The Role of Noise in Specific Detectivity of InAs/GaSb Superlattice MWIR Bariodes

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Abstract: In this paper, the results of the electrical, noise, and optical characterization of p-i-n and p-B-i-n diodes with AlSb and 4 ML AlSb/8 ML GaSb superlattice barriers in High-Operating Temperature conditions, are presented. Experimental and theoretical noise parameters were compared. Both dark current and noise analysis showed that the p-Bp Bulk-i-n bariode had the best performance. P-i-n photodiodes had the highest experimental value of specific detectivity (D*) of 6.16 × 10^9 Jones at 210 K and zero bias. At about –1 V reverse bias, the bariode with AlSb/GaSb electron barrier caught up to it and both devices achieved D* = (1–1.1) × 10^8 Jones. Further optimization of the superlattice-based electron barrier should result in the improvement of bariode performance at a smaller bias, at which better noise performance is more pronounced. It was shown that neglecting the low-frequency noise component can lead to a significant overestimation of detectivity. The simple method of incorporation of low-frequency noise contribution in the detectivity calculation, without time-consuming measurements, has been proposed.

Keywords: infrared sensors; InAs/GaSb superlattice; barrier photodiode; noise performance; specific detectivity; low-frequency noise

1. Introduction

Infrared photodetectors are widely used in many branches of modern society such as environment monitoring, imaging, medicine, spectroscopy, or the military. Presently, mercury-cadmium-telluride-based technology dominates the market. However, national and international legislation works to eliminate heavy metal usage in the production of consumer products, including Hg and Cd. As a result, research to find better and safer materials is undergoing in facilities around the world. At present, two of the best candidates are antimonide-based type-II superlattices (SL) InAs/GaSb and InAs/InAsSb [1–5]. They allow for the utilization of bandgap engineering design structures with long-wavelength absorption edge practically in the entire mid-infrared spectral range [6]. Furthermore, both their growth and processing technology matured in the last decade to the point, at which discrete photodetectors, as well as focal plane arrays based on them, are becoming more common [7–9].

Lately, more and more attention is paid to the High-Operating Temperature (HOT) photodetectors, which work at temperatures from 200 K to 300 K and beyond [10–12]. In such devices, low temperatures are achieved through the use of thermoelectric cooling. They have many advantages over cryogenically cooled detectors. In particular, they allow for further decreasing the size and weight, lowering production costs as well as better power usage efficiency. As a result, their applications can be more versatile and more easily spread into the consumer market.
Increasing the operating temperature of SL-based infrared photodetectors can be achieved using different approaches. One is to use novel architecture, such as in Interband Cascade Detectors or Quantum Cascade Detectors [13,14]. Presently, the main disadvantage of such structures is their complexity. They require considerable computational effort during the design and optimization stages. Furthermore, they are hard to realize epitaxially, as the margin of error required for their proper operation is very small. Another approach is to introduce unipolar carrier barriers into mature detector designs (e.g., photocoductor or p-i-n photodiode), the purpose of which is the suppression of dark current and noise without negatively influencing the photocurrent [15–17]. The barriers can be placed for one or two types of carriers, depending on the detector structure. They can be made of either bulk material (e.g., AlSb, AlAsSb, AlGaSb) or superlattice (e.g., InAs/AlSb, AlSb/GaSb). The latter allows for better optimization of the photodetector band structure due to the utilization of bandgap engineering.

This paper is focused on photodiodes with (p-Bp-i-n) and without (p-i-n) electron barriers, based on a double heterojunction design. The Bp in p-Bp-i-n pertains to a p-type electron barrier made of either AlSb or AlSb/GaSb superlattice. The analysis of dark current, noise, and optical response is presented. The emphasis was put on the role of noise in the performance of these infrared photodetectors. Furthermore, a comparison between two semi-empirical approximations (the first including thermal and shot noise, and the second including thermal, shot, and low-frequency noise) and actual measurements is presented. The issues arising from the omission of low-frequency noise during the calculation of specific detectivity and resulting errors are addressed. Usually, noise figures for InAs/GaSb-superlattice-based devices are given for low temperatures <150 K, which is understandable since cryogenically-cooled detectors are most commonly used [18–20]. In this paper, all noise characteristics are shown in the HOT temperature range in addition to the low-temperature characterization. Furthermore, to the best of our knowledge, there are no low-frequency noise measurements reported for bariodes on GaAs substrate, in contrast to recently reported results for various detectors on GaSb substrate [19,21,22].

2. Fabrication of InAs/GaSb Superlattice Photodetectors

In this work, three types of photodiodes were compared, namely p-i-n, p-Bp_bulk-i-n with AlSb electron barrier, and p-Bp_SL-i-n with type-I AlSb/GaSb superlattice electron barrier. In Figure 1, schematic diagrams of each photodetector are shown. All samples were deposited on (100) GaAs substrates.

