synchrotron radiation in studying various gas sorption and oxidation problems by choosing a photon energy for optimum cross section and surface sensitivity. These methods should be applicable to the study of adsorption on many other systems.

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Frequency Dependence of the Electron Conductivity in the Silicon Inversion Layer in the Metallic and Localized Regimes

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The conductivity of electrons in the inversion layer of silicon has been measured from 0 to 40 cm^{-1} at 1.2°K in the metallic and localized regimes. The correlation between $\sigma(T)$ and $\sigma(\omega)$ in the localized regime suggests that the drop in conductivity at low electron concentrations is caused by the appearance of a gap at the Fermi level.

Electrons in silicon inversion layers provide us with a two-dimensional[1] electron gas whose concentration can be varied by over two orders of magnitude. The relative ease with which the electron density can be varied has led to interesting studies of many-body effects on the electron mass[2] and g factor[3] and of "localization" of the electrons at low concentrations.[4-13] The latter has recently attracted much attention but a clear picture of the character of the electron states at the Fermi level in the localized regime has yet to emerge.

Following suggestions by Mott[11] and Stern[12] a number of investigators[4-10,13] have examined the behavior of the conductivity as a function of temperature and electron concentration n_s, and concluded that the conductivity near threshold may be described by the Mott theory of Anderson localization in a two-dimensional band tail. In devices with a large amount of disorder at the interface, the agreement with the Mott[14] theory is striking, especially with regard to variable-range hopping. In other devices which have considerably less disorder as measured by fixed oxide charge, Q_{ss}, the observation of localization is somewhat embarrassing. In these experiments or devices results are obtained that raise serious questions about the applicability of the Mott theo-

ry to this system. In particular we note the systematic variation of the minimum metallic conductivity,[6,10] the observation in the localized regime of a well-behaved Hall effect[7] and magnetoconductance oscillations,[5] and the anomalous substrate-bias effect.[8] With the exception of the substrate-bias effect, the above indicate that the microscopic scattering is insufficient to produce localization. These results admit two possibilities. First, the devices are macroscopically inhomogeneous, the inversion layer broken into macroscopically insulating and metallic regions. Second, and more interesting, is the possibility that the electron-electron interaction is sufficiently strong to localize the electrons even in the absence of potential fluctuations or at least acts in concert with a relatively weaker potential fluctuation giving rise to localization at electron concentrations much larger than predicted from a one-electron theory.

To shed further light on the character of the localization in this system we have measured the frequency dependence of the conductivity, at low temperature, at electron concentrations spanning both the metallic and the localized regimes. The results are not compatible with localization produced by macroscopic inhomogeneities. The results do demonstrate that the temperature regime heretofore referred to as near-neighbor hopping[5] is in fact excitation to a mobility edge, E_c. By implication E_c is a strong function of electron concentration, hovering just above E_F. This suggests that in this system one might do better to discard the idea of a mobility edge fixed by potential fluctuations in favor of a gap in the excitation spectrum that opens at the Fermi level at low electron concentrations.

The experiments were performed on a fully processed Si metal-oxide-semiconductor field-effect transitor fabricated on the (100) surface of 25-Ω cm p-type Si. The gate oxide was steam grown to a thickness of 1400 Å. Fixed oxide charge was measured to be $+1\times10^{11}$ cm^{-2}. Electron states at the Fermi level were localized for electron concentrations less than 7.7×10^{11} cm^{-2}. The minimum metallic conductivity was 5×10^{-4} mho/sq. Although the gate area was large ($\approx 2.5\times 2.5$ mm^2), the temperature dependence of the conductivity behaved substantially as it does in devices with Corbino geometry and much smaller gate area ($\approx 1\times 0.05$ mm^2).

The *absolute* conductivity, $\sigma(\omega)$, was measured at 1.2°K from 5 to 40 cm^{-1} with a resolution of 1 cm^{-1} by use of a black-body source and a Michelson interferometer. In essence we measure the change in far-infrared radiation transmitted through the gate, oxide layer, channel, and substrate caused by modulating the electron density in the channel. For small signals and wavelengths small compared to the gate dimensions, the channel conductivity is given by

$$\mathrm{Re}\sigma(\omega)\approx -\tfrac{1}{2}(\delta T/T)(Y_0+Y_G+Y_S), \quad (1)$$

where $\delta T/T$ is the fractional change in transmission produced by introducing the channel electrons, and Y_0, Y_G, and Y_S are the wave admittances of free space, the metallic gate, and the silicon substrate, respectively. $\delta T/T$ is measured; Y_0, Y_G, and Y_S are known to better than 5%.

The relative conductivity versus n_s at 1, 1.2, 1.6, 2, and 3 cm^{-1} was measured with klystron sources. Equation (1) is inappropriate at these wavelengths but the relative conductivity can be measured at fixed frequency by the same technique.

