Unexpected resonance line shape broadening of edge-magneto plasmons of 2DES on helium

Research Center for Low Temperature and Materials Science, Kyoto University

Toshikazu Arai
Colleagues

Shuji Yamanaka

Ryohei Nishinakagawa  Hideki Yayama  Akira Fukuda  Anju Sawada
Edge of two-dimensional electron systems

Magnetic field → Cyclotron motion
Edge of two-dimensional electron systems

At large magnetic field, no current flows along electric field. $\sigma_{xx} = 0$
Skipping orbit near the edge supports current along $E$.  
(quantum hall state)
Edge of 2DES over liquid helium

Density profile near the edge can be controlled by electric field.

**strong confinement**

**weak confinement**

Density profile near the edge can be controlled by electric field.

**Sharp**

**Wide**
**Edge-magneto plasmons (EMP)**

- Collective oscillation mode: propagates along the 2DEG edge.
- Magnetic field $B$ perpendicular to the electron sheet.
- Small damping in strong magnetic field.
- Observed in various 2DEG systems:
  - GaAs / AlGaAs heterostructure,
  - Metal-Insulator-Semiconductor,
  - Helium surface state electrons
Basic Features of EMP

Propagates along 2D electron gas in only one direction.

Gapless spectrum \( \omega_{\text{emp}} \propto q \ln(1/|q|) \ll \omega_c \)

Frequency \( \omega_{\text{emp}} \propto n_e \) and \( B^{-1} \)

Small damping rate at strong magnetic field \( (\omega_c \tau >> 1) \).

Frequency:

\[
\omega_{\text{emp}} = \frac{q\sigma_{xy}}{2\pi\epsilon} \left( \ln \frac{1}{|q|w} + C \right)
\]

Damping rate:

\[
\frac{1}{\tau_{\text{emp}}} \sim -\frac{\sigma_{xx}}{4\pi\epsilon\omega \ln(|q|w)}
\]

Drude:

\[
\sigma_{xx} = \frac{ne^2\tau}{m} \frac{1}{1 + \omega_c^2\tau^2} \quad \sigma_{xy} = -\frac{ne^2\tau}{m} \frac{\omega_c\tau}{1 + \omega_c^2\tau^2}
\]

High magnetic field:

\[
\frac{\sigma_{xx}}{\sigma_{xy}} = \frac{1}{\omega_c \tau} = \frac{m}{eB\tau}
\]
Experiment

1. Reduce $V_{DC}$

2. Reduced density

3. Back to initial $V_{DC}$

4. Reduce $V_{GR}$

Measure EMP spectrum at each $V_{GR}$.

The total number of electrons is conserved through the measurement.
Controlling the density profile near the edge

Vg = -10.0 V

T = 0.43 K, B = 3.2 T, n_0 = 3.5 \times 10^{12} \text{ m}^{-2}

Controlling the density profile near the edge

T = 0.43 K, B = 3.2 T, n_0 = 3.5 \times 10^{12} \text{ m}^{-2}

EMP electrodes

guard ring

CW freq.
sweep

EMP electrodes

guard ring

Sharp

Wide

n(r)

n(r)

r

r

w

w

V_g

V_g
EMP Line Shapes

$V_G = -10 \text{ V}$

$V_G = -9 \text{ V}$

$V_G = -8 \text{ V}$

$V_G = -7 \text{ V}$

$V_G = -6 \text{ V}$

$V_G = -5 \text{ V}$

$V_G = -4 \text{ V}$

$V_G = -3 \text{ V}$

$V_G = -2 \text{ V}$

$V_G = -1 \text{ V}$

$T = 0.43 \text{ K}$, $B = 3.2 \text{ T}$, $n_0 = 3.5 \times 10^{12} \text{ m}^{-2}$
Double Lorenzian fitting

Lorenz functions

First resonance
\[ L_1(\omega) = \frac{a_1}{\left( (\omega_1^2 - \omega^2)^2 + \gamma_1^2 \omega^2 \right)^{1/2}} \]

Second resonance
\[ L_2(\omega) = \frac{a_2}{\left( (\omega_2^2 - \omega^2)^2 + \gamma_2^2 \omega^2 \right)^{1/2}} \]

Overall function
\[ F(\omega) = \frac{L_1(\omega) + L_2(\omega)}{\left( R^2 + (\omega L - \frac{1}{\omega C})^2 \right)^{1/2}} \]

Required by the electronics.
Guard Voltage Dependence

\[ R \propto \frac{1}{q} \]

\[ \omega_{\text{emp}} = \frac{q \sigma_{xy}}{2\pi \epsilon} \left( \ln \frac{1}{|q|w} + C \right) \]

\[ \frac{1}{\tau_{\text{emp}}} \sim -\frac{\sigma_{xx}}{4\pi \epsilon w \ln(|q|w)} \]

[Graph showing frequency and line width dependence on VG]
Surface deformation?

EMP electrodes

Guard ring

Previous

New

Immersed guard ring
Immersed guard ring result

Line width broadenings are observed even with the immersed guard ring.

$T = 0.15\, \text{K}, \quad B = 3.2\, \text{T}$

$V_{GR} = -20.0\, \text{V}$

$V_{GR} = 0.0\, \text{V}$
The broadening is NOT governed by density transition layer $w$. 

**Linewidth – Density transition layer**
Linewidth – 2DES radius

Broadening is NOT governed by 2DES radius.
Controlling lateral confinement potential

1. Reduce $V_{DC}$
   
2. Reduced density
   
3. Back to working $V_{DC}$
   
4. Reduce $V_{GR}$

Measure EMP spectrum at each $V_{GR}$.

Large $\Delta V_{DC}$ corresponds to strong lateral confinement.

The total number of electrons is conserved through the measurement.
Large $\Delta V_{DC}$ corresponds to strong lateral confinement.
In the context of controlling lateral confinement, weak confinement is indicated to facilitate easier broadening. The diagram illustrates the relationship between guard electrode potential ($V_{G}$) and minimum line width, along with the impact of different Δ$V_{DC}$ values (12 V, 10 V, 8 V, 6 V, 4 V, 3 V, 2 V). The graph shows a clear linear relationship between $V_{G}$ (minimum line width) and Δ$V_{DC}$, emphasizing the potential control strategy.
Controlling lateral confinement potential

Solve \( \nabla^2 \phi(r) = 0 \)

under appropriate boundary conditions.

\( \phi(\text{surface}) = V_e \), where 2DEG exists.
Set the 2DEG edge to $r=0$. 
Move $V_e$ to zero.

**Initial rise of the confinement potentials are the same!!**
Magnetic Field Dependence

Magnetic field does not affect the turning point.
Sharp switching is observed at strong magnetic field.
Conventional EMP
and Boundary Displacement Wave (BDW)


Conventional EMP

BDW

Rigid boundary  Movable boundary

Compressible liquid  Incompressible liquid

\[ \omega_{\text{EMP}} = \frac{\gamma_{\text{EMP}}}{B} \]
\[ \omega_{\text{BDW}} = \frac{\gamma_{\text{BDW}}}{B} \]

(Frequency difference is small at large B)

Small damping  Large damping
Summary

- EMP spectrum was studied with controlling lateral confinement potential.

- Unexpected line broadenings were observed when the confinement potential is weak.

- The broadening can be qualitatively explained by boundary displacement wave.

- The lateral confinement electric field determines EMP or BDW to occur.

- Strong confinement: EMP, Weak confinement: BDW

- Frequencies of EMP and BDW are close at high magnetic field.

- BDW damping is larger than EMP.