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NEGATIVE MAGNETORESISTANCE IN A TWO-DIMENSIONAL RANDOM SYSTEM OF Si-MOS INVERSION LAYERS

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We have measured negative magnetoresistance of Si-MOS inversion layers with electron concentrations $N_s = 0.8 \sim 6 \times 10^{12}\ \mathrm{cm}^{-2}$ at temperatures $T = 1.3 \sim 20\ \mathrm{K}$ and have analysed the data in terms of recent scaling theory of Anderson localization in two dimension. The parameter α is less than unity in the whole N_s and T region which suggests effects of intervalley scattering and mutual Coulomb interaction of electrons. Energy relaxation process in the present system is found to be not the electron-phonon scattering.

I. Introduction

Negative magnetoresistance (or magnetoconductance) observed in the metallic conduction region of silicon n-channel inversion layers at low temperatures is characterized by the anisotropy in which only the magnetic field component perpendicular to the surface contributes to the magnetoresistance [1]. This anisotropy shows that the phenomenon is related to the orbital motion of electrons.

Recently, Hikami, Larkin and Nagaoka [2] have developed a theory of negative magnetoresistance in a two-dimensional random system based on recent scaling theory of Anderson localization [3]. We have reported that the magnetic field dependence of negative magnetoresistance in the theory is in good agreement with our observations [4].

In the present paper, we will report further results of the analysis of experimental data which include the carrier concentration dependence of the constant parameter, α, the temperature dependence of the energy relaxation time and the saturation value of negative magnetoresistance.

II. Experimental

Measurements have been performed on n-channel MOSFETs fabricated on (100) surfaces of p-type silicon with peak mobilities of 3500 and 14000 $\mathrm{cm}^2/\mathrm{V{\cdot}s}$ at 4.2 K. The resistance and the Hall voltage have been measured using ordinary Hall bridges with the channel width of 0.1 mm and the channel length of 1.0 mm at temperatures from 1.3 to 20 K and at carrier concentrations between 0.8 and $6 \times 10^{12}\ \mathrm{cm}^{-2}$. In the following analysis we have assumed that the carrier concentration N_s is independent of the magnetic field H by the reason that the Hall coefficient is independent of H. Our assumption is guaranteed by Fukuyama's theory of Hall effect [5].

The channel conductivity σ in the magnetic field at several temperatures are shown in Fig.(1). At very low magnetic field the channel conductivity is proportional to H^2, though we can not observe such a magnetic field dependence in the scale of magnetic field in Fig.(1). As the magnetic field becomes higher, σ rises rapidly up with increasing H. At high magnetic fields σ reaches a saturation value, although the saturation of magnetoconductivity is not observed clearly for the sample 55-8 (low mobility sample) in Fig.(1), because the magnetic field up to 13 kOe is not sufficiently strong for low mobility samples. In high mobility samples ($\mu \gtrsim 10000\ cm^2/V\cdot s$) we have clearly observed the saturation of magnetoconductivity.

The magnetic field dependence of the channel conductivity is well described by the theory of Hikami et al. Results calculated by Hikami et al.'s formula [2],

$$\Delta\sigma = -\frac{n_v \alpha e^2}{2\pi^2 \hbar}\left[\log\frac{1}{\tau_\varepsilon a} - \psi\left(\frac{1}{2} + \frac{1}{\tau_\varepsilon a}\right)\right], \qquad (1)$$

are shown by full lines in Fig.(1). They reproduce strikingly well experimental magnetoconductivity data (squares) by using appropriate values for τ_ε and α except a high field region near the saturation field. In eq.(1), n_v is the valley degeneracy, α a constant which is expected to be unity if the spin-orbit interaction and magnetic scattering are weak, $\psi(x)$ the Digamma function, τ_ε the energy relaxation time and $a = 4DeH/\hbar c$ for the diffusion coefficient D.

