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Subterahertz Emission from a Grid-Gated GaAs/AlGaAs Heterostructure

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A subterahertz emission from a grid-gated structure lithographically fabricated on a GaAs/AlGaAs heterostructure was observed at liquid helium temperatures. The frequency of observed emission was equal to about 75 GHz and was almost independent of the voltage biasing the emitter. The Gunn effect is proposed as a possible explanation of the emission. This hypothesis, however, is critically discussed and further experiments are indicated which could lead to a definite identification of the physical mechanism of emission.

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1. Introduction

Terahertz instrumentation suffers from the lack of cheap semiconductor cw monochromatic sources, thus the quest for constructing such devices seems to be a permanent effort of many research groups. In our opinion, three semiconductor-based solutions meet the demand of researchers: photomixers based on visible-light diodes [1], frequency multipliers [2], and quantum cascade lasers [3]. We do not consider here picosecond pulsed sources based on interaction of femtosecond laser pulses with semiconductor since they are neither cw nor monochromatic [4]. Each of these instruments shows its disadvantages. All of them are expensive, photomixers generate only μW powers, THz–quantum cascade lasers (QCL) work only at low temperatures. For these reasons, it is necessary to look for alternative solutions. For instance, an appealing proposal to use field-effect transistors (FETs) as gate-voltage-tunable emitters [5] did not lead to construction of a working device, although some preliminary experiments indicated a possibility to use nanometer FETs as THz generators [6–8]. The most probable reason of a break down of this project was the fact that it seems that FETs emit mainly a low-frequency radiation (of the order of 10 GHz) and only small-intensity high harmonics of the fundamental frequency fall into the sub-THz band [9, 10].

A natural candidate for a THz generator would be a device based on two-dimensional plasma (2DEP) oscillations since this is a medium whose resonant frequency falls within the THz band. A two-dimensional plasma, as a basis for a THz source, offers a few advantages: it can be lithographically processed, tuned with a gate voltage, on-chip integrated, or be active in a broad range of temperatures. For all these reasons, experiments aiming to observe a voltage-tunable emission from oscillations of two-dimensional plasma are still in progress, in spite of the fact that the first observation of a THz emission resulting from radiative decay of a 2DEP is dated at about half a century ago [11]. In that experiment, emission, stimulated by a current flow, was observed with a frequency f dependent on the concentration of electrons n_s of a 2DEP residing at an Si/SiO$_2$ interface, and the observed $f(n_s)$ dependence followed that of gated 2D plasmons.

Plasmons do not couple to photons propagating outside an infinite and uniform sample because of the principle of momentum conservation: a photon carries momentum negligible with that of a plasmon. To overcome this constriction, a special coupler has to be a part of the device. Typically, the coupler is formed by a metallic grid whose period Λ defines the wavelength $\lambda_n = \Lambda/n$ of subsequent plasmonic modes. Such a grid-coupler, with a period of 3.52 μm was used in the experiment reported in Ref. [11].

An experimental arrangement in which current flows in a 2D layer in proximity to a metallic grid resembles the configuration of the Smith–Purcell experiment [12], discovered in electronic vacuum tubes more than 60 years ago, where a beam of high-energy electrons (with the energy of the order of 10^5 eV) passes over a metallic diffraction grating. The interaction of the electrons in the beam with electrons in the grating gives rise to visible light whose wavelength and polarization depend on parameters of the experimental system (the beam velocity, grating period, angle of observation, etc.). A natural candidate to observe the Smith–Purcell effect in solids was a high electron mobility heterostructure with a metallic grid on its surface, i.e., the arrange-

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ment used in Ref. [11]. In fact, the authors of Ref. [11] argued that the observed emission was not due to the Smith–Purcell effect because its frequency depended on the plasma density, which is not predicted for the Smith–Purcell effect.

