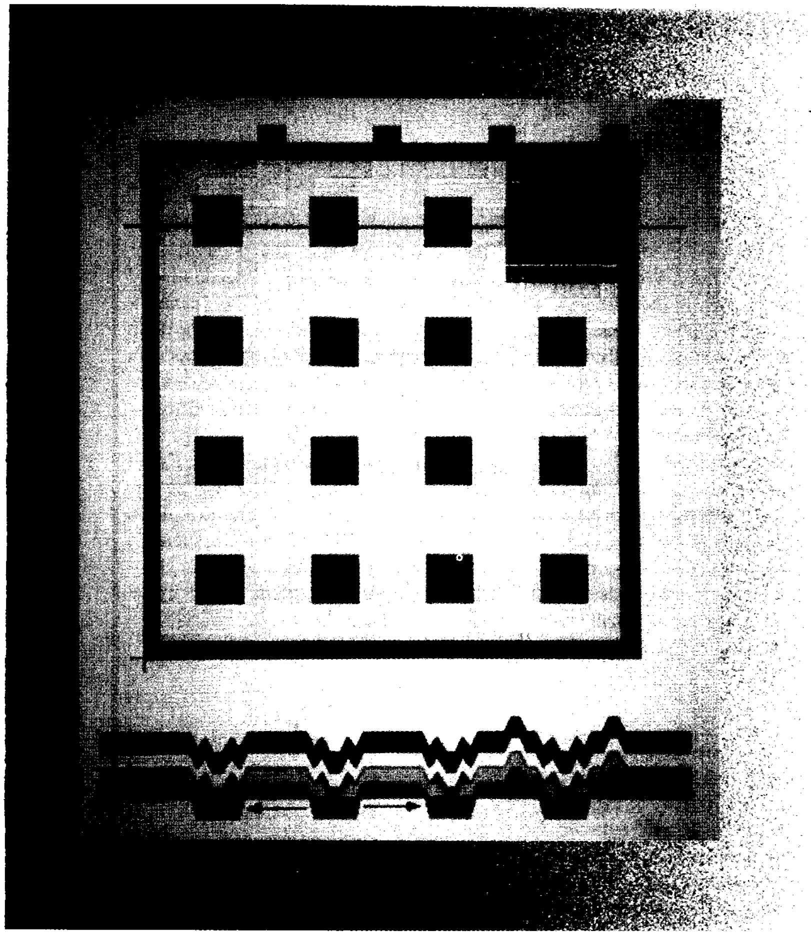

Shot noise and thermal noise have long been considered the results of two distinct mechanisms, but they aren't

White Noise in MOS Transistors and Resistors

by Rahul Sarpeshkar, Tobias Delbrück, and Carver A. Mead

We live in a very energy-conscious era. In the electrical engineering community, energy-consciousness has manifested itself in an increasing focus on low-power circuits. Low-power circuits imply low current and/or voltage levels and are thus more susceptible to the effects of noise. Hence, a good understanding of noise is timely.

Most people find the subject of noise mysterious, and there is, understandably, much confusion about it. Although the fundamental physical concepts behind noise are simple, much of this simplicity is often obscured by the mathematics invoked to compute expressions for the noise.

The myriads of random events that happen at microscopic scales cause fluctuations in the values of macroscopic variables such as voltage, current, and charge. These fluctuations are referred to as noise. The noise is called "white noise" if its power spectrum is flat and "pink noise" or "flicker noise" if its power

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spectrum goes inversely with the frequency. In this article, we shall discuss theoretical and experimental results for white noise in the low-power subthreshold region of operation of an MOS transistor. A good review of operation in the subthreshold region may be found in Mead [1]. This region is becoming increasingly important in the design of low-power analog circuits, particularly in neuromorphic applications that simulate various aspects of brain function [1-4]. A formula for subthreshold noise in MOS transistors has been derived by Enz [6] and Vittoz [7] from considerations that model the channel of a transistor as being composed of a series of resistors. The integrated thermal noise of all these resistors yields the net thermal noise in the transistor, after some fairly detailed mathematical manipulations. The expression obtained for the noise, however, strongly suggests that the noise is really "shot noise," conventionally believed to be a different kind of white noise from thermal noise.

