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Low frequency noise in reverse biased double heterostructure P-InAsSbP/n-InAs infrared photodiodes

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Abstract

Low frequency reverse current noise is studied for the first time in InAsSbP/InAs double heterostructure (DH) photodiodes in the frequency range 1 Hz – 10⁴ Hz at 300 K and 100 K. At room temperature, the noise in DH photodiodes is 1/*f* and might be significantly lower (by ~17 dB) than in single heterostructure (SH) InAsSbP/InAs photodiodes. In the practically most important regime of low reverse currents, *I_{rb}*, the current dependence of spectral noise density is proportional to *I_{rb}*², both at 300K and 100K. The reverse current noise might provide the limit for the detectivity of DH photodiodes at *I_{rb}* > 3×10⁻⁶ A at 300K and *I_{rb}* > 8×10⁻⁹A at 100K.

1. Introduction

Mid-infrared (3 to 5 μm) InAs bulk photodetectors known since 60-es of the last century have been recently upgraded via implementation of p-i-n and p-n heterostructure architectures [1-3]. Maximum of room temperature responsivity in InAs based detectors corresponds to wavelengths of 3.3-3.4 μm which make them attractive for optical measurements of hydrocarbons, e.g. the partial vapor pressure/concentration of C₂H₅OH [4]. Mid-infrared photodiodes (PDs) have also found several important applications in medicine [5], thermophotovoltaic energy production [6], and radiometric temperature measurements [7,8] (see also [9] and references herein).

Double heterostructure (DH) InAsSbP/InAs photodiodes (PDs), designed and fabricated by our group [10], have demonstrated several advantages over single heterojunction (SH) InAsSbP/InAs PDs. The potential barrier in the n-InAsSbP/n-InAs isotype junction of the InAsSbP/InAs double heterostructures enhances photogenerated carrier localization in the absorbing layer with respect to the p-InAsSbP/n-InAs/n⁺-InAs single heterostructures [10]. As a result, the DH photodiodes exhibit higher zero bias resistance *R_o*, higher sensitivity and lower capacitance than the SH photodiodes [11].

Besides, double heterostructures offer more freedom for post-growth procedure. For example, a double side “protection” of InAs absorbing layer by the InAsSbP layers simplifies

1 fabrication process of substrate free arrays with enhanced shortwave sensitivity. The reason for
 2 this is that InAsSbP layers are characterized by a large diffusion length of photogenerated carriers
 3 and they can also serve as a stop layers during chemical etching off InAs substrate [12].
 4

5 Furthermore, DH InAsSbP/InAs PDs also demonstrated lower forward bias noise at 300K,
 6 a crucial parameter for photodiodes [13]. However, the most important operation mode is the
 7 reverse bias mode providing high speed performance of photodiode as an element of focal plane
 8 array with standard readout circuitry [9]. Because of this, the noise investigation under reverse
 9 bias and, especially, at low temperatures under BLIP conditions, serves to evaluate the practical
 10 perspectives of DH InAsSbP/InAs PDs.
 11

12 In this paper, we study the low frequency noise in InAsSbP/InAs/InAsSbP double
 13 heterostructure at reverse bias at 300 and 100 K.
 14

15 2. Experimental

16 DH PDs described previously in [13,14] consist of 120 μm thick heavily doped n⁺-InAs
 17 (100) substrate, 2 μm thick n-InAsSbP cladding layer, 3 μm thick and 230 μm in diameter
 18 (operation area $A= 4.15\times 10^{-4} \text{ cm}^2$) n-InAs absorbing active layer with electron concentration n
 19 $\sim 5\times 10^{16} \text{ cm}^{-3}$, and 2 μm thick P-InAsSbP cladding (contact) layer. The energy diagram of similar
 20 PDs could be found in Refs. [15,16]. The measured capacitance-voltage characteristics were linear
 21 in the C^{-3} - V coordinates.
 22

