Excitation of edge magnetoplasmons in a two-dimensional electron gas by inductive coupling

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We apply a novel inductive coupling technique to study edge magnetoplasmons (EMP) in two-dimensional electron gases in the time domain. This technique is mostly appropriated for measurements on gated samples in the low-magnetic-field limit. We obtain time delay, amplitude, and broadening of the EMP as a function of the magnetic field. © *1997 American Institute of Physics.* [S0003-6951(97)00251-9]

The excitation spectrum of two-dimensional electron gases (2DEGs) in high magnetic fields is known to have low-frequency modes propagating along the edge of the sample.[1–3] Recently, there has been an interest in these edge magnetoplasmons (EMP) in both semiconductors and on the surface of liquid helium.[4–8] Low-frequency edge magnetoplasmons promise to be an appropriate tool for the investigation of the edge structure in semiconductor 2DEGs, which can be very complicated in high magnetic fields. According to theoretical models the main part of the charge in EMPs is concentrated in a strip of width l along the edge boundary. In an ungated structure this width is equal to:[1]

$$l_0=\frac{2\pi\ \mathrm{Im}(\sigma_{xx})}{\epsilon\omega}, \tag{1}$$

where ω is the EMP frequency, $\sigma_{xx}(\omega)$ is the dissipative conductivity, and ϵ is the static dielectric permittivity. Experimentally, the width of the boundary layer is found to oscillate with magnetic field according to Eq. (1), reaching a minimum value of about 5 μm.[5] Because the width of the edge channels defining the edge structure of the sample does not exceed 1 μm one has to find ways to decrease the width of the EMP charge distribution.

In gated samples the electric field and the Hall current of an EMP are restricted to a strip of width $\approx d$, where d is the distance between the gate and the 2DEG. For typical values of $d\approx 1000$ Å, the EMP could thus be suitable for the investigation of the edge structure in gated samples. Unfortunately, according to simple theory the damping of the EMP is expected to increase in gated samples.

So far, most experimental studies[4,3,9] have been made in the frequency domain. Capacitive coupling to the sample edge usually has been used to reach the maximum possible Q-factor of the resonance. In all these experiments samples without a gate or samples with a relatively large distance between gate and 2DEG have been used.

Two different methods allowing time domain measurements have been developed in the past few years. In Ref. 5 the EMP propagated along a mesa edge. Two small gates operated as ''pulser'' and ''detector'' in the regime of capacitive coupling to the sample edge. A very different experimental technique was used in time domain measurements on gated samples.[6,7,10] A pulse of electrochemical potential difference along the sample edge was applied using two ohmic contacts. Another ohmic contact was used to investigate the equilibration process in the sample. The advantage of the last technique is its applicability to systems with a large attenuation of the EMP, the disadvantage is the strong influence of the ohmic contacts on EMP damping and velocity.

In the present work we employ an inductive coupling technique to investigate EMPs in the time domain. We show that this technique is useful for measurements in both the low-magnetic-field limit and in high magnetic fields.

The samples investigated are GaAs/AlGaAs heterojunctions with a 2D electron density of 3.36×10^{11} cm^{-2} and a mobility of $\mu=5\times 10^5$ cm^2 V^{-1} s^{-1}. The distance between gate and 2DEG is equal to 3000 Å. The mesas (Fig. 1) have nearly stadium shape with two elliptical etched areas inside. The rectangular gate covers the inner section of the mesa and part of the etched areas. Applying a negative gate voltage we deplete the 2DEG under the gate so that in the inner part of the sample the path of the EMP consists of four sections: in two of them the EMP travels along the boundary between the 2DEG and the gate, and in the other two along the edge of the etched areas. The traveling time along the etched boundaries is expected to be much smaller than along the gated edges due to the geometrical size relation of 1:4 as well as to the difference in velocity. Apart from the gate in the etched areas two metallic loops are placed operating as pulser and detector. The length of the mesa is equal to 4 mm, the mesa width is about 1 mm, the width of the 2D electron strip after depletion of gated sample region is 150 μm. To receive bet-

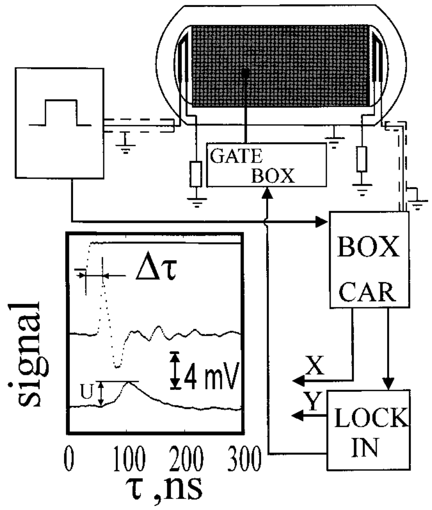

FIG. 1. Schematic diagram of the heterostructure device used and scheme of the experimental setup. The insert in the picture depicts experimental traces: the upper curve is for the exciting pulse; the middle curve is for response at the detector in a weak magnetic field ($B=0.12$ T); the bottom curve is for response at the detector in strong field ($B=8.8$ T). The insert shows only the rise of the exciting pulse and the corresponding part of the received pulses. The scale in the figure corresponds to the signal before the lock-in amplifier (two lowest curves).

ter inductive coupling with EMPs traveling along the inner edge, the metallic loop should be narrow and should be placed close to the edge of the etched area. In our samples the width of the metallic loop is equal to $\Delta=250\ \mu$m, its length is $l=900\ \mu$m. The distance between the etched edge and metallic loop is 50 μm and the width of the metallic strip of the loop is equal to $w=25\ \mu$m.

