Plasmonic properties of asymmetric dual grating gate plasmonic crystals

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We report on numerical study of dispersion properties and frequency dependent absorption characteristics of asymmetric dual grating gate terahertz (THz) plasmonic crystals. The study shows that the dispersion relations of plasmons in a two-dimensional electron gas (2DEG) capped with asymmetric dual grating gates have energy band gaps in the Brillouin zones. Depending on the wave vector, the plasmons can have symmetrical, anti-symmetrical, and asymmetrical charge distributions that are different from the ones for uniform gratings case. Plasmons in the studied plasmonic crystal exhibit both tightly confined/weakly coupled behavior and propagating/strongly coupled behavior depending on the plasmonic modes. The responsivity of the plasmonic detector based on asymmetric dual grating gate does not monotonically decrease with the frequency, which is in contrast to the responsivity of uniform grating THz detectors.

The cross-section of an asymmetric dual grating gate terahertz plasmonic device under THz illumination is represented, where excited plasmons are shown in red.

1 Introduction

Plasmonic terahertz oscillations in various types of field effect transistors (FETs) [1, 2] are used for THz detection [3–6], mixing [7–9], and generation [10]. Plasmonic THz FET detectors are frequency tunable which makes them superior to the conventional detectors such as bolometers and pyroelectric detectors [11].

The 2DEG-based FETs support gated plasmons where electromagnetic fields of plasmons confined in between the 2DEG and the gate. FETs also support ungated plasmons where electromagnetic fields of plasmons are localized in the ungated regions [15]. In an FET with periodically spaced gates, the grating gate supplies the necessary momentum in order to excite the plasmons by compensating the momentum mismatch between the THz waves in free space and the THz plasmons in the 2DEG channel.

Recently, highly sensitive terahertz detectors based on asymmetric dual-grating gate (ADGG) HEMTs have been demonstrated with 25 kV W−1 record high responsivity [12] but the plasmon dispersion in such structures has not been studied. In this study, in order to better understand the THz plasmons in ADGG HEMT, we calculated the dispersion relations for a 2DEG-structured lattice with one-dimensional (1D) translational symmetry, known as a 1D plasmonic crystal. The dispersion characteristics of plasmons reveals many important properties of the plasmons such as the localization of the plasmons, the electric field profile distribution, the group velocity etc. The charge distribution along the channel of the FET is especially important since they contribute to THz detection. Unlike uniform grating gate devices, ADGG HEMT device architecture has a geometry that cannot sustain a symmetric charge distribution. An
asymmetric charge distribution can create a net dipole moment along the channel and result in a higher THz response. The THz-induced DC voltage response can be calculated by integrating the induced electric field distribution along the channel. Therefore, understanding the field and charge distribution in the device and their effect on responsivity would allow design of better performing THz detectors. In this study we also investigated the absorption spectrum of the device since the response of the detector strongly depends on the absorption. The presented analyses of the plasmonic crystal dispersion are based on the optical properties of the THz plasmons in 2D cavities which are obtained using finite difference time domain (FDTD) method.

2 Methods A commercial FDTD simulation software was used in order to investigate the electromagnetic field profile of the plasmons and the dispersion of the plasmons in asymmetric grating gate structure [13, 14]. The structure is defined as AlGaN/GaN based HEMTs with a barrier layer of AlGaN and the 2DEG formed in the GaN [15]. Figure 1 shows the cross section of the simulated structure, where the unit cell includes two gates with different lengths with Bloch boundary conditions. The excitation was provided by a dipole source with a polarization perpendicular to the gratings. The simulation is repeated for different energy and momentum values. The plasmons are excited when the momentum and energy of the incident wave matches with the energy and momentum of the plasmons. The electric field profile of the excited plasmons is monitored in the gates, AlGaN, 2DEG, and GaN regions. The 2DEG parameters are defined as a plasma material parameter, where plasma frequency and collision frequency are extracted from the previously reported experimental results for the electron concentration of $7.5 \times 10^{12}$ cm$^{-2}$ and the mobility of 40,000 cm$^2$ Vs$^{-1}$ at 4 K [16]. Such a high mobility value which can be attained at cryogenic temperatures is necessary in order to excite high quality factor plasmons and to properly distinguish the plasmonic modes. For low mobility values, the modes are broadened and cannot be individually resolved since the full width half-maximum of frequency represents the lifetime of the plasmons. The simulation is set to auto-stop when the total electric field in the simulation converges down to a small value, which is six orders of magnitude smaller than the incident field. The data are recorded for several simulations with different $k$ vectors that is added to the Bloch boundary conditions with the largest $k$ vector being half of the reciprocal lattice of the unit cell. Incident wave spectrum was selected to cover 0.1–5 THz range. The electric field profiles for each simulation were extracted to calculate the total electric field at each frequency and momentum value and mapped over a 2D graph by a custom code. It should be noted that due to the use of periodic boundary conditions, the presented results are for an infinite array of the unit cell described here accept for the responsivity measurement in Fig. 5.

