a peak at a finite frequency. The mode may be identified with propagating phase fluctuations. A complete determination of the dispersion relation has not been made.

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[1] J. T. Anderson, R. V. Carlson, and A. M. Goldman, J. Low Temp. Phys. 8, 29 (1972).

[2] R. V. Carlson and A. M. Goldman, Phys. Rev. Lett. 31, 880 (1973).

[3] D. J. Scalapino, Phys. Rev. Lett. 24, 1052 (1970).

[4] M. Cyrot, Rep. Progr. Phys. 36, 103 (1973).

[5] G. Brieskorn, M. Dinter, and H. Schmidt, Solid State Commun. 15, 757 (1974).

[6] K. Maki and H. Sato, J. Low Temp. Phys. 16, 557 (1974).

[7] E. Simanek and J. C. Hayward, to be published.

[8] J. C. Swihart, J. Appl. Phys. 32, 461 (1961).

[9] L. P. Gor'kov and G. M. Eliashberg, J. Low Temp. Phys. 2, 161 (1970).

[10] K. A. Shapiro and I. Rudnick, Phys. Rev. 137, A1383 (1965).

[11] If modes of frequencies ω_1 and ω_2, where $\omega_1 \gg \omega_2$, are coupled together, then the dispersion relation can be of the form $\omega = \omega_2 - |V|^2/|\omega_1 - \omega_2|$, where V is the coupling parameter.

[12] G. Deutscher, H. Fenichel, M. Gershenson, E. Grunbaum, and Z. Ovadiahu, J. Low Temp. Phys. 10, 231 (1973).

[13] B. Abeles, R. W. Cohen, and W. R. Stowell, Phys. Rev. Lett. 18, 902 (1967).

[14] S. R. Shenoy and P. A. Lee, Phys. Rev. B 10, 2744 (1974).

Substrate Bias Effects on Electron Mobility in Silicon Inversion Layers at Low Temperatures

A. B. Fowler
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598

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The mobility of electrons in silicon inversion layers and conductance activation energy have been measured as a function of substrate bias. The mobility increased and the activation energy decreased as the electrons were forced toward the surface. This seems inconsistent with activated conduction arising from potential fluctuations due to oxide charge.

The conductance of electrons in inversion layers in metal-insulator-silicon field-effect transistors (MOSFET's) has been the subject of many studies.[1-4] At low temperatures and all but the highest densities, the electrons lie in the lowest quantum state induced by the field perpendicular to the silicon surface. The results below are surprising because they seem in contradiction to other measurements in the temperature and carrier-density range where the conductance is thermally activated.[1,3,4] Several explanations have been offered to explain the decrease of activation energy of conductance with increasing carrier density. All depend on assuming that oxide charges near the interface play a major role. This is true for scattering by potential fluctuations,[5,6] trapping where the screening increases with charge density and lowers the trap energy,[7] and a percolation model or Mott-Anderson model[8,9] where fluctuations arise from the oxide charges.[10]

If these effects are caused by the fluctuations due to oxide charges, then forcing the electrons closer to the interface should increase the effects. It is well known[11,1] that application of substrate bias, V_s, between the source contact and the substrate reduces the free-electron charge qN_{inv} by increasing the depletion charge qN_{depl} and increases the gate voltage for conductance threshold V_t. To maintain a given N_{inv}, the gate voltage must be increased as the substrate is made more negative. Then the free electrons are forced closer to the surface. At low carrier concentrations, the effect can be strong. Stern[12] has shown that for $N_{\rm inv} \ll N_{\rm depl}$, for an acceptor density of $10^{15}/{\rm cm}^3$, and at 0 K the average distance of the electrons from the surface, $z_{\rm av}$, can be reduced from 50 to 25 Å by changing the substrate bias from 0 to -40 V. Such a change in bias might then reasonably be expected to increase the effects of the fluctuations.

Circular MOSFET's similar to those studied in Ref. 1 were studied. The oxide thickness was 500 Å; the width to length ratio was 50; the source-drain spacing was 50 μm; the substrate resistivity was nominally 10 Ω cm; and the surface was (100). Measurements were similar to those reported elsewhere[1]—small-signal conductance and transconductance with the source-drain field kept less than 1 V/cm. To determine the mobility, it is necessary to determine the threshold which was done by measuring the transconductance threshold at 77.3 K. The choice of the nitrogen threshold at helium temperatures is supported by Hall measurements[1] and magneto-oscillatory conductance results.[13] Because of a 40-mV tail, the choice is somewhat arbitrary, but results in an uncertainty in $N_{\rm inv}$ of not more than $10^{10}/{\rm cm}^2$ which does not significantly affect the results below, unless $N_{\rm inv} < 10^{11}/{\rm cm}^2$. These thresholds at different substrate biases were plotted as a function of $(1.12 - V_{\rm sub})^{1/2}$, where 1.12 V is the surface potential at threshold for zero bias. The result is an excellent straight-line relationship that allows determination of the acceptor density of about $1.4\times10^{15}/{\rm cm}^3$.

