(an embarrassingly short description of …)

Diffraction Contrast Imaging

Lecture 10

Categories of imaging

Mass-thickness contrast

- Contrast appears in the image due to differences in the inherent scattering from the sample
- Z-contrast imaging (a high-resolution version of same)

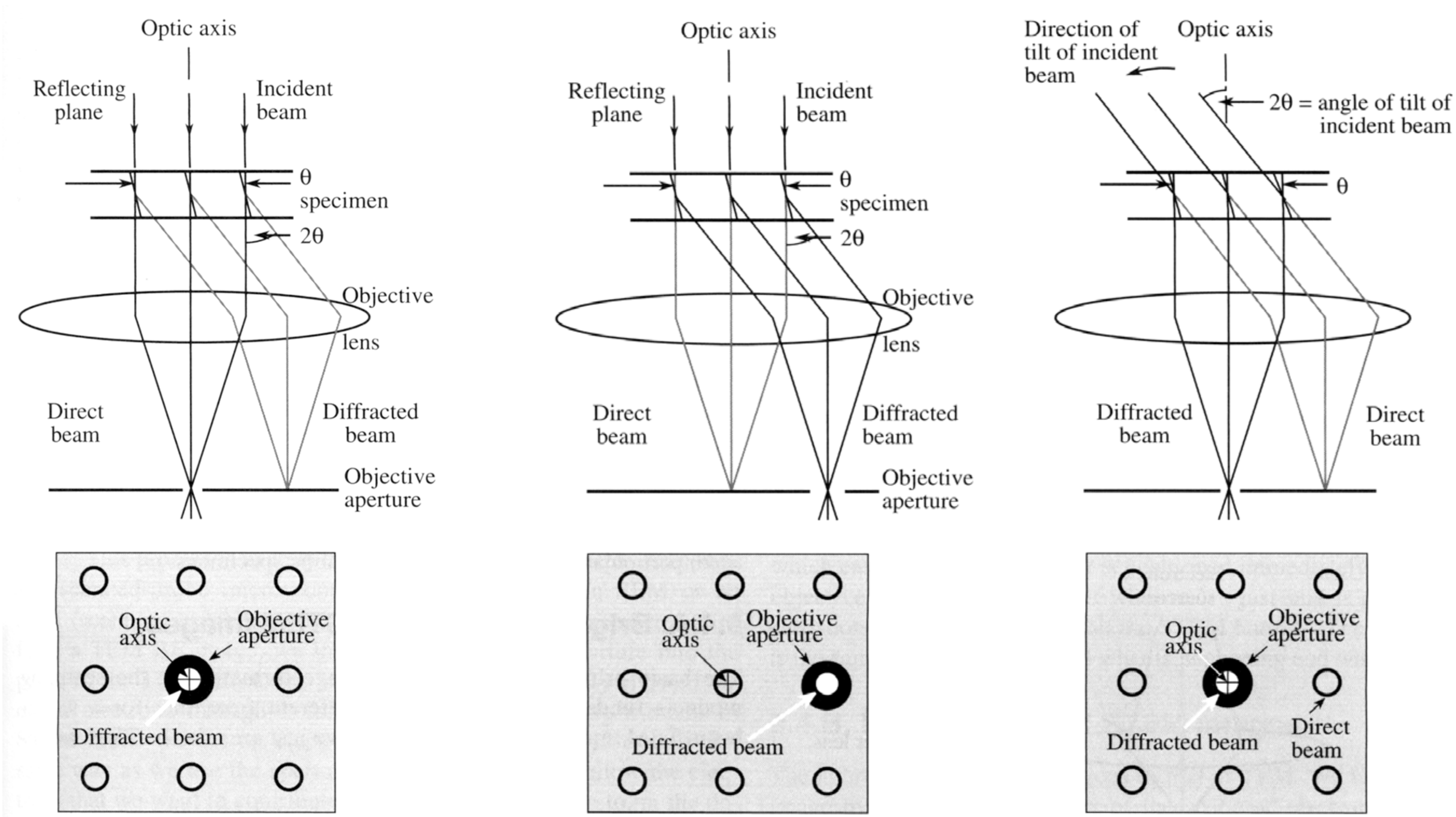
Diffraction contrast

- In crystalline materials, diffraction occurs.
- Utilizing the objective aperture, either the direct (‘un-diffracted’) beam or one of the diffract beams is selected to form the image
  - Results in crystallographic information being conveyed in the image

Phase contrast (‘high-resolution’ imaging)

- Direct and diffracted beams undergo phase shifts in the material
- An image if formed by recombining all beams and observing the resulting interference pattern

Bright Field / Dark Field Imaging

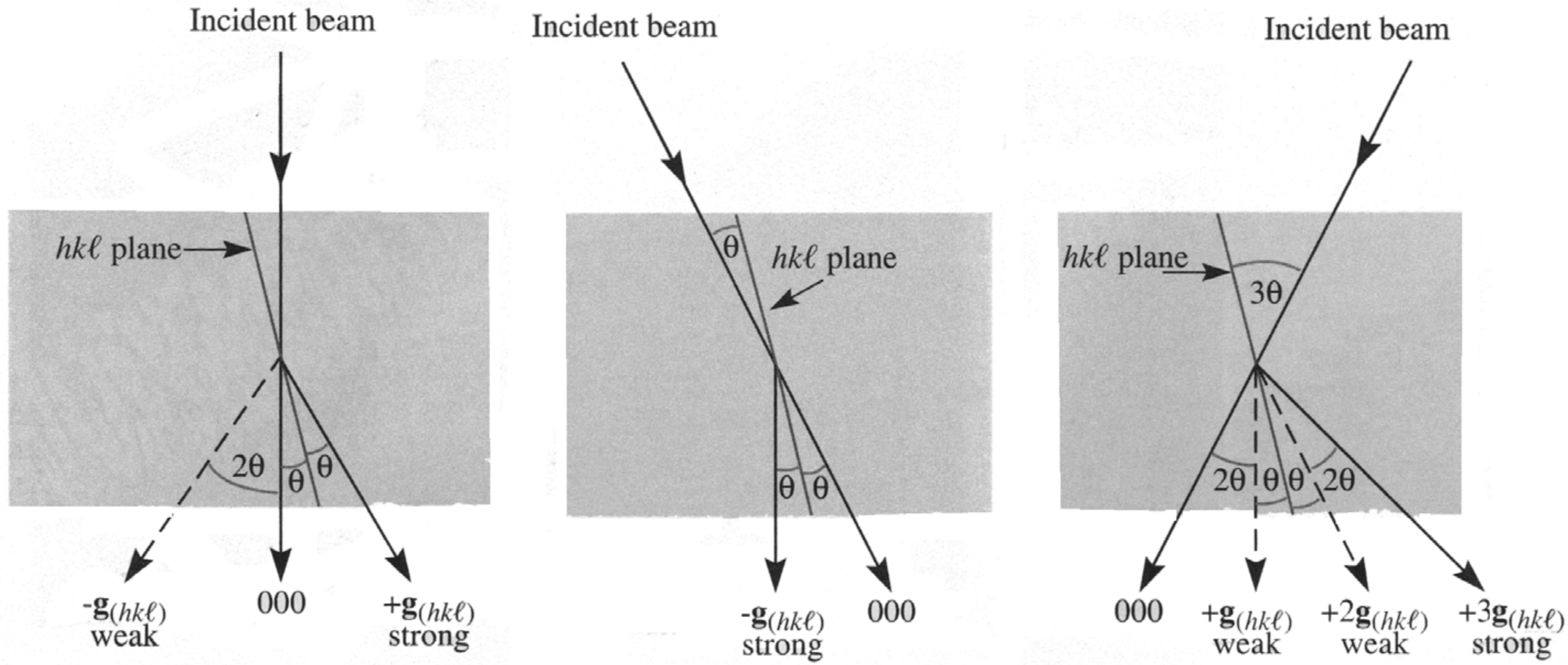


BF image formed from the direct beam

Displaced aperture DF image formed with off-axis scattered beam

CTF image where the incident beam is tilted so that the scattered beam remain on axis

