Random Electrical Noise: A Literature Survey

Research Comments from Ciphers By Ritter

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INTRODUCTION

Comments on the production, processing, detection and conversion to uniform distribution.

Producing Electronic Noise

If we wish to generate and use electrical noise, we have two main sources: Thermal and Shot. Both are fundamental sources of "white" noise, meaning that we have a deep statistical understanding of how these sources behave. Unfortunately, this may not be particularly useful if the noise we have is actually due to variable processing-related problems.

- Thermal or Johnson noise results from the Brownian motion of ionized molecules within a resistance. Thermal noise is entirely fundamental and cannot be eliminated (although the effect can be reduced by reducing or cooling the resistance).

  Carbon-composition resistors may give more noise than expected; this added noise is from device fabrication, varies widely in production, and is not necessarily "white." Thus, carbon-film, metal-film or wirewound resistors are more satisfactory thermal noise sources.

  To verify that a noise source is indeed producing thermal noise, it may be useful to "short out" the source resistance and verify a marked reduction in resulting noise (hopefully to under 1/10 of the original value). This of course implies an ability to quantify the mean amplitude of the noise signal.

- Shot noise typically results from the flow of electrons through a highly-charged field (like a vacuum tube or semiconductor junction) that makes the exact motion of each electron independent. Ultimately, electron flow is the movement of discrete charges, and surrounding the mean flow rate is a distribution related to the launch time and momentum for individual charge carriers entering the charged field.

> Shot noise is fundamental, so no true zener can be noiseless, and any especially "noisy" zener must be producing something *beyond* shot noise. Since other noise sources (especially contact noise) are typically related to device fabrication and are not necessarily "white," this "extra" noise should be avoided. We should thus seek the *lowest*-noise zeners for noise sources. Since zener noise levels will vary with current and temperature, some form of automatic gain control (AGC) may be necessary.
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> As a current, shot noise is proportional to square-root current. But as a voltage across a semiconductor junction, shot noise is proportional to the *inverse* of square-root current (see Haitz and Voltmer and Vergers). For small currents, effects other than shot noise may dominate. To verify that a semiconductor junction is producing shot noise, it may be helpful to increase the current by 100x and measure the resulting noise voltage at 1/10 the original value. This of course implies an ability to quantify the mean amplitude of the produced noise signal.

The various other properties we might measure -- such as the time between zeros (or any other level) does not seem to give us any particular distribution advantage. Possibly we could show that "any" sort of noise is sufficient for some sort of sampling to produce one uniformly distributed bit, but this has not been established.

Post-Production Analog Processing

It will be necessary to greatly amplify the noise in a linear broadband manner. This is harder than it sounds, because common self-compensated op-amps will have a 6 dB/octave rolloff for stability, and we may need 60 dB total amplification flat to perhaps MHz frequencies. (The bandwidth will define the width of the minimum pulse and the maximum rate at which the noise can be sampled.) It would seem that producing ideal noise from a fundamental source is of little help if we modify the result prior to detection.

On the other hand, actual experiments with shot noise sampled in the audio range by a PC sound system show an unexpected degree of autocorrelation between samples. Essentially, this is the ability to partially predict future values based on known past values, and thus represents a much lower entropy than we might otherwise think. Experimentally, it appears that using the difference between sample values, instead of the raw values themselves, reduces the problem. Since this may be equivalent to a digital high-pass filter, a non-flat high-pass response may be more desirable than we might have previously thought.

The noise output from zener diodes tends to vary through time and especially temperature. Even with thermal noise, some form of automatic gain control is probably necessary over production and time, and will imply some amount of short-term amplitude correlation.

Detection and Conversion to Uniform Distribution

A white noise source should have a gaussian or normal distribution of instantaneous amplitude, and I assume that the best-quality distribution defines the best-quality source. However, there are many different gaussian distributions, as parameterized by the mean and standard deviation. Which of the possibilities we actually get depends upon the noise source and sampling machinery, so this is not an easy general way to produce values in a particular normal distribution.

An easy way to convert to the flat distribution is to hash the full sample values into a hash result, which is then used as a flat random value. The hash does not have to be "cryptographic," since even a simple hash is non-reversible, provided much more information is hashed than used. Nor is a supposed inability to construct particular hash values useful in this application. Because a simple CRC can be deeply understood without assumptions, it is superior in this application to the usual ad-hoc cryptographic hash which only functions as we expect if various unproven assumptions are true.

On the other hand, suppose we adjust detection amplitude so that the noise signal is above detection exactly half the time (this probably implies some sort of automatic control, which also implies a small amount of short-term amplitude correlation). If we then sample at random times (with a wide random period between samples), we can produce one uniformly-distributed bit per sample. However, it is difficult to guarantee that any repetitive process will sample "at random times." And adjacent close samples may support unwanted correlations.

If we can detect individual noise pulses, we can assume that the number of pulses which arrive in a particular time is Poisson distributed. By increasing the detection amplitude until few pulses are detected (on average) and counting the pulses in a given time, we can get a Poisson distribution of pulse-count values. (There will always be some pulses too close together to discriminate and count separately, but we can reduce this effect with wide bandwidth, high-speed detection, and large counts.) Then we can output the parity of the current count to get one (almost) uniformly distributed random bit. We note that this method does not require random sampling times, something difficult to require of a repetitive machine.

Verification

A serious problem with many noise-based generators is that the analog noise is buried deep inside and cannot be seen or measured by the user. This is a problem because what we want from such a generator is a guarantee that the output depends upon unpredictable quantum events. If we were satisfied with random source that merely passed tests, we could easily use any one of the many deterministic statistical random number generators (RNG's) designed to pass such tests. What we want and expect is beyond what can be tested externally.

What is needed is the ability to turn off the quantum source, and see the output change. If we cannot do that, we cannot be sure that the particular device we have really does depend upon quantum information.

To verify correct operation of the noise source we might collect and verify either or both Gaussian amplitude and Poisson pulse-count distributions during normal operation. (This is in addition to some hardware check to verify that the detected noise is produced by the expected source.)

Contents

1944 -- Rice

Rice, S. 1944. Mathematical Analysis of Random Noise. *Bell System Technical Journal.* 23: 282-332. 24: 46-156.

Expected Zeros Per Second

"For an ideal band-pass filter whose pass band extends from f_a to f_b the expected number of zeros per second is"

$$2 \, [1/3 \, (f_b^3 - f_a^3) \, / \, (f_b - f_a)]^{1/2}$$

"When f_a is zero this becomes 1.155 f_b, and when f_a is very nearly equal to f_b it approaches $f_b + f_a$."