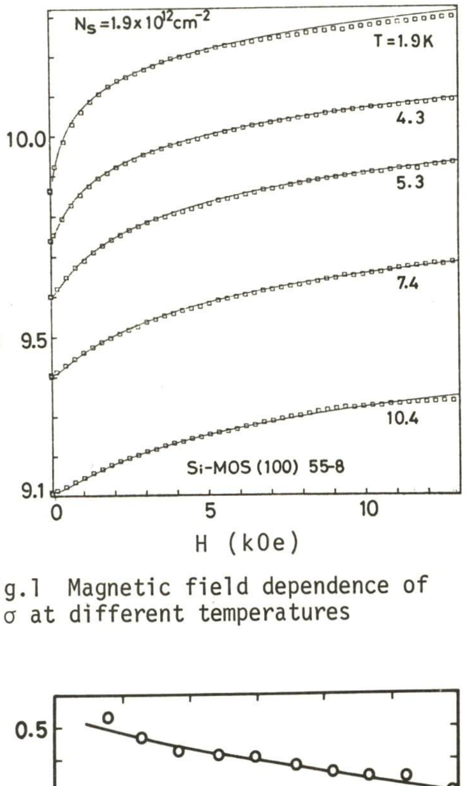

Fig.1 Magnetic field dependence of σ at different temperatures

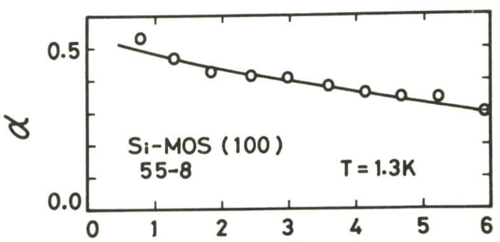

Fig.2 Carrier concentration dependence of α at T = 1.3 K

The values of α are plotted as a function of carrier concentration N_s at 1.3 K in Fig.(2). The value of α at $N_s = 0.8 \times 10^{12} cm^{-2}$ is 0.5 and gradually decreaseas with increasing N_s to 0.3 at $N_s = 6 \times 10^{12}\ cm^{-2}$.

The energy relaxation time τ_ε is plotted as a function of temperature T for $N_s = 0.8$ and $1.9 \times 10^{12} cm^{-2}$ in Fig.(3). The magnitude of τ_ε increases with increasing N_s from 2.1×10^{-12} s at $N_s = 0.8 \times 10^{12} cm^{-2}$ to 7.8×10^{-12} s at $N_s = 1.9 \times 10^{12} cm^{-2}$ at 4.2 K. The temperature dependence of τ_ε is described by T^{-p} at temperatures higher than 2 K. The exponent p increases with increasing N_s: $p = 1.33$ at $N_s = 0.8 \times 10^{12}\ cm^{-2}$ and $p = 1.75$ at $N_s = 1.9 \times 10^{12}\ cm^{-2}$.

The negative magnetoresistance appears when applied magnetic field supresses the quantum interference which causes the electron localization. The negative magnetoresistance saturates at sufficiently strong magnetic fields. The saturation value of the magnetoconductivity $\Delta\sigma_{sat} = \sigma(T,H=\infty) - \sigma(T,H=0)$ is given by

$$\Delta\sigma_{sat} = \frac{n_v \alpha e^2}{2\pi^2\hbar} \log \frac{\tau_\varepsilon}{\tau} = -\frac{n_v \alpha p e^2}{2\pi^2\hbar} \log T \quad , \qquad (2)$$

when the magnetic scattering is ignored [2]. The last expression is given by assuming $(\tau_\varepsilon/\tau) \propto T^{-p}$ where τ is the relaxation time of normal impurity scattering which is very weakly dependent of T in the present experimental condition. Figure (4) shows $\Delta\sigma_{sat}$ in high mobility samples as a function of log T. At high temperatures ($T \gtrsim 4$ K), the slope of $\Delta\sigma_{sat}$ versus log T curves are almost independent of the carrier concentration and gives $p = 0.69$.

