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Recent developments in terahertz optoelectronics/Développements récents en optoélectronique térahertz

Electro-absorption sampling at terahertz frequencies in III-V semiconductors

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Abstract

We review recent advances in the development of a new sampling technique for ultra high-speed electrical signals. It is based on the electro-absorption phenomena in semiconductors (Franz–Keldysh effect). We demonstrate that it is usable up to the terahertz range. The theory is exposed and we show two practical set-ups. The first uses the semiconductor substrate (internal sampling). The second uses a small semiconductor probe bonded on the circuit (external sampling). In this last case, the theoretical temporal resolution is about 200 fs. In practice, we measure a risetime of about 500 fs with 60 dB of dynamic range. ***To cite this article: J.-F. Lampin et al., C. R. Physique 9 (2008).***

Résumé

Échantillonnage par électro-absorption aux fréquences térahertz dans les semiconducteurs III-V. Cet article résume les récentes avancées dans le développement d'une nouvelle technique d'échantillonnage pour les signaux électriques ultra-rapides. Elle est basée sur le phénomène d'électroabsorption des semiconducteurs (effet Franz–Keldysh). Nous démontrons qu'il est utilisable jusqu'aux fréquences térahertz. Nous exposons la théorie et nous montrons deux schémas expérimentaux. Le premier utilise le substrat semiconducteur (échantillonnage interne). Le deuxième utilise une petite sonde semiconductrice placée sur le circuit (échantillonnage externe). Dans ce dernier cas, la résolution temporelle théorique est d'environ 200 fs. En pratique, nous mesurons un temps de montée d'environ 500 fs avec une dynamique de 60 dB. ***Pour citer cet article : J.-F. Lampin et al., C. R. Physique 9 (2008).***

Keywords: Terahertz pulses; Electro-absorption; Sampling; Low temperature grown gallium arsenide

Mots-clés : Impulsions térahertz ; Électro-absorption ; Échantillonnage ; Arséniure de gallium épitaxié à basse température

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1. Introduction

Several pioneers have shown that terahertz electromagnetic waves can be generated and detected via optical methods. These methods received considerable attention during the last decade. Two phenomena are generally used for the optical generation and detection of THz signals: (1) the photoconduction phenomena in semiconductors, (2) non-linear optics in non-centrosymmetric crystal (for a review, see [1]).

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If we focus on the detection methods, we can notice that the photoconduction method is very sensitive, but that the temporal resolution depends on the carrier lifetime and on the parasitic capacitive coupling. The electro-optic approach generally uses the linear electro-optic phenomena (Pockels effect): the propagation of the light in a non-centrosymmetric crystal subjected to an electric field modifies its polarization state. It has a higher bandwidth but is less sensitive and requires materials with high electro-optic coefficients like $LiTaO_3$. These materials have generally a high permittivity which creates multi-reflections in the material. These reflections are especially disturbing in the case of the sampling of an electric field above transmission lines. A compromise is needed between the sensitivity and the perturbations caused by the sampling probe [2]. Alternative materials like organic crystals have a lower permittivity but have also higher losses at THz frequencies.

Other electro-optic phenoma can be used for the sampling of electrical signals: the Kerr effect was probably the oldest [3], more complicated techniques like the electric-field induced second harmonic generation were also investigated [4]. In this article, we review another method for the sampling of terahertz signals: we use the electro-absorption phenomena that exists in semiconductors. This phenomenon is also known as the Franz–Keldysh effect (FKE). This is an electro-optic effect but the difference with the Pockels effect is that the intensity of the light is modified and not the polarization state. Another difference is that the phenomenon is strong in semiconductors used in high-speed III-V micro-electronics and opto-electronics. We will show that already developed semiconductor technologies help the fabrication of the sampling probes.

2. Theory

2.1. Perfect crystal case

FKE is similar to the Stark effect (shifting of the absorption lines of an atom in an electric field) and it is also explained by quantum mechanics. An electric field lifts the translational symmetry of a crystal along its direction. The theory shows that electron and hole wave functions are then not zero in the forbidden band (see Fig. 1). In this case, interband transitions for photon energies lower than the band gap are possible [5,6]. These transitions can be regarded as photon-assisted tunneling from the valence to the conduction band. Fig. 2 shows the optical absorption calculated for GaAs with the model of Ref. [7]. When there is no electric field, the absorption follows the well-known square root law with no absorption below the bandgap. When the electric field is higher than about 10 kV/cm an exponential decreasing absorption tail is visible for wavelength higher than 870 nm (which correspond to the bandgap of GaAs). The absorption is higher for a higher electric field (the tunnel barrier is narrower). For wavelengths lower than 870 nm ($E > E_g$), the so-called Franz–Keldysh oscillations in the absorption are visible.

