Contributed paper

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Low-frequency noises as a tool for UV detector characterisation

R. ĆWIRKO*, Z. BIELECKI[2], J. ĆWIRKO[1], and L. DOBRZAŃSKI[3]

[1]Institute of Electronic Systems, Department of Electronics, Military University of Technology, 2 Kaliskiego Str., 00-908 Warsaw, Poland

[2]Department of Military Technology, Military University of Technology, 2 Kaliskiego Str., 00-908 Warsaw, Poland

[3]Institute of Electronic Materials Technology, 133 Wólczyńska Str. 01-919 Warsaw, Poland

Ultraviolet (UV) semiconductor detectors are mainly made of materials with wide energy gap, i.e., of AlGaN, GaP, SiC, and diamond. The article describes methodology of measurements of characteristics of low-frequency noises of UV detectors and presents the developed measuring system. Basing on analysis of noise characteristics of detectors, an optimal working point of detector can be determined. The results of measurements of noise characteristics of UV detectors made of AlGaN are shown. The measurements have been carried out in wide range of temperatures for several values of a detector supply voltage.

Keywords: UV detector, GaN, low-frequency noise.

1. Introduction

UV detectors can be used in industrial automatics, space technology, medicine (investigations on a genetic code, X-ray investigations, tomography images of heart, dosimetry investigations of bones, UV sterilization systems, analytic systems), in military applications (searching of rockets, detection of chemical contamination), determination of ozone concentration in atmosphere, detection of flames, imaging of formation of high-temperature welds, various astronomical applications, industrial applications (measurement of a thickness of automotive lacquer, flaw detection), and in research [1]. They can be also used in environmental protection systems. Recently dynamic progress has been observed in intelligent weapon, individual means of chemical and biological protection, searching systems of ballistic missiles, and fire control systems in which very important role play multispectral sensors, including also UV detectors. To obtain high sensitivity of an input stage of a photoreceiver, the same maximum value of signal-to-noise ratio, minimization of possible noise sources should be done as well as optimal working point of a detector should be chosen and active element of a preamplifier should be ensured [2,3].

Semiconductor UV detectors are mainly made of materials having wide energy gap, i.e., from AlGaN, GaP, SiC compounds, and diamond [4,5]. Parameters of materials of semiconductor UV detectors, especially materials with wide energy gap strongly depend on properties and concentration of deep defect centres localized in an energy gap [6]. In dependence on electro-physical properties, deep defect centres can interact with free charge carriers as generation-recombination centres or trap centres. It mainly depends on their energetic state E_T in respect with the Fermi level E_F, active cross section for carriers capturing, and temperature. Deep defect centres cause fluctuation of concentration of free charge carriers, thus they affect noise properties of semiconductors. Moreover, deep defect centres control a lifetime of free charge carriers. This phenomenon is used in selected technological processes, e.g., for reduction of switching time of semiconductor devices such as fast multiplexers. Presence of deep defect centres in optoelectronic devices gives disadvantageous effects. For example, in LEDs the defect centres disturb the achievement of acceptable long-durating non-radiant recombination but in blue lasers, made of AlGaN compounds, they influence on significant decrease in time of their functioning. What's more, deep defect centres in semiconductor material are a source of generation-recombination noise.

2. Technology of measured detectors

The Schottky barrier solar blind photo detector has been developed in the Institute of Electronic Materials Technology – ITME labs. The epitaxial structure of the detector diode is presented in Table 1. This structure contains the relatively thick layer with a varied composition. This arrangement reduces the stress which is associated with the lattice constant mismatch of the AlGaN active layer and the AlN buffer which value is 2.4% [7]. The doping process of the N^+-AlGaN contact layer is another source of stress and defects. However, the appearance of the active layer surface was mirror like. On the basis of this structure we developed

*e-mail: rcwirko@wel.wat.edu.pl

the Schottky barrier diode. The processing steps mentioned elsewhere were applied without the major changes [8]. Photodiode is illuminated through a semi transparent thin Schottky metallization, which is a Ni/Au sandwich. The ohmic contact metal was the Ti/Al/Ni/Au system. It was deposited on the N+-AlGaN layer exposed by the reactive ion etching.

