Experimental proof of a giant thermo-voltaic effect in n-GaAs: Ultrafast camera system for 10.6 µm pulses

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Conceiving detectors and/or cameras, which can monitor the spatial and temporal beam distribution of very short and powerful CO_2 laser pulses is an important issue in the mid-IR region. A theoretical and experimental feasibility study was performed on novel detectors based on electron temperature gradients in resonant plasmas in GaAs based devices. Close to the plasma resonance, free carrier absorption can be sufficiently large leading to very strong electron temperature gradients, and hence substantial induced currents or voltages depending on the terminating resistor value. We measured responsivities of our novel and cheap detectors, which are equal to these of existing commercial detectors.

1.Introduction

From the large variety of detector principles (pyroelectric, photoconductive, photoelectromagnetic) that do exist only the photon drag effect can be used to detect ultrafast (deep sub-ns) mid-IR laser pulses having large optical power densities (>1MWcm^{-2}). The photon drag effect has a very low responsivity per unit length due the small absorption coefficient at low doping densities. In this paper we propose to use the thermo-voltage generated by large electron temperature gradients in highly doped semiconductor plasma in n-GaAs

2.The model of thermoelectric voltage calculation in multivalley conduction band structure of n-GaAs

Electromagnetic waves at medium infrared wavelengths are strongly absorbed by free electrons in highly doped n-GaAs. The absorption coefficient α_e depends on the free electron concentration n_e and becomes very large for $n_e \sim 7\times10^{18}\,cm^{-3}$ when the laser frequency is close to the plasma frequency of the semiconductor. When an intense laser pulse is incident on the n-GaAs free electron gas, this free electron gas is strongly heated up due the large free electron absorption. Along the laser's propagation direction, the optical power rapidly decreases inside the substrate. This leads to reduced heating at further propagation and hence strong electron temperature gradients are produced, which provoke a thermoelectric voltage.

We consider a sample of n-GaAs homogeneously illuminated by an electromagnetic wave propagating perpendicular to sample surfaces in the X direction. The intensity in the sample can be written down as follows:

$$W = W_0 \exp(-\alpha_e(t_e)x) \qquad (1)$$

where W_0 is the laser intensity at the illuminated sample surface $x=0$ inside the sample and α_e is a function of the electron temperature t_e. Reflection at the sample-air interface is neglected.

The $t_e(W)$ dependence can be found by solving the energy balance equation. The stationary energy balance equation is given by the following expression [1,2]:

$$\alpha_e W = P \tag{2}$$

Here P is the total power transferred to the lattice by the heated free electron gas during the energy relaxation process. The stationary regime corresponds to a situation where the optical pulses are much longer than the relaxation times of the involved nonlinear mechanisms and short enough to avoid any thermal heating of the lattice.

Substituting the dependence $t_e(W)$ into eq.(1), we find the dependencies of the laser intensity and subsequently the electron temperature on x coordinate. The dependence $t_e(x)$ results in the appearance of a thermoelectric voltage (current) in an open (closed) circuit [3]. The thermoelectric voltage U at a propagation depth $x=d$ referenced to the air-substrate interface ($x=0$) writes as follows:

$$U = \int_0^d Q(x)\frac{dt_e(x)}{dx}dx \tag{3}$$

Here Q is the coefficient of differential thermoelectromotive force (thermo-emf). Q can only be calculated by solving the kinetic equation for electron distribution function in the presence of electron temperature gradients taking into account the nonparabolicity of the Γ-valley and anisotropy of the satellite L and X valleys. The total value of Q is given by the following expression:

$$Q = (Q_\Gamma\sigma_\Gamma + Q_L\sigma_L + Q_X\sigma_X)/(\sigma_\Gamma + \sigma_L + \sigma_X) \tag{4}$$

where $\sigma_{\Gamma,L,X}$, $Q_{\Gamma,L,X}$ are the electron conductivity and the coefficient of differential thermo-emf in Γ, L and X valley , respectively.

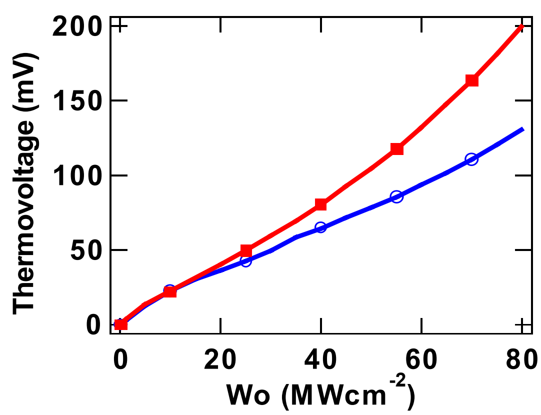

Fig. 1 Theoretical dependence of the thermo-voltage versus the optical power density for two different doping concentrations: n=2.5x10^{18}cm^{-3} (open circles), n=7.0x10^{18}cm^{-3} (closed squares) at T=300K, d=350µm.

The calculation models for α_e and t_e are described in [1,2]. For the determination of $\sigma_{\Gamma,L,X}$ and $Q_{\Gamma,L,X}$, electron interactions with impurities, acoustical and optical phonons are taken into account.

