Abstract

My Ph.D. thesis is to devoted to characterization of plasmon excitations in a two-dimensional electron gas (2DEG) exposed to terahertz (THz) radiation at magnetic fields. THz radiation covers a range of the electromagnetic spectrum of the frequency from 0.1 THz to 10.0 THz. This work originates from a wider scientific and engineering movement, started in 1990s, aiming at building an efficient and voltage-tunable semiconductor detector of THz radiation based on plasmon excitations. Properties of materials at THz frequencies, like transparency or characteristic emission or absorption lines, make potential applications of THz radiation very promising. Beside imaging, THz radiation could be used in a high speed wireless communication. Because of multiple potential applications, research on THz devices was very intense in the recent years, which led to a huge technical development. For instance, there is now a commercial THz multipixel camera available.

The inspiration of this work were papers published by M. Dyakonov and M. Shur showing that a field-effect transistor (FET) subject to THz radiation might produce a voltage drop between its two current-supplying contacts. Such a voltage drop is called a photovoltage (PV). This effect is explained as a result of a current instability caused by a plasma wave amplification at transistor's boundaries. Dyakonov and Shur predicted that a FET should respond to THz radiation at resonant frequencies, defined by its dimensions—they were expecting that a FET channel acts as a resonant cavity for plasma waves. It was not a new idea, since plasmons in a 2DEG of a finite size were observed for the first time in 1976. However, before the Dyakonov-Shur model, no resonant photovoltage signal in a FET was predicted. Moreover, Dyakonov and Shur expected that common FETs can be used as THz detectors. Resonant plasmon frequencies, expected for nanometer devices were predicted to fall into the THz range. Beside a resonant signal, a wide-frequency nonresonant PV signal was also predicted, when the electron mobility was not high enough.

In the Dyakonov-Shur theory, a FET could act both as a detector and an emitter of THz radiation. However, emission observed to the day from FETs is too weak to be used as a THz source. Another obstacle is the necessity to use cryogenic temperatures. Because of that, a FET THz emitter is currently loosing with other commercial THz sources, like quantum cascade laser, which are more efficient.

A nonresonant detection was found in many types of FETs, including silicon MOSFETs and HEMTs based on different materials, like

GaN/AlGaN, GaAs/AlGaAs and InGaAs/InAlAs. Nonresonant signal is observed even at room temperature and devices using this effect are currently being produced commercially (for example, a multipixel camera based on silicon MOSFETs). The current research considers, in particular, a spectral narrowing of a PV signal by using resonant antennas.

On the other hand, plasma resonances were found experimentally in FETs PV signal, but proved to be weak and available only at cryogenic temperatures. To understand the reason behind this result, we decided to prepare samples covered with periodic stripes of metallization, called a grid-gate—a classical system where plasmons were first observed in a semiconductor-based 2DEG—and to measure a PV signal on such structures, where plasmons should behave in already known manner. We decided to prepare also reference samples without a gate and with an uniform gate.

My field of research concerned the resonant detection in gated and ungated 2DEG. The basic task of my research was to characterize plasma excitations with a set of parameters like: magnetic field, THz radiation frequency or gate voltage bias. This was done on different samples with the use of tunable monochromatic THz sources, covering the range of 0.1–0.7 THz. One of goals was to compare PV spectra on samples of different gate shapes and without a gate. These results were extended using a few THz laser lines from the range of 1.5–1.8 THz. Additionally, we compared results obtained with monochromatic THz sources and with a wide-range nonmonochromatic THz source (Fourier spectroscopy), in order to check, whether these results are in an agreement. This an important information, since a detector can work both with monochromatic or wide spectral range THz illuminations. We characterised plasmon resonances as a function of a gate bias, as well as under an influence of visible radiation illumination. These results are of a practical importance and both can be used to tune resonant plasmon frequency in a detector.