23 At 300 K, the forward and reverse C - V characteristics of DH diodes grown in the same epitaxial
 24 process, are practically identical for different samples. However, the low frequency noise can be
 25 substantially different [12].
 26

27 We have chosen two DH samples which showed a qualitative difference in *forward* current
 28 noise [12]. The noise analysis in *reverse* bias mode at 300K, as well as at low temperature, can
 29 help to understand the origin of such a variation in noise properties of our photodiodes.
 30

31 The low frequency noise was measured in the frequency range 1 Hz– 10⁴ Hz at reverse
 32 currents, I_{rb} , from $6\times 10^{-7}\text{A}$ to $1.5\times 10^{-4}\text{A}$ at 300 K and from $4\times 10^{-9}\text{A}$ to $2\times 10^{-6}\text{A}$ at 100 K. Spectral
 33 noise density of voltage fluctuations S_U was measured across a low noise load resistance R_L ,
 34 connected in series with a diode, using 5113 EG&G pre-amplifier and Photon⁺ spectrum analyzer.
 35 The current spectral noise density, S_I , was calculated as $S_I = S_U [(R_L + R_d)/(R_L R_d)]^2$, where R_d is
 36 the PD differential resistance.
 37

38 3. Results and discussion

39 Figure 1 presents reverse current-voltage characteristics for two samples from the same batch at
 40 room temperature.
 41

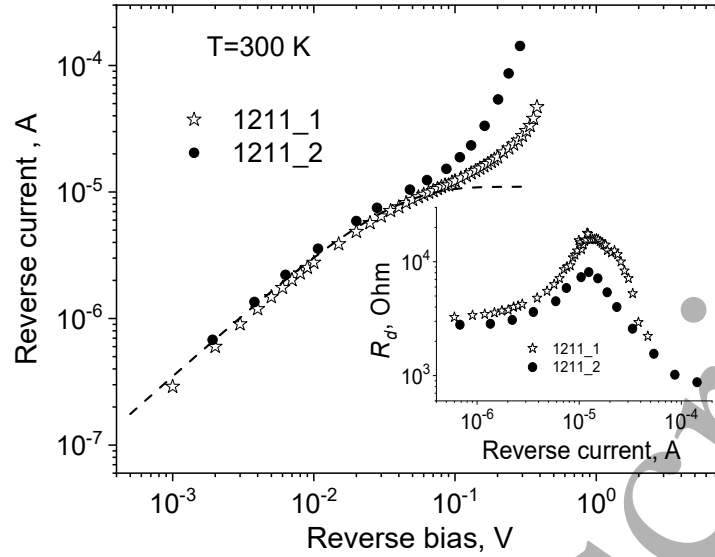


Fig. 1. Reverse current-voltage (I - V) characteristics for two diodes at 300 K. Dashed line follows equation (1) with $I_0 = 1.1 \times 10^{-5}$ A and $\beta = 1.20$. Inset shows current dependences of the differential resistance R_d for the same samples.

The characteristics of diodes are very similar and follow the modified Shockley equation (1) up to reverse bias $U_{rb} \approx 0.1$ V (reverse current $I_{rb} \approx 10^{-5}$ A):

$$I_{rb} = I_0 [1 - \exp(-qU_{rb} / \beta kT)] \quad (1)$$

where q is the elementary charge, k is the Boltzmann constant, T is the absolute temperature, I_0 is the saturation current, and β is the ideality factor. However, as we show later, the diodes noise characteristics differ considerably.

The dashed line in Figure 1 is reverse current calculation according to Eq.(1) using the parameters $I_0 = 1.1 \times 10^{-5}$ A ($I_0/A = 2.65 \times 10^{-2}$ A/cm²) and $\beta = 1.20$ which have been used to describe forward I - V characteristics of these samples [13]. Note that these values are close to the parameters in single InAs-based heterostructures, $\beta = 1.22$ and $I_0/A = 3.4 \times 10^{-2}$ A/cm² [17,18].