Expected Maxima Per Second

"For a band-pass filter the expected number of maxima per second is"

$$[3/5 \, (f_b^5 - f_a^5) \, / \, (f_b^3 - f_a^3)]^{1/2}$$

"For a low-pass filter where $f_a = 0$ this number is 0.775 f_b."

"The expected number of maxima per second lying above the line $I(t) = I_1$ is approximately, when I_1 is large,"

$$e^{-I_1^2/2 \, psi0}$$

"where *psi0* is the mean square value of $I(t)$."

1948 -- MacDonald

> MacDonald, D. 1948. The Brownian Movement and Spontaneous Fluctuations of Electricity. *Res. Appl. in Industry.* 1: 194-203.
>
> Also reprinted in: *Electrical Noise: Fundamentals and Sources.* 1977. M. Gupta, Ed. IEEE Press. 7-16.

"In 1827 the biologist Robert Brown was studying under his microscope the pollen grains, some 0.0002 inch in length, of the plant *Clarckia pulchella.*

> 'While examining the form of these particles immersed in water, I observed many of them very evidently in motion. These motions were such as to satisfy me . . . that they arose neither from currents in the fluid, nor from its gradual evaporation, but belonged to the particle itself.'"

". . . it became clear that the effect was entirely fundamental, and A. Einstein, in a series of classical papers, was the first to provide a clear analysis of the problem as arising from continuous and random molecular bombardments . . . ."

". . . von Nageli in 1879 had considered the possibility of molecular bombardment but had concluded because the impulse due to one collision was so minute, that this could not be the cause; for he opined that since all directions in space are equally likely the cumulative effect of many random collisions could only be of the same magnitude. The error is a common one and arises essentially from implicitly regarding a random process as made up of regularly alternating favourable and unfavourable events;

such a process is, however, a highly ordered one and it is those very 'runs' of favourable (or unfavourable) events, which we sometimes regard as against the 'laws of chance', which characterize a random process and give rise to the relatively large fluctuations observed."

"The essentials are well illustrated by the fundamental 'random walk' problem, as first posed by Karl Pearson in 1905. A man (presumably very drunk) takes steps of equal length, l, from a starting point O on after the other in successively random directions. Where is he likely to be after n steps? Lord Rayleigh answered the problem immediately where n is large; the probability that he is at a distance between r and r+dr from his starting point is

$$p(r)dr = (2r/nl^2)e^{-(r^2/nl^2)}\,dr.$$

"His average distance is therefore *[the integral from 0 to infinity of r * p(r) dr, or]*

$$(pi^{1/2})/2 * (nl)^{1/2}$$

"and thus increases with the square root of the time for which he continues the walk . . . ."

[It appears that the Rayleigh distribution models noise in the sense of peak amplitude over time./tfr]

1955 -- Burgess

Burgess, R. 1955. Electrical fluctuations in semiconductors. *British J. Appl. Phys.* 6: 185-190.

Also reprinted in: *Electrical Noise: Fundamentals and Sources.* 1977. M. Gupta, Ed. IEEE Press. 59-64.

SHOT NOISE

"The term 'shot noise' was originally applied to the fluctuations of current in a saturated vacuum diode due to the randomness of electron emission from the cathode." "At low frequencies such that the electron transit time *t* is small compared with (1 / w), the *[Fourier]* transform *F(f) ~ e* and the spectral density assumes the simple form (2 e I). The concept of randomness of rate of emission implies that the process is determined by a stationary Poisson distribution."

"Another important instance of shot noise arises in the other extreme from a uniform semiconductor, namely the motion of carriers across a high-field transition region, e.g. at a metallic contact or at a *p-n* junction. Normally the carrier velocities in such a region would be of the order of 10^7 cm/s and the width of the region would lie in the range of 10^{-5} to 10^{-3} cm so that the transit time would be negligible except at the highest microwave frequencies. Furthermore it may be readily shown that since the change in quasi-Fermi level for the carriers across the transition region is very nearly equal to the applied voltage, the effect of each electron transit is effectively to induce a current impulse *ed(t)*, and thus full shot noise may be attributed to the flow."

AVALANCHE NOISE

"When a barrier region is subjected to reverse bias the electric field may reach the order of 10^5 V/cm or greater, and at these fields there occur phenomena which cause a rapid increase of current and eventual breakdown; it has furthermore been observed that the current is 'noisy' in this region, becoming increasingly impulsive as breakdown is approached."

"In silicon junctions McKay[14] observed that at the onset of breakdown there appears a distinctive form of impulsive noise consisting of a random sequence of rectangular current pulses of variable duration but constant amplitude." "It is possible that the inevitable inhomogeneity of the semiconductor in the neighbourhood of the junction gives rise to small regions (or 'weak spots') in which breakdown occurs for lower applied voltage than elsewhere and this localized breakdown will switch from an 'off' to an 'on' condition and back again, triggered by random fluctuation."

1956 -- Pierce

> Pierce, J. 1956. Physical Sources of Noise. *Proc. IRE.* 44: 601-608.
>
> Also reprinted in: *Electrical Noise: Fundamentals and Sources.* 1977. M. Gupta, Ed. IEEE Press. 51-58.

"Shot noise, due to the discrete nature of electron flow, is generally distinct from Johnson noise, although in some electron devices the expression for the noise in the electron flow has the same form as that for Johnson noise. When the noise in the electron flow is greater or less than pure shot noise, the motions of the electrons must be in some way correlated. In an electron stream of low noise, the random interception of a fraction of the electron flow can reduce the correlation and increase the noise. Johnson noise and shot noise have a flat frequency spectrum."

"Many sorts of electrical signals are called noise." ". . . many engineers have come to regard any interfering signal of a more or less unpredictable nature as noise." "The theory of noise presented here is not valid for all signals or phenomena which the engineer may identify as noise."

"The theory of noise is best adapted to handling signals which originate in truly random processes, such as the emission of electrons from a photo-surface or a hot cathode, or the thermal agitation of charges in a resistor. When a cathode emits electrons at so slow a rate that we observe their effects in a circuit as separate pulses, we have *impulse noise,* and the theory of noise has something to say about this. When electrons are randomly emitted so rapidly that the pulses they produce in the circuit overlap, the statistics of large numbers applies, and the theory of noise tells us a great deal that must be true of a large class of noise signals, despite differences in the exact nature of their sources."

