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LOW–FREQUENCY NOISE MEASUREMENTS USED FOR QUALITY ASSESSMENT OF GaSb BASED LASER DIODES PREPARED BY MOLECULAR BEAM EPITAXY

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The paper reports on a non-destructive method of reliability prediction for semiconductor lasers diodes GaSb based VCSE (vertical cavity surface emitting). Transport and noise characteristic of forward biased were measured in order to evaluate the new MBE (molecular beam epitaxy) technology. The results demonstrate that the lasers prepared by new MBE technology have higher quality than the samples prepared by using the classic MBE technology.

Keywords: molecular beam epitaxy, excess nois, lasers diodes, vertical cavity surface emitting, gasb substrate

1 INTRODUCTION

Excess noise is for a long time use as a diagnostic tool in device research (from 1966) [1–4]. Some fundamental noise sources such as thermal and shot noise are well understood, and deviations can often be understood due to local heating or local carrier multiplication. 1/f noise is also fundamental but it is not clear understanding of physical origin of the 1/f noise. Because it is omnipresent, and it is a conductance fluctuation in bulk of material, it is very sensitive for current crowding phenomena and therefore an ideal diagnostic tool. Generation-recombination noise and random-telegraph-signal noise (burst noise) is not fundamentals and can be avoided often by avoiding traps at the Fermi-level, therefore this noise is a “poor” device indicator and can be avoided by improving technology [5]. The defects are the natural sources of the excess current and the excess noise and they are responsible for the changes of several measurable quantities. Physical processes in electronic devices can give a useful piece of information on the device reliability provided there is a correlation with failure mechanism [6–12]. It is known that most of failures in the flat region of the “bathtub curve” of the failure rate result from the latent defects created during the manufacture processes or during the operating life of the devices.

High sensitivity of excess electrical noise to this kind of defects is the main reason of investigation and use of noise as a diagnostic and prediction tool in reliability physics for the semiconductor devices lifetime assessment. It is generally accepted that there are some fundamental sources of noise which generate the noise background. This is the case of the thermal noise, shot noise and, as was shown recently, of the fundamental quantum 1/f noise. Besides the fundamental noise, which cannot be eliminated from any device, there exists excess noise which is believed to carry information on the device technology and structure defects which are either non-intentionally introduced during the device production or appear as results of the degradation processes during the device operation. As it is well known, the noise spectral density increases with stress and damage and varies among nominally identical devices. Therefore the excess noise is not of fundamental origin.

2 SAMPLE DESCRIPTION

On the GaSb substrate first a DBR (Distributed Bragg Reflector) mirror was grown, followed by the semiconductor laser structure consisting of n type base region, multiple quantum well active region and Buried Tunnel Junction in order to limit the area of current through the structure. On top of the structure another DBR layer composed from Si and SiO_2 was deposited. This construction allows to decrease the necessary current needed to obtain laser emission and the high reflectivity of both mirrors and amplification of the multi quantum well active region allow the laser to emit in the direction perpendicular to the device surface. Our samples represent two development stages of the MBE (molecular beam epitaxy) technology used in VERTILAS GmbH Company. The first set comprising of samples 12440, 12441, 12443 and 12444 was prepared with improved MBE technology and classic MBE technique, and second set consists of lasers diodes prepared by classic MBE technology and bonding technique with representatives of pulsed laser

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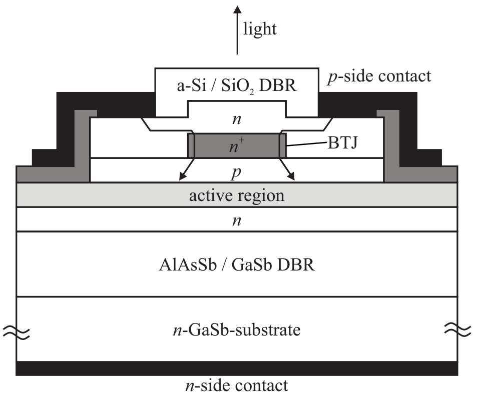

