Plasmonic polarization-sensitive detector of terahertz radiation

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Abstract. We develop a theory of the helicity driven nonlinear DC response of gated two-dimensional electron gas to the terahertz radiation. We demonstrate that the helicity-sensitive part of the response dramatically increases in the vicinity of the plasmonic resonances and oscillates with the phase shift between excitation signals on the source and drain. The resonance line shape is an asymmetric function of the frequency deviation from the resonance. In contrast, the helicity-insensitive part of the response is symmetrical. These properties yield significant advantage for using plasmonic detectors as helicity-sensitive terahertz and far infrared spectrometers and interferometers.

1. Introduction

The creation of efficient emitters and detectors in the terahertz (THz) frequency range is one of the main goals of ultrafast nanoelectronics. One of the key approaches to this problem, first proposed in 1993 [1] and actively discussed later in the context of creating terahertz emitters [2, 3] and detectors [4], is based on the use of plasma waves in a field-effect transistor. Now such a transistor is called a terahertz field-effect transistor (TERAFET) [5]. Physically, the proposed approach is based on a strong coupling of terahertz radiation with nonlinear plasma waves in the channel of a field-effect transistor [1, 4]. There are already available commercial prototypes as THz and sub-THz detectors implemented in Si, GaAs, GaN, graphene and other materials systems (see review [6]). Properly designed TERAFETs provide excellent detection of THz radiation and now already surpass existing commercial detectors in a number of parameters. The main advantages of such detectors are: the tunability, a relatively low noise level and the ability to detect signals with a high modulation frequency (up to hundreds of GHz) [7]

2. Research methods

In the present work we investigate work of the TERAFET in a field of the circularly polarized radiation which excites a sample via two antennas coupled to the source and drain. We use a hydrodynamic approach to study the resonant regime of TERAFET operation. We demonstrate that in this regime, the intrinsic FET channel shows the helicity-driven response.
The basic principle of operation of the device is as follows. Impinging radiation excites plasma waves in the FET channel. Rectification of these waves leads to a voltage drop across the structure (a constant voltage between the drain and the source of the field-effect transistor).

We use hydrodynamic equations to describe plasma waves in the channel of transistor:

\[
\begin{align*}
\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} + \gamma v &= -\frac{e}{m} \frac{\partial U}{\partial x}, \\
\frac{\partial U}{\partial t} + \frac{\partial (Uv)}{\partial x} &= 0.
\end{align*}
\]  

(1)

Here, \( v \) is the electron drift velocity, \( U \) is the local value of the gate-channel voltage, \( e \) and \( m \) are the electron charge and mass, \( \gamma \) is the inverse pulse relaxation time.

To solve these equations, boundary conditions (BC) are required. We assume that circularly polarized radiation excites plasma waves through two antennas coupled to the source and drain. Consequently, the alternating current signals at the source and source have equal frequencies, but can be shifted by phase with the shift magnitude \( \theta \) determined by antenna design and can also have different amplitudes. It is significant that the sign of the phase shift changes with a change of polarization.

Taking into account that the radiation induces a constant voltage drop \( V \) on the sample, the BC takes the following form:

\[
U(0) = U_g + U_a \cos(\omega t + \theta), \quad U(L) = U_g + V + U_b \cos(\omega t),
\]  

(2)

where \( U_g \) is the voltage between the gate and the channel, and \( U_g \) and \( U_b \) are the amplitudes of the THz signals on the two antennas.

We search for the solution of equations (1) as

\[
\begin{align*}
n &= n_0(x) + \left[ n_1(x)e^{-i\omega t} + n_{-1}(x)e^{i\omega t} \right]/2 + \ldots, \\
v &= v_0(x) + \left[ v_1(x)e^{-i\omega t} + v_{-1}(x)e^{i\omega t} \right]/2 + \ldots,
\end{align*}
\]  

(3)

where \( n_1 \) and \( v_1 \) are the amplitudes of radiation-induced plasma oscillations of density and velocity. Substituting equations (3) into equations (1), averaging over time and solving the system we find the radiation-induced voltage drop across the sample that can be expressed in terms of the amplitudes of the plasma oscillations:

\[
\frac{V}{U_g} = \frac{\gamma}{4\pi^2} \int_0^L dx \left( n_1 v_{-1} + n_{-1} v_1 - \frac{d[v_1(x)v_{-1}(x)]}{\gamma dx} \right)
\]  

