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SiC AND GaAs EMITTERS AS SELECTIVE TERAHERTZ RADIATION SOURCES

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Two types of electrically heated THz radiation emitters: (1) the Globar-SiC (black body), and (2) the highly doped GaAs plate, are considered as selective high-power terahertz (THz) radiation sources. The spectrum of the new type GaAs emitter in the 9–15 THz frequency range is determined by oscillations of free electron plasma and coupled plasmon–phonons. The thermally stimulated resonant emission of surface plasmon–phonon polaritons is experimentally observed. The radiative modes of coupled surface plasmon–phonon polaritons in the n^+-GaAs plate are identified.

Keywords: THz radiation sources, black-body radiation, coupled plasmon–phonon polaritons, SiC, GaAs

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1. Introduction

One of the most exciting areas today to explore scientific and engineering phenomena lies in the terahertz (THz) spectral region. The THz region of electromagnetic spectrum is of great importance due to rich physical, biological, and chemical processes in this range. The THz radiation is widely used for non-destructive medical scanning, security screening, quality control, atmospheric investigation, space research, for studies of works in art, etc. [1–8]. One of the key components of any application is the THz radiation source.

For non-destructive optical testing of conductivity and lattice dielectric function of semiconductor heterostructures as well as for medical imaging applications, the 1–30 THz sources with a high power (typically of 10 mW) and large beam size (~1 cm^2) of the emitted beam are needed [5, 7, 9, 10].

The aim of our experiments is to propose a compact portable relatively simple THz source emitting a wide THz radiation beam with a power density higher than 5 mW/cm^2 in the frequency range of 10–20 THz and a power density higher than 10 mW/cm^2 in the range of 20–30 THz.

In this paper, two different types of thermally stimulated THz radiation emitters are considered**:** (1) the Globar-SiC whose radiation is close to the black-body emission spectrum and (2) the highly doped GaAs with the THz emission spectrum determined by coupled plasmon–phonon oscillations.

2. Globar-SiC (black-body) THz radiation emitter

The most common far infrared sources used up to now have been black-body radiation sources, such as Globars (SiC) [1–3]. In our experiment, the SiC slab of length L = 5 cm and diameter d = 4.3 mm was electrically heated up to 950 K. The measured spectrum of the SiC sample was close to the black-body spectrum. The intensity of the black-body total radiation estimated from the Planck formula at temperature $T = 10^3$ K is 5.6 W/cm^2. The THz radiation intensity in the 0–15 THz frequency band achieves 10 mW/cm^2, but at the frequency of 1 THz, the black-body emitted intensity is only about 10 μW/cm^2.

However, the main advantage of a Globar (black body) THz radiation source as compared with other types of THz radiation sources is an unlimited possibility to increase the size of a hot Globar source and to achieve the highest radiation power density by focusing the radiated power to a smaller area. That allows us to use the Globar-SiC radiation emitters as high-power continuous wave radiation sources with a large-size radiation beam (~1 cm^2).

Figure 1 shows a schematic diagram of the experimentally realized THz radiation source based on the Globar-SiC radiation. The radiation from the Globar-SiC rod electrically heated until 950 K is directed by the collection system to the waveguide (Al tube with the inner diameter of 9.5 mm). The total Globar radiation power collected to the waveguide achieves 0.9 W. To cut a visible part of the Globar radiation, a silicon plate is used. Reflectors and filters are used to select the required THz frequency range. The THz radiation output power is measured by the pyroelectric power meter (Vector H410 *Scientech Inc.*). This radiation power in the 11–33 THz frequency range was measured by using two types of optical filters, F_1 and F_2, for 11–22 and 17–33 THz frequency ranges, respectively.

The selection of the 1–20 THz frequency range from the hot Globar radiation spectrum is a complicated problem because most of the materials used as optical elements for the visible and infrared spectra are opaque in that 1–20 THz frequency range. We have proposed [11] to use the known-for-a-long-time Reststrahlen effect in the 5–30 THz frequency range in alkali halides and polar semiconductors. We have used these materials as reflectors (mirrors) with a large reflection area (~1 cm^2) for separating the determinate frequency band from the heated-body emission spectra [11].

