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Effect of slow interface states on the quantum Hall effect

D. A. Syphers
Physics Department, Brown University, Providence, Rhode Island 02912

K. C. Woo
Physics Department, University of Illinois—Chicago, Chicago, Illinois 60680

P. J. Stiles
Physics Department, Brown University, Providence, Rhode Island 02912

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We have investigated the effects of slow interface states in Si metal-oxide-semiconductor field-effect transistors on the quantum Hall effect. These states, which are positively charged when empty, cause shifts in threshold voltage and induce changes in the quantum Hall effect. The observed changes include a widening of the spin and Landau quantum Hall plateaus as well as structure in ρ_{xx} and ρ_{xy} at fractional filling factors. The strength of the structure is seen to increase as more interface states are emptied. We have drifted a small number of sodium ions to the interface and observed a change in the character of the Landau-level oscillations to the more usual one. The structure returns upon reversing the drifting procedure. The fractional structure is compared with the fractional Hall step observed in the intrinsic InAs-GaSb system where holes provide compensating charge at the interface. The role of interfacial positive charge in the formation of new structure in the quantum Hall effect is discussed.

Slow interface states are commonly associated with the negative bias temperature instability[1] where a large negative gate bias is kept on the device while at high temperatures. The threshold voltage shifts following emptying of slow interface states due to negative gate bias are in the opposite direction of shifts due to sodium (or other positive ion) drifting. The samples we used for these experiments were found to have slow interface states as a result of processing. The time constants of these states were of the order of 10–60 s at liquid-helium temperatures. The samples used were Si Hall bar metal-oxide-semiconductor field-effect transistors (MOSFETs) with peak mobilities of about 9000 $cm^2/V\,s$ and an oxide thickness of about 800 Å.

The threshold voltage shifts can be seen in the plot of ρ_{xx} vs V_g at 8 T, as shown in Fig. 1. After an initial threshold shift, a close look shows that the threshold voltage creeps upward during a gate voltage sweep as a result of repopulation of the slow states. Changes in the structure of both the ρ_{xx} and ρ_{xy} curves are seen following the emptying of the slow states, particularly in the higher-spin split Landau levels. The effect of sodium drifting on ρ_{xx} and ρ_{xy} is shown in Figs. 2(a) and 2(b) where 2(a) shows ρ_{xx} vs V_g following sodium drifting. It can be seen that the curve of ρ_{xx} vs V_g has a more usual appearance following drifting. However, ρ_{xx} does not go to zero at the minima indicating either a much worse mobility or greater degree of inhomogeneity. The effect on ρ_{xy} is seen in Fig. 2(b) where ρ_{xy} is smaller than would be expected after drifting of sodium. A comparison between the curves shows that ρ_{xx} is considerably smaller for the higher-spin split levels in the original state of the samples before drifting. The ratio of $\rho_{xy}/\rho_{xx}(=\omega_c\tau)$ is higher in the case before drifting. It is not clear whether this is just due to the fact that ρ_{xy} is smaller after drifting due to poor mobility or scattering, or whether it is due to the existence of more localized states or some collective behavior. Following the sodium drifting, the sample was put under negative gate bias at 1.9 K to see if there were any slow states available to be emptied. No detectable shift was observed. After reversing the sodium drifting procedure, the slow states are again able to be emptied and shift the threshold voltage.

Another effect of emptying these slow interface states can also be seen in Fig. 1. Electrons in the lowest-spin and valley split level that were previously strongly localized and liberated following the emptying of the slow states. This can be seen by looking at where the onset of signal in the ρ_{xx} curves takes place. This is somewhat surprising when compared to the effect of drifted sodium ion charge at the interface which has the opposite effect of localizing more electron states.[2]

