Numerical analysis of the detectivity in n⁺–n–p and p⁺–p–n GaInAsSb infrared detectors

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Abstract

In this paper, the detectivity for n⁺–n–p and p⁺–p–n GaInAsSb infrared detectors in both the front- and backside illuminated cases are calculated and analyzed, respectively. The influence of the carrier concentration and width in each layer, as well as the surface recombination velocities at different surfaces of the detectors are considered. It is indicated that high \( R_0A \) does not guarantee the high detectivity because the quantum efficiency combines with the \( R_0A \) to determine the behavior of \( D^* \). On the base of the calculations, it is observed that the different material parameters are required for the optimum \( D^* \) in the different structures with the different directions of the light injected. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Antimonide-based semiconductor materials are receiving increased attention due to their usefulness for photonic devices, particularly emitters and detectors in 2–5 \( \mu m \) region of the spectrum [1,2]. In these materials, GaInAsSb quaternary solid solutions grown lattice matched to GaSb substrates are attractive candidate materials for opto-electronic devices in the near- and mid-infrared wavelength range. These devices can be used for environmental monitoring, optical fiber communication and infrared imaging systems [3–5]. Also GaInAsSb quaternary alloys are of great interest for creation of light sources and photodetectors in 2–5 \( \mu m \) [6–8]. There have been theoretical analysis on n–p homojunction GaInAsSb infrared detectors [9,10]. However, most detectors are fabricated in three-layer structures, in which the surface influence can be effectively reduced by the heavily-doped epitaxial layers [11,12]. Although the zero-bias resistance–area product, \( R_0A \), of GaInAsSb infrared detectors, on the base of material parameters, has been reported [13], the high \( R_0A \) does not automatically guarantee the high detectivity \( D^* \), because of the effect of the quantum efficiency \( \eta \) on \( D^* \), which is another important parameter to decide the properties of detectors. In this paper, the numerical analysis of the quantum efficiency (\( \eta \)) and the detectivity (\( D^* \)) are discussed in both n⁺–n–p and p⁺–p–n GaInAsSb infrared detectors, for both front- and backside illuminated cases. Since \( R_0A \) is independent on the light incident light, whether the detector is front- or backside illuminated cases does not affect \( R_0A \).

2. Theoretical model

The detector structures of p⁺–p–n and n⁺–n–p GaInAsSb are shown in Fig. 1. The heavily-doped
layer surface is defined as the frontside and the other layer surface is the backside. The figure of merit used to characterize the sensitivity of infrared detectors is the detectivity $D^*$, which is related with $R_0 A$ and $\eta$,

$$D^* = \frac{\lambda \eta q (R_0 A)^{1/2}}{hc}$$

$\lambda$ is the incident light wavelength, which is assumed to be 2.48 $\mu$m. $R_0 A$ and its related parameters have been evaluated in a previous paper [13]. The detailed calculation of $\eta$ and $D^*$ for front- and backside illuminated cases in $n^+–n–p$ and $p^+–p–n$ GaInAsSb infrared detectors is given in this paper.

2.1. Quantum efficiency in an $n^+–n–p$ structure

According to Dhar’s report for an $n^+–n–p$ structure [14], at a wavelength $\lambda$ where the absorption coefficient is $\alpha$, the contribution to the internal quantum efficiency $\eta$ of $n^+$, $n$, depletion and $p$ layers for the front- and backside illuminated cases is shown as follows.
2.1.1. Frontside illuminated case

