

# Experimental Methods

SS 2012

## in Solid State Physics

### 0. Organisation

see slides

### 1. Introduction

General Motivation: Feynman's distinction between theoretical and experimental physics

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Outline

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### 2. Structure of solids

#### 2.1. Diffraction

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## 2.1. Structure of solids - Diffraction

### Brief reminder of basic facts

First, we will briefly repeat the basics of the structure of solids, starting with the most idealized case, namely single crystals. The structure can be given as:

$$\boxed{\text{Crystal structure} = \text{lattice} + \text{basis}}$$

The lattice can be defined as the set of all points which can be described by:

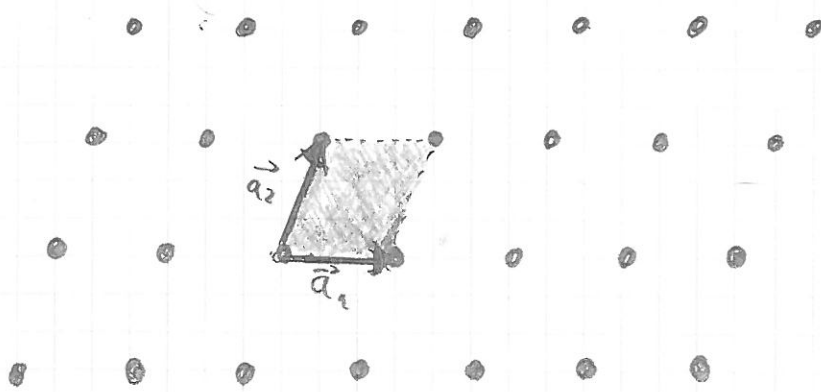
$$\vec{R} = n_1 \vec{a}_1 + n_2 \vec{a}_2 + n_3 \vec{a}_3$$

$\vec{R}$ : lattice vector

$$n_1, n_2, n_3 \in \mathbb{Z}$$

$\vec{a}_1, \vec{a}_2, \vec{a}_3$  primitive translations

Example (in two dimensions)



$\vec{a}_1, \vec{a}_2, \vec{a}_3$  define the unit cell of the crystal

Using symmetry arguments one can show that there are only 14 different lattices, called Bravais-lattices belonging to 7 crystal systems.

## The reciprocal lattice

Diffraction is best treated using the reciprocal lattice. This concept is applicable to every quantity showing a 3D-periodic structure (electron density, local magnetic moment). Remember that in one dimension, a periodic function

$$f(x) \text{ can be described by a } \underline{\text{Fourier series}}$$
$$f(x) = \sum_{n=-\infty}^{\infty} C_n e^{-inx}$$

i.e. a sum of sine and cosine functions ( $e^{ix} = \cos x + i \sin x$ ). In the same way, a function periodic in three dimensions (e.g. the electron density) can be described by a sum of plane waves:

$$f(\vec{r}) = \sum_{\vec{K}} C_{\vec{K}} e^{-i\vec{K}\vec{r}}$$

Here the sum goes over a discrete set of points  $\vec{K}$ . In the 1D-example, each sine or cosine function in the sum has the periodicity of the original function  $f(x)$ . In 3D, we also want the plane wave to show the periodicity of  $f(\vec{r})$ . This condition leads us to a definition of the reciprocal lattice:

The reciprocal lattice is the set of all wave vectors  $\vec{K}$  that describe plane waves with the periodicity of a given Bravais lattice.

Formally, we want

$$e^{i\vec{k}(\vec{r} + \vec{R})} = e^{i\vec{k}\vec{r}}$$

↑  
any lattice vector

$$\Rightarrow \boxed{e^{i\vec{k}\vec{R}} = 1}$$

Remember that such a set of vectors  $\vec{k}$  is again a Bravais lattice and can be constructed from the real space lattice vectors via:

$$\boxed{\vec{b}_i = \frac{2\pi}{\vec{a}_i \cdot (\vec{a}_j \times \vec{a}_k)} (\vec{a}_j \times \vec{a}_k)}$$