Johnson Noise

"The first source of noise which we consider is Johnson noise, the thermal noise from a resistor. The engineering fact is that a resistor of resistance R acts like a noise generator."

$$V^2 = 4\ k\ T\ R\ B$$
$$I^2 = 4\ k\ T\ G\ B = 4\ k\ T\ B\ /\ R$$

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R = resistance, ohms
G = 1/R = conductance, mhos
B = bandwidth, Hz
k = Boltzmann's constant, 1.380E-23 joules / deg. K
T = temperature in deg. K, or deg. C + 273
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"What is the source of Johnson noise? In an ordinary resistor, it is a summation of the effects of the very short current pulses of many electrons as they travel between collisions, each pulse individually having a flat spectrum. In this case the noise is a manifestation of the Brownian movement of the electrons in the resistor."

Shot Noise

"Electricity is not a smooth fluid; it comes in little pellets, that is, electrons. The flow of electrons in a vacuum tube is accompanied by a noise of the same nature as the patter of rain on a roof. Schottky, who first investigated this phenomenon, called it *Schroteffekt* (from shot); it is now usually called simply *shot noise*."

"Like Johnson noise, shot noise has a flat spectrum. This is really what we should expect of a random collection of very short pulses, each of which has a flat spectrum."

$$I^2 = 2\ e\ I_0\ B$$

e = electron charge, 1.60E-19 coulombs
I_0 = dc current, Amps
B = bandwidth, Hz

Noise with a 1 / *f* Spectrum

"A noise made up of a random sequence of short pulses, or impulses, as are Johnson noise and shot noise, has a flat spectrum. A noise made up of a random sequence of step functions would have a $1 / f^2$ spectrum. This is because a step is the integral of an impulse, and the amplitude of any frequency component of the step is 1 / (2 pi *f*) times that impulse. If the amplitude varies as 1 / *f*, the power will vary as $1 / f^2$.

1962 -- Ragazzini and Chang

Ragazzini, J and S. Chang. 1962. Noise and Random Processes. *Proc. IRE.*

50: 1146-1151.

Also reprinted in: *Electrical Noise: Fundamentals and Sources.* 1977. M. Gupta, Ed. IEEE Press. 25-30.

"In most systems which are of interest to the engineer and the designer, random processes are assumed to be Gaussian or at least assumed to be satisfactorily approximated by such a distribution." ". . . a random signal or noise is usually generated by a large number of independent events . . . ." "It follows from the central limit theorem in probability that . . . the amplitude of such a signal *[is]* normally distributed . . . ."

1964 -- Gray, et. al.

Gray, P., D. DeWitt, A Boothroyd and J. Gibbons. 1964. *Physical Electronics and Circuit Models of Transistors.* Semiconductor Electronics Education Committee, Volume 2. John Wiley and Sons.

4.4 JUNCTION BREAKDOWN

"In all real diodes there is a limiting value of reverse voltage beyond which the reverse current increases greatly without significant increase of reverse voltage." (p. 63)

"The abrupt breakdown of silicon and well-cooled germanium types has a useful non-destructive range [...]. Such diodes are widely used as voltage regulators, and devices intended for this service are called *Zener diodes* or *breakdown diodes*. (p. 64)

"There are two electronic breakdown mechanisms in the bulk semiconductor which can cause a voltage-saturated breakdown--Zener breakdown and avalanche breakdown. Zener breakdown is a direct disruption of interatomic bonds in the space-charge layer by very high electric fields (greater than 10^6 volts/cm), which produces mobile hole-electron pairs. It is the mechanism of breakdown in good crystalline insulators and it occurs in abrupt junctions between highly doped regions. Avalanche breakdown occurs when the acceleration of carriers in the space-charge region is great enough to cause ionizing collisions with atoms, thus producing mobile hole-electron pairs. Since avalanche multiplication can occur at electric fields appreciably lower than those required for Zener breakdown, avalanche breakdown will occur before the Zener voltage can be reached, except in diodes with very large impurity concentrations. Silicon voltage-regulator diodes which break down above 8 volts probably use the avalanche mechanism, whereas those which break down below 5 volts work by Zener breakdown. Between 8 and 5 volts the dominating mechanism depends on the exact impurity distribution at the junction. Both mechanisms can be present in the same diode. Note that the term *Zener diode* is often used without regard to the mechanism to identify a diode intended to operate at breakdown." (p. 65)

4.4.1 *Theory of Avalanche Multiplication*

"Avalanche multiplication occurs when the electric field in the space-charge layer is large enough so that carriers traversing the region acquire sufficient energy to break covalent bonds in their collisions with the crystal structure. Every such ionizing collision produces a hole and an electron, each of which is accelerated by the field and has a possibility of producing another ionizing collision before it leaves the space-charge region. Neglecting recombination in the layer, all the carriers produced will contribute to the total reverse current." (p. 65)

". . . the average rate at which pairs are produced by impact ionization depends not only on the electric field, but also on the distance the carrier travels. Thus, when the impurity concentration is increased, the width of the space-charge layer decreases [...] and the peak electric field at breakdown decreases." (pp. 67-68)

4.2.2 *Zener Breakdown*

"Diodes with very large values of impurity concentration have narrow space-charge regions and develop high fields at low applied voltage. As the reverse voltage increases, both the electric field and the width of the space-charge layer increase. The field reaches a large enough value to cause Zener breakdown before the width of the space-charge region is sufficient to permit avalanche breakdown. Zener breakdown is the direct disruption of covalent bonds by the electric field force, and does not require acceleration of a primary carrier by the field. Hence, the Zener breakdown voltage depends only on the maximum field and not on the length of the path in the depleted region. Zener breakdown occurs at fields of the order of 10^6 volts/cm, which are reached in abrupt junctions in silicon when the doping is about 10^{18} atoms/cm^3 and the reverse bias is about 5 volts. In such a diode, both Zener and avalanche breakdown occur simultaneously. As the doping is further increased, the path length at breakdown drops, and only the Zener mechanism prevails." (pp. 68-69)

"A very reasonable question at this point is whether [donor and acceptor doping levels] can be increased to the point where the field associated with the built-in potential barrier [...] *alone* will cause Zener breakdown, so that the diode will be a short circuit with no applied voltage. While we have not studied the theory needed to understand such devices in detail, they do indeed exist. Diodes which break down at $V = 0$, or at slight reverse bias, are called *backward diodes* because they conduct by Zener breakdown with small reverse voltage, but do not begin to show much normal diode forward conduction until an appreciable fraction of a volt of forward bias is applied. Hence, over a small voltage range, they appear like diodes which conduct when the *n*-type side is made positive. More heavily doped diodes which are still in breakdown with some forward bias are called *Esaki* or *tunnel diodes*. Until enough forward bias is applied they conduct well, as though still in breakdown. As forward bias increases, a point is reached at which [the difference between the potential barrier and the applied voltage] no longer is large enough to provide the conducting mechanism and forward current *falls* with increasing forward bias. Consequently, there is a negative resistance region. The current falls to a low value and then rises as the diode enters the region of normal conduction." (p. 69)

1965 -- Oliver

Oliver, B. 1965. Thermal and Quantum Noise. *Proc. IRE.* 53: 436-454.

