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Noise as reliability screening for semiconductor lasers

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ABSTRACT The low-frequency electrical noise in semiconductor lasers is measured and used for device-reliability screening, which is a sensitive and non-destructive method. In the experiment, we developed some approaches to improve the validity of reliability screening by using noise criteria. A new method of determining the threshold level of noise criteria is given. The experimental results show that this method is effective.

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1 Introduction

Semiconductor laser diodes (LDs) are widely used in optical fiber communication, optical sensors, medical treatment, and for pumping solid lasers. Their reliability is of great concern in practical applications. The current method used for reliability screening is electrical aging, a statistical method that is destructive, time consuming, and expensive. So, one of the most important technological challenges is to develop a new method to carry out reliability screening for semiconductor lasers without damaging the devices themselves. Noise has shown potential as a sensitive non-destructive indicator of device reliability. Recently, this method has been studied extensively [1–7]. The research results indicate that the low-frequency electrical noise has a close relation with quality and reliability of semiconductor lasers; moreover, the devices with higher noise level are usually unreliable. For manufacturers and users of semiconductor lasers, the important work is how to predict device reliability according to noise level. In this paper, low-frequency electrical noise in semiconductor lasers is used for device-reliability screening and a new method of determining the threshold level of noise criteria is given. The experimental results show that this method is effective.

2 The selection of the measuring frequency of the noise

When noise is used to carry out reliability screening of devices, a key problem is to select the measuring frequency of the noise. Vandamme et al. observed $1/f$ noise at $f = 3$ Hz as a reliability estimation for solar cells [8] and $1/f$ noise at $f = 1$ Hz as a reliability test for diode lasers [9], Dieudonne et al. measured the noise voltage of TEGFETs at 10 kHz to predict performance at low temperature [10], and Jones and Mzunzv used the noise at 10 kHz and a constant current to estimate the stability of polycrystalline silicon thin film resistors [11]. It is evident that, if devices exhibit only shot noise and $1/f$ noise, the noise measured at one specific frequency is enough to show excess $1/f$ noise and it can be used

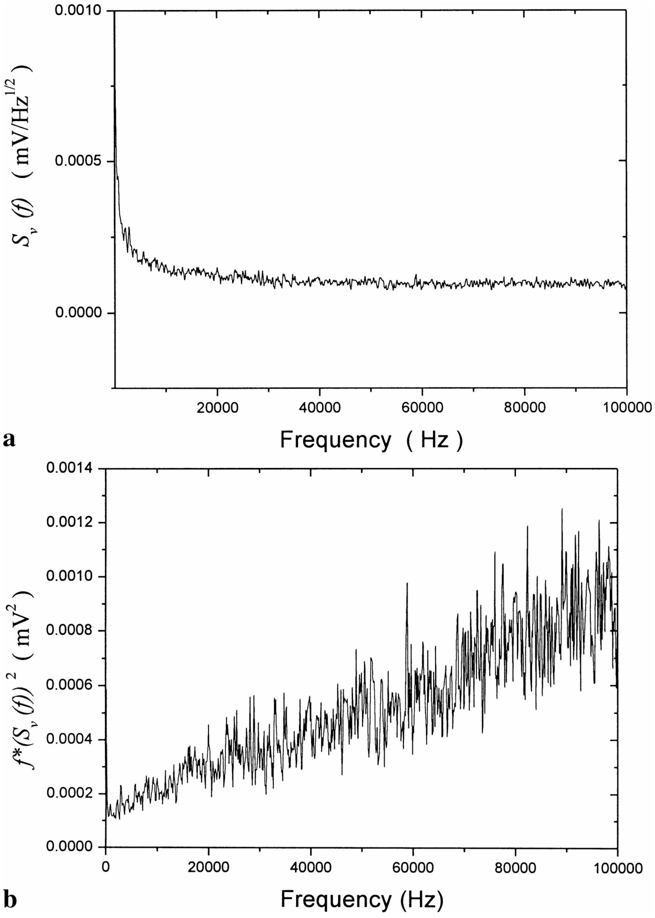

FIGURE 1 The curves of noise spectral density ($S_V(f)$) of a typical device. **a** $S_V(f) \sim f$ curve, **b** $f(S_V(f))^2 \sim f$ curve