In Solid State Physics I we learned, that constructive interference for an incoming plane wave with wave vector  $\vec{k}_0$  and an outgoing wave with  $\vec{k}$  takes place when the Laue condition is fulfilled for all  $\vec{R}$ :

$$\boxed{e^{i(\vec{k} - \vec{k}_0) \cdot \vec{R}} = 1}$$

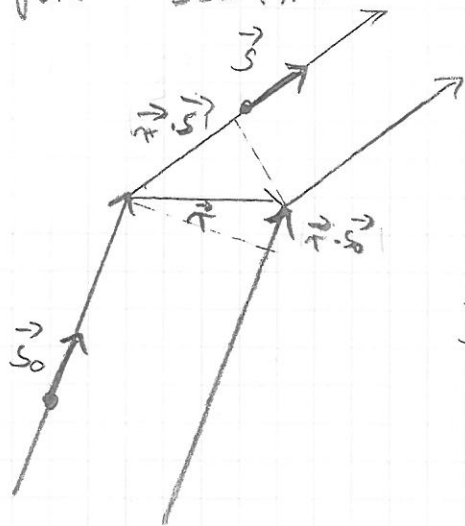
Comparing the Laue condition with the equation defining the reciprocal lattice above immediately shows the importance of the reciprocal lattice for diffraction:

The condition for constructive interference is that the difference of wave vectors  $\vec{k} - \vec{k}_0$  is a vector of the reciprocal lattice.

Ewald construction

# Diffraction and Fourier Transform (Beyond point scatterers)

We consider first the a simple model system, namely the scattering of a plane wave by two point scatterer



one scatterer at origin,  
one scatterer at  $\vec{r}$   
 $\vec{s}, \vec{s}_0$  unit vectors in  
the direction of wave

The path difference is obtained by projecting  $\vec{r}$  on both  $\vec{s}_0$  and  $\vec{s}$ .

$$d = \vec{r} \cdot \vec{s} - \vec{r} \cdot \vec{s}_0 = \vec{r} \cdot (\vec{s} - \vec{s}_0)$$

The relevant quantity is the phase difference:

$$\frac{d}{\lambda} = \vec{r} \cdot \left( \frac{\vec{s}}{\lambda} - \frac{\vec{s}_0}{\lambda} \right) = \frac{1}{2\pi\lambda}$$

We define  $\vec{k} = \frac{2\pi}{\lambda} \vec{s}$  and  $\vec{k}_0 = \frac{2\pi}{\lambda} \vec{s}_0$

$$\Rightarrow \varphi = \vec{r} \cdot (\vec{k} - \vec{k}_0) = \vec{r} \cdot \vec{K} \quad (\vec{K} = \vec{k} - \vec{k}_0)$$

The wave after the scattering process can then be written as the superposition of two plane waves: Here, one has to take care of the different amplitudes and phases of the waves.

$$A_1 e^{i(\vec{k}_1 \cdot \vec{x} - \omega t + \varphi_1)} + A_2 e^{i(\vec{k}_2 \cdot \vec{x} - \omega t + \varphi_2)}$$

$$= (A_1 e^{i\varphi_1} + A_2 e^{i\varphi_2}) \cdot e^{i\vec{k} \cdot \vec{x} - i\omega t}$$

The important part in this equation is the amplitude.

Consider now a distribution of scatterers.

Each infinitesimal volume  $dV$  gives rise to a scattered wave with an amplitude given by  $S(\vec{r})$ . The sum then turns into an integral which we call the structure factor:

$$F(\vec{k}) = \int S(\vec{r}) e^{i\vec{k}\cdot\vec{r}} dV$$
$$= \int S(\vec{r}) e^{i\vec{k}\cdot\vec{r}} dV$$

We have the result that the form factor is the Fourier transform of the scattering power  $S(\vec{r})$  (for x-rays,  $S(\vec{r})$  is the charge density)

Refresher: Fourier - Transform

A periodic function in 1D can be written as:

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(nkx) + b_n \sin(nkx)$$

$$k = \frac{2\pi}{\lambda}, \quad \lambda = \text{wavelength of periodic function.}$$

This can be written more compact using the complex exponential function:

$$f(x) = \sum_{n=-\infty}^{\infty} c_n e^{inRx}$$

Going from the sum to an integral allows the description of non-periodic functions:

$$f(x) = \int F(k) e^{ikx} dk$$

(6)

The full power of the Fourier description of diffraction becomes evident when we consider a periodic scattering power, for example the electron density in a crystalline solid. Remember that a crystal can be described as basis + lattice, i.e. a Bravais lattice with the same basis (local arrangement of atoms) at each lattice point. Mathematically, this can be described as a convolution of a 3D Dirac-comb with a function describing the basis. The Fourier Transform of such a convolution is the product of the individual Fourier transforms.

