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Resonant terahertz absorption by plasmons in grating-gate GaN HEMT structures

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ABSTRACT

Pronounced resonant absorption and frequency dispersion associated with an excitation of collective 2D plasmons have been observed in terahertz (0.5-4THz) transmission spectra of grating-gate 2D electron gas AlGaN/GaN HEMT (high electron mobility transistor) structures at cryogenic temperatures. The resonance frequencies correspond to plasmons with wavevectors equal to the reciprocal-lattice vectors of the metal grating, which serves both as a gate electrode for the HEMT and a coupler between plasmons and incident terahertz radiation. The resonances are tunable by changing the applied gate voltage, which controls 2D electron gas concentration in the channel. The effect can be used for resonant detection of terahertz radiation and for "on-chip" terahertz spectroscopy.

Keywords: Terahertz detectors, grating-gate devices, plasmons, plasmonic crystals, plasma wave electronics

1. INTRODUCTION

Plasmonic effects in semiconductor devices have great potentials for terahertz applications, such as plasmon based tunable detectors, oscillators, modulators and filters, which have been discussed in numerous publications (see, for example, [1-7]). Faster propagation velocities of charge carrier density perturbations in comparison with charge carrier drift velocities itself enables plasma wave electronic devices to overcome frequency limitation of conventional electronic devices by more than an order of magnitude. Another critical feature of plasmonic devices is easy electrical tunability of plasmon resonances. Also, plasmon wavelength is orders of magnitude shorter than the terahertz radiation wavelength at the same frequency, which allows a number of terahertz applications with sub-wavelength spatial resolution.

However, small sizes of field effect transistors and small plasmon wavelengths at terahertz frequencies also cause certain problems for efficient coupling of terahertz electromagnetic field with plasmon excitations due to dramatic mismatch between photon and plasmon wavevectors. For efficient photon-plasmon interaction the system requires a third body to comply with selection rules. As it has been shown in earlier publications (see, for example, [3]) metal grating on the surface of the device with a period matching excited plasmon wavelength can serve as such coupling element. Another requirement for the efficient coupling is large enough geometrical cross section of the device enable to capture the entire incident beam, which normally can't be narrower than the radiation wavelength. The last argument requires large-area detector size or special antenna considerations.

In this paper, we present our results on plasma resonance absorption in the large-area grating-gate GaN-based HEMT structures, which overcomes both of above mentioned limitations and provide nearly ideal coupling between external terahertz electromagnetic field and plasmon reservoir. Large cross section of the device allows for quasi-optical approach of the experiment configuration, eliminating any need of antennas, and multi-finger metal grating provides efficient coupling of incident radiation to the plasma. Our study of terahertz transmission through 2D electron gas in these structures demonstrated the transition from nearly complete transparency at frequencies outside the plasma resonances to metal-like behavior at the resonances.

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2. EXPERIMENTAL SETUP

AlGaN/GaN HEMT heterostructures used in this study were grown by memory enhanced metal-organic chemical vapor deposition (MEMOCVD®) on sapphire substrate (Fig.1). They consisted of a 100-nm-thick AlN buffer layer, 1.4-µm-thick undoped GaN layer, followed by $Al_{0.2}Ga_{0.8}N$ barrier layer, which was doped with silicon to approximately 2×10^{18} cm^{-3}. The 2D electron gas concentration was approximately 10^{13} cm^{2} at room temperatures.