The rate at which the depletion layer is formed[14] when the substrate bias is changed is complex, and depends on the initial and final biases, the temperature, the presence of light, and the substrate resistivity. For 10-Ω-cm substrates, up to several minutes were required to come to steady state; for 100-Ω-cm substrates several hours were needed. Details will be reported elsewhere.

The carrier concentration and mobility were calculated from the threshold and conductance in the usual way. The results for one sample are shown in Fig. 1. It is apparent that the mobility increases with reverse substrate bias contrary

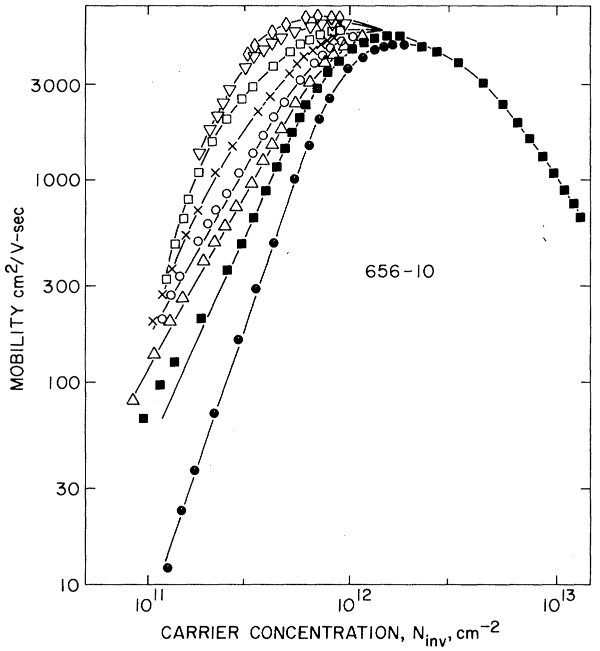

FIG. 1. Electron mobility as a function of carrier concentration and substrate bias at 4.2 K for a sample with $N_a = 1.36\times10^{15}/{\rm cm}^3$ and $Q_{0x}/q = 9.1\times10^{10}/{\rm cm}^2$. The curves, starting from the lowest, are for substrate biases of 1.0 V (●), 0 V (■), -1.0 V (△), 2.0 V (○), -4.0 V (×), -8.0 V (□), -16 V (▽), and -32 V (◇). The data coincided at higher carrier densities.

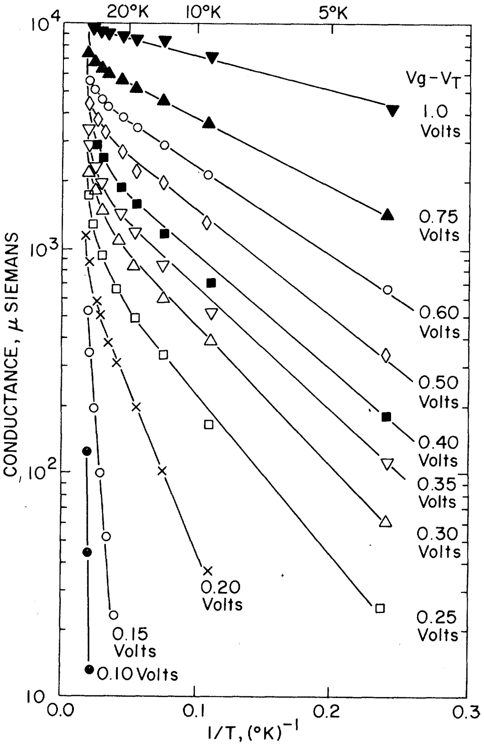

FIG. 2. Conductance as a function of temperature and gate voltage above threshold $(V_g - V_t)$, for sample 656-11 for zero substrate bias. A gate voltage above threshold of 1.0 V corresponds to a carrier density of about $4.4\times10^{11}/{\rm cm}^2$. This sample is similar to 656-10.