Technology of this device has been tuned for a long time because the AlGaN growth and doping is a complicated task when Al contents exceeds 30% [7]. We had to overcome some problems associated with the different (compared to the pure GaN case) chemical and physical AlGaN surface properties. The outcome of this activity was the device, which exhibited dark current value lower than 10 nA at –1 V bias, a Schottky barrier height of 1–1.2 V, and a solar blind detectivity of 0.1–0.15 A/W. Diode junction area was 0.8 mm^2.

Table 1. The epitaxial structure of the detector diode.

Layer	Thickness (μm)	Doping (cm^3)
Sapphire	Substrate	
LT AlN buffer	0.15	ud
AlN buffer	0.3	ud
AlGaN graded composition	1.0	ud
$Al_{0.36}Ga_{0.64}N$	0.5	N^+ 8×10^{17}
$Al_{0.36}Ga_{0.64}N$	0.2	ud

3. Low-frequency noise of UV detectors

In UV detectors, similarly as in other detectors of optical radiation, the main problem to obtain high sensitivity of a detector is to ensure maximal value of signal-to-noise ratio. Minimisation of noises level in semiconductors is much more complicated task than in conductors because here significant are physical phenomena connected with presence of an energy gap [9]. In semiconductor materials of wide energy gap, used for construction of UV detectors, the resultant noise consists of thermal noise, generation-recombination noise, shot noise, 1/*f* type noise, and in some cases also popcorn noise [10,11].

Statistical fluctuations of thermal and optical generation and recombination of free carriers in a semiconductor are a source of generation-recombination noise. Fluctuations of an average concentration of carriers cause also fluctuations in current, voltage, and electrical resistance. A spectrum of generation recombination noises is flat, till the frequency values approximately equal to inverse value of lifetime of free carriers. Frequently, analysis of generation-recombination noises is limited only to the noises caused by fluctuations in velocity of thermal generation and recombination of free carriers in a semiconductor.

A lot of expressions describing generation recombination noise are known in literature. They depend on a mechanism of generation-recombination process, i.e., if interband processes or the processes of a band-dopant level type occur.

For the intrinsic semiconductor $\Delta n = \Delta p$, a spectral power density of noises is given as Lorentz dependence [12]

$$S_{\Delta n(\omega)} = 4M(\Delta n^2)\frac{\tau}{1+\omega^2\tau^2}, \qquad (1)$$

where τ is the time constant which is characteristic for the generation-recombination process and M is the generation-recombination coefficient.

A power spectral density of generation-recombination noise for the frequency f, with assumption of the existence of a single trap can be expressed as

$$S_1(f) = 4(\Delta I_0)\frac{\tau_\varepsilon \tau_c}{(\tau_e+\tau_c)^2}\frac{\tau}{1+4\pi^2 f^2\tau^2}, \qquad (2)$$

where ΔI_o is the current fluctuation resulting from a ionisation of a single trap, τ_c is the capture time constant, and τ_e is the emission time constant when

$$\frac{1}{\tau} = \frac{1}{\tau_c} + \frac{1}{\tau_e}. \qquad (3)$$

A power spectral density of generation-recombination noise for the sample of the volume V, with assumption of the existence of one type of traps of the concentration N_T can be given in a form

$$S_{INV}(f) = 4N_T(\Delta I_0)V\frac{\tau_e \tau_c}{(\tau_e+\tau_c)^2}\frac{\tau}{1+4\pi^2 f^2\tau^2}. \qquad (4)$$

It results from Eq. (4) that maximum value of power spectral density of generation-recombination noise is for the frequency f_c when emission and capture constants are equal to each other, i.e., $\tau_c = \tau_e = \tau$, where $\tau = 1/2\pi f_c$. The frequency f_c is a frequency at which refraction (change in inclination) of a resultant noise characteristic of a detector occurs (Fig. 1).