![Figure 1](image-url)
Photodetector heterostructures were grown using molecular beam epitaxy in Riber 32P reactor. In both types of structures, p-type and n-type contact layers were made of highly doped (~10^{18} \text{cm}^{-3}) GaSb material. The absorption region consisted of 400 to 440 periods of type-II 10 ML InAs/10 ML GaSb superlattice with InSb-like and GaAs-like interfaces. The epitaxial growth of the superlattice was described elsewhere [23]. Before fabrication of p-B_{p,SL}-i-n photodiodes, the growth of 4 ML AlSb/8 ML GaSb superlattice was optimized. A series of test processes were performed, which culminated in high-quality material. In Figure 2a, the 2\theta/\omega curve measured for AlSb/GaSb superlattice using the high-resolution x-ray diffraction (HRXRD) method is shown. From its analysis, the following information was obtained: AlSb layer thickness—4.1 ML (12.5 Å; ML stands for monolayer), GaSb layer thickness—8.3 ML (25.3 Å), and perpendicular lattice mismatch \((\Delta a/a)_\perp\) of 4240 ppm. The latter is defined as follows:

\[
(\Delta a/a)_\perp = \frac{a_{\perp,SL0} - a_{\perp,GaSb}}{a_{\perp,GaSb}},
\]

where \(a_{\perp,SL0}\) is the perpendicular lattice constant of the superlattice, for which lattice mismatch is calculated, and \(a_{\perp,GaSb}\) is the perpendicular lattice constant for GaSb substrate (for test AlSb/GaSb superlattice) or GaSb buffer layer (for photodiode/bariode structures). The zeroth-order satellite peak has an FWHM of 144 arcsec. The presence of Pendellösung peaks confirmed parallelism of crystallographic planes. Furthermore, this AlSb/GaSb superlattice exhibited a smaller lattice-mismatch to the GaSb than bulk AlSb.

![Figure 2](image-url)
Device heterostructures underwent structural quality tests using the HRXRD method. In Figure 2b–d, 2θ/ω curves are shown. The summary of structural details of photodiode heterostructures under consideration and lattice mismatch (Δa/a)⊥ between both absorber superlattices and barriers and GaSb buffer are given in Table 1. For all samples, higher-order satellite peaks up to the fifth order are observable, which is an indication of their high quality. The AlSb/GaSb superlattice electron barrier in p-Bp_SL-i-n heterostructure differed slightly from the test one. The layer thicknesses were AlSb—4.4 ML, GaSb—7.6 ML, and (Δa/a)⊥ was 4950 ppm.

Table 1. The summary of structural details and lattice mismatch for photodetector heterostructures obtained from HRXRD characterization.

| Structure                        | p-i-n | p-Bp_bulk-i-n | p-Bp_SL-i-n |
|----------------------------------|-------|---------------|-------------|
| Absorber                         |       |               |             |
| GaAs IF thickness (ML/Å)         | 0.5/1.5 | 0.5/1.4       | 0.5/1.4     |
| InAs layer thickness (ML/Å)      | 10.0/30.3 | 9.9/30        | 10.2/31     |
| InSb IF thickness (ML/Å)         | 1.5/4.8  | 1.5/5.0       | 1.5/5.0     |
| GaSb layer thickness (ML/Å)      | 10.1/30.7 | 9.8/30        | 9.9/30.1    |
| (Δa/a)⊥ (ppm)                   | −920          | −280          | −280        |
| electron barrier                 |       |               |             |
| type                            | −             | bulk AlSb     | AlSb/GaSb SL|
| AlSb layer thickness (ML/Å)      | −             | −/500         | 4.4/13.6    |
| GaSb layer thickness (ML/Å)      | −             | −             | 7.6/23.1    |
| (Δa/a)⊥ (ppm)                   | −             | 11,800        | 4950        |

Photodetectors were designed to operate in back-side illumination configuration and p-type contact layers are on the top of the structure. There were three reasons behind this choice. Firstly, it was to minimize losses related to the high free-carrier absorption in p-type GaSb in the mid-wavelength spectral range. Secondly, materials used as electron barriers have a large value of (Δa/a)⊥ to the buffer, namely 11,800 ppm for AlSb and 4950 ppm for 4 ML AlSb/8 ML GaSb. It could result in worsening of both structural and optical quality of 10 ML InAs/10 ML GaSb absorber superlattice if grown on top of such barrier layers. It would also negatively impact figures of merit of the photodetector. Finally, a double pass of infrared light through the absorption region could be achieved in such a configuration due to reflection from the top contact. Barriers were intentionally doped with beryllium to minimize the effects of valence band offsets between them and neighboring layers.

After the growth, heterostructures were further processed. Circular mesa structures were formed using the reactive ion etching-inductively coupled plasma dry etching method. The diameters of the photodiodes were 300 µm. Electrical contacts were made by the deposition of Ti/Au metallization using the magnetron sputtering method. After dicing, sample photodetectors were mounted onto test sub-assemblies using wire bonding. Finally, dark current, noise, and optical characterizations were performed.

