XBN\textit{n} barrier photodetectors based on InAsSb with high operating temperatures

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Abstract. We demonstrate the suppression of the bulk generation-recombination current in nBn devices based on an InAsSb active layer (AL) and a AlSb\textit{As} barrier layer (BL). This leads to much lower dark currents than in conventional InAsSb photodiodes operating at the same temperature. When the BL is \textit{p}-type, very high doping must be used in the AL ($nB_n^+\textit{p}^-$). This results in a significant shortening of the device cutoff wavelength due to the Moss–Burstein effect. For an \textit{n}-type BL, low AL doping can be used ($nB_n\textit{n}$), yielding a cutoff wavelength of $\sim 4.1 \ \mu\text{m}$ and a dark current close to $\sim 3 \times 10^{-7} \ \text{A/cm}^2$ at 150 K. Such a device with a 4-\textmu{m}-thick AL will exhibit a quantum efficiency (QE) of 70\% and background-limited performance operation up to 160 K. We have made $nB_n\textit{n}$ focal plane array detectors (FPAs) with a $320 \times 255$ format and a 1.3-\textmu{m}-thick AL. These FPAs have a 35\% QE and a noise equivalent temperature difference of 16 mK at 150 K and f/3. The high performance of our $nB_n\textit{n}$ detectors is closely related to the high quality of the molecular beam epitaxy grown InAsSb AL material. On the basis of the temperature dependence of the diffusion limited dark current, we estimate a minority carrier lifetime of $\sim 670$ ns. © 2011 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.3572149]

Subject terms: Shockley-Read-Hall; generation-recombination; diffusion currents; infrared detectors; high operating temperatures; indium arsenide antimonide; XBN; nBn.

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1 Introduction

The maximum operating temperature of a solid state infrared detector is usually determined by its dark current, which increases exponentially with temperature. In standard mid-wave infrared (MWIR) photodiodes operating under conditions of background-limited performance (BLIP), this dark current is almost universally produced by so-called generation-recombination (G–R) centers (also known as Shockley–Read–Hall traps) in the depletion region of the device. A reverse bias applied to the diode activates these G–R centers, which provide energy levels close to the middle of the bandgap. As a result, the amount of thermal energy needed to excite an electron out of the valence band or into the conduction band is approximately halved. Electron-hole pairs are generated that are immediately removed by the conduction band is approximately halved. Electron-hole pairs are generated that are immediately removed by the electric field of the depletion region. The G–R current typically varies with temperature as $\sim T^e^{E_{GR}/k_B T}$ where $E_{GR}$ is roughly equal to half the zero temperature semiconductor bandgap, $s \sim 1.5$ and $k_B$ is Boltzman’s constant.

In 2003, a new type of heterostructure device was proposed, termed here CBN\textsubscript{th}, in which no depletion layer exists in any active narrow-bandgap region.\textsuperscript{1} C and B\subscript{th} stand for contact and \textit{n}-type barrier layers, and \textit{n} for an \textit{n}-type narrow-bandgap photon-absorbing layer. This device is similar in some respects to that proposed by White in 1983, in which two narrow-gap semiconductors (not necessarily the same material) surround a \textit{p}-type wide-bandgap semiconductor and in which a barrier only exists in the conduction band.\textsuperscript{2} A related device was also proposed by Maimon and Wicks in 2006 to which they gave the name nBN, where \textit{n} stands for the doping in identical narrow-gap semiconductors and B stands for an undoped central barrier layer.\textsuperscript{3} In all cases, the \textit{n}– or \textit{p}-type semiconductor on one side of the barrier constitutes a contact layer for biasing the device, while the \textit{n}-type narrow-bandgap semiconductor on the other side of the barrier is a photon-absorbing layer whose thickness should be comparable to the absorption length of light in the device, typically several microns. The most significant difference between the CBN\textsubscript{th} device in Ref. 1, and the other devices, is that the barrier in the CBN\textsubscript{th} device contains \textit{n}-type doping, which is tailored to ensure that the bands in the narrow-bandgap photon-absorbing layer are flat, right up to the barrier, or else contain a narrow accumulation layer immediately next to the barrier. This is achieved, regardless of the level of \textit{n}-type doping in the photon-absorbing layer, which should ideally be kept low to ensure good optical properties. Because there is no depletion, the G–R contribution to the dark current from the photon-absorbing layer is totally suppressed. The dark current is then limited to the diffusion contribution, which varies typically as $\sim T^e^{E_{diff}/k_B T}$, in which $E_{diff}$ is roughly equal to the zero-temperature semiconductor bandgap and $s \sim 3$ (s > 1.5 in the case of a highly doped photon-absorbing layer; see the Appendix).