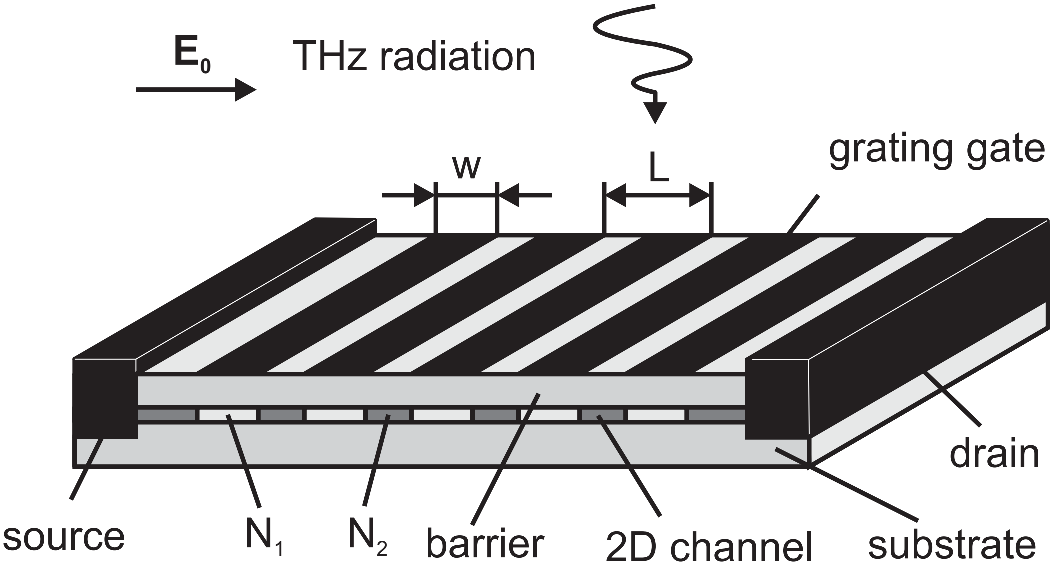

Fig. 1. GaN-based 2D electron gas large area grating-gate HEMT structure on sapphire substrate [8]. N_1 and N_2 are concentrations of gated and ungated 2D electron gas, which has an order of magnitude 10^{13} cm^2 at room temperatures. Electron concentration under the gates can be controlled by applying voltage on gate fingers. Terahertz beam had normal incidence and its polarization was perpendicular to the gate fingers.

Metal grating gates with periods L from 1.5 µm to 3.5 µm were evaporated on top of the structure. The barrier layer between 2D electron gas and the grating was 21 nm. Gaps between gate fingers for structures with L=1.5 µm or 3.5 µm periods was 0.5 µm, so that the gate width W was equal 1 µm and 3 µm correspondingly (Fig.1). Ohmic contacts and gates were fabricated using e-beam evaporated Ti/Al/Ti/Au and Ni/Au metal stacks, respectively. The view of the structure is shown on Fig.2a and scanning electron microscope image of the corner fragment of the structure is shown on Fig.2b. Active region of the structures was approximately 2.5mm x 2.5mm covered by the periodic gate fingers, so that the L=1.5 µm and 3.5 µm period devices had about 1600 and 700 gate fingers, respectively. Such large active area of the devices made them suitable for efficient focusing of incident terahertz radiation and their study by methods of conventional Fourier spectroscopy.

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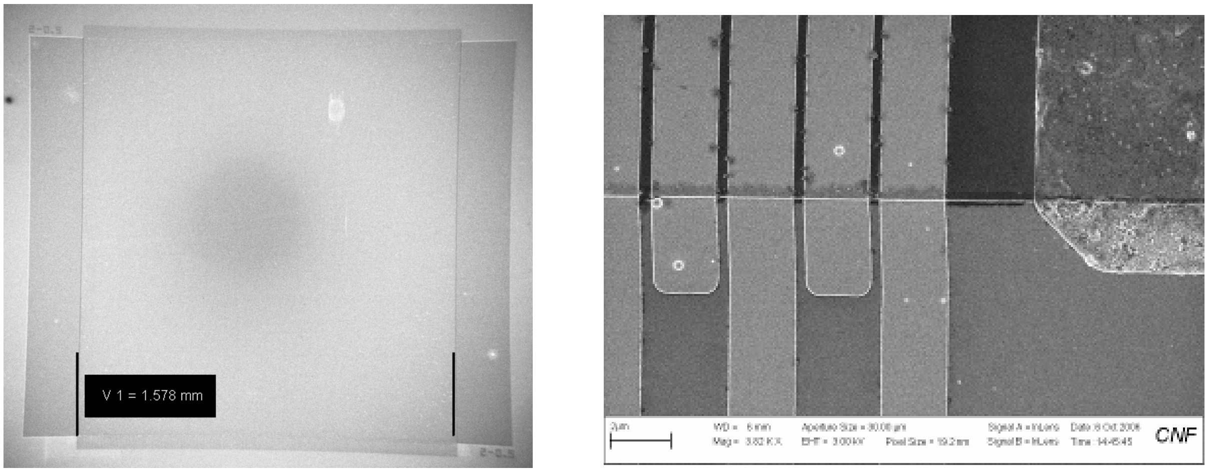