The dc conductivity was measured *in situ* not only at 1.2°K but as a function of temperature up to 4.2°K. This provides us with $\sigma(\omega=0)$ and the temperature dependence of σ to which we relate $\sigma(\omega)$.

In Fig. 1 we show $\ln\sigma$ versus $1/T$ for n_s[15] in the metallic and localized regimes. From 4.2 to 1.2°K the activated behavior can be fitted by

$$\sigma(n_s,T)=\sigma_0(n_s)\exp[-E_A(n_s)/kT]. \quad (2)$$

The metallic behavior evinces, if anything, a weak increase of σ with decreasing T.

In Fig. 2 we show $\sigma(\omega)$ at 1.2°K from dc to 40 cm^{-1}. The gap in the spectra from 22 to 32 cm^{-1} is due to the lack of power provided by the interferometer in this spectral range. The fluctuations in the spectra from 5 to 40 cm^{-1} may be taken as noise.

At metallic densities $\sigma(\omega)$ is given by the Drude expression

$$\sigma(\omega)=(n_s e^2\tau/m^*)(1+\omega^2\tau^2)^{-1}. \quad (3)$$

Since we know n_s, e, and m^*, the electron mass, τ can be determined from $\sigma(0)$. If we determine τ in this way, both the amplitude and the frequency dependences from 5 to 40 cm^{-1} are specified. In Figs. 2(a) and 2(b) the solid line is a fit by (3) where τ is derived from $\sigma(\omega=0)$. [Actually we take $\sigma(\omega=0)$ from the $1/T=0$ extrapolation in Fig. 1. This makes little difference at metallic densities.] The agreement from 5 to 40 cm^{-1} for $n_s=(15.3\pm0.2$ and $8.3\pm0.2)\times10^{11}$ cm^{-2} is a convinc-

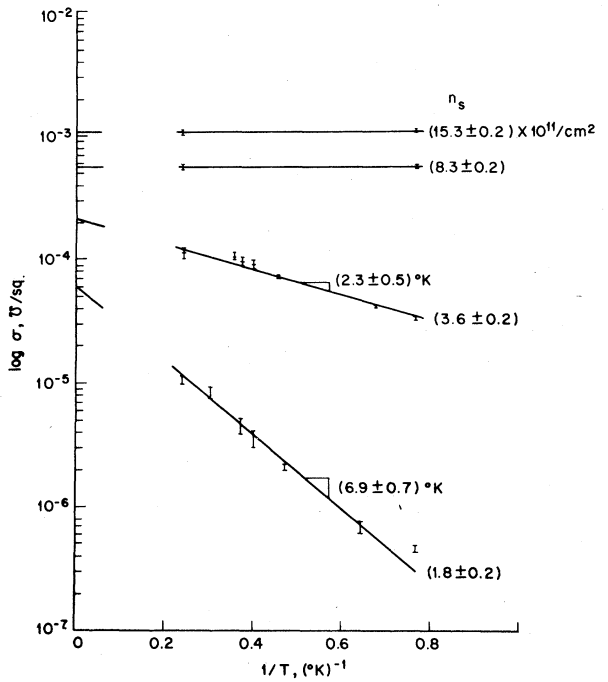

FIG. 1. Logarithm of the channel conductivity, mho/sq versus $1/T$ from 4.2 to 1.2°K. The values of σ at $1/T=0$ are shown as extrapolations.

ing demonstration of Drude behavior at metallic densities.

The microwave measurements are calibrated by the solid curve in Fig. 2(a) which interpolates between the dc and interferometer measurements. This enables us to determine the absolute microwave conductivity at the lower electron concentrations. In particular $\sigma(\omega)$ for $n_s=8.3\times10^{11}$ cm^{-2} between 1 and 3 cm^{-1} agrees reasonably well with the Drude interpolation between dc and the far-infrared measurements, both of which are absolute measurements. The scatter outside the statistically estimated error implies some systematic errors of the order of 10% in the microwave measurements.

In Figs. 2(c) and 2(d) the frequency dependence in the localized regime is shown. The solid curves are generated by Drude expressions, but here we emphasize that $\sigma(\omega=0)$ is the measured prefactor $\sigma_0(n_s)$ in expression (2). The conductivity from 5 to 40 cm^{-1} is metallic with a scattering rate given by $\sigma_0(n_s)$, the prefactor in the thermally activated dc conductivity, not the value of $\sigma(\omega=0, T=1.2°\text{K})$. Only at microwave frequencies does the conductivity drop significantly below the Drude expression and approach the dc