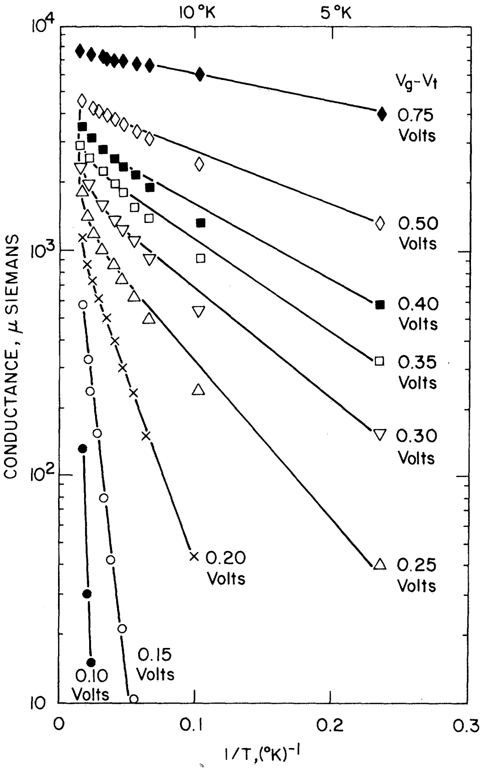

FIG. 3. Similar data as for Fig. 3 except that the substrate bias is − 3.0 V.

to expectations. For $N_{\text{inv}} < 10^{12}/\text{cm}^2$, making the substrate bias more negative has increased the mobility by more than an order of magnitude at some carrier densities. The effect seems to saturate, especially at the lowest concentrations and may, in fact, reverse, but below $10^{11}/\text{cm}^2$ the data are not as reproducible as at higher concentrations. Other samples indicated that the higher the oxide charge and, therefore, the lower the maximum mobility with $V_s = 0$, the smaller the substrate bias effect is. For $N_{\text{inv}} > 10^{12}/\text{cm}^2$ there is almost no effect because z_{av} is essentially insensitive to the substrate bias.

Measurements were made as a function of temperature above 4.2 K in order to determine the dependence of activation energy on N_{inv} and V_s. In Figs. 2 and 3, data are shown as a function of gate voltage above a threshold chosen in an arbitrary but consistent way. It is obvious that the effect of substrate bias is to reduce the activation energy.

Both of the above sets of experiments would seem to indicate that the effect of substrate bias forcing the electrons closer to the interface is to reduce the effects of the fluctuations, which is an unexpected result. It may be that the role of screening[15] is imperfectly understood, and that the fluctuations are much more effectively screened than expected as the electrons are forced to the surface. Another possibility is that the tail states of the higher quantum levels are populated, and that the effect of substrate bias, which increases the splitting, is to depopulate those levels and to increase the Fermi energy in the ground state. This would increase the conductance and decrease the activation energy. This explanation seems somewhat implausible, since magneto-oscillatory conductance measurements[13] tend to show that only the ground state is occupied. These measurements are difficult, but not impossible for $N_s < 10^{12}/\text{cm}^2$. A change of the period of the oscillations with substrate bias would tend to support this model.

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[1] F. F. Fang and A. B. Fowler, Phys. Rev. 164, 614 (1968).

[2] Y. C. Cheng and E. A. Sullivan, J. Appl. Phys. 45, 188 (1974).

[3] M. Pepper, S. Pollitt, C. J. Adkins, and R. E. Oakley, Phys. Lett. 47A, 71 (1974); M. Pepper, S. Pollitt, and C. J. Adkins, J. Phys. C: Proc. Phys. Soc., London 7, L273 (1974); and other work to be published by these authors.

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

[5] J. R. Brews, J. Appl. Phys. 43, 2306 (1972).

[6] Y. C. Cheng, J. Appl. Phys. 44, 2425 (1973).

[7] F. Stern and W. E. Howard, Phys. Rev. 163, 816 (1967).

[8] N. F. Mott, Elec. Power 19, 321 (1973).

[9] F. Stern, Phys. Rev. B 9, 2762 (1974).

[10] E. Arnold, Bull. Amer. Phys. Soc. 18, 1605 (1973).

[11] J. A. van Nielen and O. W. Memelink, Philips Res. Rep. 22, 55 (1967).

[12] F. Stern, private communication.

[13] A. R. Tokuda and P. O. Lauritzen, IEEE Trans. Electron Devices 21, 606 (1974).

[14] F. Stern, Phys. Rev. Lett. 18, 546 (1967).

[15] A. B. Fowler, F. F. Fang, W. E. Howard, and P. J. Stiles, Phys. Rev. Lett. 16, 901 (1966), and J. Phys. Soc. Jpn., Suppl. 21, 331 (1966).