Also reprinted in: *Electrical Noise: Fundamentals and Sources.* 1977. M. Gupta, Ed. IEEE Press. 129-148.

Statistics of Thermal Noise

". . . any linearly filtered or amplified thermal noise wave has a Gaussian distribution of instantaneous amplitude."

"Usually the Gaussian amplitude distribution of thermal noise is developed on the basis of a model source containing a very large number of independent generators each of which produces an infinitesimal contribution to the resultant amplitude. For example, in a resistor, each conduction band electron as it is buffeted about produces a random current wave. The total current is then shown to have a Gaussian distribution by the Central Limit Theorem."

". . . the envelope, A(t), *[that is, the peak amplitude]* of any thermal noise wave has a Rayleigh distribution . . . ."

Shot Noise

"Whenever discrete particles arrive at random times there will be fluctuations in the rate of arrival. It is these fluctuations that constitute shot noise."

"Let us assume that a particle is equally likely to arrive at any time, and that the average rate of arrival is r." "Under these conditions the numbers of arrivals in a given length of time are distributed according to the well-known Poisson distribution."

". . . when the average number of arrivals during the observing time is large, the fluctuations will approach a Gaussian distribution about the mean with sigma = $n^{1/2}$."

1966 -- Thornton et. al.

Thornton, R., D. DeWitt, E. Chenette and P. Gray. 1966. *Characteristics and Limitations of Transistors*. Semiconductor Electronics Education Committee, Volume 4. John Wiley and Sons.

4 *Noise*

4.0 INTRODUCTION

"'Noise' is a term used to signify extraneous signals which do not convey any useful information for the problem at hand, and which can only be described by their statistical properties." (p. 134)

4.1 ANALYSIS INVOLVING NOISE SOURCES

4.1.1 *Introduction*

"Noise sources are unpredictable in the sense that instantaneous waveforms can not be predicted over any significant interval of time. One can, however, describe noise sources in statistical terms, such as probabilities, mean-square values, and correlation functions." (p. 135)

4.1.3 *Spectral Density*

"The voltage wave from a noise source *v(t)* will contain a great many frequency components. To indicate how these components are distributed as a function of frequency, we may plot what is called the *spectral density*, a graph versus frequency of *mean-square noise voltage per unit bandwidth*. This graph might be obtained by feeding the source into a filter which passes unattenuated all frequencies in a band delta-*f* centered at f_0, and completely rejects all other frequencies."

"Because the ordinary Fourier transform for a random signal is not defined (because it does not, in general, yield convergent integrals), we cannot use conventional Fourier techniques to find the spectral density of the noise. Instead, we must first form the *autocorrelation function* of *v(t)* is defined as

```
R(tau) = limit as T -> infinity of                    (4.3)
         1/(2 T) x integral from -T to T of
         v(t)v(t + tau)dt
```

The spectral density is then by definition the Fourier transform *W(f)* of the autocorrelation function *R(tau)*. That is

$$W(f) = \text{integral from -infinity to +infinity of } R(tau)\ e^{-(j)(2pi)(f)(tau)}\ d(tau) \qquad (4.4a)$$

For real time functions, *R(tau)* is a real, even function of *tau*. Thus, *W(f)* can be written as

```
W(f) = integral from -infinity to +infinity of     (4.4b)
       R(tau) cos(2pi)(f)(tau) d(tau)
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"It is clear . . . that because *R(tau)* is real, *W(f)* is a real, even function of *f*; that is, *W(f) = W(-f)*." (pp. 136-137)

"The spectral density *W(f)*, defined above, is a 'two-sided' representation; that is, it is defined in terms of both positive and negative frequency. However, by convention in noise analysis, the spectral density is defined in terms of positive frequency only (i.e., 'one-sided'). Because of the fact that *W(f) = W(-f)*, as shown above, conversion from the two-sided representation to the one-sided spectral density, designated here as *S(f)*, involves nothing more than multiplying by a factor of two to account for the contributions of *W(f)* at negative frequencies." (p. 137)

4.2 NOISE IN A *pn* JUNCTION DIODE

4.2.1 *Shot Noise in Reverse Bias*

"If a *pn* junction is several volts back-biased, then, roughly speaking, all the minority carriers within one diffusion length of the junction will move by diffusion into the space-charge region and be attracted across it by the high electric field. These carriers create a current; but, because of the discrete nature of the electronic charge, the current will appear to a first approximation as a series of impulses . . . . The time at which any one carrier traverses the junction is statistically independent of the time that any other carrier traverses the junction, and thus the current pulses can be assumed to be completely independent of one another. As stated in Sec. 4.1.3, we find the spectral density of this current waveform by finding first the autocorrelation function, defined in this case as" (p. 138)

