surface. At levels below ≈ 40-mW absorbed power, the drop has a nearly spherical shape. The resolution in this picture is limited by the scanning raster to ~ 10 μm on the crystal.

The lifetime of the drop in this crystal (sample CR15) has been measured to be 490 μsec from the decay of the total luminescence intensity from the entire crystal after the laser is switched off.[2,5] The long lifetime is a consequence of the reduced density of electron-hole pairs in the drop under stress. Alfvên-wave experiments for this sample geometry have determined the drop radius to be of order 0.3 mm at the same laser power. Most recently we have performed time-resolved slit-scanning experiments[5] which agree well with the Alfvên-wave data, as well as the photographs reproduced here. We regard the Alfvên-wave results as strong evidence that the image we have photographed here is that of a single drop and not a cloud of small drops. For unstressed Ge we observe a much weaker and more diffuse video image, which translates with the laser spot, consistent with a cloud of small drops having a much lower average electron-hole density.

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[1]R. S. Markiewicz, J. P. Wolfe, and C. D. Jeffries, Phys. Rev. Lett. 32, 1357 (1974), and 34, 59(E) (1975).

[2]J. P. Wolfe, R. S. Markiewicz, C. Kittel, and C. D. Jeffries, Phys. Rev. Lett. 34, 275 (1975).

[3]The vidicon has a Pb-salt photoconductive surface sensitive at 1.75 μm.

[4]It is known that contact stresses of this sort produce a maximum shear stress below the surface, as discussed by J. P. Wolfe, S. M. Kelso, R. S. Markiewicz, and J. E. Furneaux, to be published.

[5]Wolfe *et al.*, Ref. 4.

Localization and the Minimum Metallic Conductivity in Si Inversion Layers

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We observe the "minimum metallic conductivity," σ_m, to be a decreasing function of surface-state charge density, Q_{ss}, near the Si-SiO_2 interface. This dependence of σ_m on Q_{ss} is contrary to Mott's concept of minimum metallic conductivity, but explains the large differences in σ_m reported in the recent literature.

Carriers in Si inversion layers constitute a two-dimensional (2D) electronic system whose density n_s can be varied by more than two orders of magnitude. Several recent papers have reported carrier localization in this system at low temperatures.[1-7] This phenomenon, which has been called Mott-Anderson localization, is characterized by a transition from metallic conduction at high n_s to thermally activated conduction at low n_s [this transition occurs at $n_s \sim 10^{12}/\mathrm{cm}^2$ for an n-type (100) inversion layer] and its cause has been attributed to potential fluctuations at the Si-SiO_2 interface. Although all the reported data agree on the qualitative features of this transition, there exist large differences in the value of the reported minimum metallic conductivity, σ_m, below which the conductivity becomes thermally activated. In particular, while we reported in Ref. 2 the value $\sigma_m \sim 6\times10^{-4}\ \Omega^{-1}$, Pepper *et al.* reported $\sigma_m \sim 2\times10^{-5}\ \Omega^{-1}$ which is an order of magnitude lower than other reported values.[3-6] Mott's concept of minimum metallic conductivity,[8] applied to a 2D system, requires that σ_m be relatively insensitive to material parameters and parameters characterizing the potential fluctuations. Since the wide variation of σ_m reported in the literature seriously questions the concept of a minimum metallic conductivity, it is important to establish this variation on a firmer experimental footing.

We have chosen surface-state charge density, Q_{ss}, near the Si-SiO_2 interface[9] as a convenient parameter to characterize potential fluctuations at the interface and studied the dependence of σ_m on Q_{ss}. It is the purpose of this Comment to report results from this study and to point out that the differences in σ_m, as reported in recent literature, are consistent with the Q_{ss} dependence of

σ_m observed in our experiment. We attribute these differences in σ_m to the differences in the interface potential fluctuations of the devices used by the different groups and conclude that the minimum metallic conductivity in this 2D electronic system indeed depends on Q_{ss}, which is a widely used parameter for characterizing Si-SiO_2 interface properties.

