Terahertz Emission by Nanoporous GaP(111)B

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***Abstract*—We have studied the emission of terahertz radiation from nanoporous semiconductor matrices of GaP excited by the femtosecond laser pulses. We observe 3-4 orders of magnitude increase of terahertz radiation emission from the nanoporous matrix compared to bulk material.**

The terahertz (THz) region of spectrum is important for a variety of applications ranging from security scanners, subsurface non-destructive testing of materials to bio/chemical identification of drugs and explosives, and time-domain spectroscopy (TDS) [1], [2]. However, compared to other spectral regions, breakthrough in these high-tech fields has been hindered by a shortage of readily available powerful and compact coherent sources [3].

In recent public literature, it has been shown that the efficiency of THz emission can be increased to a great extent if the bulk semiconductor is replaced with a structured surface [4]. Fabrication of porous matrices is another way to create a large semiconductor surface without destruction of the crystalline perfection. This allows reaching high aspect ratio and extreme density of pores [5]. Such matrices can be produced using a well developed technique of anodic electrochemical etching. It is also known that surface THz emitters based on GaP have larger dynamic range and wider spectra [6], [7].

Therefore, in this work we study the THz emission from the nanoporous GaP matrices (por-GaP). THz transients and their Fourier spectra for bulk n-type GaP (bulk-GaP) and por-GaP excited with femtosecond optical pulses were measured using THz-TDS method and compared to each other.

The nanoporous matrices of GaP (see insert in Fig. 1) were fabricated by anodic electrochemical etching of industrial n-type GaP wafer of LEC-grown with carrier concentration 3.7×10^{18} cm^{-3} and orientation (111)B. The electrochemical etching was carried out in KOH aqueous electrolyte in the potentiostatic regime for 240 seconds at voltage 8 V and at constant temperature (23° C). Parameters of electrochemical etching was chosen according to with theoretical description of the etching process for GaP [5]. The morphology and structure of the porous layers were studied using Scanning Electron Microscope JEOL JSM–7001F (SEM). As result we have fabricated nanoporous GaP matrices with the following parameters: pore diameter 26±3 nm, wall thickness 27±5 nm, direction of the pores $[111]$B, thickness of the porous layer 40±1 μm, aspect ratio more than 1500 and porosity of the porous layer 65±10%.

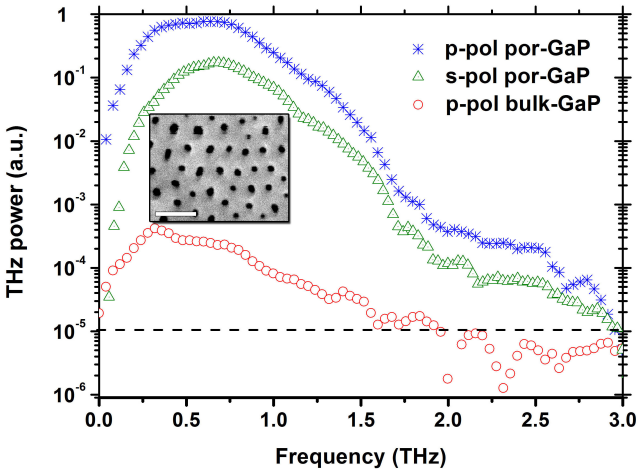

Fig. 1. Terahertz emission spectra (Fourier transform). Blue stars and green rectangles are spectra of THz emission from the nanoporous GaP sample (p- and s-polarizations of THz radiation, respectively). Red circles is spectrum of THz emission (p-polarization of THz radiation) from the bulk-GaP. Dashed black line is the noise level (at 10^{-5}). Spectra were obtained at the excitation wavelength of 515 nm and power of 550 mW. Insert shows Scanning Electron Microscopy image of surface of the nanoporous GaP matrix. The scale bar indicate 100 nm.

The experimental setup for the spectral investigation of THz excitation is based on an amplified Yb:KGW laser system operating at 1030 nm with pulse duration 160 fs and pulse repetition rate 200 kHz. The investigated surface emitters were excited with the output beam, and radiated THz signals were detected in a photo-conductive GaAsBi antenna and illuminated by a small part of the Yb:KGW laser beam, whose power was reduced to 5 mW by two beam splitters. The frequency-domain spectra were retrieved using fast Fourier transforms. The setup provides the opportunity to work in the frequency range up to 3 THz with the dynamic range of 10^5 at 0.75 THz.