Because an nBN\textsubscript{th} device with the same \textit{n}-type barrier doping as for a CBN\textsubscript{th} device will work on the same principle, we have chosen the general name XBn\textsubscript{th} to describe all such barrier devices in which the G–R current is suppressed by ensuring that no depletion layer exists in any active narrow bandgap region.\textsuperscript{4} The corresponding devices in which all doping polarities are reversed, and in which a barrier exists...
only in the valence band, are termed \( \text{XB}_{n,p} \), and include both CB\(_{n,p} \) and PB\(_{n,p} \) architectures.

In conventional diodes operating in the MWIR wavelength range, the diffusion current at 77 K is typically several orders of magnitude lower than the G–R current, while at room temperature it is several orders greater. \( T_0 \) is defined as the crossover temperature at which the diffusion and G–R currents are equal. Figure 1 shows a typical Arrhenius plot of the dark current in a conventional diode. The lower portion has a slope that is roughly half that of the upper portion. When multiplied by the Boltzmann constant, the slopes correspond to the activation energies for G–R and diffusion limited behavior, respectively. The dashed line is an extension of the high temperature diffusion limited region to temperatures below \( T_0 \). It represents the behavior of an \( \text{XB}_{n,n} \) or \( \text{XB}_{p,p} \) barrier device in which there is no G–R current. At temperatures below \( T_0 \), an \( \text{XB}_{n,n} \) or \( \text{XB}_{p,p} \) device offers two important advantages. First, it should exhibit a higher signal-to-noise ratio than a conventional diode operating at the same temperature. This is depicted by a vertical arrow in Fig. 1. Second, it will operate at a higher temperature than a conventional diode with the same dark current. This is depicted by a horizontal arrow in Fig. 1. \( \text{XB}_{n,n} \) or \( \text{XB}_{p,p} \) devices also offer advantages for device fabrication. Because the barrier layer is fully depleted, it provides a natural insulator with which to isolate the pixels in a detector. These pixels can be defined very simply by etching through the contact layer up to the barrier. It is often possible to carry out this process using a suitable selective etch. Although the process is frequently described as “passivation” free, it is necessary to apply some sort of surface chemical treatment, such as the deposition of a dielectric film, in order to avoid oxidation of the exposed barrier layer, especially if it contains aluminum (which is often the case).

In this work, we report on the electrical and optical properties of \( n \text{Bn} \) devices, based on \( n \)-type active layer (AL) and contact layer (CL) made from InAsSb, and a barrier layer (BL) made from AlSbAs, all closely lattice matched to a GaSb substrate. We compare devices to both \( n \text{Bn} \) and \( p \text{Bn} \) doping, denoted \( n \text{B}_{n,n} \) and \( n \text{B}_{p,n} \), respectively. InAsSb was chosen as the AL material, because it exhibits a high \( T_0 \) value (~180 K). As discussed in an earlier work,\(^4\) the value of \( T_0 \) increases with the AL bandgap; thus, a material such as InAsSb with a bandgap wavelength close to 4.2 \( \mu \)m represents a good compromise that delivers both a high operating temperature and reasonable MWIR sensitivity.

This paper is organized as follows. In Sec. 2, the main experimental techniques are described. The epilayer design and basic structural properties of the layers grown by molecular beam epitaxy (MBE) are presented in Sec. 3. Measurements of the doping levels in the AL and CL are presented in Sec. 4, based on a capacitance-voltage (C–V) profiling technique. The temperature and voltage dependence of the dark current is presented in Sec. 5, where strong suppression of the G–R current is demonstrated over a wide range of AL doping levels. The dark current is analyzed in terms of contributions proportional to the area and perimeter of the device, respectively. The perimeter contribution is related to lateral diffusion of minority carriers outside the mesa region. The dark current density is used to estimate the minority carrier lifetime and diffusion length, as a function of the AL doping. In Sec. 6, these results are compared to the diffusion length deduced more directly from photocurrent measurements, and the agreement is shown to be quite reasonable. Measurements of the spectral photoresponse are also used, in order to determine the internal quantum efficiency, \( \text{QE}_{\text{int}} \), and cutoff wavelength, \( \lambda_{\text{c}} \), for devices with different AL doping levels. A background-limited performance (BLIP) temperature of ~160 K at \( f/3 \) is estimated for an optimized device. Finally, in Sec. 7, a 320 \( \times \) 256 focal plane array (FPA) detector with a 30-\( \mu \)m pitch is demonstrated. At 150 K, it has a noise-equivalent temperature difference (NETD) of 16 mK at \( f/3 \).