3. Results and Discussion

3.1. Dark Current Characteristics

Dark current-voltage characteristics were measured for each photodiode in a wide range of temperatures using a setup consisting of Keithley 2612A source-measure instrument and Janis CCS-150 closed-cycle cryocooler. Samples were isolated from the environmental background radiation using a cold shield, which was cooled to around 10 K during the measurements. Differential-resistance-area product (RdA) as a function of bias was calculated from experimental I–V data. In Figure 3a,b, J–V and RdA–V curves for considered photodiodes at 210 K are shown, respectively. This temperature was chosen as it corresponds to the one achievable through miniature three-stage thermoelectric coolers. Large differences in electrical characteristics between particular photodetectors
were observed. The lowest dark current density was obtained for the p-B\textsubscript{p\_bulk}-i-n bariode, whereas the highest was for the p-i-n diode. Comparison between bariodes indicated that p-B\textsubscript{p\_SL}-i-n has a higher dark current. Both unbiased barrier photodiodes had similar values of \( R_0A \) parameter of about 17 \( \Omega \text{cm}^2 \) for p-B\textsubscript{p\_bulk}-i-n and ~18 \( \Omega \text{cm}^2 \) for p-B\textsubscript{p\_SL}-i-n. However, for the latter device, it was the highest value whereas p-B\textsubscript{p\_bulk}-i-n achieved a higher value of ~100 \( \Omega \text{cm}^2 \) with a small reverse bias of 104 mV. The classic p-i-n photodiode had a maximum \( R_dA \) value of 2.4 \( \Omega \text{cm}^2 \) for zero bias. It is noteworthy that the photodetectors in this paper were not passivated, which could further decrease the dark current density.

![Figure 3.](image)

In Figure 3c, dark current densities at −50 mV bias are plotted as a function of reciprocal temperature. The p-i-n photodiode had the highest dark current density in the entire temperature range of 77 K–300 K. The p-B\textsubscript{p\_bulk}-i-n bariode had the smallest dark current density and outperformed the p-B\textsubscript{p\_SL}-i-n by more than one order of magnitude for \( T < 200 \text{K} \). In Table 2, activation energies \( E_{a2} \) and \( E_{a3} \) obtained from the analysis of the curves in Figure 3c and their corresponding temperature ranges are given. All photodiodes had very small (<10 meV) activation energies in low-temperature ranges (\( \Delta T_2 \) and \( \Delta T_3 \)), which suggests surface leakage channel as the main shunt current source. A more detailed analysis is needed to identify a specific mechanism. The behavior of photodiodes differs
more at higher temperatures ($\Delta T_1$). The activation energies $E_{a1}$ for the p-B$_{p\_SL-i-n}$ bariode and the p-i-n photodiode were close to half of their bandgap energy at 300 K ($E_{g\_300 K}$), which were equal to $\approx 250$ meV and 235 meV, respectively. These values indicate that the operation of these detectors in the $\Delta T_1$ temperature range is limited by the generation–recombination (g-r) component of the dark current and/or shunt currents since it was shown that they can exhibit similar behavior and are influenced by the defect states in the junction area [24]. On the other hand, p-B$_{p\_bulk-i-n}$ had the highest activation energy, which was closer to the value of $E_{g\_300 K} \approx 250$ meV ($E_{a1} \approx 0.88 \times E_{g\_300 K}$). This suggests that both diffusion and g-r dark current components are limiting its performance, with the former being the dominant one. The values of $E_{g\_300 K}$ for p-i-n photodiode were estimated using the Varshni relation, which is described in Section 3.3. On the other hand, the $E_{g\_300 K}$ for both bariodes was determined from measurements of spectral current responsivity $R_I$ at 300 K (not shown in the paper).

| Photodetector  | $\Delta T_1$ | $E_{a1}$ (meV) | $\Delta T_2$ | $E_{a2}$ (meV) | $\Delta T_3$ | $E_{a3}$ (meV) |
|----------------|---------------|----------------|---------------|----------------|---------------|----------------|
| p-i-n          | >244 K        | 111            | 100–244 K     | 2.5            | <100 K        | 1.4            |
| p-B$_{p\_bulk-i-n}$ | >240 K        | 220            | 112–240 K     | 2.6            | <112 K        | 9.3            |
| p-B$_{p\_SL-i-n}$ | >260 K        | 132            | 104–260 K     | 9.2            | <104 K        | 6.8            |

3.2. Noise Characteristics

The setup used for low-frequency noise measurements and the small-signal equivalent circuit of a photodiode were described in Ref. [25]. In Figure 4a, power spectral densities measured at $T = 200$ K for the low and high bias voltages are shown. In general, power spectral densities exhibit $1/f$ dependence, but some Lorentzian ($S_\nu \sim 1/(1 + (f/\text{const.})^2)$) inclusions appear, especially for the low biased detector with a bulk AlSb barrier. The analysis of the noise signal in the time domain, illustrated in Figure 4b, reveals that Lorentzian is connected with random telegraph noise (RTN). Such noise is attributed to the carrier capture/emission by extended defects present in the depletion region [26]. At a small voltage bias of $-10$ mV, the low-frequency noise magnitude is the lowest for the p-B$_{p\_bulk-i-n}$ detector. The significant difference in the magnitude is especially observed for low bias voltage and at low frequencies. For $U = -500$ mV, p-i-n photodiode had the highest noise magnitude in the entire measured frequency range, whereas p-B$_{p\_bulk-i-n}$ had the smallest. The p-B$_{p\_SL-i-n}$ was in-between, however, its $S_0$ decreased to the level of p-B$_{p\_bulk-i-n}$ at $f \approx 10$ kHz.