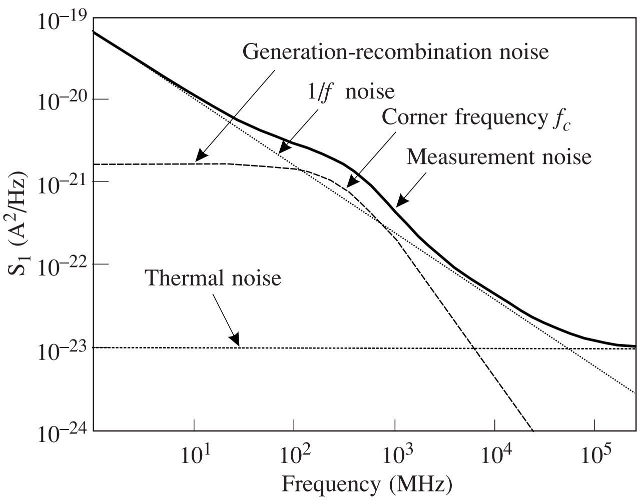

Fig. 1. Distribution of power spectral density of noise with regard to noise component of 1/*f* type noise, thermal noise, and a component of generation recombination noise.

Within the range of low frequencies, significant is $1/f$ type noise. The best results are obtained when a photodetector operates within a range of frequencies in which generation-recombination noise is a dominant one. It is achieved due to adequate modulation of a source signal and application of a filter in readout electronic which transmits a required frequency spectrum. A bandwidth depends on a kind of applications.

In some detectors a popcorn noise appears. The sound of this noise, called a popcorn-noise, heard at the loudspeaker output is similar to the blowing up popcorn grains. It can be imagined also as short pulses on a background of other noises. Their amplitude is of one order of magnitude higher than white noise amplitude. Short pulses are ascribed to collision ionisation of neutral dopants caused by highly-energetic electrons which increase their energy to the value of above the critical one. A critical field is dependent on an equilibrium state between energetic amplification and network losses. The critical field limits the voltage which can be efficiently used for the given detector, first of all for surplus noise produced during collision ionisation process. A value of electric field in a detector of optimal parameters is lower than a value of critical field of collision ionisation. Popcorn noise is caused by network defects, i.e., metal dopants or improper technology of manufactured electric contacts. Improvement in this technology minimises this effect. Usually, the popcorn noise depends on bias direction.

Figure 1 shows distribution of power spectral density of UV detectors noises with regard to noise components [13].

The obtained noise characteristics of UV detectors can be given in a form of:

- dependence of spectral density of noise power as a function of frequency for selected temperature values,
- dependence of spectral density of noises power as a function of temperature for selected frequencies,
- dependence of spectral density of noises power as a function of detector bias voltage.

Knowing these characteristics, optimal temperature of a detector can be chosen as well as transmission band and bias voltage for which the lowest resultant noise of a detector can be achieved and its the best detectivity can be ensured.

The authors' experience shows that the decreased working temperature of a detector, aimed at improvement in signal-to-noise ratio, is not always a proper decision. If a semiconductor has a lot of defects while generation-recombination component dominates, the decreased temperature can cause even increase in resultant noises level in spite of reduced component amplitude of thermal noise. Thus, designers of input stages of photoreceivers, with UV detectors, should know the above described characteristics.

Analysing these characteristics, one can estimate how many defects are in a detector's material. Moreover, knowing noise characteristics, a detector's reliability during long time can be predicted.

4. Description of a measuring system

Measurements of noise characteristics of AlGaN detectors were made using measuring set-up shown in Fig. 2. This set-up comprises nitrogen flow cryostat, so noise characteristics of detectors can be measured within the range of 77–360 K. Further temperature decrease, down to 10 K, is