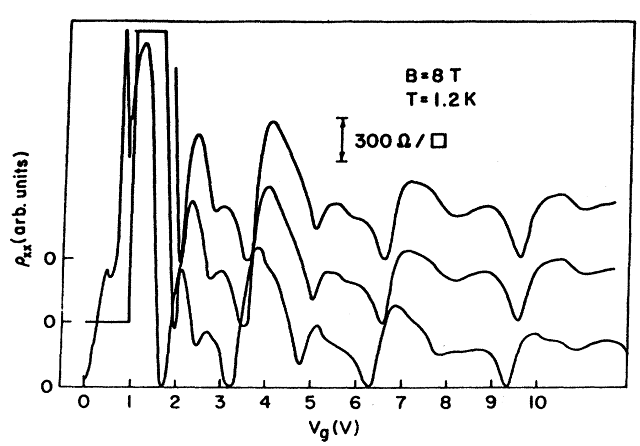

FIG. 1. Longitudinal resistivity as a function of gate voltage in the presence of slow interface states.

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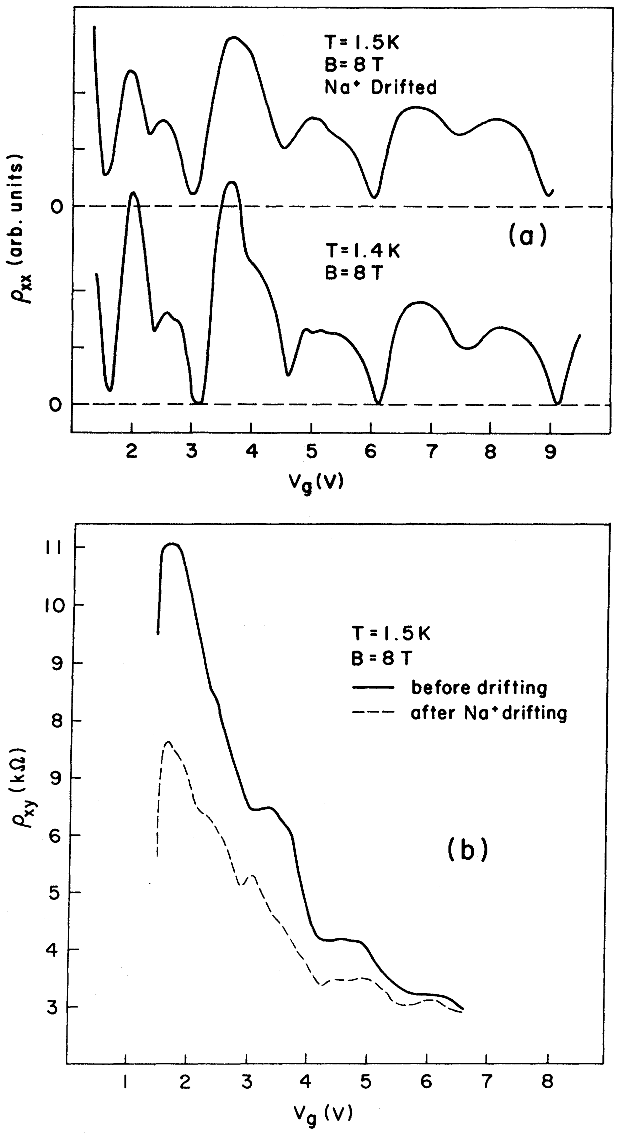

FIG. 2. (a) Longitudinal resistivity as a function of gate voltage before and after sodium drifting. (b) Transverse resistivity as a function of gate voltage before and after drifting.