(1) Quantum efficiency in the n+ region:

\[ \eta_n = \frac{\alpha L_{pn}}{\alpha^2 L_{pn}^2 - 1} \left[ A \sinh \left( \frac{t_{n+}}{L_{pn}} \right) + B \cosh \left( \frac{t_{n+}}{L_{pn}} \right) + \alpha L_{pn} e^{-2t_{n+}} \right] \]

\[ B = \gamma_p A - (\gamma_p + \alpha L_{pn}) \]

\[ A = \left( \gamma_p + \alpha L_{pn} \right) \left[ \cosh \left( \frac{t_{n+}}{L_{pn}} \right) - \gamma_{an} \sinh \left( \frac{t_{n+}}{L_{pn}} \right) \right] - (\gamma_{an} + \alpha L_{pn}) e^{-2t_{n+}} \]

\[ + \gamma_p \sinh \left( \frac{t_{n+}}{L_{pn}} \right) \left[ \cosh \left( \frac{t_{n+}}{L_{pn}} \right) + \gamma_{an} \sinh \left( \frac{t_{n+}}{L_{pn}} \right) \right] \]

(2) Quantum efficiency in the n region:

\[ \eta_n = \frac{\alpha L_{pn}}{\alpha^2 L_{pn}^2 - 1} \left[ C \sinh \left( \frac{t_{n+}+t_{n-}}{L_{pn}} \right) - D \cosh \left( \frac{t_{n+}+t_{n-}}{L_{pn}} \right) - \alpha L_{pn} e^{-2(t_{n+}+t_{n-})} \right] \]

\[ C = \frac{D \sinh \left( \frac{t_{n+}+t_{n-}}{L_{pn}} \right) - e^{-2(t_{n+}+t_{n-})}} {\cosh \left( \frac{t_{n+}+t_{n-}}{L_{pn}} \right)} \]

\[ D = e^{-2(t_{n+}+t_{n-})} \left[ \gamma_{an} \cosh \left( \frac{t_{n+}}{L_{pn}} \right) - \sinh \left( \frac{t_{n+}}{L_{pn}} \right) \right] - (\gamma_{an} + \alpha L_{pn}) e^{-2t_{n+}} \cosh \left( \frac{t_{n+}+t_{n-}}{L_{pn}} \right) \]

\[ + \gamma_{an} \sinh \left( \frac{t_{n+}}{L_{pn}} \right) \left[ \cosh \left( \frac{t_{n+}+t_{n-}}{L_{pn}} \right) + \gamma_{an} \sinh \left( \frac{t_{n+}}{L_{pn}} \right) \right] \]

(3) Quantum efficiency in the depletion region:

\[ \eta_{ad} = e^{-2(t_{n+}+t_{n-})} - e^{-2(t_{n+}+t_{n})} \]

(4) Quantum efficiency in the p region:

\[ \eta_p = \frac{\alpha L_{np}}{\alpha^2 L_{np}^2 - 1} e^{-2(t_{n+}+t_{n})} \left( \alpha L_{np} = \frac{(\alpha L_{np} - r_e) e^{-2(d-w_p)} + \left[ r_e \cosh \left( \frac{d-w_p}{L_{np}} \right) + \sinh \left( \frac{d-w_p}{L_{np}} \right) \right]} {r_e \sinh \left( \frac{d-w_p}{L_{np}} \right) + \cosh \left( \frac{d-w_p}{L_{np}} \right)} \right) \]

2.1.2. Backside illuminated case

(1) Quantum efficiency in the p region:

\[ \eta_p = \frac{\alpha L_{np}}{\alpha^2 L_{np}^2 - 1} \left( \frac{\alpha L_{np} + r_e - e^{-2(d-w_p)} \left[ r_e \cosh \left( \frac{d-w_p}{L_{np}} \right) + \sinh \left( \frac{d-w_p}{L_{np}} \right) \right]} {r_e \sinh \left( \frac{d-w_p}{L_{np}} \right) + \cosh \left( \frac{d-w_p}{L_{np}} \right)} - \alpha L_{np} e^{-2(d-w_p)} \right) \]

(2) Quantum efficiency in the depletion region:

\[ \eta_{ad} = e^{-2(d-w_p)} - e^{-2(d+w_n)} \]