We solve the mystery of how one generates a shot-noise answer from a thermal-noise derivation by taking a fresh look at noise in subthreshold MOS transistors from first principles. We then rederive the expression for thermal noise in a resistor from our viewpoint. We believe that our derivation is simpler and more transparent than the one originally offered in 1928 by Nyquist, who counted modes on a transmission line to evaluate the noise in a resistor [5]. Our results lead to a unifying view of the processes of shot noise (noise in vacuum tubes, photodiodes, and bipolar transistors) and thermal noise (noise in resistors and MOS devices).

In subthreshold MOS transistors, the white-noise current power is $2qI\Delta f$ (derived later) where I is the dc current level, q is the charge on the electron, f is the frequency, and Δf *is the bandwidth. In contrast, the flicker-noise current power is approximately* $KI^2\Delta f/f$, where K is a process- and geometry-dependent parameter. Thus, white noise dominates for $f > KI/2q$. For the noise measurements in this article, taken at current levels in the 100 fA to 100 pA range, white noise was the only noise observable even at frequencies as low as 1 Hz. Reimbold [8] and Schutte [9] have measured noise for higher subthreshold currents— greater than 4 nA— but have reported results from flicker-noise measurements only.

Our results, to our best knowledge, are the first reports of measurements of white noise in sub-threshold MOS transistors. We will show that they are consistent with our theoretical predictions. We also report measurements of noise in photoreceptors—circuits containing a photo diode and an MOS transistor— that are consistent with theory. The photoreceptor noise measurements illustrate the intimate connection of the equipartition theorem of statistical mechanics with noise calculations.

The measurements of noise corresponding to minuscule subthreshold transistor currents were obtained by conveniently performing them on a transistor with $W/L \approx 104$. The photoreceptor noise measurements were obtained by amplifying small voltage changes with a low-noise, high-gain, on-chip amplifier.

Shot Noise

Imagine that you are an electron in the source of an MOS transistor. You shoot out of the source, and if you have enough energy to climb the energy barrier between the source and the channel, you enter it. If you are unlucky, you might collide with a lattice vibration, surface state, or impurity, and fall right back into the source. If you do make it into the channel you will suffer a number of randomizing collisions. Eventually, you will actually diffuse your way into the drain. Each arrival of such an electron at the drain contributes an impulse of charge.

Similarly, electrons that originate in the drain may find their way into the source. Thus, there are *two independent* random processes occurring simultaneously that yield a forward current I_f from source to drain and a reverse current I_r from drain to source. Since the barrier height at the source is less than the barrier height at the drain, more electrons flow from the source to drain than vice versa and $I_f > I_r$.

$$
\begin{aligned}
I &= I_f - I_r \\
&= I_f e^{\frac{-V_{ds}}{U_T}} \\
\Rightarrow I &= I_f\left(1 - e^{\frac{-V_{ds}}{U_T}}\right) \\
&= I_{sat}\left(1 - e^{\frac{-V_{ds}}{U_T}}\right)
\end{aligned}
\tag{1}
$$

where I is the measured channel current, V_{ds} is the drain-to-source voltage, $I_f = I_{sat}$ is the saturation current of the transistor, and $U_T = kT/q$ is the thermal voltage.

Because the forward and reverse processes are independent, we can compute the noise contributed by each component of the current separately and then add the results. Thus, we first assume that I_r is zero, or equivalently that C_D — the concentration of electrons at the drain end of the channel— is zero. The arrival of electrons at the drain may be modeled by a Poisson process with an arrival rate, λ. A small channel length, L; a large channel width, W; a large diffusion constant for electrons, D_n; and a large concentration of electrons at the source, C_S, all lead to a large arrival rate. Because the current in a subthreshold MOS transistor flows by diffusion, the electron concentration is a linear function of distance along the channel, and the forward current, I_f, and arrival rate, λ, are given by,

$$I_f = q D_n W \frac{C_s}{L} \tag{2}$$

$$\lambda = I_f / q \tag{3}$$

Powerful theorems due to Carson and Campbell, as described in standard noise textbooks such as [10], allow us to compute the power spectrum of the noise. Suppose we have a Poisson process with an arrival rate of λ, and each arrival event causes a response $F(t)$ in a detector sensitive to the event. Let $s(t)$ be the macroscopic variable of the detector that corresponds to the sum of all the $F(t)$'s generated by these events. Then, the mean value of $s(t)$ and the power spectrum $P(f)$ of the fluctuations in $s(t)$ are given by

