- Magnetismus der Leitungselektronen.
- Atomarer Magnetismus
- Magnetische Wechselwirkungen
- Ferro- und Antiferromagnetismus
- Grundbegriffe der Supraleitung
- London-Gleichungen
- Cooper-Paare
- Supraleiter 1. und 2. Art
- Josephson-Effekte

Wiederholung



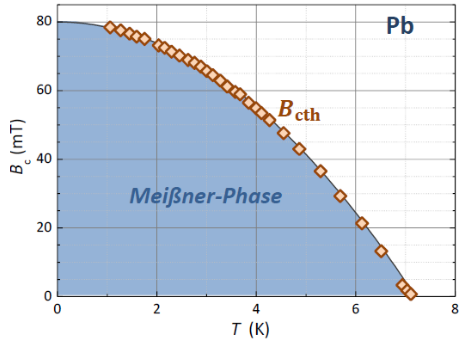


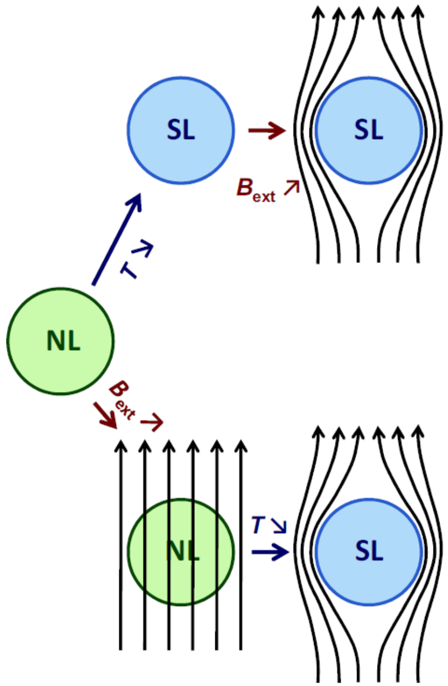


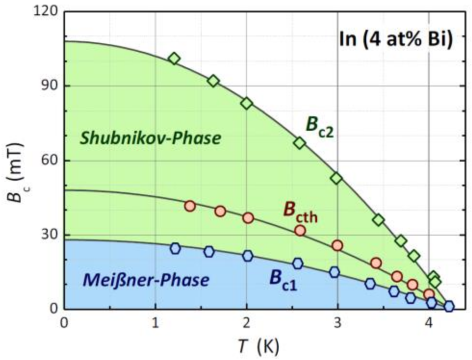

MAP OF SUPERCONDUCTIVITY
WHEN DOES A SUPERCONDUCTOR SUPERCONDUCT?
LOW TEMPERATURES
LOW ENOUGH MAGNETIC FIELDS*
SMALL ENOUGH ELECTRIC CURRENTS*
*THESE CAN BE VERY LARGE
SUPERCONDUCTING ELEMENTS
ELECTRICAL RESISTANCE
PHASE TRANSITION OF ELECTRONIC PROPERTIES
TEMPERATURE
TRANSITION TEMPERATURE (Tc)
PHASE TRANSITIONS
SOLID
LIQUID
GAS
LOWER TEMPERATURE
EXAMPLE OF PHASE TRANSITIONS OF MATERIAL PROPERTIES
PHASE DIAGRAMS
WATER PHASE DIAGRAM
PRESSURE
SUPERCONDUCTIVITY PHASE DIAGRAMS
TYPE-I
MAGNETIC FIELD
NORMAL CONDUCTOR
SUPER-CONDUCTOR
TYPE-II
CRITICAL TEMPERATURE IN KELVIN
YEAR
NOBEL PRIZE IN 1987
LIQUID NITROGEN
LIQUID HELIUM
MERCURY
THEORIES
GINZBERG-LANDAU THEORY (PHENOMENOLOGICAL THEORY)
YEAR 1950
NOBEL PRIZE 2003
BARDEEN, COOPER, SCHRIEFFER
YEAR 1957
BCS THEORY
NOBEL PRIZE 1972
(MICROSCOPIC THEORY)
ELECTRON
SPIN 1/2
FERMION
OBEYS THE PAULI EXCLUSION PRINCIPLE
COOPER PAIR
SPIN 0 OR 1
BOSON
OBEYS BOSE STATISTICS
CONVENTIONAL SUPERCONDUCTORS
CONDENSATE
PHONON INTERACTIONS
ENERGY GAP
BUT DOESN'T EXPLAIN HIGH TEMPERATURE SUPERCONDUCTIVITY
UNCONVENTIONAL SUPERCONDUCTORS
MAGNETIC INDUCTION
PERMANENT MAGNET
INDUCED CURRENT DIES AWAY
NORMAL METAL
ZERO RESISTANCE
SUPERCONDUCTIVITY DISCOVERED IN 1911
NOBEL PRIZE IN 1913
EDDY CURRENT KEEPS GOING FOREVER
ZERO ELECTRICAL RESISTANCE
SUPERCONDUCTOR
MEISSNER EFFECT
MAGNETIC FIELD
NORMAL MATERIAL
SUPERCONDUCTOR
MAGNETIC FIELD EXPELLED
DISCOVERED IN 1933
SUPERCONDUCTING MATERIALS
ELEMENTAL SUPERCONDUCTORS
ALLOY SUPERCONDUCTORS
CUPRATE SUPERCONDUCTORS (CERAMICS)
IRON BASED SUPERCONDUCTORS (PNICTIDES)
ORGANIC SUPERCONDUCTORS
CARBON BASED SUPERCONDUCTORS (FULLERINES)
MAGNETIC FIELD
VORTICES
CIRCULATING SUPER CURRENT
ROOM TEMPERATURE SUPERCONDUCTIVITY AT
15°C
AT 270 GIGAPASCALS
DISCOVERED IN 2020
CARBONACEOUS SULFUR HYDRIDE
HIGH PRESSURE SUPERCONDUCTIVITY
QUANTUM DEVICES
S.Q.U.I.D
SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE
JOSEPHSON JUNCTION
NOBEL PRIZE IN 1973
JOSEPHSON JUNCTION
SUPERCONDUCTING TECHNOLOGY
MRI MACHINES
PARTICLE ACCELERATORS
TOKAMAK FUSION REACTOR
QUANTUM COMPUTERS
RADIO FREQUENCY ANTENNAS
FUTURE OF SUPERCONDUCTIVITY
SUPERCONDUCTING TRANSMISSION LINES
SUPERCONDUCTING LEVITATION
EFFICIENT SUPERCONDUCTING MOTORS OR GENERATORS
APPLICATIONS OF QUANTUM COMPUTERS
SIMULATE SUPERCONDUCTIVITY!
THEORY
WHAT IS THE MECHANISM FOR HIGH TEMPERATURE SUPERCONDUCTIVITY?
ROOM TEMPERATURE SUPERCONDUCTIVITY!
COULD REVOLUTIONISE ELECTRONICS
BUT NEEDS:
HIGH CRITICAL CURRENT
HIGH CRITICAL FIELD
GOOD MATERIAL PROPERTIES
BY DOMINIC WALLIMAN © 2021
YOUTUBE DOMAIN OF SCIENCE