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for reliability estimation. This specific frequency depends on the ratio of $1/f$ noise to shot noise, and its value is usually less than 10 kHz [12]. But, from the experimental results and theoretical analysis, the excess noise in semiconductor lasers is usually made up of the superimposition of $1/f$ noise and generation and recombination (g-r) noise [1, 13].

The $1/f$ noise is usually attributed to fluctuations in the surface recombination velocity, and its intensity coincides with surface defects [14, 15]. The generation and recombination of carriers in surface-energy states and the density of surface states are important factors contributing to $1/f$ noise, and the interfaces between silicon and oxide layers are also $1/f$ noise sources. It is obvious that the $1/f$ noise level has a close relation with device surface quality. The $1/f$ noise due to mobility fluctuation has been described by Hooge et al. [16]. Its spectrum can be characterized by the Hooge formula:

$$S_i(f) = \frac{\alpha_{\mathrm{H}} I^2}{fN} ,$$

where $S_i(f)$ is the current noise spectral density, N is the total number of free carriers, α_{H} is the Hooge parameter, and f is the measuring frequency. It is also found that the Hooge parameter is not a constant and depends on lattice defects [17] and it is verified that crystal defects cause a $1/f$ noise increase [18]. The deep-level impurities and defects in devices contribute to g-r noise [18, 19]; the intensity and corner frequency of g-r noise are sensitive to the concentration and position of deep-level defects, respectively.

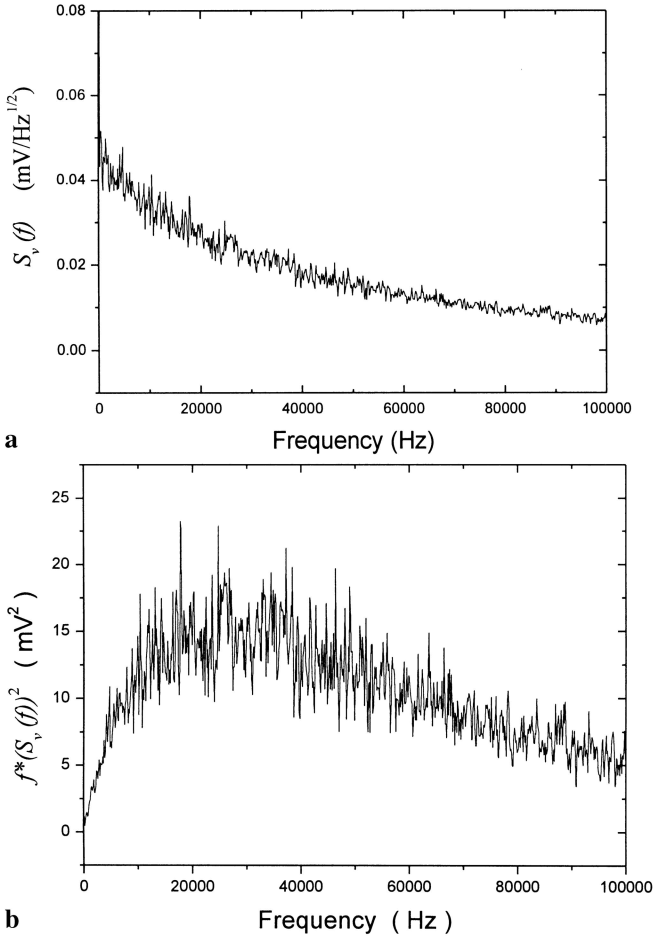

FIGURE 2 The curves of noise spectral density ($S_{\mathrm{V}}(f)$) of a device with g-r noise. **a** $S_{\mathrm{V}}(f) \sim f$ curve, **b** $f(S_{\mathrm{V}}(f))^2 \sim f$ curve

As a consequence, the noise measured at one specific frequency is not enough to show both $1/f$ noise and g-r noise and we should consider all noise mechanisms; both $1/f$ noise and g-r noise are used for reliability screening.