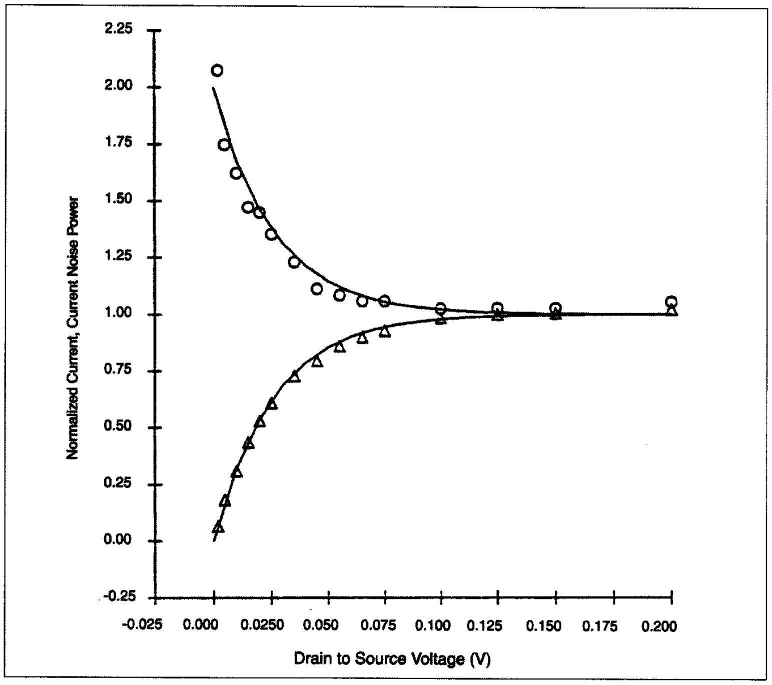
$$\overline{s(t)} = \lambda \int_{-\infty}^{\infty} F(t)dt \tag{4}$$

$$\overline{s(t) - \overline{s(t)}^2} = \lambda \int_{-\infty}^{\infty} F^2(t)dt \tag{5}$$

$$= \int_0^{\infty} P(f)df \tag{6}$$

$$= 2\lambda \int_0^{\infty} |\psi(f)|^2 df \tag{7}$$

where $\psi(f) = \int F(t)e^{-j2\pi ft}dt$ from the limits of minus to plus infinity, is the Fourier trans-



1. Measured current and noise characteristics of a subthreshold MOS transistor. The lower curve is the current normalized by its saturation value I_{sat} so that it is 1.0 in saturation and zero when V_{ds} is 0. The upper curve is the noise power ΔI^2 normalized by dividing it by $2qI_{sat}\Delta f$, where Δf is the bandwidth and q is the charge on the electron. As the transistor moves from the linear region to saturation, the noise power decreases by a factor of two. The lines are fits to theory using the measured value of the saturation current and the value for the charge on the electron $q = 1.6 \times 10^{-19}$ C.