(4)

Amplitudes \( n_1, v_{-1}, n_{-1}, v_1 \) are found from linearized equations (1)

\[
\begin{align*}
(\gamma - i\omega) v_1 + s^2 \frac{\partial n_1}{\partial x} &= 0, \\
-i\omega n_1 + \frac{\partial v_1}{\partial x} &= 0,
\end{align*}
\]  

(5)  

(6)

which are solved with account of the BC (2.) These amplitudes vary in space with the wave vector

\[
k = \frac{\sqrt{\omega(\omega + \gamma')}}{s} = \frac{\Omega + i\Gamma}{s},
\]  

(7)

where

\[
s = \sqrt{\frac{eU_g}{m}}
\]  

(8)
is the velocity of plasma waves in the channel, which is controlled by the gate voltage. As a result of calculations, a final equation for the wave induced voltage is obtained:

\[
V = \frac{\omega}{\sqrt{\omega^2 + \gamma^2}} \frac{\alpha (U_0^2 - U_z^2) + \beta U_g U_b \sin \theta}{4 U_g [\sin (kL)]^2},
\]

(9a)

\[
\alpha = \left( 1 + \frac{\gamma M}{\pi \omega} \right) \sinh^2 \left( \frac{\Gamma L}{s} \right) - \left( 1 - \frac{\gamma M}{\pi \omega} \right) \sin^2 \left( \frac{\Omega L}{s} \right).
\]

(9b)

\[
\beta = 8 \sinh \left( \frac{\Gamma L}{s} \right) \sin \left( \frac{\Omega L}{s} \right).
\]

(9c)

3. Results

Equation (9) was analyzed in different limiting cases. Below we present the results for the two most interesting regimes

3.1. High frequency regime

\( \omega_0 \ll \gamma \ll \omega \), where \( \omega_0 = \pi s / L \) - frequency of plasma oscillations.

In this case \( \Omega \approx \omega, \Gamma \approx \gamma / 2 \), and the response

\[
V = \frac{3(U_0^2 - U_z^2)}{4U_g} + \frac{4U_g U_b e^{-\gamma L/2} \sin(\pi \omega / \omega_0) \sin \theta}{U_g}
\]

(10)

The \( \theta \)-dependent contribution in equation (10) is exponentially small with increasing length \( L \), however equation (10) demonstrates harmonic dependence on phase shift \( \theta \) and frequency \( \omega \).

3.2. Resonance case

\( \omega \gg \gamma, \omega_0 \gg \gamma \). The response shows series of the sharp peaks at \( \omega = \omega_N \). In the vicinity of \( N \)-th resonance (\( N \neq 0 \)), we find a very sharp (resonant) dependence on the radiation frequency:

\[
V(\delta \omega) = \frac{(U_0^2 - U_z^2) (3\gamma^2 / 4 - \delta \omega^2) + 4U_g U_b (-1)^N \delta \omega \sin \theta}{4U_g (\delta \omega^2 + \gamma^2 / 4)}
\]

(11)

\[ \delta \omega = \omega - \omega_N, \quad \omega_N = \pi N s / L, \]

(12)

where \( \omega_N \) - resonance frequency.

The response shows nontrivial behavior as a function of the frequency of the incoming signal. It can be seen that equation (11) is the sum of two terms, polarization-independent part, which obeys the symmetry \( \delta \omega \rightarrow -\delta \omega \) and helicity-driven part which changes sign under this operation. This is illustrated on figure 1, where the response is displayed at different phase shifts: \( 0 < \theta < \pi / 2 \).
Figure 1. Resonance dependence of the voltage response at a given frequency [formula (11)] at different phase shifts $\theta$.

To conclude, it is shown that the “phase” contribution to the response increases sharply near plasma resonances. This contribution harmonically depends on the phase shift and shows an asymmetric dependence on the excitation frequency in the vicinity of the plasmonic resonances. Hence, it can be easily separated from conventional symmetric contribution, which is not sensitive to radiation polarization. This result can be directly used to create phase-sensitive THz spectrometers and interferometers.

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