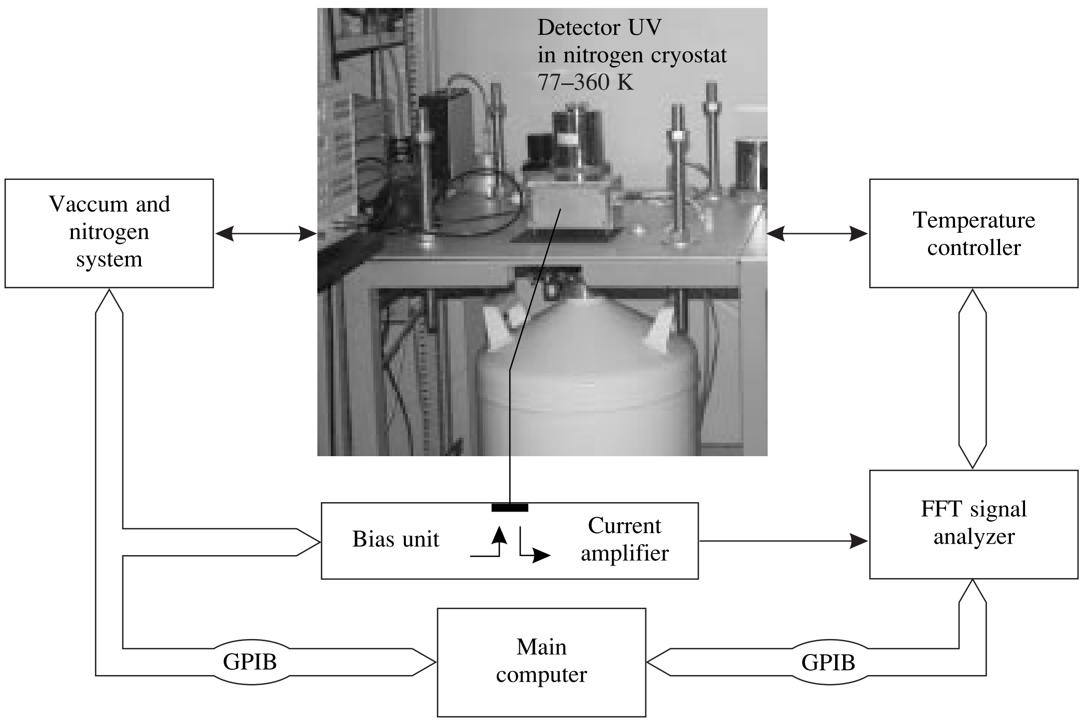

Fig. 2. Functional-block diagram of a measuring system.

possible using helium LN_2 Leybold cryostat. However, significant disturbances can appear resulting from operation of a compressor located in a measuring head of cryostate. Choice of adequate connectors, their proper fixing and data recording only in time windows, when a compressor piston is a source of the lowest mechanical vibrations, can minimise influence of trybo- and piezoelectric disturbances to the acceptable levels.

Many activities have been undertaken to minimise environment disturbances affecting the measuring set-up. The most important were:

- location of a measuring system in a shielding cabin of the dimensions 2×4×4 m,
- application of a special antistatic floor in a shielding cabin and in the room in which the cabin is situated,
- performance of a special system of current supply with direct connection to energetic switchboard,
- application of extended mains filters and uninterruptible emergency power suppliers,
- performance of a special ground system for the developed measuring system,
- application of room air-conditioning system,
- application of low-noise concentric cables with graphite fillers in intermodule connections,
- selection of measuring devices of the lowest level of self-disturbances, e.g., battery supply, transoptory interface between analogue and digital systems, "break in operation" in a digital part during measurement, and the like.
- application of battery supply of detectors,
- selected measuring frequencies, without the frequency for which the highest level of disturbances is observed (mainly frequency of 50 Hz and harmonic frequencies),
- automation of long-lasting measurements eliminating presence of operator in a shielding cabin),
- performance of measurements mainly during the days off when the level of outside disturbances is the lowest one.

In order to avoid frosting of a sample during its cooling, vacuum is produced in the cryostat by means of two pumps, i.e., oil pump and turbomolecular pump of the Leybold firm. The vacuum level is measured with a ITR090 Ionivac sensor which is a combination of Pirani head and Bayarda Alpert head with a hot electrode. ITR090 sensor operates with microprocessor IT23 pressure meter providing monitoring of indications and signalling alarm thresholds.