form of $F(t)$. Each electron arrival event at the drain generates an impulse of charge q that corresponds to $F(t)$. Thus, we obtain

$$\bar{I} = q\lambda \tag{8}$$

$$\overline{(I-\bar{I})^2} = 2q^2\lambda\int_0^{\Delta f} df \tag{9}$$

$$= 2q\bar{I}\Delta f \tag{10}$$

where Δf *is the bandwidth of the system. Eq. 10 is the well-known result for the shot-noise power spectrum. Thus, the noise that corresponds to our forward current is simply given by* $2qI_f\Delta f$. Similarly, the noise that corresponds to the reverse current is given by $2qI_r\Delta f$. The total noise in a given bandwidth Δf *is given by*

$$\Delta I^2 = 2q(I_f + I_r)\Delta f$$
$$= 2qI_f\left(1 + e^{\frac{-V_{ds}}{U_T}}\right)\Delta f$$
$$= 2qI_{sat}\left(1 + e^{\frac{-V_{ds}}{U_T}}\right)\Delta f \tag{11}$$

where $I_{sat} = I_f = I_o \exp\{(\kappa V_g - V_s)/U_T\}$ corresponds to the saturation current at the given gate voltage. Note that as we make the transition from the linear region of the transistor ($V_{ds} < 5U_T$) to the saturation region, the noise is gradually reduced from $4qI_{sat}\Delta f$ to $2qI_{sat}\Delta f$. This factor of two reduction occurs because the shot-noise component from the drain disappears in saturation. A similar phenomenon occurs in junction diodes, where both the forward and reverse components contribute when there is no voltage across the diode. As the diode gets deeply forward or reverse biased, the noise is determined primarily by either the forward or reverse component respectively [11].

The flatness of the noise spectrum arises from the impulsive nature of the microscopic events. We might expect that the flat Fourier transform of the microscopic events that make up the net macroscopic current would be reflected in its noise spectrum. Carson's and Campbell's theorems express formally that this is indeed the case. The variance of a Poisson process is proportional to the rate, so it is not surprising that the variance in the current is just proportional to the current. Further, the derivation illustrates that the diffusion constant and channel length simply alter the arrival rate as described by Eq. 3. Even if some of the electrons recombined in the channel, corresponding to the case of a bipolar transistor or junction diode, the expression for the noise in Eq. 11 is unchanged. The arrival rate is reduced because of recombination. A reduction in arrival rate reduces the current and the noise in the same proportion. The same process that determines the current also determines the noise.

Experimental measurements were conducted on a transistor with $W/L \approx 10^4$ for a saturation current of 40 nA (Fig. 1). A gigantic transistor size was used to scale up the tiny subthreshold currents to levels between 10 nA and 1 μA and make them easily measurable by a low-noise off-chip sense amplifier with commercially available resistor values. The shot noise scales with the current level so long as the transistor remains in subthreshold.

The noise measurements were conducted with a HP3582A spectrum analyzer; the data were taken over a bandwidth of 0-500 Hz. The normalized current noise power $\Delta I^2/(2qI_{sat}\Delta f)$ and the normalized current I/I_{sat} are plotted in the figure. The lines show the theoretical predictions of Eqs. 1 and 11. Using the measured value of the saturation current, the value for the charge on the electron, and the value for the thermal voltage, we were able to fit our data with no free parameters whatsoever. Notice that as the normalized current goes from 0 in the linear region to 1 in the saturation region, the normalized noise power goes from 2 to 1 as expected. Fig. 2 shows measurements of the noise power per unit bandwidth $\Delta I^2/\Delta f$ *in the saturation region for various saturation currents* I_{sat}. Since we expect this noise power to be $2qI_{sat}$, we expect a straight line with slope $2q$, which is the theoretical line drawn through the data points. As the currents start to exceed 1 to 10 μA for our huge transistor, the presence of $1/f$ noise at the frequencies over which the data were taken begins to be felt. The noise is thus higher than what we would expect purely from white-noise considerations.

Shot Noise vs. Thermal Noise

We have taken the trouble to derive the noise from first principles even though we could have simply asserted that the noise was just the sum of shot-noise components from the forward and reverse currents. We have done so to clarify answers to certain questions that naturally arise:

- Is the noise just due to fluctuations in electrons moving across the barrier or does scattering in the channel contribute as well?
- Do electrons in the channel exhibit thermal noise?
- Do we have to add another term for thermal noise?