3 Results and discussion The effective index of a resonant mode is a combination of gated and ungated plasmon effective indices since they are coupled and cannot be separated from each other. When we consider a uniform grating gate device with a very short gate length and long ungated region length, the effective index of the resonant mode will be close to ungated mode effective index since the effect of the gate is very small. Conversely, in the long gate length device, the effective index of the mode will be closer to the gated effective index of the plasmons since the effect of the ungated region is very small. So, the effective index of a resonant mode is expected to be in the region between the gated effective index and ungated effective index shown in Fig. 2(a). Also, for the short gates the effective index will be smaller compared to the longer gates. The effective indices (Fig. 2(a)) are calculated via FDTD mode calculation method by taking the cross section of the gated and the ungated regions. The mode profile of the plasmons for gated and ungated regions are shown in Fig. 2(b) for 2 THz. The gated plasmonic modes at lower frequencies are highly screened by the gate and tightly confined over the AlGaN region. Higher frequency modes tend to be closer to 2DEG with less screening resulting in smaller gate effect, which causes a dramatic index difference at lower frequencies. This effect can be observed in Fig. 2(a), as the frequency increases, the effective index difference between the gated mode and ungated mode decreases. The effective index of plasmons under the gate is 15 times higher than the ungated plasmons at 1 THz.

Figure 2 shows the plasmonic dispersion characteristics calculated using FDTD method. The $x$-axis represents the plasmon momentum $\Gamma_x$ in $x$ direction where $\Gamma_x$ at 0.5 is $G/2 = n\pi/L$, $G$ is the reciprocal lattice vector ($2\pi L$), $n$ is an integer; $L$ is the unit cell length. The peak points are extracted using a custom code. The dispersion curves for the grating gated devices show that a band gap is opened up in several energy bands in which there are no propagating plasmons. The resulting dispersion curves are not similar to the uniform grating dispersion curves like having cavity-like standing wave bands [14].

A periodic structure causes Bragg scattering of plasmons. This scattering results in forward and backward
traveling waves, which forms a standing wave due to their constructive interference. If plasmon momentum is half of the reciprocal lattice vector $G$ or 0, plasmons interfere constructively in the structure forming two standing wave profiles with different energy levels at the band edges. The high energetic plasmon standing wave profile, $E_+$, tends to localize over the lower index region, and the low energetic plasmon standing wave profile, $E_-$, tends to localize over the high index region. This is a result of the splitting of the bands at Brillion zones. If the energy of the plasmons falls between these two energy levels, plasmons interfere destructively resulting in no propagation along the structure [17]. This behavior of plasmons causes formation of a band gap, which is known as the plasmonic band gap.

Figure 3(c) is an example for $E_+$ for which the mode is localized around the gated region 2 and Fig. 3(b) is an example for $E_-$ for which the mode is localized around the gated region 1. Since the gated region 1 is wider than the gated region 2, the mode in the gated region 1 has a tighter confinement than the one in the gated region 2, which results in higher screening of plasmons and higher effective index of plasmons in the gated region 1.