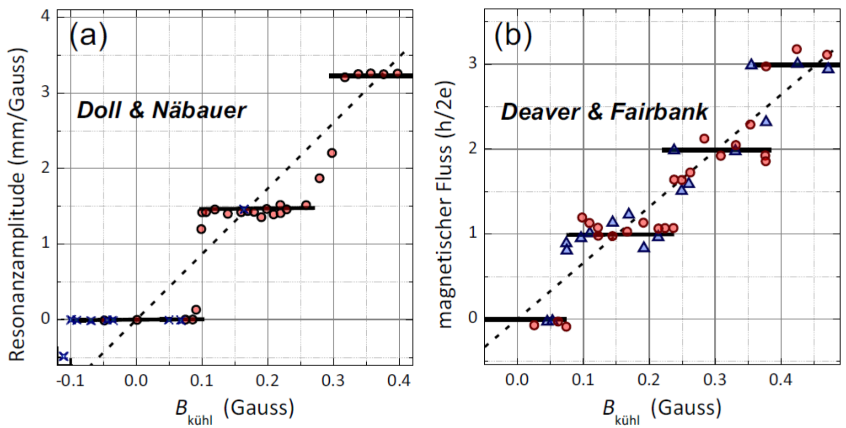
Wiederholung

- Supraleitung führt zu widerstandslosem Stromtransport bei tiefen Temperaturen
- Supraleiter sind perfekte Diamagneten (Meissner-Effekt)
- Typ I und Typ II Supraleiter
- Flussquantisierung









Wiederholung

London Gleichungen

1. London-Gleichung

$$\frac{m_s}{q_s^2 n_s}\frac{\partial \mathbf{J}_s}{\partial t} = \mathbf{E}$$

mit $\Lambda = m_s / n_s q_s^2$ = London-Koeffizient

➔ beschreibt ***widerstandslosen Stromtransport***

2. London-Gleichung

$$\nabla \times (\Lambda \mathbf{J}_s) + \mathbf{b} = \mathbf{0}$$

➔ beschreibt ***perfekte Feldverdrängung***

Wiederholung

- Makroskopische Wellenfunktion

Grundhypothese: es existiert eine ***makroskopische Wellenfunktion***

$$\psi_s(\mathbf{r},t) = \psi_0(\mathbf{r},t)\, e^{i\theta(\mathbf{r},t)}$$

$$|\psi(\mathbf{r},t)|^2 = \psi^*(\mathbf{r},t)\,\psi(\mathbf{r},t) = n_s(\mathbf{r},t)$$

Strom-Phasen-Beziehung

$$\mathbf{J}_s(\mathbf{r},t) = \frac{q_s n_s(\mathbf{r},t)\hbar}{m_s}\left\{\underbrace{\nabla\theta(\mathbf{r},t) - \frac{q_s}{\hbar}\mathbf{A}(\mathbf{r},t)}_{\mathbf{v}}\right\}$$

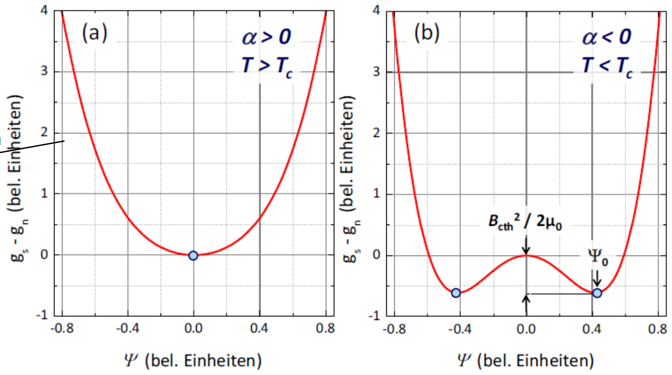
Energie-Phasen-Beziehung

$$\hbar\frac{\partial\theta(\mathbf{r},t)}{\partial t} = -\underbrace{\left\{\frac{1}{2n_s}\Lambda J_s^2(\mathbf{r},t) + q_s\phi_{\mathrm{el}}(\mathbf{r},t) + \mu(\mathbf{r},t)\right\}}_{\text{Gesamtenergie}}$$

Wiederholung

- Ginzburg-Landau Theorie

Landau-Theorie der Phasenübergänge



$$\mathfrak{g}_s = \mathfrak{g}_n + \alpha|\Psi|^2 + \frac{1}{2}\beta|\Psi|^4 + \frac{1}{2\mu_0}\overbrace{(\mathbf{B}_{\rm ext} - \mathbf{b})^2}^{(\mu_0 \mathbf{M})^2} + \frac{1}{2m_s}\left|\left(\frac{\hbar}{\imath}\nabla - q_s\mathbf{A}\right)\Psi\right|^2 + \ldots\,.$$

1. Ginzburg-Landau Gleichung

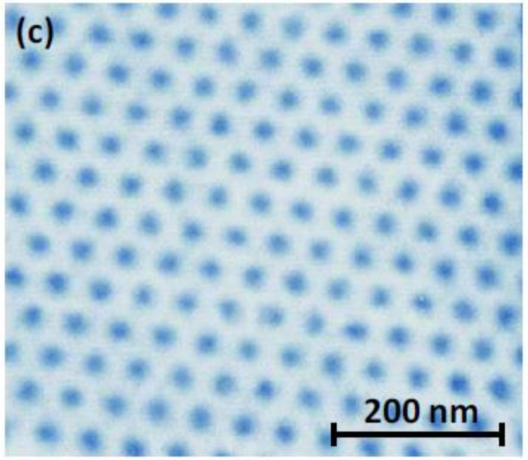
$$0 = \frac{1}{2m_s}\left(\frac{\hbar}{i}\nabla - q_s\mathbf{A}\right)^2\Psi + \alpha\Psi + \beta|\Psi|^2\Psi$$

Ginzburg-Landau Kohärenzlänge

$$\xi_{\rm GL} = \sqrt{-\frac{\hbar^2}{2m_s\alpha}}$$

2. Ginzburg-Landau Gleichung

$$\mathbf{J}_s = \frac{q_s\hbar}{2m_s}\frac{1}{i}(\Psi^\star\nabla\Psi - \Psi\nabla\Psi^\star) - \frac{q_s^2}{m_s}|\Psi|^2\mathbf{A}$$