Fig. 1. Structure of VERTILAS laser diodes 12440–12444

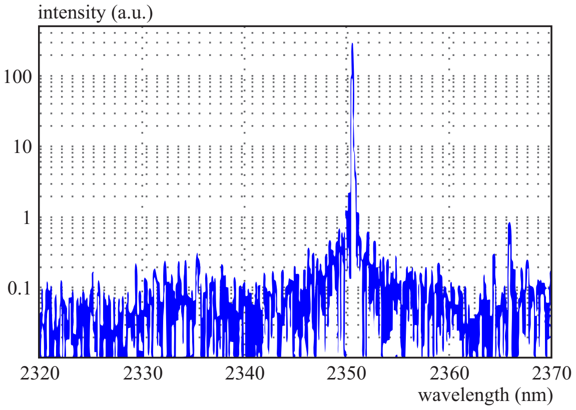

Fig. 2. Plot of intensity versus wavelength for continuous laser diode No. A1847

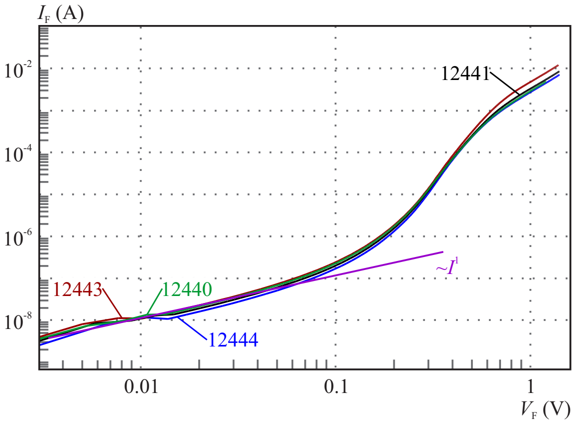

Fig. 3. Plot of $\log I$ versus $\log V$ for laser diodes No. 12440 and 12441 and 12443 and 12444 in forward bias direction

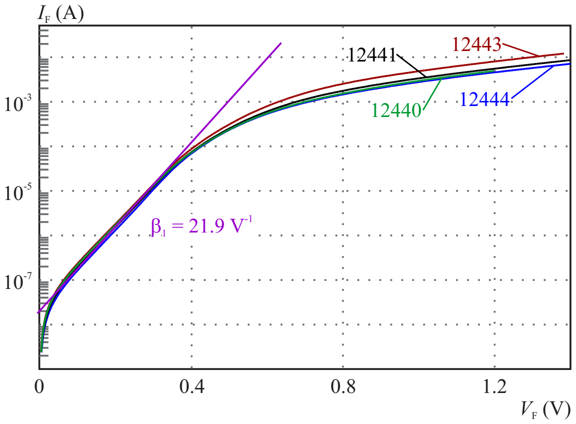

Fig. 4. Plot of $\log I$ versus $\operatorname{lin} V$ for laser diodes No. 12440 and 12441 and 12443 and 12444 in forward bias direction

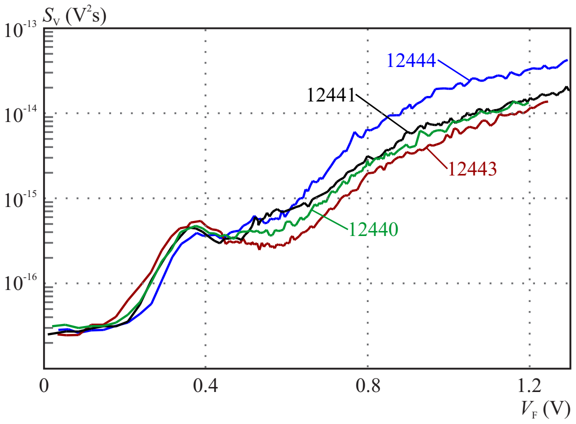

Fig. 5. The noise spectral density as a function of forward voltage for laser diodes No. 12440 and 12441 and 12443 and 12444. The value of load resistance was $R_L = 1\text{k}\Omega$.

diode Nos. A1883 and A1884 and continuous laser diodes Nos. A1847 and A1853. The structure of these lasers, produced by VERTILAS GmbH Company, can be made as single mode lasers with very low threshold current emitting single mode with a wide tuning range for usage in the gas detection systems. In Fig. 1 is a cross section of such a laser. In Fig. 2 is a plot of the spectral intensity of laser No. A1847 at $I_F = 6$ mA and temperature 293 K.

