Magneto-Optical Kerr Effect, Enhanced by the Plasma Resonance of Charge Carriers

H. Feil and C. Haas

Laboratory of Inorganic Chemistry, Materials Science Center, University of Groningen, The Netherlands

(Received 23 June 1986)

It is shown by model calculations that the dispersion of the diagonal part of the dielectric constant near the plasma edge in a metallic crystal has a strong influence on the magneto-optical properties. The plasma edge leads to resonancelike peaks in the Kerr rotation and Kerr ellipticity spectra and to a strong enhancement of the magnitude of the Kerr effect. The sharp and very large peaks observed in the Kerr effect of several transition-metal and rare-earth compounds are not necessarily related to sharp magneto-optical transitions, but could be a result of the presence of the plasma edge at the same frequency.

PACS numbers: 78.20.Ls, 71.45.Gm

The magneto-optical Kerr effect is of interest for optical readout of magnetically stored information in erasable video and audio disks.[1] For these applications a large value of the Kerr rotation is required. Other applications of the Kerr effect are microscopy for domain observation[2] and the study of monolayer-range films.[3]

Magneto-optical measurements are also a valuable tool in the study of the magnetic properties and electronic structure of magnetic materials. Optical reflection measurements can be used to determine the diagonal elements of the dielectric tensor. A disadvantage is that the reflection spectra of many intermetallic compounds do not show a pronounced fine structure; as a consequence the information obtained from reflection spectra about the electronic structure is not very detailed, but is mainly limited to the joint density of states. The Kerr effect, in contrast, is a difference technique. Kerr spectra show more fine structure and give interesting information, in particular, for transition-metal and rare-earth compounds.[4-7] Rare-earth compounds are of great current interest because of mixed valence and valence fluctuations. However, the interpretation of the Kerr spectra in terms of electronic transitions is quite complicated. In this paper we show that a pronounced peak in the Kerr spectrum does not necessarily correspond to a particular magneto-optically active electronic transition. In fact, in metallic magnetic compounds, the plasma resonance of the free charge carriers may induce a resonance-shaped magneto-optical Kerr-effect spectrum. We demonstrate by some simple model calculations that this interplay of magneto-optically active electronic transitions with the plasma resonance of free charge carriers can result in a strong enhancement of the Kerr rotation and Kerr ellipticity.

The Kerr effect is related to the material properties by the equation[8]

$$\phi_K + i\varepsilon_K = \varepsilon_{xy}/\varepsilon_{xx}^{1/2}(1-\varepsilon_{xx}), \tag{1}$$

where ϕ_K is the Kerr rotation, ε_K is the Kerr ellipticity, and ε_{xx} and ε_{xy} are the diagonal and off-diagonal parts of the complex dielectric tensor, respectively. The off-diagonal part ε_{xy} is the origin of the magneto-optical Kerr effect, and it has contributions from interband and intraband electronic transitions. From Eq. (1) we note that for nonnegligible $\varepsilon_{xy}(\omega)$ the Kerr effect will be large if the denominator $\varepsilon_{xx}^{1/2}(1-\varepsilon_{xx})$ is small. In particular, a large resonancelike enhancement of ϕ_K and ε_K is expected in the frequency region where the real part of ε_{xx} is equal to 1. That is in the vicinity of the plasma edge of metals.

In order to demonstrate the enhancement effect, we present some model calculations. We consider a metal with the diagonal part of the dielectric constant given by

$$\varepsilon_{xx}(\omega) = \varepsilon_0(\omega) + \varepsilon_{\text{intra}}(\omega). \tag{2}$$

The complex dielectric constant $\varepsilon_{xx} = \varepsilon'_{xx} - i\varepsilon''_{xx}$ contains a contribution $\varepsilon_0(\omega)$ from interband transitions. The second term describes, by a simple Drude-type equation, the intraband transitions of the charge carriers:

$$\varepsilon_{\text{intra}}(\omega) = 1 - \omega_{p0}^2/(\omega^2 - i\omega/\tau). \tag{3}$$

The scattering of the charge carriers is characterized by a relaxation time τ, related to the electrical conductivity σ by $\sigma = ne^2\tau/m^*$. The unscreened plasma frequency ω_{p0} is related to the concentration n of the charge carriers by $\omega_{p0}^2 = 4\pi ne^2/m^*$; m^* is the effective mass. The coupled plasma frequency ω_p is determined by the condition $\varepsilon'_{xx} = 0$. We represent the interband transitions by a single oscillator,

$$\varepsilon_0(\omega) = A/(\omega_1^2 - \omega^2 + i\omega/\tau_1), \tag{4}$$

at an energy $\hbar\omega_1$ with a damping $\hbar/\tau_1$ and a strength A.

