A.C. Conductivity and the Electron Localization in Si MOS-FET under High Magnetic Fields

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There have been many studies of the electron localization in the 2-dimensional electron system in Si MOS-FET under high magnetic fields. We have investigated the Shubnikov-de Haas effect appearing in σ_{xx} by employing two new experimental means: measurements in pulsed high magnetic fields up to 37 T and a.c. measurements in the frequency range up to 50 MHz. Some new aspects of the localization are observed in these new experimental conditions which have not been attempted in previous works.

The samples used in the experiment were circular ones (Corbino disk) fabricated on the (100) surface on p-type substrates. Measurements of σ_{xx} for the d.c. and a.c. bias current accross the source-drain electrodes. In the a.c. measurements, the real part of σ_{xx} was measured using a phase sensitive detector. For measuring the Shubnikov-de Haas effect in pulsed magnetic field, the gate voltage was swept at the top of the pulsed fields within a time where the fields could be regarded as constant. A superconducting magnet was also employed for a more precise measurement below 15 T.

Fig. 1 shows a typical example of the experimental recordings of the Shubnikov-de Haas oscillation at various field strength. As the magnetic field was increased, the gate voltage width for the non-conducting region (σ_{xx} = 0) increased. In addition, a remarkable feature was observed for the peak associated with the lowest Landau level (0↑+). At H=6 T, the lowest peak (0↑+) was indiscernibly small. As the field was increased, however, this peak grew up, whereas the height of other peaks showed smaller field dependence. The magnetic field dependence of the (0↑+) peak can be accounted for by considering the increase of the density of states in the Landau level with increasing magnetic field as in the following.

Fig. 2 shows the magnetic field dependences of the height of the (0↑+) peak, $(\sigma_{xx})_{peak}$, and the number of immobile electrons n_{im} estimated from the gate voltage width where σ_{xx}=0 on the left sides of the (0↑+) peak. The figure also shows the total number of electrons which can be accomodated in the (0↑+) level, $n_t = eH/hc$. It can be seen that both n_{im} and σ_{xx} increase with increasing field. The line representing n_t crosses with that of n_{im} at H = 4.2 T, from where $(\sigma_{xx})_{peak}$ begins to be non-zero. This fact can be interpreted in terms of the mobility edge model.[1] The present result also indicates the localized states are formed only in the electron side of the (0↑+) level.

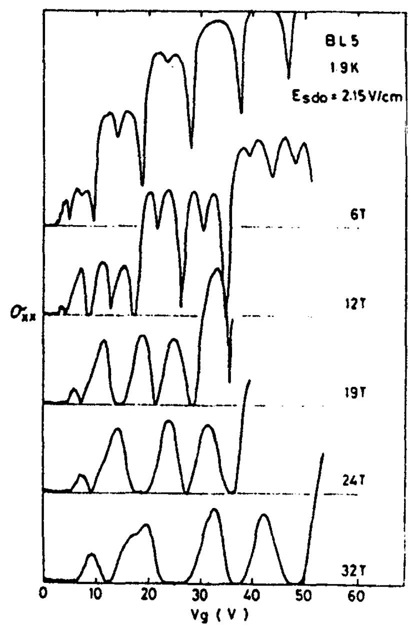

Fig. 1. Conductivity σ_{xx} as a function of gate voltage V_g for sample BL5.

The a.c. conductivity was measured in both pulsed fields and a steady field of 15 T.[2] Fig. 3 shows the Shubnikov-de Haas oscillation at 15 T for various frequencies. As is seen in the figure, each peak of the oscillation is more and more sharpened, as H increased. Namely, the non-conducting regions are widened, and the conductivity at the tail parts of

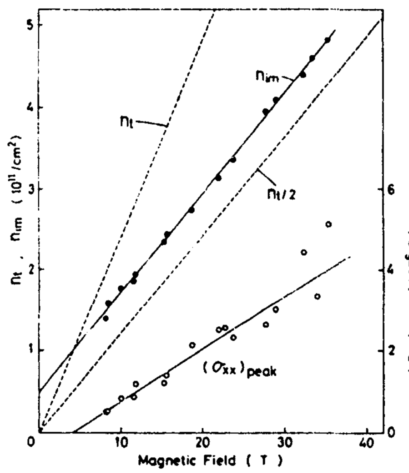

Fig. 2. $(\sigma_{xx})_{peak}$ for (0↑+) level, n_{im} and n_t as a function of magnetic field.