(3) Quantum efficiency in the n region:

\[ \eta_n = \frac{\alpha L_{pn}}{\alpha^2 L_{pn}^2 - 1} \left[ A \sinh \left( \frac{d+w_n}{L_{pn}} \right) + B \cosh \left( \frac{d+w_n}{L_{pn}} \right) + \alpha L_{pn} e^{-2(d+w_n)} \right] \]
A = \frac{e^{-\frac{d+e}{t_{mn}}}}{\cosh\left(\frac{d+e}{t_{mn}}\right)} - B\sinh\left(\frac{d+e}{t_{mn}}\right) \cosh\left(\frac{d+e}{t_{pn}}\right)

B = \frac{(\gamma_{mn} - zL_{pn})e^{-\frac{d+e}{t_{pn}}}\cosh\left(\frac{d+e}{t_{pn}}\right) - e^{-\frac{d+e}{t_{pn}}}\left[\sinh\left(\frac{d+e}{t_{pn}}\right) + \gamma_{mn}\cosh\left(\frac{d+e}{t_{pn}}\right)\right]}{\cosh\left(\frac{d+e}{t_{pn}}\right) + \gamma_{mn}\sinh\left(\frac{d+e}{t_{pn}}\right)}

(4) Quantum efficiency in the n⁺ region:

\eta_{n⁺} = \frac{zL_{pn}^2}{2L_{pn}^2 - 1}\left[C\sinh\left(\frac{d+t}{t_{pn}}\right) + D\cosh\left(\frac{d+t}{t_{pn}}\right) + zL_{pn}e^{-\frac{d+e}{t_{pn}}}\right]

C = \frac{e^{-\frac{d+e+t}{t_{pn}}}e^{-\frac{d+e+t}{t_{pn}}}}{\sinh\left(\frac{d+e+t}{t_{pn}}\right) + \gamma_{p}\cosh\left(\frac{d+e+t}{t_{pn}}\right)}

D = \frac{e^{-\frac{d}{t_{pn}}}e^{-\frac{d}{t_{pn}}}}{\gamma_{p}\cosh\left(\frac{d}{t_{pn}}\right) + \sinh\left(\frac{d}{t_{pn}}\right) - \gamma_{mn}\sinh\left(\frac{d}{t_{pn}}\right)}

In the above two groups of equation, the symbols of D, L and r are defined by D = KT\mu/\epsilon, L = (D\epsilon)^{1/2}, r = LS/D.

2.2. Quantum efficiency in a p⁺–p–n structure

The expressions of the quantum efficiency for the front- and backside illuminated cases in a p⁺–p–n structure are the same as those in an n⁻–n–p structure, but the parameters in an n⁺–n–p structure should be exchanged to the corresponding ones in a p⁺–p–n structure, which are shown as following:

n⁺→p⁺; L_{pn}→L_{np}; L_{n}→d; L_{p}→t; \gamma_{p}\cosh\left(\frac{d+e+t}{t_{pn}}\right) - \gamma_{mn}\sinh\left(\frac{d+e+t}{t_{pn}}\right)

The parameters before the arrow are in the n⁺–n–p structure and those after the arrow are in the p⁺–p–n structure.

3. Results and discussion

The calculations have been performed on n⁻–n–p and p⁺–p–n Ga_{0.8}In_{0.2}As_{0.19}Sb_{0.81} infrared detectors operated at 300 K and 2.5 μm wavelength. The results of this model are displayed mostly in the form of plots of \eta and D⁺ versus the carrier concentrations and material widths, for front- and backside illuminated cases. The basic parameters are listed in Table 1 and related parameters have been shown in Ref. [9].