In the experiment, we firstly measure the low frequency voltage noise spectrum density ($S_{\mathrm{V}}(f)$) of the devices (the typical result is shown in Fig. 1a), and then draw the $f(S_{\mathrm{V}}(f))^2$ curve. If the $f(S_{\mathrm{V}}(f))^2$ curve has no pump (shown in Fig. 1b), the noise at $f = 2.5$ Hz was used for reliability screening; if the $f(S_{\mathrm{V}}(f))^2$ curve has a pump (shown in Fig. 2b, and its noise spectrum density is shown in Fig. 2a), it means g-r noise exists in the device [19], which was immediately screened out.

3 The selection of measurement current

The factors contributing to noise include nonradiative recombination centers drawn in by impurities and defects in the active region, a bad state of the surface or interface, large leakage, a bad ohmic contact, etc. All these factors affect device reliability. The defects and impurities in the active region and facet are associated with the noise level (S_{v1}) of the devices operating at low bias current [5, 6]. The series resistance and contacts contribute to the noise level (S_{v2}) of the devices operating at higher bias current [6]. So, when the noise is used to estimate device reliability, both S_{v1} and S_{v2} should be measured and considered. However, in early studies only S_{v2} was measured [1–4]. In our report, S_{v1} is also used for reliability screening.

4 Noise measurement and results analysis

At room temperature, the low-frequency voltage noise spectrum and noise value at $f = 2.5$ Hz were measured with the operating bias current of 20 μA (lower bias current) and 5 mA (higher bias current). The devices we used were 980-nm InGaAsP/InGaAs/GaAlAs separate-confinement heterostructure (SCH) double quantum well (DQW) high-power lasers. The DQW structure was grown by metal-organic chemical vapor deposition (MOCVD). The broad contact stripe is formed by wet chemical etching through the p^+-GaAs cap layer outside the 100 μm-wide stripe to prevent current spreading, and using 150-nm-thick SiN_x as an insulating layer to define the metal contact stripe. Devices with a cavity length of 800 μm were coated (8%/90%) and mounted p-side down on copper heat sinks. For most of the devices, the threshold currents are about 120 mA, and the slope efficiencies are about 0.6 W/A. The noise-measuring results for 30 devices (first group) which came from the one epitaxy and followed the same technological process are shown in Table 1. S_{v1} and S_{v2} are noise at $f = 2.5$ Hz of devices operating with the bias current of 20 μA and 5 mA, respectively; $\log(S_{\mathrm{v1}})$ and $\log(S_{\mathrm{v2}})$ correspond to their logarithm value. Three devices exhibit g-r noise, and were immediately screened out.

The histogram of the noise (logarithm value) distribution is shown in Fig. 3, which exhibits a normal distribution.