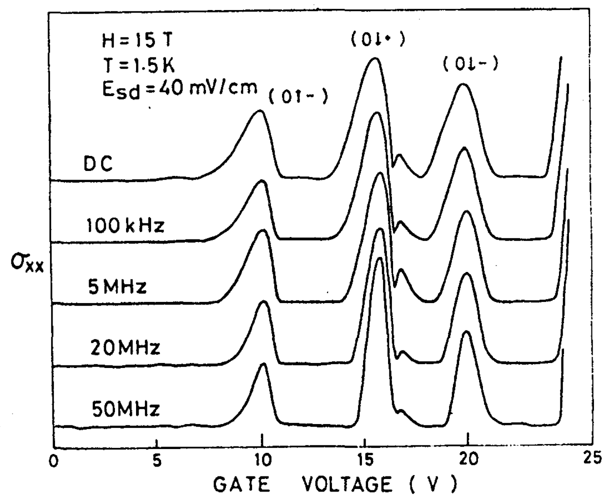

Fig. 3. Shubnikov-de Haas oscillation at various frequencies for sample BL5.

each peak is decreased relative to the peak value. In another words, the increase of the frequency looks equivalent to the decrease of the temperature. This striking feature can be seen more clearly in Fig. 4 and Fig. 5 which show the frequency dependences of the conductivity at the tail part of a Shubnikov-de Haas peak and the number of immobile electrons estimated from the gate voltage width of the non-conducting region. As is shown in Fig. 4, the conductivity in the tail parts varies obeying the Drude-type frequency dependence, $\sigma \propto 1/(1+\omega_c^2\tau^2)$. Fig. 6 shows the height of each peak at d.c. and 20 MHz as a function of the square of temperature. The temperature dependence of $(\sigma_{xx})_{peak}$ is T^2-like at high temperature region. However, $(\sigma_{xx})_{peak}$ for (0↑-) and (0↓-) decreases with decreasing temperature at lower temperature, indicating that the conductivity around the peak has also some localized character.

Considering that the conductivity in usual hopping conductions increases with increasing frequency, the present experimental result is quite surprizing because the frequency dependence is just opposite. The amplitude of the source-drain bias voltage is adjusted to take the same value for all the frequencies. Fig. 7 shows the number of immobile electrons n_{im} at 2 MHz as a function of the source-drain bias voltage. n_{im} starts to decrease abruptly at about 2 V/cm. The measurement was done at much lower E_{sd} than 2 V/cm. Therefore, the observed frequency dependence was not caused by any effect of the source-drain field. The characteristic relaxation time τ ($\sim 10^{-6}$-10^{-8}s) in the observed frequency dependence is many orders of magnitude larger than the relaxation time the carrier scattering. It is difficult to elucidate such a long relaxation time. The reason of the observed striking phenomenon is not clear at present. It might be

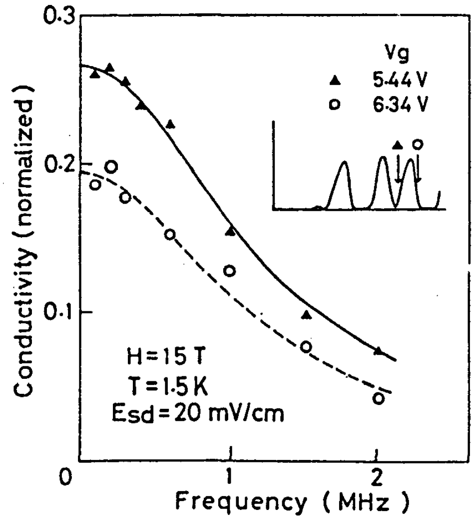

Fig. 4. The conductivity of the tail parts of the (0↓-) peak relative to the peak value as a function of frequency. The solid and the broken curves represent the Drude-type frequency dependence for sample SN9.

