

Thermally activated features in $1/f$ noise in silicon on sapphire

M. B. Weissman

*Department of Physics, University of Illinois at Urbana-Champaign,
Urbana, Illinois 61801*

R. D. Black

*Department of Electrical Engineering, University of Illinois at Urbana-Champaign,
Urbana, Illinois 61801*

P. J. Restle and T. Ray

*Department of Physics, University of Illinois at Urbana-Champaign,
Urbana, Illinois 61801*

(Received 14 September 1982)

Reproducible spectral features were found in the low-frequency noise in silicon-on-sapphire (SOS) wafers. These features moved in frequency as a function of temperature, with a range of activation energies from ~ 0.4 to ~ 0.7 eV. The relation between the log slope of the frequency spectrum and its temperature derivative was qualitatively similar to that predicted by a formula derived by Dutta *et al.* for noise with a range of activation energies. However, systematic quantitative deviations were found which demonstrate the existence of a wide range of temperature-independent prefactors in the rate expressions.

Most theories of $1/f$ noise in semiconductors, including the McWhorter theory¹ and various "fundamental" theories²⁻⁴ do not predict any important temperature dependences of the kinetics giving the $1/f$ spectrum. For pure $1/f$ noise, extending over a frequency range in which the entire observable range is included, changes in kinetics with temperature are not observable. However, Dutta *et al.*^{5,6} have shown that small deviations from a $1/f$ power law are observable in metal films, thus giving an experimental parameter with which to observe kinetic changes. They found that these deviations correlated with the temperature dependence of the noise power in a way which indicated that thermally activated kinetics were involved. We report here the observation in silicon-on-sapphire (SOS) of noise spectral features which can be directly seen to shift in position as the temperature changes, unmistakably indicating thermally activated kinetics.

Three SOS samples were prepared, each doped n type ($\sim 5 \times 10^{16}$ carriers/cm³) and with a thermally grown surface oxide layer. The preparation of one sample SOS5 has been described in detail elsewhere.⁷ The epitaxial silicon was ~ 670 nm thick. SOS6 and SOS7 were made in the same way, but with a brief wet oxidation step (4 min at 650 and 750 °C, respectively) following the dry oxidation step. Wet oxidation produces a more porous ($\sim 3\%$ less dense) oxide layer next to the silicon.⁸ Each sample was etched in a cross-shaped pattern described previously.⁹

Noise measurements were made by standard

methods, using batteries in series with wire-wound resistors for current sources. PAR 113's were used as amplifiers and a PAR 4520 Fast Fourier analyzer was used to process the raw data. Noise spectra were recorded on disk and integrated using an LSI 11/23 computer. For ease in viewing and analyzing the spectra, they were integrated by octaves, which makes small deviations from a $1/f$ power law (equal octave integrals) apparent. The cross spectra between noise on orthogonal paths in the sample were used to determine spectral shapes and temperature dependences. This procedure has several advantages over the conventional use of power spectra:

(1) Essentially no Nyquist noise appears in the cross spectra, making background subtractions unnecessary.

(2) Contact noise does not appear in the cross spectra. In these samples there was no significant contact noise anyway, but this advantage can be important in other samples.

(3) Only noise from a small central region ($\sim 30 \times 30 \mu\text{m}^2$) appears in the cross spectrum. Presumably the doping and oxide properties are very uniform in this small region.

The room-temperature cross spectra of the three samples are shown in Fig. 1. Both the deviations from the $1/f$ power law and the approximate noise magnitude were reproducible and not strongly dependent on hydration of the oxide nearest the silicon. Figure 2 shows the cross spectra of SOS5 at 5, 25, 40, and 60 °C. Very similar results were obtained from SOS7, so it was not considered necessary to test

