Effect of Contacts on Terahertz Plasma Resonances in Two-Dimensional Electron Systems

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***Abstract*—We study the effect of side contacts on plasma oscillations in two-dimensional (2D) electron systems by numerical simulation. Our model is based on the kinetic electron transport equation and the self-consistent Poisson equation. We find that the contacts absorb the energy of plasma oscillations excited in the 2D electron channel and consequently this effect can be a dominant damping mechanism, surpassing the damping due to the electron collisions. We estimate the damping rate caused by the contacts and discuss its dependence on the real contact injection properties and temperature.**

I. Introduction

Plasma oscillations in 2D electron channels can be used in different heterostructure electron devices operating in the terahertz (THz) range of frequencies [1]. The excitation of the plasma oscillations leads to the resonant response in different structures with 2D channels. The quality factor of the plasma resonances $Q \propto \gamma^{-1}$, where γ is the damping rate of the plasma oscillations, is a very important factor determining the performance of different THz devices. It is usually believed that γ is determined primarily by the frequency, ν, of electron collisions with impurities and phonons. This fact comes from theoretical studies based on a hydrodynamic model of the electron transport in the 2D channel with ideal highly-conducting contacts (for example, see [2]). Several other mechanisms of the damping of plasma oscillations are known, but those are negligible in the circumstance practically concerned: electron-electron collision (viscosity in terms of hydrodynamics) is only effective for high-order modes of plasma oscillations [3], and the radiative decay is comparable to the collision frequency at low temperatures [4], [5] but negligible at room temperature. It has also been shown that side contacts can contribute to the damping due to the "penetration" of plasma oscillations into the contacts, if the conductivity of the contacts is not so large compared with that of the 2D channel [6].

In this paper, we show that the damping of plasma oscillations can strongly depend not only on the conductivity of the material of side contacts (as shown in [6]), but also on their injection properties, i.e., on the boundary conditions for the electron distribution function at the contacts. Our consideration is based on computer modeling of the transient electron processes in the 2D channel. The mathematical model used includes the Vlasov kinetic equation coupled with the 2D Poisson equation and the numerical method called the splitting scheme for solving the former. We conduct the numerical simulation based on the model, and we find that the energy of plasma oscillation is absorbed by the contacts and that the damping caused by this can be comparable or even larger than that due to electron collisions with impurities and phonons. In our best knowledge, the damping mechanism of plasma oscillations in 2D electron systems discussed here has not been known yet in the literature.

II. Model and Method of Simulation

Since we focus on the damping caused by side contacts, we consider a rather simple 2D electron system shown in Fig. 1, consisting of a heterostructure 2D electron channel with a (remote) doping and side contacts whose vertical dimension is much larger than the channel length and width. In the same spirit, the collision integral in the kinetic equation for the electron transport is omitted, i.e., we use the Vlasov equation:

$$\frac{\partial f}{\partial t} + v_x \frac{\partial f}{\partial x} + e \left.\frac{\partial \varphi}{\partial x}\right|_{z=0} \frac{\partial f}{\partial p_x} = 0, \qquad (1)$$

where $f = f(t, x, p_x, p_y)$ is the electron distribution function (y-coordinate is along the transverse direction in the channel), $\varphi = \varphi(t, x, z)$ is the electric potential, $e = |e|$ is the electron charge, p_x and p_y are the momentum in x- and y-directions, $v_x = p_x/m$ is the electron velocity, and m the electron effective mass.

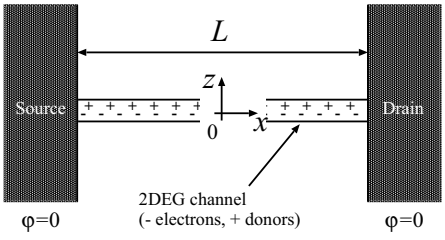

Fig. 1. Geometry of the 2D electron system under consideration.