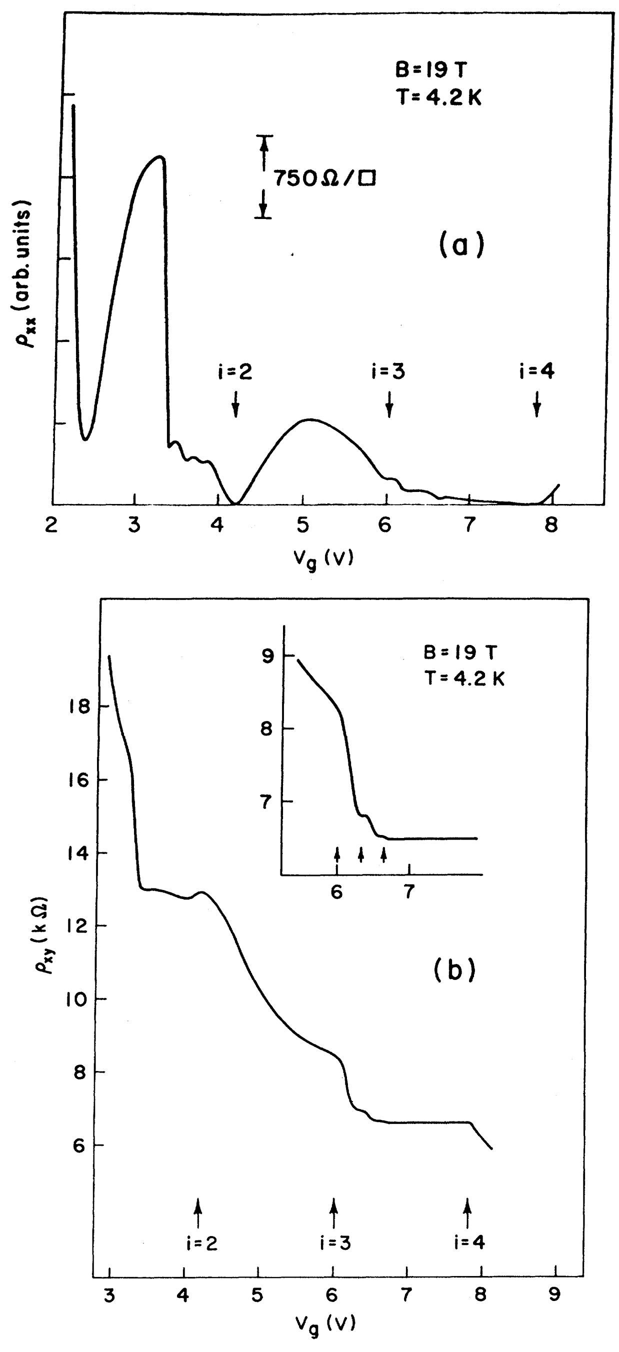

FIG. 3. Results at 19 T. (a) Longitudinal resistivity as a function of gate voltage. (b) Transverse resistivity as a function of gate voltage.

Experiments were done on these samples at high magnetic fields with some interesting results. Figures 3(a) and 3(b) show ρ_{xx} and ρ_{xy} versus the filling factor at 19 T. In this case the spin and Landau quantum Hall plateaus are considerably widened. The states that are localized for this widening come from the lower Landau level. The curve of ρ_{xx} versus the filling factor shown in Fig. 3(a) shows the second and fourth Landau level to be full of structure. In particular, the fourth Landau level has a series of small dips and peaks in ρ_{xx}. The first dip in ρ_{xx} occurs at a filling factor of 3.2 and is accompanied by a Hall step at a value of $h/(3.8e^2)$. The second dip in ρ_{xx} occurs at a filling factor of 3.4 and is accompanied by a Hall step at a value which is less than a few parts in 10^3 different from the $i=4$ quantized Hall step. For the rest of the fourth Landau level ρ_{xx} is very small and ρ_{xy} is equal to $h/4e^2$ to better than 1 part in 10^3. The inset in Fig. 3(b) shows an expanded scale of ρ_{xy} vs V_g for the fourth Landau level. The arrows in the inset indicate the positions of ρ_{xx} minima.

