Collective and localized plasmon modes in a periodically gated two-dimensional electron system: Tunable planar plasmonic crystal at terahertz frequencies

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Abstract

We show that a periodically gated two-dimensional electron system constitutes a tunable planar plasmonic crystal for terahertz frequencies. Different plasmon modes of the planar plasmonic crystal and their interaction are considered. The problem of coupling between the plasmon modes in the planar plasmonic crystal and terahertz radiation is discussed.

1. Introduction

The frequencies of the plasma oscillations (plasmons) in two-dimensional electron systems (2DES) fall within terahertz (THz) range while the plasmon wavelength is typically of a submicron scale [1]. Therefore, the plasmon excitation in 2DES is a good candidate for probing mesascopic electronic processes in 2DES and for creating THz plasmonic nanodevices.

Plasmon dispersion in 2DES [2] is given by

$$\omega = \sqrt{\frac{2\pi e^2 N q}{m^* \overline{\varepsilon}}}, \tag{1}$$

where ω and q are the plasmon frequency and wavevector, respectively, N is the sheet electron density in the 2DES, e and m^* are the electron charge and effective mass, respectively, $\overline{\varepsilon}$ is an effective dielectric function. A particular form of the effective dielectric function depends on geometry of the structure:

(i) If the 2DES is located on the surface of a substrate having the dielectric constant ε_s, then

$$\overline{\varepsilon} = (1+\varepsilon_s)/2. \tag{2}$$

(ii) If the 2DES is located on the surface of a substrate having the dielectric constant ε_s and it is capped by a dielectric layer having the dielectric constant ε_b and thickness d, then

$$\overline{\varepsilon} = \frac{1}{2}\left[\varepsilon_s + \varepsilon_b \frac{1+\varepsilon_b \tanh(qd)}{\varepsilon_b + \tanh(qd)}\right]. \tag{3}$$

(iii) If the cap layer is covered by a perfectly conductive plane (the gate contact), then

$$\overline{\varepsilon} = \frac{1}{2}\left[\varepsilon_s + \varepsilon_b \coth(qd)\right]. \tag{4}$$

ISBN 978-952-67611-2-1

Plasmon modes described by Eq. (1) with the effective dielectric functions Eqs. (2) and (3) are conventionally called the *ungated* plasmon modes, while those described by Eq. (1) with the effective dielectric functions Eq. (4) are called the *gated* plasmon modes.

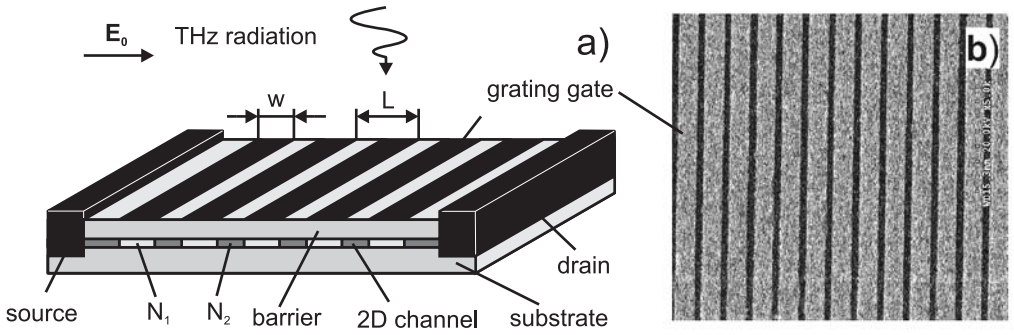

Fig. 1: (a) Schematic of the grating-gated 2DES. Terahertz radiation with polarization of the electric field across the gate fingers is incident from the top. (b) Scanning electron microscopy image of the grating-gate fragment. The period of the grating gate is 1.5 μm with the width of the slits between the grating-gate fingers of 0.35 μm (after [1]).

In this paper, we discuss the plasmon mode spectrum in a planar one-dimensional plasmonic crystal formed by a periodically gated 2DES (Fig. 1). Plasmon mode spectrum in such a structure can be electrically tuned by varying the gate voltage. We describe the transformation and interaction of different types of the plasmon modes that depend on both geometry of the grating gate and the spatial modulation of the electron density in 2DES (which is controlled by the gate voltage). We also show that the plasmon modes in the planar plasmonic crystal can be strongly coupled to THz radiation.

2. Plasmon modes in the planar plasmonic crystal

Collective as well as localized plasmon modes can be excited in the planar plasmonic crystal formed by a periodically gated 2DES [1,3]. Interaction between the plasmon modes localized in the gated and ungated regions of the 2DES can take place due to their resonant coupling. Transformation of the plasmon spectrum in the grating-gated 2DES as a function of spatial modulation of the electron density in 2DES is shown in Fig. 2. Collective plasmon mode distributed over the entire area of the structure period can be excited in the grating-gate structure with a homogeneous 2DES [Fig. 2(a)] (this is also the case in the structure with narrow gaps between the grating-gate fingers). In the case of a strong spatial modulation of the electron density in 2DES, only the plasmon modes in the ungated parts of 2DES can be excited [Fig. 2(b)]. Interaction between the gated and ungated plasmon modes for an intermediate modulation of the electron density in the 2DES is demonstrated in Fig. 2(c).