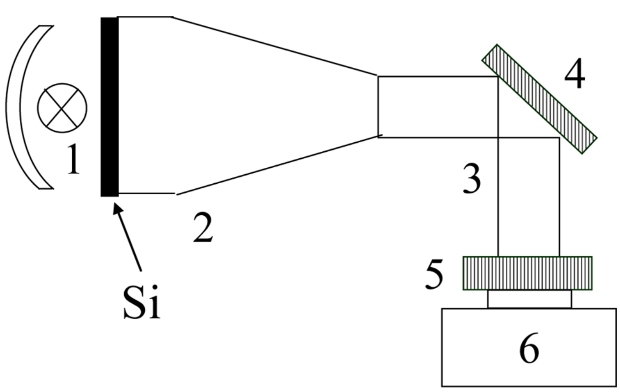

Fig. 1. Set-up of the experiment: *1* Globar-SiC rod, *2* collection system, *3* waveguide (Al tube), *4* T-ray resonant reflectors, *5* T-ray filters, and *6* spectrometer.

Table shows the experimentally observed THz source output power data dependently on the reflector type: the total power (without filters) of Globar radiation P_{total} and powers P_1 and P_2 in the 11–22 and 17–33 THz frequency ranges, respectively.

Table 1. Experimental data of the THz source output power.

Reflector	Total output power	Filter F_1 11–21 (THz)	Filter F_2 17–33 (THz)
	P_{total}(mW)	P_1 (mW)	P_2 (mW)
Al	200	6.4	19.8
Sapphire	33	5	10.6
CaF_2	21	3.4	4
BaF_2	21	1	2.6
GaAs	82	4.4	8.4
InSb	71	3	8.8

In the case of the Al-coated reflector, the observed total output power of the Globar radiation collected in the waveguide after the Si-filter is equal to 200 mW and the power values in the THz frequency range selected by the filters are P_1 = 6.4 mW and P_2 = 19.8 mW. In the range of 11–33 THz, the collected power part of the Globar radiation can be estimated as 13%. In cases of BaF_2, CaF_2, and sapphire (α-Al_2O_3) reflectors with low high-frequency refractive indexes, the reflected output power decreases up to 21–33 mW. However, a strong increase in the THz radiation part selected by the filters from the total collected radiation takes place. In the case of the sapphire reflectors, half of the reflected Globar radiation power belongs to the 11–33 THz spectrum part. In cases of CaF_2 and BaF_2 reflectors, the cuts of high-frequency parts of the Globar radiation take place at 12 and 16 THz, respectively. Due to this reason, the observed radiation power in the frequency range selected by the filters is low. In cases of GaAs and InSb reflectors, the total output power increases up to 70–82 mW due to large high-frequency refractive indexes, and the 11–33 THz part of the radiation power output is less than 17%.

One can see that the observed output power in the 11–33 THz frequency range achieves 12–25 mW at the collected Globar source total output power of 200 mW. Therefore, it is shown that a higher power level of the THz source can be achieved by the value of Globar output power which has to exceed 200 mW. Thus, a large radiation power in the THz frequency range allows us (using the Reststrahlen effect) to select the narrow frequency line ($\Delta\nu$ = 1 THz) with a sufficiently high power (10^{-3} W).

3. GaAs as a selective THz radiation emitter

The heated single crystal GaAs plates made of Te-doped 350 μm thick polished wafers are investigated as THz radiation emitters. The measured total emitted power density of a GaAs plate with the size of 8 × 20 mm^2 exceeds 20 mW at 150 °C. However, the emitted radiation spectra of the heated GaAs plate in the THz frequency range differ from the black-body radiation spectra.

The GaAs plate was heated by electric current. The thermally stimulated THz emission spectra were measured by the IR Fourier transformer–spectrometer (*Thermo Scientific Inc.* Nicolet 8700). It is found that the resonant reflection as well as emission of the THz radiation depends on temperature of the GaAs plate.

Figure 2 shows the measured reflection spectra of three samples of conductive n$^+$-GaAs with high density of free electrons in comparison with the reflection spectrum of semi-insulating (SI) GaAs.

We can see that SI GaAs has a sharp resonant reflection peak, which corresponds to the transverse optical (TO) phonon frequency ω_T and sharp reflection minimum, which corresponds to the longitudinal optical (LO) phonon frequency ω_L.

