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Low frequency noise in double heterostructure P-InAsSbP/n-InAs mid-IR photodiodes at cryogenic temperature: photovoltaic mode and forward bias

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Abstract

Low frequency photocurrent noise, as well as the forward current noise are studied for the first time in mid-infrared InAsSbP/InAs double heterostructure photodiodes at 100 K. Two types of photodiodes are identified. For the first type, the spectral noise density, S_I , depends on frequency as $1/f^\gamma$. For the second type, generation-recombination (GR) noise component dominates. Our results show that in those samples, it is one and the same local center that is responsible for the noise over the entire photocurrent range. The forward current noise in all samples is lower than that previously observed in InAsSbP/InAs single heterostructure photodiodes at 77 K. In samples demonstrating $1/f^\gamma$ noise, the spectral noise density, S_I , is proportional to the square of the current. In samples with GR noise, we also observe $S_I \sim I^2$ dependences in a certain current range. At higher currents, the noise decreases or tends to saturate. We show that at 100K, the Nyquist noise is dominant and can be used for estimating the specific detectivity at photocurrents $I_{ph} \leq 5 \cdot 10^{-9}$ A for samples showing $1/f^\gamma$ noise, and at $I_{ph} \leq 2 \cdot 10^{-9}$ A for samples presenting GR noise component. At higher I_{ph} the photocurrent noise should be also taken into account.

1. Introduction

Mid-IR photodetectors (PDs) have found widespread application in radiometric temperature measurements, biomedical monitoring, optical gas detection, flame monitors, thermovoltaic energy production [1-5]. Low frequency noise determines the photodiodes detectivity and is sensitive to structural defects in semiconductor devices [5-7]. That is why low frequency noise is the subject of intensive research for all types of PDs (see, for example, [8-12]).

Recent findings show several advantages of the A_3B_5 photodiodes (PD) devices which can make them more attractive in some applications [13-15]. In particular, zero bias resistance (R_0) measurements in InAs single heterostructure PDs have shown that their low temperature performance meets both Rule 07 and background limited operation (BLIP) criteria [16].

Most of these applications require very high signal-to-noise ratio. Therefore, a detailed knowledge of noise characteristics of both detectors and sources is of great importance.

However, there are very few data on noise measurements in InAs-based detectors. In most research publications the Johnson (thermal) noise is assumed to be dominant. Systematic studies of noise in InAs photodiodes, in particular the low frequency noise, has started in 2018. Currently, there is a number of papers on noise in single heterostructure (SH) [17,18] and double heterostructure (DH) [19,20] InAsSbP/InAs PDs operating at 100 K and 300 K. These results show the potential of high sensitive and low noise InAsSbP/InAs PDs for being used in focal plane arrays. However, low frequency noise in InAsSbP/InAs DH PDs in the photovoltaic mode of operation at low temperatures has not been studied so far, although it is this mode that is used in traditional read-out circuits.

In this paper, we focus on low frequency noise measurements in the photovoltaic mode and in the forward bias mode at 100K, where PD current-voltage characteristics can vary from sample to sample due to potential barriers height inhomogeneities, high sensitivity to surface leakage, and the presence of defects in the space charge region [21,22]. It is also important to understand the role of these phenomena for the low frequency noise and, consequently, for the diodes detectivity.

2. Experimental

We have studied the same double heterostructure InAsSbP/InAs PDs as in our previous work [20]. The $p-n$ junctions have a smooth impurity distribution in the space charge region adjacent to a 3 μm thick n -InAs absorbing layer (electron concentration $n = 5 \cdot 10^{16} \text{ cm}^{-3}$) sandwiched between two broad-band InAsSbP claddings, as shown in Fig.1. The active layer operation area A is $4.15 \cdot 10^{-4} \text{ cm}^2$.