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The potential φ in (1) obeys the self-consistent Poisson equation:

$$\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial z^2}=\frac{4\pi e(\Sigma-\Sigma_d)}{\epsilon}\delta(z), \tag{2}$$

where Σ_d is the donor sheet concentration,

$$\Sigma(t,x)=\frac{2}{(2\pi\hbar)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f\,dp_x dp_y \tag{3}$$

is the electron concentration, $\hbar$ is the reduced Planck constant, ϵ is the dielectric constant, and $\delta(z)$ is the Dirac delta function. Here we assume that we have the delta doping of donors at slightly above the 2D electron channel, and that in solving (2) the distance between them is negligible.

We conducted simulation of transient electron processes for the above-mentioned system based on (1) and (2). As the initial condition, we artificially set a nonuniform perturbation to a steady-state distribution function, and monitored the transient electron processes. In the framework of the hydrodynamic approach (with ideal boundary conditions), the result would be free oscillations of the electron concentration and potential (plasma oscillations) without damping. However, our model, which accounts for the real injection properties of electrons from the contacts into the channel and vice versa, results in the decay of plasma oscillations (see below).

As boundary conditions for (1) and (2), we set the potential at the contacts to be equal to zero,

$$\varphi|_{x=\pm L/2,z=0}=0, \tag{4}$$

and describe the distribution function at the contacts as follows:

$$f^{\pm}|_{x=\mp L/2}=f_{_F}+p_{_T}\frac{\delta E_x|_{x=\mp L/2,z=0}}{E_c}\frac{\partial f_{_F}}{\partial p_x}. \tag{5}$$

Here, $f^+=f(p_x>0)$ and $f^-=f(p_x<0)$, $f_{_F}$ is the Fermi distribution in the contacts [its explicit form is obtained by putting $\varphi_0=0$ in (6)], $p_{_T}=\sqrt{2mk_{_B}T}$, $k_{_B}$ is the Boltzmann constant, T is the temperature, and $\delta E_x=-\partial(\varphi-\varphi_0)/\partial x$ is the time-dependent part (i.e., ac) of the electric field, where $\varphi_0=\varphi_0(x,z)$ is the dc potential, E_c is the characteristic electric field determining the injection properties of the contacts. According to the boundary conditions (5), the ac electric current across the contact surfaces is proportional to the ac electric field at these surfaces: when the ac electric field there is directed towards the contacts, the amount of incoming electrons increases, and vice versa. Small values of E_c corresponds to high-resistance Ohmic contacts. At very large E_c, the electron distribution function at the contacts becomes fixed, i.e., time-independent. The latter is frequently adapted for steady-state and dynamical (see, for instance, [7])) transport simulations of semiconductor devices which uses either the kinetic transport equation or the Monte Carlo method.

The steady-state solution of (1) with (5), f_0 is found to be

$$f_0=\frac{1}{1+\exp\{[(p_x^2+p_y^2)/2m-e\varphi_0-E_f]/k_{_B}T\}}, \tag{6}$$

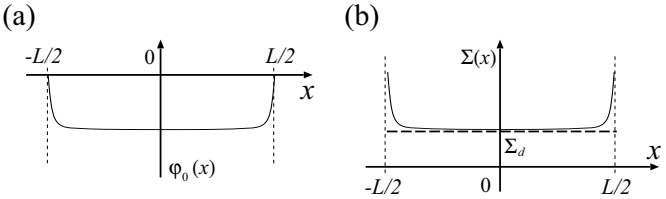

Fig. 2. Schematic views of (a) steady-state potential and (b) steady-state electron concentration in the channel.

where E_f is the Fermi energy in the contacts (measured from the bottom of the conduction band in the contacts, assuming the contacts are made of heavily doped semiconductors) and φ_0 should be calculated self-consistently according to (2) and (4). The steady-state potential and electron concentration in the channel [the latter being calculated using (3) and (6)] are schematically illustrated in Fig 2(a) and (b). As the initial condition of the simulation, we use the distribution function weakly perturbed from (6):

$$f|_{t=0}=f_0+af_0|_{x=0}\cos(\pi x/L), \tag{7}$$

where a is a parameter determining the amplitude of the perturbation.