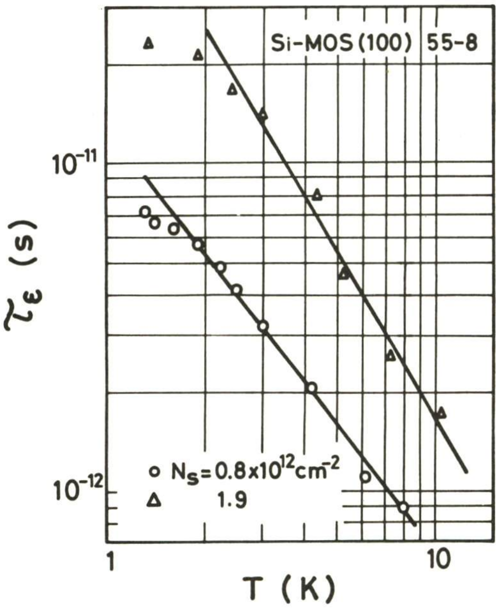

Fig.3 Temperature dependence of τ_ε

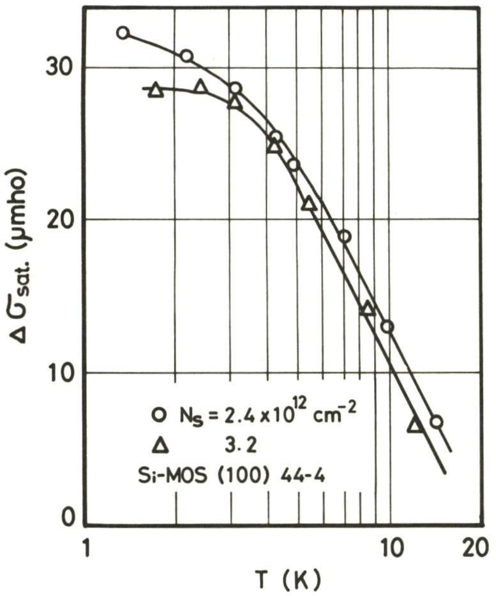

Fig.4 Temperature dependence of $\Delta\sigma_{sat}$

III. Discussion of the Results

As is described in the former section, the magnetoconductivity measurement can provide us with information of α and τ_ε independently.

The parameter α is expected to be unity for mutually noninteracting electrons if the spin-orbit interaction and magnetic scattering are weak [6,2]. Our experiments show that α is less than unity (0.5 or less in most cases) in the whole N_s- and T- region we measured. Quite recently, Fukuyama [7] has calculated effect of intervalley scattering on this problem. His result shows that $n_v\alpha = 1$ for $\tau_\varepsilon \gg \tau' > \tau_0$ (τ' and τ_0 are relaxation times due to inter- and intra-valley scattering, respectively). Importance of the intervalley scattering has been discussed by Ando [8] in connection to analysis of Shubnikov-de Haas oscillations in tilted surfaces from the (100) plane. Ando has estimated that contribution of the intervalley scattering to electron mobility is about 25% even at low temperatures. Therefore, our result of $\alpha = 0.5$ is satisfactory for $n_v = 2$.

As is shown in Fig. (2), α decreases with increasing N_s. Effect of electron-electron Coulomb interactions in this problem has been calculated by Fukuyama [9] and Larkin [10]. They have shown that the mutual Coulomb interactions reduce α appreciably. Therefore, it is highly possible that the result in Fig. (2) shows effect of mutual Coulomb interactions between electrons.

There are two processes for energy relaxation of electrons. One is electron-phonon scattering and another is electron-electron scattering. Relaxation time due to electron-phonon interaction in electrons in the (100) inversion layers at low temperatures calculated by Nakamura and Shinba [11] is proportional to T^{-3} and larger than we obtained. Therefore, the electron-electron scattering is a dominant mechanism in the energy relaxation of electrons.

Products of α in Fig.(2) and p determined in Fig.(3) are 0.67 for $N_s = 0.8 \times 10^{12}$ cm^{-2} and 0.70 for $N_s = 1.9 \times 10^{12}$ cm^{-2}. These results agree with $\alpha p = 0.69$ determined from $\Delta\sigma_{sat}$ in a high mobility sample (Fig.(4)). This fact supports consistency of the present analysis of magnetoconductivity in terms of the scaling theory of Anderson localization. The magnitude of αp in the present experiments is larger than $\alpha p = 0.52 \pm 0.05$ evaluated from temperature dependence of resistivity at lower temperatures by Bishop, Tsui and Dynes [12].

In conclusion we have measured the magnetoconductivity of Si-MOS inversion layers in the metallic conduction at low temperatures and have successfully analysed their magnetic field dependence at different carrier concentrations and at different temperatures in terms of recent scaling theory of Anderson localization in two dimension. The energy relaxation process which controls the localization length is not the electron-phonon interaction in the present system.

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