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Temperature-Dependent Resistivities in Silicon Inversion Layers at Low Temperatures

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The temperature dependence of the resistivities of n-type silicon inversion layers at liquid helium temperatures was studied in detail. The temperature dependence was found to be correlated to the mobility of the sample. Our results can be explained by Coulomb scattering, with possible contributions by surface-roughness scattering in high-mobility samples.

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The electrons in a silicon inversion layer have the properties of a quasi two-dimensional system, with the advantage that the surface electron density (n_s) and the effective thickness ($\langle z \rangle$) of the layer can be varied continuously.[1] The temperature dependence of the resistivity at liquid helium temperatures had been studied recently by several authors[2,3] and was interpreted as due to electron-phonon scattering. We have made extensive studies of this temperature dependence as a function of n_s, $\langle z \rangle$, and the quality of the device, as given by the maximum effective mobility at 4.2 °K (μ_m) which ranged from 2400 to 22 000 $cm^2/V \cdot sec$.

In the metallic regime, where the conductivity shows no activated behavior, the mobility of the inversion layer at liquid helium temperatures is known to be limited by Coulomb scattering and surface-roughness scattering, and at higher temperatures also by electron-phonon scattering.[1,4] With use of Matthiessen's rule (which is an approximation in our case[5]), the resistivity is given by

$$\rho = \rho_C + \rho_{s.r.} + \rho_{e-ph} \quad (1)$$

with obvious abbreviations. ρ_C has been observed to be temperature dependent,[4] but detailed measurements have not been made at liquid helium temperatures. ρ_{e-ph} is obviously temperature dependent and is often considered to be the dominant temperature-dependent part of the total resistivity.

Resistivities ρ of n-channel metal-oxide-semiconductor field-effect transistors, fabricated on 30–40-ohm-cm [001] p-type substrates, were measured with both two-point and four-point probes with measuring fields $\lesssim 4$ mV/cm (as guided by hot-electron–effect measurements) to avoid heating effects.[2] The devices were drawn from an inventory accumulated over a two-year period of processing experimentation. The samples were immersed in liquid helium within a light-tight container mounted with a germanium thermometer. A light-emitting diode supplied radiation to the substrate in order to assist electrostatic equilibrium. The oxide fixed charge density, Q_{ss}, was estimated from flat-band shifts in C-V measurements for thick oxide devices ($\gtrsim 1000$ Å), and estimated from mobilities for thin oxide devices. Measurements of Shubnikov–de Haas extrema for $n_s > 10^{12}$ cm^{-2} as a function of temperature on three samples have assured

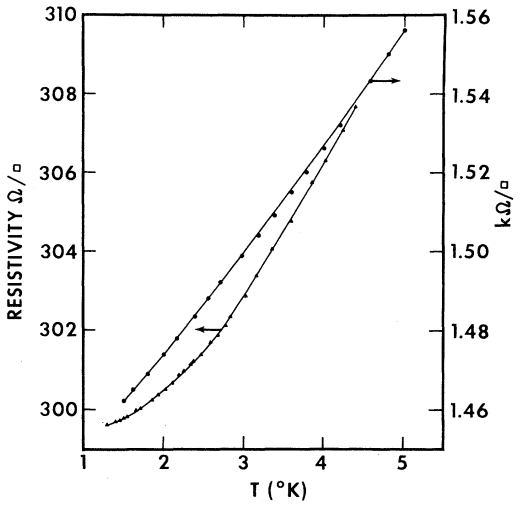

FIG. 1. Resistivity vs T. Circles, A1(80), $n_s = 1.2 \times 10^{12}$ cm^{-2}, $V_{sub} = -9.42$ V; triangles, R3L, $n_s = 1.3 \times 10^{12}$ cm^{-2}, $V_{sub} = -17.3$ V.

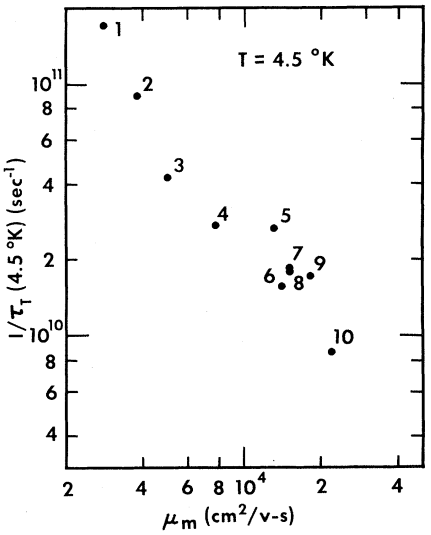

FIG. 2. $1/\tau_T$ at 4.5 °K and $n_s = 1.5 \times 10^{12}$ cm^{-2}. Our data have been interpolated to a fixed n_s and T whenever necessary to simplify discussions. Device label and V_{sub} (V) are (1) TA15, -9.41; (2) A1(80), -9.42; (3) M72-31H, -6.27; (4) M72-31, -6.27; (5) A13, -6.29; (6) M72-14, -1.25; (7) TH1, -9.41; (8) R3L, -9.42; (9) B15, 0; (10) A(2500), -9.41.

us that the resistivity changes are not due to changes in n_s with temperature.