To solve (1) with the boundary conditions (5), we adapted the numerical procedure called the splitting scheme [8], [9] (we used the cubic spline method for interpolations required in the method). The method allows to solve the Vlasov equation with the numerical accuracy of the order of Δt^2, where Δt is the time step for the numerical simulation. For detailed explanation of the method, see [8]. The Poisson equation (2) was solved by the 2D finite difference method with the boundary conditions (4) and $\partial\varphi/\partial z|_{z=\pm\infty}=0$.

III. Results and Discussion

With the boundary conditions (4) and (5) and the initial condition (7), we solved (1)-(3) numerically using the splitting scheme. Parameters of the system were chosen for the GaAs-based heterostructure ($\epsilon=12$ and $m=6.1\times10^{-29}$ g) with $E_f=0.04$ eV, $L=0.6$ μm, $\Sigma_d=0.5\times10^{12}$ cm^{-2}, and $T=77$ or 300 K. The amplitude of the perturbation was set to $a=0.1$.

Figure 3 shows the evolution of the ac potential in the channel (at $x=0$) in the response to the initial perturbation with different values of E_c and T. One can clearly see from Fig. 3 that the amplitude of the potential rapidly decreases with time, quite contrary to the theory based on the hydrodynamic model.

To clarify the reason for this damping, let us first think about the case where the contacts are ideally conducting, i.e., they act as reservoirs of electrons [$E_c\to\infty$ in (5)]. They provide the constant amount of thermal electrons to the channel, but at the same time electrons in the channel is absorbed by them. At the beginning of the perturbation, electrons in the channel oscillate in time and space due to the self-consistent ac electric field. As time goes, a part of the electrons contributing to the

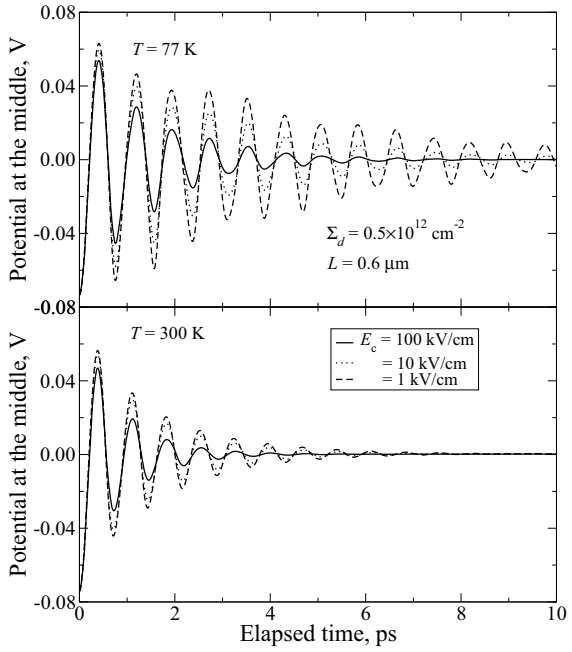

Fig. 3. Potential at $x = 0$ vs elapsed time for systems with different temperatures and different characteristic electric field E_c.

plasma oscillation go out of the channel and never come back since there is no deviation of the amount of the incoming electrons. Then, the total energy of the plasma oscillation keeps decreasing, and finally it is damped out. The finite value of E_c means there is some feedback from the contacts. The damping of plasma oscillations becomes less effective for smaller value of E_c, as shown in Fig. 3.

To study quantitatively how effective the damping due to the contacts is, we evaluate the damping rate γ as follows:

$$\gamma = \frac{1}{N-1}\sum_{n=2}^{N}\frac{\log(\varphi|_{x=0,t=t_{n-1}}/\varphi|_{x=0,t=t_n})}{t_n - t_{n-1}}, \qquad (8)$$

where the potential at $x = 0$ has maxima at $t = t_n$, $n = 1, 2, \cdots$. In (8), we calculate the rate of decrease in heights of adjacent maxima, add it up for first N maxima, and take the average. If the time-dependent part of the oscillations is in the form $e^{-\gamma t}\cos(\omega t)$, then the expression (8) reproduces γ exactly. Figure 4 shows γ as a function of E_c with different temperature. It is seen from Fig. 4 that the damping rate decreases when E_c decreases, as we mentioned above, and that the damping rate is larger at higher temperature (also graphically seen in Fig. 3). The latter fact can be explained as follows. Figure 5 illustrates the perturbed distribution functions (integrated over p_y) at the right contact, $(f - f_0)_{x=L/2}$, at $t = 0.2$ ps with different temperatures. The distributions for $p_x > 0$ correspond to electrons moving towards the contact [those for $p_x < 0$ correspond to the incoming electrons, which slightly deviates from zero due to the second term in (5)]. As seen in Fig. 5, the perturbed distribution function at the higher temperature has the wider thermal broadening and, hence, the