3.1. The detectivity in a p⁺–p–n structure

Fig. 2 shows the quantum efficiency (\eta) and its components as functions of p- and n-side carrier concentrations with other parameters in Table 1 keeping constants, in the backside illuminated case. There are some characters in Fig. 2: (1) \eta is mainly dominated by the p-side component, \eta_p; (2) the quantum efficiency in the depletion region, \eta_{dr}, decreases with increasing the p- and n-side carrier concentrations, due to the decreasing of the width in the depletion region; (3) the p-side quantum efficiency \eta_p increases with increasing the p-side carrier concentration (p) while the n-side quantum efficiency \eta_n decreases with increasing the n-side carrier concentration (n). In addition, in Fig. 2(a) the quantum efficiency in the p⁺-side (\eta_{np}) markedly rises with increasing p and becomes the main contribution to \eta in p > 5 \times 10^{17} \text{ cm}^{-3}, which makes \eta strongly increased in this range. In Fig. 2(b), \eta_n and \eta_{dr}, in n < 10^{17} \text{ cm}^{-3} are large enough to improve \eta, while in n > 10^{17} \text{ cm}^{-3}, \eta is mainly contributed by \eta_p and a little by \eta_{np}. Due to \eta_n and \eta_{dr} decreasing, \eta decreases with increasing n.
Fig. 3 shows the dependence of the detectivity \((D^*)\) in the backside illuminated case on the p-side carrier concentration \((p^+)\), the width \((d_{p^+})\) and the surface recombination velocity \((S_e)\) as parameters, under the condition of other parameters in Table 1 keeping constant. Compared to the report in Ref. [13], except that the shape of \(D^*\) is similar to \(R_0A\) with \(p^+ = 10^{18} \text{ cm}^{-3}\) in Fig. 3(a) and \(S_e = 10^{8} \text{ m/s}\) in Fig. 3(c), \(D^*\) is determined by \(\eta\) and its shape is similar to \(\eta\) in Fig. 2(a). In addition, \(\eta\) and \(R_0A\) have the similar various trend with the influence of the p^+ -side carrier concentration and the surface recombination velocity. That is, increasing \(p^+\) and \(S_e\) will simultaneously reduce \(R_0A\) and \(\eta\), therefore \(D^*\) decreases. The relation between \(D^*\) and \(d_{p^+}\) has a little difference from \(D^*\) related with \(p^+\) and \(S_e\). With the change of \(d_{p^+}\), \(D^*\) appears a intersection at \(p^+\) near to \(10^{17} \text{ cm}^{-3}\). In \(p^+ < 10^{17} \text{ cm}^{-3}\), \(D^*\) is determined by \(R_0A\) and it decreases with increasing \(d_{p^+}\) because of the same variety of \(R_0A\), while in \(p^+ > 10^{17} \text{ cm}^{-3}\), \(D^*\) first increases with increasing \(d_{p^+}\) and then the value of \(D^*\) at \(d_{p^+} = 0.5 \text{ \mu m}\) far exceeds

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<th>Basic parameters</th>
<th>(n^+–n–p) structure</th>
<th>(p^+–p–n) structure</th>
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</thead>
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<tr>
<td>Carrier concentration ((\text{cm}^{-3}))</td>
<td>(5 \times 10^{18})</td>
<td>(10^{18})</td>
</tr>
<tr>
<td>Width ((\text{\mu m}))</td>
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<td>2</td>
</tr>
<tr>
<td>Mobility ((\text{cm}^2/\text{V s}))</td>
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<td>1000</td>
</tr>
<tr>
<td>Surface recombination velocity ((\text{m/s}))</td>
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<td>0</td>
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Table 1
Basic parameters for the \(n^+–n–p\) and \(p^+–p–n\) structures

\[ T = 300 \text{ K}, \ x = 0.8, \ N = 10^{14} \text{ cm}^{-3}, \ \sigma = 10^{-15} \text{ cm}^2 \]

\(n^+–n–p\) structure \(p^+–p–n\) structure

<table>
<thead>
<tr>
<th>(n^+)-region</th>
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Fig. 2. The dependence of \(\eta\) and its components on (a) the p-side carrier concentration \((p)\) and (b) the n-side carrier concentration \((n)\) for the \(p^+–p–n\) structure in the backside illuminated case.
Fig. 3. The dependence of $D^*$ on the p-side carrier concentration ($p$) with the p$^+$-side (a) carrier concentration ($p^+$); (b) width ($d_{p^+}$) and (c) surface recombination velocity ($S_e$) as parameters for the p$^+–p–n$ structure in the backside illuminated case.
those at $d_{pt}>0.5$ μm, which is the same as $\eta$. Fig. 3 indicates that $D^*$ is the result of the joint influence of $R_0A$ and $\eta$. With the variety of the p-side width, $D^*$ is similar to that in Fig. 3(b), in which the intersection appears and moves to a higher $p$. In this case, $D^*$ is also determined by the $R_0A$ and $\eta$.

