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# Transmission and absorption based photoacoustic methods of determination of the optical absorption spectra of Si samples — Comparison

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ABSTRACT

This paper is a comparison of two photoacoustic methods of determination of the optical absorption coefficient spectra of semiconductors illustrated with results obtained from Si samples. It presents experimental transmission and absorption photoacoustic spectra of Si samples as also the appropriate models leading to the determination of optical absorption coefficient spectra. The idea and the experimental set-up of the analyzed methods are presented in the paper too. From the fitting procedure of theoretical characteristics to experimental transmission and absorption photoacoustic spectra and after computations of the optical absorption coefficient spectra three components of the optical absorption coefficient spectra of Si samples were identified i.e. band to band transitions, Urbach tail and free carrier absorption. Their parameters are given and discussed in the paper. At the end the advantages and disadvantages of both methods are discussed. To the best of our knowledge, no such proof of the correctness of the PA method of determination of optical absorption spectra has been done.



## 1. Introduction

The idea of the photoacoustic (PA) transmission spectrometer, presented in the paper, is based on the theory of the photoacoustic effect developed by Rosencwaig and Gersho [1]. General requirements concerning the apparatus for measurements of the photoacoustic effect were described by Rosencwaig in paper [2]. The intensity of a modulated beam of light absorbed in the sample generates periodic changes of the temperature of the sample. It heats up the gas in the photoacoustic cell. As a result, periodic changes of the overpressure in the photoacoustic cell are observed. This overpressure is measured by a microphone and is called a photoacoustic signal. The photoacoustic effect was next applied in the photoacoustic spectroscopy of several semiconductor materials but the analysis of the PA spectra was mainly qualitative. In a typical approach limited to thermally thick samples, the optical absorption coefficient spectrum is computed from the amplitude spectrum of the PA signal of the investigated sample obtained with the microphone detection method. This method was first applied by Gosh for the investigation of mixed crystals of ZnSeTe [3]. Apart from the microphone detection the mirage effect technique [4,5] and spectroscopic ellipsometry [6,7] methods were also applied for measurements of the optical absorption spectra of silicon and GaAs samples. Results of the conventional transmission measurements, with the photodiode detector, used for determination of the optical absorption coefficient of the polycrystalline silicon with a high oxygen concentration were presented in paper [8]. The carrier concentration dependence of the photoacoustic signal of n-type silicon by the microphone and piezoelectric transducer methods was described in paper [9]. The application of the PA method with microphone detection for measurements of the optical absorption spectra of ZnBeSe and ZnMgBeSe mixed crystals was presented in papers [10,11]. In this paper, two experimental configurations for the PA measurements are presented and discussed. In the first experimental configuration described in the paper the measured PA signal is not proportional to the energy absorbed in the sample but is proportional to the transmitted part of energy which is absorbed in the carbon black substrate, placed behind the sample, being the detector of the transmitted optical energy. In this paper it is called a transmission PA method. In the second experimental configuration the measured signal is proportional to the energy absorbed in the sample. In this paper it is called the absorption PA method. The main aim of the presented investigation was to check which experimental configuration gives better optical absorption coefficient spectra when the same samples are measured on the same experimental set-up with the same photoacoustic cell. There was no experimental photoacoustic absorption spectrum of silicon

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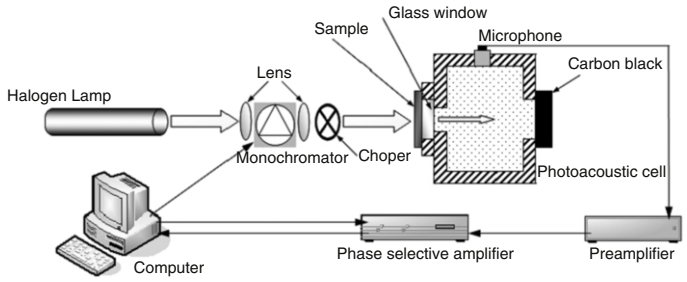


