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Low frequency noise in P-*InAsSbP*/n-*InAs* infrared light emitting diode-photodiode pairs.

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Abstract

Low frequency noise inP-InAsSbP/n-InAs infrared light emitting diode- photodiode pairs is investigated for the first time at 300 K. It is shown that photocurrent fluctuations under LED illumination are smaller than photocurrent fluctuations under a black body illumination. When the photodiode is illuminated by LED, the spectral noise density follows the 1/f dependence. In the case of a black body illumination we observe a significant contribution of generation-recombination noise.

1. Introduction

Optical instrumentation is one of the most rapidly growing industries. The demand for robust and inexpensive light sources and detectors pushes researchers to design new efficient devices operating near room temperature. Photonic devices such as lasers, light emitting diodes (LEDs) and photodiodes (PDs) meet most requirements of practical applications(e.g. for mid-IR non-dispersive infrared (NDIR) gas analyzers) successfully competing with thermal/pyroelectric detectors and incandescent lamps [1]. Recently, optically coupled mid-IR light emitting diode-photodiode pairs (photonic sensors), efficient in the important 3-4.6 μm spectral range, have proved their applicability for non-dispersive infrared analyzers of C_2H_5OH, C_nH_m, CO_2, and some other gases [2, 3].

The signal-to-noise ratio is one of the crucial parameters of any measuring system including gas analyzers based on p-InAsSbP/n-InAs(Sb) heterostructures active in the important 3-4.6 μm spectral range [3]. Recently, several papers on noise in p-InAsSbP/n-InAs PD at room and cryogenic temperatures have been published (see e.g. [4] and references herein).LEDs could be potentially quite noisy [5] and could essentially contribute to an overall LED-PD system noise.However, to the best of our knowledge there have been no attempts to measure the noise characteristics in mid-IR devices as InAsSbP/InAs LEDs and InAsSbP/InAs LED-PD pairs.

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Here, we present the first experimental study of low-frequency noise in p-InAsSbP/n-InAs mid-IR light emitting diode-photodiode pairs at room temperature.

2. Experimental

We use identical InAsSbP/InAs double heterostructures both as LEDs and as PDs (Fig. 1).

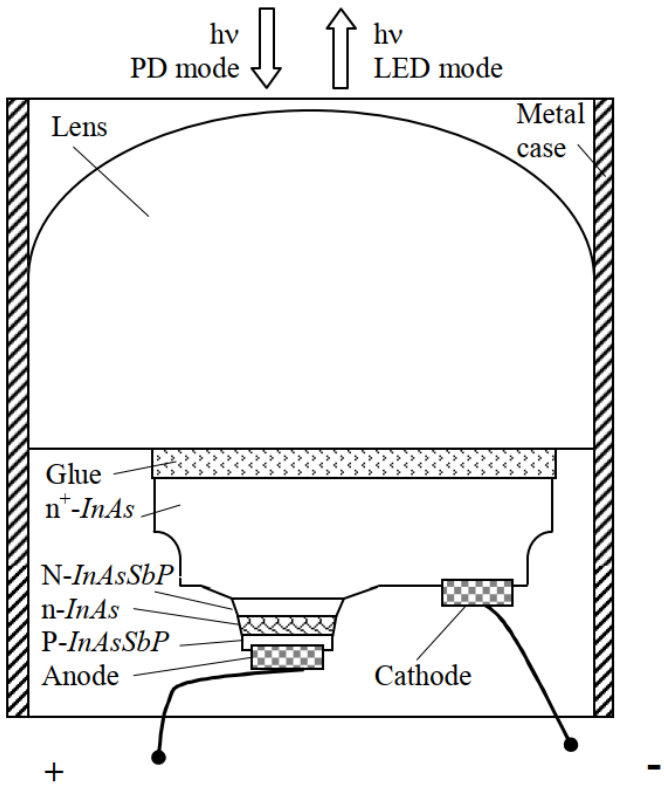

Fig. 1 Schematic of the immersion lens LED structures.

The band structure of such devices was described and discussed elsewhere [6]. The double heterostructures (DH) were grown on transparent heavily doped n^+-InAs (100) substrates with $n = 2\times10^{18}$ cm^{-3}.They contain a 3 µm thick n-InAsSbP cladding adjoining the 100 µm thick substrate, a 7- µm thick n-InAs absorber (base) with donor concentration $N_d \approx 5\times10^{16}$ cm^{-3}, and a 3-µm thick p-InAsSbP cladding/contact top layer. The thickness of the space charge region at the InAsSbP/InAs p-n junction is more than an order of magnitude smaller than both the absorber layer thickness and the carrier diffusion length [6,7].