To investigate the EMP response a combined pulse and low-frequency modulation technique was used. The excitation pulse from an oscillator was applied to a $R_0=50\ \Omega$ resistor in series with the pulser loop on the sample. The pulse duration was usually 300–400 ns, the repetition time was equal to 3×10^{-5} s. The gate was biased by both dc and ac voltage with frequency $f=10$ Hz. Thus, the amplitude of the EMP was modulated with the same frequency f in a dc bias region where a small ac modulation corresponds to a large change in the EMP attenuation (e.g., near threshold voltage $V_g=V_{th}$). The pulses received by the ''detector'' loop were analyzed using a Box Car averager with a time resolution of 3 ns and three samples for averaging. The output signal from the Box Car was used as an input signal for the lock-in amplifier. As a result for an input pulse amplitude of about 1 V we had an amplification rate of 10^6 with a power dissipation of 20 μW in the 50 Ω resistor. The main part of our experiments was made at a temperature of 0.6 K, but we have found that warming our sample to 1 K does not change the experimental results.

An example of an experimental trace is shown in the inset to Fig. 1. The received signal consists of two peaks corresponding to the rise and fall of the exciting pulse. Both peaks are observable only when the difference between the dc bias and the threshold voltage $V_{th}=-2.1$ V does not exceed the amplitude of the low-frequency modulation (insert to Fig. 2). The shape and the amplitude of the response peak are a function of magnetic field. The time delay between the

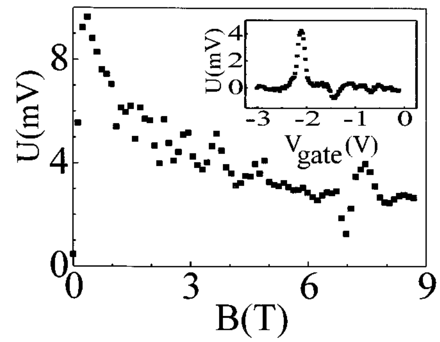

FIG. 2. The amplitude of the signal U as a function of the magnetic field B. The insert shows the amplitude of the signal U as a function of the gate voltage V_{gate} at $B=4.16$ T.

rise of the applied current pulse and the maximum of the response peak is also dependent on the magnetic field. As can be seen from Fig. 1, in high magnetic fields the sample response has the form of a wide peak similar to the smeared derivative of the exciting pulse. The shape of the signal and the time delay $\Delta\tau$ do not change when the magnetic field direction is reversed.

The amplitude of the maximum in the sample response as a function of magnetic field is shown in Fig. 2. We observe a signal even for very low magnetic fields. The signal amplitude rises with increasing magnetic field reaching a maximum at a field of ≈ 0.5 T. In high magnetic fields the amplitude of the signal decreases with increasing field.

The time delay between the rise of the exciting pulse and the maximum of the sample response $\Delta\tau$ increases with increasing magnetic field, exhibiting plateau-like structures at filling factors $\nu=4$ and $\nu=2$ (see Fig. 3). The dependence of $\Delta\tau$ on B is far from linear.

Let us first discuss the amplitude and the shape of the received signal. The azimuthal electric field E in the 2DEG near the ''pulser'' is produced both due to the finite resistance of the metallic loop (in our case $R\approx 10\ \Omega$) and due to the time variation of the magnetic flux through the ''pulser'':

$$E=\frac{1}{2l+\Delta}\left[IR+\frac{\mu_0}{\pi}\left(l\ \ln\frac{\Delta}{w}\right)\frac{dI}{dt}\right], \qquad (2)$$

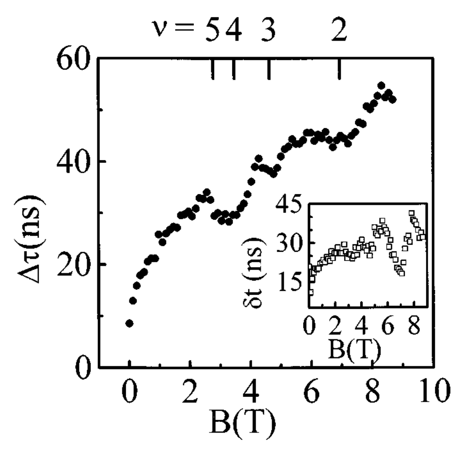

FIG. 3. The time delay $\Delta\tau$ of the signal as a function of the magnetic field B. The insert shows the full width at half maximum of the signal δt as a function of the magnetic field B.