Our derivation illustrates that the computed noise is the total noise and that we don't have to add any extra terms for thermal noise. Our experiments confirm that this is indeed the case. The scattering events in the channel and the fluctuations in barrier crossings all result in a Poisson process with some electron arrival rate. Both processes occur simultaneously, are caused by thermal fluctuations, and result in white noise. Conventionally, the former process is labelled "thermal noise" and the latter process is labelled "shot noise." In some of the literature, the two kinds of noise are often distinguished by the fact that shot noise requires the presence of a dc current while thermal noise occurs even when there is no dc current [12]. However, we notice in our subthreshold MOS transistor that when $I_f = I_r$ there is no net current but the noise is at its maximum value of $4qI_f\Delta f$. Thus, a two-sided shot-noise process exhibits noise that is reminiscent of thermal noise. We will now show that *thermal noise is two-sided shot noise.*

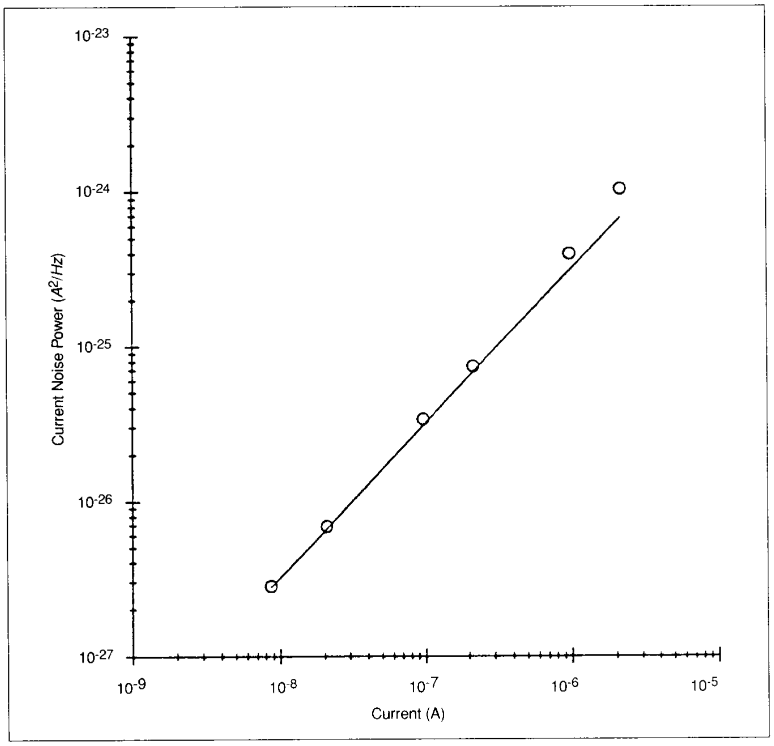
Let us compute the noise current in a resistor shorted across its ends. Since there is no electric field, the fluctuations in current must be due to the random diffusive motions of the electrons. The average concentration of electrons is constant all along the length of the resistor. This situation corresponds to the case of a subthreshold transistor with $V_{ds} = 0$, in which the average concentrations of electrons at the source edge of the channel, at the drain edge of the channel, and all along the channel are at the same value.

In a transistor, the barrier height and the gate voltage are responsible for setting the concentrations at the source and drain edges of the channel. In a resistor, the concentration is set by the concentration of electrons in the conduction band. The arrival rate of the Poisson process is, however, still determined by the concentration level, diffusion constant, and length of travel. This is so because, in the absence of an electric field, the physical process of diffusion is responsible for the motions of the electrons. Thus, the power spectrum of the noise is again given by $2q(I_f+I_r)$. The currents I_f and I_r are both equal to $qDnA/L$ where D is the diffusion constant of electrons in the resistor, n is the concentration per unit volume, A is the area of the cross section, and L is the length. Einstein's relation yields $D/\mu = kT/q$, where μ is the mobility. Thus, the noise power is given by