As we already know, the Fourier transform of the direct lattice is the reciprocal lattice. The basis is then transformed into a structure factor modulating the intensity of the reciprocal lattice points:

$$F(\vec{k}) = \int_{\text{unit cell}} \rho(\vec{r}) e^{i\vec{k}\cdot\vec{r}} dV$$

For a very complicated basis with large variations on a small scale, the resulting Fourier transform is extended in reciprocal space, meaning that the form factor can affect reciprocal lattice points up to a high order.

Here, the discrete set of coefficients is replaced by a continuously varying function  $F(k)$ .  
 $F(k)$  is the Fourier transform of  $f(x)$ .  
 Finally, everything still works the same for a 3D-function:

$$f(\vec{x}) = \int F(\vec{k}) e^{i\vec{k}\vec{x}} dV^*$$

The Fourier transform works in both directions:

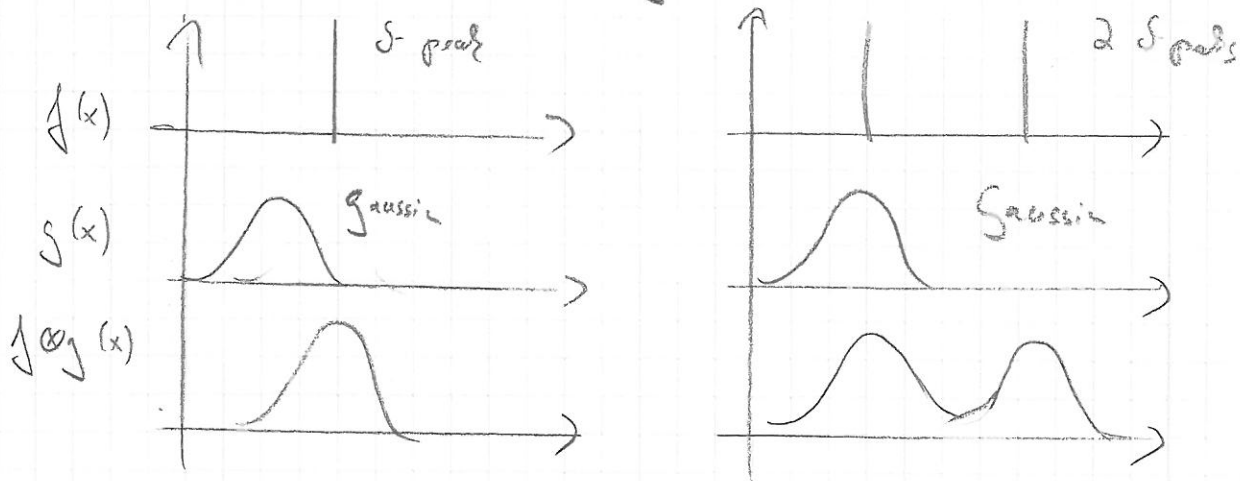
$$F(\vec{k}) = \int f(\vec{x}) e^{-i\vec{k}\vec{x}} dV$$

Convolution:

The convolution of  $f(\vec{x})$  and  $g(\vec{x})$  is defined as

$$(f \otimes g)(\vec{x}) = \int f(\vec{z}) g(\vec{x} - \vec{z}) d\vec{z}$$

This is best explained by an example:



We have: 
$$\boxed{F(f \otimes g) = F(f) \cdot F(g)}$$

There are two fixpoints of the Fourier transform:

A Gaussian with width  $\Delta x$  is transformed into a Gaussian with width  $\frac{2\pi}{\Delta x}$ .

A Dirac comb with spacing 2 is transformed into one with a spacing  $\frac{2\pi}{2}$ .



## Diffraction

A periodic lattice diffracts waves with a wavelength of the order of the lattice constant. These waves can be either electromagnetic radiation (x-rays) or matter waves (electrons, neutrons, atoms [He]).