The samples studied in this experiment are conventional two-terminal silicon metal-oxide-semiconductor field-effect transistors (Si-MOSFETs) of circular and linear geometry and also one four-terminal device, which was used to check that the effect of contact resistance at the source and drain is indeed negligible in our measurements. All the devices are fabricated on 10- to 15-Ω-cm (100)-oriented substrate material. The size of the gate area varies from 12×50 μm^2 to 250×250 μm^2 with oxide thickness varying from 1000 to 4000 Å. Q_{ss}, which is positive in all the samples, is determined from flat-band voltage shift in capacitance-voltage curves measured at 1 MHz.[9] Except for one device whose Q_{ss} is induced by the oxygen-reduction technique of Fowkes and Hess,[10] no additional process was deliberately introduced in the device fabrication to produce Q_{ss} in any of the other samples. It is assumed that Q_{ss} in these other samples results from variations in oxidation procedure and post-oxidation annealing treatment. The impurity mobile-ion charge densities, Q_0, in all the samples, as determined from conventional bias-drift measurements, are $Q_0 \lesssim 8\times10^{10}/\text{cm}^2$. The mobile-ion contamination is kept at this low level to eliminate interface potential inhomogeneities resulting from mobile-ion clustering, which has been seen at higher ion densities.[11]

In Fig. 1 the sheet resistance, ρ, of a p-channel device is plotted as a function of $1/T$, taken at fixed gate voltages V_g. n_s given in the figure caption is determined by $n_s = c_0(V_g - V_t)/e$, where c_0 is the oxide capacitance and V_t is the conduction threshold voltage at 78°K. In this sample, whose $Q_{ss} = 3.0\times10^{11}/\text{cm}^2$, the transition from metallic conduction to thermally activated conduction occurs at $n_s = (2.7\pm0.1)\times10^{12}/\text{cm}^2$. For smaller n_s, ρ shows thermally activated behavior with an activation energy, which increases with decreasing n_s. The departure of ρ from a simple exponential dependence on $1/T$ at lower temperatures is consistent with Mott's variable-range hopping conduction in a 2D system.[1,2] σ_m, which is taken as the temperature-independent conductivity at $n_s = 2.7\times10^{12}/\text{cm}^2$, is 4.2×10^{-4} Ω^{-1}.

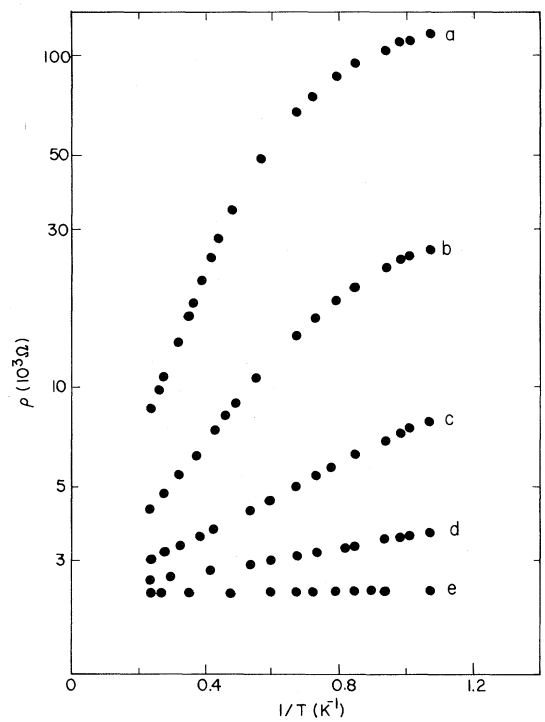

FIG. 1. lnρ versus $1/T$ for a p-channel device at various n_s: trace a, $n_s = 1.3\times10^{12}/\text{cm}^2$; trace b, $n_s = 1.6\times10^{12}/\text{cm}^2$; trace c, $n_s = 1.9\times10^{12}/\text{cm}^2$; trace d, $n_s = 2.2\times10^{12}/\text{cm}^2$; trace e, $n_s = 2.8\times10^{12}/\text{cm}^2$.

Figure 2 shows our data on σ_m as a function of Q_{ss}. The crosses indicate data from p-channel devices on n-Si and the circles indicate data from n-channel devices on p-Si. For comparison, we also show σ_m from Pepper *et al.*[1] (as a triangle) at $Q_{ss} = 8\times10^{12}/\text{cm}^2$, which is the approximate amount of charge stored in their metal-nitride-oxide-semiconductor (MNOS) device.[1] These data clearly show that σ_m depends strongly on Q_{ss}. In the range of Q_{ss} which we have studied, it decreases from $\sim7\times10^{-4}$ Ω^{-1} at $Q_{ss} = 1.0\times10^{11}/\text{cm}^2$ to $\sim4\times10^{-5}$ Ω^{-1} at $Q_{ss} = 1.6\times10^{12}/\text{cm}^2$. Although we have not measured any sample with Q_{ss} as large as the amount of charges in the devices used by Pepper *et al.*,[1] it is apparent that σ_m, reported by them, is also consistent with the general Q_{ss} dependence observed in our results. It appears that the different values of σ_m reported in the recent literature may be understood to be due to different values of Q_{ss}. Since Q_{ss} is not the only source of potential fluctuations at the interface, it is not, *a priori*, clear that such an unambiguous dependence of σ_m