The inset in Fig. 1 shows the current dependences of the differential resistances $R_d = dU_{rb}/dI_{rb}$. As expected, R_d practically does not depend on the reverse current at $I_{rb} \ll I_0$ and strongly increases at $I_{rb} \geq I_0$. At $U > 0.1$ V, the current rises dramatically causing the decrease of R_d . This current rise could be caused either by impact ionization or by tunneling in InAs/ P -InAsSbP heterojunction. Impact ionization should result in a considerable increase of low frequency noise with current, which we do not observe (see below). Thus, the probable reason for the strong current increase is the tunneling process.

Figure 2 compares the noise in *double heterostructure* and *single heterostructure* PDs at low currents, from 2 μ A to 10 μ A. Since the noise is inversely proportional to the active device

area, A , we compare the corresponding products of spectral noise density and the active diode area, $S_I \times A$. The active layer width in our DH and SH diodes are equal.

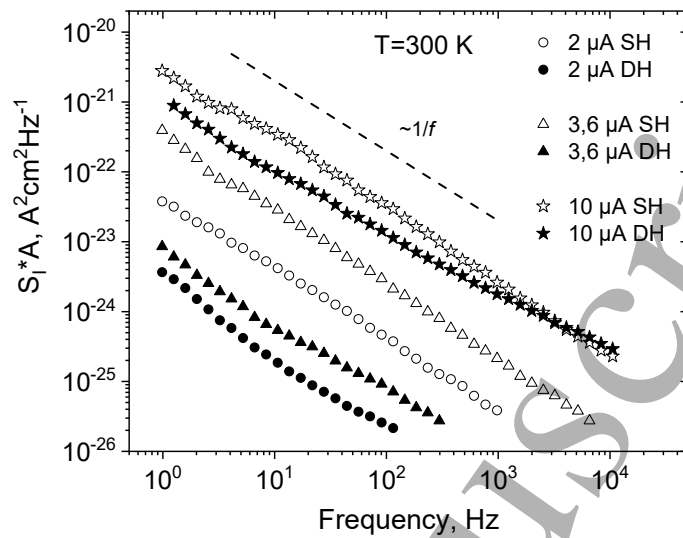


Fig. 2. Frequency dependences of the product $S_I \times A$ for DH PD 1211_2 and for SH PD [18] at three values of reverse current I_{rb} (μA): 2, 3.6, and $10\mu\text{A}$.

At the lowest current $I_{rb} = 2 \mu\text{A}$ and frequency 10 Hz, the $S_I \times A$ value in the 1211_2 DH diode is ~ 13 dB less than in the SH diode. This difference increases up to ~ 17 dB at $I_{rb} = 3.6 \mu\text{A}$. With further increase of current this difference is reduced. The strong noise growth in DH diodes coincides with the strong increase of the differential resistance (Fig.1, inset).

Note, that the $S_I \times A$ frequency dependences are close to $1/f$ for both photodiodes in the whole current range (2-10 μA) while the generation-recombination noise contribution is negligible.

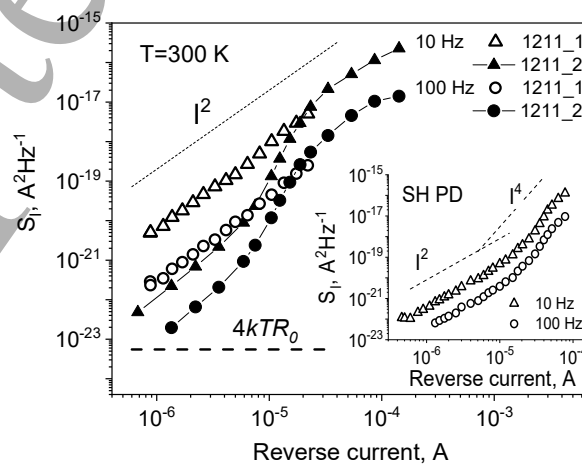


Fig. 3 Current dependences of reverse current spectral noise density, S_I for two DH diodes 1211_2 (filled symbols) and 1211_1 (open symbols) at two frequencies of analysis -10 Hz and 100 Hz. Inset shows similar dependences for SH diodes at the same frequencies f [18].

