International Journal of Thermophysics, Vol. 24, No. 3, May 2003 (© 2003)

Radiometric Analysis of Laser Modulated IR Properties of Semiconductors[1]

D. Dietzel,[2,3] J. Gibkes,[2] S. Chotikaprakhan,[2] B. K. Bein,[2] and J. Pelzl[2]

A photothermal technique for the characterization of semiconductor materials is presented, in combination with the theoretical description of the signal generation process of the effects of the charge carrier density on the IR optical properties. It relies on the excitation of charge carrier density waves by modulated laser irradiation in the visible spectrum, leading to periodical variations of the IR optical properties. The detection is based on sensing the ir transmission of the semiconductor sample. The modulated laser irradiation in the visible simultaneously leads to small temperature variations and additional signal contributions due to the modulation of the internal IR radiation, which can be minimized and eliminated by appropriate focussing conditions. A principal understanding of the signal generation mechanism has been achieved by time-dependent measurements with a gradually increasing intensity of the external IR radiation source, while frequency-dependent measurements of the modulated IR transmission signal provide quantitative information on the semiconductor properties.

KEY WORDS: charge carrier density oscillations; electronic properties; IR absorption; IR properties; IR transmission; modulation techniques; photothermal radiometry; plasma wave; semiconductors; silicon; thermal wave.

1. INTRODUCTION

The influence of the charge carrier density on the infrared properties of semiconductors is a well known effect that can be exploited for the investigation of semiconductor materials [1, 2]. In this work, an experimental

[1] Paper presented at the Sixteenth European Conference on Thermophysical Properties, September 1–4, 2002, London, United Kingdom.

[2] Experimental Physics III, Solid State Spectroscopy, Ruhr-Universität Bochum, Universitätsstraße 150, D-44780 Bochum, Germany.

[3] To whom correspondence should be addressed. E-mail: dietzel@ep3.ruhr-uni-bochum.de

arrangement is presented, by which the IR transparency of thin semiconductor samples is modified by an Ar^+ laser beam with photon energies above the band gap $h\nu > E_{gap}$. The transmitted IR radiation of an external IR source is then measured and interpreted with respect to variations of the charge carrier density. By using modulated optical excitation, charge carrier density oscillations, also called plasma waves, are excited. These oscillations depend sensitively on the electronic properties of the samples and are thus an appropriate tool for the determination of semiconductor properties. Because of the noncontact and remote detection technique, this type of modulated IR absorption (MIRA), likewise modulated IR transmission (MIRT) measurement can be appropriate to control the processing of semiconductor materials on an industrial scale, e.g., during implantation, etching, and film deposition.

Subsequently, in Section 2 the measurement device is presented. Section 3 is then devoted to the signal generation process, where we discuss the charge carrier diffusion and its influence on the transmittance of external IR radiation, which is responsible for the measured signal. In Section 4, the experimental results are discussed and compared to theoretical approximations based on the theory developed in Section 3. In the conclusions the results are reviewed and perspectives for further work are presented.

2. EXPERIMENTAL SETUP

The experimental setup, schematically shown in Fig. 1, is based on a conventional setup used for photothermal radiometry (PTR) [3, 4]. An Ar^+ laser beam with an output power up to 1 W and a spot diameter of 3 to 4 mm, intensity-modulated by an acousto-optical modulator, serves as a pump beam for the excitation of coupled charge carrier density oscillations (plasma waves) and temperature oscillations (thermal waves).

The plasma waves lead to oscillations of the IR transmittance of the sample, which is probed by the IR radiation emitted by a heated metal plate at approximately 650 K placed as a radiation source behind the semiconductor sample. In this configuration, the external IR radiation source can be considered as a gray body. It has its maximum intensity at about $\lambda_{max} \cong 4.5\ \mu m$, and the spatial distribution of the external IR radiation over the area of modulated optical excitation can be considered as homogeneous. The semiconductor sample is maintained at average temperatures of about 300 to 350 K. A HgCdTe detector with an active area of about 4 mm^2 is used to sense the transmitted IR radiation in the wavelength interval from 2 to 12 μm. The detector signal is analyzed with the help of a lock-in amplifier with respect to its amplitude and the phase shift between excitation and response of the system. In order to characterize the