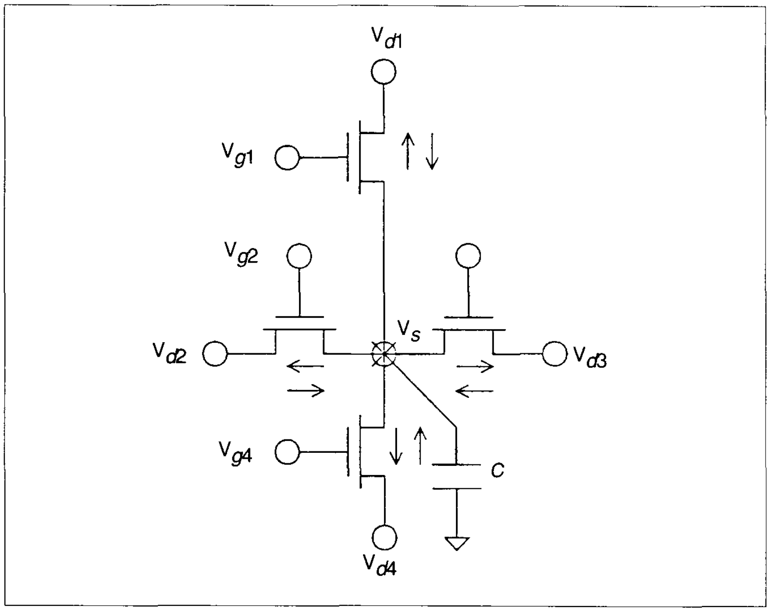
$$\begin{aligned}\Delta I^2 &= 4qI_f\Delta f \\ &= 4q\frac{q\,D\,n\,A}{L}\Delta f \\ &= 4q(\mu\,k\,T\,n)\frac{A}{L}\Delta f \\ &= 4kT(q\mu n)\frac{A}{L}\Delta f \\ &= 4kT(\sigma)\frac{A}{L}\Delta f \\ &= 4k\,T\,G\,\Delta f \end{aligned} \qquad (12)$$

where G is the conductance of the resistor and σ is the conductivity of the material. Thus, we have re-derived Johnson and Nyquist's well-known result for the short-circuit noise current in a resistor! The key step in the derivation is the use of the Einstein relation $D/\mu = kT/q$. This relation expresses the connection between the diffusion constant D, which determines the forward and reverse currents, the mobility constant μ, which determines the conductance of the resistor, and the thermal voltage kT/q.

Because of the internal consistency between thermal noise and shot noise, formu-



2. The noise power per unit bandwidth $\Delta I^2/\Delta f$ plotted vs. the saturation current I_{sat} for different values of I_{sat}. The MOS transistor is operated in saturation. Theory predicts a straight line with a slope of $2q = 3.2 \times 10^{-19}$ C, which is the line drawn through the data points. The small but easily discernible deviations from the line increase with higher levels of I_{sat} because of the increasing levels of 1/f noise at these current values.



3. A circuit with four transistors connected to a common node with some capacitance C. By convention the common node is denoted as the source of all transistors, and the forward currents of all transistors are indicated as flowing away from the node while the reverse currents of all transistors are indicated as flowing towards the node. Only the voltage V_s is free to fluctuate; all other voltages are held at fixed values so that the system has only one degree of freedom. The equipartition theorem of statistical mechanics predicts that if we add the noise from all transistors over all frequencies to compute the fluctuation in voltage ΔV_s^2, the total will equal kT/C no matter how many transistors are connected to the node or what the other parameters are, so long as all the noise is of thermal origin and the system is in thermal equilibrium.

las derived from purely shot-noise considerations, such as those in this article, agree with those derived from purely thermal-noise considerations [6].

Equipartition Theorem

No discussion of thermal noise would be complete without a discussion of the equipartition theorem of statistical mechanics, which lies at the heart of all calculations of thermal noise. We now explain how equipartition applies to noise calculations.

Every state variable in a system that is not constrained to have a fixed value is free to fluctuate. The thermal fluctuations in the current through an inductor or in the voltage on a capacitor are the ultimate origins of circuit noise. If the energy stored in the system corresponding to state variable x is proportional to x^2, then x is said to be a degree of freedom of the system. Thus, the voltage on a capacitor constitutes a degree of freedom, since the energy stored on it is $CV^2/2$. Statistical mechanics requires that if a system is in thermal equilibrium with a reservoir of temperature T, then each degree of freedom of the system will have a fluctuation energy of $kT/2$.