In Fig. 4 and Fig. 5, the detectivity is depicted as a function of the n-side carrier concentration ($n$), with the n-side width ($t$) and the surface recombination velocity ($S_p$) as parameters, in the back- and frontside illuminated cases respectively. Compared the two figures with each other, the results are completely different.

In the backside illuminated case, the light incident from the n-side surface is first through the n region and then reaches the depletion region, in which $\eta_n$ and $\eta_{dr}$ related with $t$ and $S_p$ will contribute to $\eta$ in $n < 10^{17}$ cm$^{-3}$ as shown in Fig. 2(b). Moreover from the expressions for the quantum efficiency in the backside illuminated case, we know that the n-side width is also one of the major parameters to affect the quantum efficiency in the p and p$^+$ regions. Increasing $t$ will markedly reduce $\eta_n$ and $\eta_{dr}$ and at the same time $\eta$ decreases. On the other hand, $D^*$ is determined by $\eta$. Therefore the parameters in the n region have strong influence on $D^*$ as shown in Fig. 4. With increasing $t$ and $S_p$, $D^*$ remarkably deceases and its peak moves to low $n$ with high $t$ in Fig. 4(a) and to high $n$ with high $S_p$ in Fig. 4(b), respectively.

However, in the frontside illuminated case, $D^*$ and its shape are controlled by $R_0A$ and $\eta$ through $t$ and $S_p$ only has a little influence on $D^*$ in $n < 10^{17}$ cm$^{-3}$. As for the backside illuminated case, $\eta_n$ and $\eta_{dr}$ for the frontside illuminated case improve $\eta$ in $n < 10^{17}$ cm$^{-3}$. But the intensity of the light incident form the p$^+$-side surface is weakened exponentially. When the light through the n region reaches the depletion region, $\eta_n$ and $\eta_{dr}$ are so low that only has a little influence on $\eta$. Meanwhile $\eta_p$ and $\eta_{p'}$, keep constants with the change of $n$ because they are not related with the n-side parameters. These results in this case determine that $\eta$ is almost not influenced by $t$ and $S_p$. But $R_0A$ with the change of $n$ rises up and becomes the main contribution to $D^*$. In the frontside illuminated case, $D^*$ with the change of the p$^+$- and p-side parameters are similar to but slightly higher than the one in the backside illuminated case, because $\eta_{p'}$ and $\eta_p$ that are two main components in $\eta$ are improved by the intensity of the light injected form the p$^+$-side surface and therefore $D^*$ increases.

Fig. 4. The dependence of $D^*$ on the n-side carrier concentration ($n$) with the n-side (a) width ($t$) and (b) surface recombination velocity ($S_p$) as parameters for the p$^+$–p–n structure in the backside illuminated case.
3.2. The detectivity in an $n^+–n–p$ structure

The quantum efficiency and its components in the frontside illuminated case are similar to those in Fig. 2. The light injected from the $n^+$-side surface decides that the quantum efficiency will be obviously influenced by the $n^+$-side parameters.

$D^*$ in the frontside illuminated case is shown in Fig. 6 as a function of the $n$-side carrier concentration ($n$), with the $n^+$-side carrier concentration ($n^+$) and the width ($t_n$) as parameters respectively. In this case, $D^*$ is determined by $\eta$ and its shape is similar to $\eta$ but not to $R_{0A}$. There is an interesting one in Fig. 6: with increasing $n^+$ and $t_n$, the value of $D^*$ has an opposite change, from strongly going up to going down. This is an inevitable result due to the influence of $\eta$ on $D^*$, in which $\eta_{n^+}$ related with $n^+$ and $t_n$ has much contribution. Moreover, the light injected form the $n$-side surface is first through the $n^+$ region so that the $n^+$-side width will affect not only the quantum efficiency in the $n^+$-side but also other region components. Although $R_{0A}$ can not be influenced by the $n^+$-side width [13], $D^*$ is clearly reduced by increasing $t_{n^+}$ in Fig. 6(b). As the report in Ref. [13], $R_{0A}$ in this structure is not affected by the $n^+$-side surface recombination velocity ($S_{n^+}$) because of $l_{n^+} \ll t_{n^+}$. Here we find that $\eta$ is also not related with $S_{n^+}$, and thus $D^*$ will not be changed by $S_{n^+}$.