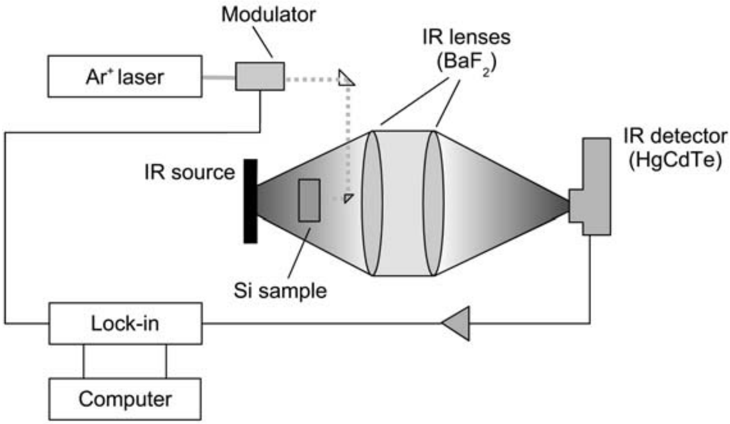

Fig. 1. Schematic of the modulated infrared transmission measurements on semiconductors, based on a conventional photothermal radiometry setup, modified by defocusing the position of the sample under investigation and by focussing an external IR radiation source.

electronic transport properties of semiconductors, measurements have been performed in this configuration by modulating the laser pump beam in the frequency range between 1 Hz and 100 kHz.

In order to reduce the signal contribution of modulated internal IR radiation generated by the modulated laser excitation, the focusing conditions for this experiment have been modified compared to the standard configuration of photothermal radiometry. By positioning the IR radiation source behind the sample and by focusing the transmitted IR radiation on the active detector area, while the semiconductor sample is placed at a defocused position between the IR source and the IR lenses (BaF_2), the effects of the modulated internal IR radiation of the sample are minimized and become negligible. Thus, the setup can be considered as a pump-probe experiment, where the Ar^+ ion laser is used as a pump beam to modulate the IR optical properties of the sample, which are sensed with the help of the external IR radiation beam.

3. BASIC THEORY OF PHOTOMODULATED IR ABSORPTION OF SEMICONDUCTORS

When illuminating the semiconductor sample with photons of energies above the band gap, $h\nu > E_{gap}$, free charge carriers are excited, which will immediately relax to the band edge ($\tau_{relax} \approx 10^{-14}$ to 10^{-12} s), releasing a certain amount of heat to the lattice. After relaxation, the charge carriers diffuse through the semiconductor releasing a second amount of heat to the lattice when they recombine. These processes lead to coupled oscillations of the temperature and of the charge carrier density, the so-called thermal waves and plasma waves. Owing to the small amplitude of the thermal waves and the low average sample temperature reached during the measurements, the thermal excitation of free charge carriers can be neglected and the charge carrier distribution $n(\vec{r}, t)$ is decoupled from the temperature field. When the spot size of the pump laser beam and the thickness of the sample are large in comparison with the typical length scales of charge carrier diffusion, the effects of the charge carrier density oscillations on the IR transmission can be described on the basis of a one-dimensional charge carrier diffusion equation [5],

$$\frac{\partial n(z,t)}{\partial t} - D_{\text{pl}} \nabla^2 n(z,t) + \frac{n(z,t)}{\tau} = \beta_{\text{opt}} \phi_0 \exp(-\beta_{\text{opt}} z) \exp(i 2\pi f t) \tag{1}$$

with the source term of optical charge carrier generation on the right-hand side and the additional term $n(z,t)/\tau$ to describe the charge carrier recombination. Here ϕ_0 is the incident photon flux density at the sample surface, β_{opt} is the optical absorption coefficient, D_{pl} is the charge carrier diffusivity, and τ is the charge carrier lifetime limited by bulk charge carrier recombination.

By considering the appropriate boundary conditions [6], which include charge carrier recombination at the sample surface characterized by the surface recombination velocity s_{sur}, the frequency-dependent complex plasma wave $\Delta n(z, f, t)$ can be calculated analytically,

$$\Delta n(z,f,t) = \left(\frac{-s_{\text{sur}} - \beta_{\text{opt}} D_{\text{pl}}}{s_{\text{sur}} + \xi_{\text{pl}}(f) D_{\text{pl}}} e^{-\xi_{\text{pl}}(f) z} + e^{-\beta z} \right) \frac{\phi_0 \beta_{\text{opt}}}{D_{\text{pl}}} \frac{1}{\xi_{\text{pl}}^2(f) + \beta_{\text{opt}}^2} e^{i 2\pi f t} \tag{2}$$

where the complex plasma wave vector is defined by

$$\xi_{\text{pl}}(f) = \frac{1}{\sqrt{D_{\text{pl}}}} \sqrt{\frac{1}{\tau} + i 2\pi f} \tag{3}$$

Owing to the interaction of free charge carriers and electromagnetic waves, the plasma waves then affect the sample's IR optical absorption coefficient. Assuming relatively small changes of the charge carrier density Δn, the variation of β_{IR} with the charge carrier density variations can be described by a Taylor series,

$$\beta_{\text{IR}}(z,f,t) = \beta_{\text{IR},0} + \beta_{\text{IR},1} \Delta n(z,f,t) \tag{4}$$

between the IR optical absorption coefficient and the charge carrier density Δn [7].