Up to now, the Smith–Purcell effect in solids has not been observed, and the main motivation of the present work was to look for this effect in a GaAs/AlGaAs heterostructure with a high-electron mobility 2DEP. As it will be shown below, we observed an emission from grid-gated structures with a frequency of 75 GHz, but the physical mechanism of the emission has not been established. We describe results obtained on mesas of different shapes and metalizations which allows us to put forward some hypothesis and to propose directions of further research.

2. Experimental techniques and results

Processing of samples was carried out with electron lithography. Four mesas of dimensions of 100 μm × 1000 μm were etched in a wafer of high-electron mobility GaAs/Al$_{0.3}$Ga$_{0.7}$As and supplied with ohmic contacts (called source and drain in the following) at the narrower ends. An Au grid on a Ti adhesive layer was prepared with a lift-off technique. Subsequent stripes of the grid, with the width of 500 nm and perpendicular to the long symmetry axis of the mesa, were separated by 500 nm slits. The grid covered all the distance between the source and drain with exception of two slits of the length of about 70 μm adjacent to the ohmic contacts. Figure 1 shows a part of the sample, adjacent to the drain.

The sample was cooled to liquid helium temperature and supplied with current pulses generated from a low-frequency generator (a lock-in technique was applied). Typically, the frequency and the aspect ratio was equal to 13–17 Hz and 0.5, respectively. The radiation was analyzed with a Michelson interferometer positioned outside of the helium cryostat. A low frequency of pulses was a necessary condition of the experiment because a slow THz detector (a Golay cell) was used in the interferometer. The experimental arrangement was described in detail in Ref. [9]. During measurements, the source and grid were connected to the ground.

At a fixed amplitude of voltage pulses, we registered the signal from the detector as a function of the length of one of the arms of the interferometer. The signal was next Fourier transformed to reveal the period P of spacial interferences of the signal. Then, the frequency of radiation f was determined as $f = 2c/P$, with c — the speed of light.

We have found that each of the four structures prepared emitted the radiation but only one of them emitted strongly enough to enable a detailed analysis of the detector's signal. Characteristic features of the emitted signal are: a rapid appearance of the signal when the voltage exceeds a certain threshold value and a relatively high

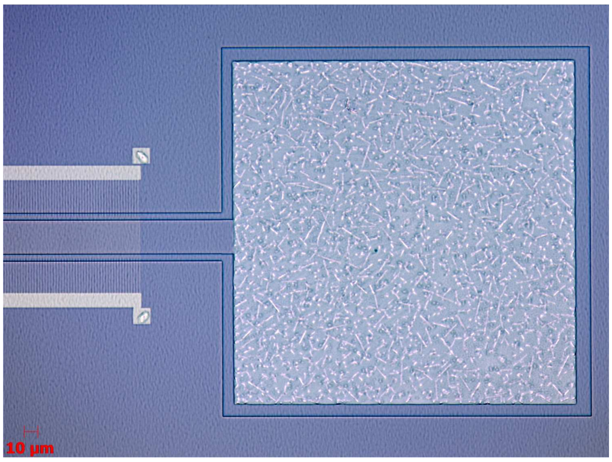

Fig. 1. An electron microscope picture of a part of the sample adjacent to the ohmic contact (big square at the right). The grid is composed of two combs with stripes of each comb (vertical) connected with a wide bar (horizontal). The slit between the ohmic contact and the grid is 75 μm-long.

