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Negative magnetoresistance in uniaxially stressed Si(100) inversion layers

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We have studied the negative magnetoresistance of a two-dimensional electron gas in uniaxially stressed Si(100) metal-oxide-semiconductor transistors. The decrease in the fitting parameter α, which is qualitatively explained on the basis of electron-electron interactions, suggests the presence of strong intervalley scattering between heavy- and light-mass subbands. The temperature dependence of τ_{in} supports the modification of the Landau-Baber scattering term in the presence of significant disorder.

Since Hikami, Larkin, and Nagaoka[1] (HLN) developed the theory of negative magnetoresistance, extensive use has been made of magnetoresistance to study the properties of a weakly localized two-dimensional electron gas in Si metal-oxide-semiconductor field effect transistors[2-5] (MOSFET's). The theoretical results can be fitted to experimental data by using a phenomenological parameter α in the expression

$$\Delta\sigma_{\text{HLN}} = -\frac{n_v \alpha e^2}{2\pi^2\hbar}\left[\psi\left(\frac{1}{2}+\frac{1}{a\tau}\right) - \psi\left(\frac{1}{2}+\frac{1}{a\tau_{\text{in}}}\right) - \frac{\tau_{\text{in}}}{\tau}\right], \qquad (1)$$

where n_v is the valley degeneracy, $\psi(x)$ the digamma function, τ the elastic scattering time, τ_{in} the inelastic scattering time, and $a = 4DeB/\hbar$ where D is the diffusion coefficient. The prefactor α has been shown to be related to the strength of intervalley scattering[3] and to be modified by electron-electron interactions.[3] In this Rapid Communication, we report on the analysis of negative magnetoresistance in uniaxially stressed Si(100) n-type MOS inversion layers in the temperature range 1.5–4.2 K.

The application of stress has been used extensively in the study of electron transport in Si MOS transistors.[6-10] On the silicon (100) surface, the electric field which quantizes motion perpendicular to the surface also breaks the sixfold degeneracy of the conduction-band minima (valleys) into a normally occupied twofold degenerate light-mass (E_0) subband with an effective mass $m^* = 0.19m_0$ in the plane of the device and a normally unoccupied fourfold degenerate heavy-mass (E_0') subband ($m^* = 0.42m_0$). The energy separation E_0'-E_0, which is typically of the order of 10 meV and arises from the difference in the effective mass of the subband minima *perpendicular* to the surface, can be overcome by the application of a uniaxial or biaxial[11] stress in the plane of the device. We have applied a compressive uniaxial stress along one of the principal crystal axes in the plane of the device which lowers the energy of the pair of E_0' valleys along this axis relative to that of the other four valleys. For a compressive stress P in the $\langle 010 \rangle$ direction, the stress-induced energy shift between the (010) valleys and the normally occupied (100) valleys is given by[7]

$$\Delta E(\text{meV}) = E^{010} - E^{100} = -0.084\,|P|\ (\text{N/mm}^2)\ . \qquad (2)$$

At sufficiently high stresses, a subband crossover can be expected and electrons will be transferred from the E_0 valleys to the E_0' valleys. At moderate electron concentrations, this transfer has been calculated to be gradual in the random-phase approximation.[12] The possible formation of a charge-density wave based on strong valley coupling during electron transfer has also attracted considerable interest,[6,7,13] but later experiments were found to be in conflict with this possibility.[9,14,15] This paper is based on experiments performed from zero stress to stresses sufficiently high as to allow electrons to occupy the light- and heavy-mass valleys simultaneously. The devices used for these measurements were polysilicon-gated Hall bars, 400 μm long by 50 μm with pairs of Hall probes separated by 100 μm. The oxide thickness was 100 nm and the peak mobility was of the order of 2.0 $\text{m}^2\text{V}^{-1}\text{s}^{-1}$. Stress was applied using a four-point bending method on chips 9 mm long by 2 mm wide, assuring a uniform stress in the plane of the devices. The stress can be considered uniform in the two-dimensional electron gas as the thickness of an inversion layer is typically 10 nm and that of a chip is 0.381 mm.