For the frontside illuminated case, the quantum efficiency in the $n$ region ($\eta_n$) is one of the contribution to $\eta$ in $n < 10^{17}$ cm$^{-3}$. Thus the change of the $n$-side width ($t$) influences the quantum efficiency and therefore affects $D^*$. Fig. 7 shows the dependence of $D^*$ on the $n$-side carrier concentration with $t$ as a parameter, in the frontside illuminated case. $D^*$ and its shape are controlled by $\eta$ and lowering the $n$-side width will improve $D^*$, especially in $n > 10^{18}$ cm$^{-3}$, $D^*$ markedly rises.

As the report for an $n$–$p$ homojunction GaInAsSb infrared detector [10], $D^*$ as a function of $p$-side carrier concentration is controlled by $R_{0A}$ and its shape is similar to $R_{0A}$, but $D^*$ is improved by increasing the $p$-side width, because $\eta$ increases and reaches saturation. This changes the trend of $D^*$ in the $n^+–n–p$ structure also appears.

Fig. 8 shows the dependence of $R_{0A}$, $\eta$ and $D^*$ on the $p$-side width with the $p$-side surface recombination velocity ($S_p$) as a parameter, in the frontside illuminated case. The surface recombination velocity reduces $R_{0A}$, $\eta$ and $D^*$, but $\eta$ is much less sensitive to the $p$-side surface recombination velocity than $R_{0A}$ and $D^*$, which can be found in Fig. 9. The shape of $D^*$ is com-
pletely different from these of $R_0A$ and $\eta$. $R_0A$ with the change of $d$ first goes down at $S_e=0$, and little by little $R_0A$ rises up as $S_e$ increases. The quantum efficiency with the change of $d$ rapidly increases and then saturates. $D^*$ goes through a peak as $d$ increases, further the peak moves to a higher $d$ as the surface recombination increases. $D^*$ can be separated into two parts at the point of the peak: $D^*$ is determined by $\eta$ before the peak and by $R_0A$ after the peak, respectively.

In Fig. 9, $R_0A$ and $D^*$ in the backside illuminated case are plotted as a function of the $n$-side carrier concentration ($n$), with the $n^+$-side carrier concentration ($n^+$) as a parameter, under the condition of other parameters in Table 1 keeping constants. $R_0A$ and $D^*$ have the similar various trends, in which the peaks moves to high $n$ with high $n^+$. In this case, $D^*$ related with other parameters and its shape are also controlled by $R_0A$, which are similar to in Fig. 9(b). Unlike in the frontside illuminated case, $\eta$ in the backside illuminated case is almost controlled by $\eta_0$, while $\eta_n$ is too low to dedicate $\eta$, which induces that the parameters in the $n^+$-side can not influence $\eta$. Moreover, $\eta_n$ and $\eta_{dr}$ only have a little contribution to $\eta$ through $t$ in $n < 10^{17} \text{ cm}^{-3}$. But as shown in Fig. 9, the value of $D^*$ is not optimum in $n < 10^{17} \text{ cm}^{-3}$. Therefore even

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**Fig. 6.** The dependence of $D^*$ on the $n$-side carrier concentration ($n$) with the $n^+$-side (a) carrier concentration ($n^+$) and (b) width ($t_{n^+}$) as parameters for the $n^--n^-p$ structure in the frontside illuminated case.

