Linewidth broadening in edge-magnetoplasmon resonance of helium surface state electrons

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Abstract. We employed edge-magnetoplasmon (EMP) resonance technique to study magneto-transport properties of 2DES where edge states play an important role. We measured EMP frequencies and linewidths of 2DES on liquid helium surface under various lateral confinement potentials. The experimental results show that as the lateral confinement potential is reduced measured EMP linewidth takes minimum at a certain strength of confinement potential and broad signal was obtained on further potential reduction. This broadening behavior is absolutely unexpected from the existing theories of conventional EMP. We consider that an oscillation mode transition is responsible for the linewidth broadening. The linewidth behavior in the strong confinement region is reasonably explained by conventional EMP, while the broad signals in the weak confinement region is not. We show our experimental data and discuss the origin of the line broadening.

1. Introduction
Edge-magnetoplasmon (EMP) is an electron density wave, which occurs in bounded two-dimensional electron systems (2DES) exposed in a perpendicular magnetic field [1, 2]. EMP wave propagates within a narrow strip near the edge where electron density gradient is finite, while density in the bulk is uniform [3]. Accordingly, EMP frequency and damping rate reflects the properties of electronic structure of 2DES edge states. Despite of the large number of publications on EMP frequencies, the number of both experimental and theoretical studies on EMP dampings is limited. The damping is an important property of EMP since it is determined by microscopic energy dissipation mechanism and it must be closely related to the electronic structure of the edge.

In this work we measured EMP damping rate of helium surface state electrons (SSEs) in various lateral confinement potentials. SSE edge structure can be easily controlled by tuning the applied potentials on confining metal electrodes and thus it is suitable to study the relationship of EMP damping and the edge state. We found that the damping mechanism dramatically changes when lateral confinement potential is very weak. In this paper we present our preliminary data and discuss the possibility of oscillation mode transition.
2. Experiment
The SSEs are formed between the parallel plate circular electrodes as shown in the inset of Fig. 1. The electrode disks are 25 mm in diameter and 3 mm apart. The pressing potential $V_{DC}$ applied to the bottom electrode determines central SSE density. The electrode surrounding SSEs (guard ring) provides lateral confinement potential. The inner diameter of the guard ring is 13 mm. By varying applied voltage $V_G$ the density profile near the edge is controlled. The curves in Fig. 1 are edge density profile calculate for our experimental conditions of strong ($V_G = -10.0$ V) and weak ($V_G = -0.5$ V) lateral confinement, respectively. The characteristic length $h$ of density transition layer where the density drops from its central value to zero is approximately the same as the depth $d$ from SSEs and the bottom electrode ($d = 1.6$ mm in this work), however, slightly steeper density drop is recognized for the strong confinement profile.

![Figure 1. (inset) Arrangement of electrodes and applied potentials for SSE confinement. $V_{DC}$ and $V_G$ are pressing and lateral confining potentials, respectively. Two curves are the calculated electron density profiles near the edge for strong (solid line) and weak (dotted line) lateral confinement.](image)

We measured EMP spectra by employing frequency sweep CW method. The electrode arrangement and EMP spectrometer are described in Ref. [4]. Some of the measured resonance curves are shown in Fig. 2. Here, the background signal of external origin is subtracted. The resonances of the normal mode (first peak) and the first higher harmonics (second peak) are clearly seen. Each resonance curve is fitted to a combination of two Lorentzian functions divided by circuit impedance:

$$F(\omega) = \frac{L_1(\omega) + L_2(\omega)}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}},$$

(1)

where $L_i(\omega) = a_i/\sqrt{\left(\omega^2 - \omega_i^2\right)^2 + \gamma_i^2\omega^2}$ ($i = 1, 2$) are the Lorentzian functions for the first and the second resonances, with adjustable parameters amplitude $a_i$, resonance frequency $\omega_i$ and damping rate $\gamma_i$. The symbols in Fig. 2 are experimental data and the curves are the fitting results. We find Eq. (1) very well expresses the data.

![Figure 2. Measured EMP resonance spectra for $V_G = -10.0$, -3.0, -0.5 V (symbols) and the fitting results to Eq. (1) (lines). $V_{DC} = 80$ V, $N_e = 1.16 \times 10^8$, $T = 0.55$ K, $B = 3.19$ T are fixed. The first peak is the normal mode and the second one is the first higher harmonics.](image)
3. Results and analysis

In order to explore the influence of lateral confinement potential on EMP, we measured EMP resonances at various \( V_G \). We carefully confirmed that the total number of electrons \( N_e \) was maintained under reduced \( V_G \). Three example signals of different \( V_G \) are shown in Fig. 2. Those were measured at \( T = 0.55 \) K, \( B = 3.19 \) T and \( N_e = 1.16 \times 10^9 \). The resonance frequency shifts lower as the confinement potential is reduced (small \( |V_G| \)), while the linewidth of \( V_G = -3.0 \) V is the narrowest. The fitting results of first peak frequency and linewidth are plotted as the symbols in Fig. 3(A)(B) as a function of \( V_G \).

