Thermal Noise in Double Injection

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Noise measurements from 500 kHz to 22 MHz and at ambient temperatures T between 140 and 350°K have been performed on a double-injection silicon diode as a function of operating point. The results indicate that at high frequencies, (i) the noise increases linearly with T, and (ii) the noise also depends linearly on the differential conductance g at the same frequency. Within at most a 5% error, the high-frequency noise is quantitatively represented by Nyquist's formula $\langle i^2\rangle = 4kTg\Delta f$ throughout the experimental range. This proves the thermal nature of the high-frequency noise of double injection. Possible limits on this result and its comparison with alternative theories are discussed.

I. INTRODUCTION

A RECENT investigation has established that in a silicon double-injection diode operated at room temperature (298°K) in the semiconductor regime ($I \propto V^2$) the noise $\langle i^2\rangle$ is quantitatively represented by

$$\langle i^2(\omega)\rangle = 4kTg(\omega)\Delta f \tag{1}$$

for $\omega > \tau^{-1}$, where τ is the common high-level lifetime of the charge carriers, k is Boltzmann's constant, T is the absolute temperature, and g is the differential conductance of the device.[1] Recombination mechanisms cause the nonlinearity of the device.[2] At high frequencies ($\omega > \tau^{-1}$), however, recombination is ineffective. Electrons and holes each carry current independently. If the charge carriers remain in thermal equilibrium with the lattice in spite of a net current, the system then constitutes a resistance even for large signals. Hence, noise at high frequencies should be thermal.

A direct test of this model is to establish the proportionality of the high-frequency noise $\langle i^2(\omega)\rangle$ with the absolute temperature T of the diode. The results of such an experiment are reported here.

II. DEVICE AND METHOD OF MEASUREMENT

The double-injection diode analyzed here is identical to that of Ref. 1. This diode consists of high-resistivity float-zone-grown p-type silicon with the dimensions given in Fig. 1. The p^+ contact is made by vacuum evaporation and subsequent alloying of Al, whereas the n^+ region is formed by Li diffusion.[3] Electrical contact to the n^+ and p^+ regions is made with a 1:1 mixture of Ga and In on brass plates. The I-V characteristics measured in the dark from 140 to 350°K are shown in Fig. 1. A quadratic behavior is observed over approximately one decade of current at each temperature. The deviation at high currents and 140°K could possibly be due to diffusion and heating effects as discussed by Baron.[4] Departures from Ohmic behavior at low currents is attributed to junction effects. Details on these characteristics are described elsewhere.[5]

The measurements are obtained by comparing the noise of the device to that of a 5722 shot-noise vacuum tube. The first stage of amplification in the noise analyzer consists of a cascode with a 2N3819 J-FET at the input. Above 5 MHz, a passive L-C network is used to tune the input. The amplifier is directly mounted to a chamber containing the device. A regulator maintains the temperature of the chamber within ±1°K over the range 110–400°K.

III. NOISE MEASUREMENTS AND COMPARISON WITH THEORY

Noise spectra and small-signal conductances have been obtained from 500 kHz to 22 MHz for all operating

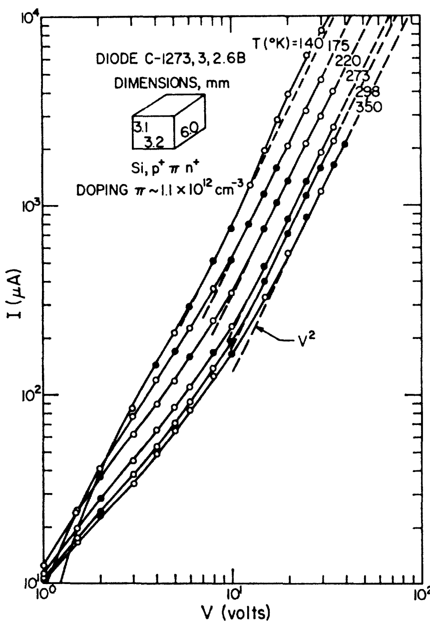

FIG. 1. I-V characteristics of a silicon double-injection diode between 140 and 350°K ambient temperature. The solid dots indicate the operating points at which noise measurements have been made.

