Proceedings of the 13th International Symposium UFPS, Vilnius, Lithuania 2007

Modeling of THz — Electro-Optical Sampling Measurements

P. Shiktorov[a], E. Starikov[a], V. Gružinskis[a], L. Varani[b] and L. Reggiani[c]

[a]Semiconductor Physics Institute
Goštauto 11, LT-01108, Vilnius, Lithuania
[b]Institut d'Électronique du Sud (CNRS UMR 5214)
Université Montpellier 2, Pl. Eugène Bataillon, 34095 Montpellier Cedex 5, France
[c]Dipartimento di Ingegneria dell'Innovazione
Università del Salento and CNISM, Via Arnesano s/n, I-73100 Lecce, Italy

We carry out a theoretical analysis of THz-electro-optical sampling experimental technique applied to semiconductor structures. The difficulties/impossibility of determining the small-signal conductivity spectrum in the framework of such a technique are analyzed and discussed.

PACS numbers: 72.20.Ht, 72.30.+q

1. Introduction

Recent experiments on ultrafast high-field transport of photoexcited carriers in superlattices and their interpretation [1, 2] have stimulated a critical discussion [3] upon the possibility to determine the spectrum of the small-signal conductivity of the Bloch oscillating electrons by using the THz–electro-optical (THz–EO) sampling technique in the time domain. The THz–EO technique allows one to measure directly the time response of the THz electric field

$$E_{\mathrm{THz}}(t) \sim \frac{\mathrm{d}j(t)}{\mathrm{d}t} \qquad (1)$$

induced by transient drift current $j(t)$ caused by the free carriers which, after being photoexcited in the sample under test, are accelerated by an applied static electric field of high intensity (above about 5 kV/cm).

In this context, the main problems under discussion are related with the ability of the experiment to provide directly the reliable information on the frequency region of THz generation due to the Bloch oscillations (BO) [4], that is:

the spectrum of the small-signal gain and the cut-off frequency of amplification and/or generation of the THz radiation. The questions posed by this discussion are concerned not only with BO but they can be more generally formulated as follows: is the THz–EO sampling technique able to provide the small-signal conductivity for other non-linear systems that can exhibit electrical instabilities? In essence, the above discussion and the related misunderstanding was originated by the lack of a clear formulation of the main assumptions used in the interpretation of experimental results: (i) to which extent the real process of photoexcitation in the presence of a strong bias can be assimilated to a Gedanken experiment that provides a response function, and (ii) is it possible to interpret the spectrum of this response function as that of the small-signal conductivity?

The aim of this report is to clarify these problems. For this sake, we consider two physical situations with different linearity levels: (i) BO in a superlattice, and (ii) Gunn-effect in a short structure where carriers undergo velocity overshoot.

2. Gedanken experiment

The main idea is based on the possibility to interpret the time domain response of the THz electric field $E_{\mathrm{THz}}(t)$ (the so-called wave form) induced by the photoexcited electrons as the transient conductivity $\sigma(t) \sim E_{\mathrm{THz}}(t)/E_0$ associated with a step-like switching on of a dc electric field E_0 at a certain time moment t_0 (the so-called Gedanken process) which allows one to obtain directly the conductivity in the frequency domain as

$$\sigma(\omega) = \int_{t_0}^{\infty} \exp(\mathrm{i}\omega t)\sigma(t)\mathrm{d}t. \tag{2}$$

The use of such an interpretation is complicated to a relevant extent by the uncertainty in the choice of the initial time moment t_0. This complication is illustrated in Fig. 1a and b. Here, Fig. 1a reports the results of Monte Carlo simulations of the instantaneous time derivative of the drift current $\mathrm{d}j/\mathrm{d}t$ in a 1 μm n-GaAs Schottky barrier diode (SBD) for different duration of the pumping pulse. Figure 1b

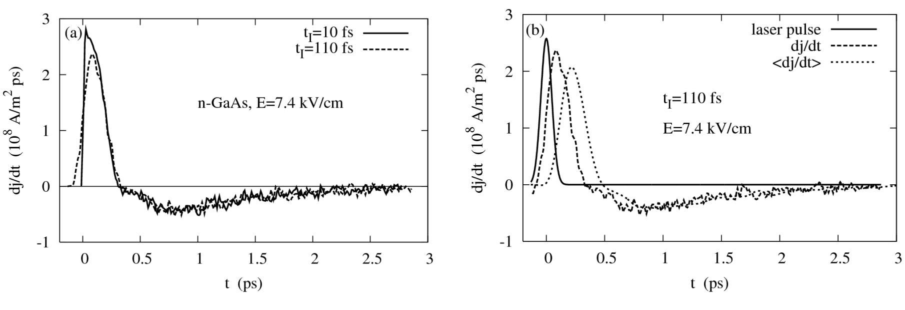

Fig. 1. Time derivative of the electron current calculated for a 1 μm n-GaAs SBD at room temperature (a) at the pumping laser pulse duration $t_{\mathrm{I}} = 10$ and 110 fs, and (b) averaged additionally over the probe laser pulse with $t_{\mathrm{I}} = 110$ fs.

illustrates the influence on the measured result $\langle \mathrm{d}j/\mathrm{d}t\rangle \sim E_{\mathrm{THz}}(t)$ obtained by the average of $\mathrm{d}j/\mathrm{d}t$ over the probe pulse performed by the wave form sampling in time. As follows from Fig. 1a and b, due to the finite duration of the pumping and probe of the optical pulses, with the increase in the laser-pulse duration t_{I} the time behavior of the wave forms at the initial stage becomes less and less similar to the step-like switching of a process in some time moment t_0 implied by the Gedanken experiment. The uncertainty in the choice of t_0 is close to $2t_{\mathrm{I}}$. Such an uncertainty, from one hand can originate an uncontrollable modulation of the response function spectrum $\sim \exp(\mathrm{i}2\omega t_{\mathrm{I}})\sigma(\omega)$. From the other hand, the often used choice of t_0 as the position of the first maximum of the measured wave forms can qualitatively change the value of $\sigma(\omega)$ in the low-frequency region of the spectrum, even arriving at changing the sign of $\mathrm{Re}\sigma(0) \sim \int_{t_0}^{\infty} \sigma(t)\mathrm{d}t$.

