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1/*f* Noise in Quantum-Size Heteronanostructures Based On GaAs and Alloys

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Abstract**—**The 1/*f* noise investigation in nanoscale light-emitting diodes and lasers, based on GaAs and alloys, is presented here. Leakage and additional (to recombination through quantum wells and/or dots) nonlinear currents were detected and it was shown that these currents are the main source of the 1/*f* noise in devices studied.

Keywords**—**Lasers, light-emitting diodes, quantum dots, quantum wells, 1/f noise.

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I. INTRODUCTION

We have investigated 1/*f* voltage noise in prototypes of $In_{0,2}Ga_{0,8}As/GaAs/InGaP$ lasers with quantum wells (QWs), light-emitting diodes (LEDs) with *InAs* quantum dots (QDs), LEDs with *InAs* QDs and $In_{0,2}Ga_{0,8}As$ quantum well (QW).

Dandridge and Taylor observed a correlation between 1/*f* intensity noise and frequency noise in the optical emission. It was noticed that laser diodes with a higher intensity noise have a larger spectral width [1]. The spectral properties of the light emission are crucial for some applications. This makes the study of the 1/*f* noise in laser diodes an important subject.

Brophy has observed for the first time 1/*f* noise in the optical output of laser diodes [2]. The noise was investigated well below the lasing threshold in a frequency range of 10 Hz - 10 kHz. A correlation was found between the optical emission noise and the noise in the diode current.

The 1/*f* noise in light-output power of four different types of heterostructure lasers was studied in paper [3]. Results of measurements were explained in terms of two models. The first one was based on fluctuations in the absorption coefficient and the second model was based on fluctuations in the number of free carriers injected into the active region.

The 1/*f* noise in optical intensity was also studied by other authors [4]-[6].

Noise and fluctuations are acquiring an increasing importance in science and technology, as witnessed by the growing number of publications in this field that appear in leading journals, see, e.g. [7]-[15].

Nature of the 1/*f* noise (named also “flicker noise”) is up to now the subject of discussion, see, e.g. paper by Bezrukov, Vandamme, and Kish [16].

The main goals of our work are as follows: (a) investigation of 1/*f* noise in nanoscale light-emitting structures, (b) determination of noise sources.

Section II of this paper is of basic type. Possible sources of 1/*f* noise and their manifestation in dependence of the 1/*f* voltage noise spectrum S_v on the bias current *I* are discussed here.

At first we consider an effect of possible 1/*f* noise in electrical parameters of quantum wells/dots. The spectrum of voltage noise caused by this effect is saturated at high current *I*. Similar saturation of noise was observed in *Ge* diodes (see, e.g., Fonger [17] and Malakhov [18]).

Then we consider an effect of 1/*f* noise in the additional components of the total current. As an example the noise in the leakage current (linear or nonlinear) is analyzed. This noise yields the effect noise maximization (at some bias current). That is the increase of the total current yields the increase of the voltage noise spectrum. At rather high currents this spectrum is decreased. Similar effect was observed in different types of diode structures by Wall [19], and Klimov with coauthors [20].

Section III contains information on tested devices and experimental data obtained. We investigated prototypes of *GaAs* nanoscale light-emitting structures manufactured at Physical-Technical Research Institute of Lobachevsky State University of Nizhni Novgorod (Russia). The I-V characteristic and dependence of 1/*f* voltage noise spectrum on the bias current were studied.

It was found that total current may consist of three components. The first one may be caused by recombination current (through QWs/QDs) responsible for light emission [21]. The second component is the leakage current. The third component is an additional nonlinear current which behavior can be significantly different from device to device.

The analysis of the dependence of 1/*f* noise spectrum on the bias current has shown that this noise is originated by the leakage and additional nonlinear current. The noise from quantum wells and dots was not detected in our measurements.

II. EQUIVALENT CIRCUIT DIAGRAM OF THE DIODE AND MODEL OF 1/F NOISE

Kleinpenning applied Hooge’s empirical relation [22] to explanation of 1/*f* noise in *p–n* diodes [23]. But some experimental results are not described by this relation, see, e.g., [17], [21]. In this paper we use rather simple physical model, which allows us to explain the 1/f noise behaviour in nanoscale structures investigated here.

The total current *I* through the structure may consist of

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three components, $I = I_r + I_l + I_n$, where I_r is current caused by recombination through quantum wells and/or dots, I_l – leakage current and I_n is an additional nonlinear current.

These currents and corresponding differential resistances are shown in equivalent circuit diagram of the diode, see Fig. 1.