Schematic diagram of the experiment is shown on Figure 2. The fs laser beam illuminated a small area on the sample surface. The diameter of beam was equal to ∼3 mm and the incidence angle was 45°. We observed the coherent photon THz emission at 45° reflection angle from the sample. The Fourier spectra of s- and p-polarized THz emission pulses from por-GaP, as well as p-polarization spectrum for bulk-GaP, are presented in Figure 1. All measurements have been

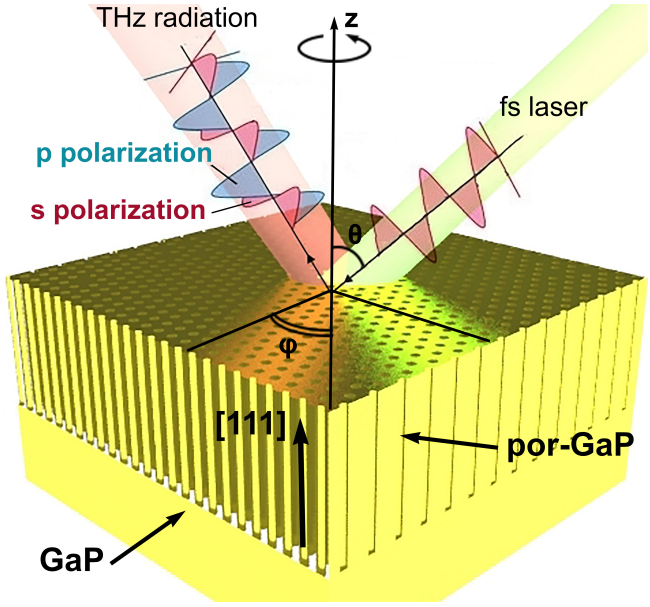

Fig. 2. Schematic diagram of the experimental geometry. Green glowing beam is a laser beam and coral cone is THz beam. S-polarized radiation has polarization perpendicular to the plane of incidence and p-polarized radiation has polarization parallel to the plane of incidence. Both polarizations are perpendicular to the propagation direction of THz radiation. The sample orientation is displayed in spherical polar coordinates, where z-axis is perpendicular to both the surface of the crystal and the (111) crystal plane, φ – azimuth angle, ϑ – zenith angle.

performed with the fixed parameters of the fs laser pulse (the excitation wavelength 515 nm and power 550 mW). We found the great increase of terahertz emission from por-GaP compared to bulk-GaP for p-polarization of the THz beam. Note that the observed increase of intensity is about 3-4 orders of magnitude in the range 0.5–1.0 THz!

The s-polarized THz emission from bulk-GaP was not observed. However, for por-GaP we have observed the s-polarized THz emission, which intensity is comparable to the intensity of the p-polarized emission from this material (see Fig. **??**). The presence of s-polarized emission for por-GaP shows that THz radiation is generated inside the porous layer, unlike in bulk-GaP, where the radiation is generated at the very surface of sample. Additional evidence for the emission occurs at microscopic surface of pores in por-GaP layer is the change of THz radiation intensity as a function of the sample rotation angle [8]. We measured the THz pulse magnitude as a function of the azimuthal angle φ by rotating the sample around the z-axis (see Fig. 2).

For cubic crystals and (111) crystallographic plane, THz amplitude is changing proportionally to sin 3ϕ (OR- and EFIOR-effects) [8]. Nevertheless, for our por-GaP samples, as well as for InAs nanowire arrays, the THz amplitude is practically independent on azimuthal angle [9], i.e. the radiation is axially symmetric. The observed data shows that increase in efficiency of THz emission is connected with the increase of the surface area. Simple estimation shows that the microscopic surface area of 40 μm thick porous layer with the pore aspect ratio equal to 1500 is 5000 times greater than the area of macroscopic surface.

Also, the enhanced THz emission in porous samples may be caused by uniform excitation of careers in relatively thick porous layer and reduced absorption of radiation by free charge carriers. The THz radiation from bulk GaP may be strongly screened by non-equilibrium charge carriers, what suppresses the conversion efficiency at high levels of excitation. In porous samples practically no absorption of long-wave radiation by free charge carriers is observed, which leads to better output of THz radiation. We associate this effect with the conductivity electrons capturing on surface states. It is also important to note that the absorption depth for pump radiation is relatively small in bulk semiconductors, which leads to rapid saturation of THz emission with the increase of excitation level. Lowering the optical density of porous semiconductor should enlarge the penetration depth in 3–5 times. A preliminary study of the absorption spectra of porous samples showed the emergence of absorption in region below fundamental edge of bulk GaP, caused by the formation of electronic states density within the band gap. This observation can be used to provide effective sample pumping by means of accurate selection of the excitation radiation wavelength.

To conclude, we observed surprisingly high efficiency of the THz emission from por-GaP. The generated THz power is up to 4 orders stronger than radiation from bulk GaP. We believe that a drastic increase of sample surface might be responsible for the observed effect. Highly precise etching process [5] allows fabricating porous matrices with pore aspect ratio more than 1500. Thus, the porous matrices are found to be a promising material for THz radiation sources.

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