2 Experimental
We have used a wide range of experimental techniques to evaluate our \( n \text{Bn} \) devices and the materials from which they are made. In this section, the main techniques are described.

2.1 X-Ray Diffraction
The composition, strain, and uniformity of the grown InAsSb layers were measured using a Philips double-crystal diffractometer. This instrument has the ability to measure rocking curves over a 5 \( \times \) 5 mm area and to map the whole surface of the 2-in. wafer.

2.2 Secondary Ion Mass Spectroscopy
Secondary ion mass spectroscopy (SIMS) was used to determine the dopant concentration above a base level of ~\( 10^{16} \text{ cm}^{-3} \) in (i) test layers grown to calibrate the doping cells in the MBE machine and (ii) device layers with a high AL doping to correlate with the doping measured by C–V profiling or deduced by fitting to the device photoresponse.

2.3 Electrical Characterization
2.3.1 Capacitance
Small signal AC capacitance versus bias (C–V) profiles were measured at a frequency of 1 MHz directly on XBn devices using a Hewlett-Packard HP4285A precision Inductance-Capacitance-Resistance (LCR) meter. The doping at the edge of the depletion region, whose position changes with bias, can be deduced from the derivative: \( d(1/C^2)/dV \), as described
in Ref. 5. In this way, the doping concentration in the AL and CL can be determined according to the bias direction. The doping in the BL can also be found by modeling the $C-V$ curve near the origin.

### 2.3.2 Dark current

Dark current measurements were made with a Hewlett-Packard 4155C semiconductor parametric analyser. The devices were wire bonded inside a flat pack, which was cooled inside an Advanced Research Systems displex cryostat with a base temperature of $\sim 8$ K. The measurements were performed in guarded mode.6

### 2.4 Optical Characterization

The photoresponse of XBn devices was measured in a test Dewar using a Bruker Equinox 55 Fourier transform infrared (FTIR) spectrometer, which has a resolution of 0.2 cm$^{-1}$. The photoresponse was calibrated with a blackbody extended radiation source using a cold narrow bandpass filter transmitting at wavelengths between 3.48 and 3.52 μm. The sample was mounted inside a Cryo Torr Instruments (CTI) closed-cycle cryostat with the substrate facing the incoming radiation and surrounded by a cold shield with an $f$-number of 3.9.

### 3 Layer Design and Growth

Figure 2 shows the band profiles of two $nBn$ devices based on an InAsSb AL and an AlSbAs BL. In one case, the BL is doped $p$-type whereas in the other it is doped $n$-type. In order to avoid significant depletion, the AL must be doped very high ($n \sim 1 \times 10^{17}$ cm$^{-3}$) when the BL is $p$-type ($nB_p n^+$). For an $n$-type BL on the other hand, there is no fundamental limit on how low the $n$-doping in the AL may be ($nB_n n$).

As shown in Sec. 6, this has important implications on the device cutoff wavelength, because high AL doping leads to a large blueshift of the absorption edge due to band-filling effects.

$nBn$ device layers were grown with both BL doping polarities in two Veeco MBE machines: a Gen III and a Gen 200. The wafers grown in the different machines are identified by the prefixes A and B, respectively. Wafers grown in the Gen III had intentional $n$-type BL doping, whereas those grown in the Gen 200 had $p$-type BL doping. Nominal layer widths were as follows: AL $\sim 1.5 \mu m$, BL $\sim 0.2-0.35 \mu m$, and CL $\sim 0.2 \mu m$. The AL doping was varied over nearly two orders of magnitude, from $4 \times 10^{15}$ to $1.5 \times 10^{17}$ cm$^{-3}$. The actual doping values measured in each sample are listed in Table 1. All the structures were grown closely lattice matched to their 2-in. GaSb substrates, with a typical strain of 500 ppm or less. In one case (B2), the strain was about twice this value. The wafers were very uniform with a typical variation along the wafer radius of $\sim 3$ s of arc in the splitting between the substrate and AL peaks of the x-ray diffraction (XRD) rocking curve.

