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# $1/f$ noise of avalanche noise

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**Abstract**

The noise of a reverse biased emitter-base junction of a bipolar silicon transistor in the low-frequency range has been investigated. Noise spectra for the transistors at a single value of direct current have been presented. A set of spectra at different direct current values was taken for one selected transistor. The presence of $1/f$ noise above the avalanche noise level has been stated. A plot of the relation between the noise level at the frequency $f = 360$ Hz and direct current value has been made. It appears that $1/f$ noise is not directly related to the direct current flowing at avalanche breakdown conditions. 

## 1. Introduction

The $1/f$ noise [1] is a random process defined in terms of the shape of its power density $S(f)$. The power or the square of some variable associated with the random process, measured in a narrow bandwith, is roughly proportional to the reciprocal frequency:

$$S(f) = \frac{\text{constant}}{|f|^{\gamma}},$$

where $0 < \gamma < 2$ and $\gamma$ is usually close to 1.

A few years ago the author proposed to use the term '$1/f$ noise' only for noise having $f^{-1.0}$ type of spectra, allowing only some small deviations [2]. However, further investigations have shown that low-frequency end of the white noise spectra exhibits sometimes different slopes and numerous scientists still use the common term '$1/f$ noise', trying sometimes to use the term '$1/f$ — like noise' [3].

Electrical $1/f$ noise represents the effect of some elementary events. The process related to a single carrier is most often accepted as an elementary event. [4, 3, 5]. There exist some theories correlating $1/f$ noise to processes related to photons and phonons (quantum $1/f$ noise). It seems that this problem can be treated in different ways, e.g. it is possible to recognize a whole packet of carriers contained in the pulse of avalanche or burst noise as an elementary component of $1/f$ noise.

The increase of $p$–$n$ junction reverse bias voltage causes an increase of electrical field strength in the depletion layer and it may bring electrons tunneling from the valence band to the conduction band (Zener effect) or it may cause impact ionization, consisting of the release of electron–hole pairs by carriers accelerated by the electric field (avalanche effect). In both cases the direct current rises abruptly. A large noise, having an amplitude in the range of 100 μA — a few mA, is related to avalanche noise only. This phenomenon has been first noticed in silicon $p$–$n$ junctions in 1952 by Pearson and Sawyer [6] and it was investigated during the next 10 years by several authors, from which we quote Refs. [7, 8]. Later the interest in avalanche noise was rather small.

Avalanche noise shows a spectrum which is flat or lightly undulated depending on the load resistance [9]. It was difficult to find a paper related to the problem of the low frequency end of avalanche noise, although $1/f$ noise at avalanche breakdown condition has been observed [10]. Avalanche noise is not useful in the low frequency range and it is not so undesired as some other kinds of noise because, in most applications, semiconductor devices are not used in the avalanche breakdown range.

The investigation of a relation between $1/f$ noise and the avalanche multiplication factor $M$ was the initial authors intention. But it became evident that it is impossible to realize this purpose. As a result, an exper-

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iment has been done to determine whether $1/f$ noise associated with avalanche noise is directly related to the direct current or to the avalanche noise itself. The investigations were conducted on reverse biased emitter-base junctions of bipolar transistors. The results of these investigations gave the author a new opinion on the essence of $1/f$ noise.

## 2. Avalanche noise investigation in l.f. range

The observation of avalanche noise of low power, low frequency BC107 and BC109 silicon transistors was conducted using a Tektronix 2440 digital oscilloscope with a wideband amplifier having a frequency range of 1 Hz–100 kHz. This observation gives a new view of avalanche noise, which differs from the observations presented in earlier papers. The saw-toothed curves appeared only in some of the investigated junctions and only at the first few seconds from the bias voltage turn on. The time domain curves of avalanche noise of the BC107 No. 19 transistor are given in Fig. 1a and b. The peak to peak amplitude is in the order of 4 mA. The time base is 10 μs/div. in the case of Fig. 1a and 1 ms/div. in the case of Fig. 1b. The investigated junction was reverse biased with a direct current of 0.15 mA at the load resistance $R_L = 20$ kΩ.