The amount of empty slow interface states depends on the sample history at room temperature just prior to cooling to liquid-helium temperatures. For the curves shown in Figs. 4(a) and 4(b) the sample was operated just prior to cooling and was cooled with a small positive voltage on the gate. Figure 4(a) shows ρ_{xx} versus the filling factor and V_g at 23 T and 0.6 K with the sample conditioned as described. Figure 4(b) shows the corresponding curve of ρ_{xy} versus the

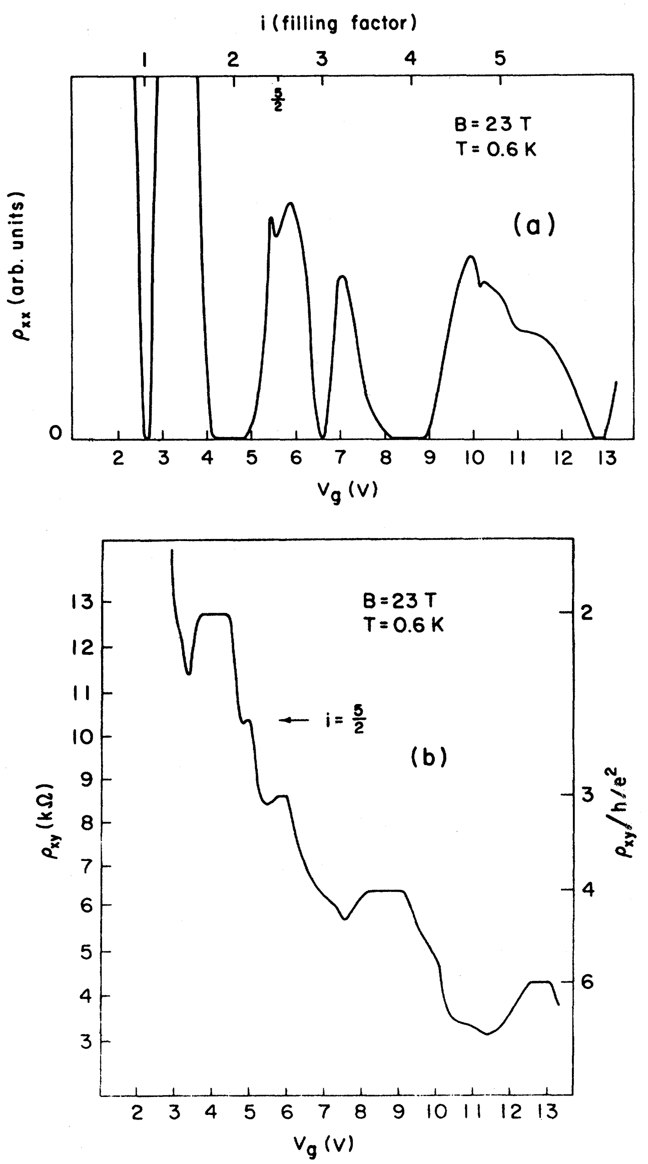

FIG. 4. Results at 23 T following change in density of interface states. (a) Longitudinal resistivity as a function of gate voltage. (b) Transverse resistivity as a function of gate voltage.

filling factor and V_g under the same conditions. Note the small structure in ρ_{xy} at a value of $h/(\frac{5}{2}e^2)$ accompanied by a dip in ρ_{xx} at a filling factor of $\frac{5}{2}$. This structure stays at the $\frac{5}{2}$ filling factor as the magnetic field is varied. The only other structure visible is in the fifth Landau level and is weaker. This is very similar to the results seen in the intrinsic InAs-GaSb system[3] where a Hall flat is observed at a filling factor of $\frac{5}{2}$ with the corresponding value in ρ_{xy} and is compared to our results in the discussion section. The small structure in our sample at a filling factor of $\frac{5}{2}$ is not seen at temperatures above 4.2 K and becomes stronger as the temperature is lowered to 0.6 K.