Two beam imaging



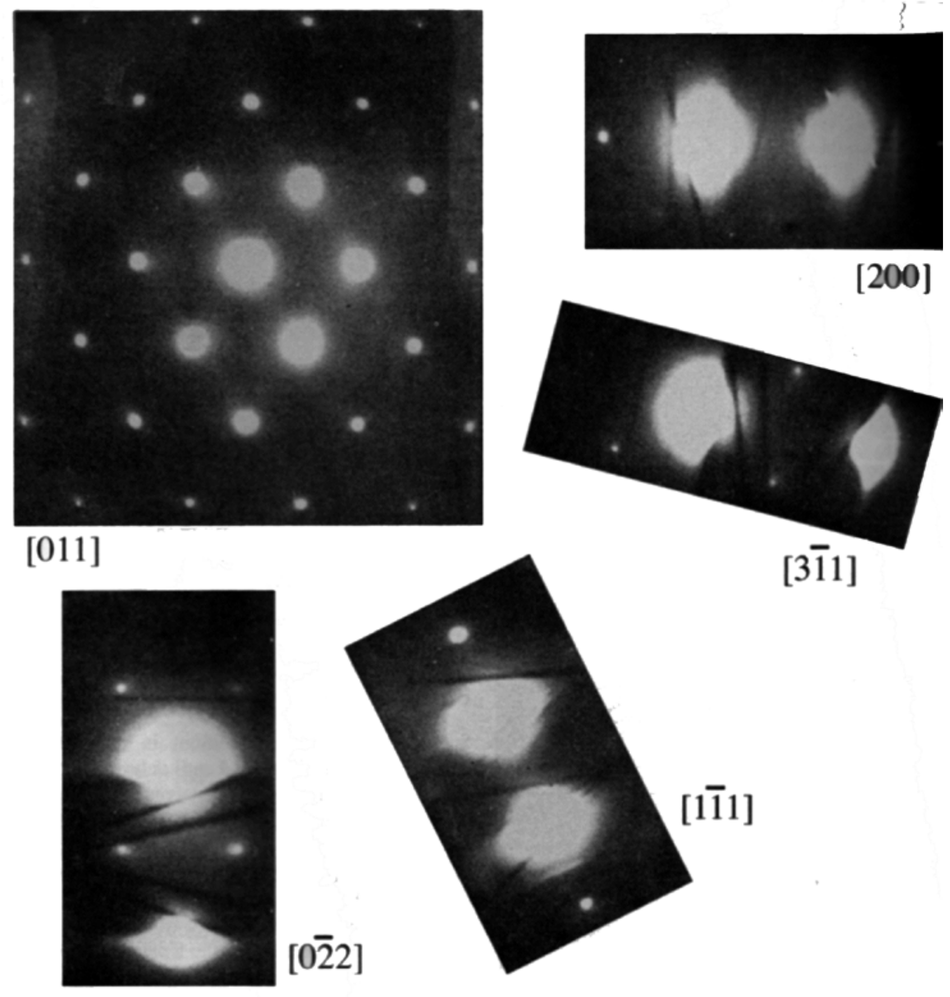
Bright Field Image **Dark Field Image** **Weak-Beam Dark Field Image**

Primary imaging mode is the "two-beam" condition

Allows readily interpretable images

Two-beam conditions

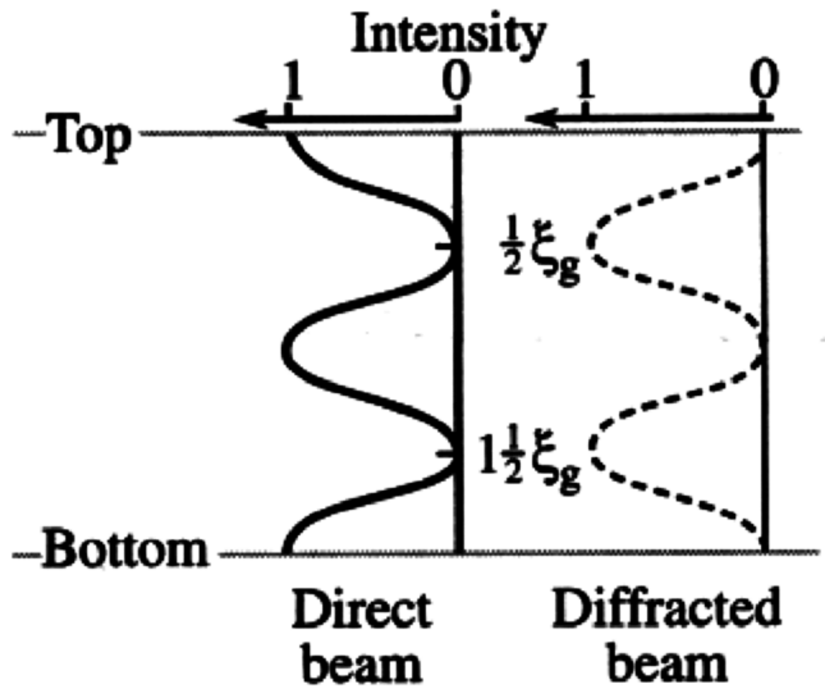
Examples of two-beam conditions near the 011 Zone Axis



Kinematical Diffraction

Assumptions

- Only two diffracted beams considered, direct and one diffracted
- Intensity of diffracted beam is small
- Single scattering event
- No 'absorption' i.e.: $I_{diffracted} << I_{transmitted}$



$$I_{Diffracted} = \frac{\sin^2(\pi z s)}{\xi_g s^2}$$

$$I_{Transmitted} = 1 - I_{Diffracted}$$

Kinematic vs. Dynamical

Can be used to explain (to first approximation) the origin much of much what we see in the microscope

However, cannot be used to accurately calculate intensity relationships

Use dynamical theory:

- Considers multiple beams
- Intensity in one or more diffracted beams can be large in comparison with transmitted beam
- Multiple scattering allowed
- “Absorption” (loss of electrons) allowed
- Can explain intensity accurately
- Very complicated to utilize practically

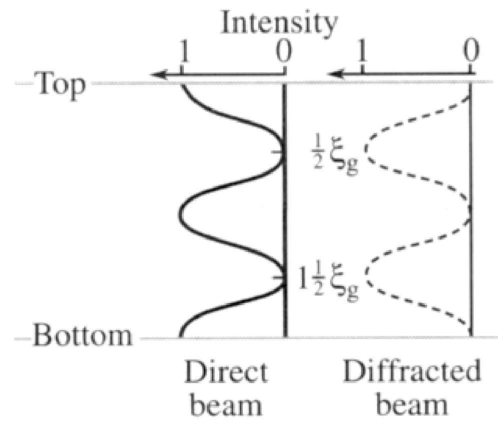
Kinematic diffraction in perfect crystals

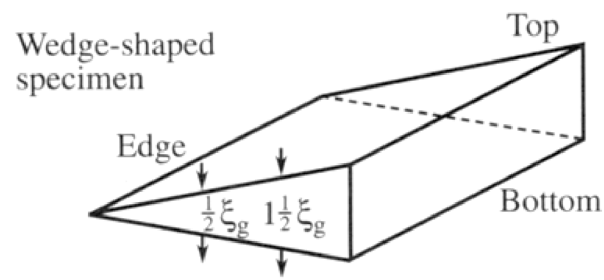
Thickness contours:

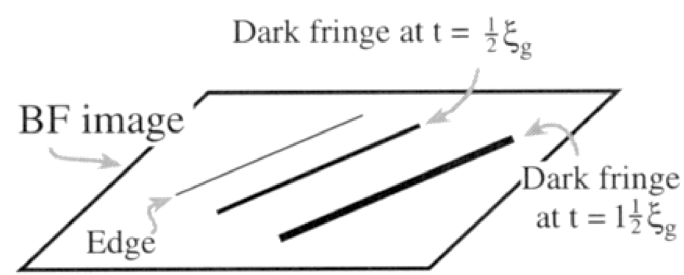
- At exact Bragg condition (s = 0), the intensity of the direct and diffracted beam oscillate in a complementary way.