The transmitted IR radiation $I_{\mathrm{trans}}(f, t)$ is then calculated by an integral over the sample thickness d,

$$I_{\mathrm{trans}}(f, t) = I_0 \exp\left(-\int_0^d \beta_{\mathrm{IR}}(z, f, t)\, dz \right)$$

$$= I_0 \exp(-\beta_{\mathrm{IR},0} d) \exp\left(-\beta_{\mathrm{IR},1} \int_0^d \Delta n(z, f, t)\, dz \right) \tag{5}$$

Based on the assumption of comparatively small charge carrier density oscillations, the exponential function with the integral can be linearized and the relation between charge carrier density oscillations and transmitted IR radiation is then given by

$$I_{\mathrm{trans}}(f, t) = I_0 \exp(-\beta_{\mathrm{IR},0} d) \left[1 - \beta_{\mathrm{IR},1} \int_0^d \Delta n(z, f, t)\, dz \right] \tag{6}$$

As we use lock-in detection, only the modulated contributions of the transmitted IR radiation, which are related to the effect of the plasma wave on the IR absorption and transmittance, are measured. Omitting the time dependence, the modulated radiometric signal can finally be described by

$$S_{\mathrm{trans}}(f) = C \beta_{\mathrm{IR},1} \int_0^d \Delta n(z, f)\, dz \tag{7}$$

For sample thicknesses d large in comparison with the charge carrier diffusion length of the material, we finally get the analytical description of the measured signal by inserting Eq. (2) into Eq. (7):

$$S_{\mathrm{trans}}(f) = C \beta_{\mathrm{IR},1} \left[\frac{-s_{\mathrm{sur}} - \beta D_{\mathrm{pl}}}{s_{\mathrm{sur}} + \xi_{\mathrm{pl}}(f)\, D_{\mathrm{pl}}} \frac{1}{\xi_{\mathrm{pl}}(f)} + \frac{1}{\beta_{\mathrm{opt}}} \right] \frac{\phi_0 \beta_{\mathrm{opt}}}{D_{\mathrm{pl}}} \frac{1}{\xi_{\mathrm{pl}}^2(f) + \beta_{\mathrm{opt}}^2} \tag{8}$$

As mentioned in Section 2, IR radiation related to the modulated optical heating of the sample can yield small additional contributions to the measured transmittance signal described by Eq. (8). These small additional contributions can be measured separately by just blocking the external IR source. Then they can be eliminated by phase-sensitive subtraction from the signals measured with the external IR source switched-on,

$$S_{\mathrm{trans}}(f) = S_{\mathrm{trans+int}}(f) - S_{\mathrm{int}}(f) \tag{9}$$

After elimination of the contributions of the modulated internal IR radiation of the sample, the signal only depends on the effects of the charge carrier density modulations and can be analyzed quantitatively on the basis of the theory of charge carrier diffusion described by Eq. (8).

4. EXPERIMENTAL RESULTS

Here we report on the first measurements on homogenously doped Si-wafers of different electronic properties. The samples additionally have been characterized by other modulated photothermal methods, namely photothermal radiometry and modulated optical reflectance [8].

For a principal understanding of the signal generation process, time-dependent measurements during the heating phase of the IR radiation source have been performed, in order to study the effects of a gradually changing external IR radiation intensity of the source and the interaction between the external IR radiation and the internal radiometric signal contributions. To this end, the experiment has first been run with the semiconductor sample not completely defocused. Figure 2 shows the modulated IR signals (amplitudes and phases) as a function of time registered at a fixed excitation frequency of 830 Hz. Before switching-on the external IR source, the signal amplitude (Fig. 2a), which is only related to the oscillations of internal IR radiation generated in the sample by modulated laser excitation, remains constant.

When, due to the increasing radiation temperature of the external IR source, the influence of the transmitted IR radiation is no longer negligible, we first observe a decrease of the measured signal until a relative minimum of the signal level is reached at about $t \approx 110$ a.u. With a further increase in the radiation temperature of the external IR source, we can observe an increase of the signal amplitude considerably above the signal level at $t = 0$. Saturation of the measured signal is reached, when the radiation temperature of the external IR radiation source becomes stationary. The three different regimes in the signal generation process can also be identified by the phase shifts of the signals (Fig. 2b), measured with respect to the modulated laser excitation. At the beginning, the photothermal signal due to modulated laser heating is dominant, while with increasing time, the signal is governed by the modulated transmittance of the external IR radiation. At intermediate times, $50 < t/\text{a.u.} < 150$, the transition between the two signal contributions, which here are of similar order of magnitude, occurs. Without the external IR radiation, at $t = 0$, we can observe a phase level of approximately 0°, while the phase retardation reaches about −180°, when the external IR radiation increases and becomes dominant.