Components I_l and I_n described by resistances R_l and R_n respectively, are parasitic in comparison with the recombination through quantum wells (or dots) I_r described by differential resistance R_r.

The parasitic resistance is divided into series resistance (R_b) and parallel resistance (R_l). Series resistance R_b can be caused by excessive contact resistance or by the resistance of the neutral regions. Parallel resistance R_l can be caused by any channel that bypasses the *p-n* junction. This bypass can be caused by damaged regions of the *p-n* junction or by surface imperfections [24].

Parallel resistance R_l has a value much larger than R_b and makes the forward hump on I-V characteristic which has about the same level as the reverse saturation current. Series resistance R_b has a relatively small value and leads to deviation from the pure exponential behavior at high forward currents.

A parasitic diode connected in parallel with the main diode makes the forward hump without increasing of the reverse saturation current. The parasitic diode displays sub-threshold turn-on caused by leakage through either surface states at the perimeter of the diode chip or defective regions within the *p-n* junction plane that have a lower barrier height than the main *p-n* junction [24].

Total voltage V_d on the diode determines the voltage V on *p–n* junction:

$$V_d = V + R_b I . \tag{1}$$

Here R_b is resistance of the diode base (neutral) region including ohmic contacts.

Recombination yields recombination current I_r. This current and corresponding differential resistance R_r are as follows:

$$I_r = I_{r0}\left\{\exp\left[V/\eta_r V_T\right]-1\right\},$$
$$R_r = \left(\mathrm{d}I_r/\mathrm{d}V\right)^{-1} = \eta_r V_T/\left(I_r + I_{r0}\right). \tag{2}$$

Here I_{r0} is characteristic current; $V_T = kT/q$ is the thermal potential, k – Boltzman's constant, T – absolute temperature, q – elementary charge; the ideality factor is η_r=2.

Recombination in quantum wells and dots produces the current of the same type. This current is the main component in our nanoscale structures.

Practically all structures exhibit a leakage current. This current may have both linear and nonlinear components; see, e.g. [19], [20].

The linear (ohmic) component I_l is characterized by resistance R_l

$$I_l = V/R_l . \tag{3}$$

Nonlinear component I_n is usually described by characteristic current I_{n0} and ideality factor η_n (which is rather large in comparison with ideality factor of recombination current, η_n >>2). These current and differential resistances Rn are equal to:

$$I_n = I_{n0}\left\{\exp\left[V/\eta_n V_T\right]-1\right\}, \tag{4}$$

$$R_n = \left(\mathrm{d}I_n/\mathrm{d}V\right)^{-1} = \eta_n V_T/\left(I_n + I_{n0}\right) \tag{5}$$

Some authors suggested, that the possible nature of current with $\eta_n \approx 3$ may be caused by tunneling of carriers through the potential barriers (across the spikes in the forbidden energy band) [25], [26].

In any case, components described by (3)–(5) are parasitic in comparison with the recombination through quantum wells (or dots) described by (2). These parasitic components were detected in all our nanoscale devices. In some devices we have seen only the linear leakage current I_l.

We assume that every component of the total current, and the base resistance R_b, may be subjected to the $1/f$ noise.

In order to explain our experimental results we use here model of mobile defects as the source of $1/f$ noise, see, e.g., [27]. In the simplest case a single defect has two metastable states described by two-level system [28].

Random switchings between states of defect yield the change of its scattering cross-section and/or ionization energy.

Change of scattering cross-section and change of ionization energy produces the noise in mobility and/ or in concentration of carriers.

Noise in mobility and noise in concentration of carriers are manifested as the noise in equivalent resistances of the diode [29], [30].

Ensemble of bistable defects, under known conditions, leads to appearance of the noise with $1/f$ spectrum.

It is convenient to represent noise in current components of total current by δR_λ, $\lambda = r, l, n$ – relative noise in corresponding equivalent resistances. Therefore, instead of (2)–(4), we have:

$$I_\lambda = \left[1-\delta R_\lambda(t)\right] I_\lambda(V), \lambda = r, l, n, \tag{6}$$

respectively.