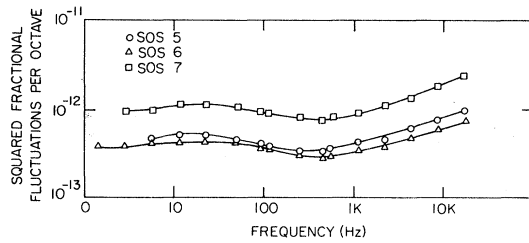


FIG. 1. Cross spectra measured on three samples, expressed in mean-square resistance fluctuations normalized by the square of the sample resistance.

the intermediate SOS6. The shift of the features to higher frequencies as the temperature is raised is unmistakable. In this respect the phenomenon in SOS is even clearer than in metal films, in which only temperature dependences and spectral slopes, not moving spectral features, were observable. The difference occurs because the features in SOS occur in narrower bandwidths than do those in metal films and because a much broader bandwidth is easily observable in the SOS samples. As a result, only small temperature changes are needed, so that one need not worry about changing regimes, for example, from phonon scattering dominated to impurity scattering dominated.

The easiest features to pick out of the spectrum are the minimum of the octave-integral spectrum and the lower-frequency maximum which appears except at 5°. The frequencies of the minimum and maximum, calculated by standard three-point interpolations on the digital record, are shown with estimated error bars in Fig. 2. These frequencies are not measured with sufficient accuracy over a wide enough range to determine the functional form of the temperature dependence. However, the only plausible way to account for the very strong temperature dependence is to assume thermal activation. The minimum can be fit using an activation energy¹⁰ of 0.39 ± 0.05 eV and the maximum with 0.66 ± 0.1 eV. Using these values we can calculate approximate prefactors f_1 and f_2 for the relations

$$f_{\min} = f_1 e^{-E_1^\pm/kT}, \quad f_{\max} = f_2 e^{-E_2^\pm/kT} \quad (1)$$

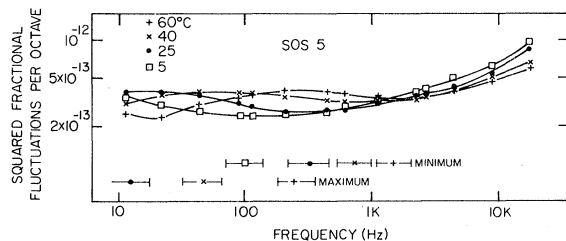


FIG. 2. Cross spectra of sample SOS5 at different temperatures.

These are $f_1 = 3 \times 10^9$ Hz and $F_2 = 4 \times 10^{12}$ Hz, with uncertainties of roughly a factor of 10. The difference is significant, indicating that the assumption of a single prefactor^{5,6} independent of E^\pm is not a very good approximation for our samples.

The maximum and minimum in the octave spectrum probably do not directly correspond to particular processes contributing to the noise. However, if all such processes had the same activation energy, and the horizontal position but not the shape of the spectrum would shift with temperature. If all contributing processes had the same prefactor, then a temperature change would cause a horizontal shift and a slight horizontal expansion or compression. The range of activation energies and prefactors found for the features reflects the obvious failure of the spectrum to behave in either of these simple ways. There must then be a range of both activation energies and prefactors of the contributing processes, although no simple identification between the features and the contributing processes may be made.

Dutta *et al.*^{5,6} showed that when the spectral features are sufficiently broad, when a single prefactor may be used, and when the net mean-square fractional resistance fluctuation (integrated over all frequencies) is temperature independent, Eq. (2) holds:

$$1 + \frac{\partial \ln S(f, T)}{\partial \ln f} = \left(\frac{\partial \ln S(f, T)}{\partial \ln T} - 1 \right) / \ln(f/f_0) \quad (2)$$

where $S(f, T)$ is the frequency spectrum of the fractional resistance fluctuations. Although we found relatively narrow spectral features and a range of prefactors, we compared our data with the predictions of Eq. (2), calculated using $f_0 = 1.1 \times 10^{11}$ Hz, the geometric mean of the values calculated above. Typical results are shown in Fig. 3. In this plot, there are no adjustable parameters—not even the f_0 appearing in the logarithmic factor. There is some tendency for the temperature dependence to imply too large a deviation from $1/f$ for small f and too small a deviation for large f . This is a consequence of using a single f_0 in the fit. There may also be a decrease in the net magnitude of the low-frequency contributions at higher temperatures, roughly proportional to T^{-1} or with characteristic energy of ~ 30 meV.