[1] H. R. Bilger, D. H. Lee, M-A. Nicolet, and E. R. McCarter, J. Appl. Phys. 39, 5913 (1968).
[2] R. Baron and J. W. Mayer, *Semiconductors and Semi-Metals* (Academic Press Inc., New York, to be published), Vol. 8.
[3] J. W. Mayer, O. J. Marsh, and R. Baron, J. Appl. Phys. 39, 1447 (1968).
[4] R. Baron, J. Appl. Phys. 39, 1435 (1968).
[5] D. H. Lee, Ph.D. thesis, California Institute of Technology, 1969 (unpublished).

points marked by solid dots in Fig. 1. In addition, the current response to a differential voltage step at the highest operating points indicates that the diode is truly operating in the semiconductor regime throughout the temperature range.[1]

Figure 2 illustrates typical spectra, taken at 220°K. A constant level is reached at all operating points above a limiting frequency. To determine the value of this white-noise level the functional dependence

$$I_{\mathrm{eq}} = c_1 + c_2 / f^{c_3} \tag{2}$$

is least-squares-fitted to the data (solid lines). From the constant c_1, an equivalent noise resistance

$$r_{\mathrm{eq}} = 2kT/qc_1 \tag{3}$$

is derived, with which the measured white noise of the diode at high frequencies is represented as

$$\langle i^2 \rangle = 4kT(1/r_{\mathrm{eq}})\Delta f, \tag{4}$$

where q is the value of electronic charge.

The differential resistance r of the diode measured at the same operating points is constant over the frequency range in which the noise spectra are also constant. The average value of r obtained from eight measurements

TABLE I. Comparison of the high-frequency differential resistance r of the diode with the equivalent noise resistance r_{eq} in the same frequency range.

Temperature (°K)	Operating point V (V)	Operating point I (mA)	r (kΩ)	r_{eq} (kΩ)
350	40.0	2.10	17.4	16.6
	35.0	1.61	19.6	19.9
	25.0	0.868	26.8	27.7
	10.0	0.164	53.9	51.6
	2.0	0.023	77.6	74.3
298	30.0	1.60	17.8	18.0
	25.0	1.12	21.4	21.6
	20.0	0.710	27.0	26.1
	15.0	0.405	35.4	32.6
	10.0	0.196	48.7	45.1
	2.0	0.024	73.5	70.5
273	25.0	1.35	18.5	18.3
	20.0	0.845	22.7	23.5
	15.0	0.480	30.8	30.4
	8.0	0.767	48.1	47.6
	2.0	0.028	62.4	59.6
220	20.0	1.34	13.1	13.1
	17.5	1.02	15.1	15.1
	15.0	0.746	17.9	19.1
	6.0	0.160	31.2	30.4
	2.0	0.037	37.4	38.0
175	17.5	1.58	7.4	8.2
	15.0	1.15	9.4	8.9
	12.5	0.800	11.0	10.9
	10.0	0.520	13.1	13.3
	5.0	0.170	17.8	18.1
140	10.0	0.760	6.9	6.9
	8.0	0.510	7.9	7.9
	6.0	0.292	9.2	9.3
	4.0	0.145	10.2	10.3

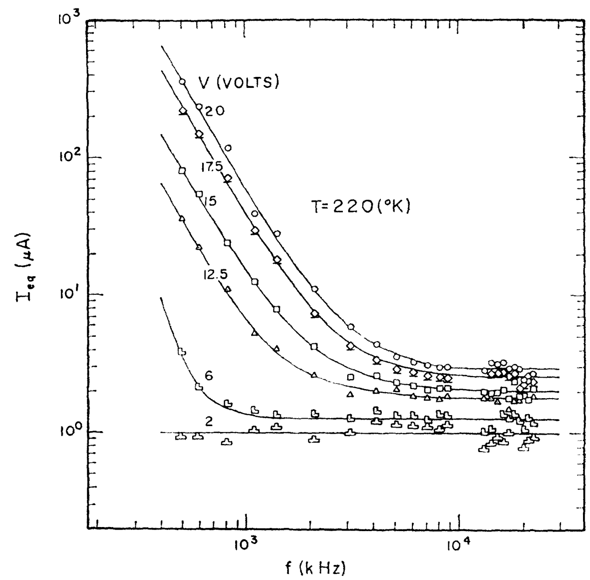

FIG. 2. Equivalent noise current $I_{\mathrm{eq}} = \langle i^2 \rangle / 2q\Delta f$ versus frequency at six operating points for the double-injection silicon diode given in Fig. 1 ($T = 220$°K).

between 1 and 22 MHz is listed in Table I. Values of r_{eq} for corresponding operating points are tabulated there also.

The values of r and r_{eq} agree very closely. This means that the high-frequency noise is represented by

$$\langle i^2 \rangle = \alpha \times 4kT(1/r)\Delta f, \tag{5}$$

where α is very close to unity and given by r/r_{eq}. A better estimate of the mean value of α is obtained from a plot of the white-noise level versus $g = 1/r$ for each temperature, as shown in Fig. 3. The dashed lines correspond to the dependences

$$\langle i^2 \rangle = 4kT(1/r)\Delta f \tag{6}$$

predicted from the model of thermal noise ($\alpha \equiv 1$). Departures from this theory, estimated by least-squares fitting of straight lines to the experimental data, yield α values of 1.00, 1.00, 1.01, 1.01, 1.04, and 1.03 ± 0.05 for 140, 175, 220, 273, 298, and 350°K, respectively. The uncertainty in the absolute-temperature value accounts for most of the error limits. Figure 3 therefore establishes the thermal origin of the high-frequency noise in double injection.