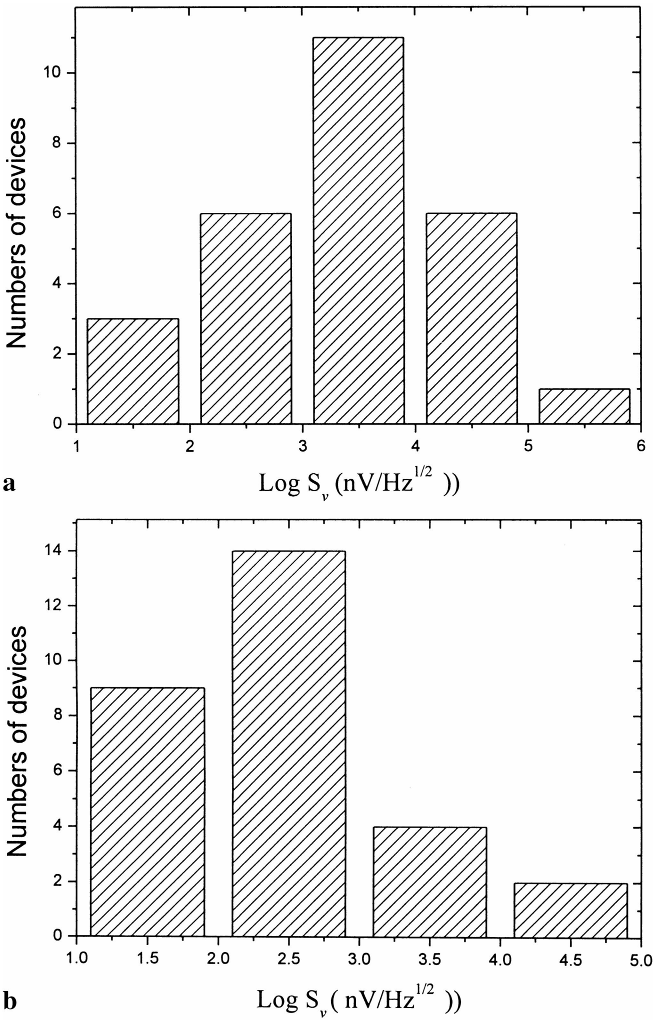

FIGURE 3 The histogram of noise value of first-group devices (30 LDs). **a** $I = 20\,\mu\text{A}$, **b** $I = 5\,\text{mA}$

Then, the mean value ($\overline{S_\text{v}}$) and the variance (σ) of noise values for 30 devices are calculated. When $I = 20\,\mu\text{A}$, $\overline{S_{\text{v}1}} = 8544.99\,\text{nV}/\sqrt{\text{Hz}}$, $\sigma_1 = 20\,124.56\,\text{nV}/\sqrt{\text{Hz}}$; when $I = 5\,\text{mA}$, $\overline{S_{\text{v}2}} = 924.82\,\text{nV}/\sqrt{\text{Hz}}$, $\sigma_2 = 2400.43\,\text{nV}/\sqrt{\text{Hz}}$.

5 Aging results

The devices were aged at 70 °C and 400 mA for 200 h. After aging, if the device threshold current is higher than 120% of the original threshold current, we assume that the device has failed. From aging results (shown in Table 1), eight devices have failed, including three devices with g-r noise. The output powers of all failed devices decreased dramatically; for example, the output powers of device no. 2505 are 229.3 mW and 138.1 mW before and after aging, respectively.

6 Determining the threshold of the noise criterion

Konczakowska [20] suggested a classification algorithm, which has been verified by reliability experiments. On the basis of noise-measurement results, the border values for quality groups are

$$S'_\text{v} = \overline{S_\text{v}} - \alpha\sigma\,,$$
$$S''_\text{v} = \overline{S_\text{v}} + \alpha\sigma\,,$$

where $\overline{S_\text{v}}$ denotes the mean value of S_v, σ denotes the variance of S_v, and α is a constant. The rule of classifying devices into three classes according to noise level is as follows:

- first class, if $S_\text{v} \leq S'_\text{v}$, high quality is expected,
- second class, if $S'_\text{v} < S_\text{v} < S''_\text{v}$, good quality is expected,
- third class, if $S_\text{v} \geq S''_\text{v}$, poor quality is expected.