Figure 4. (a) The noise power spectral density versus frequency for considered photodiodes, measured at 200 K for two bias points. (b) Noise signal in the time domain for p-B$_{p\_bulk-i-n}$ structure recorded at the output of transimpedance amplifier ($k_{in} = 10^8$ V/A), at $T = 200$ K and $U = -50$ mV.
In Figure 5a,b, power spectral density magnitude $S_i(f = 1 \text{ Hz})$ measured at $T = 84 \text{ K}$ and $T = 200 \text{ K}$ are shown as a function of bias current $I$. The dashed line in this figure follows dependence $S_i(f = 1 \text{ Hz}) \sim I^2$. The measured characteristics $S_i(I)$ match $S_i(I) \sim I^2$ dependence closely. There is no significant difference in the $S_i(I)$ magnitude for three considered types of photodetectors. If squared, dependence between $S_i(I)$ and $I$ holds, the noise coefficient can be defined as $\alpha = S_i(f = 1 \text{ Hz})/I^2$. The noise coefficients as a function of temperature are shown in Figure 5b. In this experiment, the noise was measured at voltage bias $U = -50 \text{ mV}$. In the low-temperature region ($T \approx 84 \text{ K}$), the noise coefficient for all three structures is within the range of $1 \times 10^{-9} - 2 \times 10^{-8} \text{ Hz}^{-1}$. The current-temperature characteristics (see Figure 3c) show that in the low-temperature region, the leakage shunt current $I_{sh}$ dominates. Different values of noise coefficient $\alpha_{sh} = S_i(f = 1 \text{ Hz})/(I_{sh})^2$, related to the shunt current, have been reported in the literature. For InAs/GaSb SL devices, $\alpha_{sh}$ is within the range of $3 \times 10^{-10} - 6 \times 10^{-6} \text{ Hz}^{-1}$ [21,27]. Our values of $\alpha_{sh}$ lie in the middle of that range and change with the temperature only slightly. In the high-temperature region, the diffusion and generation-recombination currents dominate the total current. It was shown that such current, especially the diffusion component, has a much lower noise coefficient [18,21,27–29]. For detectors with InAs/GaSb SL absorber, $\alpha_{g-r} = 4.8 \times 10^{-9} \text{ Hz}^{-1}$ and $\alpha_{diff} = 1.9 \times 10^{-10} \text{ Hz}^{-1}$ were found for generation-recombination and diffusion current, respectively [19]. In the high-temperature region, the noise coefficient decreases slightly for p-i-n, p-B$_{p_{SL}}$-i-n because the shunt current is still significant for these structures as compared to the diffusion current. For p-B$_{p_{bulk}}$-i-n, with low shunt current, the noise coefficient drops suggestively reaching a value of $1 \times 10^{-11} \text{ Hz}^{-1}$, which is much lower than the best (lowest) results found by us in the literature [19]. This translates into good noise performance of the p-B$_{p_{bulk}}$-i-n detector at temperatures, where current is limited by its diffusion component.

![Figure 5](image_url)

Figure 5. $S_i(I)$ characteristics measured at (a) $T = 84 \text{ K}$ and (b) $T = 200 \text{ K}$. (c) The noise coefficient $\alpha$, obtained for noise measurements at voltage bias $U = -50 \text{ mV}$, as a function of reciprocal temperature for considered photodiodes.
3.3. Optical Characteristics

Spectral current responsivity measurements were performed in the range of 3–6 µm at 210 K. The experimental setup consisted of Horiba MicroHR motorized monochromator equipped with SiC-based IR source and ruled grating with blaze wavelength of 5000 nm. The optical signal was mechanically chopped and detected using the Stanford Research Systems SR830 DSP lock-in amplifier. A calibrated lithium tantalate pyroelectric detector with a BaF\(_2\) window was used to measure the reference signal. Sample photodetectors were placed in Janis CCS-150K closed-cycle cryocooler with a KBr window.

In Figure 6a–c, results of spectral current responsivity (R\(_I\)) measurements of considered photodetectors are shown for two reverse bias values each. Long-wavelength absorption edge \(\lambda_c\) was determined to be ~4.7 µm for all analyzed photodiodes. The cause of the slight differences in \(\lambda_c\) originates mainly from the variations in both the composition and thicknesses of InSb- and GaAs-like interfaces in the InAs/GaSb superlattice in the absorption region. The former were not taken into account during the simulation of \(2\theta/\omega\) curves, in which binary interfaces were assumed. The latter are given in Table 1 in the section Fabrication of InAs/GaSb superlattice photodetectors. Dips in the spectra at wavelengths in the range of 3.3–3.5 µm in Figure 6a–c are caused by the absorption of radiation by water vapor present in the measurement chamber.