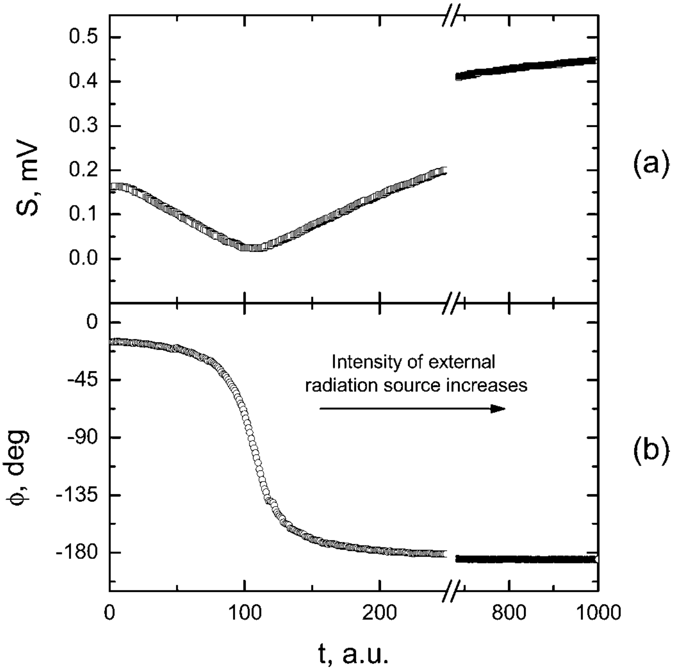

Fig. 2. Time-dependent measurement of the modulated radiometry signal, (a) amplitude and (b) phase, recorded at constant excitation frequency $f = 830$ Hz. The Joule heated external radiation source was switched on at $t = 0$, and the intensity of the external IR radiation is increasing with time.

This observation can be explained on the basis of different signal generation mechanisms. In general, the internal IR emission of the sample increases, when the temperature and charge carrier density inside the sample increase [7] and the IR transmittance decreases with charge carrier density. Thus, we can observe a phase shift between the photothermally modulated IR signal of the sample and the modulated IR transmission signal of about 180° (Fig. 2b). The transition from the conventional photothermal IR signal to the modulated IR transmission signal is also responsible for the relative minimum at the intermediate intensity of the external radiation source (Fig. 2a), at about $t = 110$ a.u.

After the stationary radiation temperature of the external IR source had been reached, an IR opaque shielding was introduced between the semiconductor sample and the external IR source. The measured signal immediately returned to the initial value, both with respect to the amplitude and the phase, which means that secondary effects, like a small increase of the stationary sample temperature, seem to be negligible compared to the signal contribution of the transmitted IR radiation.

In a next step, frequency-dependent measurements have been performed with the semiconductor samples in the defocused position and with the external IR source switched-on and off (Fig. 3). The samples under investigation were pieces of standard wafer silicon of different electrical resistance and a reference sample of glassy carbon of known optical and thermal properties. As the reference sample can be considered as semi-infinite and optically and IR optically opaque, a constant phase shift of $-45°$ and a frequency-dependent decrease of the amplitude $\propto f^{-1/2}$ can be expected [9]. In principle, this behavior, which does not depend on the thermophysical properties, can be observed in Fig. 3. The observed slight deviations are due to the frequency characteristics of the electronics used in the measurement process. As both the measurements of the silicon samples and those of the reference sample are affected by this frequency characteristics, the comparison of two frequency scans allows a quantitative interpretation with respect to the thermal and electronic transport parameters.

