Effectively exciting plasmonic resonance by supplemental gates for terahertz photodetection in a grating gated field-effect transistor

N. Guo, W. D. Hu*, X. S. Chen*, and W. Lu
National Lab for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, 500 Yu Tian Road, Shanghai, 200083, China

Abstract

An alternative-grating gated AlGaN/GaN field-effect transistor (FET) is proposed by considering the slit regions to be covered by a highly doped semiconductor acting as supplemental gates. The plasmonic resonant absorption spectra are studied at THz frequencies using the FDTD method. The simulated results show that the 2DEGs, under supplemental gates, modulated by a positive voltage, can make the excitation of the plasmon modes under metallic fingers more efficient in comparison to ungated regions in common slit grating gate transistors.

I. INTRODUCTION

The terahertz (THz) response of field-effect transistors (FETs) with a periodic metal grating gate has been widely investigated [1-7]. The metal grating gate placed in close proximity to the two dimensional (2D) electron channel is an efficient coupler between plasmons and THz radiation [8]. However, the gated plasmons are still weakly coupled to THz radiation due to the strong screening effect of the gate electrode [9,10]. Popov *et al.* have demonstrated that the ungated regions of the common 2D electron channel play an important role of electric vibrators in efficiently exciting gated plasmons [9]. In their work, the ungated regions are replaced by lateral metal contacts [9,11]. Higher order plasmon resonances up to a frequency of 15 THz are obtained and the absorption strength approaches the maximum of 0.25. The reason is that the electron liquid in lateral metal contacts is much more “rigid” than that of in the 2DEGs. So, the side metal contacts are more efficient electric vibrators to excite the gated plasmons. Therefore, we design the alternative-grating gated AlGaN/GaN field-effect transistors by considering the slit regions of the structure to be covered by a highly doped semiconductor as supplemental gates. Thus, the supplemental gates can be used to make the “ungated” 2DEGs be more “rigid” than the 2DEGs under vacuum slit by applying the positive voltages.

II. SIMULATION MODELS

The electromagnetic wave solver “EMLAB” from “Sentaurus” has been used for the calculation of the 2D FDTD method. According to the standard Yee algorithm [12], Maxwell’s equations are differentiated in the time–space dimension [4,13]. The frequency-dependent conductivity based on the Drude model is embedded into the solver [4]. In the simulation, the recursive convolution methods are used to handle dispersive media [14]. Additionally, periodic boundary conditions are imposed in the x direction for the grating gates, while perfect matched layers are imposed in the y direction.

III. RESULT AND DISCUSSION

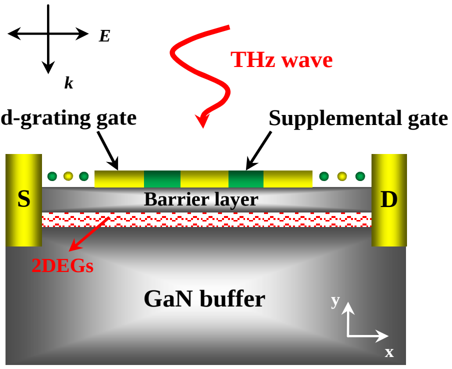

Figure 1. The schematic of alternative-grating gated AlGaN/GaN FETs. The THz wave is incident from the top side with the polarization of electric field being vertical to the gate fingers.

Figure 1 shows the schematic of AlGaN/GaN FETs with the alternative-grating gates (AGGs). Compared with the common slit-grating gates (SGGs), our slit regions are occupied by a highly doped semiconductor as supplemental gates. The metallic (yellow, 1 μm wide) and supplemental (green, 0.1 μm wide) gated fingers are arranged alternatively to fully cover the barrier, but not fully screen the channel due to the semi-screened characteristic of doped semiconductor material. Here, the doped semiconductor material, as the supplemental gate, is highly doped GaN and the doping concentration is 2×10^{18} cm^{-3}. The voltage applied to the metallic gate can be transferred to the supplemental gate due to the Ohmic contact boundary between the metallic and supplemental finger. With this type of grating gate, the density of all the channel electrons can be modulated uniformly. Other parameters of AlGaN/GaN FETs are used in calculations as follows: areal density of 2DEGs at zero gate voltage $N_0 = 1.87 \times 10^{13}$ cm^{-2}, electron relaxation time $\tau = 2.27 \times 10^{-13}$ s [9], electron effective mass $m^* = 0.2m_0$,

---

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

barrier thickness d = 10 nm and barrier permittivity $\varepsilon_b = 9$ [9]. The gold fingers with electric conductivity 4.1×10^7 S·m^{-1} are considered as the perfectly conductive strips.