The main idea is that the total $1/f$ noise is described by sources presented by relative noise in equivalent resistances of the diode:

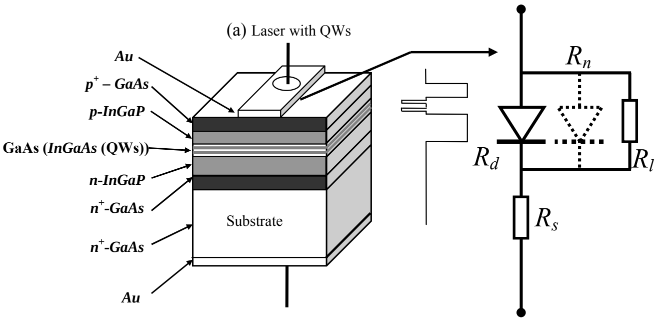
$$R_\lambda = \left[1+\delta R_\lambda(t)\right] R_\lambda, \lambda = r, l, n . \tag{7}$$

They are uncorrelated, because these sources are related with stochastic processes in different regions of the diode.

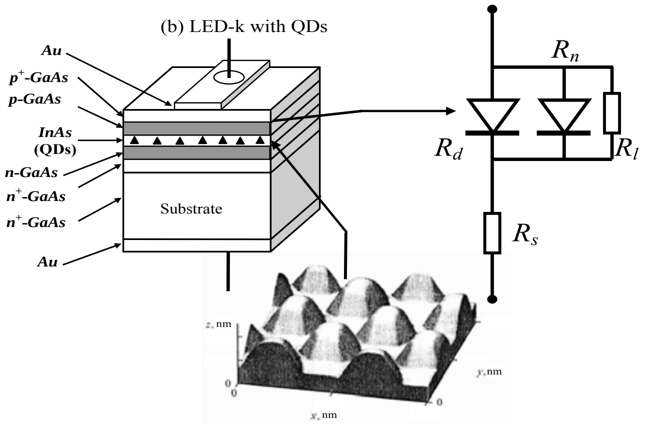
Bistable defects in the depletion region of *p–n* junction or in quantum dots/ quantum wells are the source of the noise in recombination current (λ=*r*). Noise in leakage current (λ=*l*) is usually related with processes in the perimeter of the diode. We assume that correlation between the additional nonlinear current (λ=*n*) and other components of current may also be neglected.

The model of bistable defects allows considering spectra $S_{\delta R\lambda}$ of relative 1/*f* noise in equivalent resistances be not dependent on the total current *I*.

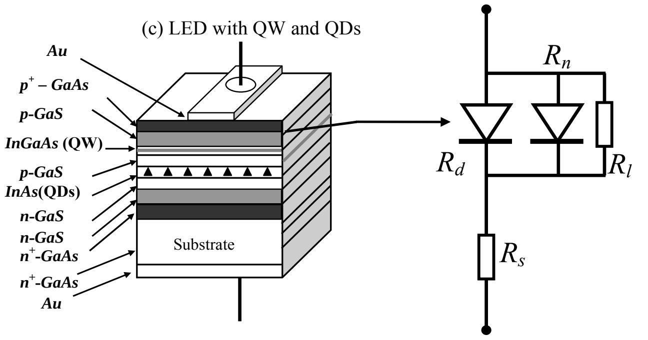
The total 1/*f* voltage noise spectrum S_v is determined by spectra $S_{\delta R\lambda}$ and effects of different components in the current *I*.



(a) Laser with QWs



(b) LED-k with QDs



(c) LED with QW and QDs

Fig. 1 Laser structure and structures of LEDs

If the main component is recombination current, $I=I_r$, and this current is also the main source of 1/*f* noise in the diode, then the spectrum 1/*f* noise is saturated at currents $I >> I_{r0}$. Similar effect was observed in *Ge* diodes, see, e.g., [17], [18]. The essence of the effect of noise saturation is as follows.

The noise $\delta R_r(t)$ in the equivalent recombination resistance is manifested as 1/*f* current noise source $i_r(t) = I_r\cdot\delta R_r(t)$, and yields 1/*f* voltage noise $v(t) = R_r\cdot i_r(t)$. The increase of the total current $I = I_r$ yields the increase of the noise current, and the decrease of differential resistance R_r determined by (2). At high currents the noise is saturated because the increase of $i_r(t)$ is compensated by the decrease of R_r.

Noise in the (linear) leakage current and/or the additional nonlinear current yields the effect of 1/*f* noise maximization (see [19], [20]) at some bias current I^*. This effect is most important for our devices studied. The essence of this effect is as follows.