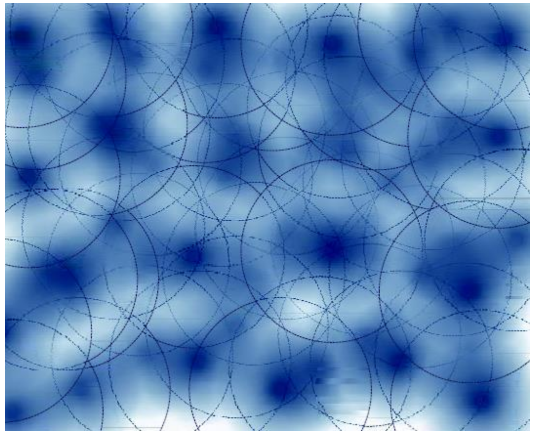


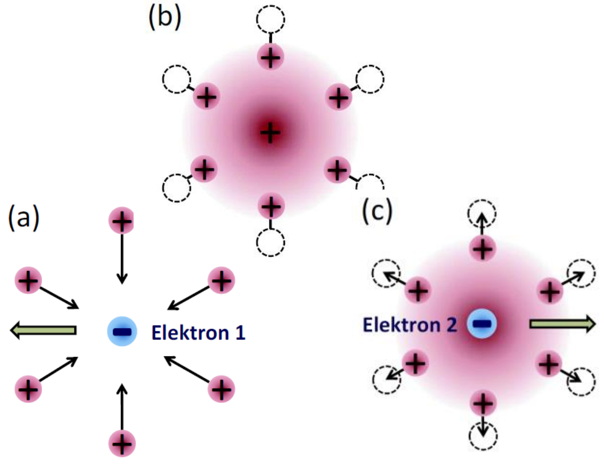
$\kappa \leq \frac{1}{\sqrt{2}}$ Typ-I Supraleiter

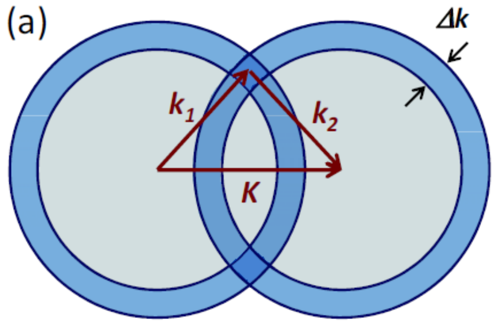
$\kappa \geq \frac{1}{\sqrt{2}}$ Typ-II Supraleiter

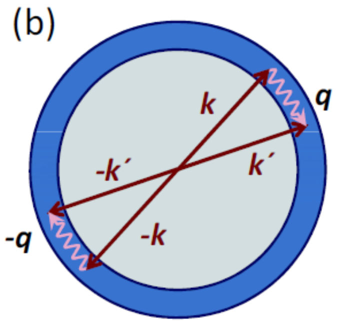
Wiederholung

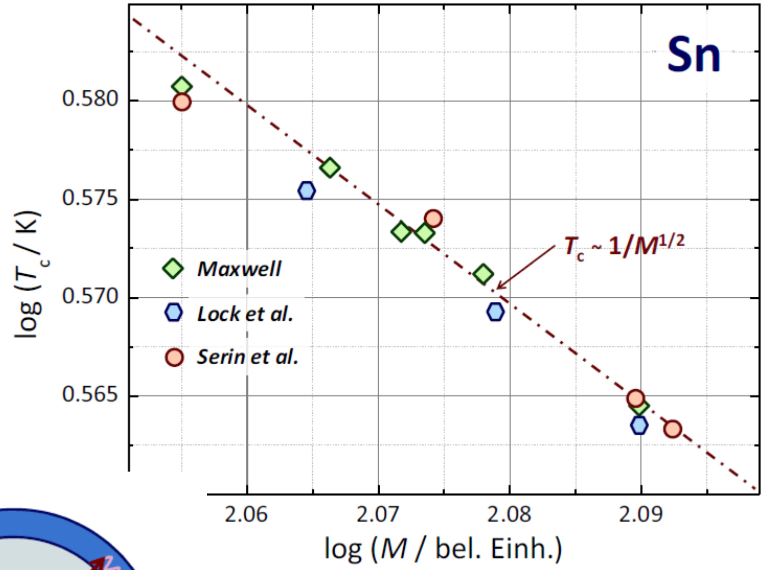
- Mikroskopische Theorie









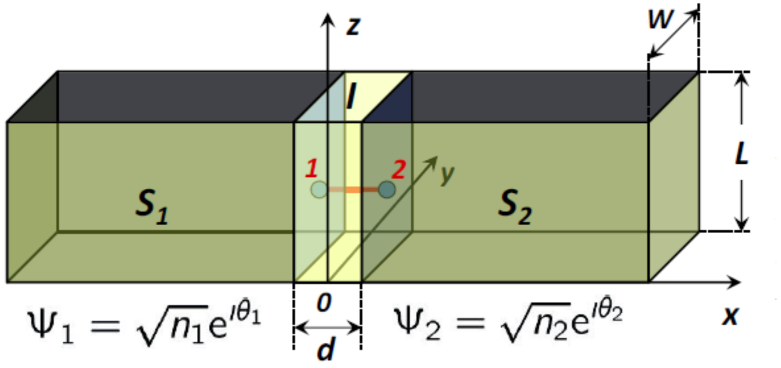


– **Ansatz** für Paarwellenfunktion: ***Produkt von ebenen Wellen***

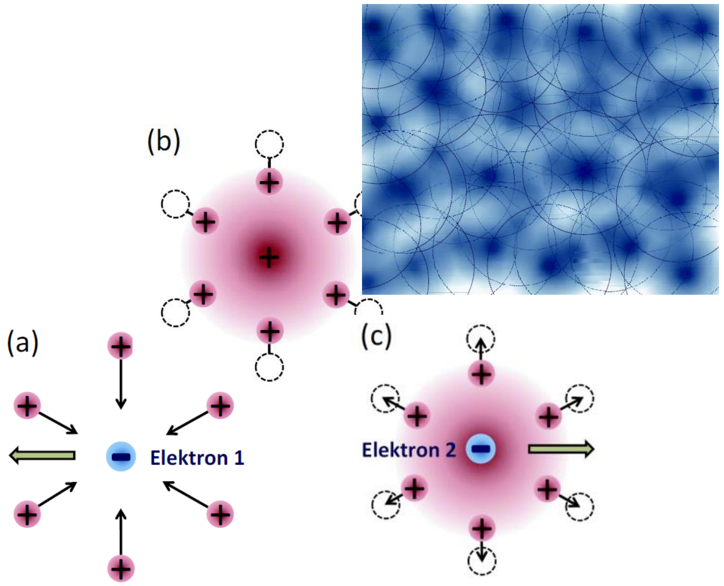
$$\Psi(\mathbf{r}_1, \mathbf{r}_2) = a \exp(i\mathbf{k}_1 \cdot \mathbf{r}_1) \exp(i\mathbf{k}_2 \cdot \mathbf{r}_2) = a \exp(i\mathbf{k} \cdot \mathbf{r})$$