```
R(tau) = limit as T -> infinity of
         1/(2 T) x integral from -T to T of
         i(t) i(t + tau)dt
```

"The spectral density of the current, $S_i(w)$, will be the Fourier transform of this *R(tau)*." (p. 140)

"In actual fact, the current waveform will not consist of impulses. When an electron crosses the space-charge layer, it induces a current waveform more closely resembling a square pulse." "The . . . width of the pulse is determined by the time it takes the electron to move across the space-charge region. Typically, the field is large enough so that the carriers reach a saturation velocity in the order of 10^7 cm/sec. Thus they move with a constant velocity and the current pulse is approximately square . . . . The exact shape of these pulses is not of prime importance here, but it is significant that *the pulses have a width on the order of the transit time* T_t *through the space-charge layer*." (p. 140)

". . . except for the dc component which does not concern us here, the spectral density has a relatively constant value of $2nq^2$ out to a frequency $f = 1/10T_t$. Thus we can consider the spectral density of the noise to be flat for all frequencies of interest in transistor circuits, i.e., below f_T ."

"On the basis that the dc current flowing through the diode is $i(t) = I_0 = nq$ *[with n being the average number of pulses per second]*, we led to the important conclusion that the spectral density of shot noise in a reverse-biased *pn* junction is virtually constant at a value

$$S_i(f) = 2\ q\ I_0$$

for f above 0." (p. 141)

4.2.2 *Shot Noise for Forward Bias*

"For a forward bias, we can resolve the diode current into two physically distinct components. On the basis of the diode equation

$$I = I_0 (e^{q^{V/kT}} - 1)$$

these components are

$$I_1 = -I_1$$
$$I_2 = I_0 e^{q^{V/kT}}$$

where I_1 is the reverse saturation current arising from thermally-generated carriers on each side, and I_2 arises from the diffusion of majority carriers against the potential barrier on each side. Whereas the average values of these currents tend to oppose each other in the total current, the noise components associated with these currents, being uncorrelated, will add in a mean-square sense." (p. 142)

"We thus conclude that a strongly forward-biased *pn* junction exhibits the full shot noise associated with its average current.

"In zero bias, and therefore with the junction in *thermal equilibrium*, the two currents I_1 and I_2 . . . cancel on the average, but their noise components are still independent, and add in a mean square sense." "So . . . we find . . . for low enough frequencies the spectral density

$$S_i(f) = 4\ q\ I_0\ .$$

Thus, the noise is identical to shot noise associated with a dc current twice as large as the reverse saturation current of the diode. Since, in fact, there is no dc current flowing under the assumed zero-bias conditions, it is convenient to eliminate I_0 . . . by rewriting in terms of the incremental diode conductance. On differentiating . . . we obtain

$$g_0 = dI / dV \text{ at } V = 0\ .$$

Thus

$$S_i(f) = 4\ k\ T\ g_0$$

." (p. 143)

1968 -- Haitz and Voltmer

Haitz, R. and F. Voltmer. 1968. Noise of a Self-Sustaining Avalanche Discharge in Silicon: Studies at Microwave Frequencies. *J. Appl. Phys.* 39: 3379-3384.

Also reprinted in: *Electrical Noise: Fundamentals and Sources.* 1977. M. Gupta, Ed. IEEE Press. 327-332.

"The studies of avalanche noise reported by Haitz are extended to frequencies up to and above the avalanche frequency w_a. It is found that the open-circuit spectral voltage density is flat within +/- 5% from less than 100 Hz up to frequencies approaching w_a."

"During the studies of low-frequency avalanche noise it became evident that special precautions have to be taken in order to prevent the generation of excessive noise resulting from nonuniform breakdown. The combination of both a guard ring to prevent edge breakdown and a small breakdown area to reduce material nonuniformities have led to satisfactory results."

"At currents below 2.5 mA the measured noise is larger than the noise predicted . . . . This discrepancy, which is typical for avalanche diodes at low current densities, is not serious. It is caused by extremely small nonuniformities of the breakdown voltage."

Fig. 2 is a graph of "Open Circuit Spectral Voltage Density" in nV/SQRT(Hz) versus "Current" in mA. At 1 mA the graph shows about 100 (nV), at 10 mA about 40, and at 0.1 mA theory indicates about 400, but the actual device shows much more. For currents of 2.5 - 20 mA, theoretical and experimental avalanche noise thus decrease with increased current. Across the graph range, theoretical noise appears to decrease by a factor of 10 with a current increase of 100.

1969 -- Gray and Searle

Gray, P., and C. Searle. 1969. *Electronic Principles: Physics, Models, and Circuits.* John Wiley & Sons.

6.5.1 Breakdown Diodes

"All junction diodes exhibit a region of behavior in the reverse direction in which large reverse currents can flow if the reverse voltage exceeds a value referred to as the *reverse breakdown voltage*. (p. 231)

"Reverse breakdown in *pn* junctions may arise from either of two mechanisms . . . . (p. 232)

"One mechanism that causes reverse breakdown in *pn* junctions is *avalanche multiplication*. The carriers that constitute the normal reverse current of a junction flow across the space-charge layer from the regions where they are in the minority to the regions where they are in the majority. Thus they move down the potential barrier at the junction and are accelerated between collisions by the field there. If the field is large enough (in the range of 2 x 10^5 volts/cm) the energy that these carriers acquire from the field between collisions is sufficient to produce a hole-electron pair when the energy is transferred to the crystal during a collision. Thus a single carrier can produce another pair of carriers, which in turn flow out of the space-charge layer and contribute to the reverse current. These *secondary carriers* can produce other pairs or *tertiary carriers* through their own collisions with the lattice. In this way the reverse current is multiplied and can become quite large." (p. 232)

"The second mechanism of junction breakdown is called *Zener breakdown*. If the electric field in the space-charge layer is strong enough (in the range of 5×10^5 volts/cm) the force that it exerts on bound or valence electrons is sufficient to strip some of those electrons away from the valence bonds, thereby creating hole-electron pairs that contribute to the reverse current. There is no multiplication effect involved in this mechanism; the pairs are produced directly by the field and not through the action of a primary carrier.

"Silicon junction diodes that are relatively lightly doped have breakdown voltages in the range of tens or hundreds of volts. In such diodes the breakdown current is produced by avalanche multiplication. Diodes that are more heavily doped have lower breakdown voltages; the space-charge layer is thinner and the electric field is larger for the same applied voltage, and avalanche multiplication sets in at lower voltages. Diodes that are very heavily doped have breakdown voltages as small as one or two volts. In such diodes the breakdown current is produced by the Zener mechanism; the electric field is very high, and the space-charge layer is so thin that carriers spend too little time in the space-charge layer to produce significant numbers of secondary carrier pairs. Diodes that break down for reverse voltages in the range of 6 to 8 volts have both mechanisms operating simultaneously.

"Note that although both avalanche and Zener mechanisms are described as "breakdown phenomena," neither is, of itself, destructive or irreversible. When the reverse voltage is reduced below the critical level, the breakdown mechanism subsides, and the junction behaves normally once again. Of course, the large currents and high voltages associated with reverse breakdown can easily cause the junction to overheat, and this can lead to irreversible destruction of the diode owing to excessively high temperatures." (p. 233)

6.5.2 Tunnel Diodes

"In junctions that are very heavily doped, the phenomenon of Zener breakdown can occur at very small reverse voltages. It can, in fact, occur at zero bias. A junction that is in Zener breakdown at zero bias will support large currents for a reverse voltage (which make the field bigger) and will gradually revert to normal operation as the applied voltage is made positive (which reduces the electric field). A forward voltage of one or two tenths of a volt may be enough to eliminate the Zener breakdown mechanism and to reduce the junction current. Further increases in forward voltage produce minority-carrier injection so that the current once again rises." "Devices behaving in this manner are called *tunnel diodes*. The name originates from a quantum-mechanical explanation of the Zener breakdown mechanism. Tunnel diodes are useful as circuit components because they have a region of *negative* incremental conductance, that is, a region in which the *I-V* characteristic has negative slope." (p. 236)

