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Nanometer near-field localization and enhancement in a split two-dimensional plasmonic system at terahertz frequencies

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ABSTRACT

We study terahertz excitation of plasmons in a two-dimensional electron system with a periodic metal grating coupler. We assume that a negative electric potential is applied to one of the grating fingers, which results in forming a slit in an otherwise continuous two-dimensional plasmonic system. We analyze numerically the excitation of plasmons in such system and study plasmonic field near the slit. We predict a deep subwavelength localization of plasmons and a dramatic field enhancement at the slit edges.

1. Introduction

Recent progress with fabrication of high-quality semiconductor heterostructures, supporting two-dimensional electron systems (2DES), and discovery of novel nanostructured materials such as graphene, a naturally occurring two-dimensional electronic material [1], opens possibilities for miniaturization of terahertz (THz) devices [2]. It was shown that excitation of plasmons – two-dimensional electron density waves – in such structures can be employed for designing next generation of terahertz photonic devices [3,4]. It was also suggested that resonant excitation of plasmons in 2DES can be utilized for designing ultracompact and efficient THz detectors [5–7]. It is important that the electron density in a 2DES (and, hence, its conductivity) can be varied by applying the electric potential [1,8], which gives an additional possibility for tuning the plasmonic response of such materials.

The wavelength of THz plasmons in 2DES is typically two or even more orders of magnitude smaller than that of free propagating THz radiation [6], therefore, allowing miniaturization of key terahertz photonic components [5,3]. Such high localization of plasmonic field suggests that it might play an important role in the THz near-field enhancement. Previously, we have shown that a defect in periodic 2DES plasmonic lattice can lead to a strong THz near-field enhancement [9], much stronger than that in metal-based THz field concentrators [10,11], due to a double-resonant interaction of the lattice and defect plasmon modes.

In this paper, we consider another mechanism of plasmonic field enhancement. We study the plasmon excitation in a 2DES with a periodic metal grating coupler that couples incident THz radiation to plasmons in 2DES. We assume that a negative electric potential is applied to one of the grating electrodes so that the gated area of the 2DES is almost completely depleted, effectively forming a slit in the 2DES. We study plasmon excitation in such a structure and analyze the plasmon-field accumulation at the slit edges. We demonstrate that, depending on the profile of the equilibrium electron density in the slit area, a deep subwavelength plasmon localization of THz near-field below $\lambda/1000$ and field enhancement factor exceeding 300 is achieved.

2. Results and discussions

We consider a 2DES with the electron density N_0 formed at the interface between a substrate and the barrier layer (see Fig. 1). We assume that both the substrate and barrier layer have the same dielectric constant $\varepsilon = 12.8$ (GaAs). A periodic metal grating with period L and finger width a is located on the front surface of the barrier layer of thickness h. The plane electromagnetic wave with electric field perpendicular to the grating fingers, $\mathbf{E}||\mathbf{x}$, is incident normally upon the structure from the top as shown schematically in Fig. 1.

Negative electric potential applied to one of the grating fingers depletes the 2DES in the gated area. For strong applied voltage reaching the pinch-off voltage of the 2DES, the total depletion occurs in the gated area, forming a slit in 2DES . (It should be noted that the electron density in the gated area does not vanish completely due to residual thermal excitation.) Note that, the rest

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of the grating, if biased, also creates periodic modulation of the electron density in the 2DES, hence tuning the frequency of the plasmon resonance in the structure. However, without loss of generality, we consider here that the entire grating is not biased and, hence, the sheet electron density in 2DES outside the slit, N_0, remains homogeneous.

Distribution of the equilibrium electron density in the transition from the depleted to undepleted 2DES is defined by the electrostatic potential surrounding the biased grating finger. Since a particular profile of the electron density in the gated area of 2DES is inessential for main effects reported in this paper, we model the electron density profile in the depleted region of 2DES with the hyperbolic tangent function

$$N(x) = (N_0 - N_s)\left[1 + \frac{1}{2}\left(\tanh\left(\chi\left(x - \frac{a}{2}\right)\right) - \tanh\left(\chi\left(x + \frac{a}{2}\right)\right)\right)\right] + N_c, \quad (1)$$

where N_s is the sheet electron density in the slit and χ is a parameter responsible for the transition steepness. The latter parameter depends on the length of the gate contact and on the distance between the gate contact and 2DES [12].

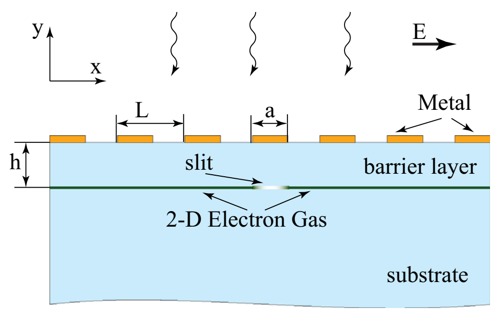

Fig. 1. Schematic of the 2DES with a periodic metal grating coupler.