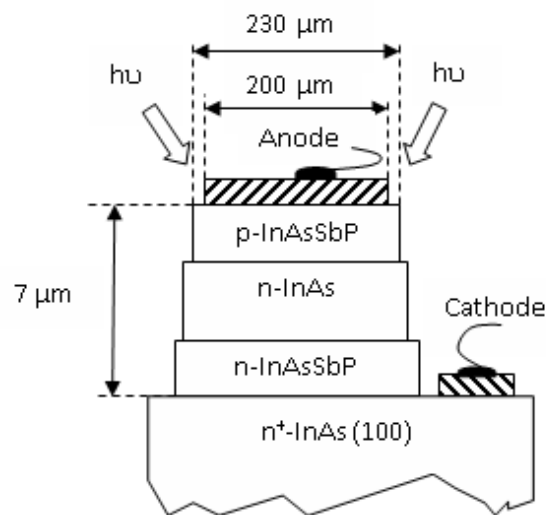


Fig.1 Schematics of the InAsSbP/InAs DH PD cross section. The photosensitive area is indicated by thick arrows.

The band structure of such samples with energy gap discontinuities $\Delta E_v = -30 \text{ meV}$ and $\Delta E_c = 119 \text{ meV}$ at the InAsSbP/InAs junctions was reported in our previous papers (see, for

example [23]). Photodiode chips/n+-InAs substrates were soldered onto a TO-18 header and covered by a transparent gel (not shown in Fig.1).

As shown in Ref. [19], even at 300 K, the noise characteristics of samples from the same batch showing virtually the same I - V and C - V characteristics can differ quite significantly. With cooling, the dispersion of these characteristics increases. At the same time, as it was observed for the backward mode of operation [20], the low-frequency noise characteristics can be qualitatively different. For a detailed study, we have selected two samples, which show a qualitative difference in the *photocurrent* noise characteristics.

Current noise spectral density was measured at 100 K in the frequency range 1 - 10^4 Hz. In the photovoltaic mode (bias voltage $V = 0$), under illumination by Globar source, the noise was measured in the photocurrent range 10^{-8} - $5 \cdot 10^{-6}$ A. Under forward bias, the current range was $5 \cdot 10^{-10}$ - $5 \cdot 10^{-6}$ A.

In forward biased diodes the voltage fluctuations, S_U , were measured across the low noise resistor R_L connected in series with the diode. In the photovoltaic mode, the low-noise resistor was parallel to the photodiode. The spectral noise density of current fluctuations, S_I , was calculated as $S_I = S_U [(R_L + R_d) / (R_L R_d)]^2$, where R_d is diode differential resistance. More details about experimental setup and measurement procedure can be found in [20].

3. Results and discussion

Forward I - V characteristics at 100K strongly differ for two samples from the same batch: the current in the sample 1211_1 is more than an order of magnitude higher than in the sample 1211_2 (Fig. 2). Moreover, the forward I - V characteristic of the sample 1211_2 exhibits a step separating two regions of exponential growth. This feature has been previously observed in p-InAsSbP/n-InAs/N-InAsSbP double heterostructure photodiodes at low temperatures and has been attributed to current leakage through the p-n junction [16]. Note that at room temperature the $I_{fb}(U_{fb})$ dependences for these samples were practically identical and followed the modified Shockley equation [19, 20].

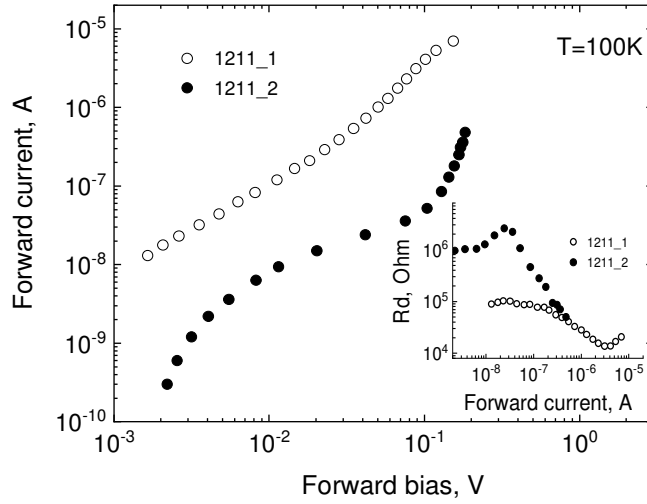


Fig. 2. Forward current-voltage (I - V) characteristics for two diodes at 100 K. Inset shows current dependences of the differential resistance R_d for the same samples.