Fits of the HLN theory to experimental data using α and τ_{in} as variable parameters at various stresses are shown in Fig. 1. The prefactor $n_v\alpha$, extracted from such fits is plotted against applied stress in Fig. 2 for a few gate voltages. At zero stress, $\tau_{\text{in}}/\tau_v \sim 5$ assuming $\tau_v \sim 4\tau$ as estimated by Ando[16] where τ_v is the intervalley scattering time. As α is expected to be approximately $1/n_v$ in the case of strong intervalley scattering,[17] i.e., when electrons are scattered several times between valleys before an inelastic collision, it is reasonable that $n_v\alpha \sim 1$ ($n_v = 2$, $\alpha = 0.5$) at zero stress. The parameter α should tend to $\alpha = 1$ for independent systems, i.e., for weak intervalley scattering.[17] The fall of the prefactor with applied stress is therefore unexpected. As stress was applied, both the E_0' and E_0 valleys were populated. These are expected to

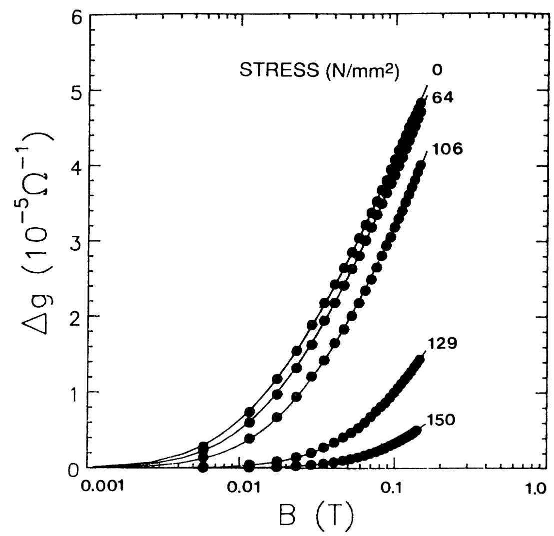

FIG. 1. Magnetoconductance for $V_G=3$ V at $T=1.5$ K at various values of applied stress. The solid lines are least-squares fit of the theory to the data points.

be independent of each other[18,19] in view of the large separation in crystal momentum that exists between them, and thus $n_v\alpha$ should have been at least equal to two ($n_v=4$, $\alpha=0.5$ assuming strong intervalley coupling within each subband). Thus, a strong intervalley scattering rate must be invoked between heavy- and light-mass valleys during electron transfer to give the observed prefactor $n_v\alpha\sim 1$ ($n_v=4$, $\alpha=\frac{1}{4}$).

The drop in the prefactor $n_v\alpha$ below one can be qualitatively explained on the basis of electron-electron interaction corrections to the conductivity in the presence of disorder. The magnetic fields used in this work are far below that required for Zeeman splitting effects to contribute to the magnetoresistance ($B \ll kT/g\mu_B$). However, an orbital contribution has been calculated[20] to give rise to a magnetoconductance correction given by

$$\Delta\sigma=(g_2-g_4)\frac{e^2}{2\pi^2\hbar}\phi(B,\gamma)\ , \tag{3}$$

where $\phi(B,\gamma)$ is a poly-gamma function whose qualitative features are similar to the HLN function and g_2, g_4 are interaction coupling constants[20,21] such that

$$g_2-2g_4=-\frac{F}{2}\left[1+\frac{F}{2}\ln\left(\frac{1.143E_F}{kT}\right)\right]^{-1}\ , \tag{4}$$

