Energy Loss Analysis in Bloch Waves

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In electron diffraction experiments with a single-crystal wedge Bloch waves can be analyzed directly because of their separation into partial waves when leaving the crystal. In a two-beam case the diffraction spot is split into a double representing two partial waves of the two Bloch waves. The energy-loss spectrum in the 220 doublet of MgO was investigated with a Möllenstedt velocity-analyzer. Two loss peaks at about 14 and 22 eV were found in each Bloch wave. Thermal losses were identified as a background in the no-loss peak.

In electron diffraction the steady state of the electrons travelling through a crystal can be described by Bloch waves. If we consider the diffraction from one set of net planes only two Bloch waves are strongly excited. In this case one Bloch wave (1) represents the electrons travelling in the net planes and the other Bloch wave (2) represents the electrons traveling between the planes. Because of the different inelastic interactions of these Bloch waves inside the crystal they are absorbed differently leading to the Borrmann effect for electrons. In a diffraction experiment with a wedge-shaped crystal the diffraction spots are split into a doublet in the diffracted beam as well as in the zero beam, corresponding to the two Bloch waves. The analysis of the fine-structure profile of the doublet allows the determination of the structure potential and the absorption coefficients of the Bloch waves as was shown earlier [1]. In the present work the energy-loss spectrum of the doublet from a MgO crystal wedge was observed and the properties of inelastic scattering and absorption coefficients were studied.

Figure 1 shows the experimental arrangement where a MgO crystal was mounted on a goniometer stage and the slit of a Möllenstedt velocity-analyzer was set perpendicular to the crystal edge. In Fig. 2 the energy-loss spectrum of the 220 doublet is shown, where (1) and (2) indicate the spots from Bloch waves (1) and (2) respectively (the scale indicates energy loss in eV). The incident energy was 45 keV. The spectrum has two peaks at about 14 and 22 eV which agree roughly with the values obtained by other observations [2]. Furthermore the spectrum shows the following characters:

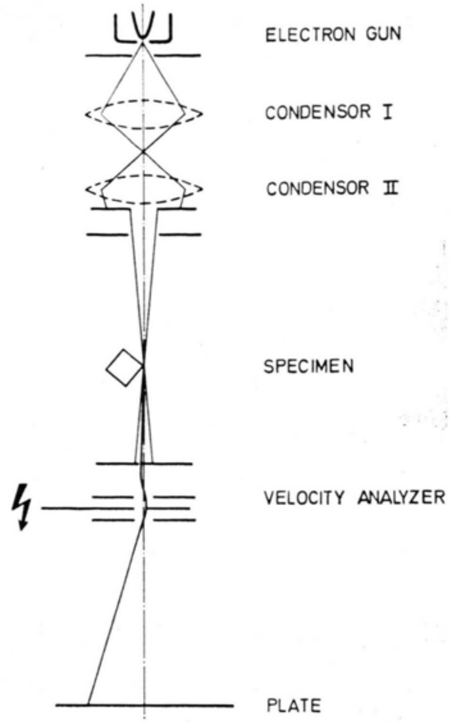

Fig. 1

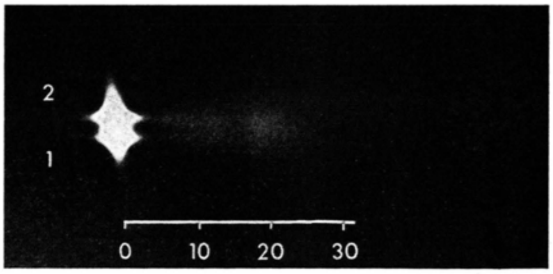

Fig. 2

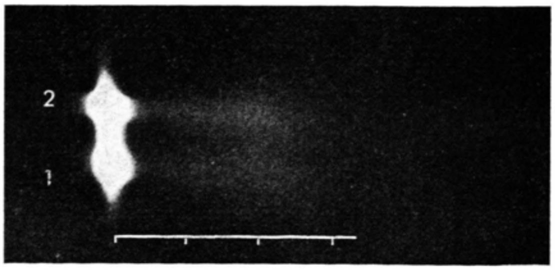

Fig. 3

a) The intensity of the energy-loss peaks is much smaller than that of no-loss peaks.