Measurements of ρ vs T for two devices is shown in Fig. 1 for similar electron densities. The temperature dependence of the poor sample is an order of magnitude larger than that of the better sample, both with somewhat different curvatures. The temperature-dependent parts of the resistivities and scattering rates were extracted from

$$1/\tau = 1/\tau_0 + 1/\tau_T; \quad \rho = \rho_0 + \rho_T, \tag{2}$$

where ρ_0 was determined by a sensible extrapolation to 0 °K. The errors indicated in subsequent figures reflect our best estimate of the extrapolation error. Since absolute values of Q_{ss} and surface roughness are difficult to obtain unambiguously we have adopted the experimentally more convenient parameter of maximum effective mobility μ_m as a measure of device quality. All of our samples have nearly the same mobility at very large surface fields ($n_s \approx 10^{13}$/cm^2), which we assume implies that the surface roughness plays a constant role. Thus, comparing μ vs n_s curves among our samples, one draws the conclusion that Coulomb scattering is dominant for the lowest-mobility devices for $n_s < 2 \times 10^{12}$/cm^2, while for the best samples Coulomb and surface-roughness scattering are comparable.

We display in Fig. 2 $1/\tau_T$ vs μ_m for ten samples at $n_s = 1.5 \times 10^{12}$/cm^2 and $T = 4.5$ °K. We note that the oxide thicknesses (d_{ox}) of the devices range from 80 to 2400 Å without any clear correlation between $1/\tau_T$ and d_{ox}. Devices with the same d_{ox}, but different μ_m, were observed to give different $1/\tau_T$ vs T data. Increasing the Q_{ss} of a device about 50% by Na^+ drifting causes an approximately proportional increase in $1/\tau_T$. Lastly, $1/\tau_T$ was found to increase about 50% when $\langle z \rangle$ was decreased about 10% by applying a negative substrate bias (V_{sub}) for the case of $n_s = 1.24 \times 10^{12}$ cm^{-2}, $T = 4$ °K with $\mu_m \approx 15\,000$ cm^2/volt-sec. The percentage change is small on low-mobility devices and in some cases reversed.

These results strongly imply that this temperature-dependent scattering is not of phonon origin. In an early paper by Stern and Howard,[6] the screening constant s for Coulomb scattering was calculated using the $q \to 0$ approximation, where q is the wave-vector change during scattering. This gives a negligible temperature dependence between 1 and 5 °K for both Coulomb and surface-roughness scattering. Recently, Stern has considered the screening problem using the full dependence of s on q and T.[5] If s is calculated as a function of q, and if the formula given by Maldague[7] is used to evaluate the temperature dependence of the polarizability, then $s(q)$ at $q \sim 2k_F$, where k_F is the Fermi wave vector, is found to be significantly dependent on temperature. Since

momentum relaxation occurs mostly at $q \sim 2k_F$, then the relaxation time τ due to scattering, averaged over the Fermi surface weighted by $\epsilon\, df/d\epsilon$, where ϵ is the electron energy and f is the Fermi-Dirac distribution, will be a stronger function of temperature than was previously thought.

Using this approach and assuming all the Coulomb scatterers are located at the Si-SiO_2 interface, Stern has calculated $1/\tau$ as functions of n_s and T.[5] For the case of Coulomb scattering, his calculations show that $1/\tau$ increases almost linearly with T, with a magnitude proportional to Q_{ss} at fixed n_s. This temperature dependence decreases with increasing n_s, which is somewhat expected because of the reduced scattering rate as well as the temperature dependence of s. Stern's calculations on surface roughness also show a linear temperature dependence at liquid helium temperatures, and the temperature dependence increases with increasing n_s.

Referring to Fig. 3, we first draw attention to the limiting cases, $(1/\tau_T)_{e\text{-}ph}$, $(1/\tau_T)_C$, and $(1/\tau_T)_{s.r.}$, for $T = 4.5$ °K plotted against n_s. $(1/\tau_T)_{e\text{-}ph}$ has been calculated for bulk acoustic modes[8] (note scale factor without which the curve would be about one decade below the abscissa). Calculations also show that $1/\tau_T$ due to scattering by Rayleigh waves[9] (not shown here) is an order of magnitude less than that due to bulk phonons. $(1/\tau_T)_C$ is the temperature-dependent part of the Coulomb scattering calculated for $Q_{ss} = 8\times10^{11}/\text{cm}^2$ without surface roughness. $(1/\tau_T)_{s.r.}$ has been calculated using surface-roughness parameters with a rms height Δ of 0.6 nm and lateral correlation length L of 1.3 nm. Calculations for the latter two cases are due to Stern.