The THz reflection spectra of high-conductivity n$^+$-GaAs are quite different from those of SI GaAs. A large increase in the reflection in a wide radiation frequency band in comparison with the reflection in the SI GaAs case is accompanied by two dips in

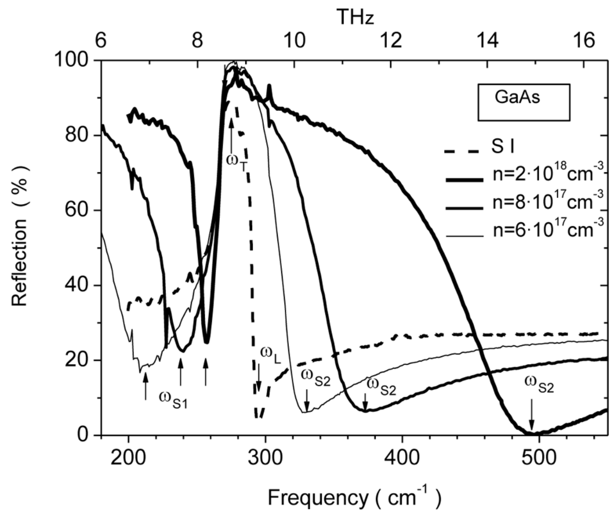

Fig. 2. THz reflection spectra of the SI and doped GaAs plates with electron densities: 6 × 10^{17}, 8 × 10^{17}, and 2 × 10^{18} cm^{-3} at T = 300 K. The frequencies of minimal reflection, ω_{S1} and ω_{S2}, are shown by arrows.

reflection spectra (labelled as ω_{S1} and ω_{S2}) for every doped samples. The frequency of reflection minimum ω_{S1} is near the GaAs bulk TO phonon frequency. The frequency ω_{S2} is larger than the bulk LO phonon frequency and increases with increasing the free electron density in GaAs. At frequencies $\omega < \omega_{S1}$, the experimentally observed reflection increases.

The interaction of free electron plasma and phonon oscillations with the THz radiation is responsible for significant changes in these spectra [3, 9, 12, 13]. The coupling between infrared-active optical phonons, plasmons, and electromagnetic waves can be so strong that they cannot be separated inside the medium. Instead, they should be regarded as coupled waves or quasiparticles known as plasmon–phonon polaritons. These longitudinal oscillations are known as the coupled plasmon–LO phonon modes [3, 12, 13].

Note that the resonance in the reflectivity spectra of highly doped GaAs with $\omega_P^2 > \omega_L^2$ does not equal the LO or TO phonon frequency as well as plasma frequency ω_P but is determined by the specific coupled plasmon–phonon oscillations.

Assuming that the interaction of THz radiation with the surface plasmon–phonon oscillations is responsible for the peaks of low reflectivity ω_S, the frequency ω_S can be estimated from the equation

$$\varepsilon(\omega_S) + 1 = 0, \tag{1}$$

where the dielectric function of highly doped GaAs is equal to [3, 12]

$$\varepsilon(\omega) = \varepsilon_{\infty}\left(\frac{\omega^2 - \omega_L^2}{\omega^2 - \omega_T^2} - \frac{\omega_p^2}{\omega^2}\right), \qquad (2)$$

where ω_p is the free electron plasma oscillation frequency in GaAs. Assuming $\omega_p \approx 420$ cm^{-1}, we obtain $\omega_{S1} \approx 250$ and $\omega_{S2} \approx 423$ cm^{-1}. This coincides with the experimentally observed data and confirms that the frequencies of reflection resonances ω_{S1} and ω_{S1} are determined by the interaction of the THz radiation with surface plasmon–phonon polaritons.

It is predicted [3, 12, 13] that at

$$\varepsilon(\omega) = 0, \qquad (3)$$

the resonant coupled plasmon–phonon oscillations are emitted from GaAs in the THz spectral range. The self-sustaining resonant oscillation at $\varepsilon = 0$ appears in the absence of incident THz radiation. Thus, the specific plasmon–phonon oscillation is not excited by an electric field of incident THz radiation. The electromagnetic field created by thermal vibrations of atoms can "leave" a crystal under certain conditions and be recorded as thermal emission of a nonblack body [3, 13].