### 4 Fabrication into Test Devices and Characterization by C–V Profiling

The $nBn$ device layers were processed into square mesa devices with areas varying between $11 \times 11$ and $300 \times 300 \mu m^2$. The CL was etched selectively up to the BL, with metal contacts deposited on the top of the mesa and on a common contact area etched down to the AL. The devices were protected against oxidation by the deposition of a dielectric film onto the exposed BL regions. For devices with areas of $100 \times 100 \mu m^2$ or more, simple contact pads were used, while smaller devices were prepared by flip-chip bonding to a silicon fan-out circuit.

### Table 1 Comparison of the fundamental bandgap energy at 150 K, $E_{G}^{\text{Arrh}}$, deduced from the electrical measurements of the diffusion current activation energy, $\Delta E$, and the fundamental bandgap energy, $E_{G}^{\text{Opt}}$, measured from the spectral response at 150 K, for devices with different $n$-type doping levels, $N_0$, in a 1.5 μm thick AL. The Moss–Burstein energy, $E_{MB}$, is determined from fitting the model described in Sec. 6 to the spectral response. For sample B2, $E_{G}^{\text{Opt}}$ was estimated from the value in B1 adjusted according to XRD strain measurements for the two samples.

<table>
<thead>
<tr>
<th>Device</th>
<th>$E_{G}^{\text{Opt}}$ (meV)</th>
<th>$N_0$ (cm$^{-3}$)</th>
<th>$E_{MB}$ (meV)</th>
<th>$\Delta E$ (meV)</th>
<th>$E_{G}^{\text{Arrh}}$ (meV)</th>
<th>$E_{G}^{\text{Arrh}} - E_{G}^{\text{Opt}}$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>306</td>
<td>$4 \times 10^{16}$</td>
<td>18</td>
<td>1.5</td>
<td>389</td>
<td>335</td>
</tr>
<tr>
<td>A2</td>
<td>302</td>
<td>$4 \times 10^{15}$</td>
<td>–</td>
<td>3</td>
<td>347</td>
<td>311</td>
</tr>
<tr>
<td>A3</td>
<td>301</td>
<td>$4 \times 10^{15}$</td>
<td>–</td>
<td>3</td>
<td>345</td>
<td>309</td>
</tr>
<tr>
<td>B1</td>
<td>302</td>
<td>$1.5 \times 10^{17}$</td>
<td>40</td>
<td>1.5</td>
<td>411</td>
<td>335</td>
</tr>
<tr>
<td>B2</td>
<td>(292)</td>
<td>$1.5 \times 10^{17}$</td>
<td>40</td>
<td>1.5</td>
<td>394</td>
<td>318</td>
</tr>
</tbody>
</table>
The first step in characterizing the fabricated devices was to immerse the larger devices in liquid nitrogen and measure their $C$–$V$ profile. As mentioned above, this gives information about the doping in each of the three device layers. Adjustable probes were used to connect with the contact pads on a device. Typical stray capacitance values were 0.1–0.3 pF. This value was determined by plotting the capacitance versus area and extrapolating back to zero. Figure 3 shows the doping profiles used to terminate the CL. This depth agrees well with the expected BL thickness is due to the contribution of two accumulation layers on each side of the BL [see Fig. 2(b)], where each accumulation layer behaves as an additional sheet of charge $\sim 25–50$ nm wide.

In forward bias, the $C$–$V$ profile rises rapidly at a depth of 0.4 $\mu$m, when the depletion layer meets a thin $n^+$ layer used to terminate the CL. This depth agrees well with the combined thickness of the BL and CL. In reverse bias, the profile shows that the doping in the AL of the device shown is constant and equal to $\sim 4 \times 10^{15}$ cm$^{-3}$.