Fig. 3 presents the frequency dependences of the forward current spectral noise density, S_I . For the sample 1211-1 the current noise depends on frequency as $S_I(f) \sim 1/f^\gamma$ (here, $\gamma=1$). In this sample, the forward current noise is higher than the reverse current noise: at the reference frequency $f=10$ Hz for $I = 2.3 \cdot 10^{-8}$ A, the *forward* current noise density is $2.2 \cdot 10^{-23}$ A²/Hz, while the *reverse* current noise density is $6 \cdot 10^{-25}$ A²/Hz [20]. Nevertheless, the forward current noise at 100 K is lower (by 4-5 dB) than the forward current noise in InAsSbP/InAs single heterostructure photodiodes at 77 K [17].

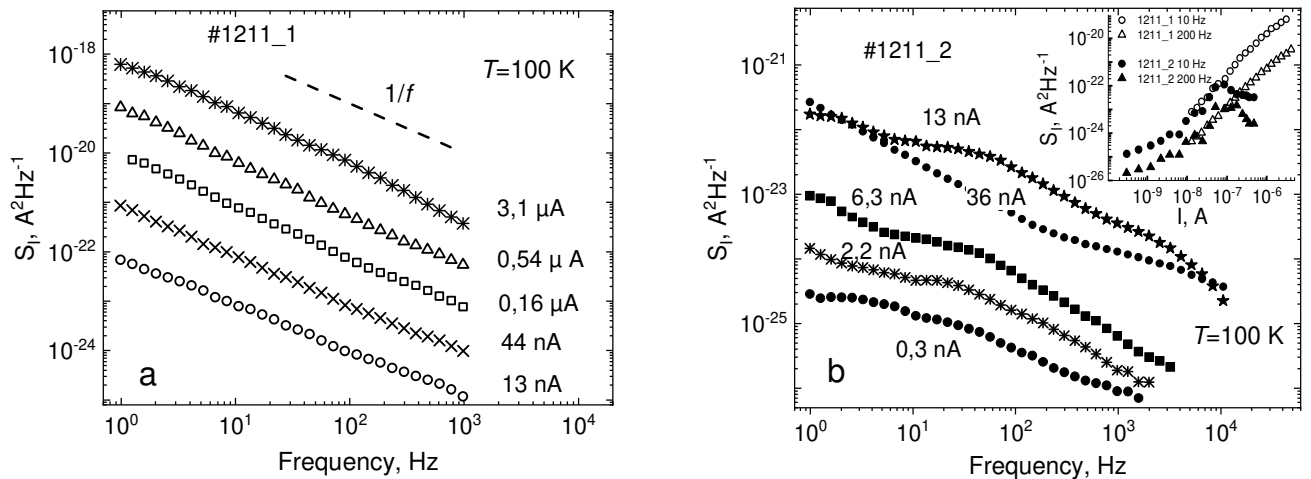


Fig. 3 Frequency dependences of the forward current spectral noise density $S_I(f)$ for several values of current I_{fb} for two DH photodiodes. (a) 1211_1. (b) 1211_2. Inset in Fig. 2(b): current dependences of noise for the same diodes at frequencies 10 and 200 Hz.