- For a wedge specimen, the separation of the fringes in the image is determined by the angle of the wedge and the extinction distance, ξ_g.

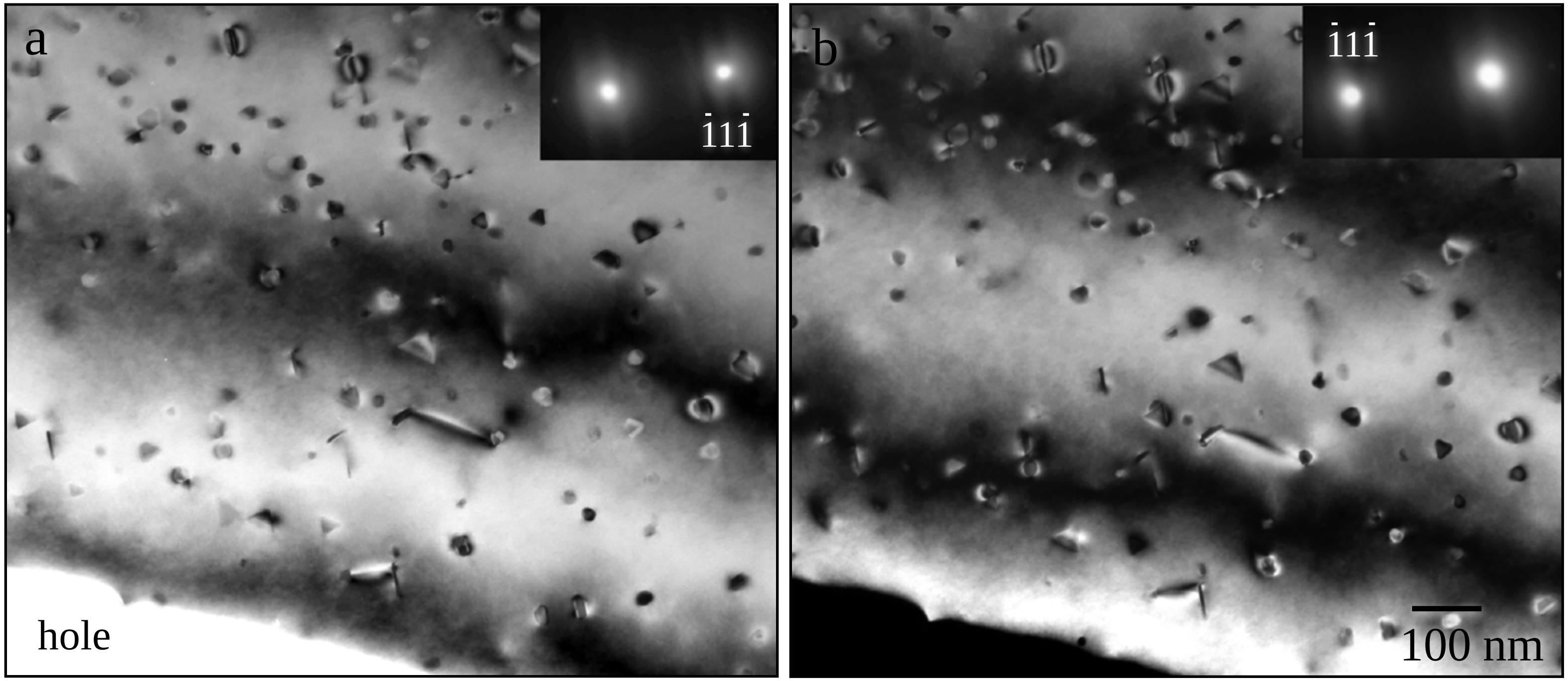
- Thus, the image may appear to be black or white depending on the thickness of the specimen where you are observing it

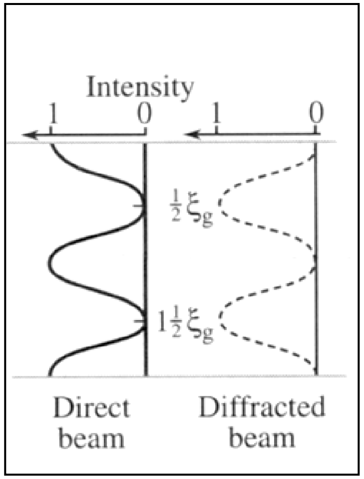






Kinematic diffraction in perfect crystals





Representative bright field (a), and dark field (b) micrograph showing thickness fringes

Courtesy V.R. Radmilovic

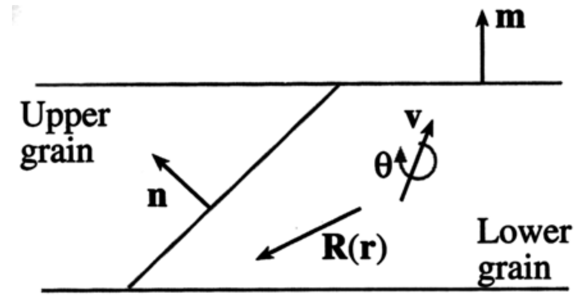
Kinematic diffraction in imperfect crystals

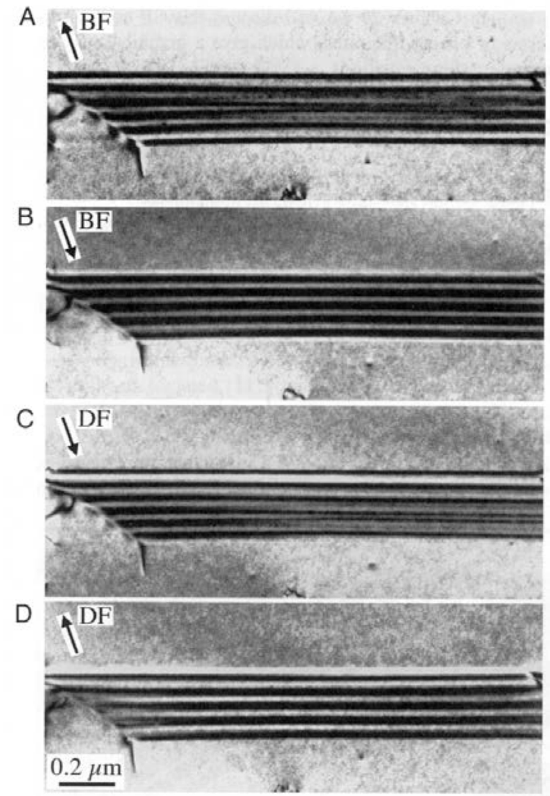
Translation / rotation between two crystals yields fringes in images