In the developed system, temperature measurements are made at two places. One sensor is situated at the cryostat's operating table, near a heater of an operating table. With LTC-60 programmed temperature regulator, it determines a value of temperature measurement in a PID regulation loop. Other sensor is situated close to the investigated detector and its indications are taken for further mathematical calculations.

As temperature sensors, the calibrated silicon diode of *D*-type are used that can operate within the range of 5–450 K.

A signal from a detector is initially amplified in a 428 Hewlett-Packard current preamplifier made by Keithley firm and next it is sent to HP3665 Hewlett-Packard signal analyser. Noise characteristics can be also determined when the detector is biased. To do this, 428 preamplifier and special bias systems are used.

Measurements of noise characteristics are time consuming. Average time necessary to obtain required temperature stability is about 3 minutes. If we want to carry out measurements of detector noises within the range from 77 K to 360 K with the step of 1 K, the time necessary for temperature stabilisation at successive measuring points is 14 hours. Thus, total measurement time is longer because it is necessary to consider the time required just for a noise measurement. As a consequence, the measuring system has been automated. The devices have been connected by means of GPIB bus and a program for measurement control has been elaborated in TestPoint.

5. Experimental results

The experimental investigations were aimed at measurement of noise characteristics of AlGaN detectors for various supply voltages in wide range of temperatures. In detectors of such a type, the resultant level of noises is mainly affected by generation-recombination noise component. Thus, knowing the characteristics of distribution of power spectral density as a function of frequency, it is possible to estimate defects concentration in the material used for detectors manufacturing. Highly concentrated deep defect centres testify on significant value of generation-recombination noise component. As a consequence, it can be observed a change in inclination of distribution of spectral density of noises power as a function of frequency.

The measurements were made in the frequency range 10–102 kHz for 2000 points in the temperature range 80–350 K with a step of 1 K. Exemplary results of measurements of four UV detectors are shown in Figs. 3 and 4.

Five representative noise characteristics were chosen for each detector for the temperatures 80 K, 142 K, 196 K, 274 K, and 350 K.

The meaurement results shown in Fig. 3 show deep defect centres. It results from a character of a course of resultant noise characteristics on comparison with a shape of noise characteristics of 1/*f* type. For various temperatures, the observed deviation of noise characteristics appears in various ranges of frequency, so in a tested detector there are deep defect centres of several types that differ in activation energy. Their concentration is so high that generation-recombination noise is significant and can be observed in total noise of the investigated detector. It results from noise characteristics that for the higher bias voltages of the detector, a noise level is higher, too. However, these differences are not significant.

The lowest level of noise is for the bias voltage of –0.2 V. For the bias voltage of –0.1 V, noise characteristics for different temperatures are as the predicted ones, i.e.,