Rectangular diode chips were designed for flip-chip bonding and had a 210 µm wide mesa (with a 170 µm circular metal anode on the top) and a rectangular metal cathode placed at the side of the mesa.

The diodes were packed in a screw metal header of the “Sr” type in a backside illumination (BSI) mode and were equipped with a 3.5 mm wide Si hyperhemispherical immersion lens as

described elsewhere [2,8]. The BSI operation mode in noise measurements in InAsSbP/InAs PDs has been used for the first time. All our previous results on photocurrent noise in InAsSbP/InAs PDs were obtained in the front surface illumination (FSI) mode of operation (illumination from the p-InAsSbP side) [4,7,9].

When operated at zero bias (U=0) the immersion lens diodes exhibited maximum responsivity of 1.4 A/W at λ_{max} =3.3 μm. The maximum LED electroluminescent intensity at λ_{max} =3.5 μm was 150 μW for a forward current I_{LED}=150 mA (Fig. 2). For I_{LED}< 50 mA the photocurrent I_{ph} in PD (facing LED at minimal distance between their immersion lenses) was proportional to I_{LED} with a transmission coefficient "Wall-Plug Efficiency" (WPE = I_{ph}/I_{LED}) of about $1.3\cdot10^{-3}$. This value is at least twice higher than our previously reported data for the InAsSbP/In(Ga)As immersion lens LED-PD pair optically coupled by a high aperture spherical mirror [10]. At I_{LED}>50 mA the I_{ph}/I_{LED} ratio declines due to Joule heating and Auger recombination enhancement.

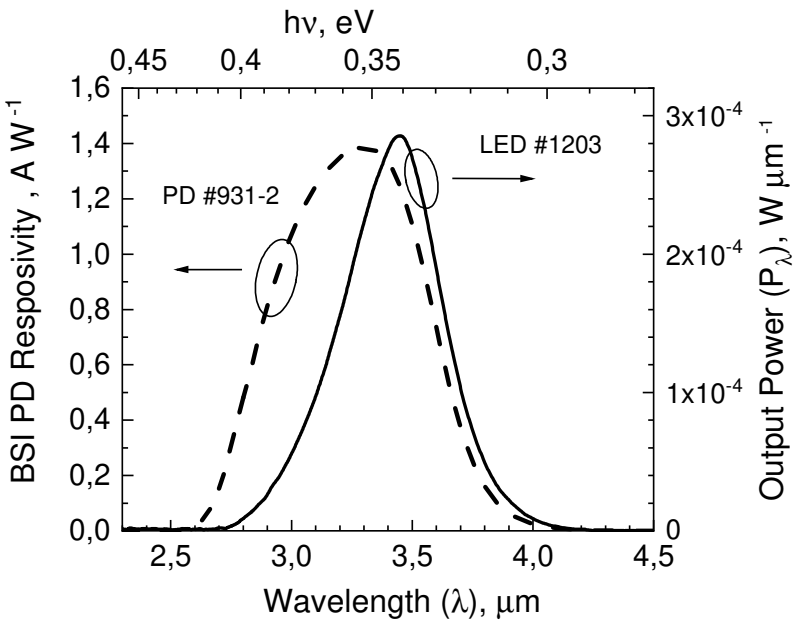

Fig. 2 Room temperature electroluminescent and responsivity spectra of InAsSbP/InAs double heterostructures immersion lens LED and PD illuminated from the substrate side (BSI mode).

We measured the spectral density of photocurrent noise S_I in the photovoltaic mode (U=0) when the PD was illuminated by a LED or by a black body source (Globar). LEDs were biased by a current source formed by a low noise battery connected in series with a load resistor. The load resistance was much higher than the LED static and differential resistances over the entire current range. The Globar source was fed by a low noise Keithley 2280S power supply. The CW incident radiation intensity was changed by varying the distance between the photodiode and the radiation source keeping the light source powering fixed.

Noise measurements were carried out at 300 K in the frequency range 1 Hz-10 kHz using a low noise EG&G 5113 pre-amplifier and a Photon+ spectrum analyzer. Voltage fluctuations, S_U, were measured across the low noise load resistor R_L connected in parallel to the PD ($R_L << R_0$, where R_0 is the PD differential resistance at zero bias). After subtraction of the measuring system background noise, the spectral noise density of photocurrent, S_I, was calculated as $S_I = S_U[(R_L + R_0)/(R_L \cdot R_0)]^2$

3. Results and discussion

Fig. 3 shows the forward current-voltage characteristic for our LED (sample #1203-1) and the differential resistance R_0 for the photodiode (sample # 931-2).