IV. DISCUSSION

An alternative theory has been advanced by van der Ziel[6] to explain the high-frequency noise in double injection. According to this model,

$$\langle i^2 \rangle = \alpha \times 4kTg\Delta f, \tag{7}$$

where

$$\alpha = 4\mu_n\mu_p/(\mu_n + \mu_p)^2 \tag{8}$$

[6] A. van der Ziel, IEEE Trans. Microwave Theory Tech. 16, 308 (1968).

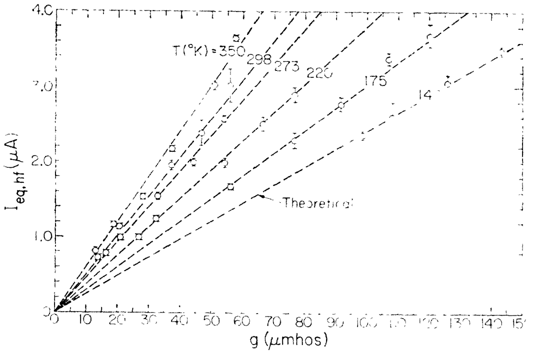

FIG. 3. Equivalent noise current $I_{eq,hf}$ at high frequencies versus the high-frequency conductance $g=1/r$ of the silicon double-injection diode at the operating points indicated in Fig. 1. $I_{eq,hf}\equiv c_1$ of Eq. (2).

and μ_n and μ_p are the electron and hole mobilities. With the standard room-temperature values of $\mu_n=1350$ cm^2/V sec and $\mu_p=480$ cm^2/V sec, Eq. (8) gives $\alpha=0.77$. From large-signal turn-on transients as described by Dean,[7] the actual values for the present diode are measured as 1280 and 410 cm^2/V sec, respectively, leading to $\alpha=0.73\pm0.06$. Both quantities are clearly inconsistent with the experimental value of $\alpha=1.00\pm0.05$. In addition, measurements of the temperature dependence of μ_n and μ_p on the diode have established that $\mu_n=1280(298°\text{K}/T)^{1.75}$ cm^2/V sec and $\mu_p=410(298°\text{K}/T)^{2.18}$ cm^2/V sec. According to Eq. (8), α should then increase by approximately 0.13 when the temperature varies from 350 to 140°K. This definitely disagrees with the results of Fig. 3 and invalidates Eq. (8), with its associated model.

Liao[8] has presented experimental results on a germanium $p^+\nu\ n^+$ structure at room temperature which appear to support Eq. (8). The range over which $I\propto V^2$ extends from 0.2 to 0.5 V; the physical length of the device is 4.5 mm. It is possible that under those conditions noise is still influenced by contact effects and diffusion. The information provided is insufficient to verify the presence of a true semiconductor regime, where such effects are negligible.

The results of Fig. 3 reveal that the thermal-noise expression of Eq. (6) is valid even where the square-law dependence $I\propto V^2$ does not hold. This conclusion does not readily follow from the theory of double injection. It was experimentally established, however, that at those operating points the current response to a differential step voltage satisfies the test $\eta=n$, where n is the power in the dc characteristic ($I\propto V^n$) and η is the ratio of final to initial current in this response. It proves that diffusion is negligible at these operating points. This suggests that as long as diffusion, recombination, and contact effects are negligible, noise in double injection is thermal.

There is no reason why this conclusion should be limited to the temperature range of this experiment, as long as the conditions above hold. A similar extension can be advanced for frequencies above 22 MHz. Neither the transit of the carriers across the device nor the dielectric relaxation should alter the mechanism of thermal noise. It is therefore proposed that Eq. (6) holds also at frequencies above $\omega=\tau^{-1}$. This prediction could be tested by measuring the noise for frequencies above $1/\theta$, where θ is the dielectric relaxation time and is of the order of $(V/I)C_0$, and C_0 is the geometrical capacitance of the structure biased at the operating point V, I. The value of r is known to change at this frequency.[2]

Below $1/\tau$, recombination determines the main features of double injection. In that frequency range, noise varies as $1/f^{c_3}$, with $1.7\lesssim c_3\lesssim 3.0$ as obtained from the least-squares fits. At fixed frequency, the noise also increases with the dc current. Both facts are consistent with the idea that generation recombination is the main source of noise at low frequencies.[1,9,10] A dependence of the general form $\langle i^2\rangle\sim I^m/(1+\omega^2\tau^2)$, $m>1$, can be anticipated for that case. Very recent results support the essential features of the model.[11]

If the physical length of a double-injection diode is progressively shortened, the structure obtained in the limit is a pn junction. It is known both theoretically and experimentally that noise of pn junctions is shotlike. It would be interesting to investigate this transition and relate the change in the noise to that in the transport mechanisms involved.

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