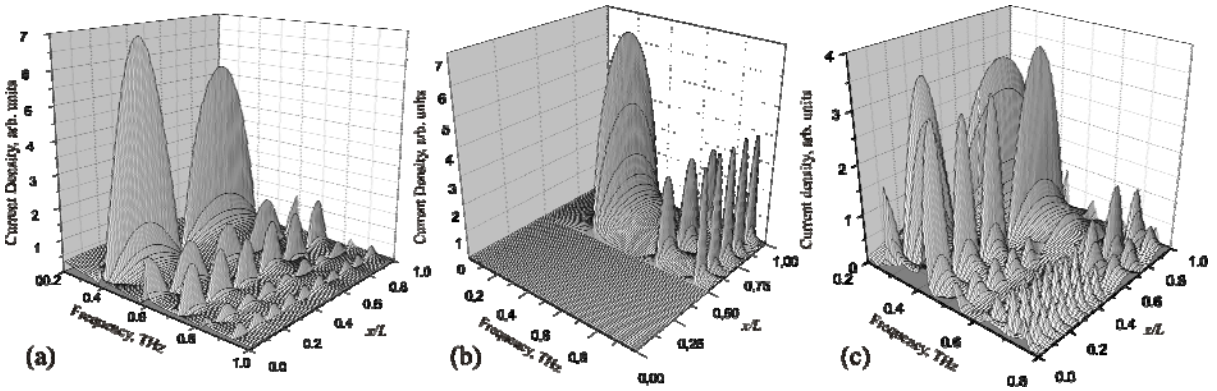

Fig. 2: Spatial waveforms of the plasmon modes in the grating-gate 2DES for (a) homogeneous 2DES, (b) strongly modulated 2DES, and (c) intermediate modulation of 2DES (after [4]). Gated part of 2DES corresponds to $0 < x/L < 0.5$, where L is the grating-gate period.

ISBN 978-952-67611-2-1

3. Coupling the plasmon modes to THz radiation

The grating gate acts as an impedance-matched antenna with a large aperture, which effectively couples the plasmon modes in 2DES to THz radiation. The coupling between the plasmons and THz radiation significantly increases in the structure with narrow slits between the grating-gate fingers [5]. In this case, strong plasmon resonances can be excited in the planar plasmonic crystal for moderate cooling of the structure or even at room temperature (Fig. 3).

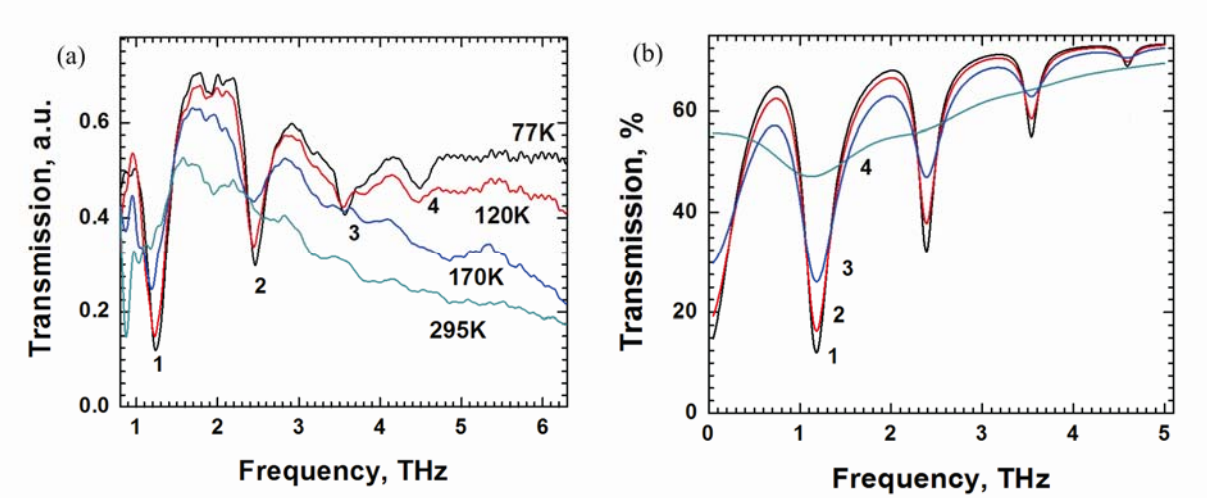

Fig. 3: Measured (a) and calculated (b) transmission spectra of the grating-gated 2DES in AlGaN/GaN heterostructure for zero gate voltage. Numbers mark transmission spectra for different temperatures from 77 K to 295 K. The period of the grating gate is 1.5 μm and the width of the slits between the grating-gate fingers is 0.35 μm (after [5]).

4. Conclusion

Terahertz plasmonic properties of the planar plasmonic crystal formed by a periodically gated 2DES strongly depend on a profile of the electron distribution in 2DES. Collective as well as localized plasmon modes can be excited in the structure. Interaction between the plasmon modes localized in the gated and ungated regions of the 2DES can take place due to their resonant coupling. Plasmon mode spectrum in a gated planar plasmonic crystal can be effectively tailored by varying the gate voltage. Terahertz radiation strongly couples to the planar plasmonic crystal when the gaps between the gated regions are very narrow. These properties of the planar plasmonic crystals make them very promising as tunable modulators and concentrators of the near field at THz frequencies.

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ISBN 978-952-67611-2-1