Magneto-optical effects are a consequence of the off-diagonal part of the dielectric tensor, $\varepsilon_{xy}(\omega)$. There will be contributions to ε_{xy} that arise from interband and intraband transitions. We want to show that even if ε_{xy} has little or no dipsersion in a particular energy region, the observed Kerr effect can show a strong frequency dependence and even an oscillatory behavior. In order to demonstrate this effect we take, for simplicity, a constant

value of σ_{xy}, independent of the frequency, related to $\varepsilon_{xy}(\omega)$ by $\varepsilon_{xy}(\omega)=4\pi i\sigma_{xy}/\omega$.

We have calculated the Kerr rotation and ellipticity from Eq. (1) for several cases. We show in Fig. 1 two of the most illustrative ones. In the first case we take for the Drude-type part of Eq. (2) the scattering parameter $\hbar/\tau=0.5$ eV, and the unscreened plasma frequency $\hbar\omega_{p0}=7$ eV. The calculation is for an interband transition at energy $\hbar\omega=3$ eV, damping $\hbar/\tau_1=7$ eV, and a strength $\hbar^2A=100$ eV.[2] We see that the imaginary part ε''_{xx} falls off slowly [Fig. 1(a)] as a result of the relatively small scattering time τ and the influence of the interband transitions described by $\varepsilon_0(\omega)$. Moreover, there is no finite frequency where $\varepsilon'_{xx}=1$, and as a consequence no resonance effects are found in the Kerr effect [Fig. 1(a)].

In the second case we take for the Drude-type part the scattering parameter $\hbar/\tau=0.1$ eV, and the unscreened plasma frequency $\hbar\omega_{p0}=5$ eV. The calculation is for an interband transition at energy $\hbar\omega=4$ eV, damping $\hbar/\tau 1=4$ eV and a strength $\hbar^2A=50$ eV.[2] In Fig. 1(b) we see that the coupled plasma energy ($\varepsilon'_{xx}=0$) is at $\hbar\omega_p=2.2$ eV. At 2.4 eV ε'_{xx} is equal to 1. This produces a strong effect in the Kerr spectrum in this region; the Kerr rotation ϕ_K and the Kerr ellipticity ε_K show a resonancelike frequency dependence and the magnitudes of ϕ_K and ε_K are enhanced. We also found that an increased steepness of the curve of ε'_{xx} vs $\hbar\omega$ near the frequency where $\varepsilon'_{xx}=1$ results in a sharper resonancelike peak in the Kerr spectrum. The calculations clearly show that the dispersion in the diagonal part of the dielectric tensor can play a dominant role in the dispersion and strength of the magneto-optical Kerr effect. We emphasize that, although the off-diagonal part of the dielectric constant is the same, the two cases of Figs. 1(a) and 1(b) show a widely different frequency dependence of the Kerr rotation and the Kerr ellipticity. Especially in the case of a steep plasma edge, due to interband transitions just above the coupled plasma frequency, the enhancement is very strong.

We now discuss Kerr-effect data of some compounds, reported in the literature, in the light of the considerations presented above. The dielectric constants of PtMnSb[9] and TmS[4] are shown in Figs. 2 and 3. The real part ε'_{xx} of the dielectric constant becomes equal to 1 at 1.6 and 2.6 eV, respectively. Precisely at these energies the Kerr effect of PtMnSb[10] and TmS shows a pronounced resonancelike structure, with a frequency dependence very similar to that obtained from our calculations [Fig. 1(b)]. We believe that the strong dispersion of the Kerr effect in this frequency region is due to the interference with the plasma edge, and not to sharp electronic transitions at 1.6 and 2.6 eV, respectively.