Figure 2 shows the THz absorption spectra of AlGaN/GaN FETs for AGGs (solid lines) with the gate voltage 0V. For the convenience of comparison, the absorption spectrum for common SGGs (dashed line) is also calculated. It can be seen from Fig. 2 that the absorption strengths of S1 to S3 for the common SGGs are higher than that for AGGs. However, the absorption strengths of S4 to S6 for the common SGGs are lower than that for AGGs. The reason is that for the lower order plasmon modes, the carrier screening effect of supplemental gates for the doping semiconductor causes the weakening of the coupling of the gated plasmons to the THz radiation. But, for the higher order plasmon modes, the high resonant frequencies make the dipole oscillations very strong. The supplemental gates between two adjoining metallic fingers provide a good conductive path in which the electric fields of dipole oscillation are well confined. Although the carrier screening effect still exists, the near-field enhancement effect is dominant and the absorption peaks are increased. The inset shows the plasmon-induced electric field distribution of the 2nd resonant mode for the AGGs device.

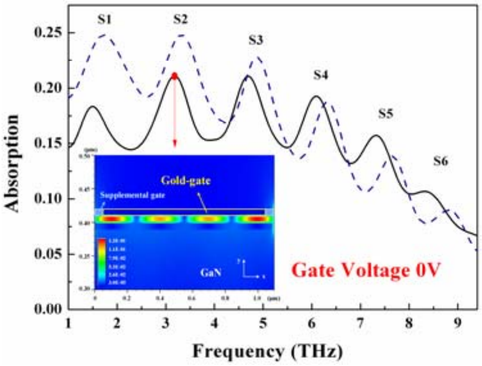

Figure 2. THz absorption spectra for AGGs (solid lines) and SGGs (dashed line) under 0V gate voltage. “S1” to “S6” are used to label the resonant peaks.

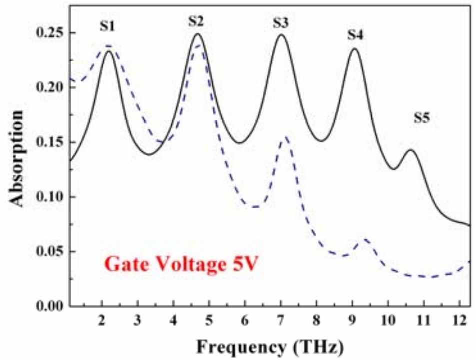

Figure 3. THz absorption spectra for AGGs (solid lines) and SGGs (dashed line) under 5V gate voltage. “S1” to “S5” are used to label the resonant peaks.

Figure 3 shows the THz absorption spectra for AGG (solid lines) and SGG (dashed line) with 5V gate voltage. For the AGGs, the absorption strengths of S1 to S4 are very high and approach the maximum absorbance of 0.25. For the SGGs, only the peak values of S1 and S2 can be close to 0.25, and then the absorption strength decreases rapidly with increasing the resonant orders. Furthermore, the higher order plasmon resonance S5 can also be excited for AGGs in comparison with that for SGGs.

IV. CONCLUSION

The plasmonic resonant absorption spectra of AlGaN/GaN FETs with an alternative-grating gate at THz frequencies using the FDTD method have been calculated. The supplemental gates are designed by covering the slit regions with a highly doped semiconductor. The 2DEGs under the supplemental gates, modulated by a positive voltage, can make the excitation of the plasmon modes under the metallic gates more efficient.

