Energy losses of electrons and its comparisons with optical data

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Aus der Curie-Temperatur [6] für EuS $T_c = 16.427\,°\mathrm{K}$ folgt $I \cong 1.99 \times 10^{-24}$ Joule.

Setzt man für $\langle \boldsymbol{S}_0\, \boldsymbol{S}_1 \rangle_T$ die aus dem Busch-Wachter-Effekt gewonnene effektive Korrelation in (5) ein, dann erhält man eine Kurve, die innerhalb der Fehlergrenzen mit der experimentellen Kurve [6] für $C_V(T)$ gut übereinstimmt (Figur 2).

Zur Konstruktion unserer Kurve in Figur 2 war keine weitere Anpassung nötig. Das angegebene Fehlerviereck ist in Abzissenrichtung durch die von Busch und Wachter [2] angegebene Temperaturbestimmtheit und in der Ordinatenrichtung durch die Unbestimmtheit der Tangentenbildung in Figur 1 bestimmt.

Es ist befriedigend, dass sich im theoretisch schwer zugänglichen Gebiet nahe T_c der qualitativ richtige Verlauf ergibt, während die Näherung der konstanten Kopplung gerade in diesem Gebiet versagt [6].

Mit diesem Resultat wollten wir die Wichtigkeit des Busch-Wachter-Effektes für das Problem der Spin-Korrelationen im Heisenberg-Ferromagneten demonstrieren. Eine eingehende Untersuchung dieser Probleme ist geplant.

Zum Schluss möchten wir Herrn Professor W. Baltensperger für wertvolle Diskussionen unsern Dank aussprechen. Herrn Dr. P. Wachter danken wir für die Bereitstellung der experimentellen Daten zum EuS.

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Energy Losses of Electrons and its Comparison with Optical Data

by **H. Raether**
Institut für angewandte Physik der Universität Hamburg

(26. IV. 68)

The interaction of light with a solid is described by the optical constants (refractive index n and absorption coefficient $\varkappa$) or the dielectric constant (ε_1, ε_2), connected with each other by $(n + i\,\varkappa)^2 = \varepsilon_1 + i\,\varepsilon_2$. By measuring the reflectance R of light of a surface or the transmission coefficient of a thin slide as function of the photon energy ($\hbar\,\omega$), one obtains with the help of the Kramers Kronig relations the values of $\varepsilon_1\,(\omega)$ and $\varepsilon_2\,(\omega)$. The ε_2 value is directly proportional to the dissipation of electromagnetic energy per sec and cm^3:

$$\frac{dW}{dt} = \varepsilon_2\,\omega\,\overline{E^2} \tag{1}$$

E means the electric field of the photon. The function $\varepsilon_2\,(\omega)$ has a pronounced structure and peaks, where certain excitations of electrons e.g. excitons, band transitions occur with high probability. The theoretical band structure can thus be checked by comparing it with the spectral dependence of ε_2. This is the important aspect of these measurements.

The interaction of electrons with a solid produces excitations of the solid, too. This is revealed by the energy losses which electrons suffer after having passed the solid (or after being reflected on its surface). The number of electrons having lost an amount of energy shows maxima at certain energy values ('characteristic energy losses'). The approach of the dielectric theory gives the number of electrons N_1 with an energy loss between E and $E + d\,E$

$$\frac{dN_1}{dE} = N_0\,d\,\mathrm{const}\,\frac{\bar{\varepsilon}_2(\omega)}{\bar{\varepsilon}_1^2(\omega) + \bar{\varepsilon}_2^2(\omega)}\,. \tag{2}$$

(N_0 number of incoming electrons, d foil thickness).

The interaction is described by the dielectric constant, too, but in a different form. In the following we identify the dielectric constant $\bar{\varepsilon}$ containing the response of the incoming (longitudinal) field of the electrons with ε representing the response of the incoming (transverse) field of the photons. Since the energy loss corresponds to the absorbed photon energy we set $\hbar\,\omega = E$.

In this formula (2) only volume effects are regarded. Surface effects are also present; they had been studied theoretically and experimentally, so that they can be separated or made very small [1].