Fig 2. The GaN HEMT structure on the left (a) and scanning electron microscope image of the right-lower corner fragment on the right (b) [8].

Terahertz transmission spectra of the structures were measured by Bruker IFS 66v/S Fourier Transform Infrared (FTIR) spectrometer at RPI at liquid nitrogen temperatures and above, and by Bomem FTIR spectrometer at UCF at liquid helium temperatures. In both experiments the highest spectral resolution was 0.03 THz ($1cm^{-1}$), which was sufficient to resolve Fabry-Perot fringes ($\Delta\nu = 0.1$ THz) caused by multiple reflections of transmitted terahertz radiation inside the cavity formed by the back face of the sapphire substrate and the metal grating. We purposely didn't use any means to eliminate these Fabry-Perot oscillations in the spectra, such as wedges or antireflection coatings, in order to evaluate absolute absorption level of terahertz radiation transmitted through the 2D gas and also detect frequency dispersion anomalies in the vicinity of the resonances. In order to mask Fabry-Perot resonances in the substrate, some spectra were taken with coarse resolution 0.1 THz (3.5 cm^{-1}).

3. RESULTS AND DISCUSSION

Fig. 3 shows transmission spectrum of the structure with period L=3.5 μm and gate length W=3 μm (see Fig.1) measured at liquid helium temperature. The sample was attached to the cold finger, which had the temperature of 4K. The sample temperature may be several degrees K higher due to thermal resistively of the contact. The transmission spectrum has a set of quasi-periodic absorption peaks with 0.52-0.55 THz spacing, associated with plasmon resonances (the spectral window of the spectrometer allowed to observe harmonics of the resonance from the 3rd to the 7th). Envelop spectral dependence is due to apparatus function of the spectrometer.

In the first approach the spectral positions of the observed absorption resonances are well described by the dispersion relation of resonant plasmons in 2D electron gas with the wavevector equal to the wavevector of the grating $g_p = 2\pi/L{*}n$, n=1,2,3…, according to [3]:

$$\omega = \sqrt{\left(\frac{n_s e^2}{m^*}\right)\left(\frac{g_p}{\varepsilon_o\left(\varepsilon_b + \varepsilon_t Coth(g_p d)\right)}\right)} \qquad (1)$$

Here ε_b , ε_t are relative permittivity below and above 2D electron gas, d = 21 nm is the spacing between 2Dgas and the grating, m^* is effective mass and n_s is electron concentration, approximately equal in our case to 10^{13} cm^{2} at zero gate voltage.

