Noise Measurement used for Reliability Screening of Optoelectronic Coupled Devices(OCDs)

Jiansheng Xu[a], Derek Abbott[b], Yisong Dai[a]

[a] Department of Electronic Engineering, Jilin University of Technology, Changchun
Jilin Province, P.R. of China 130025

[b] Department of Electrical and Electronic Engineering, The University of Adelaide
Adelaide, SA 5005, Australia

ABSTRACT

In this paper the theoretical analysis of noise sources in OCDs is given and the relation between typical defects and 1/f, g-r and burst noise is described. According to statistical results, a threshold to screen potential devices with excess noise is derived. It has been proved both in theory and by experiment that the screening criterion proposed is reasonable. Moreover, the experimental results show that the screening method of OCDs is of practical value.

Keywords: Optoelectronic Coupled Devices, Noise Measurement, Device Reliability and Screening

1. INTRODUCTION

Noise as a diagnostic tool for quality control and reliability estimation of semiconductor devices has been widely accepted and used, and there are many papers published on this area [1234].[5] It is very useful to describe the judging rules, which enable us to predict the individual quality of electronic components, based on measurements of their noise. It has showed that experimental facts about noise are presented which help us to better understand the correlation between noise in a device and its reliability. Besides, life tests and aging tests have shown that the initial noise and initial noise rate of noise increase of correlated best with their lifetime.[6]

However, the published papers on screening standards, especially on how to draw an optimal threshold value for us to screen poor quality devices are quite few. In most of the presented results there is a lack of well defined criterion for quality validation of electronic components based on the noise generated by them. The classification rules of electronic components based on their 1/f noise measurements have been presented.[5] The cases in which the method can be applicable are limited. Because of the classification rules based on only 1/f noise, previous criteria are unable to meet high quality requirements, for in some cases there is a g-r noise or even burst noise in a semiconductor device, but its 1/f noise level is as normal as for other qualified devices (in Section 4).

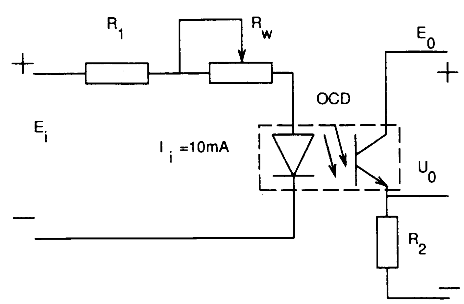

Figure 1. Measuring circuit for Optoelectronic Coupled Devices

Dr. Jiansheng Xu is a postdoctoral fellow in EEE Department , The University of Adelaide until March 2000. E-mail: jxu@eleceng.adelaide.edu.au; Telephone: +618-8303-3165; Fax: +618-8303-4360

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The purpose of this paper is to establish a screening criterion to meet the requirement of high reliability for OCDs. Figure 1 is the measurement circuit for the Optoelectronic Coupled Devices. From the Figure 1 it can be seen that an OCD is made of two parts: LED and Photodetector, both of which are P-N junction devices. The noise in OCDs below 1 MHz mainly consists of shot noise, 1/f noise, generation-recombination noise and burst noise. Shot noise and 1/f noise are fundamental. It should be noted that the noise that we are interested in here has strong relation to some typical defects in a device. For this reason it is necessary that the generation mechanisms of 1/f noise, g-r noise and burst noise in OCDs are all briefly discussed, especially on what kinds of defects can lead to these three kinds of noises. And the relation between them should be studied also.

1.1. 1/f Noise

1/f noise is caused by the number fluctuation of free charge carriers or the mobility fluctuations in a semiconductor. Its spectrum is inversely proportional to frequency in a very wide range. In homogenous semiconductors, its spectrum can be characterized by a parameter α according to

$$\frac{S_R}{R^2} = \frac{\alpha}{fN} \tag{1}$$

where S_R is the spectral power density of the noise in the resistance R, N is the total number of free charge carriers, and f is the measurement spot frequency. The parameter α then is the contribution of one electron to the relative noise at 1 Hz, assuming that the N electrons are uncorrelated noise sources.[7]

In addition, it has been found that α is not a constant, which has a value between 10^{-6} and 10^{-3}, but that α depends on the prevailing type of scattering of the electrons and perfection of the crystal lattice. In recent years much progress has been made and found that it is mainly caused by lattice scattering.