3 EXPERIMENTAL RESULTS

Lasers diodes GaSb based VCSE (vertical cavity surface emitting) prepared by molecular beam epitaxy were measured in order to evaluate the new MBE technology. Figure 3 shows $I - V$ characteristics of all of the specimens 12440 through 12444 in log-log scale. Linear regions of these characteristics in voltage interval $V_F = 0$ V to 0.1 V imply PN-junction parallel resistances to be present in all specimens. We can see that shunt resistances by all specimens 12440, 12441, 12443, 12444 should be equal to $R_{SH} = 10^6\,\Omega$. From Fig. 4 we can see that exponent β in the exponential dependence $I_F = I_0 \exp(-\beta V)$ it is $\beta = 21.9\,\text{V}^{-1}$. Given that $\beta = 1/nkT$ than value of n is equal to $n = 1.76$. It follows that current I_F has primarily generation-recombination component.

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Figure 5 reports for all 12440, 12441, 12443, 12444 specimens the noise power voltage spectral density versus forward DC voltage plots. The noise voltage was picked up across a load resistance $R_L = 1\,\text{k}\Omega$, at a pass band mean frequency of 1 kHz and a bandwidth of 20 Hz. This

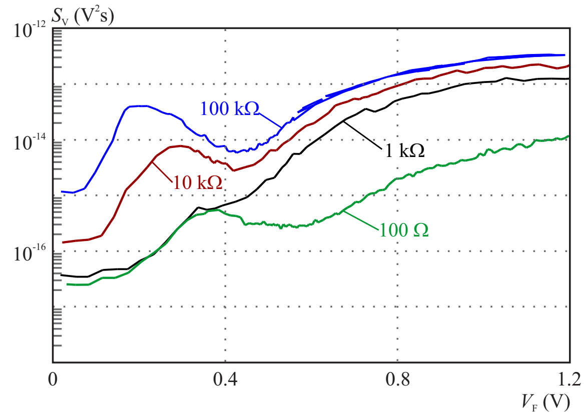

Fig. 6. The noise spectral density as a function of forward voltage and load resistors $R_L = 100\,\Omega$, $1\,\mathrm{k}\Omega$, $10\,\mathrm{k}\Omega$ and $100\,\mathrm{k}\Omega$ for laser diode No. 12443

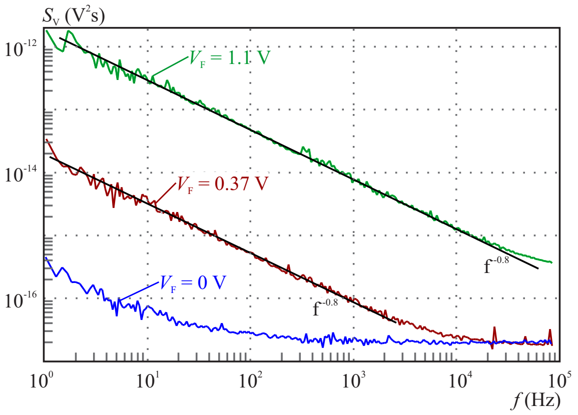

Fig. 7. The noise spectral density versus frequency for laser diode No. 12444, $R_L = 1\,\mathrm{k}\Omega$, at $V_F = 0$ V, $V_F = 0.37$ V and $V_F = 1.1$ V

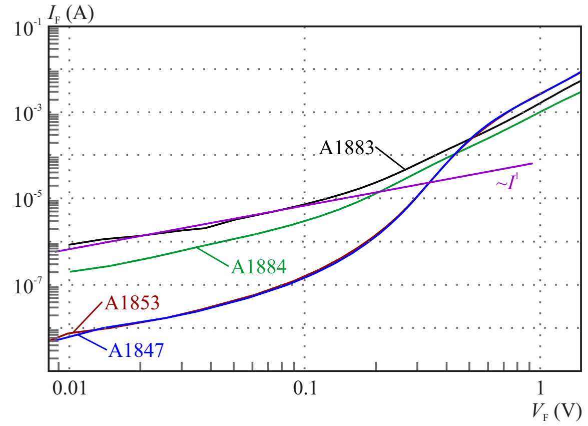

Fig. 8. Plot of $\log I$ versus $\log V$ for laser diode No. A1883 and A1884 (pulsed lasers) and A1847 and A1853 (continuous lasers) in forward bias direction

