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1995 J. Phys.: Condens. Matter 7 L435

(http://iopscience.iop.org/0953-8984/7/32/003)

J. Phys.: Condens. Matter 7 (1995) L435–L443. Printed in the UK

LETTER TO THE EDITOR

The propagation of low-frequency edge excitations in a two-dimensional electron gas in the IQHE regime

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Received 15 May 1995

Abstract. Recent theoretical studies predict a rich spectrum of edge excitations in a 2DEG in the QH regime. Experimental verification of the theory is hindered by the fact that many of these excitations are uncoupled (neutral) or weakly coupled with an external alternating electric field. We discuss the use of gates for the mutual transformation of coupled and uncoupled excitations with an external field in IQH regime. This process provides a method for the excitation and detection of neutral edge excitations. We report results of the first experimental study of the transmission of edge excitations through a gate-induced potential barrier. A strong oscillatory dependence of the magnitude of transmitted edge magnetoplasmons as a function of the gate voltage was observed. Results of an experiment with two gates in series, where one gate was intended to be the source and the second to be the detector of a neutral edge excitation, give evidence that more than one type of edge excitation can propagate along a 2DEG edge. We discuss our data in terms of existing models of low-frequency edge excitations.

The influence of edge states on the transport properties of a 2DEG in the IQHE regime has been studied intensively in the last decade. These studies resulted in a picture of edge channels (ECs) separated by a distance much longer than the magnetic length, thus allowing adiabatic transport, a consequence of the smooth boundary potential in actual 2DEG devices [1].

Recently, the dynamical properties of the edge states in 2DEGs have attracted much attention [2–9]. A microscopic theory of low-frequency edge excitations (EEs) in 2DEGs was formulated by Wen [2] showing that EEs provide a practical realization of chiral Luttinger liquids. In general, the quantum Hall state can support several branches of EEs, the number of branches being dependent on the internal structure of the bulk state [2]. In the IQH regime, the number of branches is equal to the bulk filling factor ν; the situation in the FQH regime is more complicated. It was shown [2], for example, that the $\nu = \frac{1}{3}$ fraction supports a single branch of EEs while for the hierarchical $\nu = \frac{2}{3}$ quantum Hall state, there exist two branches [2, 4, 8]. EEs can be thought of as interactive charge density waves propagating along strips, the ECs, parallel to the edge. Each EE branch is specified by relative magnitudes and phase shifts between charge oscillations in different ECs. There is one branch corresponding to the in-phase vibrations of charge in all the ECs; this is an edge magnetoplasmon (EMP) [5, 10–15]. Following [11], we will refer to all EEs except the EMP as nonequilibrium EEs, because they disturb the local equilibrium at the edge. As a simple example, we consider the EE spectrum for the $\nu = 2$ quantum Hall state. In this case there are two ECs and two branches of EEs [2, 5, 8]. One is the EMP branch and the second describes the nonequilibrium EEs which correspond to the out-of-phase vibrations of charge

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in the two ECs. These vibrations are of the same magnitude [2, 5] so at each position on the edge, the net charge associated with the nonequilibrium EE is zero. For this reason, the nonequilibrium EE is uncoupled with an external alternating electric field and is neutral. This situation is typical for other integer and fractional quantum Hall states; the nonequilibrium EEs are usually uncoupled (neutral) or weakly coupled with an external field [2, 4, 5, 8]. It is thus difficult to observe nonequilibrium EEs. The damping of nonequilibrium EEs is much stronger than that of the EMP because of the charge exchange between neighbouring ECs. This provides, another difficulty for the experimental detection of nonequilibrium EEs. It is interesting to note that EEs are also predicted in two-dimensional magnetically induced Wigner crystals and provide an alternative method for establishing this state [9].