Vandamme[1] shows that the 1/f noise parameter α increase with the concentration of dislocations and its noise spectrum is proportional to α and inversely proportional to the carrier lifetime. Konczakowska[8] has shown that there is a strong relation between bipolar device lifetime and 1/f noise.

Therefore, it is possible for us to evaluate the device quality and reliability according to its magnitude. From this point of view, 1/f noise is of great value to device quality evaluation and reliability prediction. It is verified that crystal defects, current constrictions and the number of crystal defects increasing all cause 1/f noise to increase. The experimental results [9] have proved that 1/f noise in the specimen with more dislocations is at least one order of magnitude larger than that of the specimen with fewer dislocations.

At present, a major cause of 1/f noise in semiconductor devices is traceable to properties of the surface of the material. The generation and recombination of carriers in surface energy states and density of surface states are important factors, but even the interface between silicon surfaces and grown oxide passivation are centers of noise generation. It is obvious that 1/f noise intensity has a relation to the generation-recombination center (surface defect) numbers in device oxide layer. Thus, the relation between device surface quality and 1/f noise is closely related and can be used to help us screen poor quality devices according to their intensity of excess noise.

1.2. g-r Noise

Generation-recombination (g-r) noise is a conductance fluctuation due to number of fluctuations of carriers. The noise distribution density is Gaussian and its signal spectrum can be expressed as Lorentzian.

$$\frac{S_R}{R^2} = \frac{S_V}{V^2} = \frac{S_I}{I^2} = \frac{A\tau_0}{1+(\omega\tau_0)^2} \tag{2}$$

Here, $\tau_0=1/\omega_0$ is the characteristic time corresponding to a characteristic (or corner) frequency f_0 or ω_0, and $\omega=2\pi f$ is the angular frequency of measurement. G-r noise has a Gaussian amplitude distribution function because it is actually made up from the superposition of a very large number of independent random telegraph signal processes with the same characteristic time. The coefficient, A, is a measure of the number of such individual processes. It depends on g-r center density, current and device structure.

G-r noise is often absent in high quality silicon devices, but not yet in heterostructures, where lattice defects are often a problem. In poor quality devices, the g-r noise is generated at the contacts or at the surface. In better samples, the dominant conductance noise source is in the bulk. Hence , g-r noise is a useful diagnostic tool to study trap centers in compound semiconductors.

Thus it can be seen that g-r noise in a device has a direct relation to semiconductor defects (impurities, damage etc). Therefore, it has become an effective method of analyzing bulk defects and reliability screening by means of measuring g-r noise.

By experimentation it has been shown that the defects (dislocation, deep-level impurities) in the emitter junction and surface are the main sources of transistor g-r noise especially as a p-n junction is in a forward biased state.

1.3. Burst Noise

A random telegraph signal (RTS) known as burst noise, is often observed in p-n junction devices such as diodes, transistors and detectors, operating under forward biased conditions. All authors have attributed the phenomenon to defects located in the neighbourhood of the emitter base junction.

Hsu [10] first presented a physical model of explaining burst noise. In this model, it is thought that heavy metal impurities deposited in the charge region of p-n junction is the major cause of this noise.

But Blasquez [11] has found that so-called "pure" lattice dislocation can also cause burst noise even when heavy metal impurity deposits have been removed. Therefore it seems that metal impurity precipitates are not indispensable to produce burst noise. Dai, *et al*[12] has given a new burst model, which emphasizes the built-in electric field in the p-n junction and the variation of the potential barrier near the defects. This model not only is consistent with the experimental results given by Blasquez,[11] but also can explain various burst noise waveforms.[12]

Burst noise spectrum is not Gaussian as are the other types of noise. The voltage noise spectrum of RTS fluctuation is mainly due to number fluctuations of carriers. The current noise spectral density of burst noise has the shape of Lorentzian,[13]

$$S_I(f) = \frac{A_b {\tau_b}^2}{1 + \omega^2 {\tau_b}^2} \tag{3}$$

where A_b is a constant depending on the nature of the defects and τ_b is defined as $1/\tau_b = 1/\tau_1 + 1/\tau_2$. According to the random switch mode ,[14] during the time interval dt, an open switch has the probability dt/τ_1 of closing, and a closed switch a probability dt/τ_2 of opening. The information on the defects is contained in the parameter A_b and τ_b.