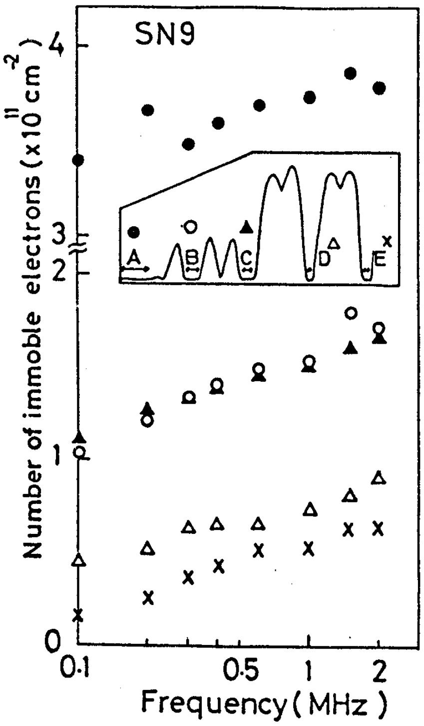

Fig. 5. The frequency dependence of the number of immobile electrons at various gaps for sample SN9.

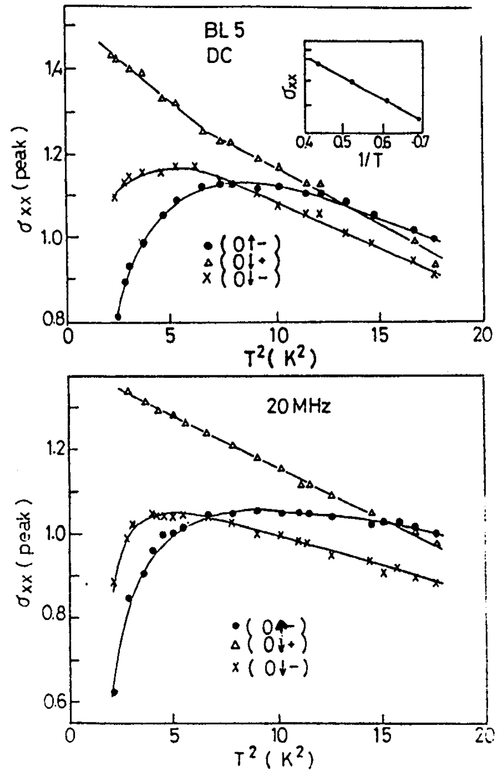

Fig. 6. Plot of $(\sigma_{xx})_{peak}$ against T^2 for sample BL5. The inset shows the $(\sigma_{xx})_{peak}$ vs. 1/T at the low temperature region.

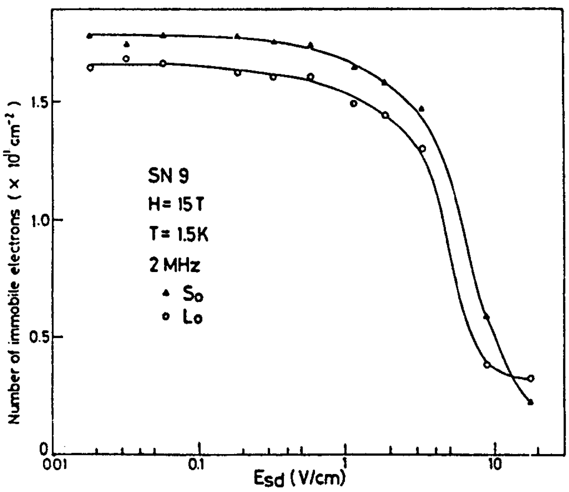

Fig. 7. Number of immobile electrons vs. E_{sd}. So indicates the gap between (0↑-) and (0↓+), L_0 between (0↓-) and (1↑+).

explained by some characteristic length over which electrons move during a period of the a.c. bias voltage as compared with the localization length. Further theoretical and experimental investigations are worth trying to clarify the mechanism of the remarkable frequency effects mentioned above.

References

1. N. Miura, Y. Iwasa, T. Itakura and G. Kido: J. Phys. Soc. Jpn. 51 (1982) 1228.
2. Y. Iwasa, G. Kido and N. Miura: Solid State Commun. 46 (1983) (in press).