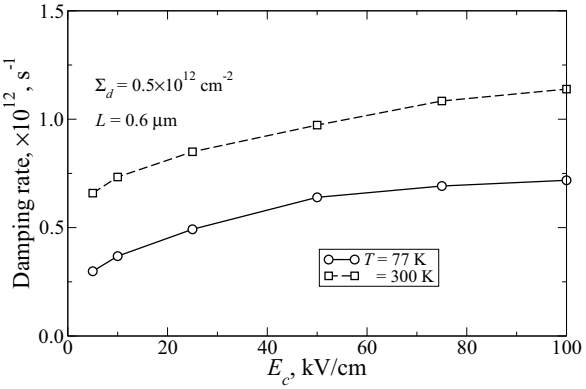

Fig. 4. The damping rate γ as a function of the characteristic electric field E_c, with different temperature.

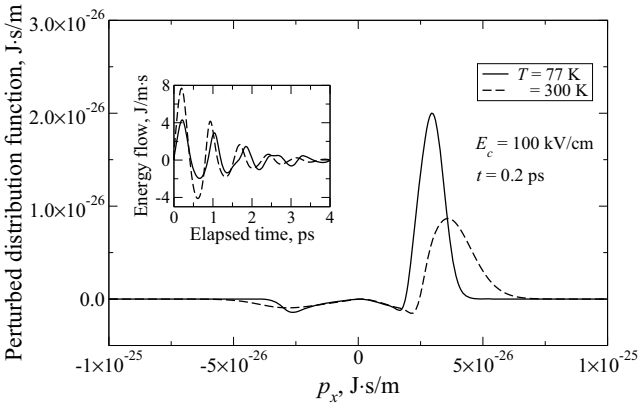

Fig. 5. Perturbed distribution functions at the right contacts, $(f - f_0)_{x=L/2}$, at $t = 0.2$ ps with $E_c = 100$ kV/cm and different temperatures. The inset shows the evolution of the energy flow at $x = L/2$.

faster average electron velocity, yet having almost the same amount of electrons. Since electrons move towards the contacts faster, the damping at higher temperature is stronger. The inset in Fig. 5, which shows the energy flow at the right contact, $\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} v_x[(p_x^2+p_y^2)/2m]f dp_x dp_y$, gives a clearer evidence of this.

Although (8) is a rough estimate of the damping caused by the contacts, let us compare it with the damping rate for electron collisions, $\nu/2$. The collision frequency ν for heterostructure systems depends strongly on the temperature, and it is inversely proportional to the mobility μ. Assuming that $\mu = 9000$ and 10^5 cm^2/Vs at $T = 300$ and 77 K, respectively, for the GaAs heterostructure, we estimate $\nu/2 \sim 10^{12}$ and 10^{11} s^{-1} at each temperature (from the formula $\nu = e/\mu m$). From these estimations and values of γ shown in Fig. 4, we find that at $T = 77$ K the damping caused by the contacts surpass significantly that caused by electron collisions (several times larger), and that even at $T = 300$ K the former mechanism is comparable to the latter.

IV. Conclusion

In conclusion, we have studied the damping mechanism of plasma oscillations in 2D electron systems with side contacts. We have carried out the computer simulation of the transient electron processes in the 2D electron channel using the Vlasov kinetic equation coupled with 2D Poisson equation. We have found that the contacts absorb the energy of plasma oscillations in the channel, resulting in their damping. It has been shown that the damping rate estimated can surpass that of the electron collisions.

The work at the University of Aizu was supported by the Grant-in-Aid for the JSPS Fellows and by the Grant-in-Aid for Scientific Research (S) from the JSPS, Japan.

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