Besides, burst (or RTS) noise is a problem typical for submicron MOST's or bipolar devices with crystallographic damage in sensitive areas[15] and this noise is also temperature and bias dependent. The origin of burst noise is related to the dislocations and other crystallographic defects, as well as metallic precipitates.

A number of experiments have already shown that lattice dislocation is the major source of burst noise for both bipolar transistor and integrated circuit. It has been found by experiment that this kind of noise has relation to serious defects in a device. Therefore, devices with burst noise often degrade faster and at least show a poor noise behavior.

2. SCREENING CONDITIONS OF 1/F NOISE , G-R NOISE AND BURST NOISE

It can be seen that 1/f noise , g-r noise and burst noise are all fluctuations in the conductance. Strasilla and Struut[16] demonstrated that experimentally observed burst noise consists of a random telegraph signal superimposed on 1/f noise, but the two processes are statistically independent. Dislocations and electromigration in metalization affect device reliability and has been identified as the main source of device failure.

For P-N junction devices, it has been shown that 1/f noise, g-r noise and burst noise are three typical noise sources, which are caused by surface defects, impurities, and dislocations, etc. For high quality of OCDs, these defects should not be allowed to exist. However, according to above discussion, 1/f noise is closely related to the surface states of the semiconductor device, g-r noise related to device bulk defects such as impurities, dislocations, etc., and burst noise is related to lattice dislocation as well as heavy metal impurity deposits. Besides, emitter region edge dislocation make both 1/f noise and burst noise increase at the same time in most cases.

Hence in order to exclude these defects and meet high reliability, we can use the three independent noise parameters as reliability indicator for quality estimation of OCDs.

Thus, it can be seen that an excess noise is closely associated with some defects in the devices and/or imperfections of technology. So through noise measurement, their noise amplitudes can be used to indicate the defects. The device with burst noise can be found from its instantaneous waveform in the time domain, g-r noise can be found through noise component analysis or ratio of noise value at 10 Hz to noise value at 1 Hz and is used to judge whether there is g-r noise or not. 1/f noise can be judged by the amplitude of voltage noise values at 1 Hz. Therefore, an optimal threshold value may be established to reject the device with burst noise, excess g-r noise or excess 1/f noise.

However, from the generation mechanisms of 1/f, g-r and burst noise, it can be seen that the probability to generate these three type noise by the same defect is quite small although some defects may cause any two of them simultaneously in some cases. No correlation has been observed between 1/f parts and g-r or white parts of the spectrum in optical and electrical fluctuations, which is in good agreement with the results given by Orsal, *et al.*[17] Therefore it is necessary that there be three independent screening conditions to meet the requirement of high reliability if the devices with excess 1/f, g-r or burst noise need to be rejected.

In this paper the screening conditions proposed are

a. $V_n(1\ \text{Hz}) \geq 80000\ \text{nV}/\sqrt{\text{Hz}}$

b. $V_n(10\ \text{Hz})/V_n(1\ \text{Hz}) \geq 0.6$

c. with burst noise

3. MEASURING CIRCUIT AND MEASURING SYSTEM

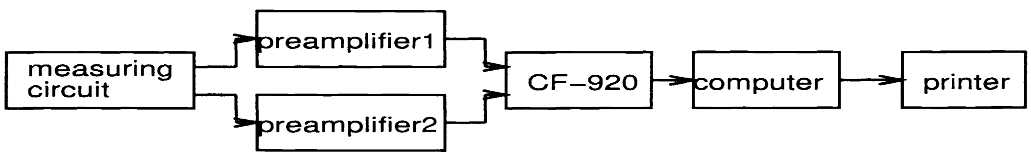

Figure 2. The measurement system block diagram for the optoelectronic coupled devices