For sample 1211_2, the contribution of generation-recombination (GR) noise is observed over the entire current range (Fig. 3b). However, in the region $10^{-8} \leq I_{fb} \leq 10^{-7}$ A, the

noise in both samples is very close and the spectral noise density S_I is proportional to I_{fb}^2 (inset in Fig. 3b). For higher currents, the noise in 1211_1 diode follows the same dependence $S_I \sim I_{fb}^2$ while the noise in 1211-2 diode *decreases*. At low currents, $I_{fb} \leq 1 \cdot 10^{-8}$ A, the noise was measurable only for the sample 1211_2, the spectral noise density S_I being proportional to $\sim I_{fb}^{0.75}$. In this sample, the forward current noise is also lower than in single heterostructure photodiodes at 77 K [7]. Moreover, at low currents, $I_{fb} \leq 1 \cdot 10^{-8}$ A, the difference reaches 10÷13 dB.

The decrease of noise with current has been previously observed in p-n junctions based on wide-band materials (SiC, GaN) ([24,25] and references herein) and, recently, in DH p-InAsSbP/n-InAs infrared photodiodes at 300K [9]. It was suggested in Ref. [9] that GR centers responsible for the noise were located within the diode active region.

In Ref. [19] the noise decreased at forward current $I_{fb} \geq 2 \cdot 10^{-4}$ A (current density $j_{fb} \geq 0.5$ A/cm²). Here, we observe a similar decrease at much lower currents $I_{fb} \geq 10^{-7}$ A (current density $j_{fb} \geq 2.5 \cdot 10^{-4}$ A/cm²). At these low forward current densities, the noise most probably originates from the space charge region of the InAsSbP/n-InAs heterojunction, rather than from the active diode region as it was assumed in [19].

Figure 4 shows $S_I(f)$ dependences for reverse bias mode and photovoltaic mode for sample 1211_1. In the current range from 23 nA to 500 nA, the amplitudes of the reverse current noise and the photocurrent noise are very similar, although their frequency dependences are different. While for reverse current $S_I \sim 1/f$, for photocurrent $S_I \sim 1/f^\gamma$, where γ changes from 2 to 1.5 with current increasing from 23 nA to 500 nA.

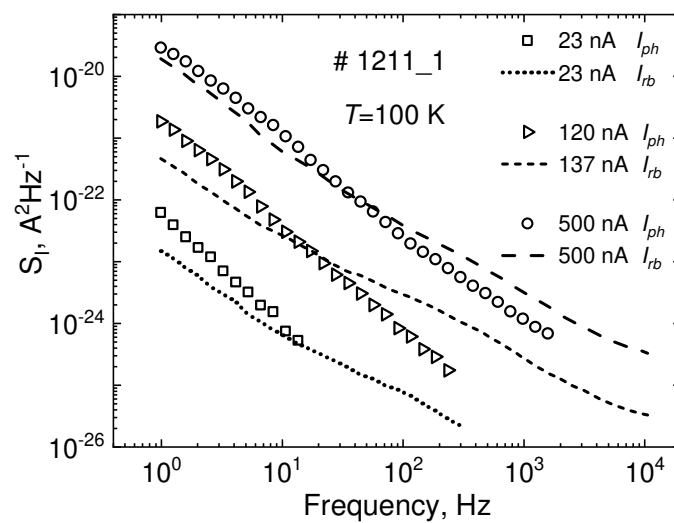


Fig. 4 Frequency dependences of the current spectral noise density $S_I(f)$ for diode 1211_1 at several current values: for photocurrent I_{ph} (open symbols) and for reverse current I_{fb} (dashed lines).

For sample 1211_2, the frequency dependences of the photocurrent noise $S_I(f)$ show significant contribution of GR components over the entire current range, $2 \cdot 10^{-8} \leq I_{ph} \leq 5 \cdot 10^{-6}$ A (Fig. 5). In spite of difference in noise spectra, for both samples, 1211_1 and 1211_2, the noise depends on current as $\sim I^2$ with the same amplitude up to $I_{ph} = 4 \cdot 10^{-7}$ A (inset to Fig.5). Note, that over this current range, the values of differential resistance R_d under forward (Inset to Fig. 2) and under reverse bias [10] are strongly different for two samples.

