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Thermostimulated THz Radiation Emission of GaAs at Surface Plasmon-Phonon Polariton Frequencies

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The THz radiation reflection, absorption and emission spectra of conductive *n*-GaAs/air surface are considered. The influence of thermostimulated surface plasmon-phonon (SPP) polariton oscillations on THz radiation reflection, absorption and emission of high conductivity GaAs polished plates with electron density $n = 7 \cdot 10^{17}$ cm^{-3} and $4 \cdot 10^{18}$ cm^{-3} and thickness of 350 μm is studied experimentally. The frequencies of thermostimulated transverse and longitudinal optical phonons and SPP oscillations, which characterize a heated lattice state, were determined. It is found that the heated highly doped interface layer (GaAs/air) emits the THz radiation at selected frequencies of SPP oscillations in the (7 – 8) THz and (10 – 15) THz ranges. It is shown that thermal heating of the GaAs/air interface enhances the absorption of the incident THz radiation. The huge decrease of the incident radiation reflectivity at the SPP frequencies with an increase of GaAs temperature is observed experimentally.

Keywords: thermostimulated THz radiation emission, surface plasmon-phonon polaritons, GaAs, black-body radiation.

1. INTRODUCTION

Recently, it was experimentally observed that the reflection spectra of conductive flate *n*-GaAs plate are characterized by reflection dips at coupled free electron plasma and interface (GaAs/air) phonon oscillation frequencies [1 – 3].

In this paper, the influence of thermostimulated non-coherent surface plasmon-phonon (SPP) oscillations on THz radiation reflection, absorbtion and emission is experimentally investigated.

2. SURFACE PLASMON-PHONON WAVES

The SPP waves arise in the frequency range where dielectric function is negative. The dielectric function of highly doped GaAs can be describe as

$$\varepsilon(\omega) = \varepsilon_\infty \left(\frac{\omega^2 - \omega_L^2}{\omega^2 - \omega_T^2} - \frac{\omega_p^2}{\omega^2} \right), \quad (1)$$

where ε_∞ is the optical dielectric constant, ω_T and ω_L are the transverse optical (TO) and longitudinal optical (LO) phonon frequencies, respectively, and ω_P is the plasma frequency. $\varepsilon(\omega)$ is negative in a wide range of frequencies $\omega_T < \omega < \omega_L$ in a pure crystal and at $\omega < \omega_P$ in highly doped crystal.

We assume that two type frequencies of SPP, ω_{S1} and ω_{S2}, are the roots of equation $\varepsilon(\omega) = -1$. Note that $\omega_{S1} < \omega_T$ and $\omega_{S2} > \omega_L$.

The spectral density of states of the surface plasmon–phonon waves of thermostimulated field depends on the distance from the semiconductor surface [3 – 10].

The spectra of electromagnetic emission of SPP non coherent oscillations are remarkable different in near and far zones from a semiconductor surface. The spectral changes occur due to losses of evanescent modes of SPP waves of a flat GaAs plate. At very close distance, an observer would surprisingly see almost monochromatic emission with SPP phonon energy [9].

The calculated density of states of SPP waves of thermally stimulated field is very large at small distances ($<10^{-2}$ μm), but disappears at a distance longer than 1 μm.

This means that SPP vibrations can not be responsible for the experimentally observed far-field emitted electromagnetic radiation. However, the great surface electric field of near monochromatic thermostimulated plasmon-phonon wave near to GaAs/air surface can be responsible for the reflection, transmission and absorption of incident electromagnetic waves.

The condition $\varepsilon(\omega) < 0$ means that electromagnetic radiation can not propagate in bulk GaAs.

Indeed, the radiation transmission through the GaAs layer is not observed experimentally in a wide range of frequencies, where $\varepsilon(\omega) < 0$ (see Fig. 1).

3. THERMOSTIMULATED REFLECTIVITY

In our experiments, we used the method of thermally stimulated emission of vibrational state in single crystals and interfaces [5 – 8].

The high conductivity GaAs polished plates with density of electrons $n = 7 \cdot 10^{17}$ cm^{-3} and $4 \cdot 10^{18}$ cm^{-3} and thickness of 350 μm were heated by electric current. The reflection and emission spectra of the heated GaAs plate were measured by IR spectrometer-transformer Nicolet 8700 (Thermo Scientific).

The magnitude of the measured thermally excited signal is determined by the difference of temperatures of the GaAs sample, T, and detector, T_0. In our experiments, the temperature of the heated GaAs sample achieved 350 °C and temperature of the detector in all experiments was 20 °C.

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Figure 2 demonstrates the temperature-dependent THz reflection spectra of the heated GaAs plate.