In Fig. 1, the measuring circuit for OCDs is shown, where the input current I_i=10 mA, $E_i = E_o$=6 V. Fig. 2 is the measurement system block scheme, a double channel preamplifier cross-spectrum measurement method has been adopted. In order to accurately measure the equivalent input noise power spectrum, the swept sine-wave method [18] is adopted to measure system gain $G(f)$, which includes the testing OCD gain $G_1(f)$ and cross-spectrum density estimate gain $G_2(f)$, i.e., $G(f) = G_1(f)G_2(f)$. The output noise power spectrum is calculated by a FFT spectrum analyzer (CF-920, made in Japan). The equivalent input noise spectrum is expressed as

$$S_i(f) = \frac{S_o(f)}{G^2(f)} \tag{4}$$

In the testing system, the cross spectrum density estimate method [19] is used to reduce the noise contribution of two preamplifiers. The reason is that the two sets of batteries are used as the power supplies for the preamplifiers so that the noise in the two preamplifiers themselves are uncorrelated, so that the measuring system can be used to measure a much smaller signal than usual.

The frequency range of the cross-spectrum estimator in the measurement system is from 1 Hz-100 kHz. Simultaneously, during the measuring process, 512-time spectral averaging is adopted to ensure the high precision of the cross-spectral estimation. The measured results show that the precision of measuring system is superior to 4% .[19]

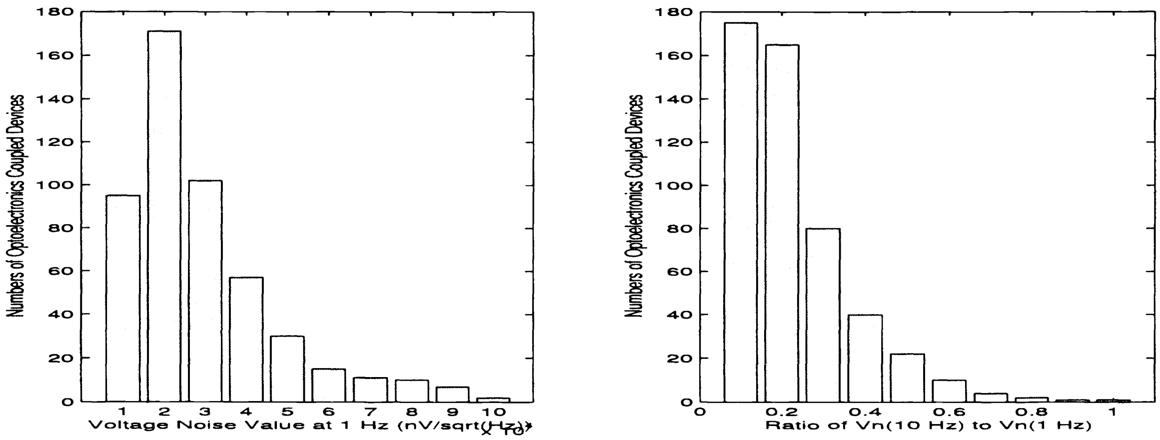

Figure 3. (a) Statistical measurement results of the noise voltage of OCDs at 1 Hz (b) Statistical measurement results of $V_n(10\ \text{Hz})/V_n(1\ \text{Hz})$

4. EXPERIMENTAL RESULTS

The device will be rejected if it meets any one condition of the three. First, the condition (a) is used to reject the device with excess 1/f noise and the value, 80000 $\text{nV}/\sqrt{\text{Hz}}$, is a statistical value for 500 OCD (fabricated by China Shuzhou Semiconductor Factory) measurement results. The statistical results of OCD is shown in Fig. 3.

Condition (b) is used to reject the device with g-r noise, for we have found in most cases that the noise power spectrum of the device with g-r noise is usually shown in a platform from 1 Hz to 10 Hz. Therefore, the ratio of $V_n(10\ \text{Hz})$ to $V_n(1\ \text{Hz})$ is chosen as a judging threshold to discern whether there is a g-r noise or not, and the ratio of $V_n(10\ \text{Hz})$ to $V_n(1\ \text{Hz})$ is quite different if the device without g-r noise. An example is shown in Figure 4.

