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The study on a screening threshold for reliability estimation of optoelectronic coupled devices

J. Xu[a,*], D. Abbott[b], Y. Dai[a]

[a]Department of Electronic Engineering, Jilin University of Technology, Changchun, 130025 People's Republic of China

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

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Abstract

According to noise sources of optoelectronic coupled devices (OCDs) and device reliability estimation method, a screening threshold is proposed for OCDs, which can be used to screen potential devices with excess noise, such as 1/*f*, *g*–*r* and burst noise. By this method, the device reliability can be improved and high reliability requirements can be met. The experimental results show that the method is of practical value. © 2000 Elsevier Science Ltd. All rights reserved.

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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 in this area [1–6]. In fact, 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.

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 criteria 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 in Ref. [6], but the cases in which the method can be applicable are limited. Because of the classification rules based on only the 1/*f* noise, the criteria were unable to meet high quality requirements. 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 (Section 3).

The purpose of this paper is to establish a screening threshold to meet the requirement of high reliability for optoelectronic coupled devices (OCDs). Then, through theoretical analysis and by experiment, it can be proved that the screening threshold is reasonable and applicable.

Fig. 1 is the measurement circuit for the OCDs. Practically, we found cases where device static parameters were all normal but operation failures occurred under normal operation. In our analysis, we found that excess noise was so large in some devices that it can dominate the signal completely, so that the device cannot work normally. For this reason, we try to use noise measurement as a diagnostic tool to screen the potential devices with the defects that cause excess noise.

In Fig. 1, it can be seen that an OCD is made of two parts: LED and photodetector, both of which are p–n junction devices. So it can be concluded that the noise in OCDs below 1 MHz consists mainly of shot noise, 1/*f* noise, generation-recombination noise and burst noise. Among them, shot noise and 1/*f* noise are fundamental. It should be noted that the noise that we are interested in here should have a strong relation to some typical defects in a device. In Ref. [7] the generation mechanisms of 1/*f* noise, *g*–*r* noise and burst noise in OCDs are discussed, especially on what kinds of defects can lead to these three kinds of noises. Ref. [7] also discusses the relation between these noises. In this paper, we will mainly discuss the determination of a threshold to reject potential devices with excess 1/*f*, *g*–*r* and burst noise.

* Corresponding author. Department of Electrical and Electronic Engineering, The University of Adelaide, Adelaide 5005, Australia. Tel.: + 61-8-8303-3165; Fax: + 61-8-8303-4360.

E-mail address: jxu@eleceng.adelaide.edu.au (J. Xu).

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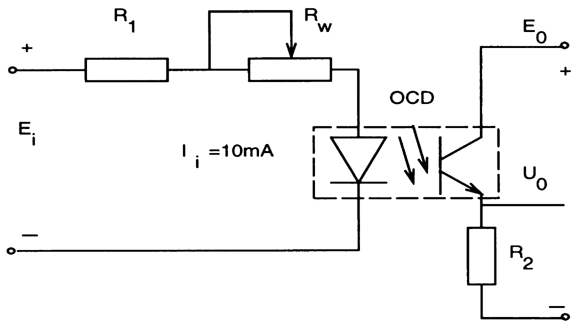

Fig. 1. Measuring circuit for optoelectronic coupled devices.

2. Screening conditions of 1/*f*, *g–r* and burst noise

Generally, it has been already accepted that 1/*f* noise is closely related to the surface states of the semiconductor device, *g–r* noise is related to device bulk defects such as impurities, dislocation, and burst noise is related to lattice dislocation as well as heavy metal impurity deposits. From the generation mechanisms of 1/*f*, *g–r* and burst noise, it can be seen that the probability to generate these three types of noise by the same defect is quite small although some defects may cause more than one of them simultaneously in some cases.

Hence, in order to exclude these defects and meet high reliability, we can use the three independent noises, 1/*f*, *g–r* and burst noise, as reliability indicators for quality estimation of OCDs. In this way even if some defects can cause two or three of them at the same time, such as emitter region edge dislocation which makes both 1/*f* noise and burst noise increase at the same time in most cases, can also be rejected.

Therefore, because an excess noise is closely associated with some defects in the devices and/or imperfections of technology, noise measurement amplitudes can be used to indicate the defects. In practice, we found that the device with burst noise can be found from its instantaneous waveform in the time domain. The device with *g–r* noise can be found through noise component analysis or ratio of noise value at 10 Hz to noise value at 1 Hz (which will be explained and proved in later part), which is used to judge whether there is *g–r* noise or not. And the device with 1/*f* noise can be judged by the amplitude of voltage noise value at 1 Hz.

Therefore, it is necessary that there be three independent screening conditions to meet the requirement of high reliability to reject the devices with excess 1/*f*, *g–r* or burst noise.

In this paper the screening conditions are:

(a) $V_n(1\ \text{Hz}) \geq 500\ \text{nV}/\sqrt{\text{Hz}}$
(b) $V_n(10\ \text{Hz})/V_n(1\ \text{Hz}) \geq 0.6$
(c) with burst noise.

