Terahertz ratchet effect in two-dimensional electron system gated by a periodic metal grating with asymmetric unit cell

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Abstract

Terahertz ratchet effect in a two-dimensional electron system gated by a periodic metal grating with an asymmetric unit cell is studied theoretically. It is shown that the galvanoplasmonic response based on ratchet and plasmon-drag effects is several orders of magnitude stronger than conventional photogalvanic response in two-dimensional electron system. Because of that the galvanoplasmonic effects can be used for sensitive detection of terahertz radiation.

1. Introduction

Direct electric current flowing in a material system with no applied electric force is usually referred to as the galvanic current. Galvanic currents can appear as a result of mechanical stress, chemical reaction, or heat in the system. Photogalvanic response in a two-dimensional electron system (2DES) appears under its illumination by terahertz (THz) radiation [1, 2]. Although direct galvanic current appears in this case due to the action of the THz electric (and magnetic) field, the average electric force exerted onto the system is zero. Because of that the photogalvanic response can be interpreted as a result of the ratchet effect [1, 2]. The photogalvanic effects usually involve a local nonlinear response of 2DES, while a non-local nonlinear response of 2DES produces only small contribution to the entire photogalvanic effect.

In this paper, the galvanoplasmonic response based on ratchet and plasmon-drag effects in 2DES gated by a periodic metal grating with an asymmetric unit cell (Fig. 1(a)) is studied theoretically.

2. Basic Equations

Plasmon oscillations in 2DES can be described by the hydrodynamic equations

$$\frac{\partial V(x,t)}{\partial t} + V(x,t)\frac{\partial V(x,t)}{\partial x} + \frac{V(x,t)}{\tau} + \frac{e}{m^*}E(x,t) = 0, \quad (1)$$

$$e\frac{\partial}{\partial t}N(x,t) - \frac{\partial}{\partial x}j(x,t) = 0, \quad (2)$$

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where $E(x,t)$ is the oscillating in-plane electric field depending on the time t and coordinate x in the 2EDS plane (x-axis is directed along the periodicity of the structure), τ is the electron momentum relaxation time due to electron scattering in 2DES, $N(x,t)$ and $V(x,t)$ are the electron density and hydrodynamic velocity of electrons in 2DES, respectively, $j(x,t) = -eN(x,t)V(x,t)$ is the electron current density induced in 2DES. There are two nonlinear terms in Eqs.(1) and (2): the second term in the Euler equation, Eq.(1), which describes the nonlinear electron convection in the 2DES, and the product $N(x,t)V(x,t)$, which defines the current density in the continuity equation Eq. (2). The time average of the nonlinear current yields the plasmon-galvanic current. It should be noted that either of the two nonlinear terms vanishes in the case of a uniform oscillating current flowing in 2DES. Therefore, those nonlinearities are related to non-uniform oscillating electric currents inherent in the plasma oscillations. It also means that the galvanoplasmonic current is entirely caused by a non-local response of 2DES.

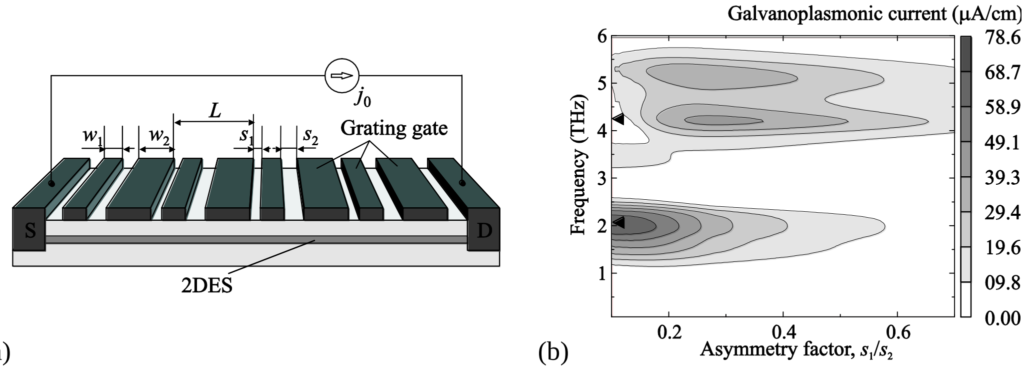

Fig. 1: (a) Schematic view of the 2DES gated by a periodic metal grating with an asymmetric unit cell. External THz wave is incident normally from the top. (b) Galvanoplasmonic current density as a function of THz frequency and the asymmetry factor s_1/s_2. The 2DES is strongly depleted under the grating-gate fingers of width w_1 while the grating-gate fingers of width w_2 are floating. Characteristic dimensions of the grating gate are L=1300 nm, w_1=600 nm, w_2=500 nm. Black triangles at the ordinate axis mark the frequencies of the fundamental and the second-order plasmon modes in the structure.