For x-rays we have:

$$E = \hbar \omega, \quad k = \frac{2\pi}{\lambda}, \quad \frac{\omega}{k} = c$$

$$\Rightarrow \lambda = \frac{2\pi}{k} = \frac{2\pi}{\omega} \cdot c = \frac{2\pi}{\hbar E} \cdot \hbar c$$

$$\Rightarrow \lambda = \frac{\hbar c}{E}$$

Remember:  $1 \text{ eV} \hat{=} 12345 \text{ \AA}$   
(exact:  $12398 \text{ \AA}$ , error 0,4%)

$$\Rightarrow 1 \text{ \AA} = 10 \text{ keV}$$

For matter waves (de Broglie)

$$\lambda = \frac{2\pi}{k}, \quad p = \hbar k, \quad E = \frac{1}{2} m v^2 = \frac{p^2}{2m}$$

$$\Rightarrow \lambda = \frac{2\pi}{k} = \frac{2\pi \hbar}{p} = \frac{h}{\sqrt{2mE}}$$

$$\Rightarrow E = \frac{h^2}{\lambda^2} \cdot \frac{1}{2m}$$

$$\lambda = 1 \text{ \AA} \Rightarrow E = 150 \text{ eV}$$

$$E = 0,1 \text{ eV}$$

$$E = 0,02 \text{ eV}$$

Remember: Thermal energy at room temperature:

Image

$$kT = \frac{1}{40} \text{ eV} = 0,025 \text{ eV}$$

(9)

## Types of radiation

What is the longest wavelength of radiation for that we can still observe diffraction?

2 maximal  $\Rightarrow$  2 minimal

Smallest  $k$ -vectors for given  $\vec{G}$  in the case of back-scattering:

$$\vec{k} - \vec{k}_0 = \vec{G}, \quad \vec{k} = -\vec{k}_0$$

$$\Rightarrow 2\vec{k} = \vec{G}$$

$$\Rightarrow \vec{k} = \vec{G}/2$$

minimize  $\vec{G}$  close to origin, eg.  $\vec{G} = \vec{b}_1$   
cubic lattice:  $b_1 = \frac{2\pi}{a}$

$$\Rightarrow \lambda_{\max} = \frac{2\pi}{k_{\min}} = \frac{\pi}{G_{\min}} = \frac{\pi}{2\pi} a = \frac{a}{2}$$

$\Rightarrow$  The wave length must be on the order of the lattice constant.

The structure factor is in reciprocal space  
while the basis is in real space.

By an experimental determination of  $F_{\vec{k}}$  for  
all  $\vec{k}$  one could in theory determine  $\rho(\vec{r})$   
(and hence the structure of a solid) using  
just a Fourier transform. However,  $F_{\vec{k}}$  gives  
the (complex) amplitude of the plane wave,  
but experimentally one can only determine  
the intensity  $I$ , with  $I \sim F_{\vec{k}}^2$ . The  
important phase information is lost  
during squaring. Therefore, structure deter-  
mination is not so simple, one has to  
start with assuming a crystal structure  
and then refine it in an intelligent way.

## Low energy electron diffraction (LEED)

As mentioned above, also matter beams can be diffracted by a crystal due to the wave-particle duality. As the electrons with the suitable wavelength for diffraction at an atomic lattice have a very short mean free path (remember the universal curve), methods based on electrons are very surface sensitive which makes them important tools for surface science.

The diffraction of electrons by a 'crystalline surface' was first observed in 1927 by Davisson and Germer using a Ni crystal (Nobel price for Davisson, 1937, shared with Thomson). This discovery led to the development of low energy electron diffraction (see figure of typical setup). Electrons are extracted from a thermal emitter and focused by electrostatic lenses onto the sample into a spot of the order of  $1 \text{ mm}$ . The diffracted  $e^-$  pass a number of grids and are finally accelerated onto a fluorescent screen allowing to inspect the diffraction pattern. The first grid is on ground potential to assure field free electron motion, the second grid (or second and third) allow to reject inelastically

scattered  $\vec{e}$  through a retarding voltage. The LEED patterns are usually imaged with a camera and analysed using a computer.

The diffraction from a two dimensional lattice can be described with the formulas we repeated above. In fact, the reduction to two dimensions makes the treatment a little easier. As the presence of the surface breaks translational symmetry in one dimension, the component of the momentum of the electron in this direction is no longer conserved (remember Noether's theorem: "If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved in time.")