1971 -- Johnson

Johnson, J. B. 1971. Electronic Noise: the first two decades. *IEEE Spectrum.* 8: 42-46.

Also reprinted in: *Electrical Noise: Fundamentals and Sources.* 1977. M. Gupta, Ed. IEEE Press. 17-21.

"In the 1918 paper, Dr. Schottky evidently assumes that the grosser current fluctuations produced by faulty tube structures . . . have been, or can be, eliminated, and he is left with two sources of noise that are of a much more fundamental nature. One he calls the 'Warmeefekt,' in English now commonly named 'thermal noise.' This is a fluctuating voltage generated by electrical current flowing through a resistance in the input circuit of an amplifier, not in the amplifier itself. The motion of charge is a spontaneous and random flow of the electrical charge in the conductor in response to heat motion in its molecules."

"In the case of the 'thermal noise' . . . "the electric charge is in effect held in long bags with walls relatively impervious to electrons at low temperature. The mass transport of charge along the bag, or wires, under the influence of heat motion, sets up the potential differences that generate the fluctuating output of the amplifier."

"When now one end of the conductor, the 'cathode' of the tube, is heated to incandescence, electrons can be emitted from the cathode surface to travel across the vacuum toward the anode. The electrons are emitted at random times, independent of each other, and they travel at different velocities, depending on initial velocity and voltage distribution for electron passage. In the case of a small electron emission, a small nearly steady flow of current results, with a superimposed smaller alternating current whose amplitude can be calculated from statistical theory. This small current flowing though the amplifier generates the 'Schroteffekt,' or shot effect, in the amplifier."

". . . for frequencies above certain values, the noise power is constant up to very high frequencies. For thermal noise this constant power extends also to low values, while for shot noise there are many exceptions and variations."

1972 -- Millman and Halkias

> Millman, J. and C. Halkias. 1972. *Integrated Electronics: Analog and Digital Circuits and Systems.* McGraw-Hill.

3-11 BREAKDOWN DIODES

"Diodes which are designed with adequate power-dissipation capabilities to operate in the breakdown region may be employed as voltage-reference or constant-voltage devices. Such devices are known as *avalanche*, *breakdown*, or *Zener diodes*." (p. 73)

Avalanche Multiplication

"Two mechanisms of diode breakdown for increasing reverse voltage are recognized. Consider the following situation: A thermally generated carrier [...] falls down the junction barrier and acquires energy from the applied potential. This carrier collides with a crystal ion and imparts sufficient energy to disrupt a covalent bond. In addition to the original carrier, a new electron-hole pair has now been generated. These carriers may also pick up sufficient energy from the applied field, collide with another crystal ion, and create still another electron-hole pair. Thus each new carrier may, in turn, produce additional carriers through collision and the action of disrupting bonds. This cumulative process is referred to as *avalanche* *multiplication*. It results in large reverse currents, and the diode is said to be in the region of *avalanche breakdown*. (p. 74)

Zener Breakdown

Even if the initially available carriers do not acquire sufficient energy to disrupt bonds, it is possible to initiate breakdown through a direct rupture of the bonds. Because the existence of the electric field at the junction, a sufficiently strong force may be exerted on a bound electron by the field to tear it out of its covalent bond. The new hole-electron pair which is created increases the reverse current. Note that his process, called *Zener breakdown*, does not involve collisions of carriers with the crystal ions (as does avalanche multiplication). (p. 75)

"The field intensity increases as the impurity concentration increases, for a fixed applied voltage. It is found that Zener breakdown occurs at a field of approximately 2×10^7 V/m. This value is reached at voltages below about 6 V for heavily doped diodes. For lightly doped diodes, the breakdown voltage is higher, and avalanche multiplication is the predominant effect. Nevertheless, the term *Zener* is commonly used for the *avalanche*, or *breakdown*, *diode* even at higher voltages." (p. 75)

3-12 THE TUNNEL DIODE

"A *p-n* junction diode of the type discussed in Sec. 3-1 has an impurity concentration of about 1 part in 10^8. With this amount of doping, the width of the depletion layer, which constitutes a potential barrier at the junction, is of the order of a micron. This potential barrier restrains the flow of carriers from the side of the junction where they constitute majority carriers to the side where they constitute minority carriers. If the concentration of impurity atoms is greatly increased, say, to 1 part in 10^3 (corresponding to a density in excess of 10^{19} cm^{-3}), the device characteristics are completely changed. This new diode was announced in 1958 by Esaki, who also gave the correct theoretical explanation for its volt-ampere characteristic.

The Tunneling Phenomenon

The width of the junction barrier varies inversely as the square root of the impurity concentration [Eq. (3-21)] and therefore is reduced to less than 100 Angstroms (10^{-6} cm). Classically, a particle must have an energy at least equal to the height of a potential-energy barrier if it is to move from one side of the barrier to the other. However, for barriers as thin as those estimated above in the Esaki diode, the Schrodinger equation indicates that there is a large probability that an electron will penetrate *through* the barrier. This quantum-mechanical behavior is referred to as *tunneling*, and hence these high-impurity-density *p-n* junction devices are called *tunnel diodes*." (p. 77)

12-12 NOISE

Thermal or Johnson, Noise

The electrons in a conductor possess varying amounts of energy by virtue of the temperature of the conductor. The slight fluctuations in energy about the values specified by the most probable distribution are very small, but they are sufficient to produce small noise potentials within a conductor. These random fluctuations produced by the thermal agitation of the electrons are called the *thermal*, or Johnson, noise. The rms value of the thermal-resistance noise voltage V_n over a frequency range f_H - f_L is given by the expression

$$V_n^2 = 4\ k\ T\ R\ B \qquad (12\text{-}51)$$

where

k = Boltzmann constant, 1.380E-23 J/deg K
T = resistor temperature, deg K = deg C + 273
R = resistance, ohms
$B = f_H - f_L$ = bandwidth, Hz

It should be observed that the same noise power exists in a given bandwidth regardless of the center frequency. Such a distribution, which gives the same noise per unit bandwidth anywhere in the spectrum, is called *white noise*." (p. 401)

"If the conductor under consideration is the input resistor to an ideal (noiseless) amplifier, the input noise voltage to the amplifier is given by Eq. (12-51). An idea of the order of magnitude of the voltage involved is obtained by calculating the noise voltage generated in a 1-M resistance at room temperature over a 10-kHz bandpass. Equation (12-51) yields for V_n the value of 13uV." (p. 402)

Shot, or Schottky, Noise

Shot noise is attributed to the discrete-particle nature of current carriers in semiconductors. Normally, one assumes that the current in a transistor or FET under dc conditions is a constant at every instant. Actually, however, the current from the emitter to the collector consists of a stream of individual electrons or holes, and it is only the time-average flow which is measured as the constant current. The fluctuation in the number of carriers is called *shot noise*. The mean-square shot-noise current in any device is given by

$$I_n^2 = 2\ q\ I_{\mathrm{dc}}\ B$$

where

q = electronic charge, 1.60E-19 coulombs
I_{dc} = dc current, Amps
B = bandwidth, Hz

If the load resistor is R_L, a noise voltage of magnitude $I_n R_L$ will appear across the load." (p. 402)

1976 -- Ott

Ott, H. 1976. *Noise Reduction Techniques in Electronic Systems.* John Wiley & Sons.

THERMAL NOISE

