Room temperature terahertz emission from grating coupled two-dimensional plasmons

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Room temperature terahertz emission from grating coupled two-dimensional plasmons

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Room temperature terahertz (far infrared) radiation emission from double grating coupled GaInAs/AlGaAs/GaAs heterojunctions is reported. Theoretical calculations of plasmon absorption spectrum are performed using a first principles electromagnetic approach. They correctly reproduce the frequency range and overall shape of the main (broad-band) part of the experimental spectra. The results clearly indicate that important part of the observed room temperature terahertz emission spectra can be due to the radiative decay of hot two-dimensional plasmons in the grating structure. © 2008 American Institute of Physics. [DOI: 10.1063/1.2919097]

The frequency of plasma oscillations in low dimensional systems increases with lowering the dimension and can reach frequencies in the terahertz region. Therefore, different devices/structures of micron and submicron size supporting low-dimensional plasmons were intensively studied as possible candidates for solid-state far-infrared (FIR)/terahertz sources.1–10

Mechanisms of plasma wave excitation/emission can be divided (by convention) into two types—(i) incoherent and (ii) coherent type like. The first is related to thermal excitation of broad-band nonresonant plasmons by hot electrons.1–4 The second is related either to the plasma wave instability mechanisms such as Dyakonov–Shur5 or to the electron transit-time effect,11 where coherent plasmons can be excited either by hot electrons, or also by optical phonon emission under near ballistic electron motion.12

Historically, first experimental observations of terahertz emission from two-dimensional (2D) plasmons involved the first incoherent mechanism: the radiative decay of hot plasmons. Many authors proposed the radiative decay of grating coupled 2D plasmons in semiconductor heterostructures as one of the most promising candidates for tunable solid-state FIR/terahertz sources.1–4,8

Terahertz emission from coherent plasmon excitations in both cryogenic and room temperatures were also studied.6,7,14–15 Room temperature terahertz emission interpreted in terms of the Dyakonov–Shur instability was observed from nanometer size GaInNAs and GaN/AlGaN transistors.6,7 Also, room temperature optically excited resonant plasmon modes were observed in double grating gate structures.16–18

Up to now, it was not clear if at room temperatures any incoherent hot plasmon emission can be excited/observed. Here, we report on room temperature terahertz emission from dual grating coupled GaInAs/AlGaAs/GaAs heterojunctions. The spectra of the electrically excited terahertz emission were measured by using Fourier transform spectroscopy. Theoretical calculations of plasmon spectra made in a first principles electromagnetic approach allowed identifying unambiguously the main part of the observed spectra due to radiative decay of grating coupled hot 2D plasmons.

The structure is based on a high electron mobility transistor that incorporates doubly interdigitated grating gates that can periodically confine 2D plasmons and, hence, effectively convert the nonradiative plasma waves to electromagnetic radiations. The device was fabricated by using InGaP/InGaAs/GaAs material systems. The 2D plasmon layer is formed within a quantum well in the InGaAs channel layer. The grating gate was formed with 65 nm thick Ti/Au/Ti by a standard lift-off process. Table I shows the detailed description of two different samples used in the experiment.

The samples were placed in the source position of the vacuum cavity of the fast Fourier transform spectrometer. The radiation intensity was measured by Si bolometer. The experimental procedure was as follows: first, the reference (background) spectrum (the spectrum of the sample with no current flowing through the channel) was performed. This spectra contained information about the 300 K blackbody emission modified by spectral functions of all spectral elements (beamsplitter, filters, etc.) of the spectrometer. Then, the spectra of the sample with different dc bias currents flowing through the channel were measured. The final results S were obtained by normalizing the spectra with a current by the reference spectrum. It represents/Corresponds to the relative increase of the emission due to current.

Results for two different samples are shown in Fig. 1. One can see relatively broad spectra starting from about 0.5 THz with maxima around 2.5 THz for the first sample (S1) and around 3.0 THz for the second one (S2). The emission intensity versus voltage is shown in the inset of Fig. 1(a). One can see that the emission intensity is a nonlinear

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function of the applied voltage/current, which is close to a quadratic function with a thresholdlike behavior. For both samples, the emission dies off abruptly around 6.5 THz. In order to check for possible reasons of this feature of the spectra, we performed the transmission and reflectivity measurements of the GaInAs/GaAs sample wafer with and without grating metallization. In both cases, we obtained very similar spectra shown in the inset of Fig. 1(b). One can clearly see that the $\sim6.5$ THz cut of the emission spectra can be attributed to the Reststrahlen band of one of the InGaP/InGaAs/Gas heterostructure materials.19

According to Kirchhoff’s law, the spectral density of thermal emission at frequency $\omega$ by the unit area of the sample heated to temperature $T$ is $I(T,\omega)=A(\omega)I_0(T,\omega)$, where $I_0(T,\omega)$ is the spectral density of the energy flux of the blackbody radiation (integrated over the semispace of emission angles) and $A(\omega)$ is the absorbance of the grating structure. We calculate the absorption spectrum of the grating structure in a first principles electromagnetic approach.20,21