- Stacking faults
- Grain boundaries
- Translation boundaries
- Phase boundaries
- Surfaces (if stepped)

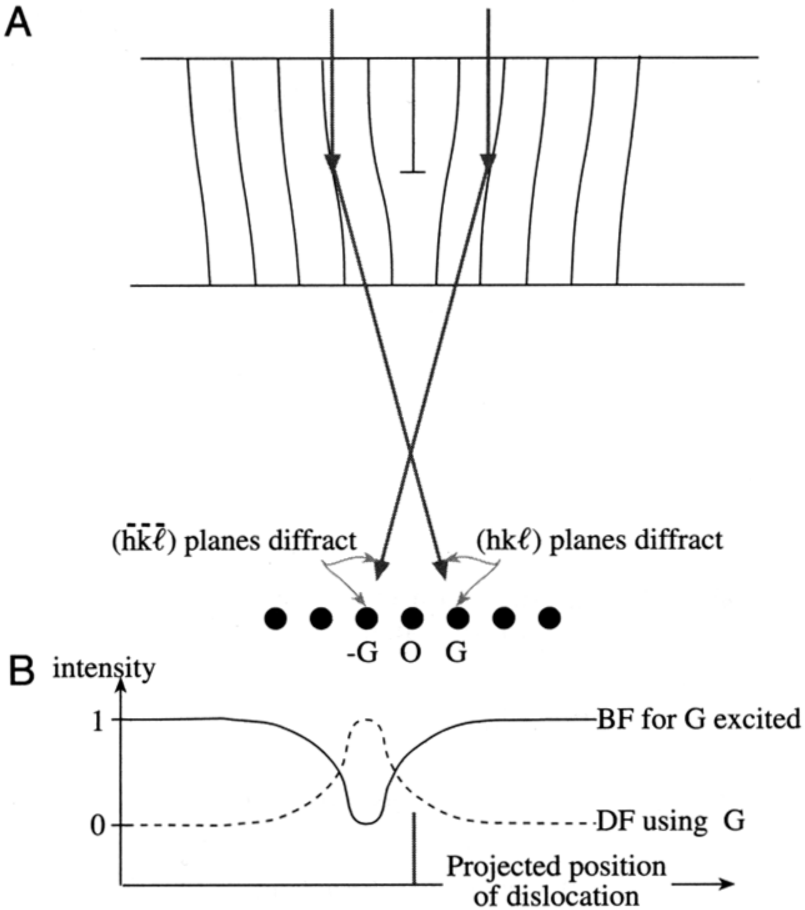
Electron wave has a different amplitude & phase in each crystal

- Results in a fringe pattern





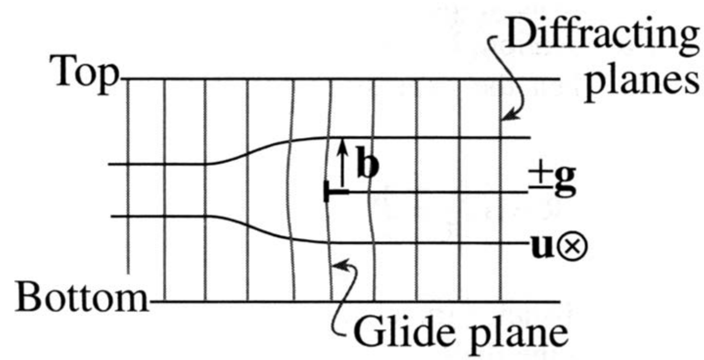
Kinematic diffraction in imperfect crystals



(A) The specimen is tilted slightly away from the Bragg condition ($\mathbf{s} \neq 0$). The distorted planes close to the edge dislocation are bent back into the Bragg-diffracting condition ($\mathbf{s} = 0$), diffracting into G and –G as shown. (B) Schematic profiles across the dislocation image showing that the defect contrast is displaced from the projected position of the defect.

Strain field of dislocation causes local diffraction differences

Seen as line of contrast in the image (if oriented correctly …)



Buckling of the glide planes arises because of the term $\mathbf{g}\cdot\mathbf{b}\times\mathbf{u}$ and is important because it complicates the analysis of $\mathbf{b}$.

g·R causes the contrast and for dislocations, R changes with z.

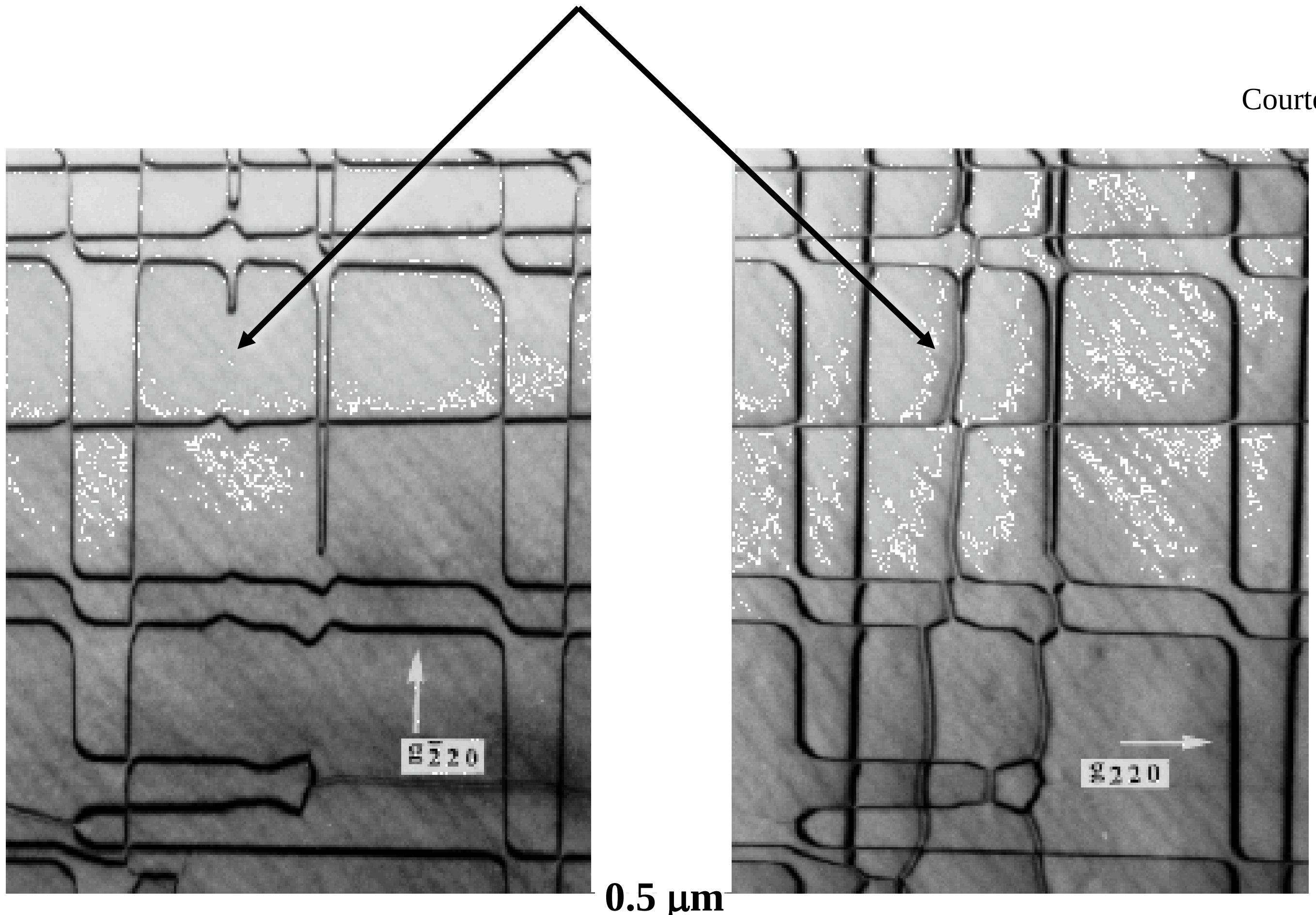
g·b = n; if we know g and we determine n, then we know b.