As Equation (2) demonstrates the polarisability of the solid (proportional to ε) comes into play in the case of electrons. This has some consequences:

a) Since $|\varepsilon| = |\varepsilon_1 + i\,\varepsilon_2|$ has high values near those frequencies which correspond to electron transitions, the probability of these excitations being proportional to ε_2 in the case of light, is reduced by $1 / |\varepsilon|^2$ in the case of electrons.

b) As $|\varepsilon|$ has very small values near the plasma frequency ω_p of the solid (in the case of a quasi free electron gas $\omega_p^2 = n\,e^2/m\,\varepsilon_0$), the probability of these excitations, called plasmons, is rather high compared with that of excitons and band transitions in general.

As an example Figure 1 compares the $\varepsilon_2(E)$ with the $\varepsilon_2(E)/|\varepsilon(E)|^2$ or $-\mathrm{Im}\ 1/\varepsilon$ curve of GaP. The maxima of ε_2 at lower energies are less pronounced in the energy loss function $-\mathrm{Im}\ 1/\varepsilon(E)$ and displaced by a small a mount, whereas the absorption function $\varepsilon_2(E)$ does not indicate at all the plasma excitation.

This different behaviour comes from the following situation: If light enters a solid with its electric vector parallel to the boundary (normal incidence), the transverse electric field passes continuously and displaces all electrons of the solid uniformly in all planes parallel to the boundary, no polarization interferes. If however electrons

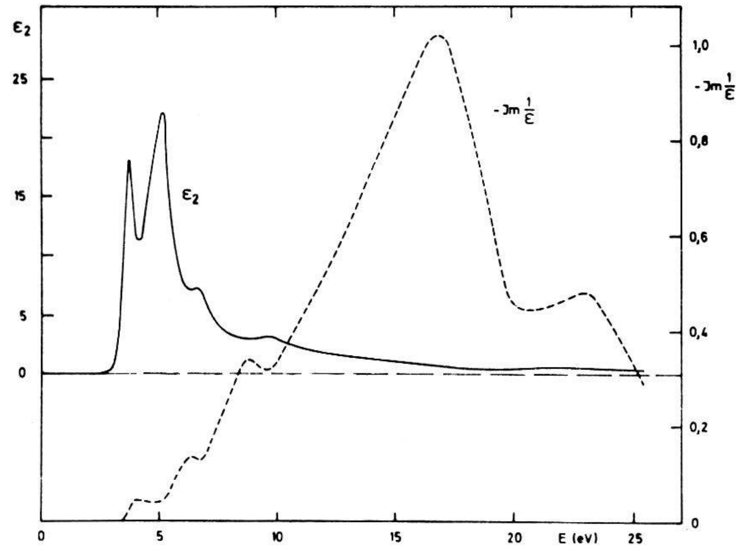

Figure 1a

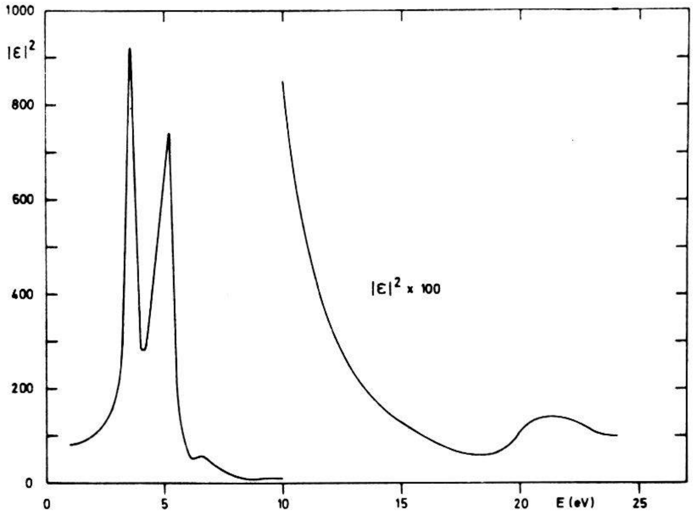

Figure 1b

Figure 1a shows the spectral dependence of ε_2 and $-\operatorname{Im} 1/\varepsilon$ of GaP, Figure 1b shows that of $|\varepsilon|^2$.

enter a solid, the longitudinal field inside amounts to $1/\varepsilon$ of that outside (on account of the continuity condition for $D_{\text{norm}} = \varepsilon E$): it is small at high ε and vice versa.

