The Tunable Plasmonic Resonant Absorption in Grating-gate GaN-based HEMTs for THz detection

Weida Hu*, Lin Wang, Nan Guo, Xiaoshuang Chen*, and Wei Lu
National Lab for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, 500 Yu Tian Road, Shanghai, China 200083

Abstract

The plasmonic resonant phenomenon in terahertz wave band for GaN-based high electron mobility transistors is investigated by using finite difference scheme. Strong resonant absorptions can be obtained with large area slit grating-gate serves both as electrodes and coupler. Such kinds of plasmonic resonant detection devices are compatible to the well-developed GaN process, and possibly overcome the difficulty in fabricating ultra-short-gate devices for terahertz applications.

I. INTRODUCTION

Far infrared (terahertz) remote sensing technology can potentially be used in the astronomy and atmosphere detections. The quality of remote sensing image is strongly restricted by device performance of the THz detection. The plasmonic wave resonant detector basing on slit-grating-gate transistor is one of important devices which can realize tunable and room-temperature THz detection. However, the detection frequency, quantum efficiency, and work temperature of the device cannot fulfill the requirements of remote sensing applications.

Furthermore, utilization of terahertz (THz) radiation in detection of biological and chemical agents is anticipated for long time. Since rotational and vibrational spectra of many molecules locate at terahertz domain, specific terahertz absorption patterns allow the identification, quantification of these molecules. Because of these, terahertz spectroscopy and imaging systems can have important applications (i.e. explosive detection, medicine quality control, and nondestructive evaluation) and have grown dramatically in the last decade [1, 2]. These systems require THz detectors with fast response time. And the most common THz detectors available now include bolometers [3], pyroelectric detectors, schottky diodes [4].

Recently, there has been growing interests in semiconductor plasmonic detectors which utilize plasma wave for generating signals [5]. The collective motions of two dimensional electron gases (2DEG) behave like shallow water under the gate. And hydrodynamic nonlinearity can produce photoresponse in the form of constant source-drain voltage (under open circuit condition) or direct current (with fixed drain voltage) under the irradiation of THz electromagnetic field. In the regime of off-resonance, the photoresponse is a smooth function of gate voltage as well as frequency, while the resonant structure in the photoresponse can be achieved if the resonant condition is satisfied. Since the resonant frequency is proportional to the square root of gate voltage, the devices have inherent advantage of tunability by electrical bias. These would eliminate bulky filters, mirrors and other element to realize compact monolithic detector array [6].

In this paper, we review our recent numerical simulation works on the new kinds of tunable plasmonic resonant detectors basing on slit-grating-gate double-channel and single-channel HEMTs. The results of these work will offer a great sustain to realizing of the tunable and room-temperature THz detections.

II. DEVICE DESCRIPTION AND DISCUSSION

The plasma wave frequency follows this simple linear relation: $\omega = sk$, s is plasma wave velocity ($s = (eV_{gs}/m^*)^{0.5}$) and k is plasma wave vector. In previous GaAs material system, typical surface electron concentration is 10^{12}cm^{-2}, this require very short gate length in order to utilize plasma wave for resonant detection [7]. The gate length usually lies in the deep sub-micrometer domain for GaAs material system. Therefore, devices with higher electron density and mobility are important in the reduction of burden during the technique processing. Recently, gallium-nitride (GaN) system has attracted great interest due to their unique properties such as large band gap and strong polarization effect. As compared with other III-V HEMT devices, GaN-HEMTs have received wider recognition as potential devices for high-frequency and high-power microwave applications [8]. The electron density in the channel of AlGaN/GaN HEMT can be an order of magnitude higher than GaAs HEMT. This will reduce limitation of deep-submicron meter gate length devices like GaAs HEMT for THz detection according to the dispersion law of plasma wave. In previous GaAs HEMTs, periodic grating gate has been used to expand the frequency domain in THz detection. This relies on the higher order resonant plasmon modes excitations with the help of spatial dispersion of grating gate. However, the maximum resonant frequency has not yet exceeded 5THz with the length of gate finger around 1 μm due to the low frequency of fundamental plasmon mode and radiative damping of higher order plasmon mode. And in our recent paper, we also perform electromagnetic simulation of the plasmon resonant oscillations of GaN HEMTs with periodic grating gate serves both as coupler and electrodes. The device structure is shown in Fig.1 schematically. The thickness of barrier and buffer layers is consistent with normally ones, and the electron

---

* Corresponding author: wdhu@mail.sitp.ac.cn, xschen@mail.sitp.ac.cn.

978-1-4673-1604-0/12/$31.00 ©2012 IEEE

density and mobility in the channel are around $2\times10^{13}\text{cm}^{-2}$ and $1200\text{cm}^2/\text{Vs}$. The simulation is performed in the finite difference scheme with drude-optical conductivity to describe electromagnetic wave transport and damping along the channel.