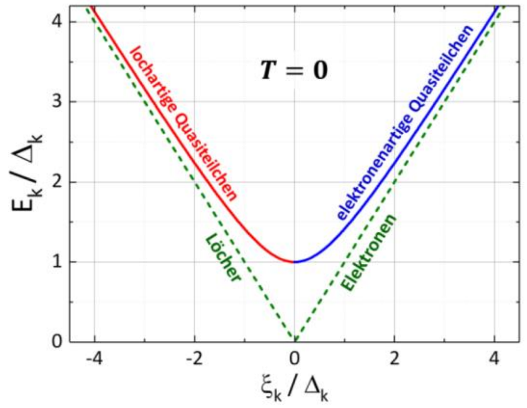
Zusammenfassung

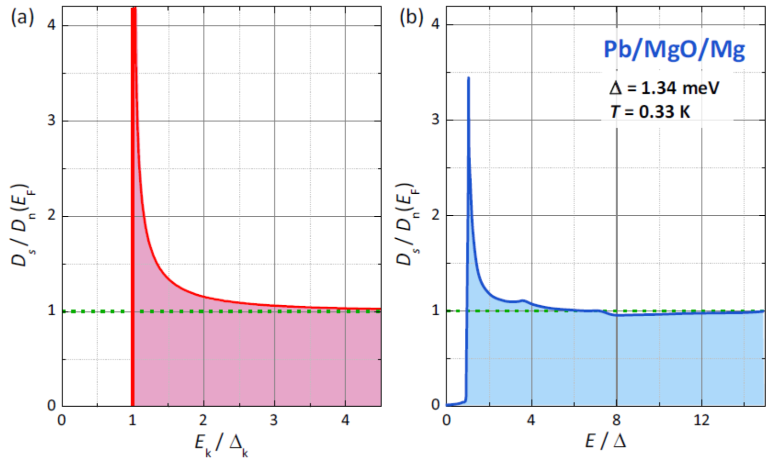
- Mikroskopische Theorie der Supraleitung
- Cooper Paare
- Grundlagen der BCS Theorie
- Energie-Lücke und Quasi-Teilchenanregung
- Josephson Effekt



$$J_s(\varphi) = J_c \sin \varphi$$







Wiederholung

- Atome im magnetischen Feld
- Hund’sche Regeln

– Berechnung der Energieänderungen ΔE_n der atomaren Energien in Störungstheorie 2. Ordnung:

$$\Delta\mathcal{H} = \frac{\mu_B}{\hbar}(L_z + g_s S_z)\, B_z + \frac{e^2 B_z^2}{8m}\sum_i (x_i^2 + y_i^2)$$

$$\Delta E_n = \langle n|\Delta\mathcal{H}|n\rangle + \sum_{n\neq n'} \frac{|\langle n|\Delta\mathcal{H}|n'\rangle|^2}{E_n - E_{n'}}$$

$$\Delta E_n = \frac{\mu_B B_z}{\hbar}\langle n|L_z + g_s S_z|n\rangle$$ *Langevin-Paramagnetismus*

$$+ \frac{\mu_B^2 B_z^2}{\hbar^2}\sum_{n\neq n'}\frac{|\langle n|L_z + g_s S_z|n'\rangle|^2}{E_n - E_{n'}}$$ *Van Vleck-Paramagnetismus*

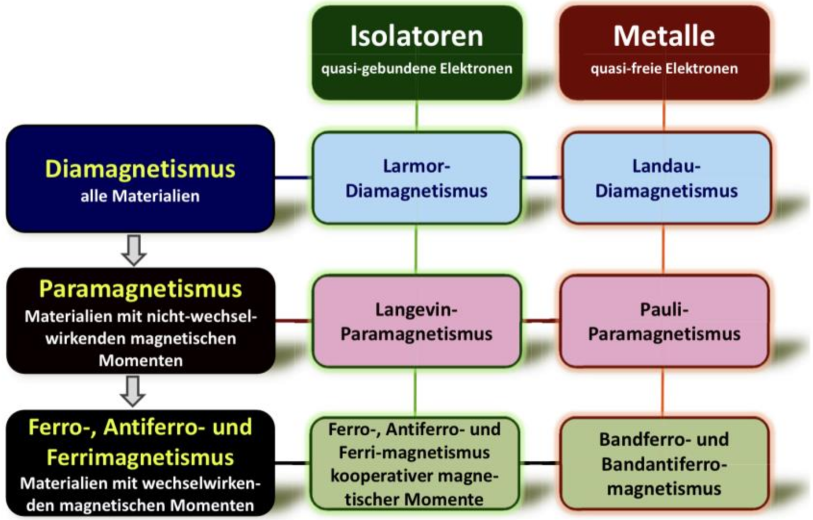
$$+ \frac{e^2 B_z^2}{8m}\langle n|\sum_i (x_i^2 + y_i^2)\,|n\rangle$$ *Larmor-Diamagnetismus*

2. Ordn

I. **Maximierung von S**:
Minimierung der Coulomb-Abstoßung: fol
gleichem Ort sein

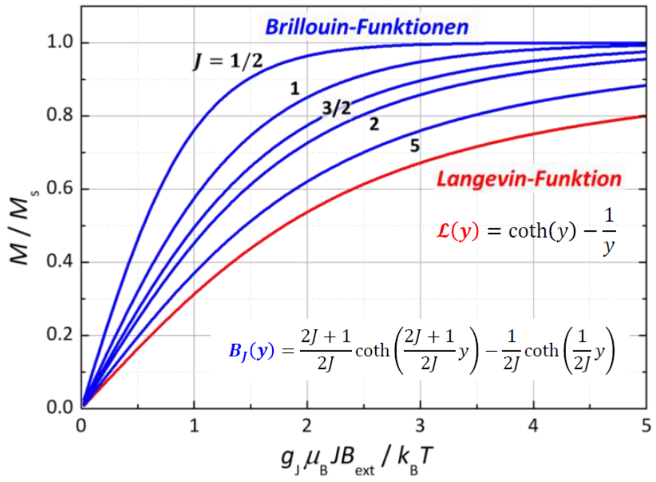
II. **Maximierung von L**:
Reduktion der Coulomb-Energie durch gle
bei halber Füllung liegt $L = 0$ vor (wegen

III. **Kopplung von L und S zu J**:
Minimierung der Spin-Bahn-WW:

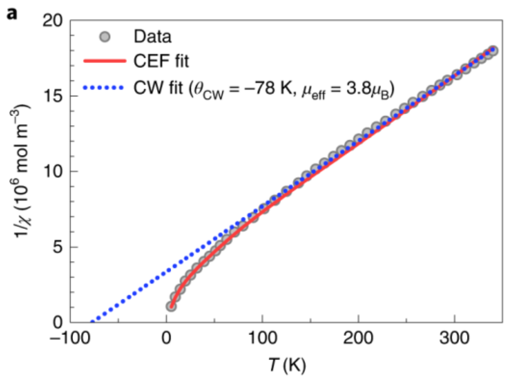


Wiederholung

- Magnetisierungskurven, Brillouin-Funktion



- Curie-Gesetz



Suszibilität

$$\chi = \mu_0 \cdot \left(\frac{\partial M}{\partial B}\right)_{T,V} \overset{\frac{\mu_0 B}{k_B T} \ll 1}{\approx} \overbrace{\frac{\mu_0 \cdot \mu_B^2}{k_B T}}^{C} = \frac{C}{T}$$