The 1/*f* noise in the equivalent leakage resistance $\delta R_l(t)$ and equivalent nonlinear resistance $\delta R_n(t)$ is manifested in current noise

$$i(t) = I_l \delta R_l(t) + I_n \delta R_n(t). \tag{8}$$

The last one produces the voltage 1/*f* noise on differential resistance *R* of the diode $v(t) = R\cdot i(t)$. Here $R = (R_r^{-1} + R_l^{-1} + R_n^{-1})^{-1}$, see Fig. 1. The voltage drop on the base resistance R_b is omitted here. The 1/*f* voltage noise spectrum S_v caused by noise in leakage and nonlinear currents is determined as

$$S_v = V_l^2 S_{\delta Rl} + V_n^2 S_{\delta Rn}, \tag{9}$$

here $V_l = I_l R$ and $V_n = I_n R$ are transformation coefficients.

Let us, for simplicity, consider noise in linear leakage (that is $I_n = 0$). At small current, when I-V characteristic of diode is nearly linear $R \approx const$, the leakage noise is manifested as in linear resistor, $S_v \sim I^2$. At rather large current, when $R << R_l$ and the increase of the voltage on *p*–*n* junction is logarithmically slow, $V \sim \ln I$, as it follows from (2) and (3), the increase of leakage noise $i_l(t)$ is also slow. But resistance of the diode is decreased much faster, proportionally to the current, $R_r \sim I^{-1}$. Thus, after maximum at some current I^* the 1/*f* voltage noise spectrum decreases nearly proportionally to I^{-2}. In the simplest case of very small linear leakage on the background of noiseless recombination current, $R_l >> R_r(I=0) = 2V_T/I_{r0}$, we find $I^* = I_{r0}\cdot[\exp(1) - 1]$ and $V = 2V_T$.

In the case of additional nonlinear current subjected to the 1/*f* noise the maximum becomes somewhat wider and the decrease of S_v at high currents is slower than I^{-2}.

III. EXPERIMENTAL RESULTS AND DATA TREATMENT

A LF noise measuring setup was used in our experiments (see Fig. 2).

Channel (electrical) provides measurement of so-called open-circuit voltage noise *v*(*t*) across diode under test (DUT). The diode is biased by a noiseless current. The bias resistance R_B was always at least 20 times larger than the differential resistance of the diode.

Amplified noise was sampled with rate 48 kHz, digitized by two-channel 2×24 bit A/D converter ADS224x48® (Insys®, Moscow), and saved on PC hard disk by 1 million samples per channel. Afterwards, the obtained data were processed by multifunctional analyzer [31]–[45] developed in programming environment LabVIEW® (National Instruments®, USA).

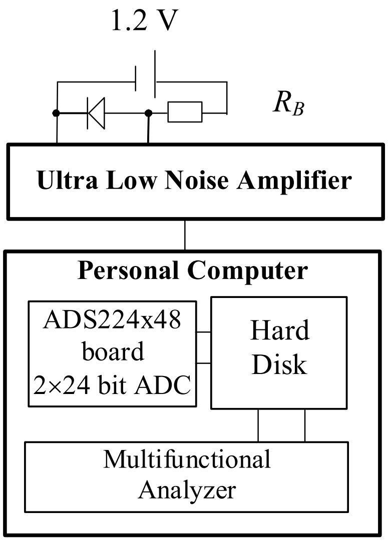


Fig. 2 Block-diagram of LF noise measuring setup

We have investigated prototypes of light-emitting diodes (LEDs) and laser diodes based on *GaAs* nanoscale structures:

1) LEDs with InAs quantum dots (QDs),
2) LEDs with InAs quantum dots and $In_{0,2}Ga_{0,8}As$ quantum well (QW),
3) Lasers with two $In_{0,2}Ga_{0,8}As$ quantum wells.

The laser structure is shown in Fig. 1 (a) and has the following composition:

- n^+–*GaAs* (1.0.0) substrate, thickness d=160 µm;
- n^+–*GaAs* buffer layer, $n=10^{18}$ cm^{-3}, mobility μ=2000 cm^2/(V·s), d =700 nm;
- Two *InGaP* wide–zone bounding layers, $n=p=10^{18}$ cm^{-3}, μ_n=700 cm^2/(V·s), μ_p=35 cm^2/(V·s), d=500–550 nm;
- *GaAs* cavity layer, d=750–800 nm, containing two $In_{0,2}Ga_{0,8}As$ quantum wells close to middle of the region, d=9 nm;
- p^+–*GaAs* contact layer, $p=10^{19}$ cm^{-3}, μ=100 cm^2/(V·s), d=500–550 nm.