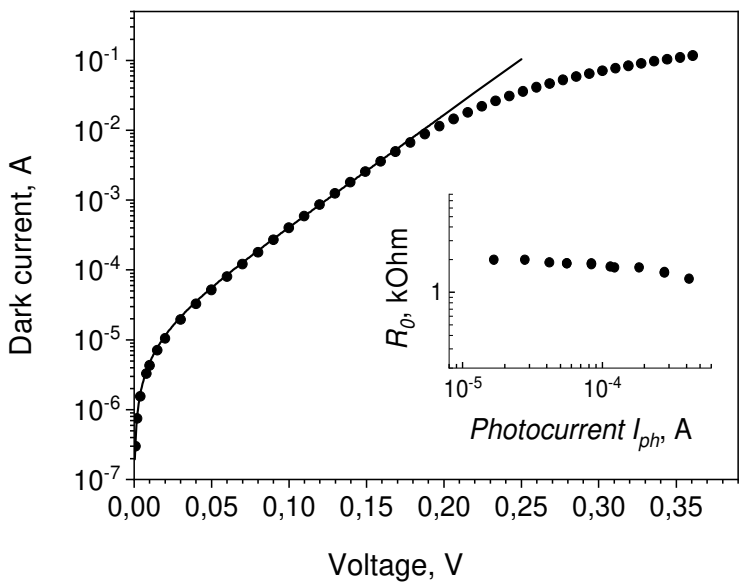

Fig. 3 Forward current-voltage characteristic for one of the samples. Solid line represents Eq. 1 with $I_0 = 1.05\times10^{-5}$ A and $\beta = 1.05$. Inset: photodiode differential resistance R_0 at zero bias as a function of photocurrent I_{ph}. T=300 K.

The current-voltage characteristics are practically identical for all samples, whether they were used as LEDs or PDs. In the current range 10^{-5} A $\leq I \leq 2\cdot10^{-3}$ A they follow the modified Shockley equation:

$$I = I_0\left[exp\frac{qU}{\beta kT} - 1\right], \qquad (1)$$

with $I_0 = 1.05\times10^{-5}$ A and the ideality factor $\beta = 1.05$. Here, q is the elementary charge, k is the Boltzmann constant, and T is the temperature. The zero bias differential resistance R_0, as expected, is very close to the value $R_d = \frac{\beta kT}{qI_o} \approx 1.6$ kOhm following from Eq.(1) at low currents.

The normalized to mesa area A noise spectral density ($S_I \cdot A$) at the referent frequency 10 Hz, is shown in Fig.4 for the sample #931-2 and for the sample #1211-2 studied previously in Ref. [9]. In all cases, the spectral noise density is proportional to $\sim I_{ph}^2$. The sample #1211-2, illuminated by the Globar source (full circles), has been shown to have a very low $1/f$ like photocurrent noise [9]. The noise in the sample #931-2 studied here is substantially less (Fig. 4).Thus, the PD#931-2 demonstrates the lowest observed photocurrent noise in P-InAsSbP/n-InAs infrared photodiodes at room temperature.

Surprisingly, when comparing the photocurrent noise in the sample #931-2 illuminated by Globar and by LED, we found that in the latter case the noise is lower by ~1.5-2 dB (see Fig.4).