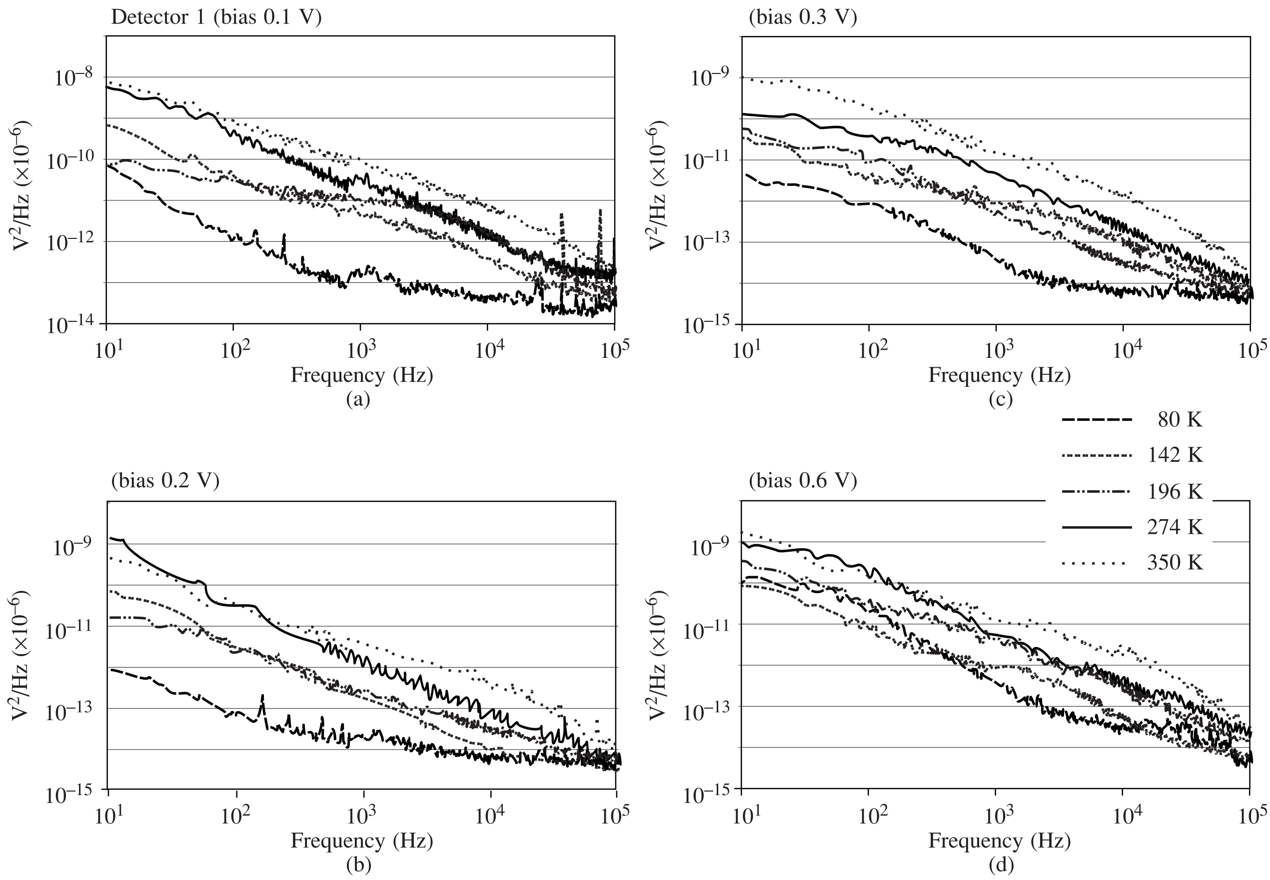

Fig. 3. Selected noise characteristics of detector No 1 for four values of bias voltage.