In this letter we study, experimentally, the propagation of EEs through regions with filling factors different from that of the rest of the 2DEG. These regions are defined by gate-induced potential barriers. The study is motivated by the possible use of a gate-controlled inhomogeneity for the transformation of one EE into another EE. EEs which are coupled with an external field can be easily excited and detected. Thus, the mutual transformation of coupled and uncoupled (neutral) EEs with an external r.f. field can provide a tool for the excitation and detection of neutral EEs. The transformation of EEs is illustrated in figure 1 for the case of an IQHE state with filling factor $\nu = 2$, the inhomogeneity being a strip with $\nu^* = 1$. In figure 1 the incident wave is considered to be an EMP corresponding to unit magnitude of charge oscillations in the ECs. The deflection of the 2nd EC (figure 1) results in that immediately after the strip there is an unequal population of ECs. For simplicity, we assume that only the 1st EC carries charge immediately after the strip, as it would in the d.c. case. The unequal population of the ECs means that the excitation propagating after the strip is not just an EMP, but must be considered as a superposition of all EEs existing at a given filling factor. For $\nu = 2$ only two EEs (the EMP and the neutral nonequilibrium EE) may propagate along the 2DEG boundary, so for situation shown in figure 1, a distribution of charge at $x > 0$ is given by

$$\begin{vmatrix} Q_1(x,t) \\ Q_2(x,t) \end{vmatrix} = \frac{1}{2}\begin{vmatrix} 1 \\ 1 \end{vmatrix} \exp(ik_1x - i\omega t) + \frac{1}{2}\begin{vmatrix} -1 \\ 1 \end{vmatrix} \exp(ik_2x - i\omega t). \qquad (1)$$

The first term is the EMP and the second is the nonequilibrium EE. $Q_{1(2)}$ is the charge modulation on the first (second) EC, $k_i = k_i(\omega)$ are the wavevectors of the EEs. Factors $\frac{1}{2}$ in (1) are taken to reflect the initial charge distribution among the ECs at $x = 0$. In this example, the strip effectively serves as the source of a neutral EE. Conversely, if a neutral EE is incident on the strip, it will be partially transformed into an EMP, and could therefore be detected.

Gate-induced potential barriers are widely used for the creation and detection of the nonequilibrium population of ECs [16–18]. The idea of using gates for excitation and detection of nonequilibrium EEs is prompted by the close relation between these EEs and d.c. adiabatic transport [16–18]. The essential common feature is that the local equilibrium at the edge is disturbed. However, in the d.c. case, the initial nonequilibrium population of ECs would be kept forever if equilibrium processes are neglected, while under r.f. measurement conditions, an oscillating charge in one EC induces a charge density wave in another, so that the distribution of charge between ECs changes along the sample edge (see (1)). Direct charge transfer between adjacent ECs towards equilibrium population is responsible for the violation of d.c. adiabatic transport and for the damping of nonequilibrium EEs. The results of d.c. experiments [16–18] allow us to estimate the mean free path of nonequilibrium EEs to be of the order of several hundred microns.

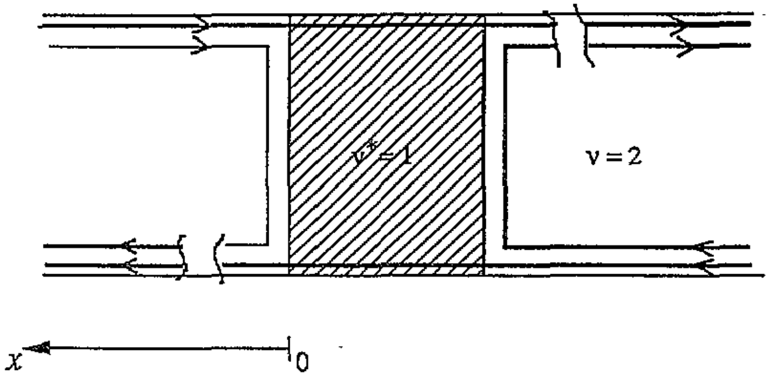

Figure 1. Schematic illustration of the transformation of the EMP incident on the strip with filling factor different from that of the rest of the 2DEG. The ECs carrying the charge density waves are shown in bold.