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**Fig. 7.** The dependence of $D^*$ on the $n$-side carrier concentration ($n$) with the $n$-side width ($t$) as a parameter for the $n^--n^-p$ structure in the frontside illuminated case.
Fig. 8. The dependence of $R_0A$, $\eta$ and $D^*$ on the p-side width ($d$) with the p-side surface recombination velocity ($S_e$) as a parameter for the n$^+$–n–p structure in the frontside illuminated case.
though the n-side width changes $D^*$, the optimum $D^*$ cannot be obtained in that range.

As for the frontside illuminated case, $D^*$ in the backside illuminated case appears a peak with the change of the p-side width ($d$). Fig. 10 shows $D^*$ as a function of the p-side width ($d$), with the n$^+$- and n-side carrier concentrations as parameters, which are corresponding to the peak of $D^*$ in Fig. 9. The value of the optimum $D^*$ are at $d = 10 \, \mu m$ or so. Moreover, high $D^*$ will be obtained with high $n^+$ and $n$.

In order to find the optimum $D^*$ with the material parameters in the different structures with different directions of the light injected, the values of $D^*$ and the corresponding conditions and parameters are shown in Table 2. $D^*$ in the frontside illuminated case is higher than that in the backside illuminated case, either for the n$^+$–n–p structure or for the p$^+$–p–n structure, because $\eta_n$ in the frontside illuminated case is higher than the one in the backside illuminated case, which improves $\eta$ and $D^*$.

Depending on these calculation, we know that $D^*$ is much higher than those in the experimental reports [15,16]. Therefore these results are useful to improve the properties of GaInAsSb infrared detectors through the material growth and device fabrication.

**Fig. 9.** The dependence of $R_oA$ and $D^*$ on the n-side carrier concentration with the n$^+$-side carrier concentration ($n^+$) as a parameter for the n$^+$–n–p structure in the backside illuminated case.

**Fig. 10.** The dependence of $D^*$ on the p-side width ($d$) with the n$^+$- and n-side carrier concentrations as parameters for the n$^+$–n–p structure in the backside illuminated case.
4. Conclusion

In this paper, the numerical analysis of the detectivity in the p+−p−n and n+−n−p structure Ga0.8In0.2As0.81Sb0.19 infrared detectors are performed, based on the material parameters and the direction of the injected light. The behavior of $D^*$ is influenced by the $R_0A$ and the quantum efficiency. The conclusions are drawn as follows.

1. The high $D^*$ is obtained with the light incident from the surface of the heavily-doped layer.
2. The surface recombination velocity in the p-type material is one of the most important parameter to affect $D^*$. The higher surface recombination velocity is, the lower $D^*$ is.
3. The values of parameters in the heavily-doped layer are important to affect $D^*$. In the p+−p−n structure, lowering the parameters in the p-side will effectively improve $D^*$, in which it is not related with the direction of the incident light. However, in the n+−n−p structure, except for the surface recombination velocity of the n-side that does not change $D^*$, $D^*$ in the frontside illuminated case requires the low value of the parameters in the n+−n−p structure, while in the backside illuminated case, the high n−p-side carrier concentration is useful to improve $D^*$ and the n-side width does not affect $D^*$.
4. For the p+−p−n structure, except that $D^*$ in the frontside illuminated case varies with the n-side carrier concentration in a way that is similar to that of $R_0A$, $D^*$ is dominated by the quantum efficiency in other conditions.
5. For the n+−n−p structure, in the frontside illuminated case, $D^*$ with the variety of the n-side carrier concentration is controlled by the quantum efficiency, while $D^*$ with the variety of the p-side carrier concentration is dominated by $R_0A$. However in the backside illuminated case, $D^*$ is controlled by $R_0A$ either with the variety of the p-side carrier concentration or with that of the n-side carrier concentration.
6. The p-side width (d) in the different structures has different influences on $D^*$. For the p+−p−n structure, lowering d in the higher p-side carrier concentration ($p > 10^{17}$ cm$^{-3}$) will improve $D^*$. However for the n+−n−p structure, an optimum d can obtain the best $D^*$.

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References