3. Screening threshold analysis

The device will be rejected if it meets any one of the three conditions given above. First, the condition (a) is used to reject the device with excess 1/*f* noise and the value, $500\ \text{nV}/\sqrt{\text{Hz}}$, is a statistical value for 500 OCD (fabricated by China Shuzhou Semiconductor Factory) measurement results, which is considered from both economic cost and practical reliability requirement.

Condition (b) is used to reject the device with *g–r* noise because we have found that the noise power spectrum of device with *g–r* noise usually showed a platform from 1 to 10 Hz in most cases. Therefore, the ratio of $V_n(10\ \text{Hz})$ to $V_n(1\ \text{Hz})$ was chosen as a judging threshold to discern whether there is a *g–r* noise or not. The reason is that the

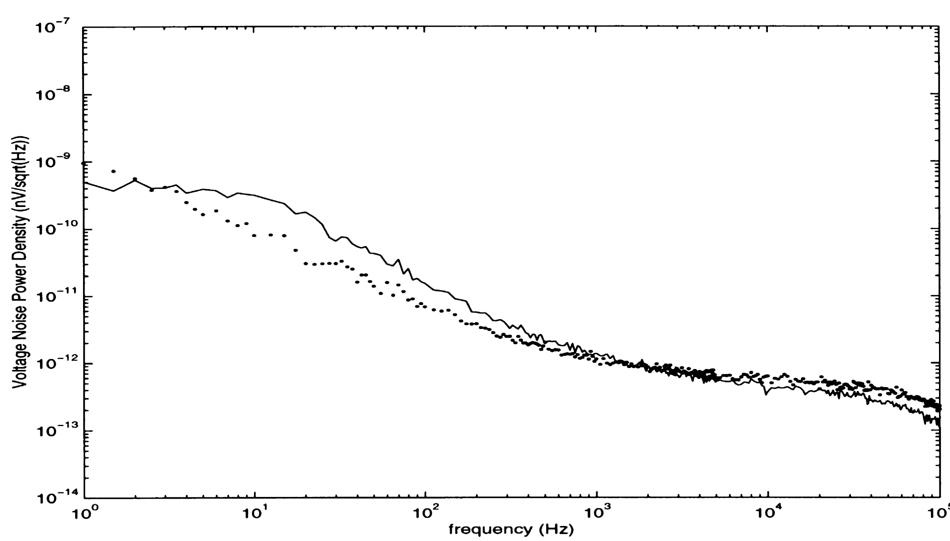

Fig. 2. Curves of PSD of device #131 with *g–r* noise (solid) and device #12 without *g–r* noise (dotted).

Table 1
The measurement results of device # 131 and #12

No. of OCDs	1 Hz (V^2/Hz)	10 Hz (V^2/Hz)	Corner frequency f_0(Hz)	V_n(10 Hz)/ V_n(1 Hz)
#131	4.30×10^{-10}	3.14×10^{-10}	15	0.88
#12	5.58×10^{-10}	7.92×10^{-11}	15	0.37

ratio of V_n(10 Hz) to V_n(1 Hz) is quite different if the device is without g–r noise. An example is shown in Fig. 2.

The output voltage noise measurements were carried out with an emitter load R_2 and were analysed, 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:

$$S(f) = A + \frac{B}{f} + \sum_{i=1}^{N} \frac{\frac{C_i}{f_{0i}}}{1 + \left(\frac{f}{f_{0i}}\right)^2} \quad (1)$$

where A is the shot noise, B is the amplitude of 1/f noise, C_{0i}/f_{0i} is the plateau value of g–r noise caused by defects (impurities, lattice defects or damages), f_{0i} is the corner frequency of g–r noise, and N is the number of excess g–r noise sources in a p–n junction.

The curve fitting results are as follows, and only one g–r noise component is found in both #131 and #12 (Table 1).

for #131

$$S(f) = 4 \times 10^{-18} + \frac{6.8 \times 10^{-15}}{f} + \frac{1.28 \times 10^{-13}}{1 + \left(\frac{f}{f_0}\right)^2} \quad (2)$$

for #12

$$S(f) = 8 \times 10^{-18} + \frac{2.21 \times 10^{-14}}{f} + \frac{4.2 \times 10^{-15}}{1 + \left(\frac{f}{f_0}\right)^2} \quad (3)$$

According to the Eqs. (2) and (3), it was found that the amplitudes of shot noise and 1/f noise in #131 and #12 were only a little different. However, 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. This means that in this specimen #131 it is possible for a device to have 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 OCDs, we found that the corner frequency of g–r noise was about 10–30 Hz, and the spectral curve was more flat in this frequency region. As a consequence, the selection of the ratio of V_n(10 Hz) to V_n(1 Hz) as the reliability screening indicator was 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 was found that the sum of samples with excess 1/f noise was 19, with excess g–r noise was 18 and with burst noise was 14. Among them, only four samples met conditions (a)–(c) at the same time, i.e. they had excess 1/f noise, g–r noise and burst noise simultaneously. 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.