Profile curves qualitatively similar to those shown in Fig. 3 have also been obtained from $nB_p n^+$ samples with a $p$-type BL. In this case, however, higher doping levels were used in the AL and CL for the reasons given in Sec. 1. The higher doping levels also allowed the $C$–$V$ results for the doping concentration to be compared to those deduced from other methods, namely, the absorption spectrum$^7$ or spectral response (see Sec. 6), and SIMS measurements (on a small part of the same wafer). The agreement between all four methods was very good.

5 Dark Current

In this section, we present results of the dark current measured as a function of temperature for samples with different AL doping levels. We investigate the activation energy of the dark current at a fixed reverse bias (AL positive with respect to CL) for samples with both $n$- and $p$-type BL doping. Typical results are shown in Fig. 4 for samples A3 and B2. Sample A3 ($nB_p n$) had a low-doped AL ($4 \times 10^{15}$ cm$^{-3}$) and an $n$-type BL, while sample B2 ($nB_p n^+$) had a very high-doped AL ($1.5 \times 10^{17}$ cm$^{-3}$) and a $p$-type BL.

Figure 4(a) shows an Arrhenius plot of the dark current for sample A3 at both small ($\sim 0.3$ V) and large ($\sim 1.0$ V) reverse bias values. At a small bias, a single slope is seen in the plot down to less than $\sim 130$ K, while at large bias the dark current diverges from the low bias curve at temperatures below $T_0 \sim 200$ K. The slope of this region is about half that of $T_0$. Qualitatively, the observed behavior can be attributed to the absence of a depletion region in the AL at low bias and a current that is then essentially due to diffusion-limited processes only. When the bias is increased a depletion layer develops in the AL and this gives rise to the more usual two-slope temperature dependence seen in standard diode devices, namely, diffusion-limited behavior at high temperatures and $G$–$R$–limited behavior at low temperatures.

Figure 4(b) shows the corresponding results for sample B2. Even though this sample has a $p$-type BL, the $G$–$R$ current still appears to be suppressed at low bias. Although the $n$-type AL has a depletion layer due to the presence of a $p$–$n$ junction at its boundary with the $p$-type BL, the AL doping level in B2 is sufficiently high to limit the degree of band bending in this layer at low bias to a level rather less than half the AL bandgap. Thus, the most effective $G$–$R$ centers in the AL are not activated. These centers only become activated when more bias is applied and the amount of band bending is increased.

The dark current density for B2 in Fig. 4(b) at 150 K and $−0.1$ V ($\sim 8 \times 10^{−7}$ A/cm$^2$) is comparable to the low-bias dark current densities measured on the other devices to be discussed, A1, A2, A3, and B1, which were all in the low $10^{−7}$ A/cm$^2$ range. In this series of samples, the AL doping increases monotonically, from $4 \times 10^{15}$ to $1.5 \times 10^{17}$ cm$^{-3}$. As will be shown in Sec. 6, the current density in each case is about one order of magnitude lower than the photocurrent density measured at an aperture of $f/3$, and at the same operating bias.

When the doping in the AL is high, the Fermi level lies above the conduction band edge by an amount known as the Moss–Burstein energy ($E_{MB}$). For low AL doping the Fermi-level lies in the semiconductor bandgap. The boundary between the high and low doping regimes is roughly when $E_{MB}(n) \sim k_B T$. Table 1 summarizes the diffusion
Marciniak et al. showed that the zero-temperature extrapolation of the bandgap in lattice-matched InAsSb is about 36 meV above the bandgap energy at 150 K. Thus, the fundamental bandgap at 150 K determined from the electrical measurements is given by $E_G^{\text{f}} = E_G - \Delta_T - E_{MB}$. This value is compared in Table 1 to the value of the fundamental bandgap, $E_G^{\text{opt}} = \frac{hc}{\lambda_G}$, determined at the same temperature from spectral response measurements (discussed in Sec. 6).

It can be seen that the two bandgap values, $E_G^{\text{f}}$ and $E_G^{\text{opt}}$, agree to within $\sim 10\%$. Considering some of the simplifying assumptions applied in the fitting procedure for the electrical results, such as the use of a temperature-independent lifetime, $\tau_p$, this agreement is taken to be satisfactory. Thus, the results for the series A3, A2, A1, B1, and B2, in which the doping level increases monotonically, demonstrate that the dark current is essentially diffusion limited over nearly two orders of magnitude in the AL doping.

