Plasma Instability of Two-Dimensional Electron Gas in Double-Grating-Gate Transistor Structure

A. Satou, H. Shida, T. Otsuji, and V. V. Popov*
Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan
* Kotelnikov Institute of Radio Engineering and Electronics (Saratov Branch),
Russian Academy of Sciences, Saratov 410019, Russia
e-mail: a-satou@riec.tohoku.ac.jp

INTRODUCTION

Plasma waves in double-grating-gate transistor structure have been researched as candidates of compact, room-temperature operating, frequency-tunable terahertz emitters and detectors. For emission, the observation of terahertz emission at room temperature by double-grating-gate high-electron-mobility transistors was reported by Otsuji *et al.* [1], [2]. On the other hand, although there has been extensive study of the so-called Dyakonov-Shur (DS) instability in single-gate structure driven by DC current structures originating from Ref. [3], plasma instability in double-grating-gate structures has not been studied theoretically except the work by Ryzhii *et al.* about the transit-time instability [4].

In this paper, we develop a numerical model to calculate plasma spectra in a double-grating-gate structure and report on a novel plasma instability.

EQUATIONS

The double-grating-gate structure under consideration is illustrated in Fig. 1(a). Here, we consider a GaAs/AlGaAs heterostructure 2D electron gas (2DEG). Focusing on plasma waves propagating in x-direction, we use the linearized hydrodynamic equations for the electron transport in the 2DEG:

$$\begin{cases} -i\omega\Sigma_\omega + \dfrac{\partial}{\partial x}\left(\Sigma_0 v_\omega + v_0\Sigma_\omega\right) = 0, \\ \left(-i\omega + \gamma_{\rm p}\right) v_\omega + \dfrac{\partial}{\partial x}\left(v_0 v_\omega\right) = -\dfrac{e}{m}E_\omega, \end{cases} \tag{1}$$

together with the expressions of the electron current: $J_0 = -e\Sigma_0 v_0$ and $J_\omega = -e\left(\Sigma_0 v_\omega + v_0\Sigma_\omega\right)$. Here, $\gamma_{\rm p}$ is the electron collision frequency, Σ_0, v_0, and J_0 are steady-state electron concentration, electron velocity, and current density, Σ_ω, v_ω, and J_ω are their harmonic components, and E_ω is the harmonic component of in-plane electric field in the 2DEG, which is determined by the self-consistent Maxwell's equations. Note that the continuity of the steady-state current throughout the 2DEG requires $v_0(x)$ be determined by $\Sigma_0(x)$. For simplicity, we focus on the profile of the electron concentration such that the 2DEG under the gate 2 is almost depleted (see Fig. 1(b)). In this case, the maximum of the velocity, $v_{0\rm max}$, can be viewed as a parameter.

Assuming thin, perfectly conducting metallic gates with the conductivity $\sigma_{\rm M0}$, the Maxwell's equations can be reduced to the following relation between the Fourier components of the in-plane electric field and the current:

$$E_{\omega k} = \sum_{k'=-\infty}^{\infty} f_{\omega k}\rho_{\omega k k'} J_{\omega k'}, \tag{2}$$

where $f_{\omega k} = c\kappa_{\omega k}/\omega\sqrt{\epsilon}$, $\kappa_{\omega k} = \sqrt{\epsilon\omega^2/c^2 - q_k^2}$, $q_k = 2\pi/L$, and $\rho_{\omega k k'}$ is the matrix component which is derived from the Maxwell's equations and is related to the screening by the gates as well as the different dielectric constants in different layers. By performing the Fourier expansion of Eqs. (1) and the current and combining them with (2), we arrive at the following eigenvalue problem:

$$\sum_{k'}\left(\omega^2\delta_{kk'} + i\omega A_{kk'} - B_{kk'}\right) J_{\omega k'} = 0, \tag{3}$$

where $A_{kk'}$ and $B_{kk'}$ are the maxtrix components obtained from the above-mentioned procedure. By trancating the infinte matrices and solving Eq. (3) numerically, we can calculate the eigenmodes $J_{\omega k}^{(n)}$ and eigenfrequencies $\omega^{(n)}$ of the system, where n is the mode number. The condition ${\rm Im}\omega > 0$ corresponds to the instability.