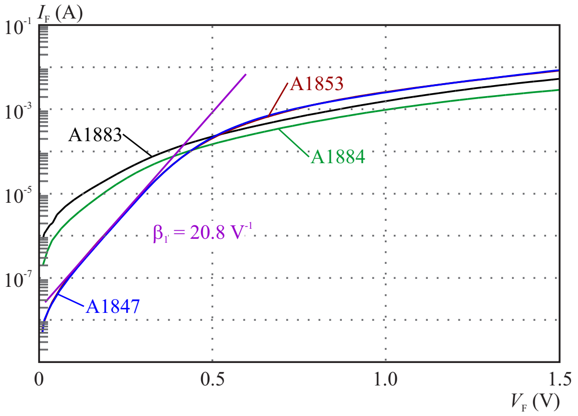

Fig. 9. I–V characteristic for laser diode No. A1847 and A1853 and A1883 and A1884 in forward bias direction

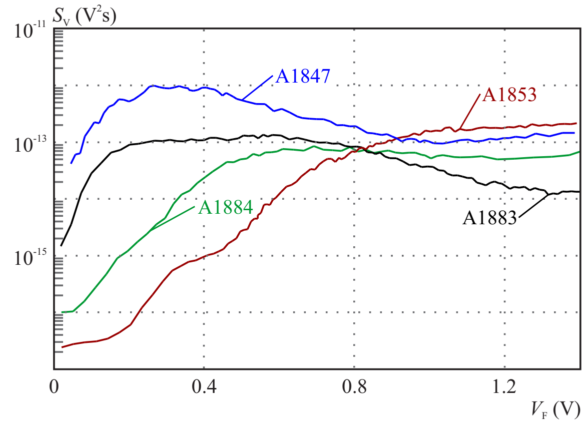

Fig. 10. The noise spectral density as a function of forward voltage for laser diodes No. A1847 and A1853 and A1883 and A1884. The value of load resistance was $R_L = 1\,\mathrm{k}\Omega$

noise characteristic measured across the load resistance versus the forward bias has its extreme value if a dynamic resistance R_D of a p-n junction under test is equal to the load resistance R_L. The curve maximum shifts to a lower forward voltage region when the load resistance increases.

The measurable quantity is the noise voltage V_N across the load resistance R_L. The voltage power spectral density S_V is given by

$$S_V = \frac{V_N^2}{\Delta f}\,, \tag{1}$$

where Δf is the bandwidth of the measuring apparatus.

The current power spectral density S_1 can be calculated as

$$S_1 = \frac{S_V}{R_P^2}\,, \tag{2}$$

Where

$$R_P = \frac{R_D}{R_L} R_D + R_L\,, \tag{3}$$

R_D is the p-n junction dynamic resistance, for which it holds and can be expressed as $R_D = 1/\beta I_F$, where $\beta = q/nkT$.

n low injection mode, the load resistance $R_L < 1/\beta I_F$. Putting $\beta = 20\,\mathrm{V}^{-1}$ and $R_L = 100\,\Omega$, the low injection current region extends up to $I_F < 5 \times 10^{-4}\,\mathrm{A}$. In the low injection region, the current noise spectral density is given by

$$S_I = \frac{S_V}{R_L^2}\,. \tag{4}$$

The voltage noise spectral density across the load resistance will reach a maximum value, S_{VM}, if the noise source internal resistance equals the load resistance (in low-frequency region).