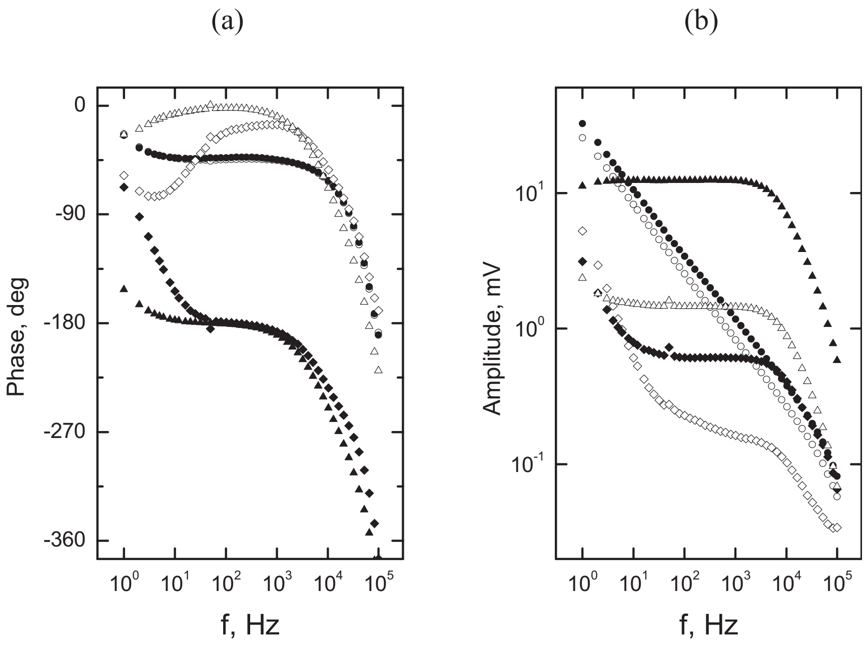

Fig. 3. (a) Phases and (b) amplitudes of the modulated radiometric signal of two silicon samples. Silicon A and B measured with (◆, ▲) and without (◇, △) external IR radiation as function of the modulation frequency, in comparison with measurements on a glassy carbon reference sample (●, ○).

For the reference sample we cannot observe any change in the signal phases (Fig. 3a) measured with (●) and without (○) external IR radiation, while the amplitudes (Fig. 3b) measured with the external radiation switched-on are increased by a small constant factor. This is not unexpected, since the reference sample of glassy carbon is sufficiently thick ($d = 4$ mm) to be IR opaque. The small increase of the signal amplitudes is due to a small dc temperature increase of the sample of about 5 to 10 K when the external IR radiation source is switched-on.

A completely different behavior has been observed for two silicon samples of different electronic properties (silicon A: ◆, ◇ and silicon B: ▲, △). For both samples, the measurements performed without external IR radiation (◇, △) show the typical behavior of frequency-dependent radiometric signals of silicon [10]. At lower frequencies (Fig. 3b), we can observe a frequency-dependent decrease of the signal amplitudes (◇, △), as the signals are dominated by the thermal wave component. In the intermediate frequency range the signal amplitudes show a plateau-like behavior, which is due to the effect of the charge carrier density waves in the non-diffusive regime, with the charge carrier lifetime τ smaller than the inverse excitation frequency, $\tau < f^{-1}$. When the plateau is completely flat for silicon B where the charge carrier effect is dominant, we can observe a decreasing signal for silicon A in the intermediate frequency range, owing to a still considerable influence of the frequency-dependent thermal wave component. At higher frequencies, $f > 10^4$ Hz, when the charge carrier lifetimes are larger than the inverse of the modulation frequency, $\tau > f^{-1}$, both amplitudes (◇, △) decrease simultaneously (Fig. 3b).

The effect of the thermal wave and charge carrier density wave contributions on the conventional PTR signal can also be found in the phases measured for silicon A and B (◇, △) without external IR radiation (Fig. 3a). While the measured phases are nearly constant and close to zero in the intermediate frequency range, where the non-diffusive plasma wave contribution is dominant, we can observe considerable phase shifts in the diffusive regions, which are either dominated by the thermal wave at low frequencies or by the plasma wave at high frequencies.

The frequency-dependent measurements performed for silicon A (◆) and B (▲) with the external radiation source switched-on show IR transmission signals, the amplitudes of which are roughly one order of magnitude larger than the amplitudes measured without the external IR radiation source (Fig. 3b). The principal change in the signal generation mechanism becomes evident in the phases of the signals (Fig. 3a), which are shifted by approximately 180° in comparison to the phases measured without external IR radiation. Thus, we can conclude that the modulated infrared transmission signals mainly reflect the effect of the plasma wave on the IR properties of the sample. This is also confirmed by the frequency dependence of the signal amplitudes (Fig. 3b). For both samples (◆, ▲), there is a typical plateau in the intermediate frequency range due to non-diffusive charge carrier density oscillations, while a frequency-dependent decay is found at higher frequencies in the diffusive limit of the plasma wave. Above about 10 Hz, the modulated IR transmission amplitudes of the silicon sample B seem to be shifted by a factor of about 10 in comparison to the PTR signal without the external IR radiation source. This is due to the dominance of the plasma wave component in the PTR signal already at relatively low frequencies. A different behavior is observed for silicon A, where we now can see the flat plateau, existing in the intermediate frequency range between 20 Hz and 2 kHz. Here we can see, that the modulated IR transmission signal can provide detailed information about the charge carrier density oscillations and the electronic properties, especially when the conventional PTR signal without external IR radiation is affected by both the thermal and plasma waves.

