PACS numbers: 78.20.Hp; 43.35.Sx
DOI: 10.1070/QE2002v032n01ABEH002130

Subnanosecond optoacoustic response of germanium in a dc electric field

N.V.Chigarev, D.Yu.Parashchuk

***Abstract*. The optoacoustic response of a thin plate of crystalline germanium is studied with a time resolution of $\sim$ 100 ns. A $\sim$ 200-ns time shift of the acoustic video pulse is detected in a $\sim$ 100-V cm^{-1} dc electric field. The mechanisms of the observed effect are discussed.**

Keywords: *picosecond optoacoustics, semiconductors, photoinduced effects.*

1. Introduction

Photogeneration of high-frequency acoustic pulses in semiconductors has attracted the attention of researchers ever since the time of creation of lasers [1]. The universal thermoelastic mechanism of excitation of sound in semiconductors, metals, and other condensed media is well known [2]. Apart from the thermoelastic mechanism, the electron deformation mechanism of sound generation [3], associated with the excitation of a free-charge carrier plasma, is also operative in semiconductors. The space – time dynamics of such a plasma determines the time profile of acoustic pulses.

The efficiency of the electron deformation mechanism is directly proportional to the electron – phonon interaction potential constant of the crystal. The electron deformation mechanism in silicon and germanium is approximately an order of magnitude more efficient than the thermoelastic mechanism upon nanosecond [2, 3] and picosecond [4] excitations. In addition, auxiliary channels for pulse shortening are possible upon the electron deformation generation of sound in the case of nonlinear recombination of an electron-hole plasma (EHP).

We recently studied the electron deformation mechanism of the optoacoustic response in germanium with a picosecond time resolution [4]. We obtained information on the types of the EHP relaxation and determined the diffusion and electron – phonon interaction coefficients in germanium. Longitudinal acoustic pulses were detected with the help of the pump – probe deflection method [4] in which the signal being measured is proportional to the slope of the surface in the region of the emergence of an acoustic pulse from the bulk at the surface.

The aim of this paper is to study the photogeneration of an acoustic pulse in germanium by an external dc electric field. The interest in such a regime of photoexcitation of sound is associated with the possibility of controlling the motion of an EHP near the surface and the possibility of shortening of the generated acoustic pulse [5].

2. Sample and measuring technique

The sample for acousto – optical experiments was a plane–parallel plate of monocrystalline germanium. Germanium was chosen because this semiconductor has been well studied and is available in the form of high-quality single crystals. The thickness of the plate oriented in the [111] direction was $\sim$ 60 μm. Both its surfaces were polished with an optical precision. A dc electric field was applied to the electrodes representing the contact paste deposited on the opposite surfaces of the plate at a distance of $\sim$ 1 mm from each other (Fig. 1). The dc electric field $E_0 \sim 100$ V cm^{-1} was produced by a controllable stabilised dc power supply. The electrode geometry provided the field E_0 parallel to the sample faces. A direct current $\sim$ 10 mA passed through the sample.

The small photoinduced deformation of the surface was detected from the angle of deflection of the probe laser beam reflected from the region under study (see Fig. 1). The

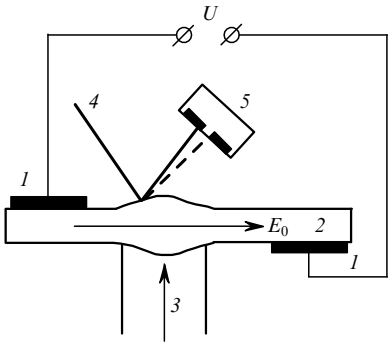

Figure 1. Schematic for exciting and probing an acoustic pulse in a crystalline germanium plate: (*1*) electrodes, (*2*) germanium plate, (*3*) pump beam, (*4*) probe pump, (*5*) position-sensitive detector.

N.V.Chigarev International Teaching and Research Laser Center, M.V.Lomonosov Moscow State University, Vorob'evy gory, 119899 Moscow, Russia; e-mail: chigarev@polys1.phys.msu.su;
D.Yu.Parashchuk Department of Physics, M.V.Lomonosov Moscow State University, Vorob'evy gory, 119899 Moscow, Russia; e-mail: paras@polys1.phys.msu.su

Received 14 June 2001
Kvantovaya Elektronika **32** (1) 76 – 78 (2002)
Translated by Ram Wadhwa

deflection method involving the excitation and probing of an acoustic pulse at the opposite faces of the plate was used in the experiment (Fig. 2). This method allowed us to eliminate the effect of deflection of the probe beam caused by the optical interaction of the pump and probe beams at the sample surface. In this case, the deflection signal is not related to the surface mechanical displacement and predominates during the probing of the acoustic action near the photoexcitation region [6].