where F is the screening factor, which is approximately one in silicon-inversion layers.[22] In the case where $\alpha \gg \tau_{\text{in}}^{-1}$, $2\pi T$, which is within the range probed by the experiments, both $\Delta\sigma_I$ and $\Delta\sigma_{\text{HLN}}$ have a $\ln B$ dependence and for a single-valley system, the parameter α can be written $\alpha=1+g_2-2g_4$. Our analysis then follows that given to explain qualitatively the drop in α below 0.5 (Ref. 20) as found at high electron concentrations in Si(100) inversion layers.[3] Writing $\alpha=(1+g_2-2g_4)/n_v$, it can be seen that a drop in the Fermi level, E_F, which occurs as stress is applied and electrons begin to occupy the E_0 valleys, will lead to an increase in g_2-2g_4 and a reduction in α. The temperature dependence of the parameter α (see Fig. 3) can similarly be explained. An increase in temperature will again lead to an increase in g_2-2g_4. The experimental data indicate a much larger interaction contribution than allowed for by theory. For example, at $V_G=3$ V and zero stress, $E_F=4.1$ meV and yields $\alpha=0.41$ at 1.5 K and 0.39 at 4.2 K. The observed prefactor gives $\alpha=0.38$ at 1.5 K and 0.31 at 4.2 K. At the highest stress applied, it is estimated from piezoresistance curves that 40% of the electrons occupy the heavy-mass valleys giving $E_F=2.46$ meV which yields $n_v\alpha=0.8$. The experiments give $n_v\alpha\sim 0.5$. Hence, quantitative agreement is poor, as

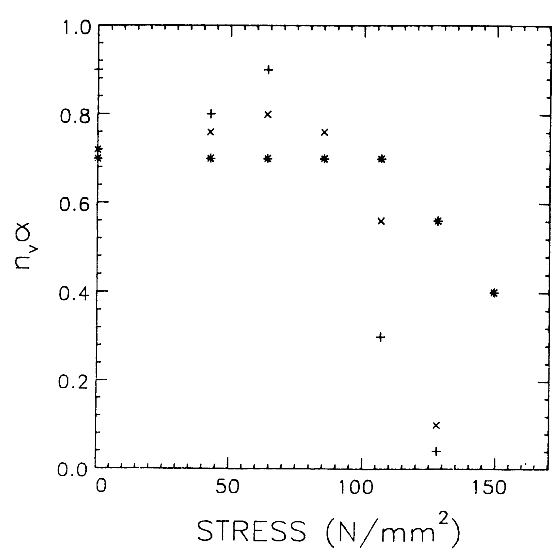

FIG. 2. Plot of the prefactor $n_v\alpha$ vs applied stress as extracted from magnetoconductance data for (+) $V_G=2$ V, (×) $V_G=2.5$ V, and (*) $V_G=3$ V.

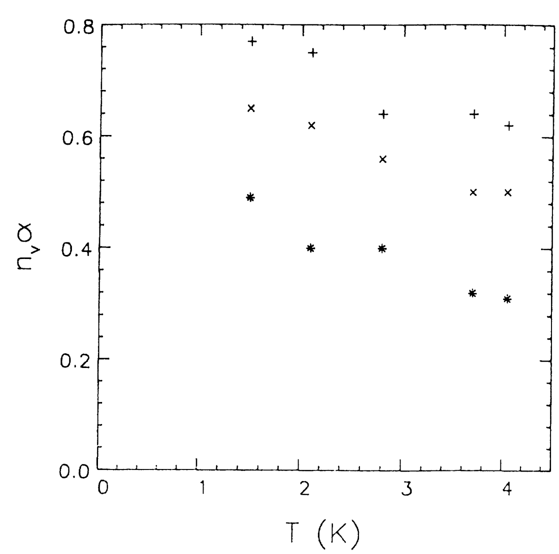

FIG. 3. Temperature dependence of the prefactor for (+) $V_G=3$ V, stress=0 N/mm^2; (×) $V_G=2.5$ V, stress=106 N/mm^2; (*) $V_G=3.0$ V, stress=150 N/mm^2.

reported by other workers.[23]

The value of the prefactor falls rapidly with increasing stress for $V_G=2$ V as shown in Fig. 2. A rapid drop in α with decrease in electron concentration has been described[3] as a possible indication of the removal of valley degeneracy from $n_v=2$ to 1 which has been predicted to occur below a given electron concentration.[24] In this experiment, the electron concentration was kept constant and the valley degeneracy was expected to be increased, not reduced with applied stress. However, the observed rapid drop in α can be shown to correspond to an increase in resistance into the strongly localized regime where the HLN theory, based on a perturbation calculation using the parameter $\hbar/E_F\tau$, is not strictly valid.