This can also be true for the high frequency limit, where the modulated IR transmission signal depends only on the plasma wave, whereas the conventional PTR signal can still by affected by thermal wave and plasma wave contributions. While the high frequency limit of the flat plateau of the IR transmission amplitudes ($f \cong 5$ to 8 kHz) gives information about the charge carrier lifetime τ, which is similar for the two silicon samples A and B, the frequency dependence of the IR transmission amplitudes, following at higher frequencies, can provide information on the influence of the samples' surface recombination velocity s_{sur}. If we compare the high frequency limit of the IR transmission amplitude of the two silicon samples (Fig. 4) with that of the signal measured for glassy carbon, for which a frequency dependent decay according to $f^{-1/2}$ can be expected [9], we can see that the IR transmission amplitudes measured for silicon B decay according to approximately f^{-1}, while for silicon A the decrease is according to approximately $f^{-1/2}$.

For the frequency limit $\tau > f^{-1}$ of Eq. (8), it can be found that the IR transmission amplitudes are related to the influence of the surface recombination velocity in the diffusive regime. For $s_{\text{sur}} \ll |D_{\text{pl}}\xi(f)|$, we get

$$S_{\text{trans}}(f) \propto f^{-1} \tag{10}$$

and for $s_{\text{sur}} \gg |D_{\text{pl}}\xi(f)|$, we get

$$S_{\text{trans}}(f) \propto f^{-1/2} \tag{11}$$

Thus, we can conclude that the charge carrier oscillations of silicon A are much more affected by a higher value of the surface recombination velocity s_{sur} than those of the silicon sample B.

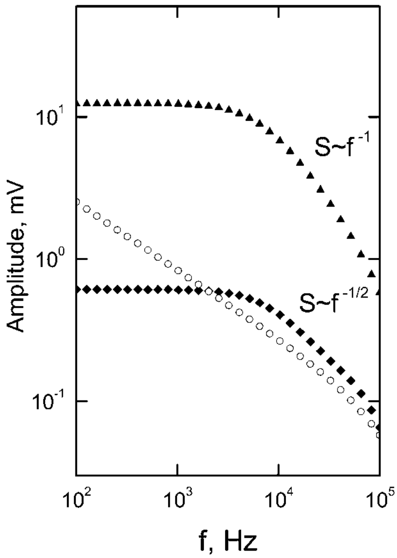

Fig. 4. High frequency limit of the modulated IR transmission amplitudes of the two silicon samples A and B (◆, ▲), measured as function of the modulation frequency with the external IR source switched-on, in comparison with the measurement for the glassy carbon reference sample (○).

The effect of the surface recombination velocity is confirmed by the quantitative interpretation of the IR transmission signals, considering both the phases and the amplitudes over the whole frequency range. Figure 5 shows the normalized phases and amplitudes obtained for the two silicon samples in comparison with theoretical approximations according to Eq. (6), where only the plasma wave effects are considered. Here, the signals measured for glassy carbon have been used as reference for normalization.

For the two silicon samples A and B the normalized data are approximated by theoretical curves, where the electronic properties are in good agreement with the values found by the quantitative interpretation of the conventional PTR signals (compare Fig. 6). Both materials show charge carrier lifetimes of about 10 to 30 μs, whereas silicon A has a much higher surface recombination velocity ($s_{sur} \approx 30\ \mathrm{m \cdot s^{-1}}$) than silicon B ($s_{sur} \approx 2\ \mathrm{m \cdot s^{-1}}$), as already indicated by the slope of the measured amplitudes in the high frequency limit. In general, we see good agreement in