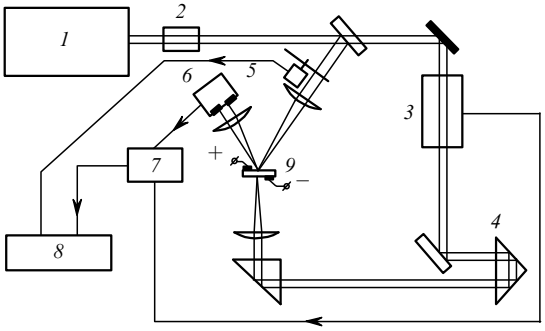

Figure 2. Scheme of the experimental setup: (*1*) picosecond laser, (*2*) frequency doubler, (*3*) electrooptical modulator, (*4*) delay line, (*5*) mechanical chopper, (*6*) position-sensitive detector, (*7*) frequency converter, (*8*) lock-in detector, (*9*) sample.

The photodetection system consisted of a high-sensitivity rf lock-in detector capable of recording relative variations $\sim 10^{-7}$ in the photocurrent [7]. The system comprised a ML-102 electro-optical modulator operating at a frequency of 6.2 MHz; a position-sensitive silicon photodetector for recording small displacements of the probe beam, which was fabricated on the basis of a FD-19 quadrant photodiode; an rf-to-acoustic frequency converter; an SR510 lock-in detector; and a mechanical chopper operating at a frequency of ~ 800 Hz.

A quasi-continuous Nd:YAG laser generating a train of ~ 100-ps pulses with a repetition rate of 100 MHz was used for pumping at 1064 nm and probing at 532 nm. The average power of the pump and probe beams at the sample surface was ~ 100 and 2 mW, respectively. The optical delay line with a corner reflector was controlled in the range 0–3 ns. The pump and probe beams were focused at the sample surface by lenses of diameters ~ 20 and 10 μm, respectively. A diaphragm of diameter ~ 10 μm made of a metal foil of thickness close to that of the sample thickness was used to make the beams coincident. A preliminary spatial combining of pump and probe beam waists was also performed using the diaphragm. A more exact tuning to the maximum gradient of the surface slope was performed by the observed signal. A SZS-22 light filter rejecting the pump beam and transmitting the probe beam was placed in front of the photodetector.

3. Experimental results

An acoustic pulse was excited upon absorption of a laser pulse at the surface of the germanium plate. The time of sound propagation to the opposite face of the plate was determined by its thickness l and velocity $c_s = 5.56 \times 10^5$ cm s^{-1} [8] of a longitudinal sound wave propagating in the [111] direction in the germanium crystal ($\tau_a = l/c_s \approx 10.8$ ns). The acoustic pulse was multiply reflected from the plate–air interface with reflection coefficients close to unity and formed echo signals, which were detected in the probe channel.

The pulse profile recorded by the cross-correlation technique reproduces the temporal dynamics of an acoustic video pulse in the germanium plate. Fig. 3 shows the measured deflection signal illustrating the interference of sound in the plate. The solid curve in Fig. 3 shows two echo signals, the maximum of the first acoustic pulse corresponding to one passage through the plate.

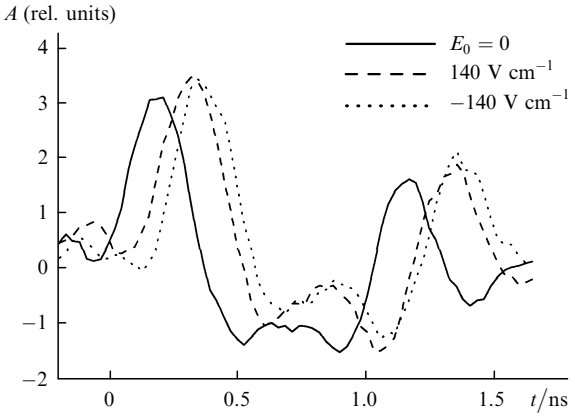

Figure 3. Profile of an acoustic pulse A in a germanium plate for different values of E_0. The position of zero on the time axis is chosen arbitrarily.

The application of a dc electric field $E_0 \approx 140$ V cm^{-1} to the sample caused the shift of the interference pattern by about 200 ps towards the increasing time delay (dashed curve). A reversal of the field caused the shift of the interference pattern by about the same amount in the same direction (dotted curve). The signal shift was directly proportional to the applied field within the measuring error.

The acoustic pulse profile could be distorted due to the sample heating caused by the electric current. This effect was estimated in a separate experiment in which the sample was heated to $\sim 80\,^\circ$C. No visible changes in the shape or shift of the acoustic pulse profile were detected.