The experiments in our institute are concerned with measuring this energy loss function of electrons $\varepsilon_2/|\varepsilon|^2$, its structure and its absolute value, and to compare it with the function $\varepsilon_2/|\varepsilon|^2$ calculated from optical data. This shall be demonstrated by some examples.

1. Al

The electrons in Al can be regarded in a first approximation as a gas of quasi free electrons. This is clearly shown by Figure 2a, in which the values of ε_1 and ε_2 derived from optical measurements [2], fit the theoretical curve of a free electron gas with $\hbar\,\omega_p = 15$ eV and $\hbar/\tau_c = 0{,}5$ eV in a large energy region. As indicated above these optical data allow to calculate the energy loss spectrum of electrons, the energy dependence as well as its value. In Figure 2b this spectral dependence ($d\,N_1/d\,E$, Equation 2) obtained on a 600 Å film is compared with that calculated with the

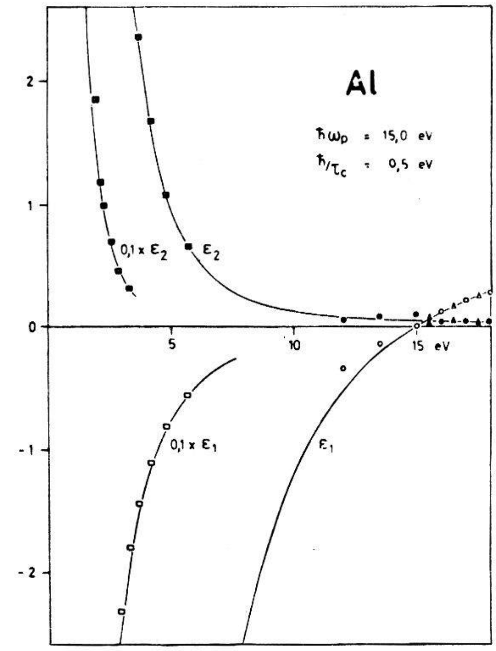

Figure 2a

represents the ε_1, ε_2 curve for Al (–: calculated dependence, points: measured values).

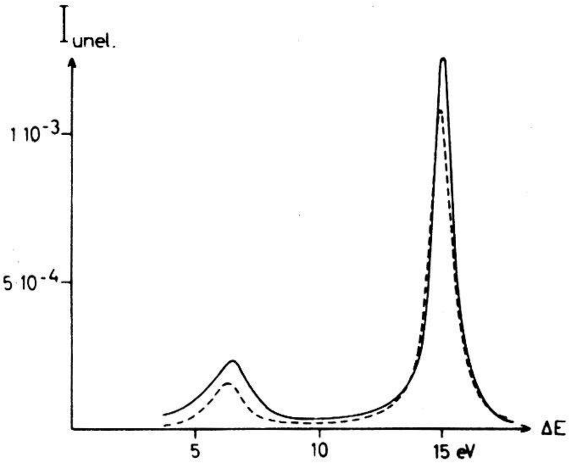

Figure 2b

The energy loss spectrum of electrons in Al (—— measured, – – – calculated)

formula (2) including surface effects. The peak at 15 eV corresponds to the excitations of volume plasmons, that at 7 eV of surface plasmons. The agreement in structure and absolute value is very good in the limits of 20% [3]. This proves the theoretical conception.

2. Ge, GaP

The semiconductors show a more complex spectral dependence of ε_2 due to the band transitions. We can derive from the electron energy loss spectrum the energy loss function and compare it with the function calculated from optical data. Figure 3 shows $-\mathrm{Im}\, 1/\varepsilon$ for monocrystalline and amorphous Ge films from electron data near the plasma frequency [4]. The values calculated from optical reflexion measurements on monocrystalline surfaces [5] lie somewhat lower; optical experiments on vaporized Ge films [6], performed 2 min after vaporization give values nearer to ours. Figure 4 represents the comparison of the same function, obtained from a monocrytalline GaP film in the plasma and in the low energy band transition region [7]. The loss function calculated from optical data and that from electron data are in good agreement in the low energy region, in the far UV region, however, the optical function is again well below our data. This disagreement is certainly due to the high sensitivity of the optical reflectance measurements against the quality of the surface.