where I is the current through the pulser. This field has to be screened by edge charge transferred by dissipative conductivity in the 2D layer, but in our system there are two mechanisms diminishing the screening: (i) The Maxwell time defining the time interval in which screening is ineffective $\tau_M = \epsilon l/\sigma_{xx}$ is relatively high, $\tau_M = 10^{-8}$ s, (ii) The charge accumulated at the edge of the sample is moving along the edge with EMP velocity. In a 2D electron system with $\sigma_{xx} \ll \sigma_{xy}$ we can neglect screening completely. The azimuthal electric field produces a Hall current in the 2DEG directed towards the edge of the etched area. If the velocity of the EMP in the gated sample part is smaller than that in the ungated part, the whole charge collected at the edge during the time $\Delta\tau$ should be transferred by the EMP to the detector during the same time. The current along the edge near the detector loop is equal to $I^d = \sigma_{xy} E(l+\Delta)$. In accordance with Eq. (2)

$$I^d \approx \frac{1}{2}\,\sigma_{xy} R_0^{-1}\left[R V_{\rm in} + \frac{\mu_0}{\pi}\left(l \ln \frac{\Delta}{w}\right) \frac{dV_{\rm in}}{dt}\right]. \qquad (3)$$

Here we have supposed that the current I in the pulser is given by the resistance R_0.

As a result, the induced voltage in the detector $V_{\rm out}$ is approximately

$$V_{\rm out} \approx \frac{\mu_0}{4\pi}\,\sigma_{xy} R_0^{-1}\left(l \ln \frac{\Delta}{w}\right)\left[R\,\frac{dV_{\rm in}}{dt} + \left(l \ln \frac{\Delta}{w}\right) \frac{\mu_0}{\pi}\,\frac{d^2 V_{\rm in}}{dt^2}\right] = \alpha V_{\rm in}. \qquad (4)$$

We suppose here that $dV_{\rm in}/dt$ is equal to $(1/\tau)V_{\rm in}$ and $(d^2V_{\rm in})/dt^2 = (1/\tau)^2 V_{\rm in}$, where τ is the rise time of the pulse. This very optimistic evaluation gives for our sample dimensions, $\tau \approx 10$ ns and $\sigma_{xy} = \nu(e^2/h)$:

$$\alpha \approx 2\nu \times 10^{-7}, \qquad (5)$$

where ν is a filling factor.

We would like to mention that there exists also capacitive coupling between the metallic loops and the EMP. Evaluating the α for this mechanism we have

$$\alpha = 4\pi\epsilon_0\,\frac{\Delta R_0}{\tau \ln^2(l/w)} \approx 10^{-5}, \qquad (6)$$

The transformation coefficient α in the case of capacitive coupling is independent of σ_{xy}.

We can conclude that in relative low magnetic fields, where σ_{xy} is high enough, we have pure inductive coupling, in high magnetic fields the capacitive coupling gives observable contribution to the output signal.

Such a picture is consistent with our experimental results, depicted in Fig. 2, where the magnetic field dependence of the output signal amplitude is qualitatively similar to that of σ_{xy} up to the field ≈ 6 T. In high magnetic fields the amplitude saturates in contrast to σ_{xy}. The coefficient α obtained from Eq. (4) is consistent with the sensitivity of our experimental setup while α obtained from Eq. (6) is one order greater than that we see in the experiment. This arise from very crude estimation of α in the case of capacitive coupling due to existence of capacitances not only between the pulser and the 2DEG but also between the pulser and the surrounding conductors.

The shape of the signal according to Eqs. (4)–(6) is expected to be similar to the sum of the smeared first and second derivatives $(dV_{\rm in})/dt + (d^2V_{\rm in})/dt^2$. In our experiment we see that in high magnetic fields it is more similar to the first derivative, in low magnetic fields a contribution of the second derivative can be observed (see Fig. 1).

Let us discuss now our experimental findings which can be attributed to the influence of the imaginary part of the longitudinal conductivity σ_{xx} on the group velocity of the EMP. We observe the EMP in a very wide interval of magnetic fields due to the fact that our experimental technique allows us to detect even strongly attenuated EMPs. The dependence of the time delay $\Delta\tau$ (proportional to the inverse group velocity) as a function of B is depicted in Fig. 3. According to Ref. 1 the frequency of the EMP is given by

$$\omega(q) = -\frac{2\pi q \sigma_{xy}}{\epsilon}\,(d l_0^{-1})^{1/2} - \frac{i}{2\tau^*}, \qquad (7)$$

where τ^* is the elastic scattering time. We expect a decrease of Im(σ_{xx}) in the quantum Hall regime and an increase at low magnetic fields. Therefore we can interpret both the oscillations of $\Delta\tau$ at filling factors $\nu = 2,4$ and the deviation of the $\Delta\tau(B)$ dependence from a straight line as a result of the Im(σ_{xx}) contribution to the group velocity.

Moreover we observe a narrowing of the response peak at filling factors $\nu = 2,4,6$ (see inset to Fig. 3). The narrowing means that the EMP dispersion decreases when the Fermi energy lies within the gap of the 2DEG spectrum. This fact is in good agreement with previous observations[4] that in gated structures at integer filling factors the EMP is dispersionless. As seen from Fig. 3 we clearly observe dispersion when the density of states has a maximum.

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