3. Spectral representation of the wave forms

The next main question is: can $\sigma(\omega)$ be determined through Eq. (2) (assumed to coincide with the small-signal conductivity) and, if so, what conditions are necessary to justify this assumption ? In essence, the above interpretation of the photoexcitation experiment implies that it gives the response to a switching on of a *large-signal* electric field E. Such a situation can be well described in the framework of the balance equations for the carriers mean velocity v and energy ε as [4]:

$$\frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{v}{\tau_v(\varepsilon)} + em^{-1}(\varepsilon)E, \tag{3a}$$

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = -\frac{\varepsilon - \varepsilon_0}{\tau_\varepsilon(\varepsilon)} + evE, \tag{3b}$$

with the usual meaning of symbols. In the general case, owing to the dependence of the effective mass $m^*(\varepsilon)$ and the velocity and energy relaxation times, $\tau_v(\varepsilon)$ and $\tau_\varepsilon(\varepsilon)$, on the average energy ε the system of Eqs. (3) is nonlinear and, hence, its linearized form does not coincide with the system itself [4]. *In other words, the small- and large-signal response are not compatible in the general case.* An exception can be the case when the system of Eqs. (3) is nearly linear. Such a situation can be realized in a superlattice (SL) with the dispersion law for a given SL period d as $\varepsilon(p) = \Delta[1 - \cos(dp/\hbar)]$ and $m^{-1}(\varepsilon) = (d/\hbar)^2(\Delta - \varepsilon)$ by supposing that $\tau_v(\varepsilon)$ and $\tau_\varepsilon(\varepsilon)$ are independent of ε. In this case [5], for the large- and small-signal response conductivities, $\sigma(\omega)$ and $\sigma_{\mathrm{s}}(\omega)$, respectively, one obtains

$$\begin{aligned}\sigma(\omega) &= \frac{1}{E}\frac{\mathrm{d}j}{\mathrm{d}t}\bigg|_{\omega} \\ &= en\mu_0 \frac{(1+\mathrm{i}\omega\tau_\varepsilon)[1 - (\varepsilon(t_0) - \varepsilon_0)/\tilde{\Delta}] - \tau_v\tau_\varepsilon \Omega_{\mathrm{B}}^2[v(t_0)/\mu_0 E]}{(\Omega_{\mathrm{B}}^2 - \omega^2)\tau_v\tau_\varepsilon + \mathrm{i}\omega(\tau_v + \tau_\varepsilon)},\end{aligned} \tag{4a}$$

$$\sigma_{\mathrm{s}}(\omega) = en\mu_0 \frac{(1+\mathrm{i}\omega\tau_\varepsilon) - \tau_v\tau_\varepsilon\Omega_{\mathrm{B}}^2}{(\Omega_{\mathrm{B}}^2 - \omega^2)\tau_v\tau_\varepsilon + \mathrm{i}\omega(\tau_v + \tau_\varepsilon)}, \tag{4b}$$

where $\Omega_{\mathrm{B}} = eEd/\hbar$ is the frequency of the Bloch oscillations, and $v(t_0)$ and $\varepsilon(t_0)$ are the initial values of the average velocity and energy of photoexcited carriers. By comparing the spectra of large- and small-signal responses (see Eqs. (4)) the resonant part of the spectra (denominator) is the same in both cases and depends on the applied electric field amplitude, i.e. $\Omega_{\mathrm{B}} \sim E$. The difference appears only in the nonresonant part (numerators), where in the case of the large-signal response (Eq. (4a)) there exists an additional dependence of the spectrum on the initial state of photoexcited carriers. As follows from Eqs. (4), the spectra of large- and small-signal response coincide when the initial state corresponds to the stationary values which are realized under action of the electric field E: $v(t_0) = e\mu_0 E/(1 + \tau_v\tau_\varepsilon\Omega_{\mathrm{B}}^2)$ and $\varepsilon(t_0) = \varepsilon_0 + \tau_\varepsilon eEv(t_0)$. However, $v(t_0)$, which coincides with the stationary velocity at a given E, cannot be practically realized under carrier photoexcitation, when $v(t_0) = 0$, and, hence, it is not possible to determine directly the small-signal spectrum of the SL conductivity in the framework of the THz–EO sampling technique.

Acknowledgments

This work was supported, in part, by French-Lithuanian project Gilibert and Lithuanian State Science and Studies Fundation contract No P-01/2007.

References

[1] Y. Shimada, H. Hirakawa, M. Odnobliudov, A.A. Chao, *Phys. Rev. Lett.* **90**, 046806 (2003).

[2] N. Sekile, H. Hirokawa, *Phys. Rev. Lett.* **94**, 057408 (2005).

[3] A. Lisauskas, N.V. Demarina, E. Mohler, H.G. Roskos in: *Proc. ICPS, 2006*, arXiv:cond-mat/0605651.

[4] S.A. Ktitorov, G.S. Simin, V.Y. Sindalovskii, *Sov. Phys. Solid State* **13**, 1872 (1972).

[5] V. Gruzhinskis, E. Starikov, P. Shiktorov, L. Reggiani, M. Saraniti, L. Varani, *Semicond. Sci. Technol.* **8**, 1283 (1993).