The plasmonic mode distribution in Fig. 3(b) has a maximum under the gated region 1 while the maximum in Fig. 3(c) is under the gated region 2. The modes corresponding to the second branch in Fig. 3(m) are shown in Fig. 3(a) and (g). The mode starts at gated region 1 and ends up in the gated region 2. Considering that the derivative of dispersion ($dw/dk$) is the group velocity, this branch corresponds to propagating plasmons with a non-zero group velocity and the mode maxima changes its location as the momentum changes. The third branch has a semi-propagating behavior as its derivative ($dw/dk$) is smaller than the one of the second branch. Hence, the mode profile at the lower side of the branch (point (b) in Fig. 3(m)) is localized in the gated region 1 (Fig. 3(b)) and as the momentum increases the mode profile does not totally relocate to the gated region 2. Instead, it partially shifts to the gated region 2. The same behavior is also observed for the fifth (Fig. 3(d) and (j)) and sixth (Fig. 3(e) and (k)) branches. Therefore, these plasmonic modes are weakly coupled localized modes. The fourth branch shows the same properties with the second branch. The mode starts at the gated region 1 and totally shifts to the gated region 2 from (c) to (i). So these modes are the strongly coupled plasmonic modes. The observed behaviors of the branches are completely different than the ones for uniform grating gate devices [14, 20, 21].

The asymmetrical unit cell results in a non-uniform plasmonic mode distribution along the channel, which causes non-uniform charge distribution with dipoles along the channel. The unit cell behaves as a net dipole source and creates a potential difference between its two ends. Therefore, the entire device with several unit cell behaves like a collection of serially connected voltage sources which could yield high responsivity for an incident THz wave.

We also calculated the absorption and response of the periodic device using FDTD method. Since we use Bloch boundary conditions, the structure can be considered as infinite number of unit cells. A perpendicular plane wave source was set up to illuminate the device from the top along with a monitor at the back of the source to record the reflected wave, another monitor at the bottom of the device buried inside the GaN layer to record the transmitted wave. We monitored the electric field in the 2DEG and integrated it along the x direction (along the 2DEG channel) to calculate the voltage response of periodic structure. Figure 4 shows the THz absorption of the periodic structure as a function of incident wave frequency. The corresponding resonant plasmons distributions are shown in Fig. 3(a)–(f), respectively. The momentum of the incident wave is set to zero in the direction of the grating momentum, and hence, the parallel component of the incident wave is zero. Seven different resonant modes are observed in the absorption spectrum with different amplitudes the maximum of which reached to 30%. This behavior is quite different from a typical absorption
spectrum for a uniform grating gate device where the absorption of the fundamental mode is the highest and absorption decreases with increasing mode number [18]. Figure 5 also shows the response of the device for the same spectral range along with the absorption in semi-log scale. There is a correlation between the THz response and the absorption, as the absorption increases, the response also increases. The responsivity of one unit cell can reach higher than 10 kV W\(^{-1}\).
which is in agreement with the experimentally measured value of $25\text{kV W}^{-1}$ for a similar ADGG HEMT \[12\].

The non-uniform responses and absorptions of the resonant modes are caused by the asymmetric unit cell. In a grating gate device, the absorption depends on the dissipation losses and radiative losses of the modes \[18\]. The dissipation loss is proportional with the frequency, as the frequency increases, the dissipation loss increases, and the radiative loss is proportional to the gate length to slit length ratio, as the ratio decreases, radiation loss increases \[19\]. The two different gate length results in different amount of radiative loss and each plasmonic mode has different amount plasmonic confinement under the gate 1 and gate 2 which results in a different amount of radiative loss in each mode. Such a behavior causes non-uniform amount of absorption as a function of frequency. Figure 4 also presents a comparison of the absorption of the ADGG device to a symmetric gate device.

4 Conclusions We investigated the dispersion characteristics of an asymmetric dual-grating gate (ADGG) HEMT structure in detail using FDTD numerical methods. The dispersion of the structure presented several energy band gaps in which no propagation is allowed. The branches in the dispersion are completely different than the ones in dispersion of uniform grating devices. ADGG device can support tightly confined/weakly coupled behavior and propagating/strongly coupled plasmonic modes with asymmetrical charge distributions. This non-uniform charge distribution along the channel can result in high responsivity which makes the ADGG devices a promising candidate for tunable solid-state THz plasmonic detectors.

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