Recently $4f$ compounds have received attention because of their large Kerr effect. Strong Kerr effects with a sharp resonance structure similar to that in TmS[4] (Fig. 3) were reported for TmSe[4] (which is a mixed-valence compound[11]) and the cerium compounds CeSb,

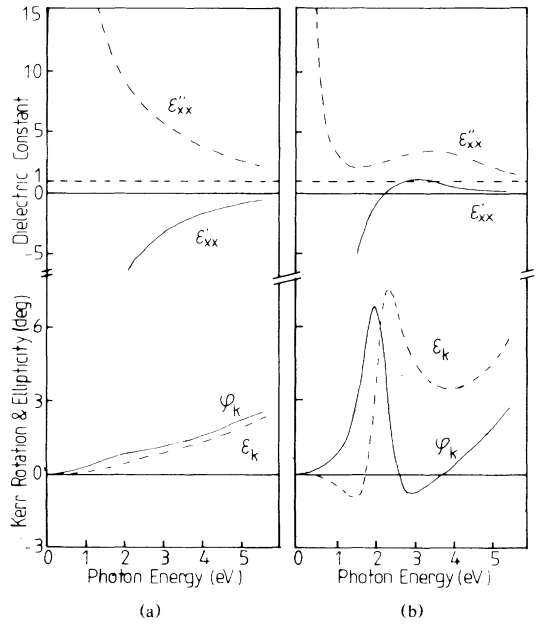

FIG. 1. Dielectric constant and Kerr effect ϕ_K, ε_K of a metallic crystal with $\sigma_{xy}=1+i$ and (a) $\hbar\omega_{p0}=7$ eV, $\hbar/\tau=0.5$ eV, $\hbar\omega_1=3$ eV, $\hbar/\tau_1=7$ eV, and $\hbar^2A=100$ eV^2. (b) $\hbar\omega_{p0}=5$ eV, $\hbar/\tau=0.1$ eV, $\hbar\omega_1=4$ eV, $\hbar/\tau_1=4$ eV, and $\hbar^2A=50$ eV^2.

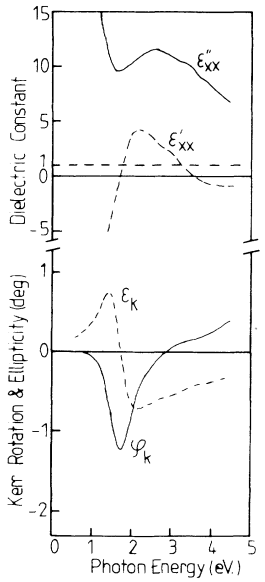

FIG. 2. Dielectric constant and Kerr effect ϕ_K, ε_K of the half-metallic compound PtMnSb at 300 K.

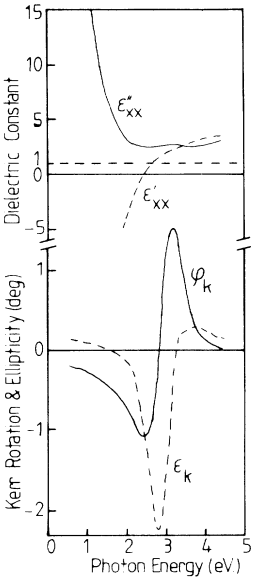

FIG. 3. Dielectric constant and Kerr effect ϕ_K, ε_K of TmS at 2 K and $B=4$ T.

$CeSb_{0.75}Te_{0.25}$, and CeTe.[12] The special chemical and physical properties of cerium and cerium compounds are due to the Ce $4f$ electron. Photoemission experiments[13] have been used to determine the energy of the $4f$ level. The giant Kerr effect in cerium compounds[10] (values up to $\phi_K=15°$ at $\hbar\omega=0.5$ eV, $T=2$ K, and $B=5$ T) was assigned to a sharp single electronic transition $4f^1 \rightarrow 4f^0 5d^1$. Of course, sharp magneto-optically active transitions with large values of ε_{xy} in a narrow frequency region lead to sharp Kerr peaks. However, the observed Kerr peaks all occur just in the frequency region where $\varepsilon'_{xx}=1$. The displacement of the Kerr peak in the series CeSb, $CeSb_{0.75}Te_{0.25}$, CeTe precisely follows the expected shift of the plasma edge, due to the change of the carrier concentration obtained by substitution of Sb by Te. This indicates that also in these compounds the sharp structure observed in the Kerr effect is caused by the plasma resonance ($\varepsilon'_{xx} \approx 1$), and cannot be considered as evidence for a sharp $4f^1 \rightarrow 4f^0 5d^1$ transition.