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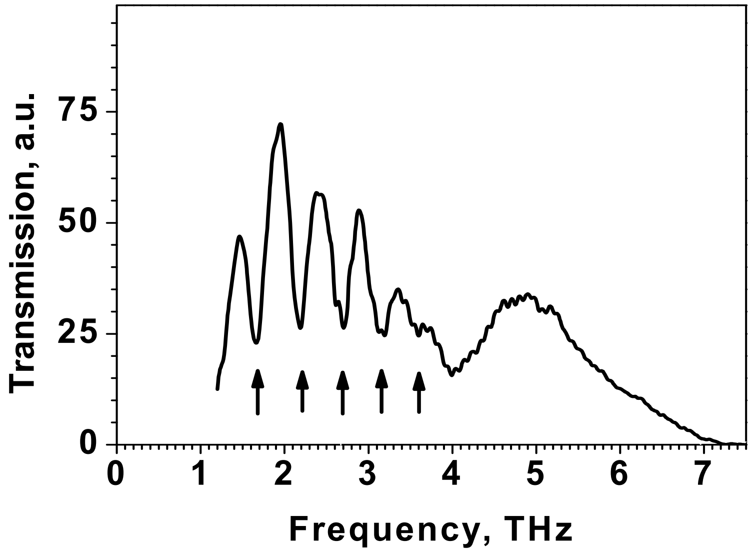

Fig 3. Transmission spectrum of the structure with 3.5 μm period and 3 μm gate length. Spectral resolution is 0.1 THz, T = 4K, gate voltage $V_g = 0$. Arrows shows 3-7 harmonics of plasmon resonant absorption.

The transmission spectrum for the structure with period *L*=1.5 μm and gate length *W*=1 μm is presented on Fig.4. The spectrum was measured at liquid helium temperature. The fundamental frequency for this structure is 1.3 THz which is approximately 2.4 larger than for the structure with *L*=3.5 μm and *W*=3 μm and which nearly corresponds to the ratio of the structure periods.

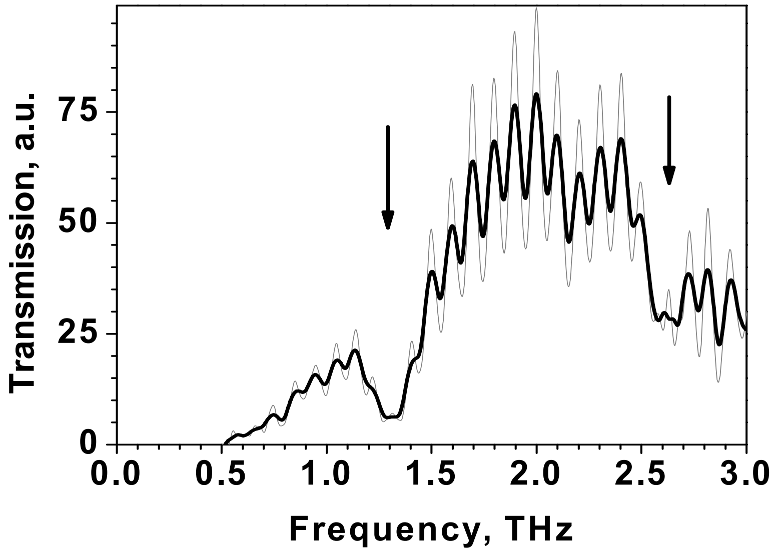

Fig 4. Transmission spectrum of the structure with 1.5 μm period and 1 μm gate length. Spectral resolution is 0.03 THz for grey curve and 0.06 for black curve. T = 4K, gate voltage $V_g = 0$. Arrows shows 1st and 2nd harmonics of plasmon resonant absorption.

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The spectrum presented on Fig. 5 demonstrates tunability of plasmon resonances by applying voltage on the gate fingers of the device and, hence, changing average concentration of 2D electron gas, which causes shift of the resonant frequencies according to the equation (1).