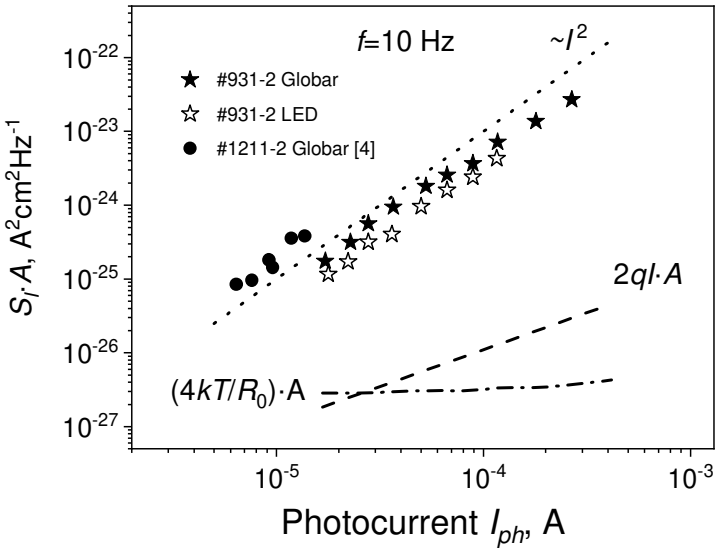

Рис. 4 Photocurrent dependences of normalized spectral noise density ($S_I \cdot A$) for two DH P-*InAsSbP*/n-*InAs* diodes at f=10 Hz. The sample 1211_2 is illuminated only by the Globar source (full circles), data from [4], the sample 931_2_2 is illuminated by Globar (full stars) or by LED (empty stars). The predictions for the shot noise, $2qIA$, and the Nyquist noise are shown by the dashed line and the dash-dotted line respectively.

To estimate the detectivity of infrared photodiodes, it is usually assumed that the thermal (Nyquist) noise is predominant. For our samples, at the referent frequency 10 Hz, the Nyquist noise might become important at photocurrents $I_{ph} \leq 3$ μA (see Fig. 4). The shot noise can be neglected over the entire current range. It can become prevailing only at high frequencies and large photocurrents. For example, at a maximal photocurrent, I_{ph} = 116 μA, the photocurrent density S_I will be dominated by shot noise at $f \approx 4\times10^3$ Hz (Fig 5).

Thus, at low frequencies, including the reference frequency 10 Hz, and over the entire current range, under illumination we observe only the proper current noise of the photodiode.

Fluctuations of light intensity inducing the shot noise as well as the equilibrium Nyquist noise do not contribute to the observed photocurrent noise.

Usually, when studying the noise properties of PDs, a black body is taken as the reference light source. In this study we observed that the photocurrent noise in the PD illuminated by LED is less than when it is illuminated be Globar (Figs 4 and 5). Moreover, under illumination by LED the photocurrent noise is $1/f$ like in the entire current range, while under Globar illumination the generation-recombination (GR) component is clearly seen at ~100 Hz for the current 51 μA (see Fig.5).

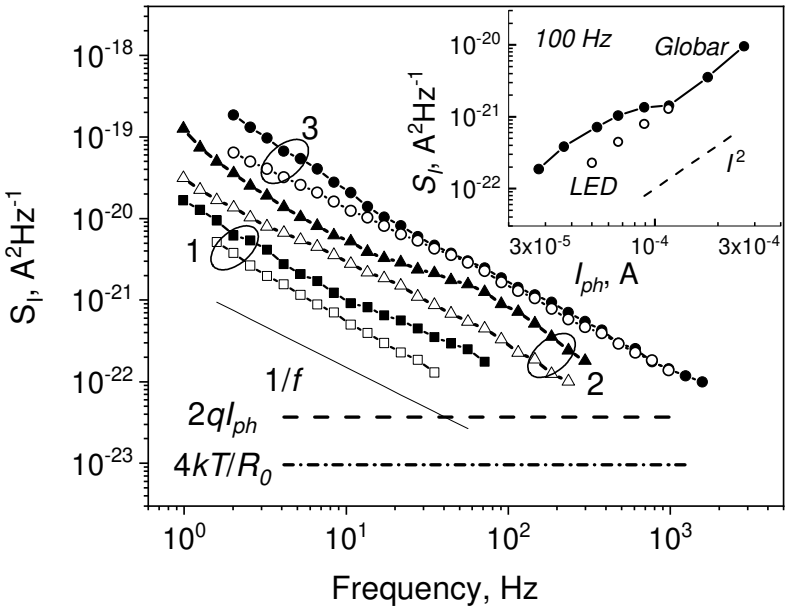

Fig. 5. PD spectral noise density at three photocurrent values: 1- 27.8μA, 2 – 51μA, and 3 – 116μA. Filled symbols represent the data obtained under Globar illumination, empty symbols - under LED illumination. The shot noise is calculated for I_{ph}=116 μA, the Nyquist noise corresponds to R_0 = 2 kOhm. T =300 K. Inset: PD noise vs photocurrent under Globar and LED illumination at f = 100 Hz.

This difference in the photocurrent noise is even more noticeable when comparing $S_I(I_{ph})$ dependences at 100 Hz (inset to Fig 5.). Extrapolating the measured $S_I(I_{ph})$ dependence under LED illumination into higher current range we observe that a substantial difference exists up to I_{ph} ~1.1 10^{-4} A. It disappears at higher photocurrents when the GR noise component is absent.