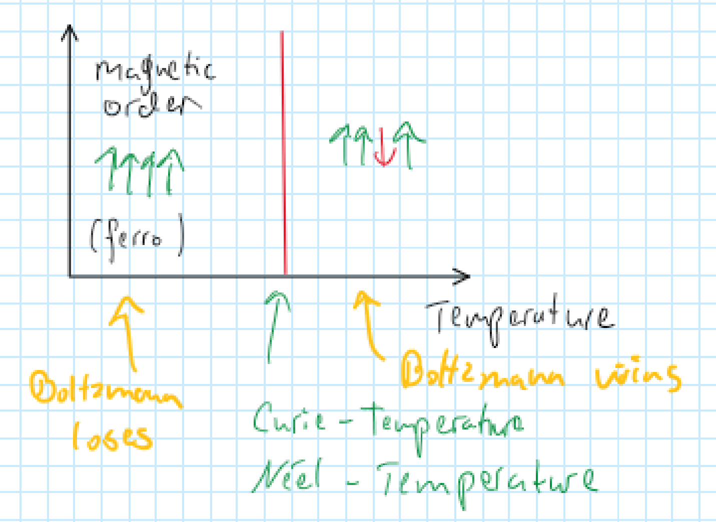
Curie-Gesetz

- Pauli-Paramagnetismus

$$\chi_P = \mu_0 \left(\frac{\partial M}{\partial B_{ext}}\right)_{V,T} = \frac{3n\mu_0\mu_B^2}{2k_B T_F}$$

Wiederholung

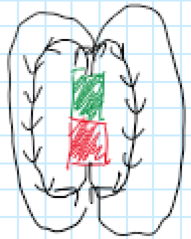
- Magnetische Ordnung



- What is the glue between?

- Magnetische Dipol-Wechselwirkung

3.1. Magnetic Dipole Interaction



$$E_D = \frac{\mu_0}{4\pi}\cdot\frac{1}{r^3}\underbrace{\left[\overset{g_e\mu_B\cdot\vec{S}_1}{\vec{m}_1}\cdot\vec{m}_2 - 3(\vec{m}_1\cdot\hat{r})(\vec{m}_1\cdot\hat{r})\right]}_{\text{MDI is anisotropic}}$$

- Austausch-Wechselwirkung

$$E^s(R) = 2E_{1s} + \frac{V+A}{1+S_{AB}^2}$$

$$E^a(R) = 2E_{1s} + \frac{V-A}{1-S_{AB}^2}$$

Wiederholung

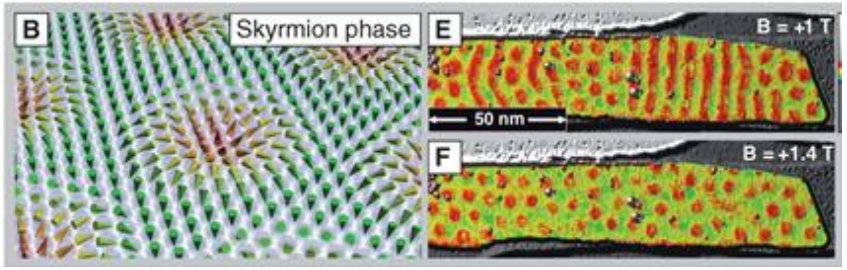
- Landau Diamagnetismus
  - für freies Elektronengas (ohne Beweis)

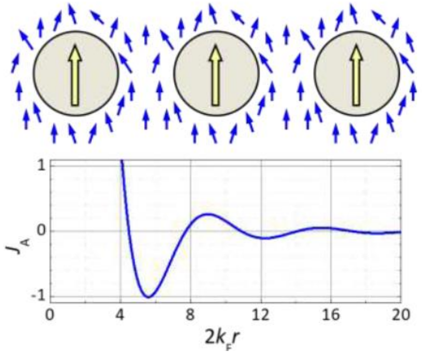
$$\chi_\mathrm{L} = -\frac{1}{3}\chi_\mathrm{P}, \qquad \chi = \chi_L + \chi_P = \frac{n\mu_0\mu_\mathrm{B}^2}{k_\mathrm{B}T_\mathrm{F}}$$

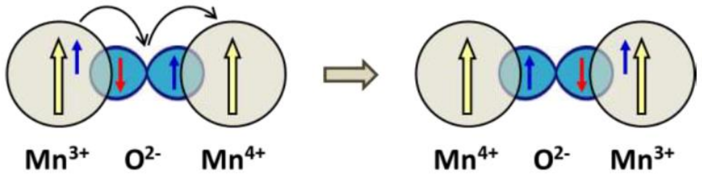
$$\chi_\mathrm{L} = -\frac{1}{3}\chi_\mathrm{P}\left(\frac{m}{m^*}\right)^2$$

- Austauschwechselwirkung
- Verschiedene Arten der Austauschwechselwirkung
- Stoner Kriterium

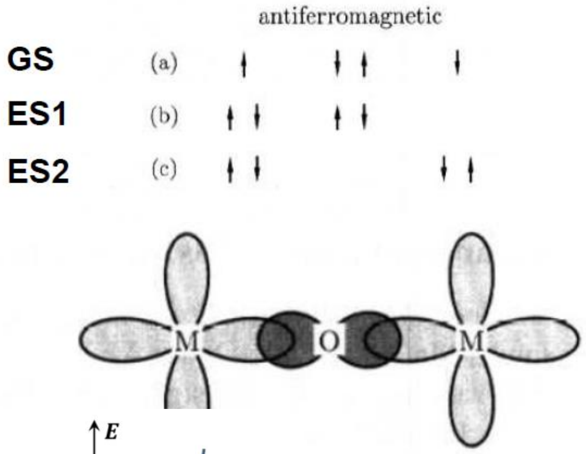
$$\mathcal{H}_\mathrm{DM} = \mathbf{D}_{ij}\cdot(\mathbf{S}_i \times \mathbf{S}_j)$$