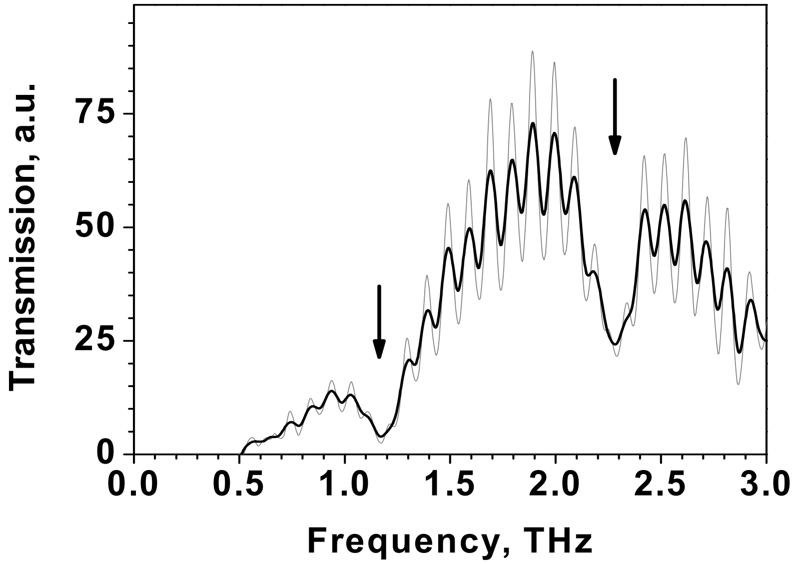

Fig 5. The same as Fig.4, gate voltage V_g = -2Volts.

Temperature dependence of observed plasmon resonances for the structure with L=1.5 μm and W=1 μm is presented on Fig.6. The resonances still appear visible at the temperature up to 170K, but disappear at T=200K and higher. The degradation of the observed resonances with temperature increase is due to decreasing electron mobility, which causes damping of exited plasma waves on the distances shorter than a half of the grating period. At higher temperatures, the excited waves of electron density don't form collective plasmon excitation but break on individual over-damped plasma waves in the vicinity of each gap between the gate fingers. This leads to a loss of phase correlation between these individual excitations and disappearance of the resonance. Note that even though the discussed plasmon modes have collective nature, their main contribution is due to gated electron gas excitations, which have relatively low frequencies. Another type of plasmon resonances [8] may be expected at higher frequencies closer to partial ungated plasmons resonances, which potentially may demonstrate higher operation temperatures.

4. CONCLUSION

We demonstrated strong coupling of incident terahertz electromagnetic field with plasmons in large-area grating-gate AlGaN/GaN HEMT structures at different temperatures from 4K to 170 K. The effect is based on resonant excitation of plasmons with the wavevector equal to the reciprocal-lattice vector of the metal grating, which served both as a gate electrode for the HEMT and a coupler between plasmons and incident terahertz radiation. At liquid helium temperatures, terahertz transmission of the structure changes from transition from nearly complete transparency at frequencies outside the plasma resonances (which is confirmed by multiple reflections between the back face of the substrate and the grating) to less than 10% transmission at the resonances. The resonances are widely tunable by changing the applied gate voltage, which controls the 2D electron gas concentration in the channel of the device.

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Changing the period of the coupler led to the proportional change of the absorption resonance frequency. At zero gate voltage, the resonance frequencies of the structures were at 1.3 THz for the structure with 1.5 micron grating and 0.55 THz for 3.5 micron grating. It is interesting to mention that highest visible harmonic of the resonance is approximately equal to the ratio between the period of structure and the length of ungated regions $L/(L-W)$. Thus, the absorption spectrum of the structure with L=3.5 μm and W=3 μm has harmonics up_to the 7th (Fig.3), while the structure with L=1.5 μm and W=1 μm only up_to the 3rd (Fig.6). According to our analysis, the frequency of highest observed harmonics (~ 3.6 THz for both structures) is defined by the grating-gate slits (L-W = 0.5 μm).