**Fig. 1.** The experimental set-up for the transmission spectra.

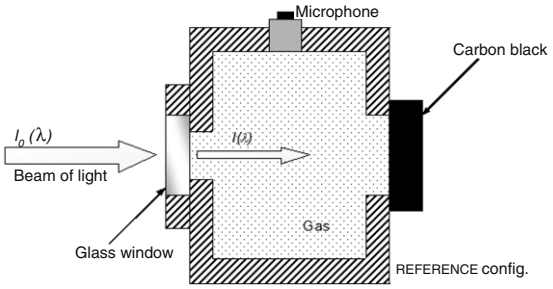


**Fig. 2.** Schematic diagram of the photoacoustic chamber in the reference configuration.

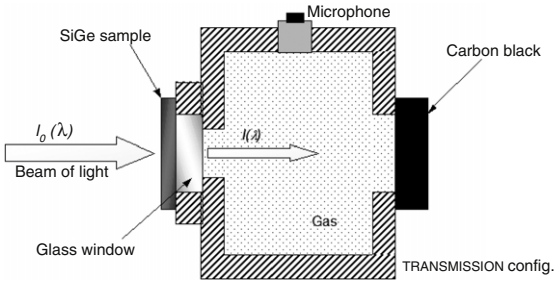


**Fig. 3.** Schematic diagram of the photoacoustic chamber in the transmission configuration.

with the fitting of a theoretical curve especially with the Urbach edge contribution in the literature before.

## 2. Experimental set up

The experimental set up applied for the measurements of the transmission spectra is presented in Fig. 1. It is, from the point of view of the apparatus, a typical configuration for photoacoustic spectral measurements. It consisted of: a halogen lamp as a source of light, a grating monochromator, a mechanical chopper, a set of lenses, a photoacoustic chamber with a microphone, a microphone preamplifier, a lock in phase selective amplifier, a computer and the closed photoacoustic chamber with a carbon black detector made of pressed carbon powder. Transmission and absorption PA measurements were computer controlled i.e. the computer controlled the grating monochromator M250 with a stepper motor, mechanical chopper and the lock in amplifier Scitec Instruments 500 MC. For the measurements a 300 W halogen illuminator was used. Measurements were performed at the frequency of modulation $f = 30$ Hz and the electret microphone with a low noise preamplifier were used for detection of the PA signal.

The schematic diagram of the photoacoustic chamber used for the calibration spectrum of the source of light is shown in Fig. 2. The beam of light goes through the glass window then it is absorbed by the thermally thick carbon black detector giving the photoacoustic signal in the photoacoustic cell. The spectrum of this signal is measured and is treated as a reference spectrum Ref($\lambda$).

The schematic diagram of the photoacoustic chamber used for the measurements of the transmission spectra of semiconductor samples is shown in Fig. 3.

The beam of light goes through the sample, then through the glass window and then it is absorbed by the thermally thick carbon black detector giving the photoacoustic signal in the photoacoustic cell. The spectrum of this signal is measured and is treated as a sample spectrum $P(\lambda)$. The transmission spectrum $T(\lambda)$ is computed as $P(\lambda)/\mathrm{Ref}(\lambda)$. From the fitting of theoretical transmission spectrum to the experimental spectrum the optical absorption coefficient spectrum and the optical reflection coefficient are determined simultaneously.

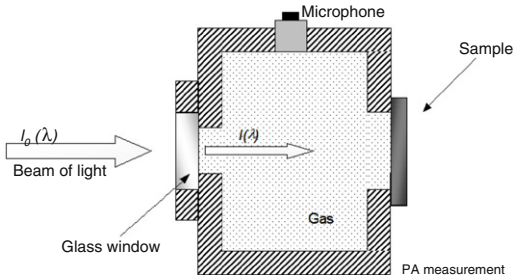


**Fig. 4.** Schematic diagram of the photoacoustic chamber used for the measurements of the PA absorption spectra in the front configuration.

The schematic diagram of the photoacoustic chamber used for the measurements of the PA absorption spectra of semiconductor samples is shown in Fig. 4.

In this configuration the beam of light goes through the glass window and then it is absorbed by the measured sample giving the PA signal in the photoacoustic cell. The spectrum of this PA signal is measured and is treated as a sample spectrum $S(\lambda)$. The PA absorption spectrum PA($\lambda$) is computed as $S(\lambda)/\mathrm{Ref}(\lambda)$. From the fitting of the appropriate theoretical spectrum to the experimental spectrum the optical absorption coefficient spectrum is computed.

## 3. Theory

The transmission spectrum in the case when the optical reflection coefficient $R$ is very small is expressed by formula (1) where $\beta(\lambda)$ is the optical absorption coefficient spectrum, $l$ is the thickness of the sample.

$$T(\lambda) = \exp(-\beta(\lambda) \cdot l). \tag{1}$$

When the optical reflection coefficient $R$ is not equal to zero, that means that the multiple internal reflections of light in the sample take place and are taken into account, the transmission spectrum can be expressed by the following formula [12].

$$T(\lambda) = \frac{(1-R)^2 \cdot \exp(-\beta(\lambda) \cdot l)}{1 - R^2 \cdot \exp(-2 \cdot \beta(\lambda) \cdot l)}. \tag{2}$$