3. KBr

The alcali halides are of special interest since there exists a pronounced structure due to excitons. To demonstrate this complex character, the energy loss spectrum of KBr is reproduced in Figure 5 [9]. One recognizes the following features:

1) The Γ-excitons (a, b) split up by the spin orbit coupling of the top valence band at the Γ point in the Brillouin zone,

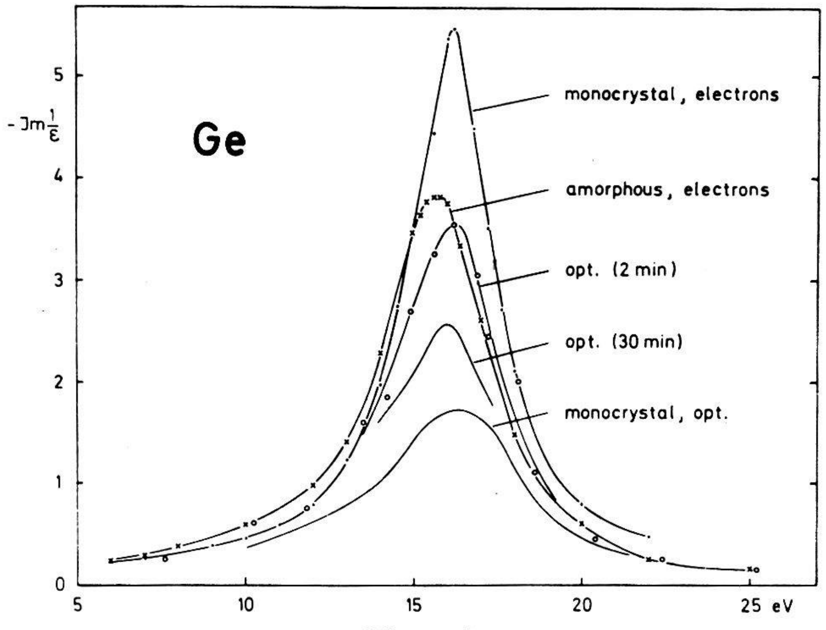

Figure 3

The function $(-\operatorname{Im} 1/\varepsilon)$ of Ge derived from electron energy loss experiments and from optical reflectance data.