Figure 3 shows the evolution of noise with current in the entire range ($10^{-6}\text{A} - 1.4 \times 10^{-4}\text{A}$) for two DH diodes. At low currents, the noise in 1211_2 sample is considerably lower (by ~ 17 dB) than in 1211_1 sample, although the I - V characteristics and the differential resistance of the two diodes are very similar (Fig.1). With current growth, the noise in 1211_2 diode strongly increases and becomes of the same order of magnitude as in the 1211_1 diode.

The noise dependence on current of the low-noise DH diode is very similar to that of the SH diode (inset in Fig.3). In the low current range, $10^{-6}\text{A} \leq I_{rb} \leq 6 \times 10^{-6}\text{A}$, for both diodes the noise depends on current as $\sim I^2$ which is typical for the case when R_d is bias independent [19].

In the intermediate current range, $6 \times 10^{-7}\text{A} \leq I_{rb} \leq 2 \times 10^{-5}\text{A}$, the noise increases as $S_I \sim I^4$ for SH diode and even stronger for DH 1211_2 diode. This current range corresponds to a significant growth of the differential resistance (see inset in Fig.1 for 1211_2 diode and Ref. [18] for SH diode). The strong noise increase in InAs SH diodes was discussed previously in Ref. [18]. This still cannot be explained by the existing models [20, 21].

With further current increase, at $I_{rb} > 2 \times 10^{-5}\text{A}$, the current dependence turns again into $S_I \sim I^2$ for DH 1211_2 sample and shows the same tendency for the SH sample. For DH diodes, in this current range R_d decreases (Fig.1). As mentioned above, the decrease of R_d could be caused by impact ionization or tunneling processes. In the case of impact ionization, we would expect a strong increase of the current noise [22]. Meanwhile, in this current range the preceding fast noise increase significantly slows down. Therefore, the most probable reason for the decrease of R_d is related to the enhancement of tunneling current which does not contribute significantly to current noise [23].

We conclude that in the DH 1211_2 diode, similarly to the previously studied SH diode, the $S_I(I_{rb})$ dependence is due to the resistance fluctuations of the P-InAsSbP/n-InAs junction barrier. The excess $1/f$ noise observed at low currents in the 1211_1 DH sample might be a manifestation of the dominating role of surface noise [20, 21].

For the low-noise DH PD, the spectral noise density at reference frequency 10 Hz equals the equilibrium thermal noise at $I_{rb} \sim 3 \times 10^{-7}\text{A}$. Thus, at currents higher than 10^{-6}A , the detectivity should be estimated by taking into account the reverse current noise.

Reverse current noise at 100 K.

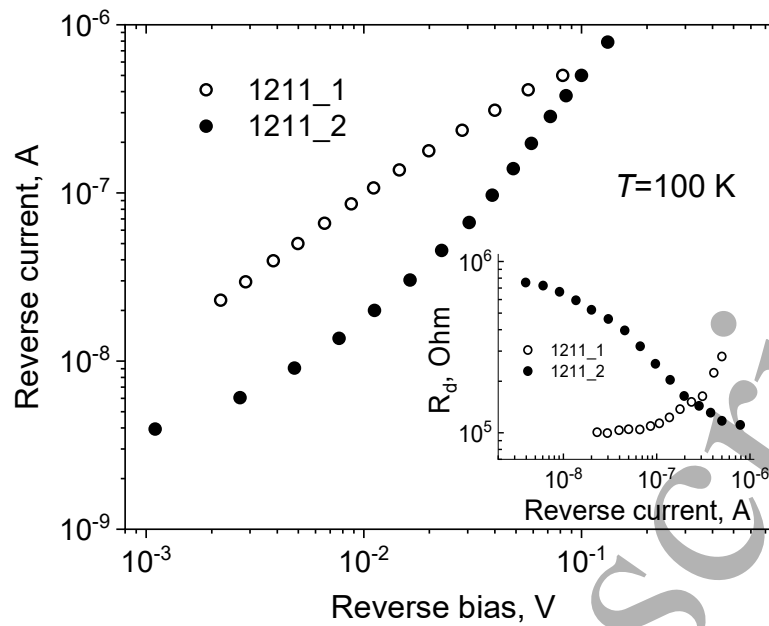


Fig. 4. Reverse current-voltage characteristics of two diodes at 100 K. Inset shows the current dependences of the differential resistance.