Thus, the mean square fluctuation ΔV^2 *in the voltage of a system with a single capacitor must be such that*

$$C\Delta\frac{V^2}{2} = kT/2$$
$$\Rightarrow \Delta V^2 = \frac{kT}{C} \tag{13}$$

This simple and elegant result shows that if all noise is of thermal origin, and the system is in thermal equilibrium, the total noise over the entire bandwidth of the system is determined just by the temperature and capacitance [13]. If we have a large resistance coupling noise to the capacitor, the noise per unit bandwidth is large but the entire bandwidth of the system is small; if we have a small resistance coupling noise to the capacitor, the noise per unit bandwidth is small but the entire bandwidth of the system is large. Thus, the total noise— the product of the noise per unit bandwidth $4kTR$ and the bandwidth of the circuit $1/RC$ is constant, independent of R. We illustrate for the example circuit of Fig. 3 how the noise from various devices interact to yield a total noise of kT/C.

Fig. 3 shows a network of transistors all connected to a capacitor C at the node V_s. We use the sign convention that the forward currents in each transistor flow away from the common source node and the reverse currents flow toward the common source node. (Our sign convention is for carrier current, not conventional current. Thus, in an NFET or a PFET the forward current is the one that flows away from the source irrespective of whether the carriers are electrons or holes. This convention results in a symmetric treatment of NFETs and PFETs). The gate and drain voltages V_{gi} and V_{di} are all held at constant values. Thus, V_s is the only degree of freedom in the system.

Kirchoff's Current Law at the source node requires that in a steady state

$$\sum_{i=1}^{n} I_f^i = \sum_{i=1}^{n} I_r^i \tag{14}$$

The conductance of the source node is given by

$$g_s = \sum_{i=1}^{n} \frac{I_f^i}{U_T} \tag{15}$$

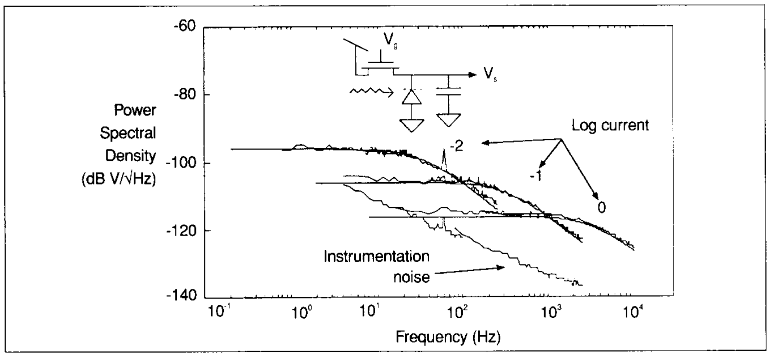
The bandwidth, Δf, *of the system is then*

$$\Delta f = \frac{1}{2\pi}\frac{\pi}{2}\frac{g_s}{C} = \frac{g_s}{4C} \tag{16}$$

where the factor $1/2\pi$ converts from angular frequency to frequency, and the factor $\pi/2$ corrects for the roll-off of the first-order filter not being abrupt. That is to say,

$$\int_0^\infty \frac{df}{1+\left(\frac{f}{f_c}\right)^2} = \frac{\pi}{2}f_c \tag{17}$$

Thus, the total noise is



4. Measured noise spectral density in units of dBV/√Hz (0 dBV = 1 V, -20dB = 0.1 V) for the voltage V_s in the circuit above. The current source is light-dependent and the curves marked 0, -1 and -2 correspond to bright light (high current), moderate light, and dim light (low current). The intensity levels were changed by interposing neutral density filters between the source of the light and the chip to yield intensities corresponding to 1.7 W/m², 0.17 W/m² and 0.017 W/m². The 1/f instrumentation noise was negligible over most of the range of experimental data. The noise levels and bandwidth of the circuit change so as to keep the total noise constant, so the areas under the curves marked 0, -1 and -2 are the same. The theoretical fits to the low-pass-filter transfer functions are for a temperature of 300 K and a capacitance of 310 fF, estimated from the layout. These results illustrate that the kT/C concept, derived from the equipartition theorem in the text, is a powerful one.