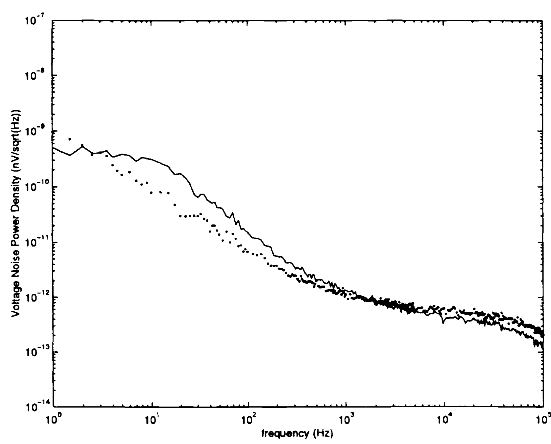

Figure 4. Curves of PSD of device #131 with g-r noise (solid line) and device #12 without g-r noise (dotted line)

The output voltage noise measurements are carried out with an emitter load R_2 and were analyzed assuming that the noise was the sum of shot noise, 1/f noise and g-r noise components. The noise power spectrum density can be expressed as:

$$S(f) = A + \frac{B}{f^n} + \sum_{i=1}^{N} \frac{C_i f_{oi}}{1 + (\frac{f}{f_{oi}})^2} \tag{5}$$

where A is the shot noise, B is the amplitude of 1/f noise, C_i/f_{oi} is the plateau value of g-r noise caused by defects (impurities, lattice defects or damages), f_{oi} is the corner frequency of g-r noise, and N is the number of excess g-r noise sources in a p-n junction.

One would suspect that n is different for devices which contain active electrical defects compared with good devices; however, the experiments[9] showed that n is slightly larger than unity(n=1.13 -1.26) for BJTs with various dislocations. Hence we use 1/f noise for reliability estimation (n=1). The measurement results of OCD #131 and #12 are listed in Table 1.

Table 1. The measurement results of No # 131 and #12

No. of OCD	1 Hz (V^2/Hz)	10 Hz (V^2/Hz)	15 Hz (V^2/Hz)	100 kHz (V^2/Hz)	Corner frequency f_o (Hz)	V_n(10 Hz)/V_n(1 Hz)
#131	4.03e-10	3.14e-10	2.36e-10	1.04e-13	15	0.88
#12	5.58e-10	7.92e-11	7.87e-11	2e-13	15	0.37

The curve fitting results are

for #131

$$S(f) = 10^{-13} + \frac{1.7 \times 10^{-10}}{f} + \frac{2.13 \times 10^{-10}}{1 + (\frac{f}{f_o})^2} \tag{6}$$

for #12

$$S(f) = 2 \times 10^{-13} + \frac{5.53 \times 10^{-10}}{f} + \frac{0.07 \times 10^{-10}}{1 + (\frac{f}{f_o})^2} \tag{7}$$

According to equation (6) and (7), it is obvious that the amplitudes of shot noise and 1/f noise in #131 and #12 are only a little different, but the amplitudes of their g-r noise are quite different: the amplitude of g-r noise in #131 is nearly 30 times larger than that of #12, which means that in this specimen (#131) it is possible for a device with excess g-r noise component although its shot noise and 1/f noise are at the normal level.

Through the noise measurement of a large number of optoelectronic coupled devices, we found that the corner frequency of g-r noise is about 10 Hz - 30 Hz, so that the spectral curve is a more flat in this frequency region. As a consequence, the ratio of V_n(10 Hz) to V_n(1 Hz) selected as the reliability screening indicator is reasonable.

Condition (c) means that the device with burst noise should be rejected in most cases because it can not only affect device reliability, but also hinder the device's normal operation, especially in digital circuits, leading to malfunction.

In our experiments, it is found that the sums of samples with excess 1/f noise are 19, with excess g-r noise is 18 and with burst noise is 14. Among them, only 4 samples meet condition (a), (b) and (c) at the same time, i.e., they have excess 1/f noise, g-r noise and burst noise at the same time. In other words, there are 15 samples with excess 1/f noise and low g-r noise, 14 samples with low 1/f noise but with excess g-r noise, and 10 samples with low 1/f noise, g-r noise but with burst noise. Hence to improve the screening reliability of OCDs, it is mandatory to use 1/f noise, g-r noise and burst noise together as a screening standard to reject some OCDs with surface and bulk defects.