Kinematic diffraction in imperfect crystals

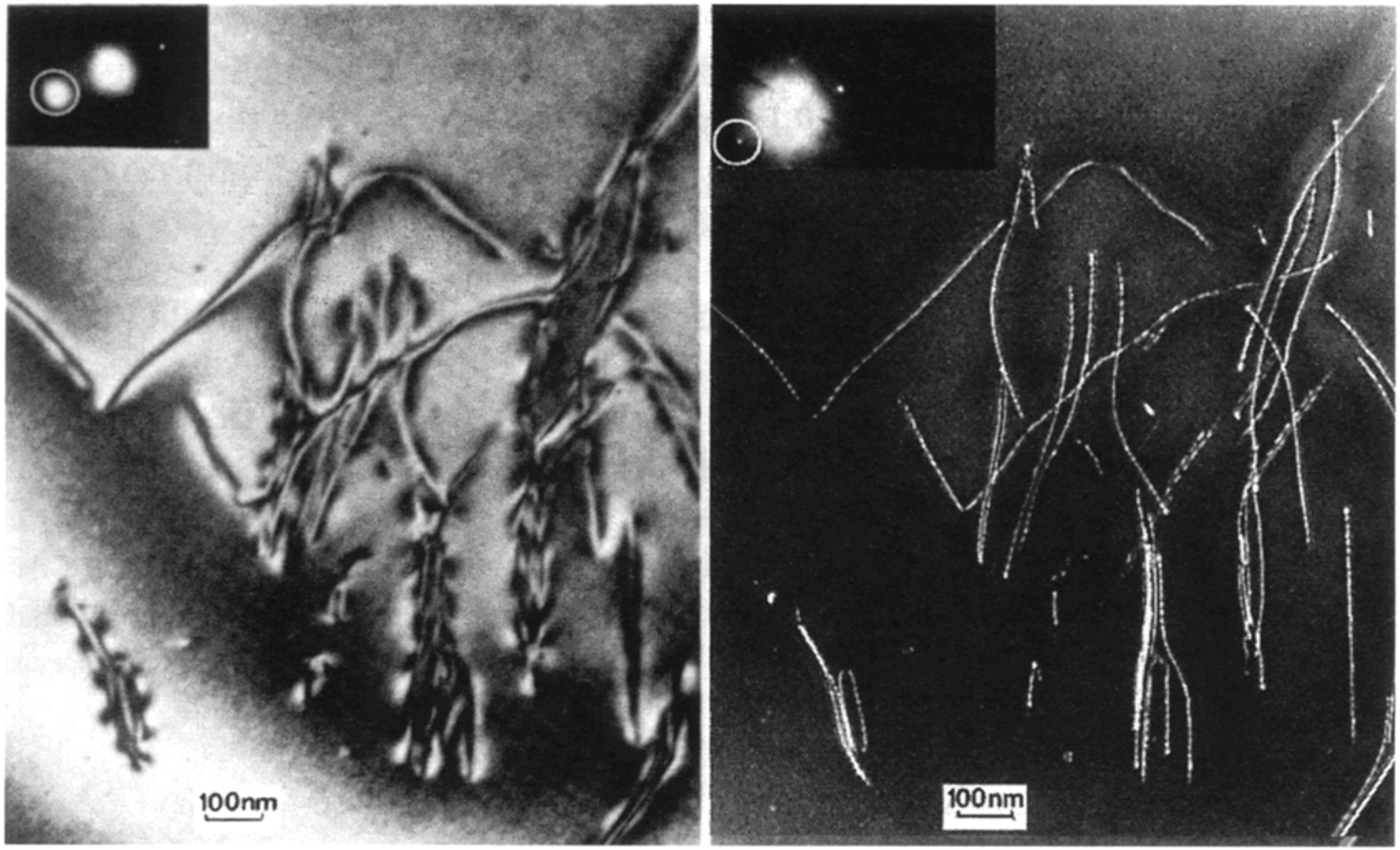
If g·b = 0, then you won't see any contrast because the diffracting planes are then parallel to R.

This is termed the invisibility criterion.