We next discuss the dependence of the dark current on mesa dimension. Figure 5 shows the ratio of the low-bias dark current at 150 K and the mesa dimension ($I/L$) plotted against the mesa dimension ($L$) for devices A1 and A2, which have medium ($4 \times 10^{16}$ cm$^{-3}$) and low ($4 \times 10^{15}$ cm$^{-3}$) doping in the AL, respectively. The other low-doped sample A3 behaves like A2, with a finite intercept on the y-axis, whereas samples B1 and B2 with high AL doping ($1.5 \times 10^{17}$ cm$^{-3}$) behave like A1, with zero intercept. In general, the dark current varies as $I = 4\alpha L + \beta L^2$, where $\alpha$ and $\beta$ represent the perimeter and bulk current densities respectively. The intercept of the $I/L$ versus $L$ plot is equal to $4\alpha$ while the slope is equal to $\beta$. Therefore, sample A1 has a negligible perimeter contribution, whereas in A2 the perimeter contribution is quite significant. This can be explained by the fact that both the minority carrier lifetime and the minority carrier mobility increase as the doping in the AL is reduced; thus, the diffusion length also increases (this point will be discussed further).

Hence, in the case of low AL doping, there can be a significant contribution to the dark current from the lateral diffusion of carriers from outside the mesa region. The intercept in Fig. 5(b) is almost independent of bias, as expected for a current that depends on lateral diffusion from outside the mesa area.

The lateral diffusion effect is demonstrated most clearly in Fig. 6, in which a similar sample to A2 was used with a low AL doping of $4 \times 10^{15}$ cm$^{-3}$. However, in this case, much smaller devices were made with dimensions of between 11 and 26 μm, in order to enhance the perimeter contribution relative to the bulk contribution. While the slope in Fig. 6 increases with bias between $-0.1$ and $-0.5$ V, signifying an increasing bulk contribution to the dark current, the intercept does not change significantly. This confirms that the perimeter contribution to the dark current is independent of bias.

In the final part of this section, we consider the minority carrier lifetimes and diffusion lengths that can be deduced from the electrical measurements already presented. As discussed in the Appendix, the bulk contribution to the diffusion current density has a simple dependence on hole lifetime, $\tau_p$, as follows: $J_{\text{diff}} = \frac{p_n\alpha L_0}{\tau_p}$, where $L_0$ is the width of the AL ($L_0 < L$), and the hole concentration is given by $p_n = n_c^2/N_c e^{-E_{MB}/kT}$ when $E_{MB} > k_BT$, and by $p_n = n_c^2/N_c$ when $E_{MB} \ll k_BT$. The value of $p_{n0}$ can be

Fig. 5 Ratio of dark current ($I$) to mesa dimension ($L$) at 150 K plotted against the mesa dimension for nB$n$ samples at their operating bias values: (a) A1 at $-0.2$ V and (b) A2 at $-0.1$ V.

Fig. 6 Ratio of dark current ($I$) to mesa dimension ($L$) at 150 K and bias values of $-0.1$ V (solid circles) and $-0.5$ V (open circles), plotted against the mesa dimension, for very small devices made from an nB$n$ structure similar to A2.
determined using fundamental constants, the heavy hole and electron effective masses (∼0.4m_0 and 0.0223m_0, respectively) and experimental values for the bandgap and Moss–Burstein energy (E_{MB}). The bandgap and Moss–Burstein energies were determined with quite a high precision at 150 K from the spectral response measurements described in Sec. 6, and also from photoabsorption measurements on calibration layers, as discussed in Ref. 7. Because the dark current in our nBn devices at low bias is essentially diffusion limited, this diffusion current can be substituted into the formula given earlier for J_{diff} to obtain a value for the hole-carrier lifetime. In this way, lifetime values of approximately 7, 18, and 670 ns have been deduced for samples B1, A1, and A2, which represent high, medium, and low AL doping, respectively. Using mobility values estimated from Hall measurements,^{11, 12} these lifetime values correspond to bulk hole diffusion lengths of roughly 2, 5, and 50 μm at 150 K. The lifetime values vary approximately inversely with doping, which is behavior that has previously been reported in similar materials, such as InSb.^{13, 14} The small diffusion lengths in B1 and A1 are consistent with the area dependence observed in the dark current for these devices, whereas the larger value in A2 is consistent with the fact that this sample displays a significant perimeter contribution, as described earlier. Note that in the latter case, the diffusion current density at the perimeter is \( J_{diff}^{p} = e \mu_{n} L_{p}^{'}/\tau_{p} \), where \( L_{p}^{'} = \sqrt{D_{p} \tau_{p}} \). The lifetime for lateral diffusion, \( \tau_{p} \), is less than the bulk lifetime, \( \tau_{p} \), when the surface recombination velocity in the etched region surrounding the mesa is finite. Because \( L_{p}^{'}\sim \tau_{p} \gg L_{0}/\tau_{p} \), the diffusion current density at the perimeter could be considerably larger than the bulk value, thereby enhancing the perimeter contribution to the dark current. This contribution was not subtracted from the total diffusion current used to estimate the bulk lifetime, \( \tau_{p} \), for sample A2; thus, the value obtained of 670 ns should be a minimum value. In Sec. 6, the lateral diffusion coefficient in the region surrounding the mesa of sample A2 is deduced directly from photocurrent measurements. The result obtained is reasonably consistent with the bulk diffusion length deduced above from the dark current.