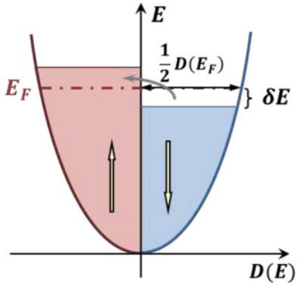






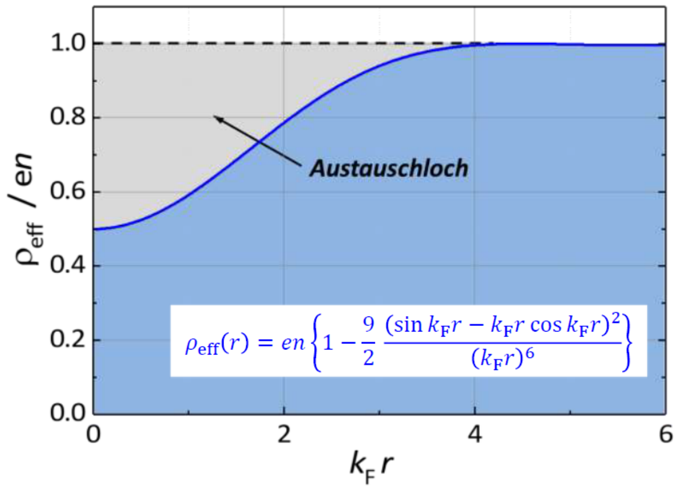
Super Exchange





Wiederholung

- Austauschloch



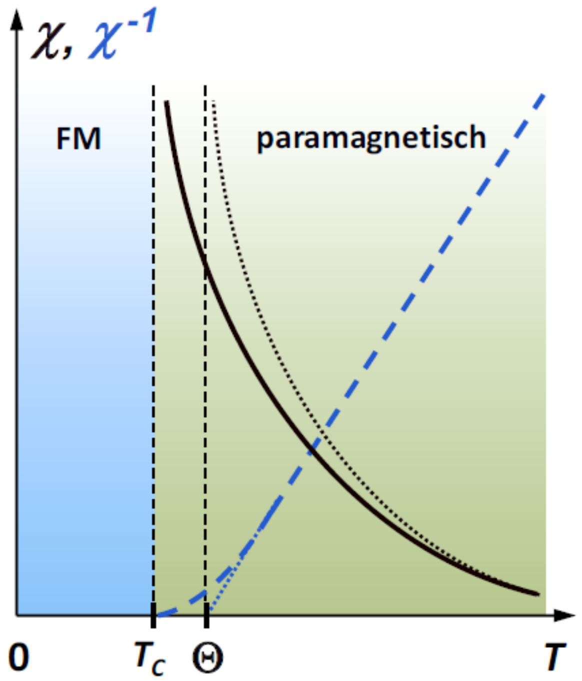
- Curie-Weiss Gesetz

$$\chi = \mu_0 \left(\frac{\partial M}{\partial B_{\text{ext}}}\right)_{T,V} = \frac{C}{T - T_C}$$

$$C = \frac{n\, \mu_0 g_J^2 J(J+1)\mu_B^2}{3k_B}$$

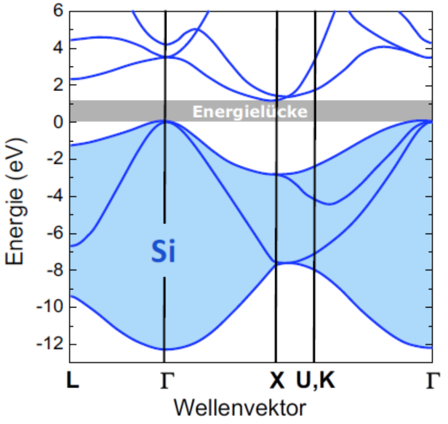
$$T_C = \gamma\, \frac{n\, \mu_0 g_J^2 J(J+1)\mu_B^2}{3k_B} = \gamma\, C$$

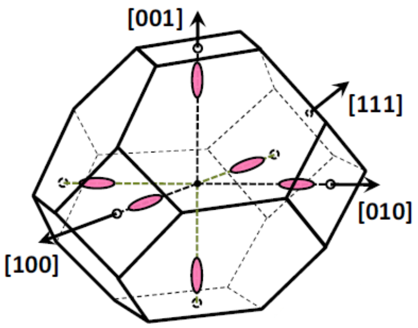
- Ferromagnetismus



Wiederholung

- Eigenschaften von Halbleitern

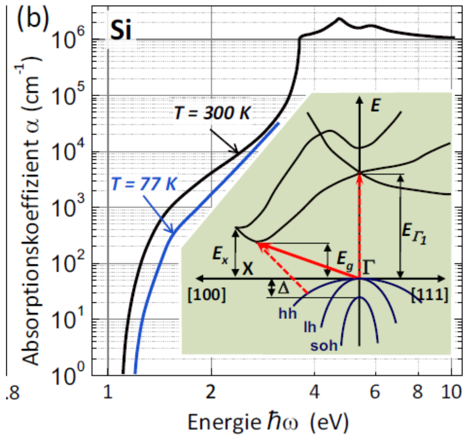




- Leitungsband und Valenzband

$$E(\mathbf{k}) = E_c + \frac{\hbar^2}{2} \sum_{ij} k_i \left(\frac{1}{m^*}\right)_{ij} k_j \qquad \text{(Elektronen)}$$

$$E(\mathbf{k}) = E_v + \frac{\hbar^2}{2} \sum_{ij} k_i \left(\frac{1}{m^*}\right)_{ij} k_j \qquad \text{(Löcher)}\,.$$



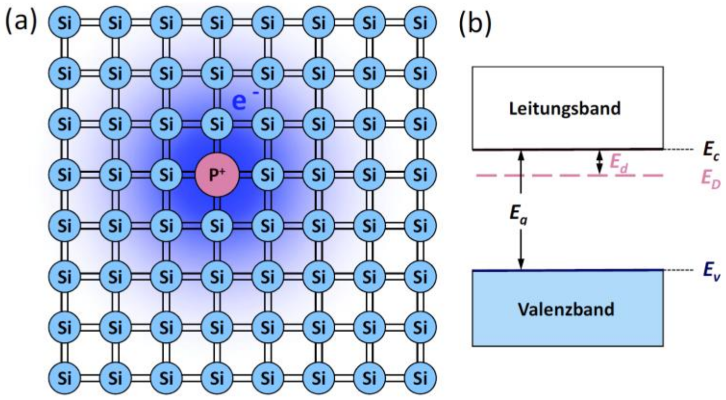
- Ladungsträgerdichte von intrinsischen Halbleitern

$$\mu = E_v + \frac{1}{2}E_g + \frac{3}{4}k_B T \ln \frac{m^*_{h,DOS}}{m^*_{e,DOS}}\,.$$

$$n_i = \sqrt{n_c \cdot p_v} = \sqrt{n_c^{eff} p_v^{eff}}\; e^{-E_g/2k_BT}$$

Wiederholung

- Eigenschaften von dotierten Halbleitern



- Wasserstoffmodel der Dotieratome

$$r_d = \frac{4\pi\epsilon\epsilon_0\hbar^2}{m_e^* e^2}$$

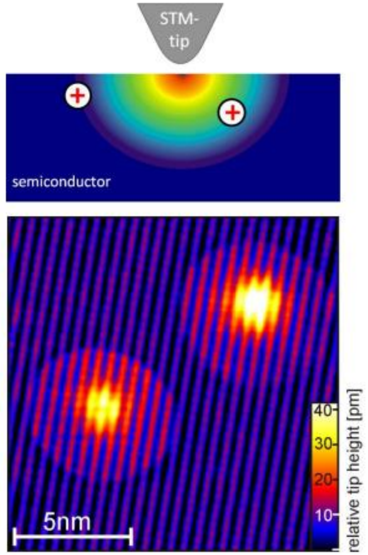
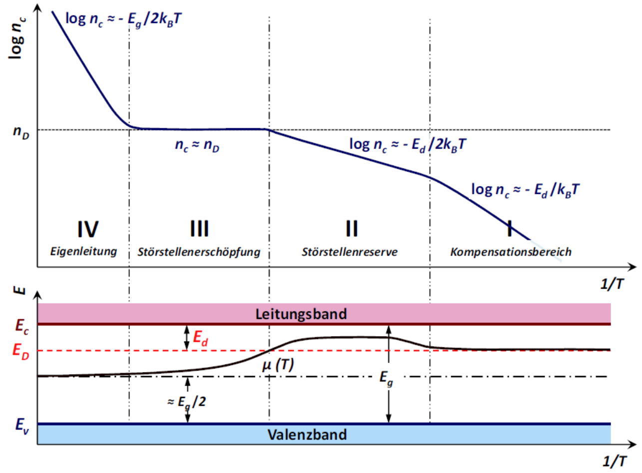


