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COMPLEX DIELECTRIC CONSTANT OF $Cd_{0.8}Mn_{0.2}Te$ CRYSTALS NEAR THE FUNDAMENTAL ABSORPTION EDGE

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The complex dielectric constant of $Cd_{0.8}Mn_{0.2}Te$ single crystals is determined from reflection measurements in the photon energy range from 1.75 to 2 eV at the lattice temperature $T = 2$ K. The light reflection model includes exciton absorption and dispersive background dielectric constant contribution. The same model is found to be efficient in describing the band of nonreciprocal reflection arising in nonzero magnetic field in the Voigt geometry.

Keywords: diluted magnetic semiconductors, excitons, light absorption and reflection

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1. Introduction

Diluted magnetic semiconductors, like $Cd_{1-x}Mn_x$-Te crystals, attract much interest because of the strong exchange interaction of electrons and holes with magnetic moments of substitution (Mn) atoms [1]. The promises of this interaction include optical isolators on the giant Faraday effect [2], spintronics [3], lasers [4], and other device applications of tunable bands and lines observed in bulk crystals, magnetic quantum wells [5–7], and dots [8, 9]. Device operation at the fundamental absorption edge is of special interest because of the most pronounced dependence of the material optical parameters on the interacting photon energy.

In the theory, existing models of light absorption and refraction near the fundamental absorption edge do either not take into account exciton effects or, on the contrary, disregard the background dielectric constant dispersion in the vicinity of the absorption edge. Tanguy [10, 11] proposed a model function including both these effects in the description of the refraction and extinction index at the fundamental absorption edge. However, the function does not refer to the exchange interaction of carrier spins with the magnetic moments of substitution atoms.

Experimental data on the $Cd_{1-x}Mn_xTe$ dielectric constant are rather scarce, even when one deals with the optical and static limiting values. Optical value of $\varepsilon_\infty = 7.25$ is inferred from the low-energy value of the refraction index of CdTe [12] and used as a background when describing exciton effects. However, experimental reflection spectra at exciton lines in CdTe/CdMnTe superlattices have been found to require the background dielectric constant as high as 9.95 [5]. Exact data on the complex dielectric constant of bulk crystals in a broad spectral range are needed both for the substrate and optical device applications.

The aim of the present study is determination of the complex dielectric constant of $Cd_{0.8}Mn_{0.2}Te$ single crystals in the absence of magnetic field. The photon energy range (1.75 to 2 eV) is selected in order to encompass the fundamental absorption edge. The complex dielectric constant is elucidated from experimental data on light reflection at oblique incidence. The light reflection model is presented, including exciton absorption and crystal background contribution.

2. Experiment

$Cd_{0.8}Mn_{0.2}Te$ single crystals with Mn molar fraction of 20% were grown by the Bridgeman method and cleaved in order to have optically clean surface. Halogen lamp radiation was directed at the angle of 45° to the surface (Fig. 1, inset). Reflected light, at selected polarization, was analysed with the use of a 0.3 m Jobin Yvon SPEX spectrometer and CCD detector, and the spectrum was referenced to that of the lamp at the same polarization without the sample. The measurements were carried out on samples immersed in liquid He at the temperature of 2 K controlled by an Oxford Spectromag^{4000} cryostat with superconducting coils.

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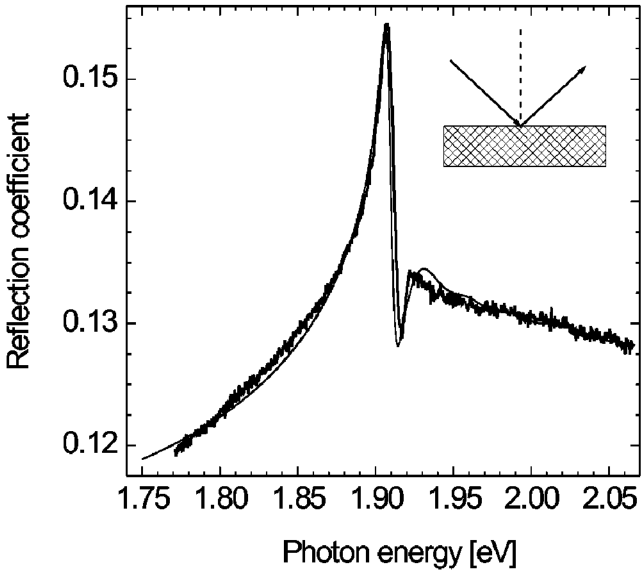

Fig. 1. Experimental light reflection spectrum of the $Cd_{0.8}Mn_{0.2}Te$ single crystal, and the calculated one (smooth line) taking into account both the excitonic and valence-to-conduction band transitions. The inset shows the scheme of reflection at the air–crystal boundary. The light electric field is in the incidence plane, and the steady magnetic field (if any) is normal to this plane.