So, S''_v is defined as the threshold of the noise criterion, i.e. a device with higher noise than S''_v is unreliable and should be

Device number	Noise $(\text{nV/Hz}^{1/2})$ $S_{\text{v}1}$	Log($S_{\text{v}1}$)	$S_{\text{v}2}$	Log($S_{\text{v}2}$)	After aging	Device number	Noise $(\text{nV/Hz}^{1/2})$ $S_{\text{v}1}$	Log($S_{\text{v}1}$)	$S_{\text{v}2}$	Log($S_{\text{v}2}$)	After aging
6	1255	3.1	197.15	2.29	Failure	2498	8070	3.91	1700	3.23	
3	g-r		3290	3.52	Failure	2509	39 960	4.6	233	2.37	Failure
B14	1532	3.18	276	2.44		B411	56.5	1.75	50.1	1.7	
13	1458	3.16	141	2.15		B38	1358	3.13	142.59	2.15	
B161	100	2	86.27	1.94		4	1532	3.19	272	2.43	
2491	16 763	4.22	52.7	1.72		2512	1288	3.11	169.8	2.23	
B392	89.2	1.95	69	1.84		2511	3980	3.6	102.3	2.01	
2495	337	2.58	127.8	2.11		2499	g-r		213.2	2.61	Failure
B311	78	1.89	46.32	1.67		2504	19 950	4.3	676.1	2.83	Failure
B291	11 200	4.05	1000	3		B271	g-r		1623.6	2.02	Failure
B33	1828	3.26	196	2.29		2497	12 590	4.1	1412.5	3.15	
B41	170	2.23	81.39	1.91		2514	398	2.6	41.69	1.62	
B39	1070	3.03	147.9	2.17		2507	645	2.81	28.84	1.46	
2505	2450	3.39	13 200	4.12	Failure	B411	367	2.56	20.89	1.32	
2508	990	3.1	152.23	2.18		B221	101 200	5.01	1995.2	3.3	Failure

TABLE 1 Noise-measuring and aging results of first-group devices (30 LDs)

α	0.2	0.3	0.4	0.41	0.45	0.5	0.56	0.57	0.6	0.67	0.8	1.6
λ	11.4	14	17.6	23	23	23	23	12	12	12	12	8.3

TABLE 2 The λ values corresponding to different α

Device number	Noise $(\mathrm{nV/Hz^{1/2}})$ S_{v1}	$\mathrm{Log}(S_{v1})$	S_{v2}	$\mathrm{Log}(S_{v2})$	After aging	Device number	Noise $(\mathrm{nV/Hz^{1/2}})$ S_{v1}	$\mathrm{Log}(S_{v1})$	S_{v2}	$\mathrm{Log}(S_{v2})$	After aging
2515	1650	3.22	111.6	2.05		2521	178	2.25	87.4	1.94	
2516	15 700	4.2	821	2.91	Failure	B21	17 500	4.24	916	2.96	Failure
2517	2320	3.37	563	2.75		B41	2610	3.42	578	2.76	
2518	96.4	1.98	51	1.71		B51	1860	3.27	480	2.68	
2519	3980	3.6	1510	3.18		B61	4210	3.62	1360	3.13	
2520	g-r		2720	3.43	Failure	B71	27 200	4.43	819	2.91	Failure
A41	17 700	4.25	320	2.51	Failure	B101	1550	3.15	110.3	2.04	
A51	10 800	4.03	412	2.61	Failure	B111	2870	3.46	1970	3.29	Failure
A91	771	2.89	92.6	1.97		B121	405	2.61	134	2.13	
A101	691	2.84	230	2.36		B151	1210	3.08	89	1.95	
A111	978	2.99	60.2	1.78		B201	1870	3.27	3370	3.53	Failure
A221	169	2.23	98.2	1.99		B211	2500	3.4	130	2.11	
A131	2100	3.32	226	2.35		B221	2140	3.3	121.5	2.08	
A141	42 300	4.63	852	2.93	Failure	B231	4650	3.67	1483	3.17	Failure
A151	34 400	4.54	329	2.52	Failure	B261	2160	3.33	84.3	1.93	
A161	8410	3.92	586	2.77		B271	2910	3.46	1210	3.08	
A171	621	2.79	72.3	1.86		B281	1100	3.04	89.1	1.95	
A181	647	2.81	64.3	1.81		A11	891	2.95	126.8	2.10	
A191	1240	3.09	131.6	2.12		A21	1301	3.11	81.6	1.91	
A201	2560	3.41	116.7	2.07		A31	13 200	4.12	2658	3.42	Failure

TABLE 3 Noise-measuring and aging results of second-group devices (40 LDs)

screened out. But a key problem is to select the right value for α. In our experiment, a new method is presented.