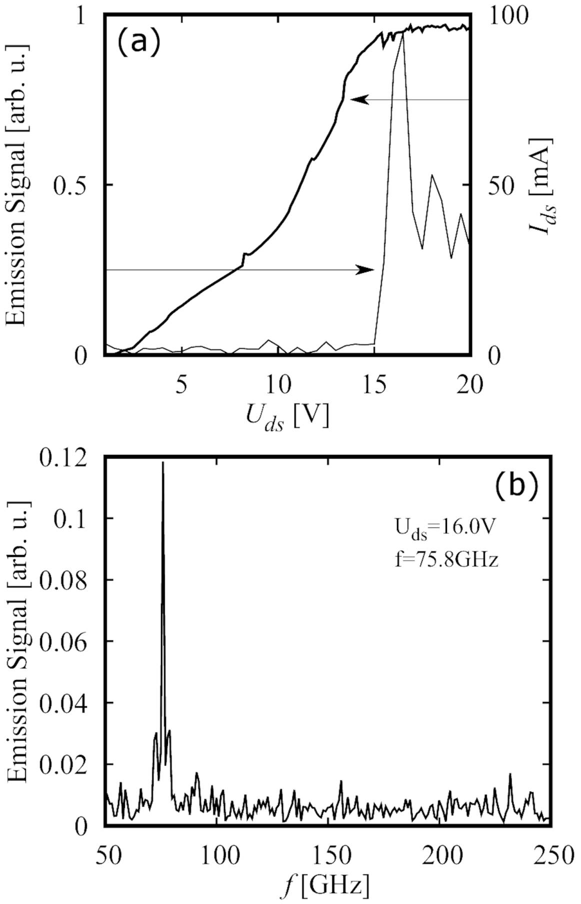

Fig. 2. (a) Dependence of the current (left scale) and the emitted signal (right scale) on the bias voltage. (b) Fourier transform of the signal measured with the interferometer at the bias voltage equal to 16.0 V..

electrical power (of the order of 1 W) required to trigger the emission (see Fig. 2a). The right part of Fig. 2 shows that the we observed a monochromatic radiation with a frequency very close to 75 GHz. We have found that the frequency of radiation was almost independent of the bias voltage in the interval from 16 V to 20 V for which it was measured.

3. Discussion

A rapid increase of the power of emitted signal indicates a threshold behaviour and points out that the emission is not related to the Joule heating of the 2DEP. In other words, with a sufficiently high bias, the electron plasma is driven into instability. Taking into account the dimensions of the structure and the frequency of radiation, we thought about the Gunn effect [13] as a possible underlying mechanism. If so, the radiation should appear at the drain side of the structure, where the highest electric field builds in. Let us note that grounding the gate and biasing the drain with the voltage U_{ds} indicates that at the drain side of the structure there appears a high voltage difference between the channel and the gate. We have verified that at the highest U_{ds}, about 50% of the drain current was flowing through the gate, i.e., we observed the emission in the condition of a leaky gate.

To verify the hypothesis that the observed emission was caused by a Gunn effect, we fabricated mesas of the width equal to 25 μm and the length equal to 30, 50, 70, and 90 μm. Taking into account that the Gunn effect is a time-of-flight phenomenon (i.e., the frequency of radiation is defined by the distance traveled by the Gunn domain and its velocity), we expected that changing the length of a device one can tune the frequency of radiation. We repeated the emission experiments on the fabricated mesas and we did not find *any* signature of emitted signal.

This surprising result indicates that a crucial factor in emission was the presence of a grid which served as an antenna for emitted radiation. Without such an antenna, the radiation is much more strongly coupled to the semiconducting substrate (it is bound in the substrate) than to the air. In fact, it is known that a detector of a THz radiation based on a field-effect transistor, should be fabricated on a thinned substrate which promotes coupling of the incident radiation with the transistor channel and not with the substrate [14]. With this observation in mind, we plan to fabricate a series of mesas, as described before, but coupled to a grid which will serve as an antenna. We should also note that a modification of the experimental system is necessary in order to introduce a faster THz detector. This will allow us to decrease the duty ratio of the bias voltage pulses and reduce the mean power delivered to the sample.

In conclusion, we observed a monochromatic radiation from a GaAs/AlGaAs high-electron-mobility heterostructure at liquid helium temperature on four samples of identical geometry, supplied with a grid-gate. We suggest that the presence of the grid is crucial for observation of the emission and propose further experimental steps which can allow us to define its physical mechanism.

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