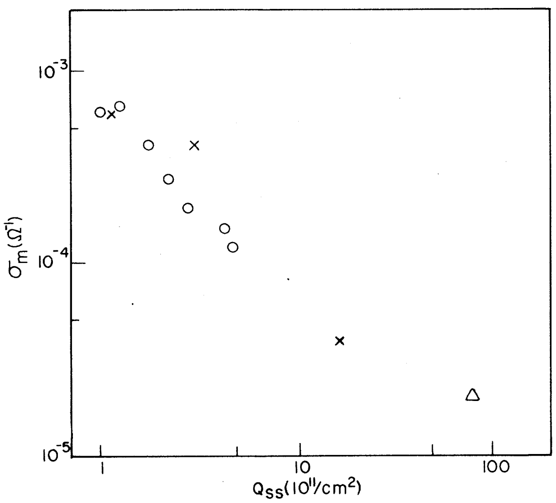

FIG. 2. σ_m versus Q_{ss}. Circles are from n-channel devices on p-Si, crosses are from p-channel devices on n-Si, and the triangle is from Ref. 1.

on Q_{ss} should be observed.

Although the dependence of σ_m on Q_{ss} demonstrated in Fig. 2 is convincing, there is at least one contrary piece of evidence. Mott *et al.*[7] report a value of σ_m close to the theoretical value, $\approx 0.07e^2/\hbar$, for a MOSFET with $Q_{ss} \approx 10^{11}/\mathrm{cm}^2$. This suggests that Q_{ss} alone may not explain the reported differences in σ_m. At the same time Hartstein and Fowler[6] find a variation of σ_m with Q_{ss} consistent with Fig. 2.

According to Mott's concept of minimum metallic conductivity, σ_m in a 2D system is relatively insensitive to parameters characterizing potential fluctuations in the system. The strong dependence of σ_m on Q_{ss}, as seen in Fig. 2, is an evidence that this minimum-metallic-conductivity concept is not valid in this 2D system. It is also important to note that this dependence of σ_m on Q_{ss} is still inconsistent with Mott's minimum metallic conductivity even if the Si inversion layer is assumed to be a three-dimensional (3D) electronic system. In the case of a 3D system, σ_m is expected to increase with increasing density of localizing centers,[8] contrary to our observation of σ_m decreasing with increasing Q_{ss}. Finally, we recall that electron-electron interaction effects may be important at low carrier densities.[2,12] In the case of an n-type (100) inversion layer, the Coulomb interaction energy between electrons exceeds their kinetic energy for $n_s < 3 \times 10^{12}/\mathrm{cm}^2$ and the Mott-Anderson localization occurs for $n_s \lesssim 1 \times 10^{12}/\mathrm{cm}^2$. Thus, many-body effects probably play an important role in this localization phenomenon and may mitigate Mott's concept of a minimum-metallic-conductivity concept in this 2D system.

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[1]M. Pepper, S. Pollitt, C. J. Adkins, and R. E. Oakley, Phys. Lett. 47A, 71 (1974); M. Pepper, S. Pollitt, and C. J. Adkins, Phys. Lett. 48A, 113 (1974).

[2]D. C. Tsui and S. J. Allen, Jr., Phys. Rev. Lett. 32, 1200 (1974).

[3]E. Arnold, Appl. Phys. Lett. 25, 705 (1974).

[4]A. Fowler, Phys. Rev. Lett. 34, 15 (1975).

[5]M. E. Sjöstrand and P. J. Stiles, to be published.

[6]A. Hartstein and A. B. Fowler, to be published.

[7]N. F. Mott, M. Pepper, S. Pollitt, R. H. Wallis, and C. J. Adkins, to be published.

[8]N. F. Mott, Phil. Mag. 26, 1015 (1972).

[9]B. E. Deal, J. Electrochem. Soc. 121, 199c (1974).

[10]F. M. Fowkes and D. W. Hess, Appl. Phys. Lett. 22, 377 (1973).

[11]T. H. DiStefano, Appl. Phys. Lett. 19, 280 (1971); D. J. Silversmith, J. Electrochem. Soc. 119, 1589 (1972).

[12]See, for example, J. L. Smith and P. J. Stiles, Phys. Rev. Lett. 29, 102 (1972).