There are significant uncertainties in the values extracted for the inelastic scattering time τ_{in}. The extraction of these values depends on the knowledge of the density of states at the Fermi energy (from which the effective diffusion constant is deduced), which is expected to vary between $D(E_F)=2m_l/\pi\hbar^2$, $m_l=0.19m_0$ at zero stress and $D_T=2(m_l+m_h)/\pi\hbar^2$, $m_h=0.916m_0$ at the highest stresses used. In addition, it is assumed that the inelastic time extracted is that of an appropriately averaged inelastic lifetime, that is, that the electrons move as if in a single system. This is supported by the behavior of the parameter α, and Hall voltage measurements which show no deviation from the single carrier formula $(ne)^{-1}$ with applied stress. The data, as shown in Fig. 4, does, however, support the prediction[25] that the Landau-Baber scattering T^2 term becomes

$$(\tau_{\text{in}})^{-1} \sim \frac{kT^2}{\hbar E_F} \ln\left(\frac{E_F\tau}{\hbar}\right) \tag{5}$$

in the presence of significant disorder, i.e., when $E_F\tau/\hbar < E_F/kT$. As stress is applied, both E_F and τ are reduced (τ can be reduced by a factor of 5–9) leading to a reduction in the T^2 coefficient, which is the slope of a set of data points in Fig. 4, assuming[2,26] $(\tau_{\text{in}})^{-1}=AT+BT^2$. Note that in the absence of a ln term or in the presence of a $E_F^{-1}\ln(E_F)$ term, the T^2 coefficient would be expected to *increase*, not decrease with increasing stress (decreasing E_F).

In conclusion, negative magnetoresistance experimental results on uniaxially stressed Si(100) n-type inversion layers have been fitted to the theory of magnetoresistance in the weakly localized regime using the phenomenological parameter α. The application of a uniaxial stress caused electrons to occupy both the heavy- and light-mass valleys simultaneously. Despite the large crystal momentum separating these valleys, our data suggests the presence of strong intervalley scattering between them. The observed decrease in α with increasing stress and the temperature dependence of this parameter can be qualitatively explained by a magnetoresistance contribution due to electron-electron interactions. Finally, the change in the inelastic scattering rate with applied stress suggests that the Landau-Baber scattering term is modified by a disorder term in the presence of significant disorder.

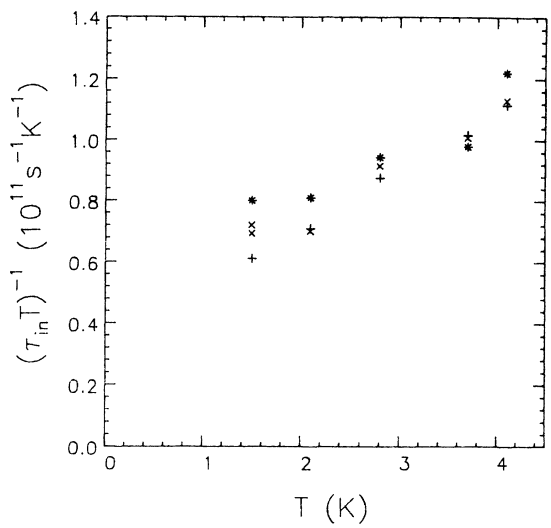

FIG. 4. Plot of $(\tau_{\text{in}}T)^{-1}$ vs T for $V_G=3$ V under an applied stress of (+) 0 N/mm^2, (×) 64 N/mm^2, (✱) 106 N/mm^2.

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