In consequence, the Lane equation can be written as:

$$\vec{k}_{\parallel} - \vec{k}_{0\parallel} = \vec{K}_{\parallel} \cdot \vec{e}$$

where  $\vec{k}_{0\parallel}$  is the wave vector component parallel to the surface of the incident  $\vec{e}$ ,  $\vec{k}_{\parallel}$  the one of the exiting  $\vec{e}$  and  $\vec{K}_{\parallel}$  a reciprocal 2D lattice vector with  $\vec{K}_{\parallel} = h \vec{a}_1^* + k \vec{a}_2^*$ .

For applying the Ewald construction, instead of reciprocal lattice points we have to consider reciprocal lattice rods normal to the surface (because there is no conservation for perpendicular momentum), see Figure.

In the usual geometry of LEED we use  $\vec{k}_{\parallel} = 0$ . The Lane equation then becomes very simple:  $\vec{k}_{\parallel} = G_{\parallel} k_{\parallel}$ .

LEED therefore visualizes the reciprocal lattice directly.

A low background and sharp LEED spots indicate a well ordered periodic surface. Poorly ordered surfaces result in broad spots and high background intensity, no spots are characteristic for amorphous sample surfaces.

Before we look at an example let us briefly recall the relation between real and reciprocal lattice in two dimensions

slide. In short, the reciprocal lattice of the square lattice is again the square lattice, and the reciprocal lattice of the hexagonal lattice is again the hexagonal lattice. As an example, we look at LEED-patterns of  $\text{In}(111)$  and  $\text{Ir}(100)$  taken in our labs (slide).

Such simple patterns are only recorded to analyze the cleanliness and orientation of the crystal. Scientific results are obtained by looking at more complicated patterns caused by adsorbate structures or surface relaxations or recording the intensity of the LEED-spots as a function of  $V$ .

# Helium atom scattering (HAS)

Of course, also He - Atoms (which are 10 000 times heavier than electrons) show both particle and wave behavior and can consequently be used for diffraction experiments. The main difference with respect to electrons is the applicability to insulating surfaces and the high energy resolution which makes the detection of surface phonons possible.

[Slide: Stern]

This technique is experimentally very demanding as the beam is created using a overpressure of He, yet the sample is kept under UHV [slide].

As an example, the detection of the adsorbate structure of  $H_2O$  on Pt is shown [slide]. Helium atom scattering is even more surface sensitive than low energy electron scattering.

# X-ray diffraction (XRD)

X-ray scattering is the oldest diffraction technique in solid state physics and by far the most widespread one for structure determination of the bulk.

It was postulated in 1912 by Max von Laue (Nobel price 1914) and experimentally verified by Friedrich and Knipping. Quickly, a lot of structures were solved by X-ray diffraction Nobel price 1915 for Bragg + Bragg

In the beginning of XRD the main experimental problem to solve was that for a given crystal the chances to see any reflex when you put it into the X-ray beam are very close to zero (remember the Ewald-construction).

Three early methods that could solve this problem are the Laue-method (use of polychromatic X-rays), the rotating crystal method, and the Debye-Scherrer-method (use of powder).

However, nowadays modern X-ray diffractometers make use of highly accurate positioning systems and fast data acquisition and just scan the whole reciprocal space to find and quantify diffraction spots.




The Laue condition can be visualized using the Ewald construction.

The theoretical treatment up to now only considered point-like scatterers. Now we can go one step further to reality and consider a certain density distribution of the scatterers in the unit cell. For x-rays, this is the electron density. In principle we just have to sum up path differences between all points in the unit cell.

The resulting quantity is the structure factor which depends on the point of the reciprocal lattice we are looking at:

$$F_{\vec{K}} = \int_{V_2} n(\vec{r}) e^{-i\vec{K}\cdot\vec{r}} dV$$

↑  
electron density of  $n(\vec{r})$

Comparison with :  
F is Fourier Transform of  $n(\vec{r})$

The structure factor is in reciprocal space what the basis is in real space.

The intensity of a reflection spot is proportional to the square of  $F$ .

The importance of  $F$  is that it depends on  $n(\vec{r})$ . So, by measuring where the reflexes are we get the lattice, and by looking at the relative intensities we get the electron density distribution, which basically is the structure of matter.