Fig. 4 shows the significant difference between the reverse I - V characteristics of two DH diodes at 100 K, in contrast to their similarity at 300 K (Fig. 1). At $U_{rb} = 2 \times 10^{-3}$ V, the current in 1211_1 diode is higher than that in 1211_2 diode by a factor of 4. This corresponds to an 8 times difference in resistances at zero bias, R_0 . We also observe a difference in the dependences of R_d on current: in the 1211_1 sample, R_d increases with current while in the 1211_2 sample it decreases. This difference in evolution appears when the reverse bias U_{rb} becomes higher than ~ 8 mV (inset in Fig 4) which corresponds to the kT value at 100K.

Such a significant variation of diodes parameters at low temperature is quite typical and is probably due to the absence of surface passivation. In addition, with temperature decrease, the potential barriers height inhomogeneities play increasingly important role. This effect has been studied in detail for Schottky barriers (see [24] and references herein).

Figure 5 shows frequency dependences of the product $S_I \times A$ for two DH diodes at $T=100$ K. The lowest noise is observed in the 1211_1 sample. Note that the current noise density at $I_{rb} = 2 \times 10^{-8}$ A is close to the equilibrium thermal noise already at $f \approx 100$ Hz.

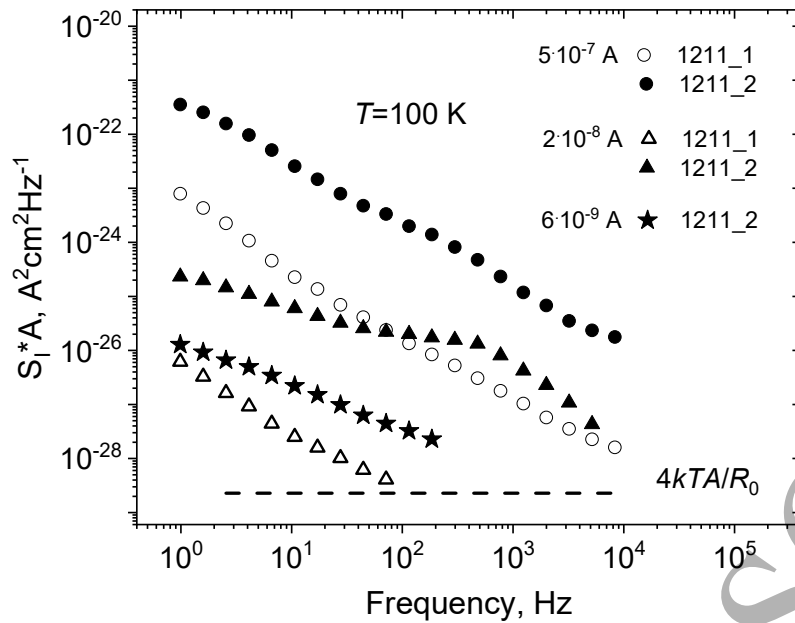


Fig. 5. Frequency dependences of the product $S_I \times A$ for two DHS diodes at three values of reverse current at 100 K. Dotted line shows equilibrium thermal noise for 1211_1 sample.

For the 1211_2 sample, the frequency dependence and the amplitude of the current noise are apparently determined by the GR noise. Interestingly, at 300 K the relation between the noise intensities in the two samples is reversed: the lowest noise at low currents was observed in the 1211_2 sample (Figs.2 and 3).

Figure 6 shows the current dependences of reverse current spectral noise density for two DH diodes at 100 K.