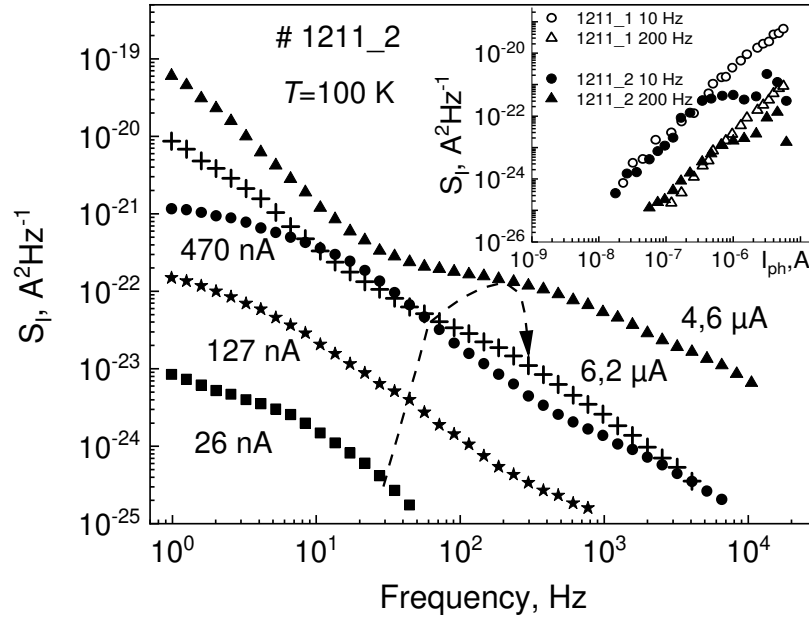


Fig. 5 Frequency dependences of the photocurrent spectral noise density $S_I(f)$ for diode 1211_2. Inset shows current dependences of noise in photovoltaic mode for diodes 1211_1 and 1211_2 at frequencies 10 and 200 Hz.

With further photocurrent increase, the noise continues to grow for sample 1211_1, while for sample 1211_2 it tends to saturate at $I_{ph} \geq 5 \cdot 10^{-7}$ A (photocurrent density $j_{ph} \geq 1.2 \cdot 10^{-3}$ A/cm²).

For detectivity estimate, one should select the largest noise between thermal noise and photocurrent noise. The equilibrium Nyquist noise spectral density $S_N = 4kT/R_0$ is equal to $\approx 5.5 \cdot 10^{-26}$ A²/Hz for sample 1211_1 ($R_0 = 10^5$ Ohm) and to $\approx 5.5 \cdot 10^{-27}$ A²/Hz for sample 1211_2 ($R_0 = 10^6$ Ohm). At the referent frequency 10 Hz, for sample 1211_1, the photocurrent noise becomes dominant at currents $I_{ph} \geq 5 \cdot 10^{-9}$ A and for sample 1211_2, at currents $I_{ph} \geq 2 \cdot 10^{-9}$ A (Inset to Fig. 5). Thus, for those current ranges, the photocurrent noise should be used for detectivity estimate in InAsSbP/InAs photodiodes, not the Nyquist noise which is currently taken into account over the entire photocurrent range [5].

Fig. 6 shows the normalized photocurrent noise $(S_I / I_{ph}^2) \times f$ which allows to isolate the GR noise contribution [26,27]. It can be seen that it is one and the same local center which is responsible for the noise over the entire photocurrent range. The decrease of the maximum of the

function $(S_I / I_{ph}^2) \times f$ and its simultaneous shift to higher frequencies correspond to the typical evolution of the Lorentzian spectrum caused by traps in the neutral base region (see, for example, [28]).