![Figure 6](image_url)

**Figure 6.** Spectral current responsivity (R\(_I\)) for (a) p-i-n, (b) p-B\(_{\text{bulk}}\)-i-n, and (c) p-B\(_{\text{SL}}\)-i-n photodiodes at 210 K, at two biases. (d) Bandgap energy of p-i-n photodiode absorber region at various temperatures and fitted Varshni relation.
In Figure 6d, experimental values of bandgap energy $E_g$ determined from $R_t$ measurements at various temperatures for p-i-n photodiode are plotted. The data were fitted to Varshni relation (red line in Figure 6d), and the following parameters were obtained: $E_{g,0} = 300 \text{ meV}$, $\alpha = 4.09 \times 10^{-4} \text{ eV} \times \text{K}^{-1}$. The $\beta = 270 \text{ K}$ was assumed as it is most commonly used for InAs/GaSb type-II superlattices \cite{30,31}. The fitting was performed for p-i-n photodiode only. For bariodes, $R_t$ spectra were measured only at 2-3 different temperatures. The values of $E_g$ of absorber region in p-i-n, p-$B_{p,\text{bulk}}$-i-n, and p-$B_{p,\text{SL}}$-i-n photodiodes at 210 K were 263 meV, 271 meV, and 273 meV, respectively. As was mentioned, the difference in $E_g$ results from variation in thickness of InSb-like and GaAs-like interfaces in InAs/GaSb superlattice (Table 1).

The measured spectral current responsivity of p-i-n photodiode increased with reverse bias from $\sim 1.2 \times W^{-1}$ for $U = 0 \text{ V}$ to $\sim 1.65 \times W^{-1}$ for $U = -0.9 \text{ V}$. It also had the highest values of $R_t$, namely $\sim 1.65-1.68 \times W^{-1}$ for wavelengths in the range from 3.55 $\mu$m to 4 $\mu$m. The photodiode with the AlSb barrier had the lowest $R_t$, which was less than 0.04 $\times W^{-1}$ in the entire measurement range. Two reverse biases were considered at 0 V and about $-1 \text{ V}$. The presence of p-n junction in all described heterostructures should enable a passive operation of these photodetectors without bias. This is clear for the p-i-n diode, for which spectral current responsivity is nearly the same with and without bias. In principle, the addition of a barrier for electrons should not negatively impact carrier transport in the heterostructure and thus device operation. This is under the condition that the barrier layer will not introduce parasitic valence band offset between absorption and/or contact regions. Based on the curves shown in Figure 6b,c for $U = 0 \text{ V}$, it is clear that an unwanted barrier for holes in the valence band is present. Both for p-$B_{p,\text{bulk}}$-i-n and p-$B_{p,\text{SL}}$-i-n bariodes, $R_t$ was less than 5 mA $\times W^{-1}$. To overcome the potential barrier, an external bias was necessary.

Spectral current responsivity was measured for various biases from 0 V to 1 V. The values of the voltage result from the limitations of the measurement setup at the time. In the case of the p-i-n photodiode, the responsivity did not change with increasing voltage. For bariodes, both p-$B_{p,\text{bulk}}$-i-n and p-$B_{p,\text{SL}}$-i-n, $R_t$ increased with reverse bias. Despite the improvement, the $R_t$ for the photodetector with the AlSb barrier was very small, <40 mA $\times W^{-1}$. This indicates that the applied external electric field failed to completely overcome the parasitic barrier in the valence band and improve device operation. On the other hand, p-$B_{p,\text{SL}}$-i-n bariode reached maximum $R_t = 1.33 \times W^{-1}$, which corresponds to about 260 times improvement. This proves that AlSb/GaSb superlattice plays a much better role as an electron barrier than the bulk AlSb layer. Nevertheless, further optimization of the AlSb/GaSb structure is necessary to eliminate the parasitic valence band offset and improve device performance.

### 3.4. Specific Detectivity

Finally, the values of specific detectivity $D^*$ based on two semi-empirical approximations ($D^*_{\text{approx.1}}$, $D^*_{\text{approx.2}}$) and measured ($D^*_\text{exp}$) $S_t$ were determined and juxtaposed. The calculations were performed for two bias voltages (0 V and $-1 \text{ V}$), for $\lambda = 4 \mu$m, $T = 210 \text{ K}$, and $f = 10 \text{ kHz}$. In general, the $D^*$ for a bandwidth of 1 Hz can be defined as follows:

$$D^* = \frac{R_t \sqrt{A}}{\sqrt{S_t}},$$

where $R_t$ is the spectral current responsivity, $A$ is the area of the detector, and $S_t$ is the noise power spectral density at a given frequency. The $S_t$ can be further described as:

$$S_t = S_t_{\text{thermal}} + S_{t,\text{Schottky}} + S_{t,\text{lf}} + S_{t,\text{other}} = \frac{4k_B T}{R} + 2qI + \frac{\alpha I^2}{T} + S_{t,\text{other}},$$

where $S_t_{\text{thermal}}$ is thermal noise PSD, $S_{t,\text{Schottky}}$ is shot noise PSD, $S_{t,\text{lf}}$ is low-frequency noise PSD, $S_{t,\text{other}}$ is the sum of other (not included) noise power spectral densities, $k_B$ is Boltzmann’s constant, $T$ is temperature, $R$ is dynamic resistance, $q$ is the elementary
charge, I is current, b is the power coefficient, which is usually assumed equal to 2, α is the noise coefficient, and f is frequency. In our case, the $S_{th}$ can be expressed as in Equation (3), assuming $\alpha = 2$, due to the behavior of the data shown in Figure 5a. To most accurately determine the specific detectivity it is necessary to measure the noise PSD for a specific device. However, when this is not an option, it is possible to use semi-empirical approximations of $S_i$. The first approximation ($S_{i\text{approx}_{-1}}$) includes only thermal and shot noise components. It is calculated using I and R extracted from the measured current-voltage curves of a photodetector. The second approximation ($S_{i\text{approx}_{-2}}$) includes thermal, shot, and low-frequency noise components. On top of I and R, it requires information about the noise coefficient $\alpha$. In this approach, it is sufficient to measure $\alpha$ for a specific bias (not necessarily the voltage for which the detectivity will be determined), for example, $-50 \text{ mV}$ in this paper as shown in Figure 5c. Then, $S_i$ can be estimated using the expression given in Equation (3) for voltage bias, for which the $S_i(\lambda) \sim I^2$. Both approximations can be further simplified, depending on the bias of the photodiode. For unbiased photodetectors, in the absence of photocurrent due to background radiation, the specific detectivity will be limited only by thermal noise. The accuracy of these approximations depends on the interaction between the aforementioned noise components, which is related to the type of the photodetector, the quality of its structure, and processing. Furthermore, their usage may lead to both under- and overestimation of $D^*$, especially under improper assumptions.

The first approximation ($S_{i\text{approx}_{-1}}$) was used to estimate the specific detectivity $D_{i\text{approx}_{-1}}^*$ for unbiased and biased photodiodes in question. For $U = 0 \text{ V}$ the $S_{\text{Schottky}}$ was about four, two, and one order of magnitude smaller than $S_{i\text{thermal}}$ for p-i-n, p-B$_p$-bulk-i-n, and p-B$_p$-SL-i-n, respectively. The non-zero shot noise component originates from the photocurrent generated due to the background radiation. The following voltages, which were used during spectral current responsivity measurements, were used in the calculation of $D^*$ under bias: $-0.9 \text{ V}$ for p-i-n, $-1 \text{ V}$ for p-B$_p$-bulk-i-n, and $-1.12 \text{ V}$ for p-B$_p$-SL-i-n. In this case, the average of power spectral density magnitude of noise measured at 200 K and 225 K, for $-1 \text{ V}$ bias was taken as an approximation for the noise at $T = 210 \text{ K}$. Based on the $S_i(T)$ function, it was determined that the character of changes of $S_i$ in this temperature range allow for the use of such an approach. The results of the calculations under the following assumptions, $T = 210 \text{ K}$, $\lambda = 4 \mu \text{m}$, and $f = 10 \text{ kHz}$, are shown in Table 3. At zero bias, the highest values of $D_{i\text{approx}_{-1}}^*$, $D_{i\text{approx}_{-2}}^*$, and $D_{\text{exp}}^*$ were obtained for p-i-n photodiode and were equal to $1.61 \times 10^{10}$ Jones, $1.61 \times 10^{10}$ Jones, and $1.6 \times 10^{10}$ Jones, respectively. They were about one to three orders of magnitude higher than for both bariodes, for which $D_{i\text{approx}_{-1}}^* = 1.43-1.52 \times 10^{9}$ Jones, $D_{i\text{approx}_{-2}}^* = 7.05 \times 10^{9}-1.52 \times 10^{9}$ Jones, and $D_{\text{exp}}^* = 1.04-1.25 \times 10^{9}$ Jones. The main reason behind lower values was negligible current responsivity of bariodes in photovoltaic operation mode, which canceled out any performance improvement due to the decrease in noise. The p-B$_p$-SL-i-n device outperformed p-i-n by about one order of magnitude in terms of $S_i$, while p-B$_p$-bulk-i-n by about two orders of magnitude. On the other hand, p-i-n achieved between 250 and 280 times larger $R_i$ than other photodetectors.