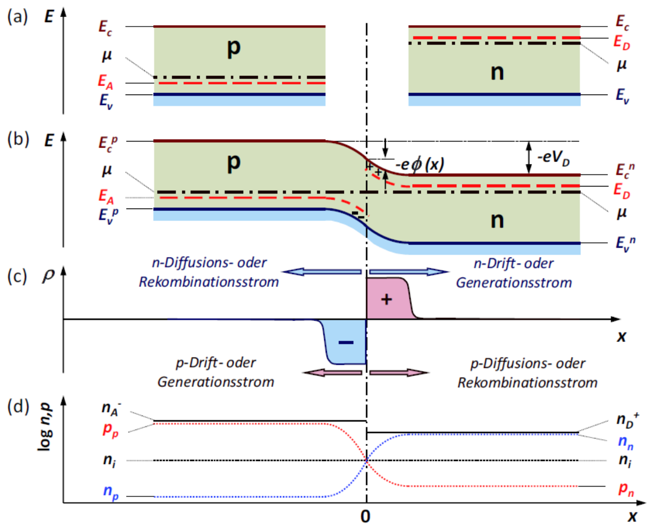
Figure I.2: The upper image sketches two donors in GaAs and the STM tip. The colored area indicates the space charge region. The lower image shows a constant current topography of two donors. The charge switching is visible by the disk-shape of enhanced topographic height.

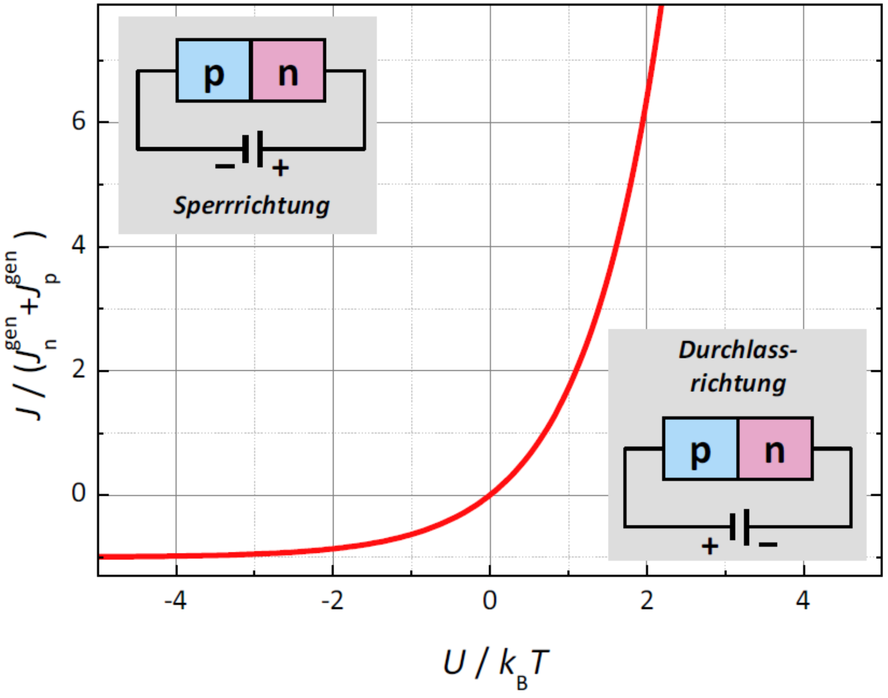
- Temperaturabhängigkeit



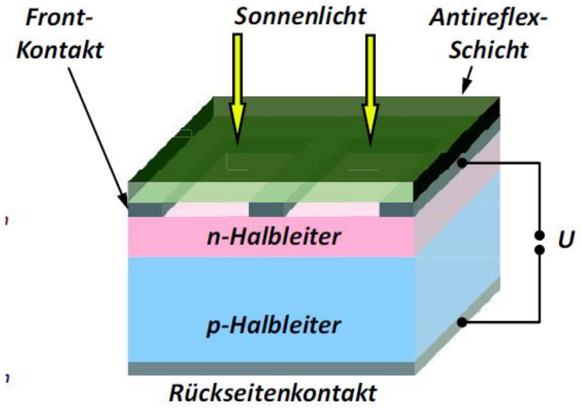
Wiederholung

- pn-Übergang





- Solarzelle



- Halbleiterheterostrukturen

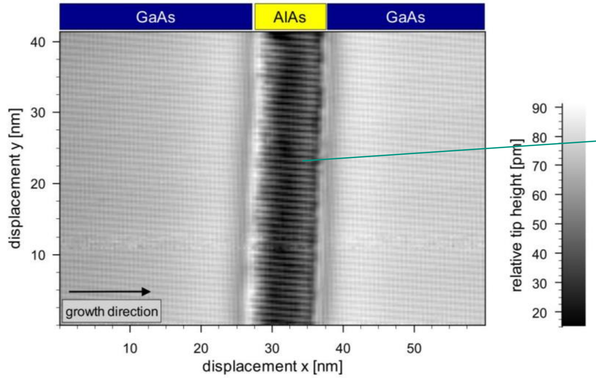
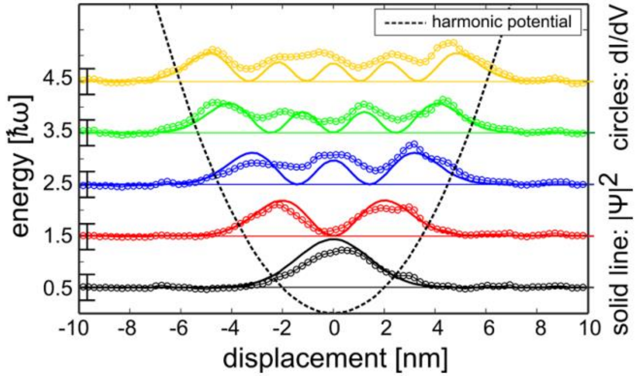


Figure 4.3: Constant current topography of the AlAs layer (marked yellow at the top of the image) embedded in GaAs (marked blue) taken at a setpoint of -2V and 0.1nA.