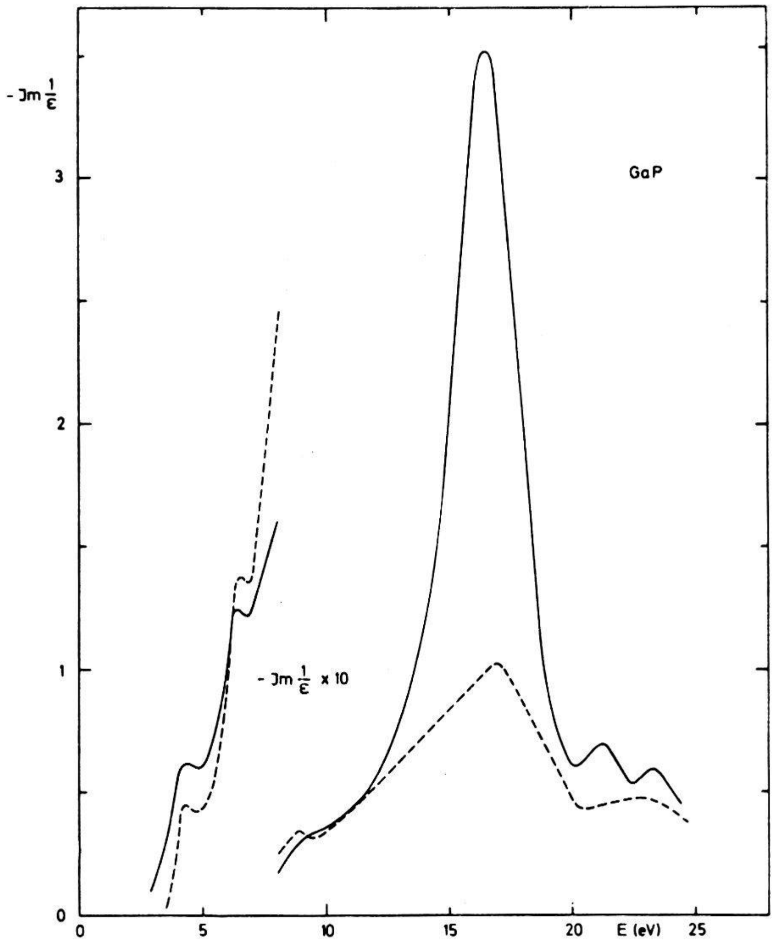

Figure 4

Energy loss function of GaP (—— electron energy losses, ... reflectance data). (The electron loss function is derived from a loss spectrum observed at a scattering angle of 3×10^{-4} rad to avoid the retardation effects which lead to additional Cerenkov maxima in substances of high dielectric constant [8]).

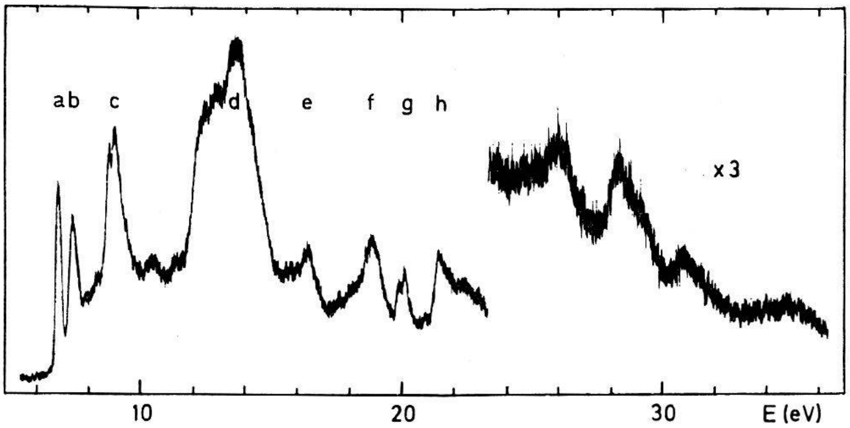

Figure 5

Energy loss spectrum of KBr at 80 °K. Electron energy 51 keV, energy width of the beam 80 meV, foil thickness 930 Å.

2) the X excitons (c) which show the small splitting of the top valence band at the X point,

3) the high energetic Γ and X excitons (g and h) at 20–21 eV, corresponding to transitions from the $3p$ K^+ level. The Γ exciton shows the spin orbit coupling splitting of this $3p$ K^+ level (19,89 eV and 20,12 eV), the X exciton could not be resolved,

4) the high peak at ca. 13,5 eV representing the plasma loss maximum, due to the $6p$ electrons of the valence band ($4pBr^-$-level).

If one deduces from this spectrum the energy loss function, one obtains the full line in Figure 6. The dotted line represents the optical function [11]. There is good agreement concerning the structure in the low energy region, but less in the high energy region. Probably these discrepancies lie in the optical measurements in the far UV, as in the case of Ge and GaP. The absolute values (left scale: electron data) show differences, still to be cleared up.