For a large number of devices, a correlation should exist between failure rate and noise level, i.e. devices with higher noise must have a large failure rate λ_1 (λ_1 is the number of failed devices with higher noise than the threshold level of the noise criterion divided by the sum total of devices with higher noise than the threshold level). Devices with lower noise must have a small failure rate λ_2 (λ_2 is the number of failed devices with lower noise than the threshold level of the noise criterion divided by the sum total of devices with lower noise than the threshold level) [12]. Otherwise, the ratio of the failures is defined as

$$\lambda = \frac{\lambda_1}{\lambda_2} .$$

Then, the optimal threshold levels of the noise criterion based on statistical analysis for a number of devices must assume that λ has a maximum [12].

In our experiment, a series of λ values corresponding to different α were calculated. From the results (shown in Table 2), when $\alpha = 0.41$, 0.45, 0.5, and 0.56, λ has a maximum value of 23. So, $\overline{\alpha} = (0.41 + 0.56)/2 = 0.485$ was selected; then the optimal threshold levels of the noise criterion for first-group devices should be:

$$\text{when } I = 20\,\mu\mathrm{A}, \quad S''_{v1} = \overline{S_{v1}} + \overline{\alpha}\sigma_1 = 18\,305.4\,\mathrm{nV}/\sqrt{\mathrm{Hz}},$$

$$\text{when } I = 5\,\mathrm{mA}, \quad S''_{v2} = \overline{S_{v2}} + \overline{\alpha}\sigma_2 = 2089.03\,\mathrm{nV}/\sqrt{\mathrm{Hz}}.$$

7 The validity of the optimal threshold levels of the noise criterion

The question arises whether the threshold criterion determined by this kind of method (in Sect. 6) is valid or not.