We used the dependence of the plasmon–phonon radiation intensity on the crystal temperature for identification of radiated modes of plasmon–phonon oscillations. The thermally stimulated THz emission and reflection spectra of the highly doped GaAs plate were measured.

Figure 3 shows the radiation spectra of thermally stimulated THz emission power P of the heated highly doped GaAs plate. One can see that two resonant emission peaks are experimentally observed at the frequencies of 250 and 450 cm^{-1}. Note that the emission spectra are modulated by sharp spikes caused by the interaction of THz radiation with water vapours in the air.

Note that the experimentally measured THz radiation resonant frequencies ω_{rad} coincide with the theoretically calculated ones of bulk plasmon–phonon oscillations in GaAs. The frequency ω_{rad} of the bulk plasmon–phonon polariton is determined by the equation $\varepsilon(\omega_{rad}) = 0$. The estimated values are $\omega_{rad1} = 253$ and $\omega_{rad2} = 442$ cm^{-1} for $\omega_p \approx 420$ cm^{-1}.

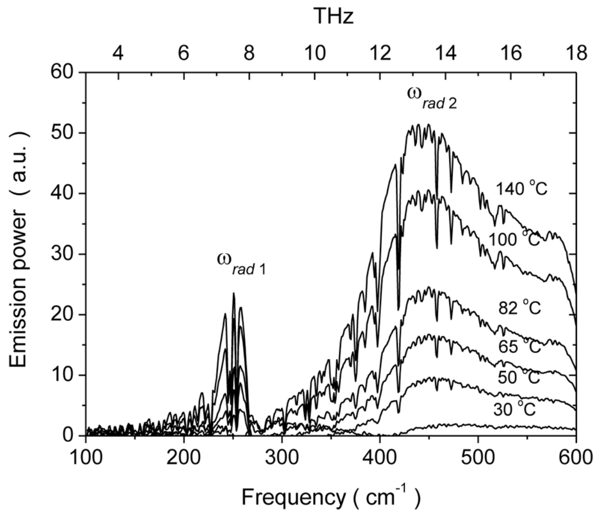

Fig. 3. THz emission power spectra of the heated highly doped GaAs plate at different temperatures.

One can see that the intensity of THz resonant radiation at resonance frequencies increases with increasing GaAs temperature. The intensity of the THz resonant radiation outside the resonant peaks is very small. However, a slow increase in intensity with radiation frequency increasing is observed. It coincides with the increase in black-body radiation intensity.

The total power density of the emitted radiation of the GaAs plate heated at 250 °C exceeds 40 mW/cm^2. This means that the heated GaAs sources with selected 7.6 and 13.3 THz frequencies can be used as high-power continuous wave THz radiation sources.

5. Conclusions

Two types of heated emitters, Globar-SiC and highly doped GaAs plate, are considered for generation of high-power THz radiation. The compact portable high-power THz radiation source useful for studying interaction of high-power THz radiation with elemental THz excitations in solids (phonons, plasmons) and with molecular oscillation excitations in biological materials is realized. The new type selective continuous wave THz radiation source in the 5–15 THz frequency range based on the radiative modes of coupled plasmon–phonon oscillations in the highly doped GaAs plate is proposed. The thermally stimulated resonant plasmon–phonon radiation of the highly doped GaAs is experimentally observed.

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SELEKTYVŪS TERAHERCŲ SPINDULIUOTĖS ŠALTINIAI SU SiC IR GaAs EMITERIAIS

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Santrauka

Nagrinėjami dviejų tipų emiteriai: 1) SiC spinduolis-globaras (juodas kūnas) ir 2) stipriai legiruota GaAs plokštelė, kaip selektyvūs didelės galios terahercų (THz) spinduliuotės šaltiniai. Naujo tipo GaAs emiterio spektras 9–15 THz dažnių ruože yra sąlygojamas laisvųjų elektronų plazmos ir surištų plazmon-fononų osciliacijomis. Eksperimentiškai stebėta termostimuliuota paviršinių plazmon-fonon-poliaritonų rezonansinė THz emisija. Identifikuotos paviršinių plazmon-fonon-poliaritonų spindulinės modos n^+-GaAs plokštelėje.