We would like to stress that whilst according to EC model of EE [2, 4, 5, 8], the EMP charge is concentrated in the ECs, the Hall current driven by the electric field of this charge flow in the 2DEG bulk. Therefore two processes contribute to the EMP velocity: the drift of the edge charge due to the confining potential and charge transfer from one part of the edge to another via the bulk by the Hall current. The ratio of these currents can be easily probed experimentally by changing the dielectric environment (that changes only the Hall current) and monitoring the corresponding change in the EMP velocity. These experiments [19] show that the edge current is insignificant when compared with the bulk Hall current. As the EMP wavelength is much longer than an edge depletion width then, within the framework of the ECs model, the distributions of the EMP potential and Hall current in the direction perpendicular to an edge are similar to those across a Hall bar in typical d.c. measurements [20]. Having accepted the EC model of EMP, one can conclude that in d.c. magnetotransport measurements, the contribution of the bulk current to the total current is significant. This conclusion is in agreement with recent calculations of edge (i_e) and bulk (i_b) direct currents in the QH regime [21, 22], where it was found that $i_b \approx i_e$ for sharp [21] and $i_b \gg i_e$ for smooth [22] boundary potentials. Of course, as far as Hall resistances are concerned, it is convenient to use the Buttiker formalism [1] and attribute the whole current to ECs.

The velocities of the nonequilibrium EEs may be determined to a much greater extent by the edge current, because charges in different ECs set up fields which compensate each other in the 2DEG bulk. If electron–electron interaction is assumed to be short-ranged, screened by a ground plate (this situation was considered in 2, 4]) then the bulk current does not influence the EEs velocities.

It should be pointed out that a different picture of EEs in 2DEGs, which does not employ the concept of the ECs, exists [7, 23, 24, 25]. The 2DEG is described by local bulk conductivities σ_{xy} and σ_{xx} and the boundary potential is assumed to be infinitely sharp [19, 20]. In this model, only one branch of excitations associated with the 2DEG boundary, the edge magnetoplasmons, was found. If the boundary potential is assumed to be smooth, then the local classical description of the 2DEG gives rise to additional 'acoustic' branches of EEs [7, 25]. The new acoustic EEs correspond to a distribution of the edge charge which oscillates across the transient strip where the boundary potential varies. It means that the acoustic modes violate the local equilibrium inside the boundary depletion strip. The time for establishing the local equilibrium inside the depletion region can be estimated from the effective conductivity (σ) across this region and the region width (w) as $t = w/\sigma \propto 10^{-12}$ s for $\sigma = e^2/h$ and $w = 1$ μm. For this reason, the acoustic modes hardly survive in the r.f. range. In contrast to this, the EC model of EEs suggests that the local equilibrium inside each EC is firmly established at any moment in time but there is no equilibrium between different ECs. The estimation of the damping of the nonequilibrium EEs within this model [5] relies on the results of d.c. adiabatic transport experiments [16–18].

The sample design and experimental technique used is illustrated in figure 2. EMPs are launched with the help of coaxial cables connected to metal electrodes (E1, E2) evaporated on the substrate close to the 2DEG mesa. Detection of EEs was made using electrode E3 connected by a coaxial cable to the receiver. Two large ohmic contacts (Oh1 and Oh2) served as absorbers of EEs. The absorbers play an essential role by ensuring a travelling wave regime for EEs. This regime is suitable for the study of EEs which are expected to decay sufficiently strongly.

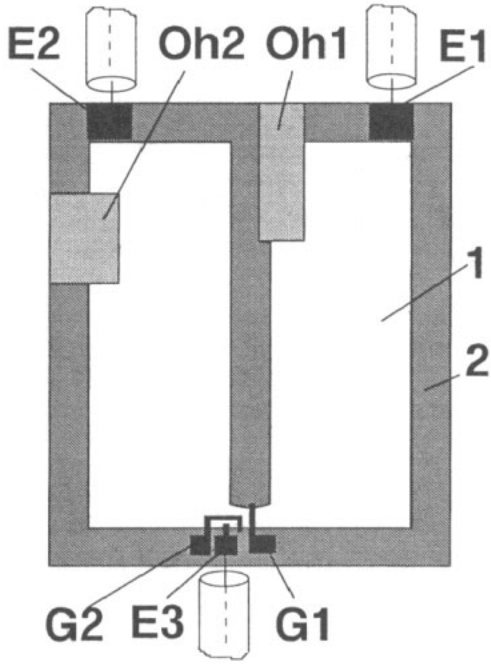

Figure 2. Schematic of the sample. 1—2DEG mesa, 2—substrate, E1, E2—exciting electrodes, E3—receiving electrode. Oh1 and Oh2 are grounded ohmic contacts. The distance between gates G1 and G2 along 2DEG boundary is 200 μm. The gates width is 150 μm.