The absence of a clear vertical shift between the predicted and observed log slopes at the points where the log slope is -1 indicates that it is approximately correct to assume a temperature-independent net noise magnitude. The inferred dependence of the net magnitude on T , averaged over the observed range, is not more extreme than about T^{-1} to T^{+1} in this temperature range.

For featureless noise, it is very hard to tell if there is a superposition of many contributions with different temperature dependences. For example, for

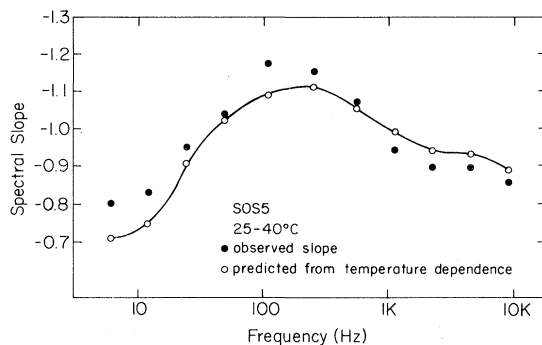


FIG. 3. Test of Eq. (2). The dots represent the logarithmic slopes of the spectra, averaged over the two temperatures. Each value is computed from the log of the ratio of the noise magnitude in the next higher octave to the magnitude in the next lower octave. The open circles represent the slopes expected from the temperature-dependent magnitudes according to Eq. (2), with the derivative of magnitude with respect to temperature calculated from a single octave at the two temperature settings. In some cases, strongly overlapping but not identical octaves, obtained with different analyzer bandwidths, were lumped together. The line through the open circles serves only as a visual guide. Random errors are much smaller than the differences between the slopes and the predicted slopes. The open circles are calculated using $f_0 = 1.1 \times 10^{11}$ Hz.

trapping noise the number fluctuations from the shallow traps are reduced while those from the deeper traps are increased as T increases. However, when there are features in the spectrum, we can follow the temperature dependence of something like a particular contribution to the noise. The absence of vertical shift in Fig. 3 and in similar plots of other samples and frequency ranges means that we also see no strong temperature dependence of the magnitude of these particular contributions. As with the results of Dutta *et al.*, the likely conclusion is that there are thermally activated transitions between states whose energies differ by much less than the activation energy.

There are some possible questions as to the relation between the spectral features and the $1/f$ noise. It may be asked why spectral features have not been observed before. In fact, Dutta *et al.* have shown that broad features are ubiquitous in metal films. Very prominent features have been found in semiconductors before.¹¹ However, so far as we know, no one has previously looked at features in semiconductors as a function of temperature while changing the temperature by small enough increments to keep the same features in the observed frequency range. It is also likely that in point contacts, with huge local strains, and in polycrystalline metal films and perhaps in transistors, there are additional sources of heterogeneity which smear out some of the narrower features.

It may also be thought that the spectral features showing thermal activation are due to some simple

relaxation processes superimposed on an underlying scale-invariant $1/f$ noise. We believe there are some arguments against that interpretation, as follows:

(1) It is evident even from casual inspection that at least two distinct Lorentzians would be needed.

(2) The ratios of each of these noises to the "true" $1/f$ noise would have to be the same for each sample.

(3) Detailed examination of the spectra shows that the features are too broad to be single Lorentzians, so that one could not avoid invoking spread-out distributions of activation energies or prefactors.

(4) Analogy with the results of Dutta *et al.* supports the idea of interpreting $1/f$ noise as resulting from a spread of activation energies. Although none of these arguments is conclusive, the most parsimonious explanation for the results is that the noise is caused by some processes which are thermally activated with the approximately $1/f$ spectrum, being a consequence both of the distribution of activation energies and of the distribution of prefactors.