REFERENCES

[1] A. R. Davoyan, V. V. Popov, and S. A. Nikitov, “Tailoring Terahertz Near-Field Enhancement via Two-Dimensional Plasmons,” Phys. Rev. Lett., vol. 108, pp. 127401, 2012.

[2] V. V. Popov, D. V. Fateev, T. Otsuji, Y. M. Meziani, D. Coquillat, and W. Knap, “Plasmonic terahertz detection by a double-grating-gate field-effect transistor structure with an asymmetric unit cell,” Appl. Phys. Lett., vol. 99, pp. 243504, 2011.

[3] D. V. Fateev, V. V. Popov, and M. S. Shur, “Transformation of the Plasmon Spectrum in a Grating-Gate Transistor Structure with Spatially Modulated Two-Dimensional Electron Channel,” Semiconductors, vol. 44, pp. 1406-1413, 2010.

[4] T. Nishimura, N. Magome, and T. Otsuji, “An Intensity Modulator for Terahertz Electromagnetic Waves Utilizing Two-Dimensional Plasmon Resonance in a Dual-Grating-Gate High-Electron-Mobility Transistor,” Jap. J. Appl. Phys., vol. 49, pp. 054301, 2010.

[5] V. V. Popov, D. V. Fateev, O. V. Polischuk, and M. S. Shur, “Enhanced electromagnetic coupling between terahertz radiation and plasmons in a grating-gate transistor structure on membrane substrate,” Opt. Express, vol. 18, pp. 16771-16776, 2010.

[6] D. Coquillat, S. Nadar, F. Teppe, N. Dyakonova, S. Boubanga-Tombet, W. Knap, T. Nishimura, T. Otsuji, Y. M. Meziani, G. M. Tsymbalov, and V. V. Popov, “Room temperature detection of sub-terahertz radiation in double-grating-gate transistors,” Opt. Express, vol.18, pp.6024-6032, 2010.

[7] L. Wang, W. D. Hu, J. Wang, X. D. Wang, S. W. Wang, X. S. Chen, and W. Lu, “Plasmon resonant excitation in grating-gated AlN barrier transistors at terahertz frequency,” Appl. Phys. Lett., vol. 100, pp. 123501, 2012.

[8] V. V. Popov, “Plasmon Excitation and Plasmonic Detection of Terahertz Radiation in the Grating-Gate Field-Effect-Transistor Structures,” J. Infrared Milli. Terahz. Waves, vol. 32, pp. 1178–1191, 2011.

[9] V. V. Popov, G. M. Tsymbalov, T. V. Teperik, D. V. Fateev, and M. S. Shur, “Terahertz Excitation of the Higher-Order Plasmon Modes in Field-Effect Transistor Arrays with Common and Separate Two-Dimensional Electron Channels,” Bulletin of the Russian Academy of Sciences: Physics, vol. 71, pp. 89-92, 2007.

[10] V. V. Popov, A. N. Koudymov, M. Shur, and O. V. Polischuk, “Tuning of ungated plasmons by a gate in the field-effect transistor with two-dimensional electron channel,” J. Appl. Phys., vol. 104, pp. 024508, 2008.

[11] V. V. Popov, M. S. Shur, G. M. Tsymbalov, and D. V. Fateev, “Higher-order plasmon resonances in GaN-based field-effect transistor arrays,” Int. J. Hi. Spe. Ele. Syst., vol. 17, pp. 557-566, 2007.

[12] K. S. Yee, “Numerical solution of initial boundary value problems involving Maxwell’s equations in isotropic media,” IEEE Trans. Antennas Propag. AP-14, pp. 302-307, 1966.

[13] T. Otsuji, M. Hanabe, T. Nishimura, and E. Sano, “A grating-bicoupled plasma-wave photomixer with resonant-cavity enhanced structure,” Opt. Express, vol. 14, pp. 4815-4825, 2006.

[14] R. J. Luebbers, F. Hunsberger, and K. S. Kunz, “A frequency-dependent finite-difference time-domain formulation for transient propagation in plasma,” IEEE Trans. Antennas Propag., vol. 39, pp. 29-34, 1991.