Theoretical dependencies of the thermoelectric voltage V_{thermo} on the incident intensity W_0 are given in Fig.1 for doping concentrations $n_0 = (2.5,\ 7)\times 10^{18} cm^{-3}$, $d = 350\mu m$ and lattice temperature $t_L = 300K$. We see that the thermoelectric voltage is weakly dependent on the doping concentration for $W_0 \le 15MW/cm^2$, but for larger optical intensities this voltage increases with increasing electron concentrations. This is explained by the fact that the thermo-emf coefficient increases with decreased electron gas degeneracy. At higher electron temperatures, the electron gas degeneracy decreases. Thermoelectric voltage V_{thermo} is about $2.5mV$ for an intensity $W_0 = 1MW/cm^2$, $n_0 = 7\times 10^{18} cm^{-3}$ and $d = 10\mu m$. Expressed in unit detector lengths, this results in a large value of 2.5 Vcm/MW. At high doping density levels the photon drag effect [4], where photon momentum is transferred to the electron gas, is quite weak. For smaller doping concentrations the thermoelectric effect will weaken and the photon drag effect becomes dominant. However, common values found in literature for the photon drag effect amount only to 0.1Vcm/MW, i.e. 25 times smaller.

3. Experiment

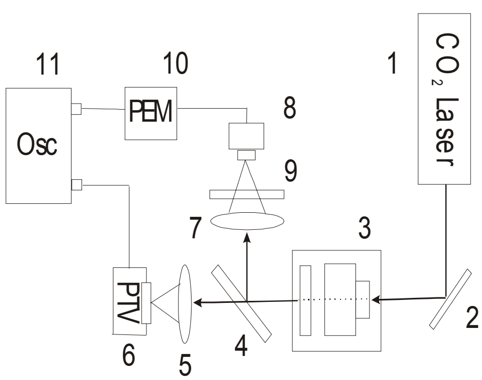

Fig. 2 Schematic layout of the optical setup.

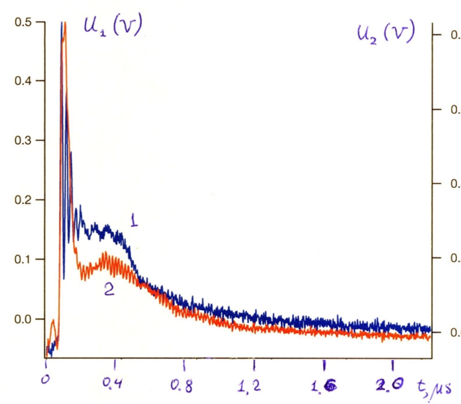

Fig.3 Comparison between a PEM-detector and PVT detector for a 0.12J 100ns long CO_2 laser pulse.

The theoretical results were experimentally verified on a 350μm thick n-doped GaAs substrate with n_e in the range $(1.5-4)\times 10^{18} cm^{-3}$. In Fig. 2 the optical scheme of the experimental setup is schematically shown. The pulse optical radiation with wavelength 10.6 μm generated by CO_2 laser 1 (pulse width is ~ 100 ns, energy ~ 0.1 J, diameter of the beam is ~ 3.5 mm) reflects on mirror M2 in the direction of the combined attenuation system 3, consisting of a pair of polarizers (a rotating and a non-rotating one) to tune the incident intensity. Afterwards the beam splits into two beams by means of a ZnSe splitter 4. The transmitted part is focused on the substrate under test 6 by means of lens 5. The reflected part is focused on the reference PEM photodetector 8 by means of lens 7. The laser beam propagating towards the PEM photodetector is drastically (98-98.5%) attenuated by attenuator 9. The electrical signal produced by the PEM detector is amplified by means of the amplifier 10. This amplified signal and the output of our detector are compared on the oscilloscope. Our detector was used without any cooling. In order to avoid overheating of the specimen, the time duration between the optical pulses was chosen 1 ~ 10 sec. The spot diameter of the beam focused on the GaAs substrate is ~ 0.3 mm. The electrical contacts of our detector were provided at one side by a probe needle and at the backside by an evaporated metal contact. The laser beam is incident on the front side close to the probe contact. The probe voltage is positive with respect to the backside of the substrate

Typical temporal evolution (μs scale) of a thermo-voltaic measurement is shown in Fig.3. The thermo-voltage U_1(V) (left ordinate scale, curve 1) and the amplified PEM-detector voltage (right scale, curve 2) are compared. In according with our calibration the sensitivity of our specimen is close to the theoretical estimation - $3mVcm^2 / MW$. Fig.3 clearly shows that the behavior of both curves is very similar. It can be seen that the slope of the front of the pulse produced by our PTV detector is the same as the slope of the PEM detector. According to our estimations the inherent speed of the PTV effect in highly doped n-GaAs is of the order of 10ps, connected with the energy relaxation time of the heated electrons. The thermo-voltaic effect can be used for direct measurements of electron temperature, power and intensity distribution.

4. Conclusions

We performed a feasibility study of exploiting the thermo-voltaic effect in n-doped GaAs for detecting short and powerful CO_2 laser pulses. The optically heated electrons create an electron temperature gradient, which on its turn produces an electrical voltage. The thermo-voltaic effect was calculated on the basis of rigorous quantum mechanical model of a multi-valley conduction band in GaAs. The idea was tested on a 350 μm thin highly doped n-GaAs sample with doping concentration in the range $n_0 \sim (1.5-4)\times 10^{18} cm^{-3}$. Theoretical and experimental results are in a satisfactory agreement. These n-doped GaAs based photodetectors allow the measurement of the powerful optical pulses without using an optical attenuation system and electrical amplifier and it is bias free.

Our investigations and estimations show that the principal characteristics (sensitivity, response time) of our PTV-detector and PEM are of the same order of magnitude. This structure is very simple and made from commercially cheap n-GaAs. The processing is very simple. The dimensions of GaAs structures can be produced large enough, up to several inches of the diameter, such that IR-camera systems are feasible.

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