$$I^2 = \sum_{i=1}^{n} 2q(I_f^i + I_r^i)\frac{g_s}{4C} = \sum_{i=1}^{n} 4qI_f^i\frac{g_s}{4C} \quad (18)$$

where we have used Eq. 14 to eliminate I_r. The voltage noise is just $\Delta I^2/g_s^2$ or

$$\Delta V_s^2 = \frac{\frac{q}{C}\sum_{i=1}^{n} I_f^i}{\sum_{i=1}^{n}\frac{I_f^i}{U_T}} = \frac{kT}{C} \quad (19)$$

The fact that the total noise equals kT/C implies that this circuit configuration is a system in thermal equilibrium. Typically, other circuit configurations yield answers for total voltage noise that are proportional to kT/C.

We obtained direct experimental confirmation of the kT/C result from our measurements of noise in photoreceptors: Fig. 4 shows a source-follower configuration that is analogous to the case discussed previously with two transistors connected to a common node. The lower current source is a photo-diode, which has current levels that are proportional to light intensity. The voltage noise is measured at the output node V_s. The voltage V_g is such that the MOS transistor shown in the figure is in saturation. The photo diode contributes a shot-noise component of $2qI\Delta f$. Thus, we obtain equal shot-noise components of $2qI\Delta f$ from the transistor and the light-dependent current source. The theory described above predicts that, independent of the current level, the total integrated noise over the entire spectrum must be the same. As the current levels are scaled down (by decreasing the light intensity), the noise levels rise but the bandwidth falls by exactly the right amount to keep the total noise constant. The system is a low-pass filter with a time constant set by the light level. Thus, the noise spectra show a low-pass filter characteristic. The voltage noise levels $\Delta V_s 2$ *are proportional to* $\Delta I^2/g_s 2$ or to $1/I$, and the bandwidth is proportional to g_s and therefore to the photocurrent I. Thus, the product of the noise per unit bandwidth and the bandwidth is proportional to the total noise over the entire spectrum and is independent of I. Hence, the area under all three curves in Fig. 4 is the same. The smooth lines in Fig. 4 are theoretical fits using a temperature of 300 K and a capacitance value estimated from the layout.

It is possible to extend our way of thinking about noise to the above-threshold region of MOS operation, but the mathematics is more difficult because the presence of a longitudinal electric field causes non-independence between the noise resulting from the forward and reverse currents. Further, the modulation of the surface potential by the charge carriers results in a feedback process that attenuates fluctuations in the mobile charge concentration— an effect referred to as space-charge smoothing.

Conclusion

The key ideas of our article begin with the derivation of a new formula for noise, Eq. 11, that is valid in the subthreshold region of operation of the MOS transistor. The noise is essentially the sum of shot-noise components from the forward and reverse currents. This noise is the total thermal noise, and no further terms need be added to model thermal noise. This view of thermal noise as a two-sided shot-noise process is fundamental, and we showed that Johnson and Nyquist's well-known expression for thermal noise in a resistor may be viewed in the same way. Thus, this article developed a unifying view of thermal noise and shot noise.

The predictions of the formula were confirmed by experimental measurements. We discussed the equipartition theorem of statistical mechanics and its relation to thermal noise, and showed how our formula and experimental measurements were consistent with its predictions. Finally, we concluded with a brief discussion of the considerations involved in extending our ideas to above-threshold operation in order to develop a single comprehensive theory of noise for the MOS transistor.

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Cover page: One tile of a gigantic transistor on a microchip (width 1 inch, length = 8 microns) used to make noise measurements of what would be miniscule currents (100 x 10^{-15} to 100 x 10^{-12} A) in a normal transistor. Figure at bottom is a vertical crossection along the horizontal line near top of chip.