In the absence of magnetic field, a reflection peak (Fig. 1) is observed at the energy of 1.907 eV which is slightly lower than the band gap of the $Cd_{1-x}Mn_xTe$ crystal calculated for Mn molar fraction of $x = 0.2$ [1, 2]. The sharp structure is evidently related to excitons, however, it seems to be superimposed on a general broad reflection maximum. These experimental features are subject to modelling with an account for excitons and interband transitions.

3. Modelling

The dielectric function is supposed to be additive:

$$\varepsilon(E) = \varepsilon_\infty\big(1 + A_\mathrm{f}(E) + A_\mathrm{e}(E)\big). \qquad (1)$$

Here ε_∞ stands for the contribution of atom core electrons, $A_\mathrm{f}(E)$ represents the fundamental absorption edge, i. e. valence-to-conduction band transitions, and $A_\mathrm{e}(E)$ is the part related to excitonic transitions.

The interband transitions are expressed by the sum of quasi-oscillator terms:

$$A_\mathrm{f} = \sum_{i=1}^{n} \frac{F_{\mathrm{f}i}}{E_{\mathrm{f}i}^2 - E^2 + \mathrm{i}E\Gamma_{\mathrm{f}i}}, \qquad (2)$$

where E_f is the oscillator energy, F_f is the oscillator strength, and Γ_f is the associated damping factor. In fact, the summation of this term ought to be expressed as an integral with the lower limit of energies $E_{\mathrm{f}1} > E_\mathrm{g}$, where E_g is the bandgap energy, and the upper one $E_{\mathrm{f}n}$ tending to infinity. However, the limited number of terms equidistant in energy is used to describe the experimental results.

The excitonic transitions are presented in the similar form with the change of subscript "fi" to "$\pm$" in Eq. (2), and the dielectric constant values are ε_+, ε_-, and $\varepsilon_\parallel$ for the σ_+, σ_-, and π transitions, respectively. In this case the summation accounts for transitions between all relevant pairs of the Zeeman levels. The complex reflection coefficient of the p-polarized wave incident on the crystal from the air at the angle ϑ [13] can be expressed as

$$r_\pm = \frac{\big[\varepsilon_\mathrm{V}\cos\vartheta + \mathrm{i}\sqrt{\sin^2\vartheta - \varepsilon_\mathrm{V}}\big] \pm (\varepsilon_{xy}/\varepsilon_{xx})\sin\vartheta}{\big[\varepsilon_\mathrm{V}\cos\vartheta - \mathrm{i}\sqrt{\sin^2\vartheta - \varepsilon_\mathrm{V}}\big] \mp (\varepsilon_{xy}/\varepsilon_{xx})\sin\vartheta}. \qquad (3)$$

Here ε_V is the effective dielectric function in the Voigt geometry:

$$\varepsilon_\mathrm{V} = \frac{\varepsilon_{xx}^2 + \varepsilon_{xy}^2}{\varepsilon_{xx}}, \qquad (4)$$

where $\varepsilon_{xx} = (\varepsilon_+ + \varepsilon_-)/2$ and $\varepsilon_{xy} = (\varepsilon_+ - \varepsilon_-)/(2\mathrm{i})$ are the components of the dielectric tensor. The presence of magnetic field normal to the saggital plane results in the nonreciprocal reflection accounted for by the last terms including the nondiagonal component of the dielectric tensor. In the absence of magnetization $\varepsilon_{xy} = 0$, and the reflection is reciprocal: $r(\vartheta) = r(-\vartheta)$. The exciton contribution is then accounted for by the single values of energy E_0, oscillator strength F_0, and the level broadening factor Γ_0.