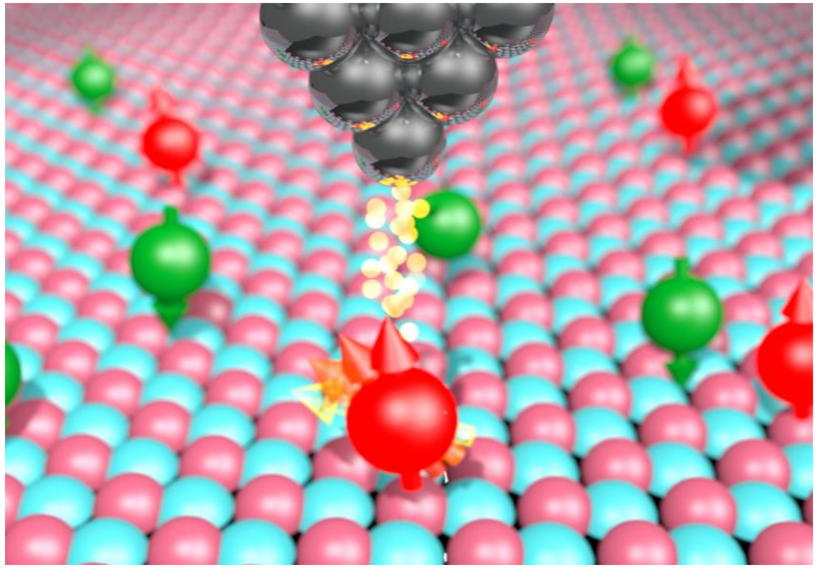


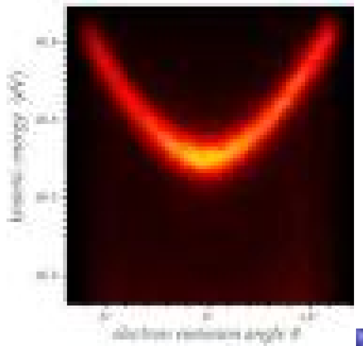
Werbung

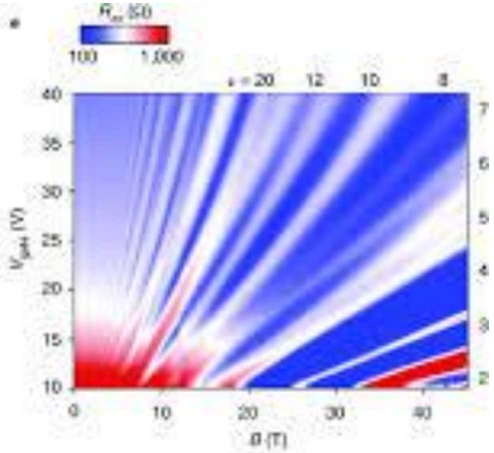
- Vorlesungen im nächsten Semester:

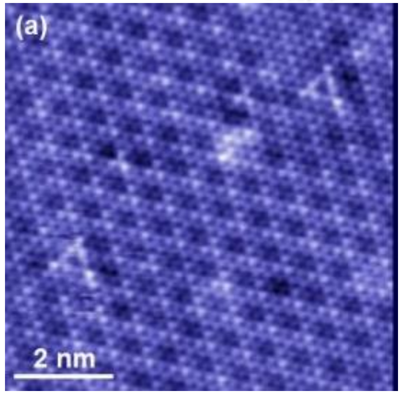
4021011 4 SWS Englisch	**Electronic Properties of Solids I** Präsenz Di 09:45-11:15 30.22 Physik-Hörsaal Nr. 4 (Kl. HS B) vom 22.10. bis 11.02. Fr 09:45-11:15 30.22 Physik-Hörsaal Nr. 4 (Kl. HS B) vom 25.10. bis 14.02.

Vorlesung (V)
Le Tacon, Matthieu
Willke, Philip





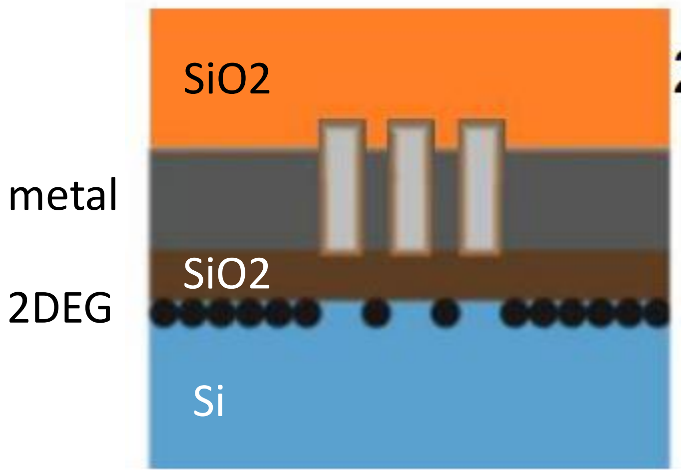




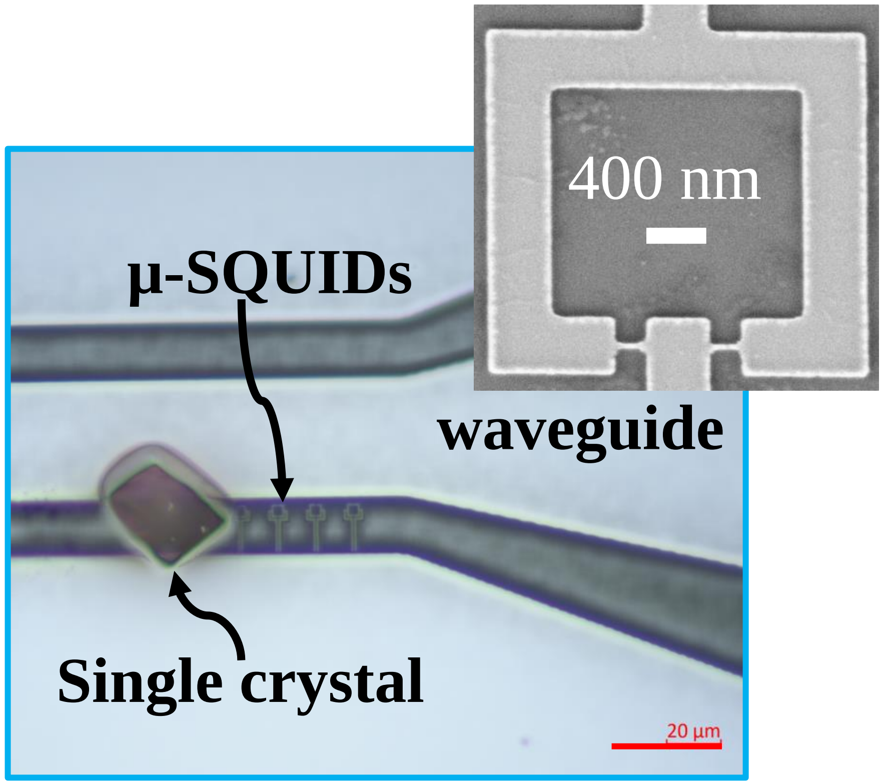
4013134 2 SWS	**Advanced Seminar: Quantum Science at the Atomic Scale: Advanced Scanning Probe Techniques** Präsenz Do 14:00-15:30 30.23 Raum 3/1 vom 24.10. bis 13.02.	**Hauptseminar (HS)** Willke, Philip Wernsdorfer, Wolfgang Wulfhekel, Wulf

Laborführungen

Daniel
(Semiconductor+Spins)



Appu
(SC + Spins)



Wantong / Máté
Spins + STM