5. DISCUSSION ON THE OPTIMAL NOISE CRITERION

For 500 GO103 optoelectronic coupled devices several parameters were measured before and after a reliability test of 1000 h. The conditions of the reliability power test are I_F=10 mA, V_{ce}=10 V, temperature=23 ^{o}C and r.h.=50%. The criterion for failure of OCDs are $|\Delta CTR/CTR| > 30\%$, $I_R > 50$ μA, $R_{iso} < 10^9$, $V_{iso} < 500$ V, $C_{iso} > 1$ pF, $I_{CEO} > 0.1$ μA and $V_R < 5$ V. After the reliability power test 47 OCDs were found to have failed, in which 31 are with excess 1/f, g-r or burst noise, and 16 with small 1/f, g-r or burst noise.

If the noise threshold levels used as a noise criterion are selected as condition (a), (b) and (c) together, then the estimated error is 4/51=7.84%.

If the condition (a) and (b) are changed into 70000 $nV/\sqrt{Hz}$ and 0.5 (which means that high reliability is required and is named as condition (1)), then 84 OCDs will be rejected with excess 1/f, g-r or burst noise and the estimated error is 37/84=44.1%.

Contrary to this case, if the condition (a) and (b) are changed into 90000 $nV/\sqrt{Hz}$ and 0.7 (which means that lower reliability is required and is named as condition (2)), then there are 31 OCDs rejected with excess 1/f, g-r or burst noise. The estimated error is 16/31=51.61%.

Now we discuss the optimal noise criteria selection for all tested samples. For a large number of OCDs, a correlation should exist between failure rate and noise level, i.e., devices which have excess noise must have a large failure rate λ_1 (λ_1 is the number of failure devices which have excess noise divided by the sum of devices which have excess noise). The devices which have non-excess noise must have a small failure rate λ_2 (λ_2 is the number of failure devices which have non-excess noise divided by sum of devices which have non-excess noise).[20] Therefore, the ratio of the failure rates is defined as $r=\lambda_1/\lambda_2$ and the results are shown in Table 2.

Table 2. failure rate and statistical experimental results of 500 specimens

condition	with excess 1/f g-r,burst noise	with small 1/f g-r,burst noise	failure rate λ_1	failure rate λ_2	failure ratio r	estimated error
(a,b,c)	51	449	60.8%	3.56%	17.1	7.84%
(1)	84	416	36.9%	3.85%	9.58	44.1%
(2)	31	469	100%	3.41%	29.4	51.6%

According to Table 2, it can be seen the right way to get optimal threshold is that estimated error and maximum failure r should be considered together, which means that the optimal noise criterion must assume that the failure rate r has a maximum value ,[20] is insufficient. And it can also be concluded that much more testing and statistical analysis needs to be done in order to get an optimal threshold for a large number of devices. It has been shown experimentally that above screening method, condition (a), (b) and (c) being selected to reject OCDs devices with excess 1/f noise , g-r noise or burst noise, is necessary and reasonable.

6. CONCLUSIONS

The noise spectra of 500 OCD have been measured, and screening thresholds and experimental results are given. On the basis of experimental results, the major conclusions are as follows:

(1) It is emphasised that all of noise mechanisms should be studied rather than noise at only specific frequency for reliability estimation of OCDs. Then it can be found that 1/f noise, g-r noise and burst noise must be used as three independent noise criteria for high reliability estimation. Moreover, it is necessary that the estimated error and the maximum value of failure ratio r should be considered together when the optimal noise threshold levels need to be found.

(2) The experimental results show that after a lifetest not all rejected devices initially exhibit an excess noise. However, the results have demonstrated that the failure rate for devices which initially exhibit high noise is about 10 times higher than the failure rate for devices which initially exhibit low noise.

(3) We select the ratio of V_n(10 Hz) to V_n(1 Hz) instead of g-r noise component of noise spectrum, because this reliability screening indicator is more simple and convenient than the calculation of g-r noise component during the practical application for screening of a large number of devices.