We expect that, similar to the electromagnetic field localization at a defect of the photonic crystal the plasmonic oscillations excited in 2DES by the grating coupler can be enhanced near the slit in 2DES. To prove this, we perform comprehensive numerical simulations using the commercial COMSOL Multiphysics solver based on the finite element method. We perform 2-D simulations, considering no variation of the field in the z-direction and searching for the field distributions in the (x–y) plane. We describe the electromagnetic response of the 2DES by a local sheet conductivity in the Drude form $\sigma_{2D}(\omega) = N(x)e^2\tau/m^*(1 - j\omega\tau)$, where e and m^* are the electron charge and effective electron mass, respectively, τ is the electron scattering time, and $N(x)$ is given by Eq. (2). Furthermore, we assume that $a = L/2 = 2\ \mu$ m, and use the material parameters typical for GaAs-based 2DES: $h = 200$ nm, $\tau = 5 \times 10^{-12}$, $m^* = 0.067$ m and $N_0 = 2.5 \times 10^{11}$ cm^{-2} [13,14]. Taking into account that the thickness of highly conductive metal grating contacts (typically, about 100 nm) is four orders of magnitude smaller than the incident THz radiation wavelength and that small skin depth prevents THz field penetration through the metal contacts, we approximate the grating gate by the sequence of infinitely thin perfect electric conductors. To model the structure, we use the supercell approximation [15]. According to this approach, we embed the structure into a large supercell periodically repeated in the x-direction. Each supercell contains the depleted region of the 2DES and 36 periods of regular lattice on either side of it.

First, we study the plasmon localization and THz field enhancement with the variation of the electron density depletion ratio $\delta = N_s/N_0$ close to the plasmonic resonance occurring at 0.335 THz. In Fig. 2(a) and (b) we present the waveforms of the plasmon electric field E_x in the vicinity of the depleted region of 2DES for two different values of the depletion ratio for the same steepness factor of $\chi = 20$. Corresponding profiles of the equilibrium electron density are also shown in Fig. 2(a) and (b). The electric field reaches its maximum near

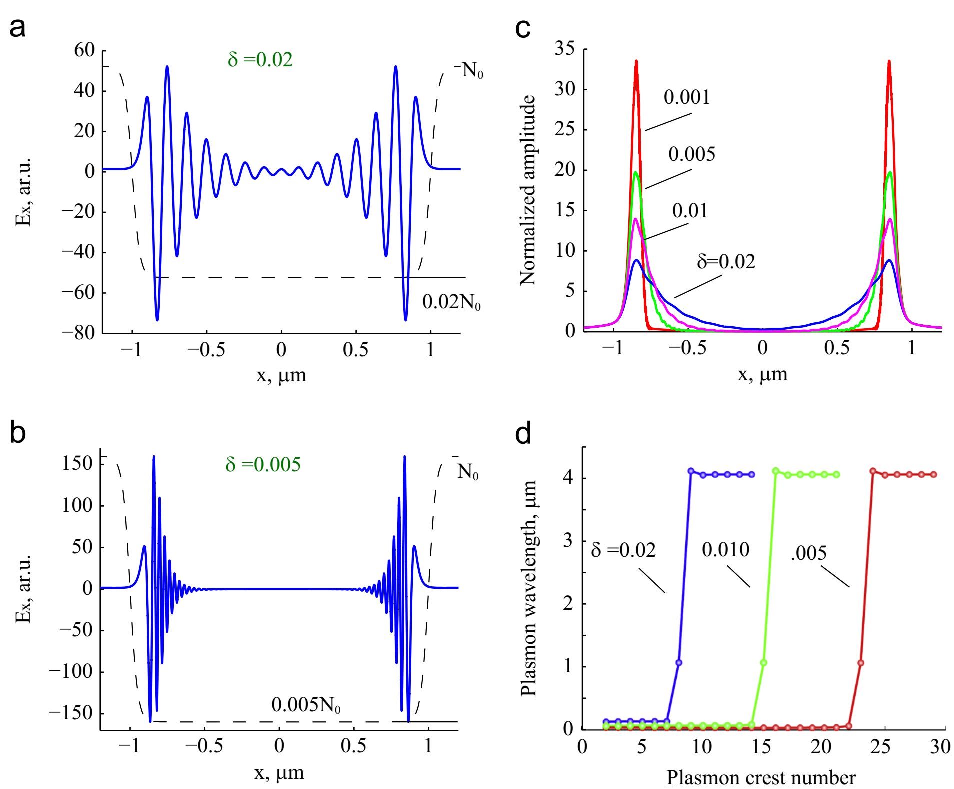

Fig. 2. (a and b) Plasmon-field waveforms at two different values of the electron density depletion ratio δ. The dashed curves show the profiles of the equilibrium electron density in the slit region of 2DES. (c) Distributions of the plasmon amplitude across the slit for different values of the depletion ratio. (d) Plasmon wavelength evolution across the slit region of 2DES as a function of the plasmon wave crest counted from the slit center for different values of the depletion ratio.