The Franz–Keldysh effect does not vary with the direction and the sign of the electric field (for a semiconductor with isotropic bands). This variation of the absorption coefficient of the semiconductor (electro-absorption) is accompanied by a variation of the real part of the refractive index (electrorefraction). We can calculate this effect with Kramers–Kronig relations, but it is generally rather weak compared with electro-absorption.

2.2. Real crystal case

In practical cases, the variation of the absorption coefficient of a semiconductor is not precisely given by the square root law for photon energies close to the bandgap. In general, it can be described by an exponential decrease (Urbach tail):

$$\alpha(E,0) = \alpha_1 = \alpha_0 \exp\bigl[s(E - E_0)\bigr] \tag{1}$$

E is the photon energy, α_0 is the absorption of the material at an energy E_0 and s is a property of the material describing the steepness of the absorption edge. In monocrystals, this absorption tail seems to be due to ionized impurities or defects that cause optical absorption via the FKE.

In this case, Franz [8] showed that the optical absorption for an electric field F is:

$$\alpha(E,F) \simeq \alpha_0 \exp\left[\frac{s^3 E_{eo}^3}{12} + s(E - E_0)\right] \tag{2}$$

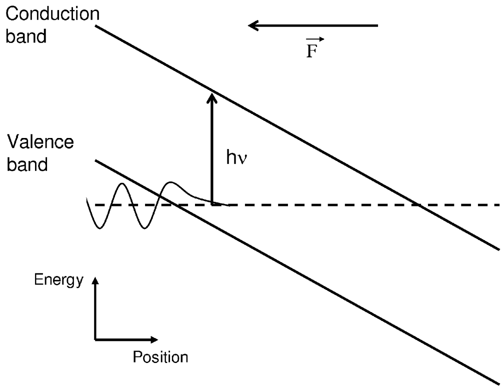

Fig. 1. Energy bands of a semiconductor in an electric field. Photon absorption at an energy lower than the bandgap is possible.

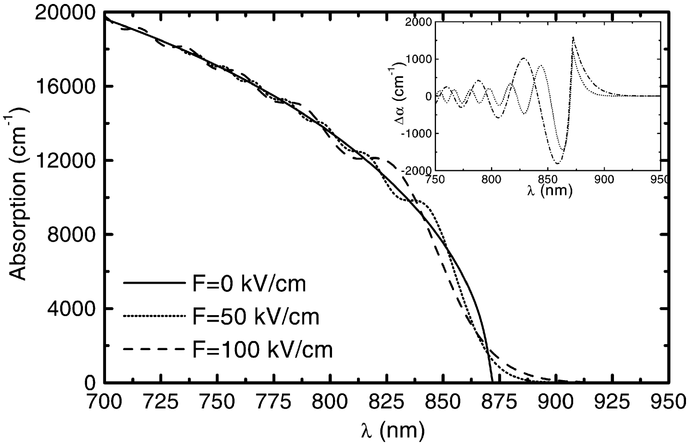

Fig. 2. Theoretical GaAs absorption spectrum for several electric fields. Insert: variation of the absorption coefficient.

where E_{eo} is the electro-optical energy:

$$E_{eo} = \left(\frac{e^2\hbar^2F^2}{2m_r}\right)^{1/3} \tag{3}$$

m_r is the reduced effective mass ($1/m_r = 1/m_e + 1/m_h$).

The absorption edge is shifted toward lower energies by $s^2E_{eo}^3/12$. In semi-insulating GaAs, the reduced mass is $0.059m_0$, s is close to 100 eV^{-1}. For a 50 kV/cm field, the electro-optic energy is 25.3 meV and the shift is 13.5 meV which can be easily measured.