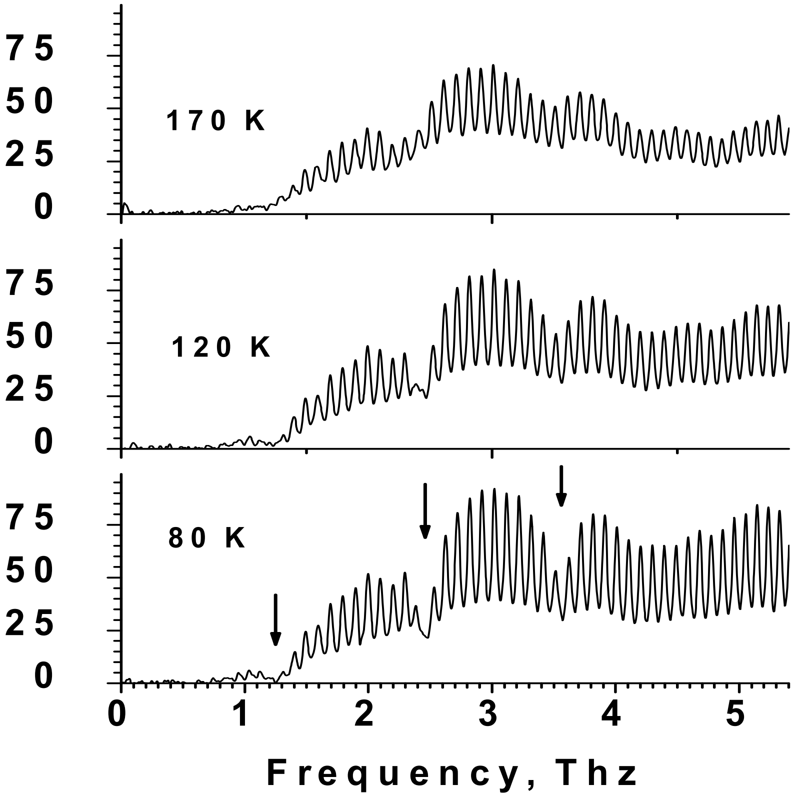

Fig 6. Transmission spectrum of the structure with 1.5 μm period and 1 μm gate length at T = 80K, 120K and 170 K. Spectral resolution is 0.03 THz, gate voltage $V_g = 0$.

The temperature dependences show dissipation of plasmon modes in the structures with the temperature increase up to 170 K. However, the resonances are still well pronounced at liquid nitrogen temperatures, which can enable numerous applications. Potential applications of the observed effect include resonant detectors of terahertz radiation, terahertz modulators, and electrically tunable terahertz spectral filters. The device can be used as an active element for "on-chip" terahertz spectroscopy.

5. ACKNOWLEGMENTS

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REFERENCES

[1] S. J. Allen, D. C. Tsui, R. A. Logan, “Observation of the two-dimensional Plasmon in silicon inversion layers,” Phys. Rev. Lett., 38, 980 (1977).

[2] D. C. Tsui, E. Gornik, and R. A. Logan, Solid State Comm., 35, 875 (1980).

[3] Zheng, Schaich, and A. H. MacDonald, “Theory of two-dimensional grating couplers,” Phys. Rev. B, 41, 8493 (1990).

[4] M. Dyakonov and M. S. Shur, “Shallow water analogy for a ballistic field effect transistor: new mechanism of plasma wave generation by dc current”, Phys. Rev. Lett., 71, 2465 (1993).

[5] X. G. Peralta, S. J. Allen, M. C. Wanke, N. E. Harff, J. A. Simmons, M. P. Lilly, J. L. Reno, P. J. Burke, and J. P. Eisenstein, “Terahertz photoconductivity and Plasmon modes in double-quantum-well field-effect transistors,” Appl. Phys. Lett, 81, 1627 (2002).

[6] V. V. Popov, G. M. Tsymbalov, D. V. Fateev, M. S. Shur, “Cooperative absorption of terahertz radiation by plasmon modes in an array of field-effect transistors with two-dimensional electron channel”, Appl. Phys. Lett. 89, 123504 (2006).

[7] W. J. Stillman and M. S. Shur, Journal of Nanoelectronics and Optoelectronics 2, 209 (2007).

[8] N. Pala, D. Veksler, A. Muravjov, W. Stillman, R. Gaska, and M. S. Shur, Resonant Detection and Modulation of Terahertz Radiation by 2DEG Plasmons in GaN Grating-Gate Structures, Proc. of IEEE Sensors Conference, Atlanta, GA, October 2007, 291-292 (2007)

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