![Figure 3. Measured EMP resonance frequency (A) and linewidth (B) of the normal mode as a function of \( V_G \) (symbols) at \( T = 0.55 \) K, \( B = 3.19 \) T and \( N_e = 1.16 \times 10^9 \). Small \( |V_G| \) corresponds to weak lateral confinement. The increase of the linewidth in weak confinement region is the broadening transition, while the frequency decreases monotonically. Lines are calculated values according to Volkov-Mikhailov [1, 5] theory of conventional EMP.](image)

The frequency behavior of Fig. 3(A) is readily understood. Since EMP propagates along the perimeter of 2DES, the resonance occur when the perimeter length is integer multiple of the wavelength. Expansion of SSE in reduced confinement leads to a long wavelength and thus a lower frequency shift. On the other hand, an unexpected behavior was observed in the linewidth. It took minimum and started to increase in reducing the lateral confinement potential. We refer to this behavior as a broadening transition. EMP damping rate is estimated as the inverse of Maxwell relaxation time \( \tau \), which depends in 2D on the wave vector component perpendicular to the edge \( q_\perp \), \( 1/\tau = \sigma_{xx}q_\perp^2/2\pi \) [5]. For the case of SSE, \( q_\perp^{-1} \) can be replaced by the density transition layer thickness \( h \). As the lateral confinement potential is reduced \( h \) increases and it results in a small damping rate, i.e., a narrow line shape. The linewidth behavior of strong confinement region, \( V_G < -5 \) V, is consistent with this consideration, however, the broadening transition in weak confinement region is unanticipated.

According to Gauss’s law, as far as \( N_e \) is constant, the electric potential \( V_e \) of SSEs can be tuned by \( V_{DC} \). The potential difference \( V_e - V_G \) determines the lateral confining electric field. Application of large positive \( V_{DC} \) increases \( V_e \) and it results in stronger confinement field. Fig. 4(A) shows EMP linewidths measured at different \( V_{DC} \)’s. The broadening transition (minimum linewidth) occurred at smaller \( |V_G| \) in increased \( V_{DC} \). This result indicates that intensified lateral confinement due to large \( V_{DC} \) must be compensated by further reduction of \( |V_G| \) in order to achieve the same confinement field. In addition, we obtained linear dependence of transition \( V_G \) on \( V_e \) (Fig. 4(B)). Therefore we conclude that the lateral confinement electric field governs the broadening transition.
Figure 4. (A) EMP linewidths measured at different $V_{\text{DC}}$’s. Temperature, applied magnetic field, total electron number and other experimental parameters were the same as Fig. 3. The $|V_G|$ of broadening transition point (minimum linewidth), indicated by arrows, shifts small when $V_{\text{DC}}$ is increased. (B) The potential of SSE layer $V_e$ is tuned by $V_{\text{DC}}$. The $V_G$ at broadening transition point is a linear function of $V_e$.

4. Discussions
As it was described in the previous section, the behaviors of both frequency and linewidth in the strong confinement region qualitatively consistent with the conventional EMP. Here we make a quantitative comparison of experimental data with the conventional EMP theory of Volkov and Mikhailov (VM)[1]. The frequency $\omega_{\text{EMP}}$ and the linewidth $\Gamma_{\text{EMP}}$ are theoretically given by

$$\omega_{\text{EMP}} = 2\pi f_{\text{EMP}} = -\frac{q_{xy}}{2\pi\epsilon} \ln(|q|a) + C, \quad \Gamma_{\text{EMP}} \sim \frac{\sigma_{xx}}{4\pi\epsilon a \ln(|q|a)},$$

respectively, where $\sigma_{xx}$ and $\sigma_{xy}$ are the components of conductivity tensor, $q$ the wave vector, $\epsilon$ the dielectric constant, $C$ geometrical constant. The length $a$ is the width of oscillating EMP charge strip. For the case of SSE, $a$ is replaced by the transition layer thickness $h$. We calculated SSE density profile and defined $h$ as the width between the edge and the radius where the density is 40% of its central value. The lines in Fig. 3 (A)(B) are calculated values using this $h$. The experimental data of strong confinement region are very well described by VM equations Eq.(2) of conventional EMP.

We suppose that the broadening transition is a oscillation mode transition from conventional EMP in strong confinement region to some different mode in weak confinement. Since our broadened mode still possesses the feature of EMP, i.e., the frequency is inversely proportional to the applied magnetic field, it may be a cousin of conventional EMP. Several novel EMP modes have been reported theoretically [6, 7] and experimentally [3, 8, 9, 10]. It would be interesting to compare our results with them.

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