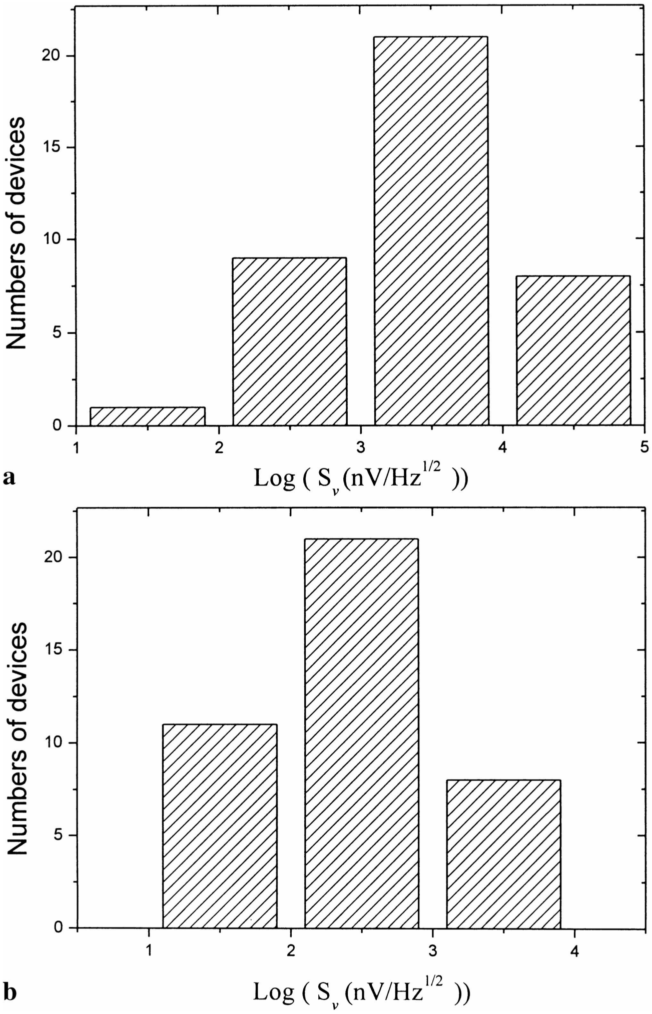

FIGURE 4 The histogram of noise value of second-group devices (40 LDs). **a** $I = 20\,\mu\mathrm{A}$, **b** $I = 5\,\mathrm{mA}$

To check this problem, we randomly sampled another 40 devices (second group), which were manufactured at the same time and by the same process as the devices used in Sect. 4, and carried out noise measurements; the results are shown in Table 3. The histogram of the noise (logarithm value) distribution is shown in Fig. 4, which also exhibits a normal distribution. The mean value ($\overline{S_{v'}}$) and the variance (σ') of noise values for 40 devices are calculated:

$$\text{when } I = 20\,\mu\text{A}\,, \quad \overline{S_{v1'}} = 6139.7\,\text{nV}/\sqrt{\text{Hz}}\,,$$
$$\sigma'_1 = 9610.86\,\text{nV}/\sqrt{\text{Hz}}\,;$$
$$\text{when } I = 5\,\text{mA}\,, \quad \overline{S_{v2'}} = 631.64\,\text{nV}/\sqrt{\text{Hz}}\,,$$
$$\sigma'_2 = 811.59\,\text{nV}/\sqrt{\text{Hz}}\,.$$

The $\overline{\alpha}$ value is still selected as 0.485. Then, the optimal threshold levels of the noise criterion for second-group devices are:

$$\text{when } I = 20\,\mu\text{A}\,, \quad S''_{v1'} = \overline{S_{v1'}} + \overline{\alpha}\sigma'_1 = 10\,800.97\,\text{nV}/\sqrt{\text{Hz}}\,,$$
$$\text{when } I = 5\,\text{mA}\,, \quad S''_{v2'} = \overline{S_{v2'}} + \overline{\alpha}\sigma'_2 = 1025.26\,\text{nV}\sqrt{\text{Hz}}\,.$$

That is to say, if the noise (S_{v1}) of a device operating with the bias current of 20 μA is higher than $10\,800.97\,\text{nV}/\text{Hz}^{1/2}$ or the noise (S_{v2}) of a device operating with the bias current of 5 mA is higher than $1025.26\,\text{nV}/\text{Hz}^{1/2}$, the device is assumed to be an unreliable device. From this reliability-screening condition, 12 devices with higher noise than the threshold level will be rejected, and one device with g-r noise, so that 13 devices should be screened out.

The devices were aged at the same conditions as in Sect. 5. After aging (the aging results are shown in Table 3), 12 devices have failed. Among the 12 devices, there are 10 devices with a higher noise level than the threshold level of the noise criterion, one device with a lower noise level than the threshold and one device with g-r noise. The λ value is 22.5; it is obvious that the threshold criterion determined by the above method (in Sect. 6) is effective.

8 Conclusion

The low-frequency electrical noise is used to carry out reliability screening of semiconductor lasers, which is a sensitive and non-destructive method. In our experiment, some improved approaches are given.

1. Both the low-frequency noise spectrum ($s_v(f)$) of a device and the noise level at one specific frequency ($f = 2.5$ Hz) were measured and used for reliability screening, which shows not only $1/f$ noise but also g-r noise in the device.
2. The noise of a device operating at low bias current (20 μA) is used to carry out device-reliability screening together with the noise in the device operating at higher bias current (5 mA). So, most factors contributing to the noise level in the device and affecting device reliability can be shown.
3. A new method of determining the threshold level of the noise criterion is given. The experimental results show that this method is effective.

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