The theoretical background is the subject of the 1st chapter of my Ph.D. dissertation. The process of samples' preparation and their description is the main topic of the 2nd chapter. Crucial points here are that we used a high-electron-mobility GaAs/AlGaAs heterostructure, produced by Vladimir Umansky at the Weizmann Institute of Science, Rehevot, Israel. These samples show a very high electron mobility, unavailable in other materials, reaching in used wafers approximately 1.5×10^6 cm^2/Vs at $T = 4$ K. Fabricated samples were, in most cases, mid-sized (0.06 mm^2), rectangular mesas of a 2DEG, some covered with a gate, some left ungated. The gates were of different forms and geometries helping to understand their influence on a response of a sample.

In the 3rd chapter, experimental techniques are explained in detail. An examined sample was used as a THz radiation detector in cryogenic temperatures, typically at 4.2 K. The sample was subject to a THz radiation emitted by a variety of monochromatic sources, including a back-wave oscillator, Virginia Diodes sources and a THz laser, covering the range of 0.1–1.8 THz or a mercury-vapor lamp used with a Fourier spectrometer. The magnetic field was perpendicular to a sample surface, and typically a response signal of the sample was measured as a function of magnetic field. The response signal was a PV generated between two current-supplying contacts of a sample.

In the 4th chapter, experimental results and their interpretation are presented. Photovoltage measurements, performed as a function of magnetic field, show a series of maxima preceding the cyclotron resonance magnetic field. A sequence of such measurements, made at different frequencies of the incident THz radiation, shows that maxima move towards higher magnetic field with increasing radiation frequency. Maxima were interpreted as subsequent modes of a magnetoplasmon excitation. A magnetoplasmon might be excited in two ways: either due to a periodicity of a grid-gate or due to a finite size of a sample. In most of samples, we have observed the latter type of a magnetoplasmon, which might be imagined as a standing wave in a resonator.

It was shown that an observability of a particular type of magnetoplasmon mode depends on ratios of frequencies of the two types of resonances and the frequency of the radiation. This effect is a result of overlapping magnetoplasmon maxima at high radiation frequencies. In order to avoid this effect, a designed detector must have a 2DEG shape as simple as possible, without unnecessary cavities in which plasmon resonances might be excited. Commercially available FETs usually show very complicated shapes with multiple plasmon cavities. In the case of grid-gated devices, the size of the overall 2DEG channel must be considerably larger than the grid-gate period. In such conditions, frequencies of plasmon resonances defined by a 2DEG mesa size are much smaller than these connected with the grid-gate period.

When a wave vector is ascribed to every observed plasmon mode, it is possible to determine a dispersion relation of a plasma wave in a wide range of frequencies and wave vectors. The dispersion relation of the observed excitation was found to be the same in ungated samples and samples with thin matallization of gates. This effect was explained as a result of THz transparency of thin (15 nm) metallic layers forming gates. However, every second mode is absent in the case of thin-gated samples. In the sample with a thick metallization of the gate, the magnetoplasmon was excited with dispersion showing an influence of a screening of the 2DEG by the gate. We explain this difference as an effect of a different efficiency of a THz screening with a metal layer in cases of thick and thin gates. Another observation is a maximum in spectra obtained in a wide range of excitation frequencies coinciding with the second harmonic of the cyclotron resonance. We explain this observation as a result of a strong, nonuniform, oscillating electric field generated by an incoming THz radiation at edges of metallic objects, in particular at edges of a gate.

The influence of the gate voltage was studied, showing shifts of magnetoplasmon maxima with the gate bias. Such a shift is a desired effect, allowing for a control of a resonant detection frequency with a bias applied to a FET's gate. In another experiment, magnetoplasmon maxima were shifted under a visible radiation illumination. Finally, it was shown, that a Fourier spectroscopy gives results in agreement with the results obtained with monochromatic radiation sources working in the same spectral range. However, only the fundamental magnetoplasmon mode is observed in the Fourier spectroscopy experiment.

Presented research characterized magnetoplasmon resonances in mid-sized samples in a range of radiation frequencies of 0.1–2.5 THz. Research presented in the thesis might allow to build sensitive and frequency-tunable detectors, and a possible device, with well-resolved plasmon resonances, is proposed in the concluding chapter.