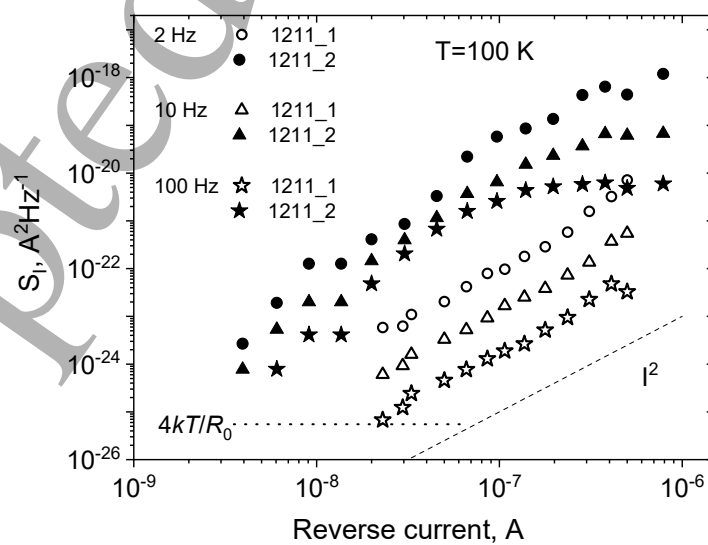


Fig. 6. Current dependences of reverse current noise for two DH diodes at three frequencies. Dotted line shows the equilibrium Nyquist noise for 1211_1 sample. $T=100$ K.

For the diode 1211_1, with the lowest noise at 100 K, S_I is proportional to I_{rb}^2 . Extrapolating the $S_I(I)$ dependence to lower currents at the reference frequency 10 Hz, we find that the current noise density equals the Nyquist noise at $I_{rb} = 8 \times 10^{-9}$ A. However, at conventional reverse bias $U_{rb} \sim 0.1$ V used for detection, the reverse current for this photodiode is much higher: $\sim 10^{-6}$ A. Thus, for the detectivity estimate at $U_{rb} \geq 0.1$ V, the reverse current noise should be taken into account, rather than the equilibrium thermal noise as it is usually done for InAs-based diodes [9].

For the photodiode 1211_2 (with a high noise level at 100 K), at low currents, the spectral noise density depends on current as $\sim I_{rb}^3$ and shows a tendency to saturate at high currents. This behavior can be attributed to the presence of the GR component. Note that in the DH PD showing a clear GR component at room temperature under *forward* bias, the noise *decreases* with current [13]. The noise-current dependences of this type were previously observed in SiC- and GaN- based p-n junctions, where they were related to GR processes or junction degradation [25,26].

4. Conclusions

Low frequency reverse current noise has been studied for the first time in InAsSbP/InAs double heterostructure (DH) photodiodes at 300 and 100 K. At 300 K, the $1/f$ noise in DH photodiodes can be significantly lower than the $1/f$ noise in InAsSbP/InAs single heterostructure (SH) photodiodes: at the reference frequency 10 Hz and reverse currents of several μ A, the noise in DH diode is by ~ 17 dB lower than in SH InAsSbP/InAs diode. This large difference is observed despite the fact that the I - V characteristics of these photodiodes are well described by the modified Shockley equation at both forward and reverse bias, the saturation current density $j_0 = 2.65 \cdot 10^{-2}$ A/cm² and the ideality factor $\beta = 1.2$ for DH PD being very close to the corresponding values for SH PD ($j_0 = 3.4 \times 10^{-2}$ A/cm² and $\beta = 1.22$).

At 100 K, for low noise double heterostructure photodiodes, the frequency dependence of the spectral noise density, S_I , is approximately $1/f$. At the reference frequency $f = 10$ Hz, the value of S_I approaches the thermal noise $4kT/R_d$ at reverse current $I_{rb} = 8 \times 10^{-9}$ A. Thus, for estimations of the detectivity of double heterostructure photodiodes at higher currents, one should take into account the reverse current noise.

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