Courtesy V.R. Radmilovic

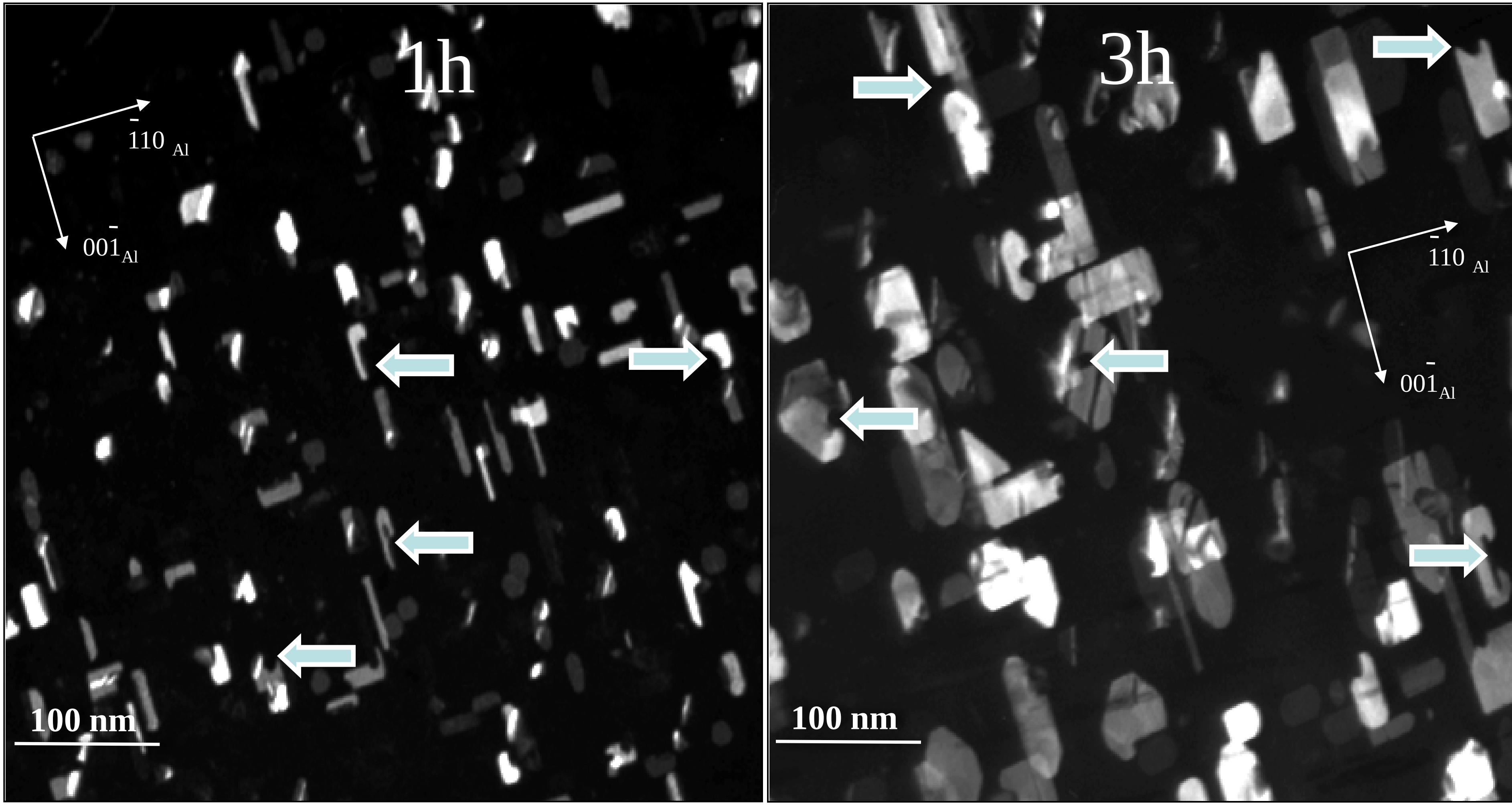


Weak-beam dark-field imaging



Dislocations in Si. Left: BF image in two-beam condition with strong $(2\bar{2}0)$ diffraction. Right: $\boldsymbol{g}$-$3\boldsymbol{g}$ WBDF image with weak $(2\bar{2}0)$ diffraction. Compare the intensities of the active diffractions (circled in inserts).

Dark-field imaging

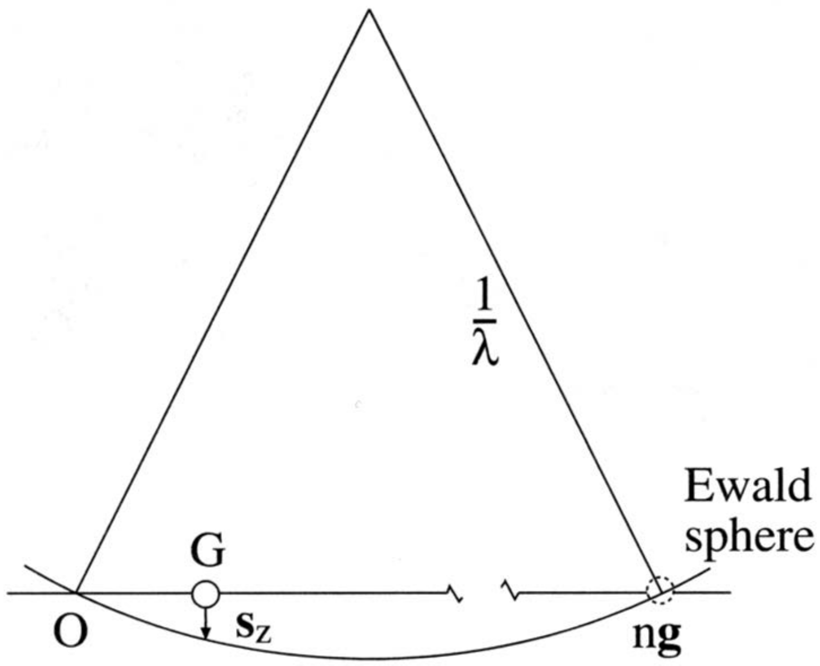


Dark field images of new Al-2at.%Cu-1at.%Si-1 at.%Ge alloy aged 1h and 3hrs (right) at 190°C; imaged using $11\bar{2}_{\theta'}$ reflection.

Courtesy V.R. Radmilovic

Weak-beam dark-field imaging

Diffraction condition



The Ewald sphere construction showing the diffraction conditions used to obtain weak-beam images. The sphere cuts the row of systematic reflections at "*n***g**" where *n* is not necessarily an integer.

$$|\phi_g|^2 = \left(\frac{\pi t}{\zeta_g}\right)^2 \cdot \frac{\sin^2(\pi t s_{eff})}{(\pi t s_{eff})^2}$$