"Thermal noise comes from thermal agitation of electrons within a resistance, and it sets a lower limit on the noise present in a circuit. Thermal noise is also referred to as resistance noise or 'Johnson noise' (for J. B. Johnson, its discoverer.)" "He showed that the open-circuit rms noise voltage produced by a resistance is

$$V_t = (4 \ k \ T \ B \ R)^{1/2}$$

where, k = Boltzmann's constant (1.38 x 10^{-23} joules / deg. Kelvin), T = Absolute temperature (deg. Kelvin), B = Noise bandwidth (Hz), R = Resistance (Ohms)." (p. 198)

"Although the rms value for thermal noise is well defined, the instantaneous value can only be defined in terms of probability. The instantaneous amplitude of thermal noise has a Gaussian, or normal, distribution." (p. 203)

"The crest factor of a waveform is defined as the ratio of the peak to the rms value." ". . . a crest value of approximately 4 is used for thermal noise." (p. 204)

SHOT NOISE

"Shot noise is associated with current flow across a potential barrier. It is due to the fluctuation of current around an average value resulting from the random emission of electrons (or holes). This noise is present in both vacuum tubes and semiconductors. In vacuum tubes, shot noise comes from the random emission of electrons from the cathode. In semiconductors, shot noise is due to random diffusion of carriers through the base of a transistor and the random generation and recombination of hole electron pairs."

"The shot effect was analyzed theoretically by W. Schottky in 1918. He showed that the rms noise current was equal to:

$$I_{sh} = (2 \ q \ I_{dc} \ B)^{1/2}$$

where q = Electron charge (1.6 x 10^{-19} coulombs), I_{dc} = Average dc current (A), B = Noise bandwidth (Hz)."

"The power density for shot noise is constant with frequency and the amplitude has a Gaussian distribution. The noise is white noise and has the same characteristic as previously described for thermal noise."

". . . by measuring the dc current through the device, the amount of noise can be very accurately determined." "A diode can be used as a white noise source. If shot noise is the predominant noise source in the diode, the rms value of the noise current can be determined simply by measuring the dc current through the diode."

(pp. 208-209)

*[Note that the above expression for shot noise current is **not** the same as shot noise voltage across a semiconductor junction./tfr]*

MEASURING RANDOM NOISE

"An oscilloscope is an often overlooked, but excellent device for measuring white noise." "The rms value of white noise is approximately equal to the peak-to-peak value taken from the oscilloscope, divided by eight. When determining the peak-to-peak value on the oscilloscope, one or two peaks that are considerably greater than the rest of the waveform should be ignored. With a little experience, rms values can be accurately determined by this method." (p. 212)

1980 -- Malvino

> Malvino, A. 1980. *Transistor Circuit Approximations, Third Edition.* McGraw-Hill.

Avalanche and zener effects

"Breakdown is cause by either of two effects: avalanche or zener. When a diode is reverse-biased, minority carriers flow in the reverse direction. For higher reverse voltages, these minority carriers can reach sufficient velocities to knock valence electrons out of their shells. These released electrons become free electrons and can attain sufficient velocity to dislodge more valence electrons. The resulting avalanche of free electrons produces a large reverse bias current.

"Zener effect is different. The electric field across the junction can become intense enough to pull valence electrons directly out of their shells. This produces a large reverse current. Zener effect is sometimes called *high-field emission* because it is the electric field that produces free electrons.

"When a diode breaks down, either avalanche or zener effect predominates. Below 6 V, the zener effect is more important. Above 6 V, the avalanche effect takes over. Diodes with breakdown voltages greater than 6 V should be called avalanche diodes. But the general practice in the industry is to refer to diodes exhibiting either effect as *zener diodes*." (p. 37)

1983 -- Warner and Grung

> Warner, R., and B. Grung. 1983. *Transistors: Fundamentals for the Integrated-Circuit Engineer.* John Wiley & Sons.

6-5 BREAKDOWN PHENOMENA IN REVERSE-BIASED JUNCTIONS

"For most junctions [...] there exists a critical voltage above which reverse current increases with voltage, sometimes very sharply. Such behavior is called *breakdown*." (p. 470)

6-5.1 Tunneling

" . . . it is possible that an electron can 'penetrate' a potential barrier, even a barrier of great height, provided the dimension *X* [barrier thickness 'of the same order as the extent of the wave function'] is small enough. Such penetration is called *tunneling*." (p. 471)

6-5.2 Avalanche-Breakdown Fundamentals

"For historical reasons, voltage regulating diodes of any sort are known commercially as Zener diodes, named for Clarence Zener who offered an early description of the direct excitation of electrons from the valance band into the conduction band. (p. 476)

"There are two general requirements for avalanche breakdown. The electric field must be large, and it must exist over a sufficiently extensive region." "Finite space is required for the carrier-multiplication to take place." (p. 477)

"It turns out also that the details of field profile are not very important." (p.477)

". . . X_T *[depletion-layer thickness]* is the best lone criterion for predicting avalanche-breakdown voltage V_B." (p. 478)

6-5.3 Avalanche-Breakdown Theory

"The experimental results given in the previous section can be explained only roughly by theory since the physical interactions are very complicated. Any avalanche-breakdown theory must begin with a study of the ionization coefficients for electrons and holes, where these coefficients represent the ability of energetic electrons and holes to produce additional carriers in pairs. Then, the theory must continue with a calculation of the conditions for breakdown of a simple one-dimensional step junction. Finally, it must address many complex issues such as the effects of junction curvature." (pp. 479-480)

1984 -- Zanger

> Zanger, H. 1984. *Semiconductor Devices and Circuits.* John Wiley and Sons.

2-4.3 "Zener" and "Avalanche" Breakdown

"Figure 2-17 shows a point, in the reverse bias portion of the graph, at which the reverse current increases sharply--the 'zener' or 'avalanche' region. The sudden increase in reverse current is the result of a very large reverse electric field." (p. 50)

"The high reverse field accelerates the conduction band (free) electrons. As these collide with valence electrons, the energy of collision may be sufficient to transfer the valence electrons into the conduction band. This increases the number of minority carriers, in tun increasing the reverse (minority) current. As the field is increased, this "multiplication" in minority carriers is accelerated and very high reverse currents are produced. This process is called 'avalanche.'" (p. 50)

"The minority carrier concentration may be increased by directly 'tearing' electrons out of the valence band (removing them from the atomic orbit) into the conduction band." [...] "The process is called 'zener breakdown.' At very high doping levels the zener breakdown occurs at lower fields than the avalanche breakdown. It is not surprising, therefore, that the diodes designed to exhibit breakdown characteristics at lower voltages are heavily doped and the process involved is the zener breakdown. (For voltages from 2.4 to 6 V the process is zener breakdown, and from 6 V up the process is avalanche breakdown.) These processes are not necessarily destructive, that is, the diode can operate in this region with no damage to the diode, provided other parameters, such as power dissipation, diode temperature, etc., are kept within bounds." (p. 51)

1987 -- Vergers

Vergers, C. 1987. *Handbook of Electrical Noise.* TAB Books, Blue Ridge Summit, PA.

SHOT NOISE

"The term 'shot noise' arose from the study of random variations in the emission of electrons from the cathode of a vacuum tube. If these variations are amplified and listened to with a pair of headphones or a loudspeaker, they sound like 'lead shot' hitting a concrete wall. Shot noise has a flat spectral density like thermal noise. Therefore, shot noise can be considered a 'white noise' process." (p. 96)

Shot Noise in PN Junctions

"The shot noise generated in a pn junction has the same mathematical form as that of the temperature limited vacuum diode. The noise seems to be generated by a noise current generator in parallel with the dynamic resistance of the diode." (p. 108)

$$I_{ns} = (2 e I_{dc} B)^{1/2}$$