We have two types of LEDs with different structures (see Figs. 1 (b) and (c)). Both types have *InAs* layer of QDs within *p–n* junction. Light-emitting diodes having index “k” in their name belong to structure, which has only a layer of QDs. Diodes without this index belong to structure, which has a layer of QDs and an additional *InGaAs* quantum well.

Both structures have n^+–*GaAs* substrate, and n^+–*GaAs* buffer layer with concentration of carriers $n=10^{18}$ cm^{-3}. Layer *n–GaAs* is a matrix for QDs growing. An active region of LEDs is represented by *InAs* QD layer and placed in the middle of abrupt *p–n* junction. Layer of p^+–*GaAs* is also buffer one.

We have studied the I-V characteristic and current dependence of spectrum S_v of $1/f$ voltage noise in light-emitting and laser diodes operating in dark and LED modes.

A few components were detected in I-V characteristic of all diodes. The first one is recombination current through QWs and/or QDs, with ideality factor $\eta\approx 2$, see (2), responsible for light emission. Other components are related to the leakage current, and the additional non-linear current, described by (3)–(5). Behavior of these components is significantly different from device to device.

At relatively high currents the base resistance R_b becomes visible with magnitudes not more than 0.3 Ohm.

All diodes exhibit $1/f^{\gamma}$ noise (Fig. 3) with the frequency exponent $\gamma\approx 1$ (Fig. 4).

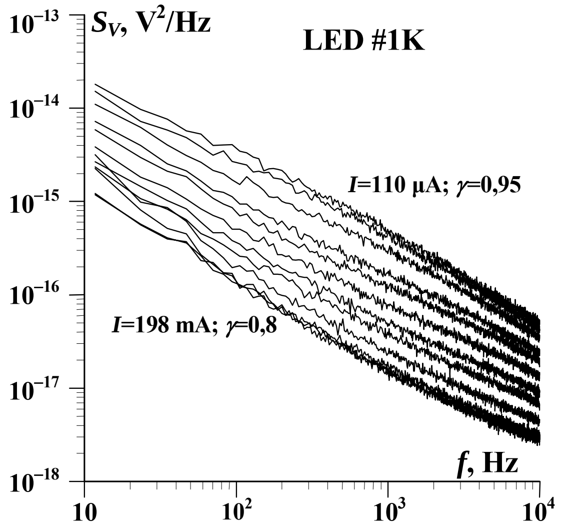


Fig. 3 Family of voltage noise spectra at different currents through the diode

The dependence of voltage noise spectrum on the bias current was investigated at the range of 50µA÷200mA for LEDs and at 50µA÷500mA for lasers.

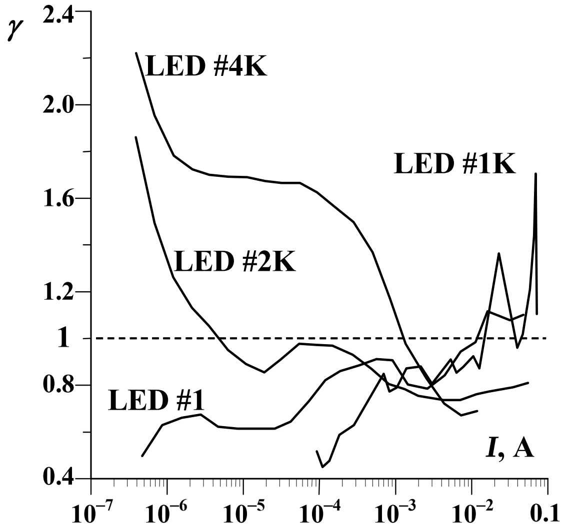


Fig. 4 Family of frequency exponent γ versus total current through the diode

While the current was increased, the spectrum was decreased as a rule.

Experimental data for I-V characteristic of LED#1, which has rather strong leakage, is shown in Fig. 5 by dots. These data may be fitted by superposition of recombination current, and nonlinear current (broken lines), $I = I_r + I_n$. Recombination in QDs (and QW) is described by $\eta_r = 2$, and $I_{r0} = 2.8{\cdot}10^{-10}$ A, see (2). In terms of (4) we have determined the ideality factor of nonlinear current η_n=4.9, and characteristic current I_{n0}=1.3·10^{-5} A. From I-V characteristic we can detect recombination and the additional nonlinear components only. If linear leakage exists, see (3), it can be described by resistance R_l > 5 kOhm, which is not pronounced in I-V characteristic. Base resistance is R_b = 0.3 Ohm.