6 Photoresponse

Figure 7 compares the measured spectral photoresponse at 150 K and −0.6 V bias (dotted lines) of 200 × 200 μm² devices made from samples B1 and A2. Note that both samples have the same AL thickness of 1.5 μm and represent high and low doping in the AL, respectively. The cutoff wavelength (at 50% of the initial rise in the response) increases with decreasing AL doping, from 3.65 μm in sample B1 (\( n = 1.5 \times 10^{17} \text{ cm}^{-3} \)), to 3.96 μm in sample A2 (\( n = 4 \times 10^{15} \text{ cm}^{-3} \)). This behavior was discussed in Ref. 7 in terms of the Moss–Burstein effect, which blocks interband optical transitions in the AL with final states in the conduction band that lie below the Fermi energy.

In Fig. 7, the measured spectral response is compared to the spectral response calculated using an optical transfer matrix model, also described in Ref. 7 (solid lines). The main parameters in the model, apart from the layer widths and refractive indices, are the internal quantum efficiency (QE_{int}), the transmission of the substrate (T_{sub}), the doping levels and bandgap energies of the AL and CL, the device temperature, and the resistivity of the metal on top of the mesa, which determines whether the device behaves as a single- or double-pass detector. In all cases, we have found that our devices are essentially single pass devices with a metal reflection coefficient of \( \eta_{met} \sim 0.2 \). The substrate transmission was measured in sample B1 by etching off the epilayers and was found to be T_{sub} = 0.65. (This value only takes the absorption of the substrate material into account and not any reflections on entering or leaving it.) In the model, we have used the same value for sample A2, but expect the error to be in range ±0.05, based on measurements of the substrate transmission in several other wafers. The doping values that we use in the model are those deduced from the capacitance measurements described in Sec. 4. The slope of the initial rise in the spectral response is very sensitive to the AL doping, and good agreement is found between the doping values determined by capacitance measurements and those that are required to achieve a good fit to the measured spectrum. The fitted wavelength corresponding to the fundamental bandgap in lattice-matched InAsSb for the three wafers A1, A2, and
B1 was found to be $\lambda_G = 3.93 \pm 0.02 \mu m$ at 88 K and $\lambda_G = 4.11 \pm 0.02 \mu m$ at 150 K, independent of the doping level.

Inspection of Fig. 7(a) and Fig. 7(b) shows that a very good fit to the measured spectral response can be achieved for both high and low doping. In the case of sample B1 [Fig. 7(a)] $Q_{\text{E int}} = 100\%$ was used. However, for sample A2 [Fig. 7(b)], the fitted value for the internal quantum efficiency was $Q_{\text{E int}} = 180\%$. The reason for this is related to lateral diffusion of photogenerated holes, from the regions surrounding the mesa, as demonstrated by the following measurements of the size dependence of the photocurrent. Note that lateral diffusion of holes from outside the mesa area was also proposed earlier, to explain the size dependence of the dark current in this sample.