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b) The energy-loss peak belonging to Bloch wave (1) is weaker than that of Bloch wave (2) similar to the no-loss peaks as one can see very clearly for a large excitation error in Figure 3.
c) The intensity of the background around the peaks at the no-loss part is stronger than that of the energy-loss peaks.

According to a simple calculation for a wedge-shaped crystal, the intensities of the no-loss peaks belonging to Bloch waves (1) and (2) are given by (see appendix)

$$J_0^{(1)} = c/\mu_1 , \tag{1}$$

$$J_0^{(2)} = c/\mu_2 \tag{2}$$

respectively, and those of the first loss peaks are

$$J_1^{(1)} = \left(\frac{\mu_{11}}{\mu_1} + \frac{\mu_{21}}{\mu_2}\right)\frac{c}{\mu_1} = J_0^{(1)}\left(\frac{\mu_{11}}{\mu_1} + \frac{\mu_{21}}{\mu_2}\right), \tag{3}$$

$$J_1^{(2)} = \left(\frac{\mu_{22}}{\mu_2} + \frac{\mu_{12}}{\mu_1}\right)\frac{c}{\mu_2} = J_0^{(2)}\left(\frac{\mu_{22}}{\mu_2} + \frac{\mu_{12}}{\mu_1}\right), \tag{4}$$

respectively. μ_1 and μ_2 are the total absorption coefficients of the Bloch waves (1) and (2), and μ_{ij} is the absorption coefficient based on the inelastic transition from the elastic Bloch wave (i) to the inelastic Bloch wave (j), constituting the loss peak in the energy-loss spectrum. $i=j$ represents an intraband transition and $i \neq j$ represents an interband transition. c is a constant depending on the intensity of the incident beam and the geometry of the wedge. The relations (1) and (2) were shown earlier [1].

The experimental result (a) and the formulae (3) and (4) indicate that μ_1 and μ_2 are much larger than the μ_{ij}'s. μ_1 and μ_2 consist of all the μ_{ij}'s due to any first-loss process and the part due to the phonon excitations. The energy-loss value due to the phonon excitations is very small. From these situations we can conclude that the absorption effect arises almost from the phonon excitations. The experimental result (c) supports the above conclusion.

The experimental result (b) and the intensity ratio between the no-loss and the first-loss peaks might give important informations on the relations among the μ_{ij}'s which depend on individual inelastic processes. More precise quantitative measurements are necessary.

We want to thank Mr. E. Schumann for constructing the energy analyzer. One of the authors (F. F.) wishes to express his thanks to Prof. Molière for giving an opportunity to work in his laboratory.

Appendix

The relation between the no-loss intensities and the first-loss intensities of electrons passing a parallel sided crystal is given by

$$\mathrm{d}I_0^{(1)}/\mathrm{d}t = -\mu_1 I_0^{(1)}, \qquad \mathrm{d}I_0^{(2)}/\mathrm{d}t = -\mu_2 I_0^{(2)},$$

$$\mathrm{d}I_1^{(1)}/\mathrm{d}t = -\mu_1 I_1^{(1)} + \mu_{11} I_0^{(1)} + \mu_{21} I_0^{(2)},$$

$$\mathrm{d}I_1^{(2)}/\mathrm{d}t = -\mu_2 I_1^{(2)} + \mu_{22} I_0^{(2)} + \mu_{12} I_0^{(1)},$$

where t is the crystal thickness and $I_n^{(\mathrm{i})}$ the intensity of the n-th loss peak corresponding to Bloch wave (i). In the case of a crystal wedge the intensity is given by

$$J_n^{(\mathrm{i})} = c \int_0^\infty I_n^{(\mathrm{i})}(t)\,\mathrm{d}t .$$

The result is shown in (1) ... (4).

[1] G. Lehmpfuhl and K. Molière, J. Phys. Soc. Japan **17**, Suppl. B-II, 130 [1962].

[2] H. Venghaus, Opt. Comm. **2**, 447 [1971].