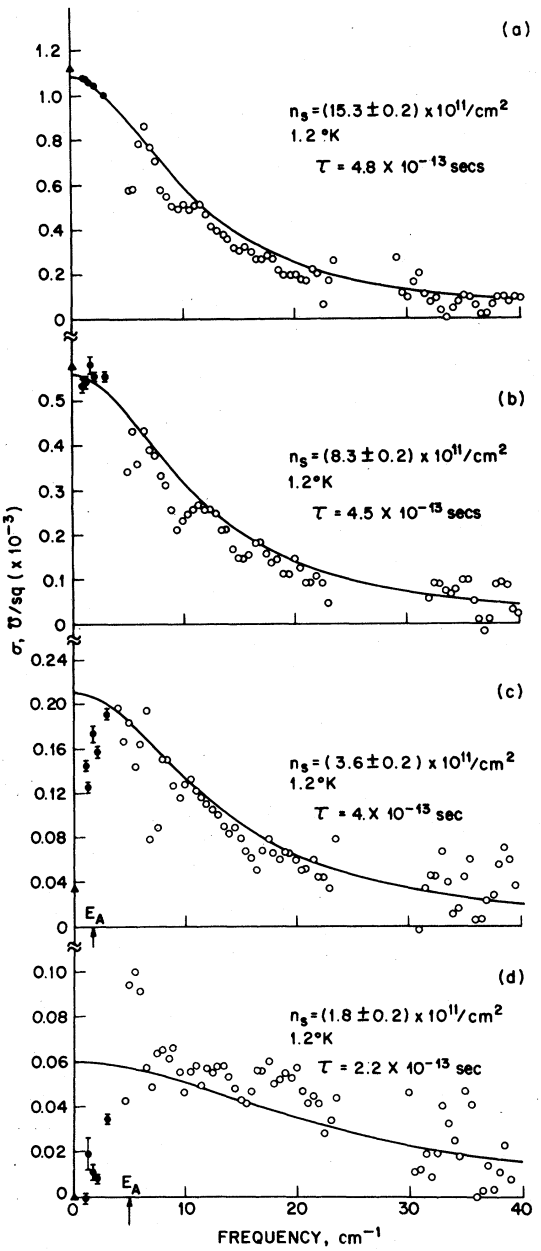

FIG. 2. Conductivity, mho/sq, at 1.2°K versus frequency in cm^{-1}. ▲, $\sigma(\omega=0, T=1.2°\text{K})$ from Fig. 1; ○, measurements with interferometer; ●, microwave measurements normalized to values at $n_s=15.3\times10^{11}$ cm^{-2}; —, Drude behavior predicted from $\sigma(n_s, \omega=0, 1/T\to0)$.

values which lie substantially below the far-infrared or Drude-like extrapolations. In Figs. 2(c) and 2(d) the thermal activation energies E_A are also indicated by the arrows and we see that the optical gap agrees with the thermal gap.

The frequency dependence of the conductivity

can be explained by macroscopic inhomogeneities only if we invoke a remarkable set of coincidences. First, the activated behavior in this model is controlled by the insulating regions, whereas the conductivity above 5 cm^{-1} is determined by the metallic regions. (At high frequencies the insulating regions are shorted by their sheet capacitance, C.) Yet we see that the high-frequency conductivity is rather intimately connected to σ_0, the prefactor in the thermally activated behavior. Second, the characteristic frequency at which we obtain metallic behavior would be given by the metallic conductivity and C. The model requires $\sigma/C \approx E_A/\hbar$ *independent* of n_s. Last, the value of C extracted from the characteristic frequency tells us the length scale of the inhomogeneities It must be >10–100 μm depending on n_s. Since we see no pathological behavior in devices with channels as narrow as 50 μm, we expect that inhomogeneities large enough to capacitively shunt the insulating regions for frequencies above 3 cm^{-1} are unlikely.

A microscopic model seems more appropriate. The agreement between the thermal and the optical gaps and the agreement between the prefactor in the activated conductivity and the conductivity for $\hbar\omega > E_A$ indicate that the high-frequency metallic behavior and low-frequency thermally activated behavior come from the same regions. It further suggests that the thermally activated dc conductivity is caused by electrons excited from below or at the Fermi level across a gap to conducting states; i.e., the dc conductivity at low n_s is reduced by the appearance of a gap in the excitation spectra.

If we insist that the gap represents an activation energy to a mobility edge produced by random potential fluctuations at the interface, then the mobility edge is a strong function of electron concentration. This is seen from the fact that $\partial E_A/\partial n_s < (dN/dE)^{-1}$, where dN/dE is the free-electron density of states. The mobility edge appears to hover just above E_F. One-electron theories of localization by potential fluctuations cannot be appropriate to these devices, a possibility that has been raised in recent literature.[13]

In summary, we have measured for the first time the frequency dependence of the inversion-layer conductivity in the metallic and localized regimes. The results are not compatible with localization by macroscopic inhomogeneities. The results do expose in a graphic way a gap in the excitation spectrum that appears at the Fermi level below a critical electron concentration. By implication electron-electron interactions play a major role in localizing the states at the Fermi level.

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