Due to spatial periodicity of the structure, the Fourier-series representation of hydrodynamic equations can be performed. Then, the solution of Eqs.(1) and (2) within the lowest order of the perturbation series in respect to the powers of $E(x,t)$ yields the galvanoplasmonic current density $j_0 = j_{dr} + j_{el}$ [3], where

$$j_{\rm dr} = -2e\,{\rm Re}\sum_{q\neq 0} N_{\omega,q}V^{*}_{\omega,q} \quad \text{and} \quad j_{\rm el} = -e\sum_{q\neq 0} N^{(0)}_{q}V_{0,-q}$$

with $N_{\omega,q}$ and $V_{\omega,q}$ being the amplitudes of the spatiotemporal Fourier-harmonics of the oscillating electron density and hydrodynamic electron velocity, respectively, in 2DES at the frequency ω of the incident THz wave, $V_{0,q}$ being the amplitudes of the spatiotemporal Fourier-harmonics of the hydrodynamic electron velocity at zero frequency, $q = 2\pi / L$ being the reciprocal lattice vectors of the periodic grating gate, and $N^{(0)}_q$ being the amplitudes of the spatial Fourier-harmonics of the equilibrium electron density $N^{(0)}(x)$ in 2DES. The values of $N_{\omega,q}$ and $V_{\omega,q}$ are proportional to the first power of the electric-field amplitude $E(x,t)$, whereas $V_{0,q}$ is proportional to the second power of that. The values $N_{\omega,q}$, $V_{\omega,q}$, and $V_{0,q}$ can be calculated by solving Eqs.(1) and (2) in the Fourier representation. The electric-field amplitude $E(x,t)$ induced in the grating-gated 2DES by incident THz wave is calculated in self-consistent linear electromagnetic approach described in [4].

3. Results and Discussion

The both galvanoplasmonic currents $j_{\rm dr}$ and $j_{\rm el}$ vanish in the structure with a symmetric unit cell ($s_1 = s_2$) because a net galvanoplasmonic current can appear only in the structure without the center of inversion in the 2DES plane. In the structure under consideration, the center-of-inversion symmetry is broken due to asymmetry of the grating-gate unit cell ($s_1 \neq s_2$). In the structure with a spatially homogeneous 2DES, $j_0 = j_{\mathrm{dr}}$, where j_{dr} is the galvanoplasmonic current due to the electron drag by the plasmon wave in 2DES. In the structure with a spatially modulated electron density in 2DES, additional galvanoplasmonic current j_{el} caused by the electrostriction of the electron plasma in 2DES appears. The galvanoplasmonic current j_{el} totally originates from the electron convection term in the Euler equation. Contribution j_{el} to the total galvanoplasmonic current can be interpreted as the plasmonic ratchet, which appears due to the fact that a spatial profile of the equilibrium electron density distribution in 2DES is laterally shifted from the plasmon-mode waveform in 2DES gated by the grating-gate with an asymmetric unit cell. For strong spatial modulation of the electron equilibrium density in 2DES, the plasmonic ratchet contribution to the net galvanoplasmonic current can be comparable with or even greater than the plasmon-drag contribution.

Although the galvanoplasmonic effect is entirely based on a non-local nonlinear response of the 2DES, it can be several orders of magnitude stronger than conventional photogalvanic effects in 2DES. Considerable enhancement of the galvanoplasmonic current occurs because the plasmon momentum is several orders of magnitude larger compared to the photon momentum at THz frequency.

Assuming the characteristic parameters of 2DES in InGaP/InGaAs/GaAs heterostructure gated by the grating-gate of a micron period with an asymmetric unit cell of sub-micron characteristic dimensions, we demonstrate theoretically (see Fig. 1(b)) that the galvanoplasmonic current density can exceed 70 μA/cm in 2DES with strong spatial modulation of the equilibrium electron density for the fluence of incident THz radiation 1W/cm^2 at room temperature [5].

4. Conclusion

Terahertz ratchet effect in 2DES gated by the grating gate with an asymmetric unit cell is studied theoretically. It is shown that the THz galvanoplasmonic response based on ratchet and plasmon-drag effects can be several orders of magnitude stronger than conventional THz photogalvanic response in 2DES. Because the plasmon frequencies in 2DES fall within the THz band, the galvanoplasmonic effects can be used for sensitive detection of THz radiation.

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