The main part of investigations was made on EB junctions of transistors, reverse biased at 12 V through a load resistance $R_L$ controlled in the range of 100 Ω to 100 kΩ. The noise voltage $u_n$ was measured by means of a selective nanovoltometer Unipan 237 with a bandwith $B = 0.027f$. Next the relative noise temperature $T_{rn} = T_n/T_0$ was determined, where $T_n$ is the noise temperature considered as the temperature at which thermal noise of a junction would be equal to

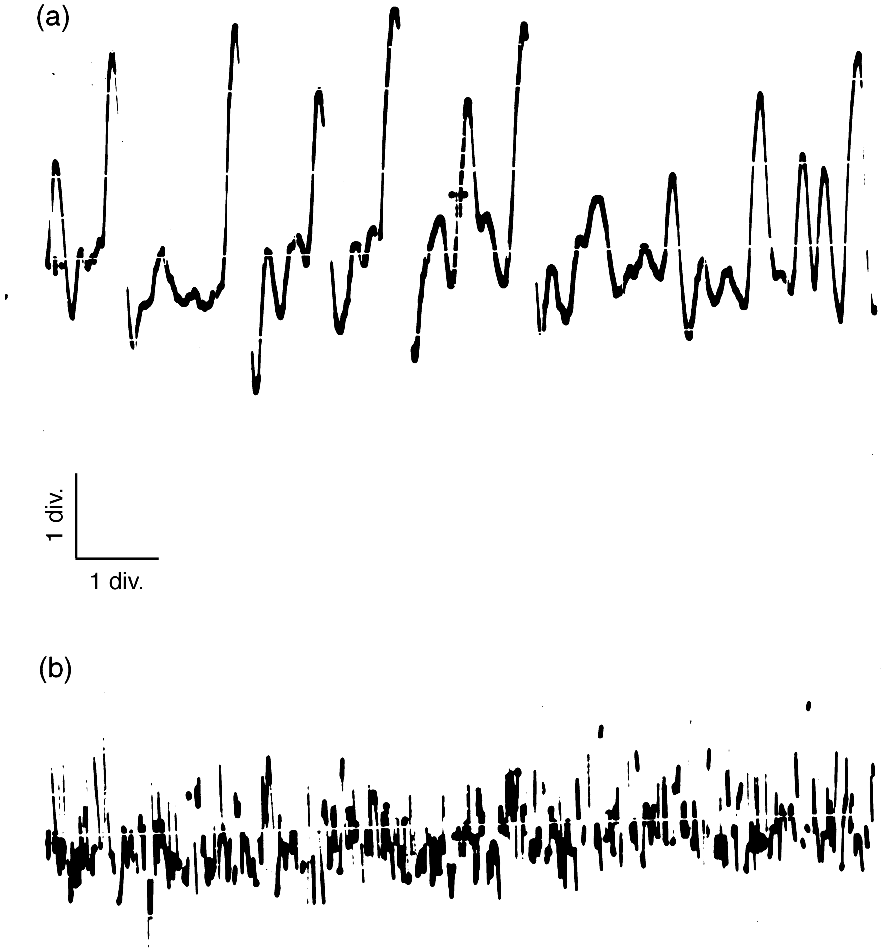


Fig. 1. Oscillograph records of avalanche noise of the reverse biased EB junction of BC107 No. 19 transistor. Vertical scale: 1 mV/div., horizontal scale: (a) 10 μs/div., (b) 1 ms/div.

the total noise of a junction at the reference temperature $T_0 = 300$ K.

With the increase of the *p–n* junction reverse voltage tunneling noise appears first followed by avalanche noise. All our measurements, the results of which are presented in Figs. 2–4, were conducted at a reverse voltage above 8 V taking into consideration that we were always operating in the avalanche noise regime. The exact indication of the transition threshold from tunneling to avalanche is rather troublesome [11] and we did not try to determine it.

In most of the transistors tested, the component which increases with decreasing frequency appears above the flat part of the spectrum. This component can be recognized as $1/f$ noise in the commonly accepted sense. Some transistors at reverse current did not show $1/f$ noise in the investigated frequency range, especially in the case of a high level of avalanche noise. The noise spectra of six transistors at reverse current resulting from the load resistance $R_L = 510\,\Omega$ in the frequency range of 180 Hz to 20 kHz are presented in Fig. 2. The BC109 No. 53 transistor at a direct current $I_r = 5.4$ mA does not show $1/f$ noise. The transistors BC107 No. 19 ($I_r = 6$ mA) and BC107 No. 27 ($I_r = 5.1$ mA) have $1/f$ noise, which is observable below a frequency of 1 kHz. It can be assumed that $1/f$ noise of the BC109 No. 40 transistor ($I_r = 4.7$ mA) appears above the avalanche noise level at about 1.5 kHz, but the BC107 No. 3 ($I_r = 6.7$ mA) and BC107 No. 5 ($I_r = 6.2$ mA) transistors show $1/f$ noise below 5 kHz.

As far as we know, no paper was published concerning the top frequency limit of $1/f$ noise. It is commonly known that above some frequency, $1/f$ noise disappears in the white noise such as thermal noise, shot noise or *g–r* noise and in our case avalanche noise.