It is known that the normalized noise $(S_I/I_{ph}^2)\cdot f$ vs f dependence allows to reveal the GR noise contribution [11,12]. The existence of a single maximum in Fig. 6 shows that there is a single local center responsible for the GR noise over the entire photocurrent range. The maxima of the curves correspond to the condition $2\pi f\times\tau$=1, where τ is the relaxation time of the center occupancy [13]. For the observed GR noise, τ varies from ~ 3×10^{-4}s to ~ 2×10^{-3}s depending on the photocurrent value. This range of τ, as well as the decrease of the amplitude of the maximum

on the curves$(S_I/I_{ph}^2)\cdot f$,and its simultaneous shift towards high frequencies are typical for GR noise caused by traps in the neutral base region (see, for example, [14]).

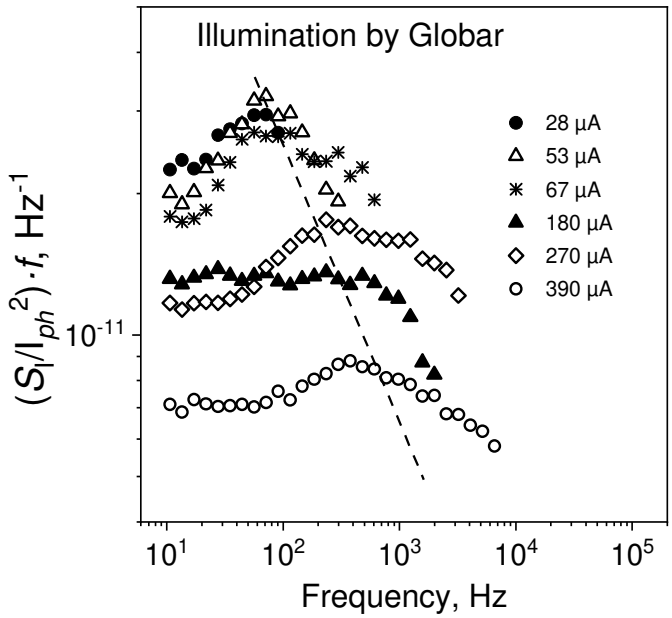

Fig. 6. The frequency dependences of the $(S_I/I_{ph}^2)\cdot f$ product at several photocurrents I_{ph} under illumination by the Globar.

We assume that the origin of the observed GR noise lies in the base region where the light is absorbed. Indeed, if the GR noise was due to fluctuations of the population of a trap level in the space charge region, then the observed noise (for a fixed photocurrent value) should be the same regardless of the spectral composition of radiation.

However, the GR noise is observed only under illumination by Globar, while it is absent when the diode is illuminated by LED.

Therefore, we believe that the trap responsible for the observed GR noise is situated in the base. The noticeable GR noise is created by illumination in the spectral region $\lambda < 3.5\mu m$ which changes the trap occupancy. The generation-recombination fluctuations of the nonequilibrium carrier (hole) concentration should lead to the fluctuations of the flux of holes entering the space-charge region, i e to the photocurrent noise.

There is no generally accepted theory of noise generated by the *photocurrent*. The theories developed for reverse current noise [15-19] can not be used for the interpretation of our results. Thus, further research is needed to clarify the nature and the localization of local centers responsible for the observed GR noise.

4. Conclusion

We have studied for the first time the room temperature low-frequency noise in P-InAsSbP/n-InAs infrared LED-PD pairs. Identical double InAsSbP/InAs immersion lens heterostructures were used as LEDs as well as photodiodes. We compared the photocurrent noise under illumination by LED and by a black body source (Globar).

In both cases the spectral noise density S_I depends on photocurrent I_{ph} as $S_I \sim I_{ph}^2$.At the referent frequency 10 Hz, the photocurrent noise might become less than the thermal noise at photocurrents $I_{ph} \leq 3$ μA. The shot noise can be neglected over the entire current range.

Under illumination by LED, the photocurrent spectral noise density depends on frequency as $S_I(f) \sim 1/f$ over the entire current range. When the PD is illuminated by Globar, the 1/f noise increases slightly and the GR component appears in the frequency range 70-700 Hz at currents $<10^{-4}$ A.This effect might be due to the absorption of Globar photons with energy higher then photons emitted by LED, which has are relatively narrow emission spectrum.

To clarify the nature and localization of the local center responsible for the observed GR noise further research is needed.

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