4. Results

The reflection model fitting to the experimental data at B=0 is in reasonable agreement with experiment (Fig. 1) if the optical dielectric constant value is $\varepsilon_\infty = 7$ and the sum of eight equidistant oscillator contributions is taken for the interband transitions with the parameter range of $1.934 \le E_{\mathrm{f}i} \le 2.145$ eV, $0.28 \le F_{\mathrm{f}i} \le 0.48$ (eV)^2, and $\Gamma_{\mathrm{f}i} = 5.8 \cdot 10^{-2}$ eV. The oscillator strength $F_{\mathrm{f}i}$ is a bell-shape function with the maximum at 2.085 eV. The best fit of experimental data was obtained with the exciton parameters $E_0 = 1.909$ eV, $F_0 = 3.89 \cdot 10^{-3}$ (eV)^2, and $\Gamma_0 = 8.0 \cdot 10^{-3}$ eV. The value of E_0 agrees well with the free exciton energy estimated for $x = 0.2$ at $T = 1.4$ K [14] and exceeds slightly the energy of the reflection peak attributed to

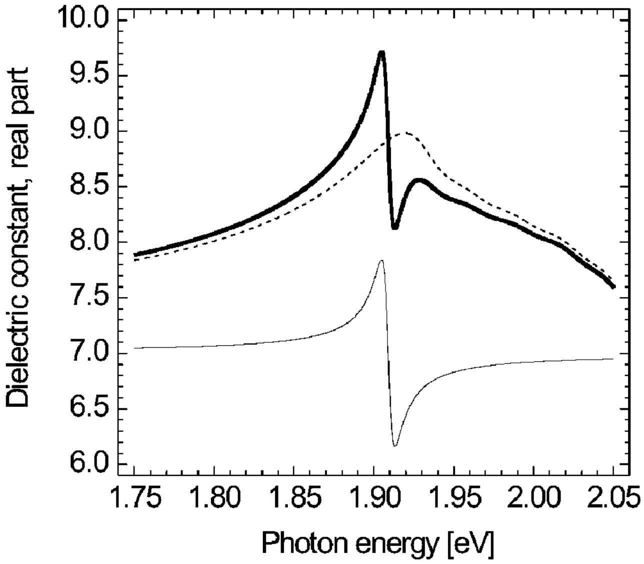

Fig. 2. The real part of the $Cd_{0.8}Mn_{0.2}Te$ dielectric constant (solid line) determined from the model fitting to the experimental data on reflectivity, and the partial contributions of excitons (thin solid line) and valence-to-conduction band transitions (dashed line) with $\varepsilon_\infty = 7$ retained.

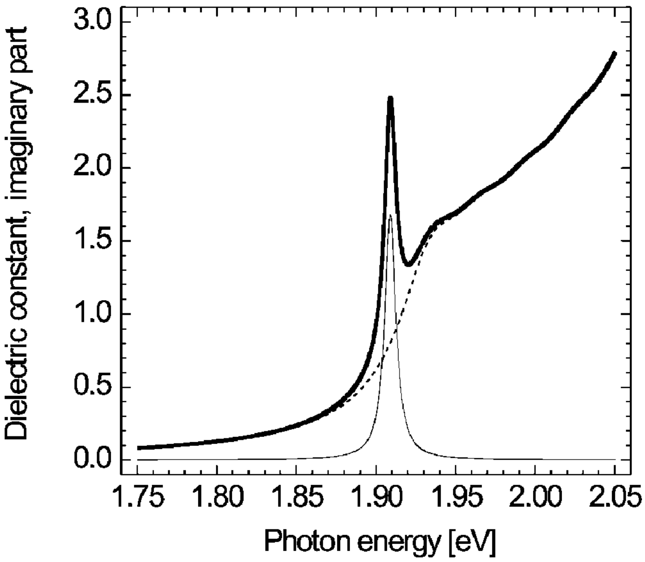

Fig. 3. The imaginary part of the $Cd_{0.8}Mn_{0.2}Te$ dielectric constant with the same curve designation as in Fig. 2.

the excitation from the top of the valence band (Te $5p$ states) to the Cd $5s$ states [15].

