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Intensity dependent deflection spectroscopy for absorption measurements

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Abstract. We report on a method for the characterization of optical absorption in semiconductors at photon energies below the bandgap energy. We use intensity dependent deflection spectroscopy to measure spatially resolved the optical absorption and to separate the occurring absorption mechanisms. To this end, we take advantage of the different intensity scaling of these mechanisms and extract the material parameters by fitting the intensity dependent absorption to a physical model. Our method enables a simple but sufficient determination of crucial optical loss properties (e.g. impurity related absorption and two-photon absorption) in various semiconductor systems, e.g. substrates for optical components or solar cells.

1 Introduction

The performance of a variety of optical applications, e.g. in photovoltaics and telecommunication, is strongly influenced by optical absorption processes [1], [2]. The determination of the strength of each of these processes is desirable in order to physically understand the optical loss behaviour of the respective application and potentially enable ways for their tuning. The widely used method to distinguish between different absorption processes is time-resolved absorption spectroscopy: in this approach, the different time scaling of various loss processes (e.g. free carrier creation, phonon-assisted absorption and pure field effects) is utilized [3]. However, this method requires synchronized short pulse excitation and detection which makes it experimentally challenging and expensive concerning measurement infrastructure. We developed a different approach, combining well established spatially resolved deflection spectroscopy [4] and intensity dependent measurements. Fitting the intensity dependent deflection signal to a physical model that describes the different power scaling of optical loss effects enables the separation of these effects by simple cw detection. The extraction of actual material parameters such as the linear attenuation coefficient and the two-photon absorption coefficient is performed by calibrating the setup and utilizing affiliated finite element (FEM) computations. We reproduced well known absorption parameters for silicon and gallium arsenide in order to verify our measurement method. Furthermore, we determined the strength of the Franz-Keldysh effect in cadmium telluride for the first time as $C_{\mathrm{FK}} = [8.7 \ldots 16.9] \times 10^{13}\ \mathrm{m^{-1} s^{-1/2}}$.

2 Experimental setup

The experimental setup is sketched in figure 1. We utilize deflection spectroscopy [4] with a cw laser diode at a wavelength of 1310 nm as probe source. Its deflection is probed by a quadrant detector. The pump source is an Er-doped fs fibre laser with centre wavelengths of about 1600 nm (used for Si and GaAs) or 800 nm (used for CdTe). The ultra-short pulses lead to peak intensities of above $10^{13}\ \mathrm{W/m^2}$ at which nonlinear absorption effects are significant loss contributions. The pump intensity is scanned over more than two orders of magnitude in order achieve an intensity dependent deflection signal. Spatial resolution is enabled by shifting the readout point where pump and probe beam cross each other.

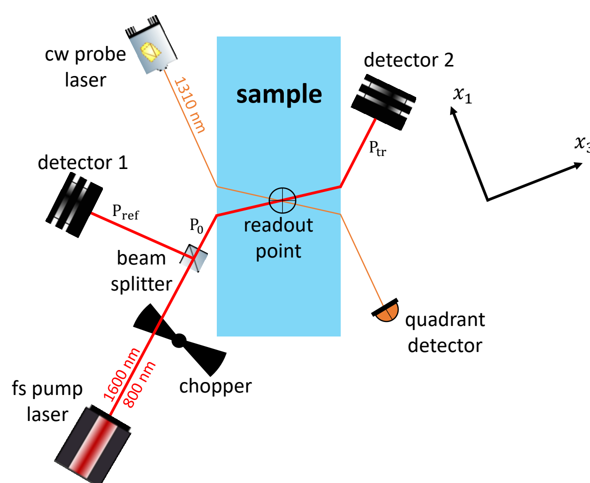

Fig. 1. Deflection setup for absorption measurements.

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3 Modelling of absorption mechanisms

The modelling of the absorption mechanisms and their influence on the deflection signal is necessary to determine quantitative material parameters. The modelling is divided into three parts: first, free charge carriers are created due to linear absorption from defect states (the corresponding material parameters is the linear attenuation coefficient α) and due to quadratic two-photon absorption [5] from the valence band (two-photon absorption coefficient β). This directly leads to a refractive index change and thus to a deflection signal. The dynamics of this process is described by the carrier diffusion equation that is numerically solved by FEM.