The optical absorption is given by:

$$\alpha(E,F) \simeq \alpha_1 \exp\left(\frac{F}{F_0}\right)^2 \tag{4}$$

where:

$$F_0 = \sqrt{\frac{24m_r}{s^3e^2\hbar^2}} \tag{5}$$

Consider a slab of semiconductor of thickness d which is illuminated by a monochromatic beam with a photon energy E. The incident intensity is I_0, the transmitted intensity is I. If we ignore the surface reflections, the transmission is given by:

$$\frac{I}{I_0} = \exp(-\alpha d) = \exp\left[-\alpha_1 d \exp\left(\frac{F}{F_0}\right)^2\right] \tag{6}$$

Fig. 3 shows the transmission I/I_0 versus the electric field for various $\alpha_1 d$. If an ac voltage is applied to the slab and if the peak field $F \ll F_0$, the FKE is very weak and the modulation is difficult to measure. If the peak field is approximately equal to F_0 the transmitted light is non-linearly modulated: the modulation components are the even harmonic of the ac voltage frequency (the FKE is not sign dependent).

The decreasing curves of Fig. 3 have a quasi-linear section. If we apply an ac field with a dc bias of about F_0 to $2F_0$ a linear modulation can be obtained. When the electric field increases the transmitted light decreases. For a maximum sensitivity the bias field and the ac field to measure must be colinear.

To get an idea of the sensitivity of the FKE, it is interesting to calculate F_0 for a practical case. For a 10 μm thick semi-insulating GaAs crystal with semi-transparent electrodes on the two faces, F_0 is close to 40 kV/cm which corresponds to 40 V between the two electrodes. For $\alpha_1 d = 0.2$ (which corresponds to $E \simeq 1.39$–1.40 eV or a wavelength of about 880–890 nm), we have a relative variation of the transmitted light of 3%/V. This sensitivity is obtained for a bias field $F_b \simeq 1.3F_0$ which corresponds to 50 V.

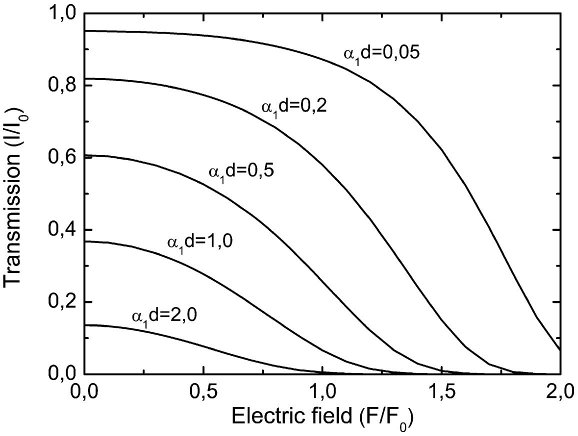

Fig. 3. Light transmission through a semiconductor slab versus the normalized applied electric field for various $\alpha_1 d$.

In the last case the electric field is uniform, but for coplanar electrodes F_b is not uniform. This non-uniformity combined with the non-linearity of the FKE has a great consequence: high-field regions ($F_b \geqslant F_0$) will modulate the optical beam even if there are small but the contribution of low-field regions ($F_b \ll F_0$) will be negligible even if the beam has a long path in these regions. This is a big difference with the Pockels effect which is linear. It contributes to the very good temporal resolution of the method.

2.3. Requirements of the semiconductor

We can give some requirements of the best semiconductor for FKE:

- FKE is a shift of the band edge of a semiconductor. The wavelength of the laser must correspond to photon energies close to the bandgap. GaAs is a good choice for Ti:sapphire lasers (870–900 nm range). InP is also compatible with these lasers (920–950 nm range).
- The semiconductor crystal must be very resistive: too much free carriers can screen the electric field to measure. These carriers can also heat the crystal via the Joule effect due to the bias field. A variation of temperature shifts the bandgap (0.5 meV/K for GaAs near 300 K).
- When the light illuminates the semiconductor electron–hole pairs are created and then can perturb the detection like free carriers. To decrease this phenomenon the photon energy must be smaller than the band gap in order to keep a small optical absorption. This undesirable photocurrent can also be decreased in a short carrier lifetime material. As we will see, the temporal resolution of the technique is not linked to the carrier lifetime as for photoconductive sampling.
- To decrease the value of the static field necessary to have a linear detection, F_0 must be low, so the reduced effective mass must be low also (Eq. (5)). III-V compounds are the most interesting. The steepness s of the absorption edge must be as high as possible. The semiconductor must have a direct bandgap with a very low concentration of impurities, point defects and dislocations. Unfortunately high resistivity and short carrier lifetime materials have generally a high density of point defects.

3. Electro-absorption sampling

The last section is a quasi-static description of the FKE (the electric field varies slowly). The FKE is in fact a tunnel effect, and it is intrinsically very fast. For GaAs, the quasi-static description is valid for time-varying electric field up to the picosecond time scale. We can use it to sample THz fields, this technique is called electro-absorption sampling (EAS).