The set of spectra at a direct current value in the range of $I_r = 0.038$ mA to $I_r = 27$ mA is given for one of the tested transistors (Fig. 3). For the two highest current values: $I_r = 15.3$ mA and $I_r = 27$ mA we have found straight lines with a slope of about 1.5. These straight lines bend above 5 kHz and we observe the transition from $1/f$ noise to white noise. However, for all lower current values in the range of $I_r = 0.038$–6.7 mA, the flat part of the spectrum related to avalanche noise and the $1/f$ curve which increases when the frequency decreases are clearly visible. It is difficult to estimate the slope of these curves but it seems that it does not exceed the value of 1.5. Strictly speaking we observed $1/f^{\gamma}$ noise with $\gamma$ not greater than 1.5 and according to the definition given at the beginning of the paper we called it as a $1/f$ noise [1, 12].

The dependence of $T_{rn} = f(I_r)$ determined at the frequency $f = 360$ Hz displays an irregular course (Fig. 4). The lack of monotonicity between noise level and direct current value shows that the $1/f$ noise present here is not directly related to this current flow. It can

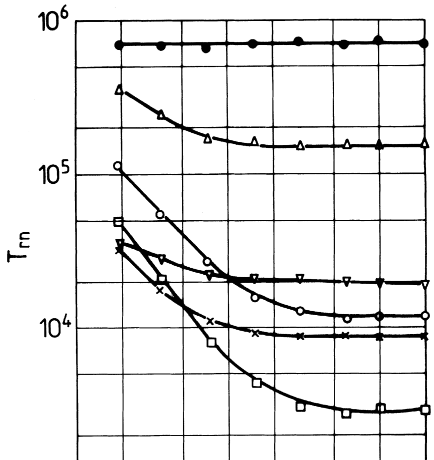


Fig. 2. L.f. noise spectra of the reverse biased EB junction of bipolar transistors at the load resistance $R_L = 510\,\Omega$. (a) (△) transistor BC107 No. 19, $I_r = 6.0$ mA, (b) (▽) BC107 No. 27, 5.1 mA, (c) (○) BC107 No. 3, 6.7 mA, (d) (□) BC107 No. 5, 6.2 mA, (e) (•) BC109 No. 53, 5.4 mA, (f) (×) BC109 No. 40, 4.7 mA

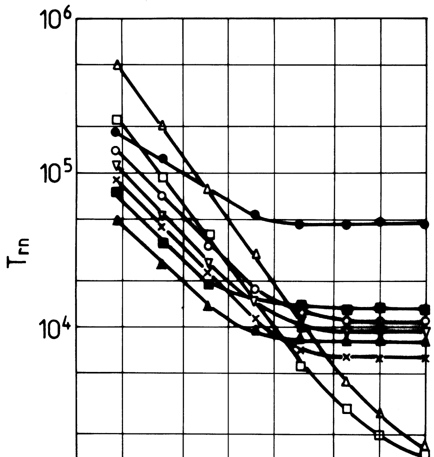


Fig. 3. L.f. noise spectra of the reverse biased EB junction of BC107 No 3 transistor at different load resistance and current $I_r$ values: (a) (△) $R_L = 100\,\Omega$, $I_r = 27$ mA, (b) (□) 200 Ω, 15.3 mA, (c) (×) 510 Ω, 6.7 mA, (d) (▽) 1 kΩ, 3.6 mA, (e) (•) 5.1 kΩ, 0.75 mA, (f) (○) 20 kΩ, 0.19 mA, (g) (■) 51 kΩ, 0.076 mA, (h) (▲) 100 kΩ, 0.038 mA.

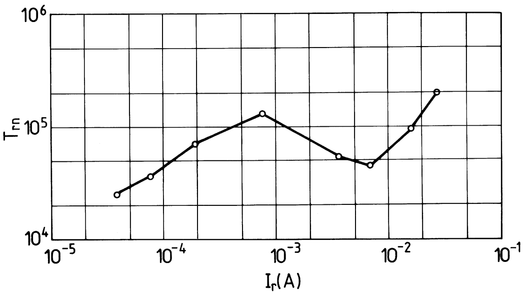


Fig. 4. Relative noise temperature $T_{rn}$ of the EB junction of BC107 No. 3 transistor vs reverse current $I_r$ at the frequency $f = 360$ Hz.