The typical r.f. voltage applied to E1 or E2 was 2 mV. Either a high-frequency lock-in amplifier or vector voltmeter was used as a receiver to measure both the magnitude and phase of the signal. The sample was fabricated on a GaAs–AlGaAs heterostructure with a carrier density of 3.5×10^{11} cm^{-2} and mobility of 10^6 cm^2 V^{-1} s^{-1}.

The signal amplitude and phase as functions of magnetic field are shown in figure 3. The voltages on G1 and G2 were slightly positive (+0.2 V) to compensate for the initial depletion due to metal deposition. A signal is seen only for the direction of B that corresponds to EMP propagation from E1 to E3. For the opposite direction of B the EMP goes from E1 to

Ohl and is absorbed. The unidirectional nature of EMP propagation has been appreciated in theory for a long time and observed in [13], but the inset in figure 3 is the first demonstration of how the effect develops with a magnetic field. We note that the signal is seen to disappear at surprisingly low values of negative B. The magnitude and phase of the signal in figure 3 are measures of the damping and velocity of the EMPs respectively. The maxima in the magnitude in figure 3 take place at integer ν values because EMP damping is minimal in the QH regime [10–13, 15].

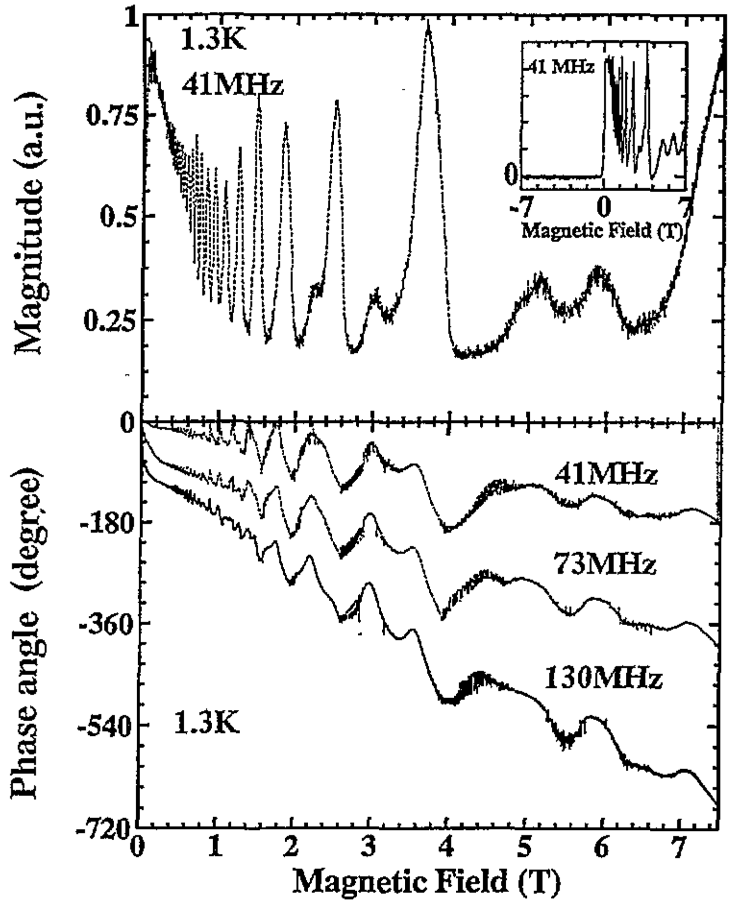

Figure 3. Magnetic field dependences of the magnitude and phase of the signal. Exciting electrode—E1. R.f. magnitude applied to E1 is 2 mV. Inset: the magnitude versus magnetic field for both directions of the field.

The phase can be expressed as

$$\phi = -\left[\frac{L\omega}{v(B)} + \phi_0(B,\,\omega)\right]$$

where L (= 1.5 cm) is the distance between E1 and E3 along the 2DEG edge (figure 2), $v(B) \propto B^{-1}$ is the EMP velocity [15] and ϕ_0 describes a possible phase shift between the EMPs and the external exciting electric field. The negative sign reflects the phase lag between the received signal and the reference. From the data in figure 3, the EMP velocity is estimated to be 10^8 cm s^{-1} for $\nu = 2$. This value and oscillations of ϕ near integer filling factors are in agreement with previous measurements made by a different technique [15].