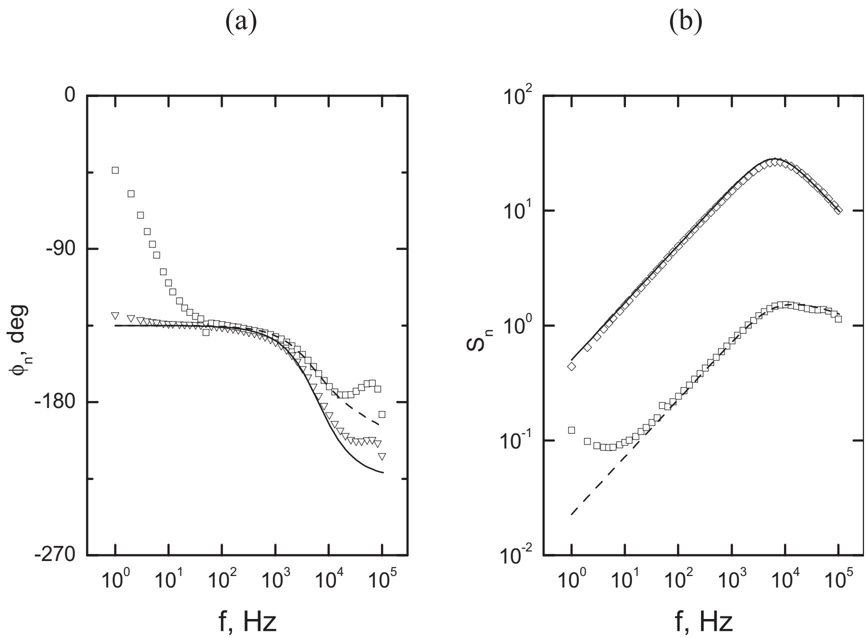

Fig. 5. (a) Phases and (b) amplitudes of the normalized modulated IR transmission signals of the two silicon samples A and B (□, ▽), measured with the external IR radiation source switched-on as a function of the modulation frequency in comparison with theoretical approximations considering the effects of the plasma wave on the IR transmittance.

Fig. 5 between the experimental data and the theoretical approximations, with the exception of smaller deviations in the normalized phases for very low and very high excitation frequencies. The deviations at the low frequencies may be due to nonnegligible thermal wave contributions generated by the modulated laser excitation. The deviations at higher frequencies may be due to a nonnegligible IR absorption length in the micrometer range for the reference sample, leading to subsurface radiation contributions influencing the signal phase of the reference sample, when the penetration depth of the thermal wave is of the order of the IR absorption length [3].

The quantitative theoretical analysis, considering effects of the thermal wave and the plasma wave of conventional radiometric measurements under optimal focusing conditions and without external IR radiation (Fig. 6), shows that measurements on silicon A are affected by the thermal wave over the whole frequency range, while the PTR signal of silicon B is dominated by the plasma wave above about 100 Hz. The theoretical approximations in Figs. 5 and 6 are based on the same set of electronic

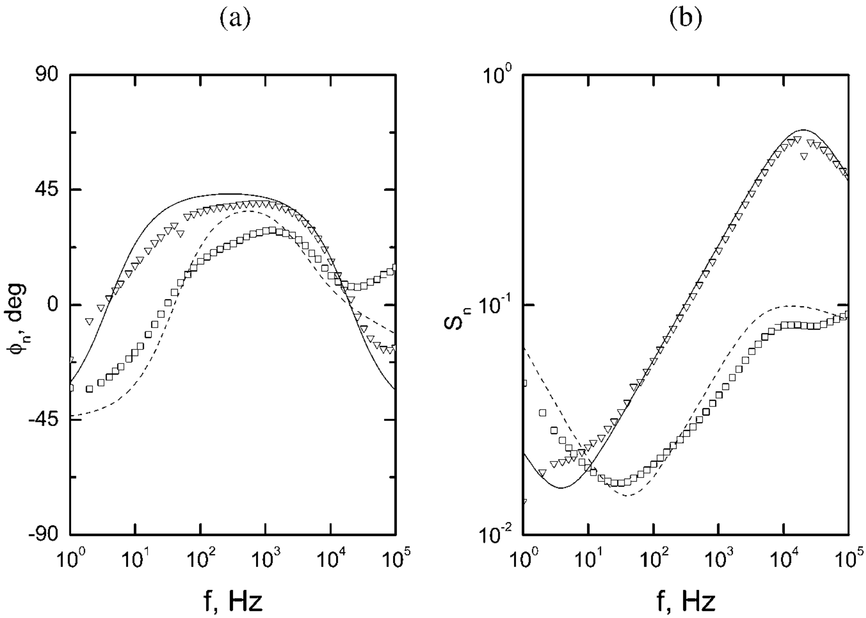

Fig. 6. Normalized phases and amplitudes of the radiometric signal of two silicon samples A and B (□, ▽), measured without external IR radiation as a function of the modulation frequency in comparison with theoretical approximation considering contributions of the thermal wave and the plasma wave. The assumed electronic parameters are in good agreement with the parameters, which have previously been evaluated by the modulated transmission measurements (compare Fig. 5).

parameters, which have been determined by the frequency-dependent modulated IR transmission measurements alone. Using these parameters, the conventional PTR measurements have then been interpreted with respect to the quantitative determination of the thermal transport parameters.

5. CONCLUSION AND OUTLOOK

In this work a measurement technique has been developed relying on the measurement of the IR transmission of semiconductors modulated by optically excited charge carrier density waves. Time-dependent measurements of the modulated transmission signal with gradually increasing intensity of the external radiation source contributed to a principal understanding of the signal generation mechanism, especially with respect to the interaction between the modulated IR transmission signal and the conventional PTR signal produced by the modulated laser beam irradiation in the visible spectrum.