There is some evidence that the thermally activated process is diffusion. It is the most common process in which slow thermally activated transitions are made between states of nearly equal energy. In metal films, a correlation between the cohesive energies and the temperatures of peak noise power⁵ supports this idea, and mechanisms have been proposed by which the diffusion of scatterers would cause mobility fluctuations.^{12,13} In silicon, however, there is strong evidence that the fluctuating occupancy of surface states is involved in generating the noise,¹⁴ and this has been born out by detailed experiments on Hall-effect noise in these particular SOS samples.⁷ We believe that the evidence is sufficient to support preliminary speculation on a model incorporating these facts.

There are fast shallow surface states on Si surfaces and at Si-oxide interfaces. There are also relatively rapidly diffusing ions (e.g., Si and Na) in surface layers.¹⁵ The depth of a surface state would be slowly modulated by the Coulombic interaction with nearby diffusing ions. It is easy to calculate that the modulation in depth exceeds kT at room temperature, so that, averaged over time, a much broader band of surface states would have fluctuating occupancy than in the standard fixed-depth models.^{1,15} This difference can account for the very weak temperature dependence of the noise magnitude of particular features, which is incompatible with trapping models in which features are associated with traps of a particular depth. We intend to expand on these remarks in a future paper.

ACKNOWLEDGMENTS

We are very grateful to Jerry Gilliland of Hewlett-Packard for the SOS wafers and to G. Anner for use

of microelectronics facilities. This work was supported by NSF Grant No. DMR 80-07097 and, through facility usage at the Materials Research Laboratory, by NSF Grant No. DMR 80-20250.

-
- ¹A. L. McWhorter, in *Semiconductor Surface Physics*, edited by R. H. Kingston (University of Pennsylvania, Philadelphia, 1957), p. 207.
- ²P. H. Handel, *Phys. Rev. A* **22**, 745 (1980).
- ³K. L. Ngai, *Phys. Rev. B* **22**, 2066 (1980).
- ⁴R. P. Jindal and A. Van der Ziel, *J. Appl. Phys.* **52**, 2884 (1981).
- ⁵P. Dutta, P. Dimon, and P. M. Horn, *Phys. Rev. Lett.* **43**, 646 (1979).
- ⁶P. Dutta and P. M. Horn, *Rev. Mod. Phys.* **53**, 497 (1981).
- ⁷R. D. Black, P. J. Restle, and M. B. Weissman (unpublished).
- ⁸A. B. Glaser and G. E. Subak-Sharpe, *Integrated Circuit Engineering* (Addison-Wesley, Reading, Mass., 1979), pp. 227–236.
- ⁹R. D. Black, W. M. Snow, and M. B. Weissman, *Phys. Rev. B* **25**, 2955 (1982).
- ¹⁰We loosely refer to the activation potential as an energy, although there is probably an activation volume as well.
- However, because silicon and sapphire have slightly different coefficients of thermal expansion, the pressure is not the same at the different temperatures. Thus the temperature dependence of the rate does not correspond exactly to an activation enthalpy or an activation energy.
- ¹¹P. Vandevoorde, C. K. Iddings, W. F. Love, and D. Halford, *Phys. Rev. B* **19**, 4121 (1979).
- ¹²M. Yakota, in *Proceedings of the Second International Conference on $1/f$ Noise* (unpublished).
- ¹³M. B. Weissman, in *Proceedings of the Sixth International Conference on Noise in Physical Systems*, edited by P. H. E. Meijer, R. H. Moutain, and R. J. Soulen (Dept. of Commerce, Washington, D.C., 1981), p. 133.
- ¹⁴A. Van der Ziel, in *Advances in Electronics and Electron Physics*, edited by L. Marton and C. Marton (Academic, New York, 1979), Vol. 49, p. 225.
- ¹⁵A. S. Grove, *Physics and Technology of Semiconductor Devices* (Wiley, New York, 1967), pp. 334–355.