We plot two sets of data, TA15 and A13. From their magnitudes and also Q_{ss} dependence we conclude that phonon scattering is an unimportant contribution to the temperature-dependent mobility in this temperature range. For the case of TA15 whose mobility is strongly limited by the Q_{ss}, we have excellent agreement between theory and experiment. As expected with reduction in Q_{ss} by a factor of 6 – 7 (data A13), a corresponding reduction in $1/\tau_T$ occurs. In this case we believe that the surface-roughness contribution may be observable since the slope of $1/\tau_T$ vs n_s is less than the TA15 data, as predicted from theory. The theory also predicts a change in the sign of $d(1/\tau_T)/dn_s$ at $n_s \sim 2\times10^{12}$ cm^{-2} for $Q_{ss} \sim 10^{11}$ cm^{-2}. Measurements have not been made in this region since this effect was not previously anticipated and it demands extreme accuracy as $\Delta\rho/\rho$ will be very small. Further measurements in this region will test the model for surface-roughness scattering.

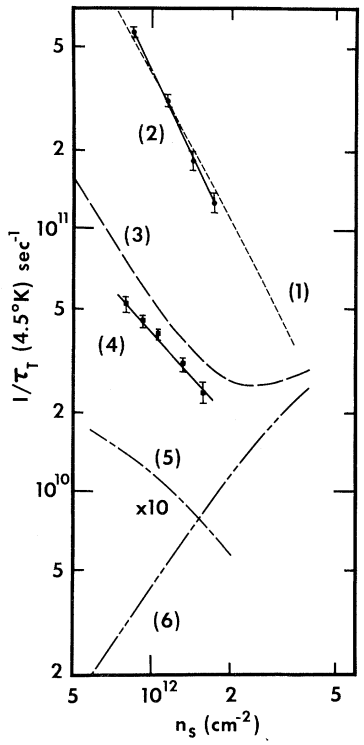

FIG. 3. $1/\tau_T$ at 4.5 °K vs n_s. (1) Coulomb scattering, $Q_{ss} = 8\times10^{11}$ cm^{-2}. (2) TA15 data, $Q_{ss} \sim 8\times10^{11}$ cm^{-2}, $V_{sub} = -9.41$ V. For this sample and others having large Q_{ss}, the effect of substrate bias is a few percent on $1/\tau_T$ and does not change the slope of $1/\tau_T$ vs n_s. (3) Coulomb scattering and surface roughness scattering, $Q_{ss} = 10^{11}$ cm^{-2}, $\Delta = 0.6$ nm, $L = 1.3$ nm. (4) A13 data, $Q_{ss} \sim 10^{11}$ cm^{-2}, $V_{sub} = -6.29$ V. (5) Scattering by bulk phonons, $\Xi_u = 12$, $\Xi_d = -8$ eV. Note factor of 10. (6) Surface-roughness scattering, $\Delta = 0.6$ nm, $L = 1.3$ nm. All calculations use $V_{sub} = 0$.

Qualitatively, the substrate bias results can be understood as device-quality dependent. Surface roughness remains nearly constant among devices, and thus its relative contribution to $1/\tau_T$ increases as quality improves. Since Coulomb[6] and surface roughness[10] scattering rates are proportional to $\approx\langle z\rangle^{-1}$ and $\langle z\rangle^{-6}$, respectively, decreasing $\langle z\rangle$ by substrate bias will cause a small percentage change in $1/\tau_T$ when the scattering is Coulomb dominated; the percentage increases as Q_{ss} is reduced.

In conclusion, we suggest that Coulomb and possibly surface-roughness scattering are the

dominant mechanisms causing a temperature-dependent resistivity between 1 to 5 °K. The calculated magnitudes of the electron-phonon scattering are too small to explain our data, and are without a mobility dependence. Their contributions to our high-mobility samples may have produced the curvature of ρ vs T, but theory predicts negligible contributions even in these cases. The anomalous scattering suggested by Kawaji[3] and also localization effects[11] will give a temperature dependence $\sim \ln(1/T)$, which may also have contributed to this curvature. The effects of analyzing the data with such additional terms have been estimated and do not change our conclusions. Any observed effect attributed only to electron-phonon scattering should be shown to be independent of mobility.

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Classical Local-Field Effect in Reflectance from Adsorbed Overlayers

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The role of the local-field effect in differential reflectance spectroscopy is studied within a classical model for an ordered overlayer of a weakly adsorbed species on a metal substrate. Results for Ar on Al at two coverages strongly indicate the importance of the local-field effect in such optical studies.

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There has been a great deal of interest in recent years in the use of differential-reflectivity methods to study the electronic properties of adsorbed objects on a variety of substrates. In particular, experiments have been reported[1,2] on differential reflectance spectra from rare-gas atoms adsorbed on metallic and oxide surfaces down to submonolayer coverages. In this paper we report on the first quantitative and detailed study of the classical local-field effect in such systems, and its possible implications for the measurement of optical reflectance. Our results, showing a striking correlation with experiments, suggest that the local-field effect is indeed quite important in surface reflectance spectroscopy. Although no systematic study of the role of the local-field effect in this problem has been attempted in the past, ideas rather similar to ours have appeared