### Table 3. The values of specific detectivity $(D^*)$ calculated for given biases, at $\lambda = 4 \mu \text{m}$, at $T = 210 \text{ K}$, at $f = 10 \text{ kHz}$.

| Photodiode        | U (V) | $S_{i\text{approx}_{-1}}$ (A$^2$/Hz) | $S_{i\text{approx}_{-2}}$ (A$^2$/Hz) | $S_{i\text{exp}}$ (A$^2$/Hz) | $D_{i\text{approx}_{-1}}^*$ (Jones) | $D_{i\text{approx}_{-2}}^*$ (Jones) | $D_{\text{exp}}^*$ (Jones) |
|-------------------|-------|------------------------------------|------------------------------------|-------------------------------|----------------------------------|----------------------------------|--------------------------|
| p-i-n             | 0     | $3.45 \times 10^{-24}$            | $3.45 \times 10^{-24}$            | $3.35 \times 10^{-24}$       | $1.61 \times 10^{10}$           | $1.61 \times 10^{10}$           | $6.16 \times 10^{9}$         |
|                   | $-0.9$| $6.55 \times 10^{-22}$            | $3.89 \times 10^{-18}$            | $1.45 \times 10^{-19}$       | $1.63 \times 10^{9}$           | $2.11 \times 10^{7}$            | $1.1 \times 10^{8}$         |
| p-B$_p$-bulk-i-n  | 0     | $9.8 \times 10^{-26}$             | $1.11 \times 10^{-25}$            | $3.59 \times 10^{-26}$       | $1.43 \times 10^{8}$           | $1.35 \times 10^{8}$            | $2.4 \times 10^{8}$          |
|                   | $-1$  | $1.37 \times 10^{-24}$            | $1.63 \times 10^{-23}$            | $4.97 \times 10^{-20}$       | $2.44 \times 10^{8}$           | $7.05 \times 10^{7}$            | $1.3 \times 10^{6}$         |
| p-B$_p$-SL-i-n    | 0     | $4.87 \times 10^{-25}$            | $4.88 \times 10^{-25}$            | $7.28 \times 10^{-25}$       | $1.52 \times 10^{8}$           | $1.52 \times 10^{8}$            | $1.25 \times 10^{8}$         |
|                   | $-1.12$| $3.27 \times 10^{-22}$            | $2.27 \times 10^{-18}$            | $9.34 \times 10^{-20}$       | $1.76 \times 10^{9}$           | $2.12 \times 10^{7}$            | $1.04 \times 10^{8}$        |

The values of specific detectivity calculated using the first approximation decreased with a bias for simple photodiode mainly due to larger noise and increased a little for
bариод. Для p-i-n фотодиода, $D^*_{\text{approx}\,_1}$ уменьшилась в одну порядковую величину с большим пределом из-за большей $S_i$ на значение $1.63 \times 10^9$ Джоулей. С той же стороны, $D^*_{\text{approx}\,_1}$ уменьшилась слегка для p-B p SL-i-n до $2.44 \times 10^8$ Джоулей и в результате уменьшения $R_i$ (4.64 раза). На другой стороне, $S_i$ увеличилась до 881 раза, а $R_i$ - до 300 раз для последней ($D^*$ пропорционален $1/\sqrt{S_i}$). Эти значения $S_{i\_\text{approx}\,_2}$ были отображены от одного до четырех порядков величин больше, чем $S_{i\_\text{approx}\,_1}$. Следовательно, значения $D^*_{\text{approx}\,_2}$ уменьшились для всех фотодетекторов, как и $D^*_{\text{approx}\,_1}$, из-за большей величины $S_{i\_\text{approx}\,_2}$. В целом, результаты показали, что этот приближенный подход может быть полезен для определения специфической чувствительности для многих фотодетекторов.

На нулевом уровне, значения $S_{i\_\text{approx}\,_1}$ были близки к экспериментальным вариантам, особенно для p-i-n фотодетектора. Как результат, $D^*$ вел себя в той же форме, что и приближенная схема приближения в таких условиях. На другой стороне, при более высоких уровнях, было отмечено, что $S_{i\_\text{approx}\,_1} \ll S_{i\_\text{exp}}$ и $D^*_{\text{approx}\,_1} \gg D^*_{\text{exp}}$. Это означает, что только джоунсон и снот компоненты не являются достаточными для правильного приближения чувствительности.