At voltages of up to $V_F = 0.2$ V, specimens 12440 through 12444 feature a noise component corresponding to the thermal noise background of the measuring apparatus only. Subsequently, the noise spectral density starts to grow up to reach a value of $S_{VMAX} = 6 \times 10^{-16}\mathrm{V}^2\mathrm{s}$ at voltages of about $V_F = 0.35$ V. This maximum is reached at a voltage at which the junction dynamic resistance matches the load resistance. A monotonous growth of the noise voltage is observed in all specimens at voltages over $V_F = 0.6$ V. It reaches $S_V = 1 \times 10^{-14}\mathrm{V}^2\mathrm{s}$ to $S_V = 3 \times 10^{-14}\mathrm{V}^2\mathrm{s}$ at the voltage $V_F = 1.2$ V, being most pronounced for specimen 12444. The source of this noise type locates in the additional series resistance and contact resistance regions. Specimens 12440, 12441, 12443 and 12444 feature a comparable quality from which specimen 12443 features the best parameters.

In Fig. 6 results are shown for the noise voltage power spectral density versus DC voltage plots. The noise voltage was measured across load resistance $R_L = 100\,\Omega$, $1\,\mathrm{k}\Omega$, $10\,\mathrm{k}\Omega$ and $100\,\mathrm{k}\Omega$ respectively. The pass band central frequency was 1 kHz, the band-width being equal to 20 Hz. A marked excess current component can be observed at higher voltages, reaching maximum at the power match point, where the PN junction dynamic resistance equals the load resistance. This peak is shifting towards lower DC voltage if the load resistance is increased.

Figure 7 reports the noise voltage power spectral density versus frequency plots for the laser diode No. 12444. The noise voltage is measured across the load resistance $R_L = 1\,\mathrm{k}\Omega$. The characteristic for voltage $V_F = 0$ V shows background noise of equipment. The characteristics for voltage $V_F = 0.37$ V and $V_F = 1.1$ V show voltage power spectral density *ie* in the power match region respectively in the contact region. In both these areas ($V_F = 0.37$ V and $V_F = 1.1$ V) are the excess noise of type $1/f$.

Figure 8 displays the I–V characteristics of reference specimens, which have been prepared using classic MBE technology. The shape of the linear function it follows that parallel resistances are shunting the PN junction. The shunt resistances of samples A1883 and A1884 (pulsed lasers) are equal $R_{SH} = 10^4\Omega$ and $5 \times 10^5\Omega$ respectively and for specimens for specimens A1847 and A1853 (continuous lasers) are higher and equal $R - SH = 10^6\Omega$. At Fig. 9 we can see that exponent β for samples A1853 and A1847 (continuous lasers) are $\beta = 20.8\,\mathrm{V}^{-1}$. From these follows that current I_F has primarily generation-recombination component. By other samples A1883, A1884 (pulsed lasers) we can see at voltages $V_F < 0.4$ V a high pronounced excess current component.

In Fig. 10 we observed the noise power voltage spectral density S_V versus the applied DC forward voltage plots for specimens A1847 and A1853 and A1883 and A1884 which had been prepared by using the classic MBE techniques. We can see a markedly higher magnitude of the PN junction excess noise than in specimens 12440 through 12444. Specially for samples A1884 and A1883 (pulsed lasers). Spectral density reaches by sample A1884 at voltage of around $V_{F1} = 0.2$ V value $S_{V\max} = 1.2 \times 10^{-12}\mathrm{V}^2\mathrm{s}$ and for sample A1883 value $S_{V\max} = 1 \times 10^{-13}\mathrm{V}^2\mathrm{s}$. Similarly, the excess noise magnitude at the voltage $V_F = 1.1$ V, where the predominant role played by the additional series noise and the contact region noise type, exceeds $S_V = 10^{-13}\mathrm{V}^2\mathrm{s}$ for specimens A1883 and A1884. It follows from both the I–V and the noise characteristics that the technology of the group of specimens, which have been prepared using the improved MBE technology and sample classic MBE technique, results in higher-quality laser diodes (samples 12440–12444).