With the above parameters the complex dielectric constant for the $Cd_{1-x}Mn_xTe$ crystal is presented in Figs. 2 and 3 by solid curves. Partial contributions of excitons (thin curves) and the interband transitions (dotted curves) are shown as well. Exciton contribution is significant in a rather narrow energy range close to the exciton line, whereas interband transitions (represented

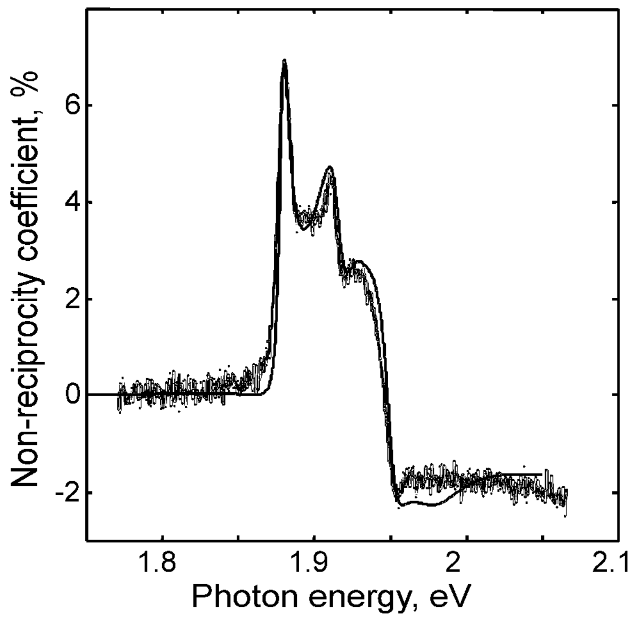

Fig. 4. Measured nonreciprocity factor and its modelling result (smooth line) for the $Cd_{0.8}Mn_{0.2}Te$ single crystal at $B = 2$ T.

by the series of oscillator contributions) are seen to be significant in the entire energy range of interest.

The same model was used to describe the nonreciprocal reflection arising in the nonzero magnetic field due to the crystal magnetization that enters in the first power in the nondiagonal term of the dielectric constant ε_{xy}. As it is obvious from Eq. (3), the reversal of magnetization direction is equivalent to the reversal of the incidence angle. The nonreciprocity factor is the ratio $\eta = 2(R_{+B} - R_{-B})/(R_{+B} + R_{-B})$, where $R_\pm = |r_\pm|^2$. The sharp peculiarities of the nonreciprocal factor (Fig. 4) allow for much more exact measuring of the Zeeman splitting as compared to conventional reflection experiments. The left peak relates to the lowest-energy transition induced by right-hand photons (σ_+), the central one is formed by both σ_+ and σ_- transitions with very close energy values, and the strongly suppressed right peculiarity is created by the highest-energy σ_- transition. As seen in Fig. 4, the modelling reasonably describes the band of nonreciprocal reflection observed in experiments.

5. Conclusion

The model based on the multiple quasi-oscillator function accounting for various kinds of transitions presents a convenient tool for the complex dielectric constant elucidation from experimental reflection data at the fundamental absorption edge. The real part of the complex dielectric constant of $Cd_{0.8}Mn_{0.2}Te$ single crystals exhibits a peak value of 9.7. It is related both to free excitons and to additional highly broadened dispersive contribution. The latter is seemingly caused by interband transitions but the participation of excitons localized in the disordered potential wells or dots of the semimagnetic solid solution is not excluded. The values of the complex dielectric constant given in Figs. 2 and 3 are ready for use in the material technology and optical applications.

The quasi-oscillator function is readily applicable to the material research in magnetic fields, as shown by the comparison of experimental and model data on the nonreciprocal light reflection. The peaks of nonreciprocal reflection present refined data on the Zeeman splitting.

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$Cd_{0,8}Mn_{0,2}Te$ KRISTALŲ KOMPLEKSINĖ DIELEKTRINĖ SKVARBA TIES FUNDAMENTINĖS SUGERTIES KRAŠTU

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Santrauka

Iš šviesos atspindžio matavimo duomenų 1,75–2 eV fotonų energijos verčių ruože įvertinta $Cd_{0,8}Mn_{0,2}Te$ kristalų kompleksinė dielektrinė skvarba $T = 2$ K gardelės temperatūroje. Šviesos atspindžio modelyje atsižvelgta į eksitoninę sugertį ir liktinį dispersinį kristalo įnašą į dielektrinę skvarbą. Taikant modelį šviesos atspindžio neapgręžiamumui aprašyti magnetiniame lauke Voigt'o geometrijoje, kai šviesa krenta į kristalą įžambiai, pasiektas geras eksperimento ir skaičiavimo duomenų atitikimas; surasti eksitono fizikiniai parametrai (Zeeman'o suskilimas, eksitono linijos plotis).