The large Kerr peaks in TmS and TmSe[4] have also been attributed to an exchange splitting of the plasma edge. An exchange splitting will result indeed in a resonancelike peak of the Kerr effect at the plasma frequency. However, generally the combination of a plasma edge with a nondiagonal dielectric constant ε_{xy} leads to a magnitude splitting of the plasma resonance; this effect is independent of the microscopic origin of ε_{xy}. In Ref. 4 it is assumed that ε_{xy} is due to skew scattering of charge carriers. However, our calculations show that also if ε_{xy} is due to magneto-optically active interband transitions, a resonancelike behavior of the Kerr effect near the plasma edge is expected. We conclude that the coincidence of the maximum of the Kerr ellipticity with the plasma frequency does not prove the free-electron origin of ε_{xy}.

Several uranium compounds also have large magneto-optical effects.[6,14] In these materials the off-diagonal conductivity is quite large. However, the Kerr rotation and Kerr ellipticity show maxima at a different energy from the energy of the maximum of the off-diagonal conductivity. This again is due to the strong dispersion in the diagonal dielectric constant, due to the charge carriers and interband transitions.[15] In order to assign magneto-optic effects to specific electronic transitions, one should consider maxima of the off-diagonal conductivity; the maxima in the Kerr rotation and ellipticity are not representative. In the case of a very sharp Kerr effect a problem arises in the calculation of the conductivity tensor from reflection and Kerr measurements. The sharp Kerr effect is mainly caused by a steep plasma edge. In the calculation one effect is divided by the other, leading to relatively large errors in the conductivity tensor. This is especially the case when the position of the plasma edge is temperature dependent and the two measurements are not performed at the same temperature.

We conclude that for many magnetic metallic materials with a steep plasma edge, the sharp peaks in the Kerr effect are not due to sharp electronic transitions, but rather to the influence of the plasma resonance. The plasma resonance leads to a strong enhancement of the Kerr effect. Considerations of this enhancement can be useful in the search for materials with a large Kerr effect for technological applications.

The authors wish to thank J. Dijkstra for helpful suggestions.

[1]K. H. J. Buschow, P. G. van Engen, and R. Jongebreur, J. Magn. Magn. Mater. **38**(1), 1–22 (1983); M. Hartmann, B. A. Jacobs, and J. J. M. Braat, Philips Tech. Tijdschr. **42**, 41 (1985).

[2]F. Schmidt, W. Rave, and A. Hubert, IEEE Trans. Magn. **21**, 1596 (1985); D. A. Herman, Jr., and B. E. Argyle, IEEE Trans. Magn. **22**, 772–774 (1986).

[3]S. D. Bader, E. R. Moog, and P. Grünberg, J. Magn. Magn. Mater. **53**, L295 (1986).

[4]W. Reim, O. E. Huesser, J. Schoenes, E. Kaldis, P. Wachter, and K. Seiler, J. Appl. Phys. **55**, 2155 (1984).

[5]J. L. Erskine and E. A. Stern, Phys. Rev. B **8**, 1239 (1973).

[6]W. Reim, J. Schoenes, and O. Vogt, Phys. Rev. B **29**, 3252 (1984).

[7]W. Reim and P. Wachter, Phys. Rev. Lett. **55**, 871 (1985).

[8]P. N. Argyres, Phys. Rev. **97**, 334 (1955).

[9]P. A. M. van der Heide, W. Baelde, R. A. de Groot, A. R. Vroomen, P. G. van Engen, and K. H. J. Buschow, J. Phys. F **15**, L75–L80 (1985).

[10]R. A. de Groot, F. M. Mueller, P. G. van Engen, and K. H. J. Buschow, Phys. Rev. Lett. **50**, 2024 (1983).

[11]*Valence Fluctuations in Solids,* edited by L. M. Falicov, W. Hanke, and M. P. Maple (North-Holland, Amsterdam, 1981).

[12]W. Reim, J. Schoenes, F. Hulligen, and O. Vogt, J. Magn. Magn. Mater. **54–57**, 1401–1402 (1986).

[13]A. Franciosi, J. H. Weaver, Nils Martensson, and M. Croft, Phys. Rev. B **24**, 3651 (1981); Y. Baer, R. Hauger, Ch. Zürcher, M. Campagna, and G. K. Wertheim, Phys. Rev. B **18**, 4433 (1978).

[14]W. Reim, J. Schoenes, and O. Vogt, Solid State Commun. **47**, 597 (1983).

[15]J. Schoenes, Phys. Rep. **66**, 187 (1980).