By intentional defocusing of the sample under investigation, the signal contributions related to the modulated internal IR radiation have been minimized and became negligible, so that only the modulated infrared transmission (MIRT) signal is measured. By frequency-dependent measurements on two different silicon samples, it was demonstrated how this technique can be used for a quantitative analysis of the semiconductor properties, based on the theory of plasma wave modulated IR transmission. Good agreement between the measured data and the theory of modulated infrared transmission has been achieved, providing quantitative information on the semiconductor properties. The advantage of this measurement technique is that the charge carrier properties can be measured independently of the thermophysical parameters, which in the conventional photothermal radiometry or thermoreflectance of semiconductor materials are always coupled to the charge carrier properties. Once the information on the charge carrier properties has been obtained separately from the modulated infrared transmission signal, the thermal parameters can be determined from the conventional PTR signal using the same experimental setup. Thus, the electronic and thermal material properties of semiconductors can be evaluated by combining these two techniques. Since the electronic and thermal parameters are decoupled in the modulated IR transmission measurement, the reliability and accuracy of the measurement will be better.

Although a relatively good quantitative description of the measured signals has already been obtained, a more detailed study of the sensitivity limits of this measurement technique has still to be done, especially with respect to the spectral analysis of the IR transmission and eventual information on the semiconductor band structure. Based on theoretical simulations for measurements of the modulated optical reflectance and assuming literature data for the charge carrier diffusivity, we expect, that the sensitivity for modulated infrared transmittance is sufficient for charge carrier lifetimes τ from 1 μs to 1 ms and for surface recombination velocities s_{sur} from 0 to 100 $m \cdot s^{-1}$ [11].

Comparing the theoretical approximations and the data measured by photothermal radiometry (Fig. 6a and 6b) with the theoretical approximations and the data measured by the modulated IR transmission (Fig. 5a and 5b), one can expect that the sensitivity of the modulated IR transmittance may even be better than the sensitivity of the photothermal radiometry, especially, when we have in mind that the modulated IR transmittance depends on a minor set of parameters, namely only on the electronic transport parameters, whereas the photothermal radiometry signal depends both on the electronic and the thermal transport parameters.

Although the conventional PTR signal amplitude has significantly been reduced by the changed focussing conditions, there may still be a minor contribution to the measured transmittance signal. Further improvements of the measuring conditions are possible by using more intense IR radiation sources and spectroscopic techniques, where the detection is limited to a smaller wavelength interval in the infrared by using appropriate cut-on and cut-off filters.

For spectroscopic techniques an intense monochromatic IR source and appropriate filters in front of the detector can be used, so that only the intensity modulations of the transmitted monochromatic radiation is sensed. The signal contribution due to the modulation of the internal IR radiation, although still present in the sample, should then be completely negligible, as the internal IR radiation related to thermal waves is always distributed over a broad wavelength interval.

REFERENCES

1. A. H. La Rosa, B. I. Yakobsen, and H. D. Hallen, *Appl. Phys. Lett.* **70**:1656 (1997).
2. A. Salnick, A. Mandelis, H. Ruda, and C. Jean, *J. Appl. Phys.* **82**:1853 (1997).
3. D. Dietzel, A. Haj Daoud, F. Macedo, J. Bolte, J. Pelzl, and B. K. Bein, *Photoacoustic & Photothermal Phenomena*, F. Scudieri and M. Bertolotti, eds., *AIP Conf. Proc. 463* (1999), pp. 321–323.
4. J. Bolte, J. H. Gu, and B. K. Bein, *High Temps.–High Press.* **29**:567 (1997).
5. D. Fournier, in *Photoacoustic and Photothermal Phenomena III*, Springer Series in Optical Sciences, D. Bicanic, ed. (1992), pp. 339–348.
6. C. Christofides, F. Diakonos, C. Christou, M. Nestoros, and A. Mandelis, *J. Appl. Phys.* **80**:1713 (1996).
7. A. Mandelis, A. Othonos, C. Christofides, and J. Boussey-Said, *J. Appl. Phys.* **80**:5332 (1996).
8. D. Dietzel, H. Röcken, J. Pelzl, and B. K. Bein, *Surf. Coat. Tech.* **142–144**:429 (2001).
9. B. K. Bein, S. Krüger, and J. Pelzl, *Canad. J. Phys.* **64**:1208 (1986).
10. T. Ikari, A. Salnick, and A. Mandelis, *J. Appl. Phys.* **85**:7392 (1999).
11. D. Dietzel, J. Pelzl, and B. K. Bein. *Rev. Sci. Instrum.* **74**:604 (2003).