The experimental dependences of the signal on the voltage on G1 for different values of ν are presented in figure 4. The curves retain the similar shape in the frequency range used (from 10 to 130 MHz). We have also studied the reflection of EMPs from the potential barrier induced by G1 by launching the EMPs from electrode E2. As the bias on G1 became more negative, an increasing signal was detected on E3. The signal displayed similar 'oscillations' to those shown in figure 4.

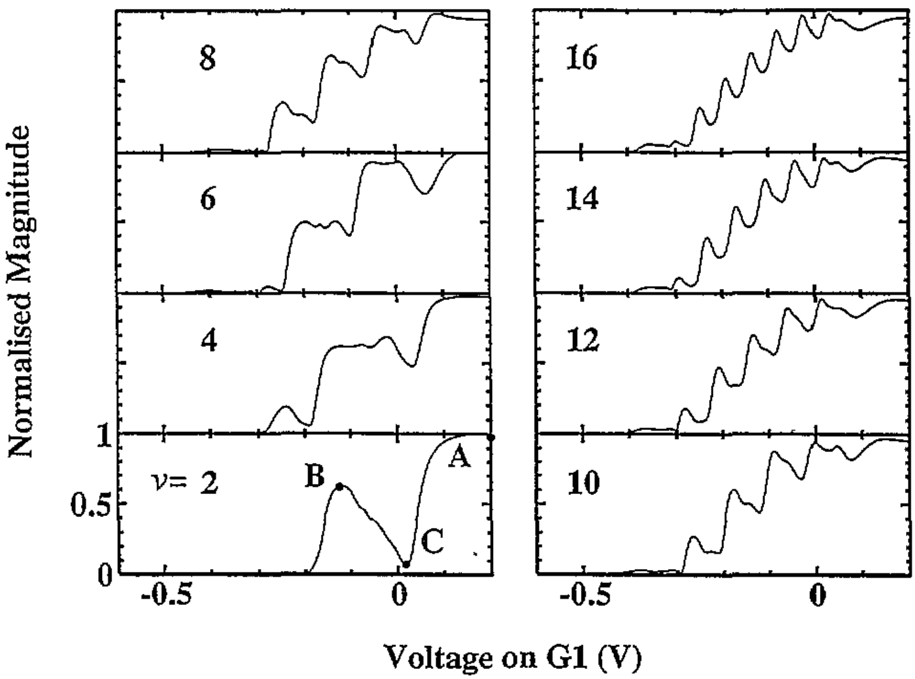

Figure 4. Magnitude of the signal at E3 as a function of voltage on gate G1 for different integer filling factors. Exciting electrode—E1; frequency—41 MHz; temperature—0.3 K.

Unfortunately, at present there is no theory describing the propagation of EEs in a 2DEG containing domains with different filling factors, neither within the classical electrodynamical approach, nor within the EC model. Without quantitative theory it is difficult to understand the rather complicated shape of the curves in figure 4. From the point of view of the EC model the 'oscillations' seen on the curves are evidently due to the deflection of the next EC. For $\nu \leqslant 12$ the curves resolve the deflection of ECs which differ only in electron spin orientation.