Второй приближенный подход дал значения $S_{i\_\text{approx}\,_2}$ для p-i-n и p-B SL-i-n, которые были сравнимы с теми значениями, которые использовали при первом приближении и экспериментальными значениями. Для p-B p SL-i-n значение $S_{i\_\text{approx}\,_2}$ было близко к $S_{i\_\text{approx}\,_1}$, и они были меньше (около 2.75 раза) чем $S_{i\_\text{exp}}$. Эта разница исходит от предположения, что отношение $S_{i(I)} \sim I^2$, которое не применимо для этого бариода при малых токах (рис. 5б). Эти результаты согласуются с тем, что 1/f шум является не-равновесным компонентом, который исчезает при стремлении к нулю. Следовательно, значения $D^*_{\text{approx}\,_2}$ также были схожи с $D^*_{\text{approx}\,_1}$ и $D^*_{\text{exp}}$. При более высоких уровнях, значения $S_{i\_\text{approx}\,_2}$ были оценены при двух или четырех порядках величин для p-i-n и p-B SL-i-n фотодетекторов, соответственно. Это означает, что отношение $S_{i(I)} \sim I^2$ не применимо для большого темного тока. Это можно подтвердить данными на рис. 5б, которые показывают это отклонение для $I > 4 \times 10^{-5}$ А для p-i-n фотодетектора и $I \geq 1 \times 10^{-5}$ А для p-B SL-i-n бариода. На этом уровне, данные для $S_{i(I)}$ для больших токов были приписаны к функции с мощностью без предположения, что $b = 2$ в уравнении (3). Следующими значениями $a$ и $b$ были получены: для p-i-n фотодетектора $a = 5 \times 10^{-12}$, $b = 1.195$; для p-B p SL-i-n бариода $a = 2.5 \times 10^{-12}$, $b = 1.195$. Эти значения были использованы для пересчета $S_i$ с помощью второго приближения. Последующие результаты были получены: для p-i-n $S_{i\_\text{approx}\,_2} = 2.82 \times 10^{-19}$ (A²/Hz); для p-B p SL-i-n $S_{i\_\text{approx}\,_2} = 6.29 \times 10^{-20}$ (A²/Hz). Оба значения都非常接近实验情况。这证明了这种近似方法是正确的，如果$I(0)$与$S_i$的值有关。在另一方面，$S_{i\_\text{approx}\,_2}$ превышала значение $S_{i\_\text{approx}\,_1}$ на три порядка величин. Это означает, что компоненты шума отсутствуют в этом детекторе, кроме теплового, шоттовского, и низкочастотного. Рис. 5а,б показывают, что предположение $b = 2$ справедливо для широкого диапазона токов, что подтверждает, что предложеный второй приближенный метод может быть полезен в определении специфической чувствительности для многих фотодетекторов.

Как было показано, опустить низкочастотный шум при расчете специфической чувствительности является необоснованным без дополнительной информации о величине шума. Тем не менее, это является обычной практикой [32–37], даже если детектор является вольт-втушенным. Этот подход может привести к значительному переоценке чувствительности в определении медленно изменяющихся ИК источников.
4. Conclusions

In this paper, electrical, noise, and optical characteristics of p-i-n, p-B<sub>bulk</sub>-i-n, and p-B<sub>SL</sub>-i-n photodiodes were presented. The main subject was focused on device operation in HOT conditions. Both dark current and noise analysis showed that p-B<sub>bulk</sub>-i-n bariode had the best performance in these areas whereas p-i-n photodiode was the worst and p-B<sub>SL</sub>-i-n placed in-between. Optical characterization showed that at zero bias, p-i-n photodiode had the highest spectral current responsivity, while both bariodes had much lower values of R<sub>I</sub>. With higher bias R<sub>I</sub> for p-i-n was still the highest, however, a larger increase in R<sub>I</sub> was observed for p-B<sub>SL</sub>-i-n. The highest specific detectivity was achieved for p-i-n detector in photovoltaic operation mode. Both p-i-n and p-B<sub>SL</sub>-i-n photodiodes had almost the same values of D* at ~−1 V reverse bias. Obtained results indicate that at zero bias, both proposed electron barriers introduced parasitic valence band offsets, which effectively blocked the generated photocurrent. As such, the design of the bariodes could not be fully utilized. This suggests that with better optimization of electron barrier, a further improvement in the performance of bariode with AlSb/GaSb barrier could be achieved. This would be especially important at smaller bias, at which the gain from better noise performance in bariodes is more pronounced.

The specific detectivity of the photodiodes in question was determined using two semi-empirical approximations and empirical data. A simple method of incorporating the low-frequency noise contribution into the detectivity calculation, without time-consuming measurements, has been proposed. This approach is valid as long as the S<sub>i</sub>(I) ~I<sup>2</sup> relation used in this approximation holds. It was shown that neglecting the low-frequency noise component can lead to a significant overestimation of detectivity.

Author Contributions: Conceptualization, K.C. and A.J.; methodology, K.C., Ł.C., I.S., A.J.; validation, K.C., Ł.C., I.S. and A.J.; formal analysis, K.C., Ł.C.; investigation, K.C., Ł.C., I.S. and A.J.; resources, A.J.; data curation, K.C.; writing—original draft preparation, K.C., Ł.C.; writing—review and editing, K.C., Ł.C., E.P.-P. and A.J.; visualization, K.C.; supervision, A.J.; project administration, A.J.; funding acquisition, A.J. All authors have read and agreed to the published version of the manuscript.

Funding: This work was partially supported by the National Centre for Research and Development (project No. POIR.04.01.04-00-0123/17 and by the Minister of Education and Science of the Republic of Poland within the Regional Initiative of Excellence program for years 2019–2022, project number 027/RID/2018/19, the amount granted 11 999 900 PLN.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing does not apply to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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