$$s_{eff} = \sqrt{s^2 + \frac{1}{\zeta_g^2}}$$

$$\zeta_{eff} = \frac{\zeta_g}{\sqrt{w^2 + 1}}$$

Kinematic diffraction in imperfect crystals

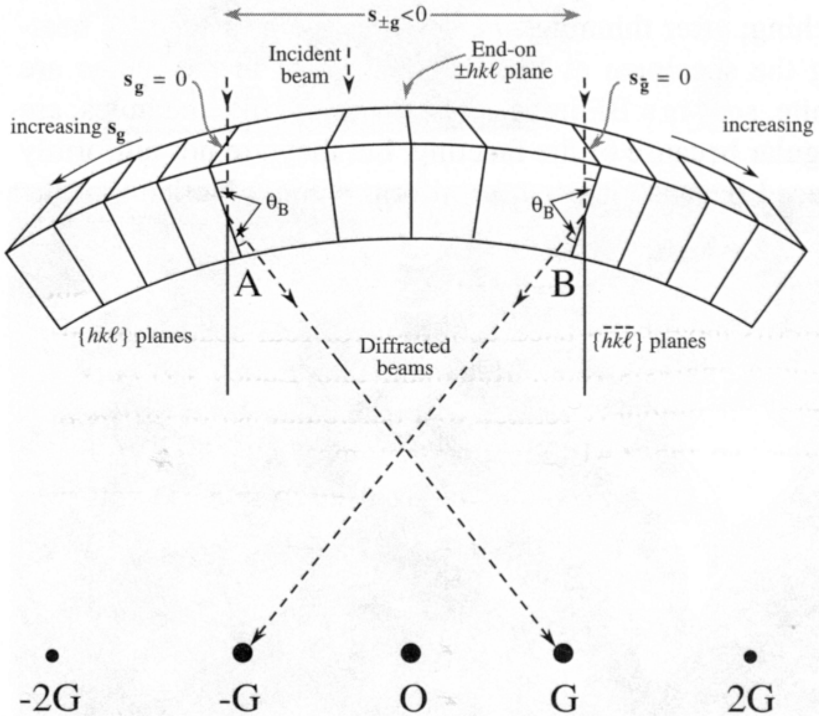
Bright field image

Dark field image

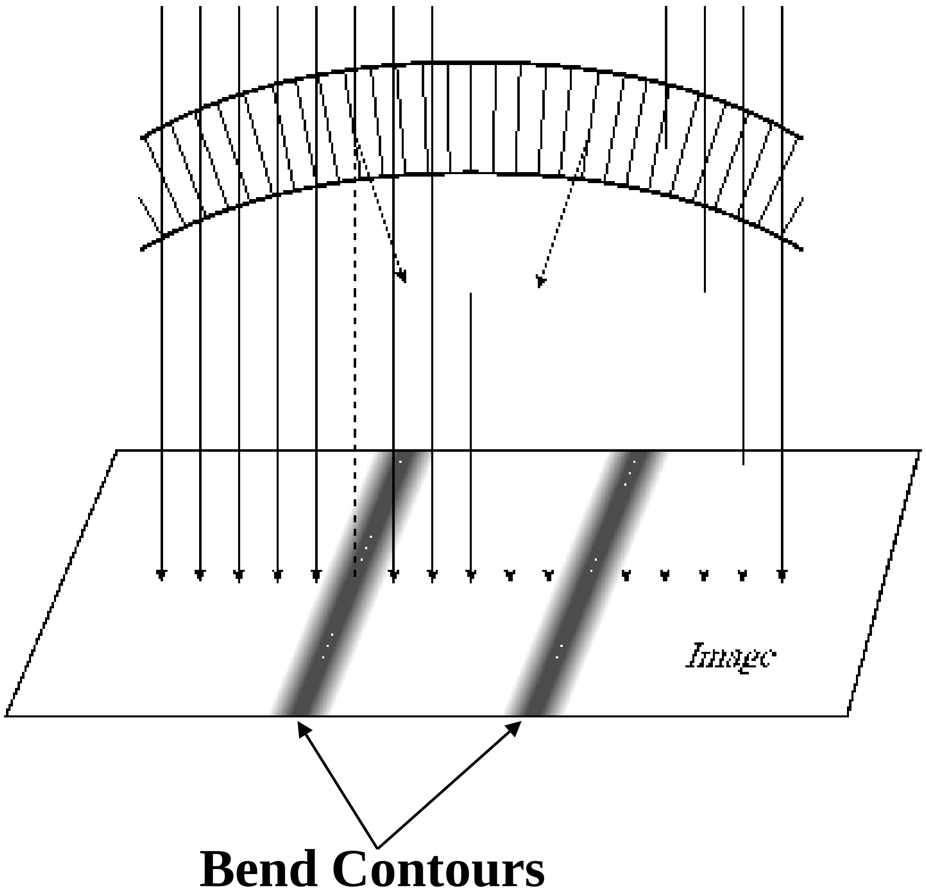
'Weak beam' dark field image

Kinematic diffraction in perfect crystals

Bend Contours

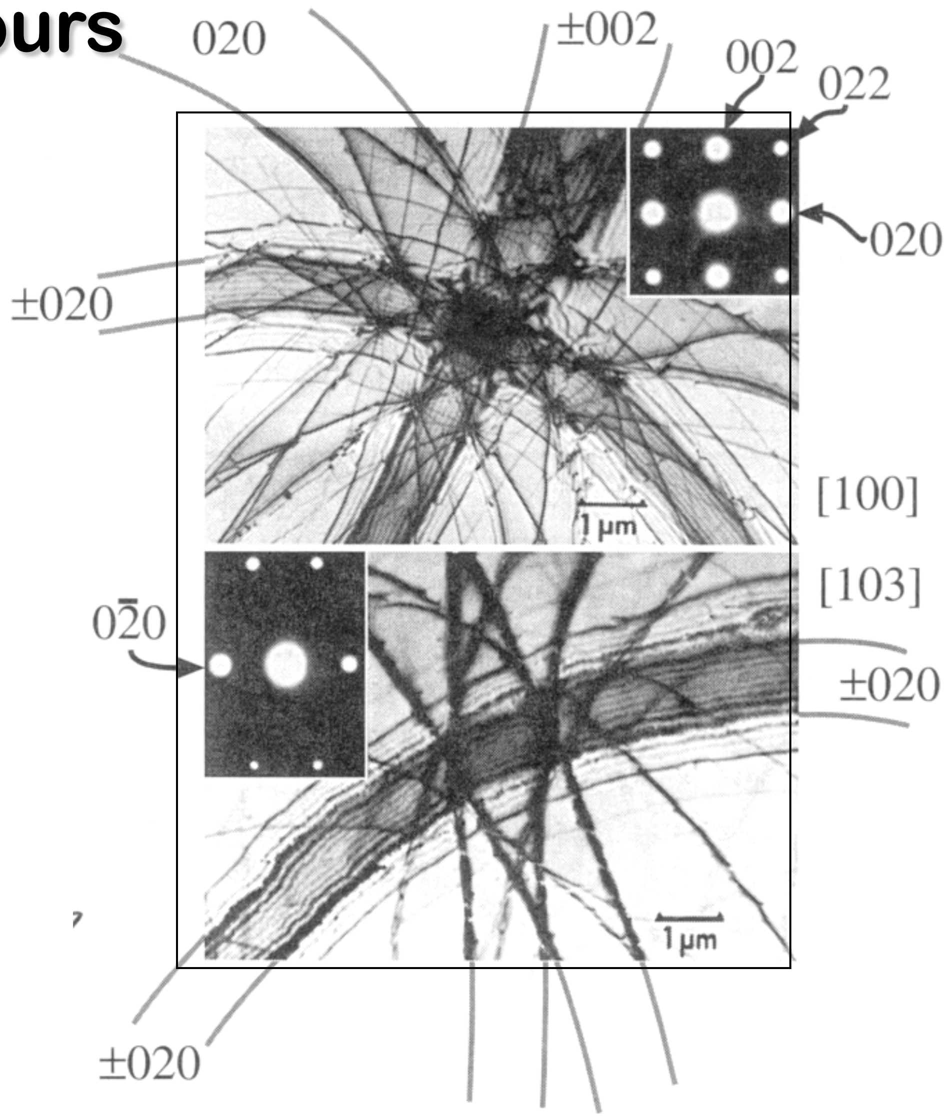


The origin of bend contours shown for a foil symmetrically bent on either side of the Bragg conditions. When the ***hkl*** planes are in the Bragg condition, the reflection G is excited.