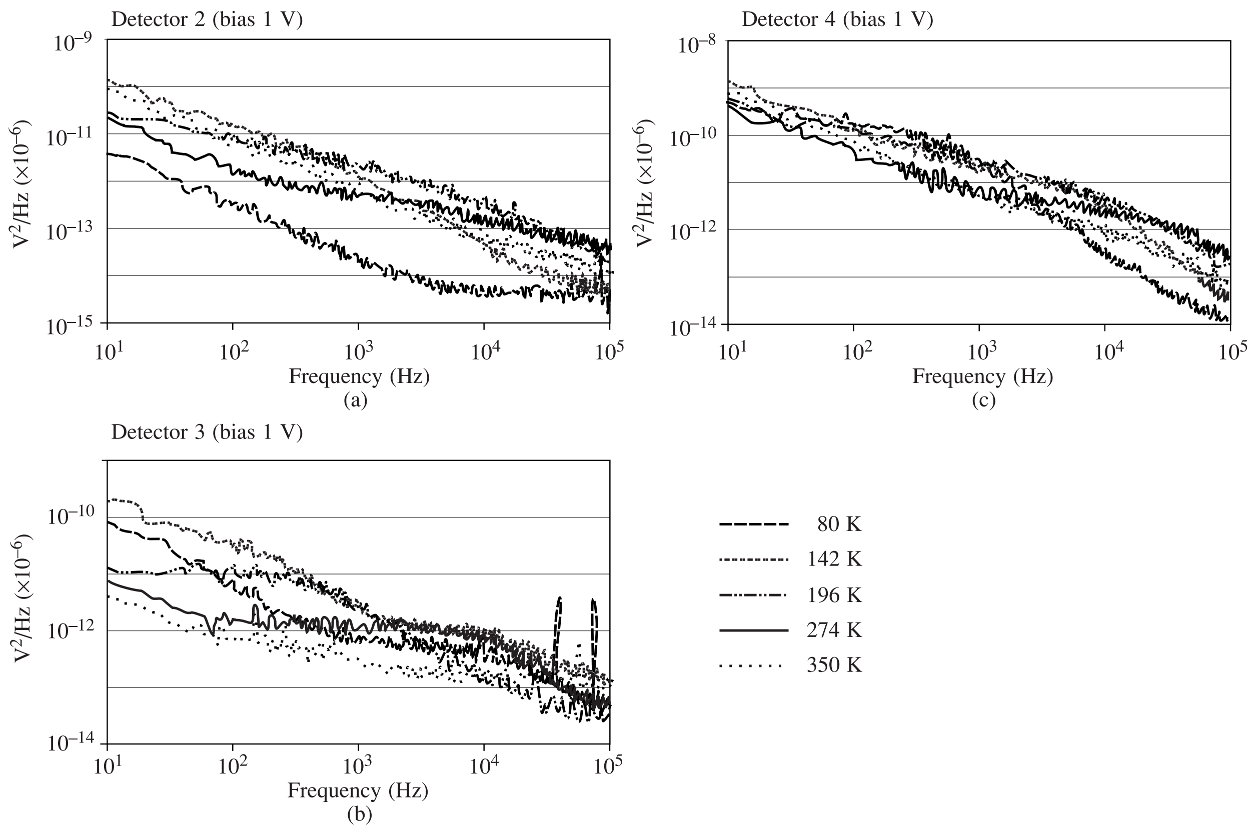

Fig. 4. Selected noise characteristics of detectors No 2, No 3, and No 4 for a bias voltage of 1 V.

a characteristic of distribution of spectral density of noise power determined at a temperature of 350 K is above other characteristics which were determined for the lower temperatures. When the detector supply voltages are higher, this rule is not proper. For example, for bias of a value –0.2 V, the level of a detector noise at a temperature 274 K is higher than at 350 K (in a frequency range up to ~100 Hz). Also the level of detector noise at 124 K is higher than at a temperature 196 K despite the fact that a reverse effect was expected. Such a course of characteristics results from a significant component of generation-recombination noise in resultant noise of a detector. Figure 4 presents measurement results of power spectral density of noises for three other detectors of the same series. These detectors were polarised with 1 V voltage and other measurement conditions were identical as for the first detector.

It results from the carried out measurements that a distribution of spectral density of noise of the same deectors is different that a shape of a characteristic of $1/f$ type noise. A corner frequency of these characteristics is for various frequecies and for various temperatures what testifies on strong infuence of deep defect centres.

Exemplary, for frequency of 10 Hz, noise level for detector No 2 is 1.2E-16 V^2/Hz, detector No 3 is 2,2 E-18 V^2/Hz, and for detector No 4 is 1,2 E-15 V^2/Hz. The lowest level of a resultant noise was observed for detector No 3. However, at the temperature of 196 K, the course of noise characteristic of this detector is influenced mainly by generation-recombination noise. A role of $1/f$ type noise is negligible.

6. Conclusions

The developed measuring system and the proposed measuring methodology of noise measurements of UV detectors provide a choice of optimal working point of a detector for which noise is of minimum value. Due to known characteristics described in this work it s possible to determine optimal bias voltage and optimal temperature of AlGaN detector ensuring its highest detectability.

Using the measuring set-up proposed by the authors, the investigations of detectors for complete determination of influence of defect structure of material on a level of its own noises and selection of detectors manufactured by various producers. On the basis of analysed noise characteristics, reliability of UV detectors made with various technologies can be predicted.

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