RESULTS AND DISCUSSION

In the following calculation, we chose parameters as shown in Fig. 1(a) and (b) and $\gamma_{\rm p} = 0$ for simplicity. Among eigenmodes calculated, we selected those who satisfy $\mathrm{Im}\omega > 0$ and identified them as instable modes. Figure 2(a) shows plasma frequencies ($\mathrm{Re}\omega/2\pi$) and increments ($\mathrm{Im}\omega/2\pi$) of these modes as functions of $v_{0\max}$, while Fig. 2(b) shows their current profiles. It is shown in Fig. 2 that the instability takes place between about $10^3 - 10^4$ m/s. This instability can be attributed to the derivative term of the velocity in the Eular equation, i.e., the variation of the steady-state velocity at boundaries of the 2DEG and depleted regions beneath the gate 1 and 2, respectively. This instability is similar to the DS instability, which takes place due to the asymmetry of boundary conditions, and has not been known for double-grating-gate transistor structures so far.

CONCLUSION

We developed a numerical model for the calculation of plasma spectra of a 2DEG in a double-grating-gate structure based on the linearized hydrodynamic equations and Maxwell's equations. We found a novel plasma instability associated with the variation of the steady-state electron velocity in the 2DEG.

ACKNOWLEDGMENT

This work was financially supported by JSPS Bilateral Joint Project between JSPS and RFBR.n The computation was mainly carried out using the computer facilities at Research Institute for Information Technology, Kyushu University.

REFERENCES

[1] T. Otsuji *et al.*, "Grating-bicoupled plasmon-resonant terahertz emitter fabricated with GaAs-based heterostructure material systems," Appl. Phys. Lett. **89**, 263502 (2006).
[2] T. Otsuji *et al.*, "Emission of terahertz radiation from dual grating gate plasmon-resonant emitters fabricated with InGaP/InGaAs/GaAs material systems," J. Phys.: Condens. Matter **20**, 384206 (2008).
[3] M. Dyakonov and M. Shur, "Shallow water analogy for a ballistic field effect transistor: new mechanism of plasma wave generation by dc current," Phys. Rev. Lett. **71**, 24645 (1993).
[4] V. Ryzhii, A. Satou, M. Ryzhii, T. Otsuji, and M. S. Shur, "Mechanism of self-excitation of terahertz plasma oscillations in periodically double-gated electron channels," J. Phys.: Condens. Matter **20**, 384207 (2008).

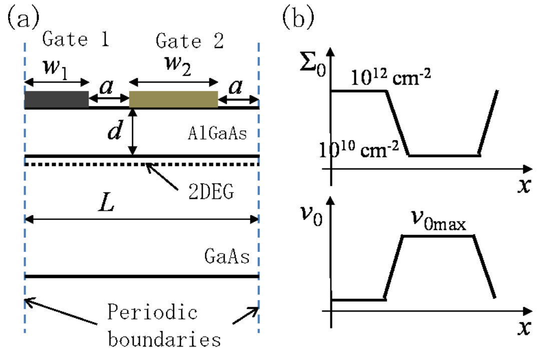

Fig. 1. (a) Schematic view of the double-grating-gate transistor structure under consideration and (b) profiles of steady-state electron concentration and velocity.

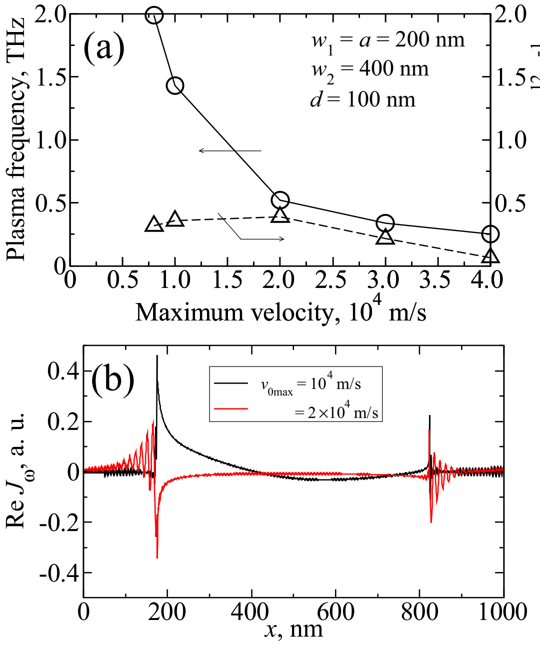

Fig. 2. (a) Plasma frequencies and increments of the instable modes and (b) current profile of several modes where $x = 0$ is shifted at the center of the gate 2.