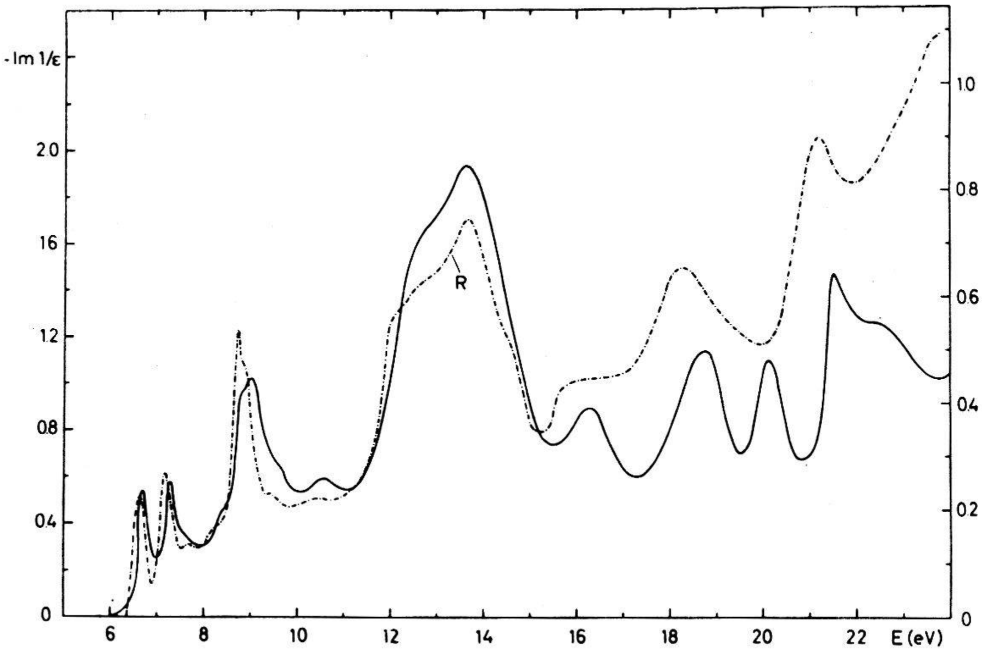

Figure 6

Energy loss function of KBr. Electron loss data: full line. Optical data: dotted line.

The accuracy of the energy loss intensity measurements can be made sufficiently high that they can be regarded in the higher energy region as more reliable than the optical data. This had been applied to derive from $(-\mathrm{Im}\, 1/\varepsilon)_{el}$ by a Kramers Kronig transformation the $(\varepsilon_1, \varepsilon_2)$ values or the absorption coefficient μ resp. the reflection coefficient R [9, 10]. Figure 7 compares the reflexion coefficient R, obtained from electron experiments (full line) with optical data [12]. Recent optical results [13] are in very good agreement with our data, also in the high energy region.

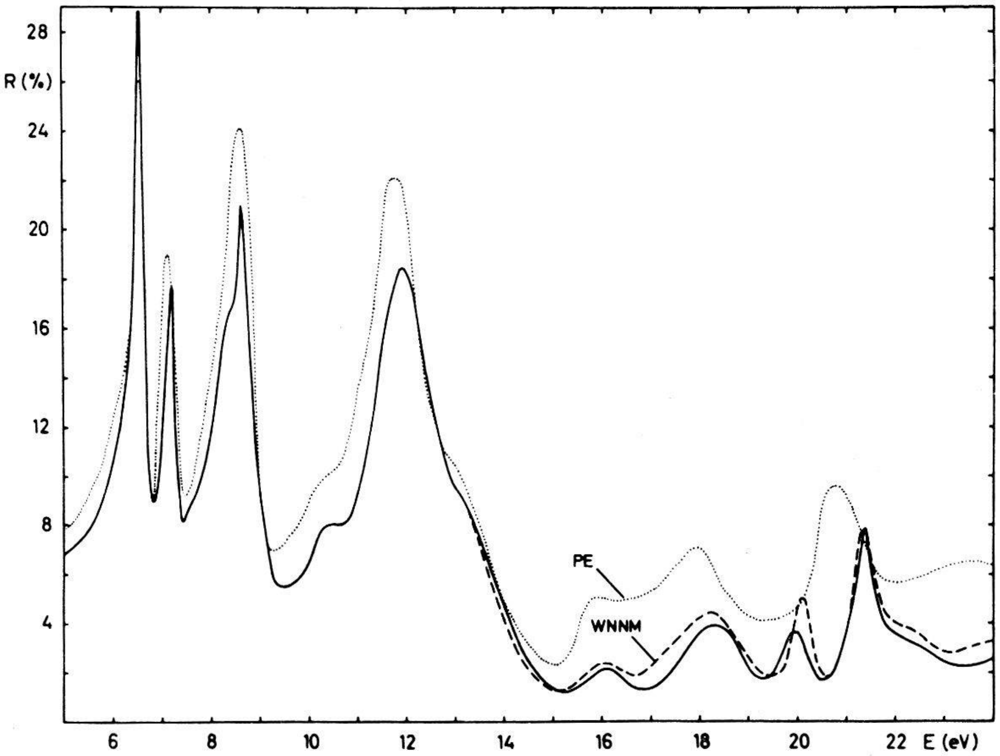

Figure 7

Spectral reflectance curve of KBr deduced from electron loss data (full line) compared with optical measurements.

These examples demonstrate that the energy analysis of electrons having passed a crystal, contains a detailed information of the excitations of the solid.

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