To detect the process of the mutual transformation of EEs, we have performed an experiment with two gates (G1 and G2) in series. Figure 5 shows the dependence of the signal on G2 voltage for biased G1 for $\nu = 2$. Here we use the term 'bias' to refer to the deviation of a gate voltage from the initial setting +0.2 V. Curves 1 to 3 in figure 5 correspond to biasing of G1 shown by points A, B and C in figure 4 respectively. In this experiment, the biased G1 was intended to be a source of neutral EE due to the partial transformation of the incident EMP. This neutral EE should then be partly transformed into an EMP by G2 and therefore detected. The main result of figure 5 is that *normalized* curves have a different shape. This does not seem to allow explanation by any theory which predicts only one branch of EE. If we assume that only EMP can propagate along the edge then the only difference gate G1 can make is to change the magnitude of the EMP incident on G2. This means that normalized curves in figure 5 should all have identical shape, provided that (i) the measurement is carried out in the linear regime so there is no dependence of the normalized signal on r.f. power, and (ii) the magnitude of the EMP incident on gate G2 is kept constant whilst the voltage on G2 is being swept. All the reported data were taken at r.f. power levels well below that at which nonlinear effects appear. The second condition is held if there is no EMP wave reflected back from G2 towards G1 and then reflected back from G1 towards G2. This EMP interference process would result in a dependence of the normalized signal on G1 bias, but it is prohibited by the unidirectional nature of EMP propagation. In [13], in the time domain measurement, the propagation of EMP pulse was studied with exciting and detecting electrodes separated by distance of 50 and 100 microns. No signal was observed for the direction of magnetic field which does not allow the EMP propagation between the electrodes. It is therefore safe to consider that in our experiments with 200 microns separation between G1 and G2, the magnitude of any EMP signal reflected from G2, and thus reaching G1, is negligible.

If we admit that more than one type of EEs can exist, then the difference between the curves in figure 5 can be attributed to the different distribution of the r.f. power among these EEs. We shall explain this in terms of the EC model. Within the framework of the EC model, there are two branches of EEs at $\nu = 2$ and the difference between the curves in figure 5 is due to different fractions of the EMP and the neutral EE propagating after G1. For the nominally unbiased G1 (+0.2 V on G1), the EE incident on G2 is the EMP. The voltage on G2 transforms the EMP into two EEs (EMP and the neutral EE) and this influences the shape of curve 1 in figure 5. However, what is important now is that the shape of curve 1 corresponds only to an EMP incident on G2, and therefore this curve can be considered as a ‘fingerprint’ of an EMP. When G1 is biased, both EMP and neutral EE propagate after G1. The neutral EE can induce a signal at E3 because it is partially transformed into an EMP by G2. This transformation (illustrated by icons in figure 5) can be understood in the same way as that shown in figure 1. So, the signal at E3 for biased G1 can be viewed as a superposition of two signals induced separately by two incident waves (EMP and neutral EE) on G2. The data in figure 5 allow us to extract the signal induced by the nonequilibrium EE. Let us consider curve 3 in figure 5. For the nominally unbiased G2 (+0.2 V on G2), the nonequilibrium EE incident on G2 does not induce a signal because it brings a zero net charge under E3 (see the right icon in figure 5). So the signal at $V_{G2} = +0.2$ V is completely due to the EMP incident on G2. If there were no nonequilibrium EE incident on G2 then the dependence of the received signal on G2 voltage would coincide with curve 1 in figure 5. Neglecting possible phase shifts between the signals induced by the EMP and the nonequilibrium EE, we can consider a difference between curves 3 and 1 (shown in the inset in figure 5) as a signal caused by the nonequilibrium EE. This signal maximum occurs when one EC is deflected (see the middle icon in figure 5), whilst an undeflected EC brings a nonzero charge under E3. As it is seen from figure 5, the difference between curves 3 and 1 is several times larger than that between curves 2 and 1. According to our interpretation, it means that biasing G1 at point C in (figure 4) results in a more effective transformation of the EMP into a neutral EE than biasing G1 at point B.

It should be noted that the gates' metallization (figure 1) strongly disturbs the propagation of EEs under the gates. In [5, 14, 15, 19] it was shown that a metal surface