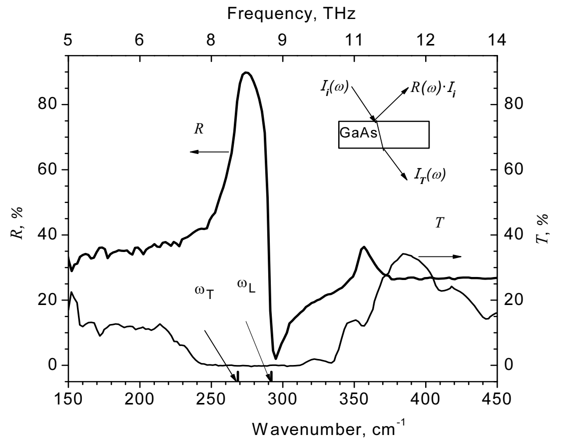

Fig. 1. Reflection R and transmission T spectra of the semi insulated GaAs in the THz range. The frequencies of transverse ω_T and longitudinal ω_L optical phonons are shown by arrows

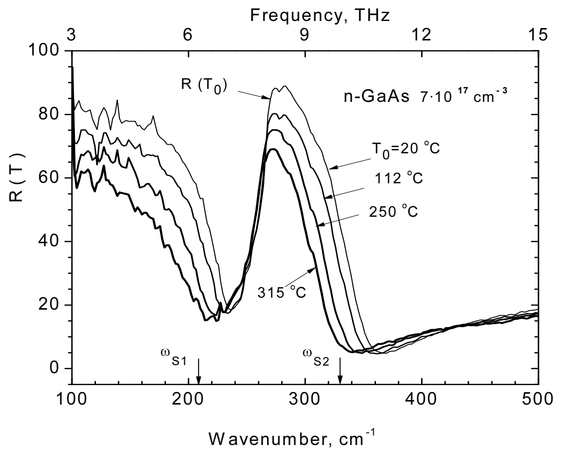

Fig. 2. Reflection spectra $R(T)$ from the highly doped ($n = 7\cdot10^{17}$ cm^{-3}) GaAs plate at different temperatures. The frequencies of surface plasmon-phonon oscillations of GaAs/air interface, ω_{S1} and ω_{S2}, are shown by arrows

The experimentally measured reflection coefficient $R(T)$ decreases with increasing temperature T of GaAs sample in a wide range of the measured spectra of (100 – 400) cm^{-1}.

We assume that the thermally stimulated THz radiation absorption $I_{abs}(T)$ by surface plasmon-phonon polaritons is responsible for the temperature-dependent behavior of reflectivity spectra:

$$I_{abs}(T) = \left[R(T_0) - R(T)\right] I_K\,, \tag{2}$$

where I_K is the intensity of the incident (black body) radiation in the measuring channel of IR spectrometer and $R(T_0)$ is the reflectivity at $T_0 = 20\,°\mathrm{C}$. Note that the $I_{abs}(T)$ is a result of transmission of incident wave I_K through the GaAs/air interface at the frequencies of SPP oscillations, ω_{S1} and ω_{S2}.

The data of Fig. 2 show that the maximum of $I_{abs}(T)$ takes place at $\omega_{S1} = 210$ cm^{-1} and $\omega_{S2} = 330$ cm^{-1}. That coincides with the surface plasmon-phonon frequencies for the GaAs sample ($n = 7\cdot10^{17}$ cm^{-3}). However, the $I_{abs} \approx 0$, at frequencies $\omega_{S1} = 260$ cm^{-1} and ω_{S2}>350 cm^{-1}, where $\varepsilon(\omega) > 0$.

Figure 3 shows the frequencies of SPP determined from the $R(T_0)/R(T)$ spectra. Note that the huge decrease of reflectivity at SPP frequencies is observed.

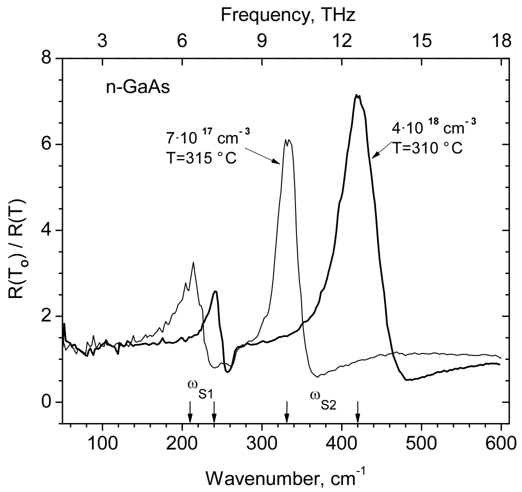

Fig. 3. The spectra of $R(T_0)/R(T)$ for GaAS with different electron densities $n = 4\cdot10^{18}$ cm^{-3} and $n = 7\cdot10^{17}$ cm^{-3}. The frequencies of surface plasmon-phonon oscillations of GaAs/air interface ω_{S1} and ω_{S2} are shown by arrows

Therefore, it is observed that the thermal excitation of SPP oscillations are followed by the increase of radiation absorption and the decrease of radiation reflection.