For frequencies higher than a few THz and for electric fields higher than 10 kV/cm, a different regime called dynamic Franz–Keldysh effect is predicted by the theory [9]. The effects of this regime on the sensitivity, linearity, and temporal response of the sampling are not clear for the moment.

3.1. Semiconductors

The requirements given in Section 2.3 are almost fulfilled for low-temperature-grown GaAs and $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ (LTG-GaAs and LTG-AlGaAs). These materials are often used as ultrafast photoconductors [1] but a completely different application is possible with EAS.

The growth is done by molecular beam epitaxy at substrate temperatures between 200 and 300 °C. When they are annealed at 600 °C, these materials are semi-insulating (10^6 to 10^7 $\Omega\,\mathrm{cm}$) and have a high breakdown field (>300 kV/cm). The carrier lifetime is very short: 0.1 to 10 ps. The steepness of the optical absorption is low just after the growth but it is greatly improved when the annealing is done. The growth temperature results from a compromise between the material quality and the carrier lifetime. Short carrier lifetime limits the undesirable photocurrent but not the temporal resolution of EAS.

Fig. 4 shows the relative variation of the intensity transmitted by a 1 μm-thick LTG-GaAs free-standing membrane. The two sides of the membrane were metallized with a 10 nm-thick gold layer. The transmission spectra were measured for an applied voltage of 10 V ($F = 100$ kV/cm) and of 0 V. The relative variation is then calculated. A comparison with the model of Ref. [7] applied to GaAs is also plotted.

The order of magnitude of the effect is well described, the maximum modulation is obtained around 875 nm. The discrepancies between the two curves can be explained by the Fabry–Pérot effect and the variations of the real part of the refraction index (which were neglected in the calculations). Above the bandgap, Franz–Keldysh oscillations are more damped than the theory.

3.2. Terahertz experimental set-ups

The semiconductor used to sample the high frequency electric field is generally very close to a propagation structure adapted to the terahertz band (transmission line or waveguide). Two configurations are possible: the semiconductor is a part of the transmission line (internal sampling), or the semiconductor is not part of the transmission line but it is placed very close like a probe (external sampling).

An optical probe beam is used to quantify the electro-absorption in the semiconductor layer. The most simple way is to measure the optical intensity with a photodiode in a transmission configuration. But it can be also interesting to place a mirror behind the semiconductor layer and to collect the beam after a double passage (reflection configuration). The FKE modulates directly the intensity of the optical beam, the set-up is then more simple than with the Pockels effect. The remaining part of the set-up is similar to a standard THz set-up. The optical source is a tunable pulsed laser in order to adjust the wavelength exactly at the maximum of the FKE.

In the results reported here, the generation of the THz pulses is done by photoconduction in short lifetime semiconductors. The photon energy must then be higher than the bandgap but EAS requires a photon energy lower than the bandgap (Section 2.3). There are two solutions to this contradiction: (1) two wavelengths are generated (for example by second harmonic generation in a non-linear crystal); (2) two different semiconductors are used for the generation and for the sampling.

Fig. 5 shows the experimental set-up used in the first case [10]. The typical sample is a coplanar stripline (CPS) patterned on a LTG-GaAs layer made on a semi-insulating substrate. The backside of the substrate is polished and covered with an anti-reflection coating. The optical source is Ti:sapphire laser tuned to a wavelength close to 900 nm. It emits 120 fs duration pulses at a repetition rate of 76 MHz. The beam is split in two parts: the pump beam generates the THz pulse and the probe beam is used for the EAS. The pump beam is converted to 450 nm thanks to second harmonic generation (SHG) in a baryum β-borate crystal. It is modulated by a mechanical chopper and focused on the CPS with an objective lens. The probe beam is focused on the CPS metallic strips through the substrate. The reflected beam is measured by a photodiode. The signal is then detected with a lock-in amplifier. The optical delay between the pump and probe pulses is variable thanks to a computer controlled delay line.