The slow states seen in these samples are a result of processing, but it is not clear what their exact origin is. They could in fact be due to a layer of sodium ions near but not at the interface and the slow nature of the states a result of tunneling between the inversion layer and these states. They do not have to be sodium ions, however; they only have to be positively charged. The fact that the structure disappears after sodium drifting does not necessarily mean that the initial states are due to sodium; the sodium could merely be screening the effects of another positively charged center. However, there is reason to believe that these slow states may be sodium related. The number of sodium ions drifted for the curve in Fig. 2 is less than $3\times10^{10}/\mathrm{cm}^2$ and the mobility of the device has dropped dramatically. Comparing this to data on sodium drifted samples[2] one would expect that drifting of such an amount of sodium to the interface from the gate would have two effects: The width of the Hall plateaus would increase and the mobility would decrease slightly. This is not consistent with our data and would indicate a layer of sodium ions near the interface as a likely candidate for the source of these slow states. Such a layer near the interface drifted a small distance would have a greater effect on mobility than would fewer ions drifted from the gate to the interface, due to greater potential fluctuation at the interface, even though both would cause the same shift in threshold voltage. This explanation of the origin of the slow states is also consistent with the fact that the drifting was done at room temperature where the ions will not move very far in a short time. Nonetheless, these slow states may be due to an entirely different result of processing than sodium contamination.

Anomalies of the type presented here could also be explained by a nonhomogeneous distribution of positively charged centers in the oxide. However, these anomalies were seen in all samples across the wafer, indicating a homogeneous distribution rather than some local distribution of states. Any other type of local nonuniformity could not account for the observed structure.

Our observation of a small Hall step at a filling factor of $\frac{5}{2}$ lends itself to a comparison with other observations of fractional quantum Hall steps. The fractional quantum Hall effect (QHE)[4,5] was recently discovered following much work on the integer QHE[6–10]. In the fractional QHE, Hall steps at filling factors less than 2 with only odd denominators have been observed in high mobility GaAs-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ samples. No structure at filling factors with even denominators has been seen in this system. There have been many recent theoretical attempts to explain these results.[11–13] These fractional steps appear to be an intrinsic collective effect to the two-dimensional (2D) electron system in the lower Landau levels at low temperatures. More recently, there have been observations of a higher fractional quantized Hall step in the system of electrons and holes in intrinsic InAs-GaSb structures.[3] This system exhibits a Hall step of value $h/(\frac{5}{2}e^2)$ at $f=\frac{5}{2}$ and a concurrent dip in ρ_{xx}, but it does not approach a zero ρ_{xx} state. Other structure is seen in the sixth Landau level in that system but not at other fractional filling factors. This is similar to our results, except that we have structure in the fifth Landau level not the sixth. The similarity between the systems is that in both cases there is positive charge near, but not too near, the interface. In our system, the effect disappears as a certain kind of additional positive charge is drifted to the interface. In the InAn-GaSb system the effect disappears when the 2D electron well is made thinner and thus closer to the positive charge. In any case, our observations confirm that higher fractional Hall steps are probably due to a different interaction than the fractional Hall steps in the high mobility

GaAs-$Al_xGa_{1-x}As$ devices. Further, we have observed Hall plateaus that do not correspond to the correct filling factor values where the ρ_{xx} dips occur. One set does have a complementary symmetry, a value for ρ_{xy} of $h/(3.8e^2)$ at a filling factor of 3.2, but the Hall step following it does not.

Most of our observed structure can be compared with two previous observations of anomalous dips in ρ_{xx} near a Hall flat[14,15] and may help to explain their data. In our case, as well as theirs, there are dips in ρ_{xx} on the lower Landau-level side of a zero ρ_{xx} state. In one case[14] the structure was observed to disappear following application of very high source-drain fields. This would not be surprising if there were positively charged states a short distance into the oxide so that a high source-drain field would reduce the tunneling barrier. Once such a state was filled it would not affect the conductivity.

In summary, we have shown that the existence of positively charged centers related to slow interface states causes anomalies in the Landau-level oscillations. These states can have the effect of widening the Hall plateaus, inducing fractional Hall structure, and liberating previously localized states in the lowest-spin and valley split level. The strength of the new structure increases as more interface states are emptied and a larger positive charge is induced near the interface. The origin of these slow states is not entirely clear, although there is strong reason to believe they are due to a layer of sodium ions near the interface as a result of processing.

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