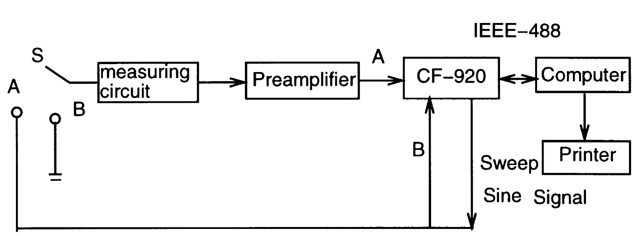

Fig. 3. The measurement system block diagram.

4. Measurement system

Fig. 3 is the measurement system block scheme, in which 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 [8] is adopted to measure the system gain $G(f)$, which includes the testing OCD gain $G_1(f)$ and cross-spectrum density estimation 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 (SOKKI CF-920). The equivalent input noise spectrum is expressed as $S_i(f) = S_0(f)/G(f)^2$

In the testing system, the cross-spectrum density estimation method [9] was used to reduce the noise contribution of two preamplifiers. The reason was that two sets of batteries were used as the power supplies for the preamplifiers so that the noise in the two preamplifiers themselves were uncorrelated. So, the measuring system can be used to measure a much smaller signal than usual.

The frequency range of the measurement system is from 1 Hz to 100 kHz. Simultaneously, during the measuring process, 512 time-spectral averaging was adopted to ensure the high precision of the cross-spectral estimation. The measured results showed that the precision of the system was superior to 4% [9].

5. Discussion on experimental results and optimal noise criterion

For 500 GO103 OCDs several parameters were measured before and after a reliability test of 1000 h. The conditions

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 ratio *r*	Estimate error (%)
(a)–(c)	51	449	17.1	7.84
(1)	84	416	9.58	44.1
(2)	31	469	29.4	51.6

of the reliability power test are $I_F = 10$ mA, $V_{ce} = 10$ V, temperature = 23°C and r.h. = 50%. For OCDs, several important properties are current transmitting rate (CTR), the insulation resistance (R_{iso}), voltage (V_{iso}) and capacitance (C_{iso}) between the input and output terminals, and reverse leakage current (I_{ceo}) and working voltage (V_R). The criteria for failure of OCDs are $|\Delta CTR/CTR| > 30\%$, $I_R > 50$ *mA*, $R_{iso} > 10^9\ \Omega$, $V_{iso} < 500$ V, $C_{iso} > 1$ pF, $I_{ceo} > 0.1\ \mu A$ and $V_R < 5$ V. After the reliability power test 47 OCDs were found to have failed, in which 31 were 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 are selected as conditions (a)–(c) together, the estimated error is 4/51 = 7.84%. If the conditions (a) and (b) are changed into 450 nV/$\sqrt{Hz}$ and 0.5 (which means that high reliability is required and 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 conditions (a) and (b) are changed into 550 nV$\sqrt{Hz}$ and 0.7 (which means that lower reliability is required and 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 the 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) [10]. Therefore, the ratio of the failure rates is defined as $r = \lambda_1/\lambda_2$ and the results are arranged and shown in Table 2.

From Table 2, it can be seen the right way to get optimal threshold is that minimum estimated error and maximum failure ratio *r* should be considered together, which means that the optimal noise criterion must assume that the failure ratio *r* has a maximum value [10], is insufficient. Also, it can 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. The experimental results have shown that the screening method, conditions (a)–(c) being selected together to reject OCDs 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. Based on the results, the major conclusions are obtained as follows:

1. 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.
2. It is necessary that the estimated error and the maximum value of failure ratio *r* should be considered together in order to obtain optimal noise thresholds.
3. In this paper the ratio of $V_n(10\ Hz)$ to $V_n(1\ Hz)$ was chosen as a screening threshold instead of *g*–*r* noise component analysis of noise spectrum, for this reliability indicator is more simple and convenient than the calculation of *g*–*r* noise component, especially during the practical screening of a large number of devices.

After noise measurements, all OCDs can be classified into groups with different reliability level based on their noise level. Consequently, based on the method presented in this paper, it is possible to evaluate the reliability of each device individually, especially to meet higher reliability requirements. Thus, the method proposed in this paper can be extended to the applications of other kinds of semiconductor devices' screening as well.

There are several problems that need to be addressed to improve prediction accuracy and screening method, in order to get an optimal screening threshold for other kinds of semiconductor devices. Some of these are:

1. The study and analysis of intrinsic noise sources in a semiconductor device.
2. The link between typical defects and noise sources, such as 1/*f*, *g*–*r* and burst noise. Also, are there other defects which may be related to other noise sources or causes?
3. There are some devices, whose noise values are quite normal when initial tests are carried out. However, after an ageing test they are already in early failure and should be rejected. There might exist some hidden defect in the OCDs. Reliability prediction can be improved greatly if these defects are identified. One of the methods to solve this problem is to test a device over a given time to determine changes in behaviour such as ΔV_n.
4. A further advance would be a reasonable prediction of device life expectancy, based on excess noise measurement and analysis.

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