Fig. 6 shows a typical waveform measured on a GaAs CPS biased at 60 V. The CPS consists of two 10 μm wide Ti/Au strips separated by a 25 μm wide slot. The measured risetime from 10 to 90% is 1 ps and the signal to noise ratio is about 1000. The spectrum covers the 0–1 THz range as expected from the theory. In fact, in this measurement the risetime is partly limited by the generation: the THz pulses are generated by photoconduction with high energy photons (2.75 eV). Phenomena like inter-valley scattering diminish the efficiency and limit the risetime

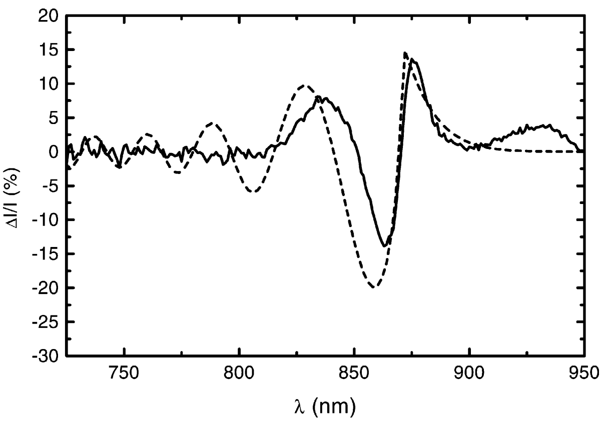

Fig. 4. Experimental electro-absorption spectrum of LTG-GaAs (straight line) and theoretical calculation for $F = 100\ \mathrm{kV/cm}$ (dashed line).

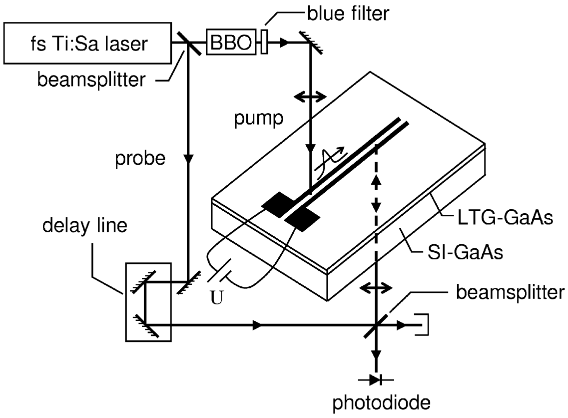

Fig. 5. Internal EAS experimental set-up.

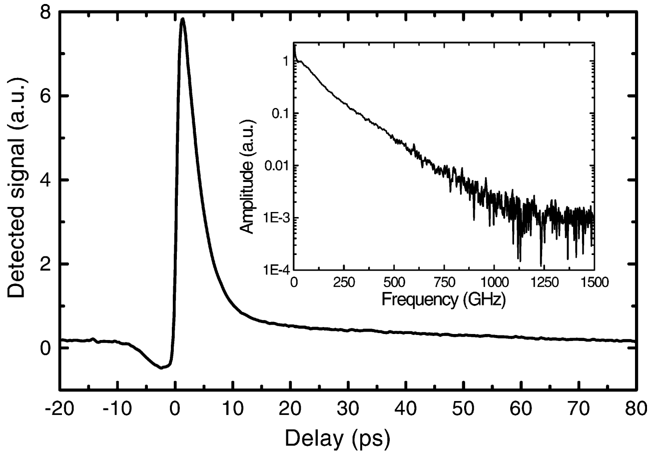

Fig. 6. Typical waveform measured by internal EAS.

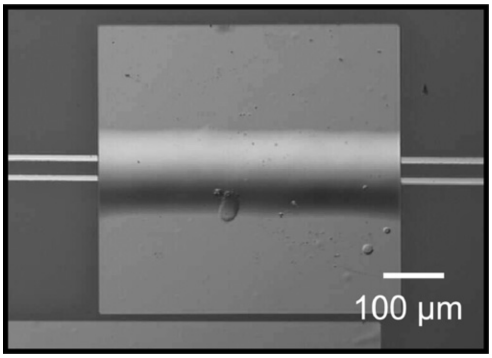

Fig. 7. Optical view of a LTG-GaAs layer bonded on a 500 nm thick Ti/Au CPS.

of the photocurrent. Another phenomenon that limits the temporal resoliution is the dispersion of the probe beam in the GaAs substrate.

The second set-up uses two semiconductors with two different bandgaps: LTG-GaAs and LTG-AlGaAs. If the bandgap difference and the wavelength of the laser are conveniently chosen the generation of the THz pulses via photoconduction and the EAS will be both possible with the same laser wavelength. For the temporal resolution, it is also an advantage if the two beams are focused on the front side of the sample.