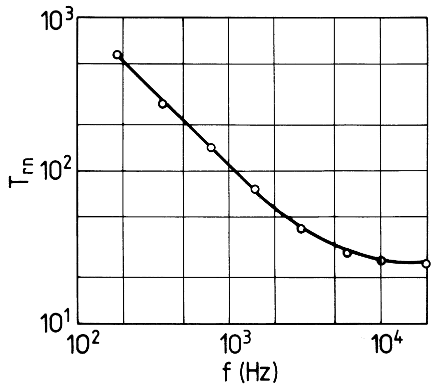


Fig. 5. L.f. noise spectrum of forward biased BC107 No. 3 transistor at the current $I_f = 110$ mA.

be assumed that the observed $1/f$ noise is first of all related to avalanche noise itself.

Certainly it can be considered whether $1/f$ noise should be related to avalanche noise or to the basic phenomenon of impact ionization. The multiplication factor is a measure of impact ionization. This factor is expressed as $M = I_r/I_t$, where $I_t$ is the tunneling current initiating the multiplication process and $I_r$ is the junction reverse current at the point of $M$ determination. This factor behaves similarly as the current $I_r$ and thus it is difficult to perceive a direct relation between $1/f$ noise and impact ionization.

It seems that for the magnitude of $1/f$ noise related to avalanche noise the time domain course of avalanche noise and especially the quantity and the time domain distribution of the larger pulses are crucial. In our case this distribution can change significantly between the particular values of direct current $I_r$ because of the current level control by the load resistance $R_L$ applied. As shown in [9], the shape of the avalanche noise spectrum depends to a large degree on the value of this resistance.

The high level of the observed $1/f$ noise is a next confirmation of its relation to avalanche noise. For a forward current as large as $I_f = 110$ mA at a frequency of $f = 360$ Hz, the value of the noise is only $T_{rn} = 280$ (Fig. 5), whereas for a reverse current of $I_r = 27$ mA at the same frequency the relative noise temperature $T_{rn}$ reaches a value of $2{*}10^5$.

The changes of noise level with direct current at a frequency of 20 kHz, noticeable in Fig. 3, are unexpected. It appears, that the equation for the avalanche noise spectral density $S = 2qI_tM^3$ is not fulfilled here. This equation is valid only for equal ionization rates of electrons and holes in the junction. However the equations for unequal ionization rates are similar [9, 11, 13–15] and they cannot be fulfilled either.

In the quoted work [10] results contradictory to the above equations were also obtained. The white noise level decreases there with the increase of $M$. However the authors of this paper used $u_n^2/B$ as a measure of diode noise level and therefore the most important value was the tested diode resistance. This resistance decreases fast with current increase. In our investigations the relative noise temperature, which behaves similar to the available noise power spectral density applies, but in spite of that the equations mentioned are still not fulfilled. The author does not undertake the endeavor of explaining this problem, which exceeds the framework of this paper.

## 3. Conclusions

The conducted experiment shows, that it is proper to consider $1/f$ noise as the result of avalanche noise. In the case of earlier stated $1/f$ noise existing under conditions of thermal equilibrium [16], thermal noise seems to be its only source. In case of other kinds of noise it can be assumed that $1/f$ noise, in the same manner, is the natural low frequency end of their spectra.

The author is aware of the fact that these short conclusions should be interpreted with caution. One can still state that there is no adequate explanation of the $1/f$ noise. Further investigations are needed in the field of noise in the time domain.

## References

[1] Keshner MS. Proc IEEE 1982;70:212.
[2] Zaklikiewicz AM. Solid-St Electr 1993;36:1477.
[3] Van Vliet CM. Solid-St Electr 1991;34:1.
[4] Van der Ziel A. Proc IEEE 1988;76:233.
[5] Hooge FN. In: Musha T, editor. Noise in Physical Systems and 1/f Fluctuations. Omsha, Tokyo, 1991:7.
[6] Pearson GL, Sawyer B. PIRE 1952;40:1348.
[7] Champlin KS. J. Appl Phys 1959;30:1039.
[8] Haitz RH. J. Appl. Phys. 1964;35:1370.

[9] Ambrozy A. Electronic Noise. Akademiai Kiado, Budapest, 1982:106.
[10] Belan J. et al. Noise in Phys Systems. In A. Ambrozy. editors. Akademiai Kiado, Budapest, 1989:263.
[11] Lukaszek W, Van der Ziel A, Chenette ER. Solid-St Electr 1976;19:57.
[12] Buckingham MJ. Noise in Electronic Dev. and Syst. John Wiley, Ellis Horwood Ltd., Chichester, 1983:143.
[13] van Vliet KM et al. IEEE Trans ED 1979;26:746.
[14] van Vliet KM et al. IEEE Trans ED 1979;26:752.
[15] Gong J et al. Phys Stat Sol 1981;63:445.
[16] Voss RF, Clarke J. Phys Rev B 1976;13:556.