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Flicker noise in semiconductors: Not a true bulk effect\textsuperscript{a)}

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From the fact that good silicon JFET's do not have any flicker noise, it is concluded that flicker noise in semiconductors and semiconductor devices cannot be a true bulk effect. Since JFET's have no semiconductor-oxide interface to speak of, whereas all other semiconductor devices do, this points to the semiconductor-oxide interface as the source of $1/f$ noise. This leads to the following model. The carriers are trapped and detrapped by oxide traps, and this gives rise to two distinct noise effects: density fluctuation noise that can be described by the McWhorter model and mobility fluctuation noise that could possibly be described by the Kleinpenning model. The two models might therefore ultimately be unified into a single model, and it would depend on the device under study whether one or the other noise effect would predominate.

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It is well known that flicker noise in semiconductors can often be represented by Hooge's empirical formula\textsuperscript{1}

$$S(f)/f^2 = \alpha/fN. \quad (1)$$

Here, $\alpha$ is a dimensionless constant of the order $2 \times 10^{-4}$, $f$ is the frequency, and $N$ is the number of carriers in the sample.

Equation (1) is usually interpreted as pointing to a bulk effect as the cause of the noise. It should then occur in all devices containing bulk material. The most notable exception to this interpretation is the complete absence of flicker noise in silicon junction field effect transistors (JFET's). It is the aim of this note to show that this puts such a low value on $\alpha$ as to make the bulk-effect interpretation virtually impossible not only in the case of JFET's, but, because of it, for all semiconductor devices. We shall also indicate how one should proceed from here.

The noise resistance $R_n$ of a good silicon JFET at room temperature can be described by

\textsuperscript{1}Electron Spectroscopy for Surface Analysis, edited by H. Ibach (Springer-Verlag, Berlin, 1977).


\textsuperscript{3}We are indebted to D. Carlson of the RCA Laboratories, Princeton, N.J., for supplying all the material used in this work.

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\textsuperscript{6}For quantitative estimates of adsorbed oxygen, we used as a calibration the oxygen Auger signal from a single-crystal (100) Si surface which had been activated to a state of negative electron affinity, in which state the oxygen adsorption is accurately known. See B. Goldstein, Surf. Sci. 35, 227 (1973).

\textsuperscript{14}P. Zanzucci (unpublished).

\textsuperscript{15}The light sensitivity of our loss peaks was not large enough to permit optical spectroscopy at less than band-gap energies, although light effects were seen at photon energies as low as 1.6 eV.
To prove this, we take a section of the channel of length $\Delta x$ having $\Delta N$ electrons. Then, according to Eq. (1),

$$S(f)/f^2 = \alpha/\Delta N$$

or

$$S(f) = \frac{q^2 \alpha \mu^2}{4\pi^2 f g(W_q) \Delta x},$$

where $g(W_q) = q \mu(\Delta N/\Delta x)$ is the channel conductance for unit length, $W_q$ is the dc bias between gate and channel, $q$ is the electron charge, and $\mu$ is the electron mobility.

According to Klaassen and Prins, we have for the short-circuited output

$$S_{1f}(f) = L^{-2} \int_{-\infty}^{\infty} F(u, f) du,$$

where $L$ is the length of the channel and

$$F(x, f) = S(f) \Delta x = \frac{q^2 \alpha \mu^2}{4\pi^2 f g(W_q)} \frac{dW_q}{dx},$$

since $I = g(W_q)dW_q/dx$. Therefore, substituting into Eq. (4), we obtain

$$S_{1f}(f) = \frac{q^2 \alpha \mu V_e}{f L^2},$$

or, since in saturation the drain voltage $V_d$ must be replaced by $V_e - V_p$, where $V_p$ is the pinch-off voltage of the device, we have in saturation

$$S_{1f}(f) = 4kT R_n = \frac{q^2 \alpha \mu}{f L^2} \frac{I(V_e - V_p)}{g_m}$$

where $g_m$ is the transconductance of the device. Hence, the noise resistance $R_n$ of the device is

$$R_n = \frac{q^2 \alpha \mu}{4 kT L^2 f} \frac{I(V_e - V_p)}{g_m}.$$

We shall now substitute numbers and take $\alpha = 2 \times 10^{-2}$, $q = 1.6 \times 10^{-19}$ C, $\mu = 1.4 \times 10^{2} \text{cm}^2/\text{Vsec}$, $k = 1.4 \times 10^{-7}$ J/degree, $T = 300$ K, $L = 10^{-3}$ cm, $I = 5$ mA, $V_e - V_p = 2$ V, and $g_m = 5 \times 10^{-3}$ mho (the latter may be slightly off, but we are only interested in orders of magnitude). This yields $R_n = 10^{10}/\Omega$.

Comparing with Eq. (2), we see that the 1/f bulk noise, if it exists in JFET's, must have a value of $\alpha$ less than $2 \times 10^{-8}$. We conclude therefore that bulk flicker noise is absent in these devices. Consequently, flicker noise in other semiconductor devices cannot be caused by a true bulk effect either, for otherwise it would occur in JFET's also.

We can go one step further. Since the JFET has no semiconductor–oxide interface to speak of, whereas all other semiconductor devices do, our discussion points to the semiconductor–oxide interface as the source of 1/f noise. It would seem that this conclusion also has a very firm basis.

There are two competing models of flicker noise in semiconductors: (a) The McWhorter model, describing the noise in terms of carrier density fluctuations governed by a tunneling process; and (b) the Kleinpenning model, in which the noise is described by mobility fluctuations. This was proposed in order to explain the 1/f noise in thermoelectric cells and in space-charge-limited diodes. In all other cases both density fluctuations and mobility fluctuations can describe the noise. It should be pointed out that flicker noise in space-charge-limited solid-state diodes requires fluctuations of the average mobility of the carriers only, whereas the flicker noise in thermoelectric cells requires independent mobility fluctuations in individual subbands.

The above considerations open up the possibility of unifying the two models. In this unified model the interaction between oxide traps and channel carriers via surface states is governed by a tunneling mechanism, and this leads to two distinct noise effects:

(1) The trapping and detrapping of carriers leads to carrier density fluctuations, as described by the McWhorter model.

(2) The fluctuating occupancy of the oxide traps modulates the free carrier scattering at the surface, and so produces mobility fluctuations of the free carriers; this might be described by the Kleinpenning model, if a certain condition is satisfied.

The condition is that the fluctuations in the individual subbands of the conduction band can be treated as being independent. Since the scattering, and hence the modulation of the scattering and consequently the mobility fluctuations, depends on the energy $E$ of the free carriers, it is clear that the conduction band must be divided into subbands to evaluate the effect. If these subbands could be treated as being independent, the full Kleinpenning model would result, and we would have given his mobility fluctuation hypothesis its theoretical underpinning.

Our considerations thus open up the possibility of an ultimate unification of the density and mobility fluctuation models for flicker noise in semiconductors. It could depend on the device under study whether noise of type 1 or 2 would predominate. This promising possibility is now under careful consideration, and we hope to report on it at a later date.