```
e = Electron charge (1.6E-19 coulombs)
I = current in amperes
B = Bandwidth in Hertz
```

"Likewise we may determine the shot noise voltage by applying Ohms Law." *[E = IR]*

$$E_{ns} = (2 e I_{dc} B r_d^2)^{1/2}$$

[or]

$$E_{ns} = r_d (2 e I_{dc} B)^{1/2}$$

where r_d is the dynamic resistance of the junction." (p. 109)

"From electronic physics it is known that the dynamic resistance of a pn junction depends on temperature and the direct current flowing through the junction. The dynamic resistance represents the ratio of a small change in diode voltage to a corresponding change in diode current."

$$r_d = k\ T\ /\ e\ I_{dc}$$

[we substitute and get]

$$E_{ns} = (\ 2\ k\ T\ B\ r_d\ )^{1/2}$$

"It is obvious . . . that the shot noise voltage across the pn junction has an equation very similar to that of a thermal noise process."

[we can substitute again and get]

$$[\ E_{ns} = k\ T\ (\ 2\ B\ /\ e\ I_{dc}\ )^{1/2}\ ]$$

```
k = Boltzmanns constant (1.38E-23 Joules/deg. Kelvin)
T = Temperature in degrees Kelvin
B = Bandwidth in Hertz
```
r_d = junction dynamic resistance
```
e = Electron charge (1.6E-19 coulombs)
```

"There is a rather interesting relation between the shot noise voltage across the junction and the dynamic resistance r_d. Since r_d is inversely proportional to direct current, the dynamic resistance falls as direct current increases. This causes the shot noise voltage across the junction to decrease." ". . . shot noise current is proportional to the square root of direct current where dynamic resistance is inversely proportional to direct current. We find that if direct current increases, dynamic resistance falls more quickly than shot noise current rises. The result is that shot noise voltage becomes inversely related to" *[the square root of]* "direct current." (p. 110)

1989 -- Horowitz and Hill

Horowitz, P. and W. Hill. 1989. *The Art of Electronics.* 2nd Ed. Cambridge University Press.

6.14 Zener Diodes

"Zener diodes can be very noisy, and some IC zeners suffer from the same disease. The noise is related to surface effects, however, and *buried* (or *subsurface*) zener diodes are considerably quieter."

[Since shot noise is a fundamental effect, there can be no zener diode which does not produce this noise. But if some zeners are especially "noisy," the extra noise does not come from the fundamental effect and so must have a suspicious statistical distribution./tfr]

Figure 6.22 is titled: "Voltage noise for a low-noise zener reference diode similar to the type used in the 723 regulator" and plots e_n voltage noise ($uV/Hz^{1/2}$) versus zener current (mA). The graph shows somewhat less than 0.1 uV noise for 0.1 mA, and somewhat less than 0.01 uV noise for 10 mA. In this graph, the noise is inversely related to the square root of the current. (p. 335)

Johnson noise

"Any old resistor just sitting on the table generates a noise voltage across its terminals known as Johnson noise. It has a flat frequency spectrum, meaning that there is the same noise power in each hertz of frequency (up to some limit of course). Noise with a flat spectrum is also called 'white noise'." (p. 430)

". . . a 10k resistor at room temperature has an open-circuit rms voltage of 1.3uV, measured with a bandwidth of 10kHz . . . ." (p. 431)

Shot nose

An electric current is the flow of discrete electric charges, not a smooth fluidlike flow." "If the charges act independent of each other, the fluctuating current is given by

$$I_{noise}(rms) = I_n R = (2 q I_{dc} B)^{1/2}$$

where q is the electron charge (1.60×10^{-19} coulomb) and B is the measurement bandwidth. For example, a 'steady' current of 1 amp actually has an rms fluctuation of 57nA, measured in a 10kHz bandwidth; i.e., it fluctuates by about 0.000006%."

"The shot-noise formula . . . assumes that the charge carriers making up the current act independently. That is indeed the case for charges crossing a barrier, as for example the current in a junction diode, where the charges move by diffusion; but it is not true for the important case of metallic conductors, where there are long-range correlations between charge carriers." (p. 432)

Measuring the noise voltage

"The most accurate way to make noise measurements is to use a true rms voltmeter." "If you use a true rms meter, make sure it has response at the frequencies you are measuring . . . ." "True rms meters also specify a 'crest factor' . . . ." "For Gaussian noise, a crest factor of 3 to 5 is adequate."

"You can use a simple averaging-type ac voltmeter instead . . . ." "To get the rms voltage of Gaussian noise, multiply the 'rms' value you read on an averaging ac voltmeter by 1.13 (or add 1dB)."

"A third method . . . consists of looking at the noise waveform on an oscilloscope: The rms voltage is 1/6 to 1/8 of the peak-to-peak reading . . . . It isn't very accurate, but at least there's no problem getting enough measurement bandwidth." (p. 454)

Terry Ritter, his current address, and his top page.

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