Second, the free charge carriers recombine after a certain lifetime and are generating heat. This leads to a local temperature rise in the sample and consequently to another signal contribution. As this process is much slower than the free carrier recombination (few ms half-life compared to several ns charge carrier lifetime), the temperature related deflection signal is much stronger than the charge carrier related signal. An exemplary FEM computed temperature field in the GaAs sample is depicted in figure 2.

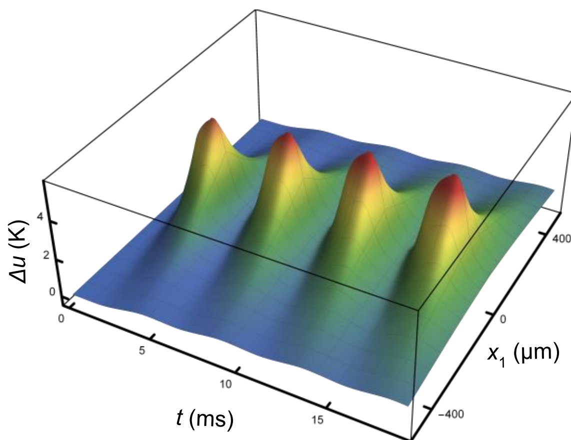

Fig. 2. Computed spatially and time-resolved temperature rise in the GaAs sample for a peak intensity of $10^{13}\ \mathrm{W/m^2}$.

Third, the electric field of the pump laser itself leads to a change of the dielectric function of the sample material. The dominating pure field effect in the investigated wavelength and intensity regime is the Franz-Keldysh effect (FKE) [6]. It changes both the refractive index (primary effect) and the absorption coefficient, which consequently influences the charge carrier and heat creation (secondary effect). Its strength is described by the material parameter C_{FK}.

We finally formulate a model function based on FEM computations that describes the measured deflection signal X as a function of the pump beam intensity I_0 with the material parameters α, β and C_{FK} as free coefficients.

4 Experimental results

The intensity dependent deflection signal $\{X|I_0\}$ is measured for each sample material at several readout positions. The measurements are fitted by the model function $X(I_0)$ and the three absorption related material parameters are extracted. One measured data set for the GaAs sample and the corresponding fit function are shown exemplarily in figure 3.

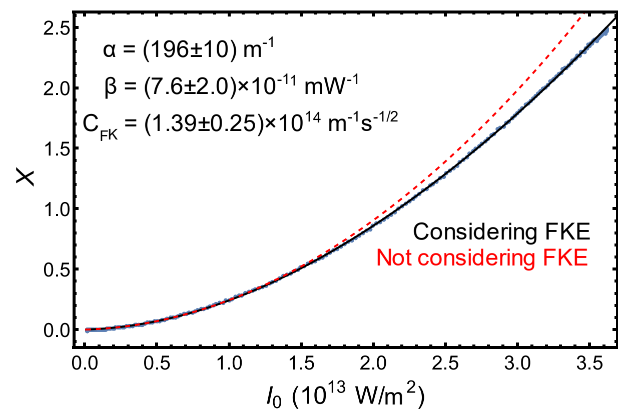

Fig. 3. Measured intensity dependent deflection signal (blue dots) in the GaAs sample, corresponding fit functions with (black line) and without (red line) considering the Franz-Keldysh effect and extracted material parameters.

For very low intensities ($I_0 \leq 10^{12}\ \mathrm{W/m^2}$) the absorption behaviour is predominately linear. For higher intensities, two-photon absorption is the dominant effect. However, for very high intensities ($I_0 \geq 1.5 \times 10^{13}\ \mathrm{W/m^2}$) the FKE is an additional contribution that must be considered. To conclude, we established a simple experimental method for the spatially resolved characterization of absorption mechanisms in semiconductors by combining deflection spectroscopy with intensity dependent measurements. Utilizing this method, we reproduced absorption related literature values for GaAs and Si. Furthermore, we determined the strength of the FKE in CdTe as $C_{\mathrm{FK}} = [8.7 \ldots 16.9] \times 10^{13}\ \mathrm{m^{-1}s^{-1/2}}$.

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