The slide shows three rather famous XRD-patterns which are, however, not very suitable from a didactic point of view. The first is the first pattern obtained experimentally by von Laue using copper sulfate ( $\text{CuSO}_4$ ), the second pattern from a DNA-crystal (fiber) leading to the discovery of the helical structure of DNA (Nobel prize for Watson and Crick 1962 - medicine) and the last one is a pattern with an unusual 10-fold symmetry (not possible in a Bravais lattice) leading to the discovery of quasicrystals (Nobel prize Shechtman 2011 - chemistry).

Back to more technical issues: The exact positioning of a crystal is performed with a diffractometer slide, the most easy to understand geometry is the Eulerian Cradle. With such a diffractometer, the reciprocal space can be mapped systematically. The use of x-rays with variable energy as available at a synchrotron finally enables one to access a large portion of reciprocal space. As the crystal structures of almost all samples of interest to solid state physics is rather simple, they have been solved some time ago. Nowadays, diffractometers at synchrotrons are much used for structural biology to determine the structure of biomolecules slide (28)

## Neutron diffraction

The last technique in this part of the lecture is neutron diffraction. As the neutrons are electrically neutral, they mainly interact with the nucleus of the target, thus penetrating far into the sample. To neutrons, the crystal really looks very much as the idealized array of point scatterers. The slide summarizes important properties of neutrons. The scattering length of neutrons varies a lot with  $z$  (in contrast to x-rays) slide. This enables one to determine the positions of light elements and to distinguish between neighbors in the periodic table. The key differences between neutrons and photons are summarized in the slide. The possibility to determine the position of light atoms in the vicinity of heavy ones was the key to solve the crystal structure of the superconductor YBCO ( $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ ) slide.

A unique property of neutron scattering is that it is sensitive on the magnetic moment of the atom as it has a magnetic moment by itself. Therefore, magnetic order can be revealed and explained on the slides. As an example, one of the first experiments of this kind revealed the antiferromagnetic order in MnO at low  $T$  slide

# Microscopy

## Electron microscopy

In electron microscopy an image is obtained with the aid of electrons which have passed through, have been reflected from, or emitted by an object. Electron beams are formed by electron optical systems with the use of magnetic lenses. The image is usually obtained using a CCD-camera. The basic features of the method are:

- the possibility of obtaining very large magnification and high resolution down to the atomic scale
- additional chemical and structural information due to the physics of electron-matter interaction and due to electron diffraction
- in-situ experiments possible (heating, deformation, irradiation)

### Transmission electron microscopy (TEM)

In a TEM, a beam of high energy electrons (80-400 eV) is passed through an ultra thin sample ( $< 1 \mu\text{m}$ ) and then a magnified image of the sample is formed using electromagnetic lenses. The first TEM was built by Ernst Ruska in 1931 (Nobel Prize 1938.)

[slide]

As electrons interact strongly with matter, the whole TEM - setup is inside a vacuum tube [slide] which is build up right to avoid distortions in the lens system due to gravity. Electrons are provided by an electron gun, very often a heated tungsten wire. The lens setup is closely related to an optical microscope. A condensor stage is used to provide homogeneous illumination of the sample. The image of the sample is obtained by two lenses and can be viewed using a CCD camera.

There are different modes of operation: The bright field mode is the most simple one. Here, contrast is directly formed by differences in electron adsorption across the sample. This can be treated with the Beer-Lambert Law:

$$T = \frac{I}{I_0} = e^{-\sigma l N}$$

intensity of transmitted light
absorption cross section
number density

transmission
thickness

intensity of incident light
 $\sigma = \int(Z)$

In consequence, the intensity is especially diminished by thick regions of the sample or regions containing heavy elements. Example: Graphene [slide]

The dark field mode uses the effect that electrons are diffracted from a crystal lattice. As can be seen already in a model system containing one lens [slide], besides the image of an object (in this case a periodic array of dots) which is created in the image plane (i.e. on the screen), there is the corresponding diffraction pattern which is created in the back focal plane of the lens. The reason for this is simply that here all parallel rays from all points of the sample merge in one specific point. As we have discussed above, in this case the phase difference becomes important and constructive and destructive interference occurs. A particular nice feature of the TEM is that the focal length of the electron-optical lens can be adjusted by applying a voltage, very different from an optical microscope. Thus, just by flipping a switch, one can bring the diffraction pattern on the screen, allowing exact determination of the crystal structure of the area of interest. [slide] This is called selected area electron diffraction (SAED). Using a movable aperture can select only some of the diffraction spots for image formation, which will then show additional contrast (dark field mode) [slide]