4. THERMOSTIMULATED THz EMISSION

Figure 4 demonstrates the thermally excited THz emission $I_{em}(T)$ spectra of the highly doped (10^{17} cm^{-3} and $4\cdot10^{18}$ cm^{-3}) GaAs samples in a range of (100 – 600) cm^{-1}.

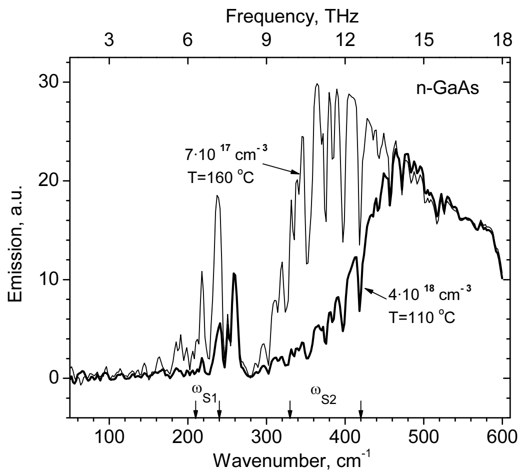

Fig. 4. Thermally stimulated THz emission spectra of the heated n-GaAs plate for different doping concentrations. The frequencies of surface plasmon-phonon oscillations of GaAs/air interface ω_{S1} and ω_{S2} are shown by arrows

One can see that the thermally stimulated radiation intensity spectrum is characterized by two maxima at frequencies ω_{S1} and ω_{S2}, which correspond the SPP resonance frequencies $\omega_{S1} = 210\ \mathrm{cm}^{-1}$ and $\omega_{S2} = 330\ \mathrm{cm}^{-1}$ for the GaAs samples with $n = 7\cdot10^{17}\ \mathrm{cm}^{-3}$ and $\omega_{S1} = 240\ \mathrm{cm}^{-1}$ and $\omega_{S2} = 420\ \mathrm{cm}^{-1}$ for GaAs with $n = 4\cdot10^{18}\ \mathrm{cm}^{-3}$.

Therefore, the thermal excitation of surface plasmon-phonon oscillations is responsible for the observed thermally stimulated THz emission.

At $\omega > 500\ \mathrm{cm}^{-1}$, the dielectric function of the GaAs sample becomes positive. This means that the emitted radiation does not belong to the surface plasmon-phonon polariton emission, and it is determined by thermally enhanced black body radiation.

According to the Kirchhoff law, the thermally excited radiation emission is given by

$$I_{em}(\omega,T) = [1 - R(\omega,T)]I_{bb}(\omega,T)\ , \tag{3}$$

where $R(\omega,T)$ is the reflection coefficient and $I_{bb}(\omega,T)$ is the equilibrium intensity of emission, which is independent on a material of the black body cavity.

The thermally excited surface plasmon-phonon polaritons induce the strong decrease of the reflection $R(\omega,T)$, and consequently, the increase in the intensity of thermally stimulated THz emission.

We assume that the observed emission resonance maxima correspond to the reflection coefficient resonance minima ω_{S1} and ω_{S2}.

Because of a strong decrease of the reflection coefficient $R(\omega,T)$ with temperature, the emitted light intensity $I_{em}(\omega,T)$ can achieve the value close to the $I_{bb}(\omega,T)$.

Consequently, the heated GaAs plate can be used as a high-power continuous wave radiation source in selected (7 – 8) THz and (10 – 15) THz frequency ranges.

5. CONCLUSIONS

It was found that the interface layer (GaAs/air) in the frequency range where $\varepsilon(\omega) < 0$ is transparent to the THz radiation only at frequencies of the surface plasmon-phonon (SPP) oscillations. The temperature rise enhances the density of SPP and increases transmittance T of the interface layer, and therefore, reduces the reflectivity R. Thermostimulated THz radiation emission I_{em} from the heated GaAs is determined by black body radiation intensity I_{bb} multiplied by transmittance: $I_{em} = (1 - R)I_{bb}$. The huge decrease of the reflectivity at SPP frequencies with an increase of GaAs temperature was experimentally observed. The frequencies of SPP oscillations were determined experimentally from the measurements of the reflectivity spectra.

Acknowledgments

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