Then, we can estimate the relative intensity of the thermal terahertz emission measured in the experiment as

$$S(\omega,T) = \frac{A(\omega)}{A(\omega)+A_0} \frac{I_0(\omega,T)-I_0(\omega,T_0)}{I_0(\omega,T_0)} ,$$  

where $T_0$ is the thermostat temperature (300 K) and $T$ is the plasmon temperature. The relative emission intensity $S(\omega,T)$ describes the relative increase of terahertz emission intensity due to heating the plasmons by dc bias. It is normalized by intensity of the background thermal terahertz emission without current. The background thermal emission is described by the phenomenological factor $A_0$. This phenomenological factor $A_0$ (emissivity factor $A_0<1$) describes a level of background/reference thermal emission in a real structure, as compared to the blackbody thermal emission. Its typical value for metals is $A_0=0.1$. In our approach, $A_0$ is a fitting parameter—changing its value changes the amplitude of the observed emission spectrum $S(\omega,T)$ but does not change essentially the shape of the emission spectrum. Because the inequality $\hbar \omega/(kT_0) \ll 1$, where $\hbar$ and $k$ are the Plank and Boltzmann constants, respectively, is well satisfied (for room temperatures and terahertz frequencies), the blackbody thermal emission is correctly described by the Rayleigh–Jeans law $I_0(\omega,T)=kT\omega^4/(2\pi c)^2$. Then, it follows from Eq. (1) that the shape of the terahertz emission spectrum is fully controlled by terahertz absorption spectrum $A(\omega)$ but is not influenced by the spectrum of the blackbody emission,

$S(\omega,T) = \frac{A(\omega)}{A(\omega)+A_0} \frac{\Delta T}{T_0}$,

where $\Delta T=T-T_0$. The inset in Fig. 2 shows the calculated dependence of the emission power at terahertz frequency on the square root of the electron temperature (it is proportional to bias current/voltage). A steep superlinear temperature dependence in the grating-gated structure explains the fast growing nonlinear dependence of the emission power on the bias voltage observed in the experiment (Fig. 1). We evaluate the background thermal ($T=300$ K) emission power at a frequency of 1.16 THz from the sample as 150 $\Delta T$ nW, where $\Delta T(1/\lambda)$ is the terahertz detector frequency window with $\lambda$ as the terahertz emission wavelength. Assuming $\Delta T(1/\lambda)=2$ cm$^{-1}$, we obtain that the intensity of terahertz emission corresponding to the plasmon temperature range shown in the inset of Fig. 2 falls into the nanowatt region.

Because in the long-period structure the plasmon resonances follow each other in frequency with a smaller frequency shift, the neighboring plasmon resonances strongly overlap and, hence, they are not so well resolved in the corresponding emission spectra. Also, in the long-period structure, only higher-order plasmon modes can emit high terahertz frequencies (above 4 THz). These higher-order plasmon modes weakly couple to terahertz radiation, which explains a very smooth high-frequency shoulder of the emission spectrum in the long-period structure. The high-frequency shoulder of the emission spectrum in the long-period structure actually behaves similar to the emission spectrum of the structure without grating gate, where thermally excited plasmons do not couple to terahertz radiation (dashed curve in Fig. 2). In the calculated short-period structure spectrum, the fundamental plasmon resonance appears

<p>| Geometrical parameter description of the double grating gate structures. |
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<tr>
<th>$L_{G1}$ (nm)</th>
<th>$L_{G2}$ (nm)</th>
<th>Fingers ($L_{G1}/L_{G1}$)</th>
<th>Ungated space (nm)</th>
<th>$L/W$ (µm)</th>
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<tr>
<td>S1</td>
<td>100</td>
<td>1800</td>
<td>15/16</td>
<td>100</td>
</tr>
<tr>
<td>S2</td>
<td>70</td>
<td>300</td>
<td>60/61</td>
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at around 3 THz and the second one at about 4.5 THz. This may explain a pronounced bump around 5 THz in the high-frequency shoulder in the short-period structure experimental spectrum. Of course, the emission spectra in the actual double grating structure must be more complex compared to that in a single-grating structure modeled numerically. In principle, two different sorts of plasmon cavities can be formed under the metal fingers of different widths in the double grating structure. Also, oblique plasmon modes can lead to some broadening.

The attribution of the main part of the observed terahertz emission spectra to the noncoherent hot plasmon mechanism does not exclude existence of the emission related to the coherent plasmon instability mechanisms. The terahertz emission due to the Dyakonov–Shur plasmon instability as well as the Ryzhii–Sato–Shur transit-time instability may also take place at the same time. Usually, these coherent plasmon excitations are believed to have sharp spectral features. However, once current is flowing through the structure, the carrier density in the cavities formed by the grating fingers is not constant but changes monotonously along the channel. This is due to the self-polarization effect—the potential slope between source and drain modifies effective gate voltage for the gates formed by the grating fingers. Therefore, the plasma resonant frequency is distributed from source to drain regions. Recent finite difference time domain simulations reveal that the near-field emission clearly exhibits the spectral shifting along source to drain. They can result in spectral broadening at the far field due to superposition of all the near-field patterns. Therefore, self-polarization effects can significantly broaden the emission spectrum related to the coherent modes and the broad-band part of the observed spectra can also contain terahertz emission originating from coherent plasma excitation mechanisms. Some coherent/resonant terahertz emission can be probably related to weak sharp features seen on the spectra, but clearly more studies are necessary to identify their origin.

Room temperature terahertz emission from double grating coupled GaInAs/AlGaAs/GaAs heterojunctions was reported. The main (broad-band) parts of the emission spectra were interpreted as due to radiative decay of hot 2D plasmons modified by the Reststrahlen band absorption of the GaInAs layers. While in the structure without the grating gate the emission intensity decreases monotonously with increasing frequency, the grating gate couples the thermally excited plasmons to terahertz radiation, hence producing a nonmonotonous broad-band emission spectrum. Our results showed that the radiative decay of hot plasmons in grating coupled semiconductor heterostructures with 2D gas can be a candidate for room temperature FIR/terahertz sources.

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22. T. Otsuji and T. Nishimura, to be presented at DRC2008, June 2008, Santa Barbara, CA.