# High-resolution transmission electron microscopy (HRTEM)

The most recent development in electron microscopy is the HRTEM (e.g. at the Ernst Ruska Centre of RWTH Aachen and FZ Jülich). These instruments have a spatial resolution of down to  $0.5 \text{ \AA}$ . The slide visualizes the increase of resolution over the past generations of TEMs. The key to this improvement was the correction of errors in the lens system, first the correction of spherical aberration, and most recently the correction of chromatic aberration slide. Unlike the bright-field mode discussed above, image formation is due to phase contrast between the different paths of electrons contributing to the image. The details of this process are not completely understood, and the resulting images are sometimes difficult to interpret and even counter-intuitive. As an example, the slide shows atomically resolved HRTEM-images from  $\text{SrTiO}_3$ , an oxide with interesting electronic properties. The german artist G. Richter (well known in Cologne for his "degenerated" windows in the cathedral) was inspired by such measurements to create "Strontium" slide. Another example slide.

When accelerated electrons enter a solid, they are scattered both elastically (by interaction with the nuclei) and inelastically (by interaction with the atomic electrons). The range of electrons in matter is schematically depicted in this slide, together with typical values. Of course, for TEM the samples must be much thinner than this value.

In inelastic scattering, energy is transferred to the electrons of the sample, which may acquire enough energy and the right momentum to leave the sample on the side of the incident electron beam. The energy of these secondary electrons is much lower than the one of the primary beam, so their range in the sample is very limited (some nm). Therefore, SEM using secondary electrons is a surface sensitive technique.

Among other parameters, the secondary electron yield depends on the angle between the incoming electron beam and the surface. The yield is lowest for normal incidence and increases with increasing angle between the primary beam and the surface normal.

slide. In consequence, SEM yields a contrast characteristic for the surface morphology. For some systems, SEM can be very sensitive on the outermost surface layer. slide



## Scanning electron microscope (SEM)

Irradiation of a sample with energetic electrons causes the formation of secondary electrons, back-scattered electrons or characteristic x-rays (+ many more). slide These additional processes contain information about the sample structure and composition. However, as these processes are not coherent, it is not possible to obtain an image of the sample by optical means. This problem is solved by raster-scanning a finely focused electron beam over the area of interest and at the same time recording the signal of interest (e.g. secondary electrons). This signal can then be visualized on a screen in synchronism with the scanning e-beam, like in an old TV tube to yield the image slide. As an example, SEM micrographs of a snowflake with increasing magnification are shown. slide

In the following, we will limit ourselves to the most commonly used detection mode, namely image formation using secondary electrons.

# Low-energy electron microscopy LEEM

Low-energy electron microscopy (LEEM) was invented by Ernst Bauer in the early 1960s, but became a viable surface imaging technique only 20 years later. In LEEM, primary low energy electrons hit the sample and the reflected electrons are used to form a focused, magnified image of the surface. The spatial resolution limit of the technique is on the order of several tens of Å.

A typical LEEM-setup is shown on the slide. Electrons leave the electron gun with a relatively high energy and pass an array of lenses. A high energy means a small wavelength which is beneficial for the quality of the electron optics. In the prism array, the electrons are deflected and subsequently decelerated to 0-100 eV, making them surface sensitive probes (as in LEED). The reflected electrons are accelerated through the objective lens. In a second pass through the magnetic prism, the electrons are again deflected and finally focused on the detector, where an image of the sample surface is created. As an example, the slide shows a movie of graphite growth on Cu(111) (FOV 14.5 μm).

Just like in the TEM, the diffraction pattern of the sample is created in the back focal plane of the objective and can be projected on the screen using the right set of voltages. Due to the low energy of the electrons, the resulting pattern is a LEED-pattern. Again, as in TEM, the central (undiffracted) spot can be used to build up the image (bright field, see example above). Here, the contrast is due to local differences in crystal orientation, surface reconstruction or adsorbate coverage. In dark field mode one of the diffraction spots is used for imaging, and thus contrast between different phases or domains can be achieved [slide].

As LEEM images can be acquired very quickly, the technique is suitable for studying dynamic processes at surfaces, such as thin film growth, strain relief, etching, adsorption, and phase transitions in real time.