4. Discussion

Thus, we detected a time shift ~ 200 ps of the acoustic pulse in the optoacoustic experiment caused by a comparatively low dc electric field applied to the sample. We analysed various mechanisms of this shift, including the thermal expansion of plate caused by the electric current flowing through the plate. Let us estimate the thermal effects in greater detail, taking into account the known temperature dependences of the sound speed, mobility, and the diffusion coefficient for germanium. Note first of all that the shift of the acoustic pulse by 100 ps should correspond to the plate thickness variation $\Delta l = c_s \tau \approx 0.5$ μm caused by a relative elongation $\Delta l/l \approx 10^{-2}$. Such a value of $\Delta l/l$ corresponds to an increase $\Delta T = \beta^{-1} \Delta l/l \approx 600$ K in the crystal temperature for a linear thermal expansion coefficient $\beta = 1.8 \times 10^{-5}$ K^{-1} for germanium [9]. The sample heating by current never exceeded 100 K in the

experiment. The variation of the sound speed in germanium [8] was $\Delta c_s/(\Delta T c_s) \approx 5 \times 10^{-5}$ K^{-1}, which gives $\Delta c_s/c_s \sim 5 \times 10^{-3}$ at $\Delta T = 100$ K. The temporal shift of the profile during the pulse propagation time $\tau_p \approx 10$ ns over the plate thickness was $\Delta\tau = \tau_p \times \Delta c_s/c_s \approx 50$ ps, i.e., about one-fourth of that observed in the experiment.

Both the thermal effects considered above should lead to an increase in the time interval $2l/c_s$ between adjacent echo signals, which was not observed in our experiments. The interference pattern of the acoustic pulse moves as a whole, without any change in its shape.

The acoustic pulse profile may depend on the temperature variation of the ambipolar diffusion coefficient of an EHP: $D = k_B T \mu_a(T)/e$, where k_B is the Boltzmann constant, e is the electron charge, and $\mu_a(T)$ is the ambipolar mobility of charge carriers. The calculation of the acoustic pulse using the electron deformation mechanism taking into account the temperature dependence $D(T)$ showed the absence of noticeable changes in the profile upon heating up to ~ 100 K. In addition, a change in D should modify the acoustic signal front durations [4, 5], which was not observed in the experiment (Fig. 3). Thus, we can conclude that the influence of thermal effects on the observed acoustic profile can be neglected. This is also confirmed by the above-mentioned test experiment involving the sample heating.

The motion of free charge carriers alters the acoustic pulse profile in the electron deformation mechanism of sound generation [2]. In the absence of an external electric field, their motion is governed by diffusion. Apparently, the observed time shift of the acoustic pulse is caused by the drift of the photoexcited EHP in an electric field. Note that the drift of charge carriers occurs mainly along the sample surface, which is determined by the direction of lines of force of the electric field E_0. At 300 K, the charge carrier drift velocity $v = \mu E_0$ in a germanium crystal is $\sim 5.3 \times 10^5$ and $\sim 2.7 \times 10^5$ cm s^{-1} for electrons and holes, respectively [9]. Because these velocities are comparable with the velocity of a longitudinal acoustic wave, the drift may significantly affect the dynamics of a photoexcited EHP in the region of sound excitation. The one-dimensional model of electron deformation-induced sound excitation used by us is not suitable for an adequate simulation of the photoexcitation of sound under the conditions of the EHP drift [2, 5].

Apparently, our experiments are the first in the picosecond optoacoustics in which a photoexcited hypersonic pulse was shifted in time by applying an external electric field. Such experiments extend the potentialities of picosecond acoustics, for example, for studying thin films of various materials with a high time resolution.

Acknowledgements. This work was supported by the INTAS Grant No. 31680.

References

1. Tucker W., Rampton W. *Giperzvuk v tverdykh telakh* (Hypersound in Solids) (Moscow: Nauka, 1978).
2. Gusev V.E., Karabutov A.A. *Lazernaya optoakustika* (Laser Optoacoustics) (Moscow: Nauka, 1991).
3. Avanesyan S.M., Gusev V.E., Zheludev N.I. *Appl. Phys. A*, **40**, 163 (1986).
4. Chigarev N.V., Paraschuk D.Yu., Pan X.Y., Gusev V.E. *Phys. Rev. B*, **61**, 15837 (2000).
5. Akhmanov S.A., Gusev V.E. *Usp. Fiz. Nauk*, **162** (3), 3 (1992).
6. Rothenberg J.E. *Opt. Lett.*, **13**, 713 (1988).
7. Paraschuk D.Yu., Kulakov T.A., Nedopekin O.Yu., et al. *Rev. Sci. Instrum.*, **68**, 3989 (1997).
8. Shaskol'skaya M.P. *Akusticheskie kristally. Spravochnik* (Handbook on Acoustic Crystals) (Moscow: Nauka, 1982).
9. Grigor'ev I.S., Meilikhov E.Z. (Eds.), *Fizicheskie velichiny. Spravochnik* (Handbook on Physical Quantities) (Moscow: Energoatomizdat, 1991).