Kinematic diffraction in perfect crystals

Bend Contours

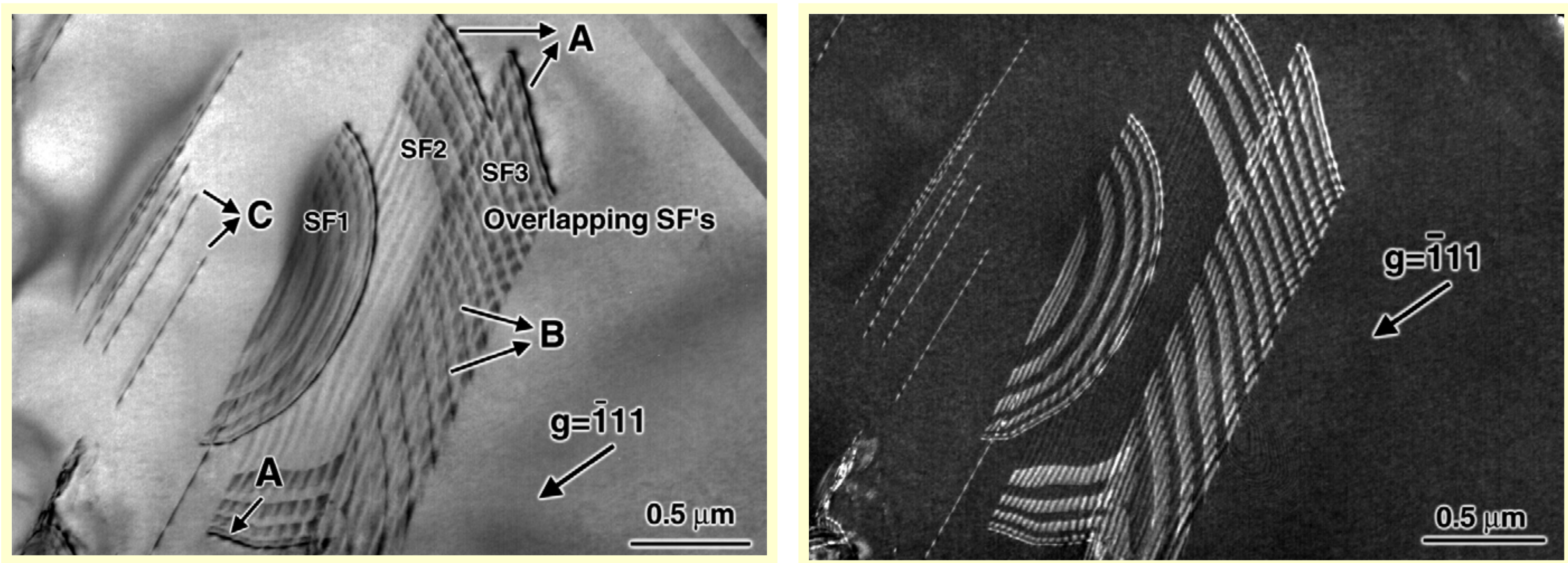


Each diffracted plane produces two bend contours

[100] crystal orientation

[103] crystal orientation

Kinematic diffraction in imperfect crystals



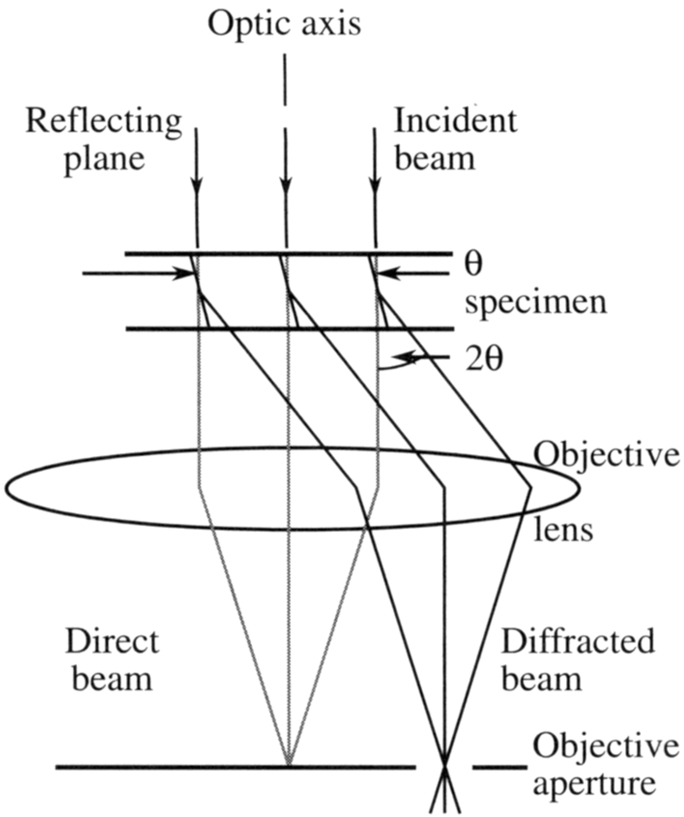
<u>g•b Contrast Analysis of Overlapping Stacking Faults and Superpartial Dislocations</u>

- **Type A: Leading dislocations of the SF 's $\Rightarrow$ 1/x [112]**
- **Type B: Trailing dislocations of the SF 's $\Rightarrow$ 1/x [112]**
- **Type C: Superpartials bounding the APB's $\Rightarrow$ 1/2 [101]**
- **Stacking Fault Displacement R $\Rightarrow$ 1/3 [$\bar{1}$11]**

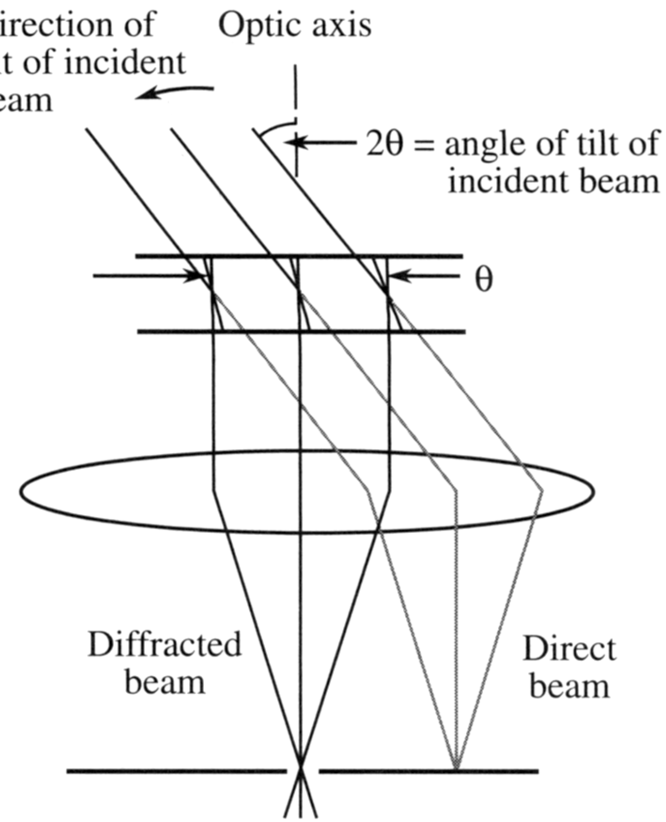
x=3 or 6

Courtesy V.R. Radmilovic

Kinematic diffraction in imperfect crystals

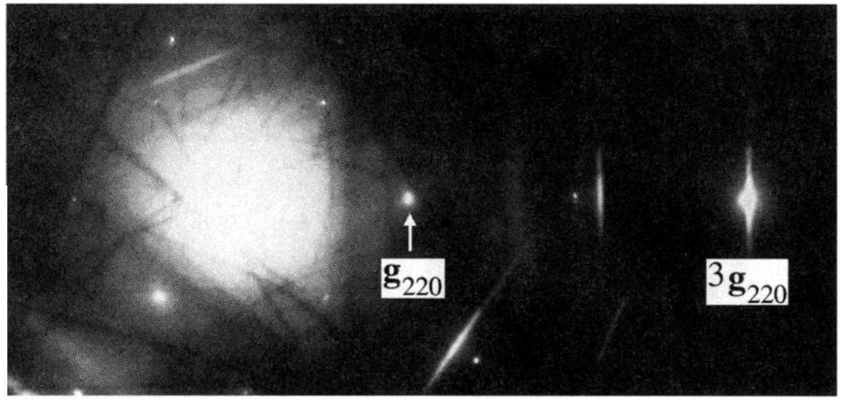


Off-axis Dark Field

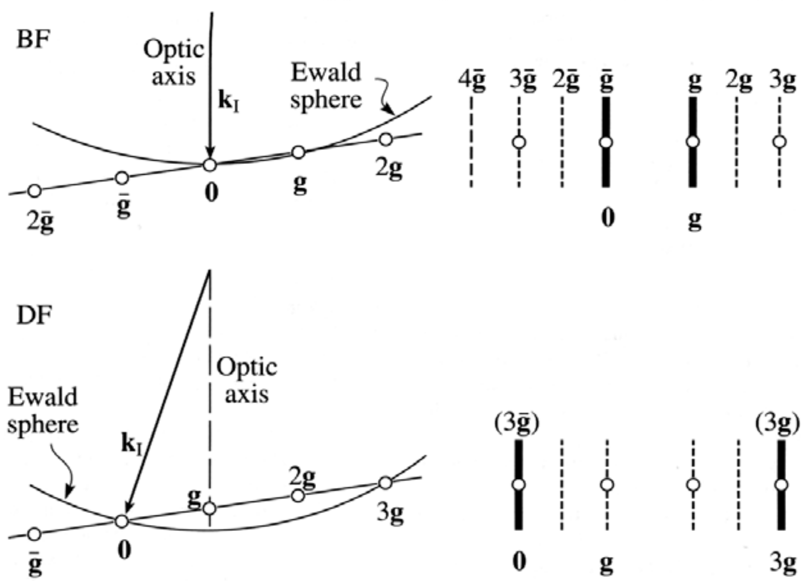


On-axis Dark Field

Weak-beam dark-field imaging



A DP obtained when the specimen is tilted to a suitable orientation for WB microscopy. Here **g** is a 220 reflection and 3**g** is



Relationship between the orientation of the Ewald sphere and the position of the Kikuchi lines for the **0**(**g**) (upper) and **g**(3**g**) (lower) diffraction conditions. The two pairs of diagrams are related by tilting the beam; the specimen has not tilted so the position of the Kikuchi lines is unchanged.