4 CONCLUSION

We have presented two development stages of the MBE technology. The set of samples 12440, 12441, 12443 and 1244 prepared with improved MBE technology and sample with classic MBE technique and set comprising of samples continuous lasers A1847 and A1853 and set of samples of pulsed lasers A1883 and A1884 prepared by classic MBE technology. Transport and noise characteristics of both specimen groups were studied. A marked excess current component was observed in the I–V characteristics of specimens pulsed lasers A1883 and A1884 in the forward voltage interval from $V_F = 0.1$ V to 0.4 V. In the group of specimens A1883 and A1884, the noise characteristics corresponding to the PN junction region featured an excess noise magnitude, which was by more than three orders of magnitude higher than that of the group of samples 12440–12444, namely $S_{V\max} = 1.2 \times 10^{-12}\mathrm{V}52\mathrm{s}$ for specimen of pulsed laser A1884. It follows from both the I–V and the noise characteristics that the technology of the group of specimens, which have been prepared by using the improved MBE (samples 12440–12444) have higher quality than the samples prepared by using the classic MBE technology.

The structure of these lasers, produced by VERTILAS GmbH Company, can be made as single mode lasers with very low threshold current emitting single mode with a wide tuning range for usage in the gas detection systems. On top of the structure another DBR layer composed from Si and SiO_2 was deposited. This construction allows to decrease the necessary current needed to obtain laser emission and the high reflectivity of both mirrors and amplification of the multi quantum well active region allow the laser to emit in the direction perpendicular to the device surface.

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REFERENCES

[1] VAN DER ZIEL, A.—TONG, H.: Low Frequency Noise Predicts when a Transistor will Fail, Electronics **39** No. 24 (1966), 95–97.

[2] GUPTA, M. S.: Applications of Electrical Noise, Proceedings of IEEE **63** No. 7 (July 1975), 996–1010.

[3] DAI, Y.: Optimal Low-Frequency Noise Criteria used as a Reliability Test for BJTs and Experimental Results, Microelectronics Reliability **31** No. 1 (1991), 75–78.

[4] CLAEYS, C.—SIMOEN, E.: Noise as Diagnostic Tool for Semiconductor Material and Device Characterization, Journal of the Electrochemical Society **145,** No. 6 (June 1998), 2058–2067.

[5] SIKULA, J.—VASINA, P.—MUSILOVA, V.: 1/f Noise in GaAs Schottky Diodes, Physica Status Solidi A-Applied research **84** No. 2 (1984), 693–696.

[6] JONES, B. K.: Electrical Noise as a Reliability Indicator in Electronic Device and Components, IEE Proceedings – Circuits Device and System **149** No. NSI (Feb 2002), 13–22.

[7] VANDAME, L. K. J.: Opportunities and Limitations to Use Low-Frequency Noise as a Diagnostic Tool for Device Quality, Proceedings of the 17th International Conference Noise and Fluctuations ICNF 2003, Prague, pp. 735–748.

[8] KOKTAVY, P.—VANEK, J.—CHOBOLA, Z.: Solar Cells Noise Diagnostic and LBIC Comparison, 19th International Conference on Noise and Fluctuations, AIP conference proceedings, vol. 922, Tokyo, Japan, 2007, pp. 306–309.

[9] BYCHIKHIN, S.—POGANY, D.—VANDAMME, L. K. J.—MENEGHESSO, G.—ZANONI, E.: Low-Frequency Noise Sources in As-Prepared and Aged GaN-based Light-Emitting Diodes, J. Appl. Phys **97** No. 12, Article Nr. 123714, 2005.

[10] KONCZAKOWSKA, A.: Lifetime Dependence on 1/f Noise of Bipolar Transistors, Proc. of Noise in Physical Systems (C. M. van Vliet, ed.), vol. 489, World Scientific, Singapore, 1987.

[11] CHOBOLA, Z.: Noise as a Tool for Non-Destructive Testing of Single-Crystal Silicon Solar-Cells, In Microelectronics Reliability, vol. 41, 2001, pp. 1947–1952.

[12] CHOBOLA, Z.: Noise as Characterization for GaSb Based Laser Diodes Prepared by Molecular Beam Epitaxy, Semiconductor Lasers and Laser Dynamics Iv, 7720, 2010.

[13] CHOBOLA, Z.: Impulse Noise in Silicon Solar Cells, Microelectronics Journal **32/9** (2001), 707–711.

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