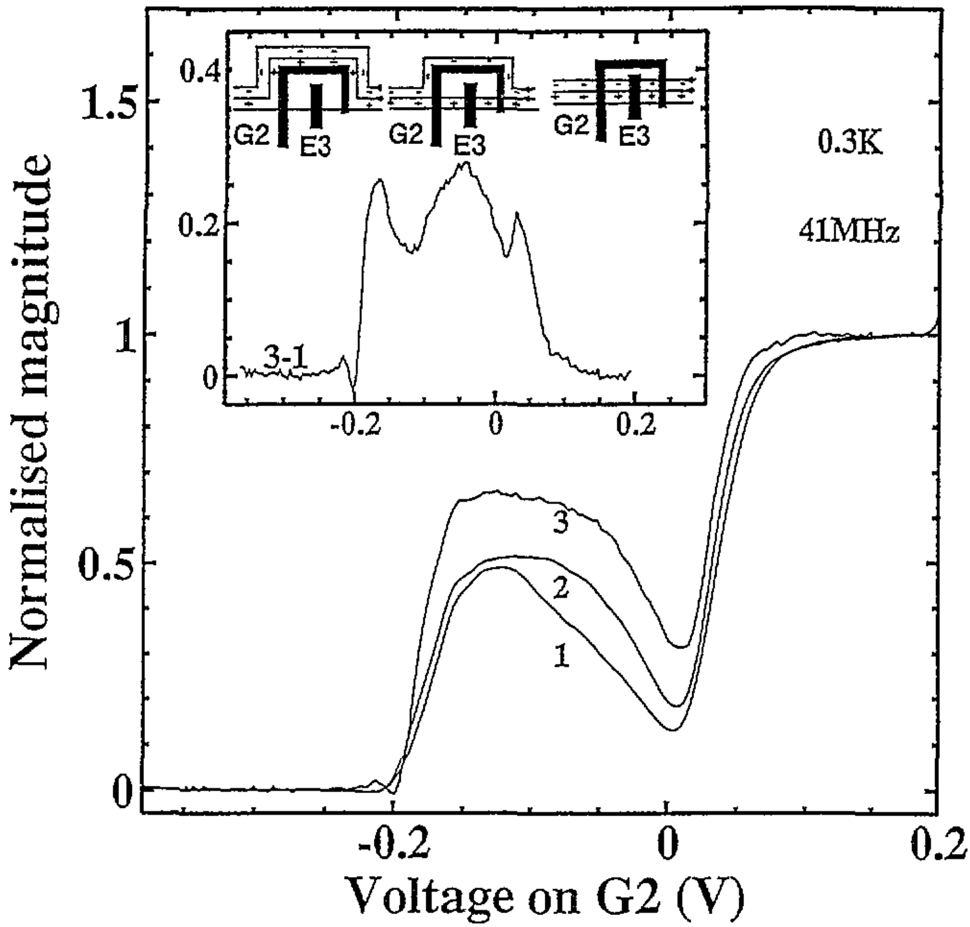

Figure 5. Magnitude of the signal at E3 as a function of voltage on gate G2. Curves 1, 2 and 3 correspond to biasing of G1 as shown by points A, B and C in figure 4, panel $\nu = 2$ respectively. Frequency —41 MHz; temperature 0.3 K. Inset: the curve is the difference between curves 3 and 1. The icons illustrate how the neutral EE incident on G2 can induce a signal on E3. The signal appears when one EC is deflected and an undeflected EC brings a nonzero net charge under E3. This process can be viewed as partial transformation of the neutral EE into an EMP by G2 (see text). Note that + and − signs represent only that part of the edge channel's charge modulation which is due to the neutral EE (see (1)).

close to a 2DEG decreases the EMP velocity. Nevertheless, we would like to stress that the crucial point in the discussion above is that whether one or several types of EEs can propagate along a *regular undisturbed* 2DEG edge (between gates G1 and G2). For this reason, the gate metallization itself cannot explain the *difference* in shape of the curves in figure 5.

At present is is not clear whether any classical description of a 2DEG can explain the data in figure 5. This question requires further experimental and theoretical work. The needed additional EEs, different from the EMP, could be the 'acoustic' modes described in [7, 21]. These modes however should be able to survive over the distance between gates G1 and G2 in order for them to be detected. An estimation of the damping of the acoustic modes was made in [7] using the assumption that dissipation does not affect the charge distribution in these modes. This is not the case in r.f. range.

In summary, we have presented for the first time, experimental data about the propagation of edge excitations in a 2DEG through domains with a different filling factor from that of the rest of the 2DEG. We found that the experimental data allow qualitative explanation within the framework of edge channel model [2–5, 8]. This explanation assumes that the propagation of the edge magnetoplasmon through a domain of different filling factor is controlled by the number of edge channels in the domain, and is accompanied by the partial transformation of the edge magnetoplasmon into a neutral edge excitation.

This work was supported by SERC. D A Ritchie wishes to acknowledge the support of Toshiba Cambridge Research Centre.

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