Why the new kind of tunable plasmonic resonant detector basing on slit-grating-gate double-channel and single-channel HEMTs are chosen? Firstly, the designs of the double channel and high-Al barrier hetro-structure into the HEMTs[9-12], as shown in Fig. 1, can supply the HEMTs with high density of two-dimensional electron gas, high mobility, and long momentum relaxation time making the detector get into the real room-temperature THz frequency detection. Secondly, a slit grating gate design is used to better couple the incoming THz signal. The slit grating gate provides the near-field interaction with the two-dimensional electron gas plasmonic resonant making the device being tunable under gate voltages[9, 11]. A new theoretical way is also developed[9], which combines the electromagnetic Finite-difference time-domain method and quantum transportation final-element method at the two-dimensional calculation boundary conditions. With the developed Drude model, the high-order resonant Restrahlen band effect, resonant enhancement at the anticrossing regime and low frequency absorption enhancement by the double-channel hybrid effect are studied[12].

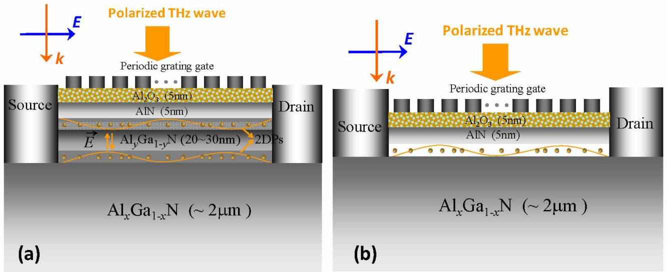

Fig.1. (a) Schematic of double-channel HEMT structure with THz wave incident from top side. (b) Schematic of single-channel HEMT structure with THz wave incident from top side. The current vibration and electron density striction are also shown along the channel.

III. CONCLUSION

The plasmonic resonances of GaN-HEMT are simulated based on the finite difference scheme. There appear two kind plasmonic oscillations along the channel of the device. Due to strong polarization effect and high electron density, superior resonant properties can be obtained even when the gate length reaches more than 1μm. This will expand the applications of plasmonic devices to the high frequency end of THz band.

ACKNOWLEDGEMENTS

The authors acknowledge the support provided by the National Natural Science Foundation of China (61006090), and the Aviation Science Fund (20110190001).

REFERENCES

[1] N. Pala and M. S. Shur, “Plasma wave terahertz electronics, ” Electron. Lett., vol. 44, pp. 1391, 2008.

[2] J. Federici, and L. Moeller, “Review of terahertz and subterahertz wireless communications,” J. Appl. Phys., vol. 107, pp.111101, 2010.

[3] M. Kroug, S. Cherednichenko, H. Merkel, E. Kollberg, B. Voronov, G.Goltsman, H. W. Huebers, and H. Richter, “NbN hot electron bolometric mixers for terahertz receivers,” IEEE Trans. Appl. Superconduct., vol. 11, pp. 962, 2001.

[4] S. Barbieri, J. Alton, H. E. Beere, E. H. Linfield, D. A. Ritchie, S. Withington, G. Scalari, L. Ajili, and J. Faist, “Heterodyne mixing of two far-infrared quantum cascade lasers by use of a point-contact Schottky diode, ” Opt. Lett., vol. 29, pp. 1632, 2004.

[5] M. Dyakonov and M. S. Shur, “Detection, Mixing, and Frequency Multiplication of Terahertz Radiation by Two-Dimensional Electronic Fluid”, IEEE Trans. Electron Devices, vol .43, pp. 380, 1996.

[6] T. Otsuji, and H. Kitamura, “Numerical analysis for resonance properties of plasma-wave field-effect transistors and their terahertz applications to smart photonic network systems,” IEICE Trans. Electron., vol. E84-C, pp. 1470, 2001.

[7] M. Dyakonov and M. S. Shur, “Plasma wave elecronics: Novel terahertz devices using two dimensional electron fluid,” IEEE Trans. Electron Devices, vol. 43, pp. 1640, 1996.

[8] O. Ambacher, J. Majewski, C. Miskys, A. Link, M. Hermann, M. Eickhoff, M. Stutzmann, F. Bernardini, V. Fiorentini, V. Tilak, B. Schaff, and L. F. Eastman, “Pyroelectric properties of Al(In)GaN/GaN hetero- and quantum well structures, ” J. Phys.: Condens. Matter., vol. 14, pp. 3399, 2002.

[9] L. Wang, X. S. Chen, W. D. Hu, and W. Lu, “Spectrum analysis of 2D plasmon in GaN-based high electron mobility transistors,” *IEEE Journal of Selected Topics In Quantum Electronics*, DOI (identifier) 10.1109/JSTQE.2012.2188381, 2012.

[10] X. D. Wang, X. S. Chen, W. D. Hu, and W. Lu, “The study of self-heating and hot-electron effects for AlGaN/GaN double-channel high-electron-mobility-transistors,” *IEEE Transactions on Electron Devices*, DOI (identifier) 10.1109/TED.2012.2188634, 2012.

[11] L. Wang, X. S. Chen, W. D. Hu, J. Wang, J. Wang, X. D. Wang and W. Lu, “The plasmonic resonant absorption in GaN double-channel high electron mobility transistors,” *Applied Physics Letters*, vol. 99, pp. 063502, 2011.

[12] L. Wang, X. S. Chen, W. D. Hu, and W. Lu, Plasmon resonant excitation in grating-gated AlN barrier transistors at terahertz frequency, *Applied Physics Letters*, vol. 100, pp. 123501, 2012.