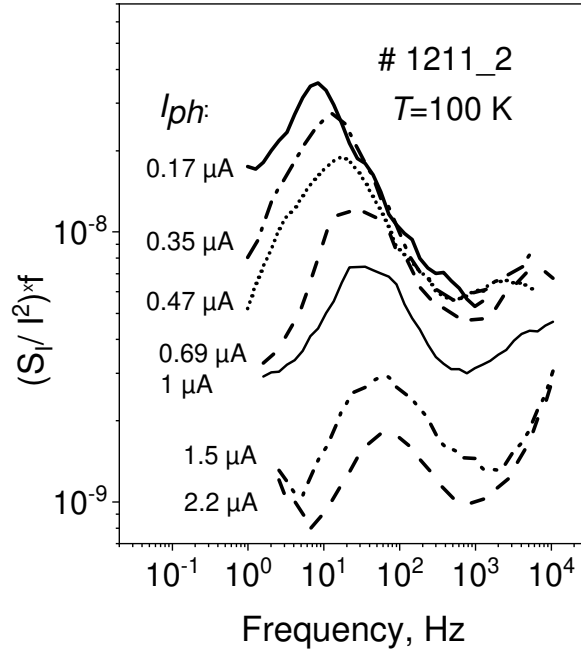


Fig. 6 Frequency dependences of the normalized photocurrent noise, $(S_I / I_{ph}^2) \times f$, for sample 1211_2 at several photocurrent values.

However, for our samples, the GR noise clearly originates from the space charge region of the P-InAsSbP/n-InAs heterostructure (Fig.1), rather than from the neutral base. Indeed, the voltage drop across the base, U_{ph} , is negligible, even for the maximal photocurrent value $I_{ph} = 2.2 \cdot 10^{-6}$ A:

$$U_{ph} = W_b F = W_b \frac{I_{ph}}{qn\mu_n A} = 2 \times 10^{-9} V,$$

where $W_b = 3 \mu m$ is the thickness of InAs base (Fig. 1), F is the electric field across the base layer, q is elementary charge, $n = 5 \cdot 10^{16} cm^{-3}$, $A = 4.15 \cdot 10^{-4} cm^2$ is base area, and $\mu_n \approx 10^5 cm^2/Vs$ is the electron mobility at 100 K [29].

To the best of our knowledge, there is no theory of noise generated by *photocurrent* in the space charge region. The most appropriate approach describing LFN originating in the space charge region is developed for forward biased *wide gap* material based diodes, where the current is formed by carrier generation in the barrier region [30]. It might be expected that extension of this approach to narrow band InAsSbP/n-InAs diodes will help to define the parameters of local centers responsible for the observed GR photocurrent noise.

4. Conclusions

Low frequency noise under forward bias and in the photovoltaic operation mode are studied for the first time in InAsSbP/InAs double heterostructure photodiodes at 100 K. Two types of photodiodes have been selected: those showing $1/f^{\gamma}$ noise and those showing GR noise.

The forward current noise at 100 K in both samples is lower than the previously observed forward current noise in InAsSbP/InAs single heterostructure photodiodes at 77 K. At currents $I_{fb} \leq 1 \cdot 10^{-8}$ A, the difference is 10÷13 dB, at larger currents this difference decreases to 4÷5 dB.

For the sample showing $1/f^{\gamma}$ noise, the spectral noise density S_I is proportional to I_{fb}^2 over the entire current range. The dependence $S_I \sim I_{fb}^2$ with a similar amplitude is also observed for the sample with a dominant GR noise component in the current range $1 \cdot 10^{-8} < I_{fb} < 1 \cdot 10^{-7}$ A. At higher currents the noise decreases.

Similarly, in the photovoltaic operation mode for $I_{ph} < 4 \cdot 10^{-7}$ A, the photocurrent noise amplitude and current dependence are the same for both samples, regardless of the noise type.

In the photovoltaic mode, as well as under the forward bias, the GR noise originates from the space charge region of the P-InAsSbP/n-InAs heterostructure rather than from the neutral base. It has been established that it is one and the same local center that is responsible for the photocurrent noise over the entire current range.

We show that at 100K, the Nyquist noise is dominant and can be used for estimates of the specific detectivity at currents $I_{ph} \leq 5 \cdot 10^{-9}$ A for sample 1211_1, and at $I_{ph} \leq 2 \cdot 10^{-9}$ A for sample 1211_2. At higher I_{ph} the photocurrent noise should be also taken into account.

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