In many important applications, we must know the reliability of each component and not of the ensemble. After noise measurements, all OCDs can be classified into groups with different reliability on the basis of their noise level. Consequently, based on the method presented in this paper, it is possible to evaluate the reliability of each device individually. Furthermore, the method proposed in this paper can be extended to the applications of other kinds of semiconductor devices' screening. Of course, further investigation may be needed to correlate the noise reliability indicators and life time of corresponding electronic devices.

REFERENCES

1. L.K.J. Vandamme, "Noise as a Diagnostic Tool for Quality and Reliability of Electronic Devices," *IEEE Trans. on Electronic Devices,*, 41(11), 2176-2187, 1994
2. B.K. Jones, "Excess Noise and Reliability in Electronic Devices," *presented at ICFN'95*, Lithuania, 573-578, 1995
3. Yisong Dai, Jiansheng Xu, Xinfa Zhang, "A Study of Optical Noise Measurement as a Reliability estimation for laser diodes," *Microelectron. Reliab,* 35(4),731-734, 1995
4. Yisong Dai, " A Precision Noise Measurement and Analysis Method used to Estimate Reliability of Semiconductor Device," *Microelectron and Reliab,* 37(6), 893-899, 1997
5. Alicja Konczakowska, "Quality and 1/f Noise of Electronic Components" *Quality and Reliab. Engineering Int.,* 11, 165-169, 1995
6. Doru Ursutiu and B.K. Jones, "Low Frequency Noise used as a Lifetime Test of LEDs," *Semiconductor Science and Technology,* 11(8), 1133-1136, 1996
7. F.N. Hooge, T.G.M. Kleinpenning, and L.K.J. Vandamme, "Experimental studies on 1/f noise," *Rep. Prog. Phys.,* 44, 449-532, 1981
8. A. Konczakowska, "Lifetime Dependence of 1/f Noise of Bipolar Transistors," *9th Int. Conf. on Noise in Physical System,"* Montreal, C.M. van Vliet Ed, Singapore, Worlds Scientific, 1987
9. M. Mihaila, K. Amberiadis, Van der Ziel A, "1/f, g-r and burst noise induced by emitter-edge dislocations in bipolar transistors", *Solid-State Electron.,* 27(7): 675-676, 1984
10. S.T. Hsu, R.J. Whitter, C.A. Mead, "Physical model for burst noise in semiconductor devices", *Solid-State Electronics,* 13(7): 1055-1071, 1970
11. G. Blasquez, "Excess noise sources due to defects in forward biased junctions", *Solid-State Electron,* 21(11-12), 1425-1430, 1978
12. Yisong Dai, Yaqin Li , Jiansheng Xu, "The discussion on physical models for burst noise in a forwarded biased p-n junction and their experimental validation," *Microelectron. Reliab.* 38(4), 671-675, 1998
13. X.L. Wu, A. van der Ziel, A.N. Birdas and A.D. van Rheenen, "Burst type mechanisms in bipolar transistors," *Solid-state Electron.,* 32(11), 1039-1042, 1989
14. A van der Ziel, *Noise in Solid State Devices and Circuits, Wiley Interscience,* New York, 1986
15. K.F. Knott, "Low energy electron beam investigation of polar transistors using scanning electron microscopy with particular reference to burst noise," *6th Int. Conf. On Noise in Physical Systems,* Gaithersbury, MD 1981, PH.E. Meijer, R.D. Mountain, and R.J. Soulen, Eds, Washington: NBS Special Publication, 97-99, no.614, 1981
16. U.J. Strasilla and M.J.D. Struut, "Measurement of white noise and 1/f noise within burst noise," *Proc. IEEE,* 1711-1713, 1974
17. B. Orsal, P. Signoret, J.-M. Peransin, K. Daulasim, and R. Alabedra, *IEEE Trans. Elec. Devices,* 41, 2151, 1994
18. A Van der Ziel, *Noise Sources, Characteristic, Measurement,* Englewood Cliffs, NJ, Prentice-Hall, 1970, ch.2, 11-17.
19. Yisong Dai, "The performance analysis of cross-spectral density estimator and its applications," *Int. J. Electronics,* 71(1), 45-53, 1991
20. Yisong Dai, "Optimal low frequency noise criteria used as a reliability test for BJTs and their experimental results," *Microelectron. Reliab,* 31(1), 75-78, 1991