These requirements are fulfilled by the epitaxial lift-off and bonding techniques that we have developed [11]. The substrate that was used for the growth of the LTG-GaAs or LTG-AlGaAs layers is etched. Small pieces ($0.1 \times 0.1\ \mathrm{mm}^2$ to $1 \times 1\ \mathrm{mm}^2$) of the 2 µm thick layers are bonded thanks to Van der Waals forces. Fig. 7 shows an example of a LTG-GaAs layer bonded on a CPS. In this case the semiconductor is not a part of the transmission line but it can be placed at an arbitrary position: it is an external sampling.

Fig. 8 shows the experimental set-up: there is no longer SHG and the two beams come from the front side. Fig. 9 shows a waveform measured on a quartz CPS (two 5 µm wide Ti/Au strips separated by a 12.5 µm wide slot). The bias voltage is 60 V. The risetime is 490 fs and the spectrum covers the 0–2.5 THz range with a dynamic of 60 dB at low frequency.

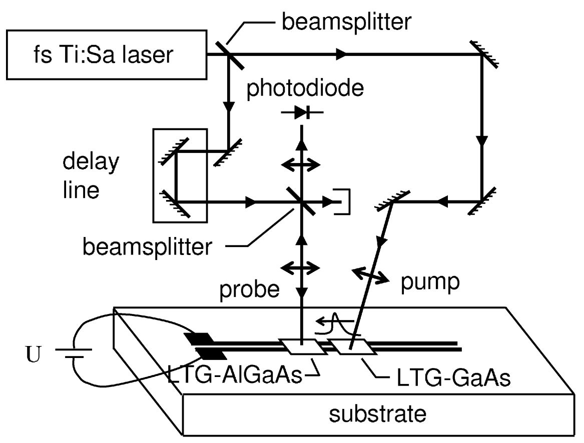

Fig. 8. External EAS experimental set-up.

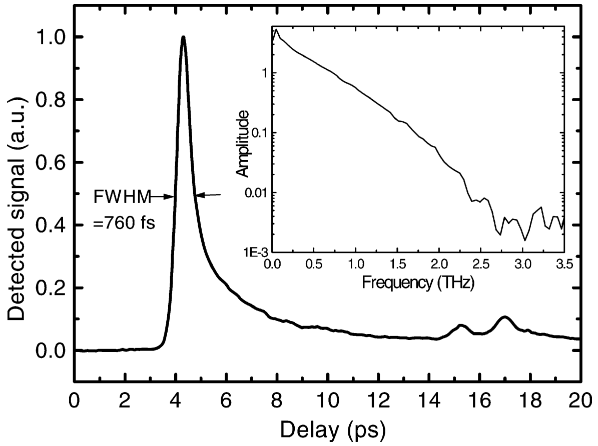

Fig. 9. Typical waveform measured by external EAS.

3.3. Temporal resolution

We can theoretically evaluate the temporal resolution of the EAS technique. It is the convolution between three times: the duration of the pulses of the probe beam (τ_L), the transit time of the optical pulse through the LTG-AlGaAs layer (τ_o) and the transit time of the electrical signal through the optical probe spot (τ_e):

$$\tau = \sqrt{\tau_L^2 + \tau_o^2 + \tau_e^2} \tag{7}$$

where

$$\tau_o = 2dn_s/c \tag{8}$$

and

$$\tau_e = wn_e/c \tag{9}$$

where d is the thickness of the semiconductor layer, w is the diameter of the spot, n_s the index of refraction of the semiconductor at the probe wavelength and n_e is the effective index of the THz mode. For a quartz CPS, $\tau_o \simeq 50$ fs and $\tau_e \simeq 100$ fs. For a 150 fs laser pulsewidth $\tau \simeq 200$ fs.

This temporal resolution is similar to the best reported values obtained by electro-optic sampling (Pockels effect), but good electro-optic materials have often high permittivities and perturb the propagation of the THz wave (echoes). Another advantage is that EAS uses well-known semiconductors and their technology. Compared with photoconductive sampling the temporal resolution of EAS does not depend on the carrier lifetime and the technique is less invasive.

3.4. Applications

EAS is used to measure the characteristics of THz transmission lines: coplanar striplines [12], coplanar waveguides, thin-film microstrip lines [13], planar Goubau lines [14] and backward-wave lines [15]. It is used also for filters [13] and antennas characterization [16].

Active devices have also been characterized by EAS: transistors, photodiodes [17] and logic circuits [18]. In this last case, the dc-bias voltage required for EAS is blocked by a series capacitor to avoid the breakdown of the circuit.

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