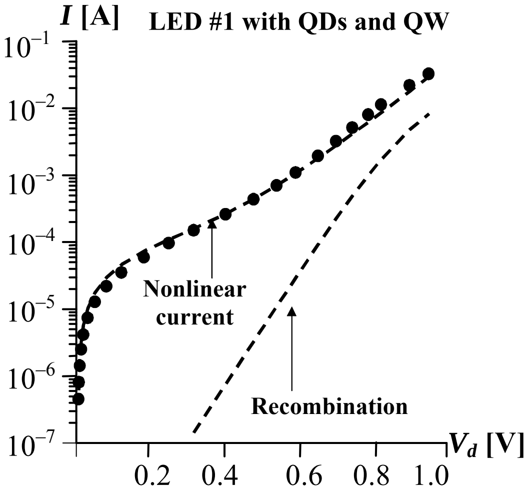


Fig. 5 Decomposition of I-V characteristic of LED#1

Experimental data for the 1/*f* voltage noise spectrum S_v (at *f*= 100 Hz) versus total current *I* are shown by dots in Fig. 6.

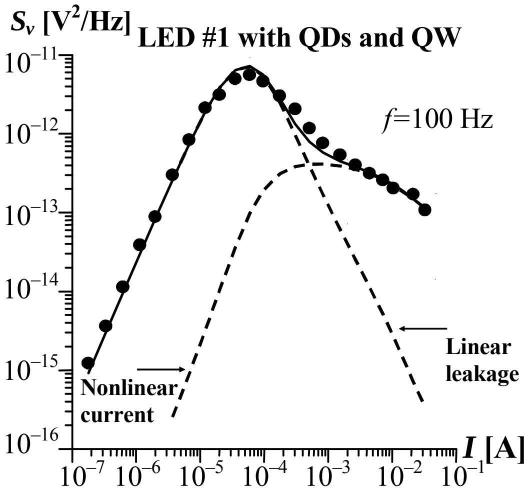


Fig. 6 1/*f* noise spectrum at *f*=100 Hz versus total current of LED#1

It was found that noise in nonlinear current does not allow us to describe the region of small currents, *I* < 0.2 mA, where maximization of S_v takes place. This part may be explained by taking into account the 1/*f* noise in linear leakage resistance R_l. Maximization of 1/*f* noise at bias current $I^* = 10^{-4}$ A yields leakage resistance R_l = 5.1 kOhm. Spectrum of relative 1/*f* noise in this resistance $S_{\delta Rl}$= 1.5·10^{-9} Hz^{-1} (at *f*=100 Hz) is extracted from experimental data.

In order to explain the total dependence of S_v on *I* we must add relative noise in additional nonlinear current characterized by spectrum $S_{\delta Rn} = 4{\cdot}10^{-11}$ Hz^{-1} at *f*=100 Hz. Effects of 1/*f* noise in linear leakage and nonlinear current components are shown by broken lines in Fig. 6. The total effect caused by both components is shown by solid line, which is in satisfactory agreement with experimental data for this diode. The accuracy of these measurements was about 5 percent.

Important result is that the linear leakage of LED#1 is not visible in I-V characteristic, but it was detected from the dependence of 1/*f* noise spectrum on the bias current.

One can see that our theoretical results are in satisfactory agreement with experimental data.

Such an analysis was applied to all types of our structures: LEDs with quantum dots; LEDs with quantum dots and quantum well; lasers with quantum wells. Through the analysis it was proved that noise data for all structures are explained by 1/*f* noise in the leakage current and additional nonlinear current.

We can note that all structures have 1/*f* noise in the linear leakage. This noise determines the spectrum behavior at low currents. These structures (except some lasers) have 1/*f* noise in additional nonlinear current, which determine 1/*f* noise spectrum behavior at high currents. Characteristics of noise in linear leakage and additional nonlinear current vary in wide range between structures. That means these two components in the total current are caused by artificial structure defects.

Thus, observed noise data are explained by 1/*f* noise in the leakage current and in the additional nonlinear current. Noise in electrical parameters of quantum wells and quantum dots was not detected in our measurements.

IV. CONCLUSION

The main results of this work are as follows:

(1) Leakage and the additional (to recombination through quantum wells and/or dots) nonlinear currents have been found in nanoscale light-emitting diodes and lasers. These currents are appeared to be the main source of electrical 1/*f* noise in devices studied. Suggested model of 1/*f* noise in the leakage and additional nonlinear currents describes the dependence of the voltage noise spectrum on the bias current in dark and spontaneous emission modes, up to lasing threshold.

(2) Noise in electrical parameters of quantum wells and quantum dots was not detected.

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