Figure 8 shows the response measured at a bias of $0.6 V$ with a narrow-bandpass filter ($\lambda = 3.50 \pm 0.02 \mu m$) for back-illuminated devices made from wafer A2 with mesa sizes between 100 and 300 $\mu m$. The solid line is a fit to the data of the form: $R(L) = R_\infty(L + 2L_p)^2/L^2$, where $L_p$ is the lateral diffusion length, and $R_\infty$ represents the response of an infinitely large device with no edge effects. The fit gives $R_\infty = 0.65 \pm 0.03 A/W$ and $L_p = 25 \pm 3 \mu m$. This should be compared to the photoresonse $R_{200} = 1.01 A/W$ at 3.5 $\mu m$ in Fig. 7(b) for a 200 $\times$ 200 $\mu m^2$ device of sample A2. Multiplying the fitted internal quantum efficiency of 180$\%$ in Fig. 7(b) by the ratio $R_\infty/R_{200}$ gives 116 $\pm$ 6%. This value represents the true internal quantum efficiency when the effect of lateral diffusion is removed. It does not include the error in the substrate transmission or any errors in the literature values of refractive indices, etc., used in the optical transfer matrix model, but is sufficiently accurate to show that the internal quantum efficiency in sample A2 is essentially 100$\%$.

Note that the procedure used here to determine the internal quantum efficiency, which involves a complete fit to the data using a model that includes all optical reflections inside the structure, is more accurate than the simpler procedure used in Ref. 7. The result of high $Q_{\text{E int}}$ in sample A2 is consistent with its large lateral diffusion length determined in the same measurement, which shows that the minority carriers are able to diffuse over distances much larger than the thickness of the AL before recombining. The value of the lateral diffusion length is smaller, however, than the bulk diffusion length of $\sim 50 \mu m$, estimated above from dark current measurements in Sec. 5. This may reflect an error in the estimated mobility value used in the determination of the bulk value but may also indicate that lateral diffusion is reduced compared with diffusion in the bulk due to the effect of a small but finite recombination velocity at the surface. Sample A3, which had the same AL doping as A2, showed size-dependent behavior qualitatively similar to Fig. 8. In contrast, the photoresponse at 150 K for A1, B1, and B2 was almost size independent. This agrees with the much smaller values of their bulk diffusion lengths, discussed earlier in terms of their higher AL doping levels. The bulk value represents an upper limit to the lateral diffusion length.

Figure 9 shows the dependence of the photoresponse at 150 K on bias for the three samples, A1, A2, and B1, plotted relative to its value at $-0.2 V$. It can be seen that between $-0.1$ and $-0.6 V$ the response deviates by $<5\%$ from its value at $-0.2 V$. Because the above estimates of the internal QE were based on data measured at a bias of $-0.6 V$, the absence of a strong bias dependence in Fig. 9 shows that the internal QE is already close to 100$\%$ at a bias of only $-0.1 V$. In the treatment of the dark current temperature dependence in Sec. 5, where it was shown that the G–R contribution to the dark current is strongly suppressed at a low bias, the value of the low bias was chosen in each case, to be where the photoresponse had already reached its maximum value.

7 Focal Plane Arrays

The large values of the internal QE and the minority carrier diffusion length in an $nB_{\text{As}}m$ sample with a low-doped AL, such as A2, combined with the sharp rise in the spectral response at 4.0 $\mu m$ shown in Fig. 7(b), imply that it should be possible to make an XB$_{\text{B}}n$ detector with a 4-$\mu m$-thick low-doped AL ($n \leq 4 \times 10^{15} \text{ cm}^{-3}$), which will exhibit a high external QE for photons in the wavelength range 3–4 $\mu m$, if proper care is taken to thin the substrate and cover it with an antireflection coating. For this configuration,
an external QE of >70% is deduced from the optical transfer matrix model discussed earlier. Such a detector is expected to exhibit a photocurrent of \( \sim 4 \times 10^{-6} \text{ A/cm}^2 \) at \( f/3 \) and a background temperature of 20°C, which is more than one order of magnitude greater than the expected dark current of \( \sim 3 \times 10^{-7} \text{ A/cm}^2 \) at 150 K, discussed in Sec. 5. At 160 K, the dark current will increase to \( 10^{-6} \text{ A/cm}^2 \), which is still only about a quarter of the photocurrent (i.e., BLIP conditions are still achieved at 160 K).

Figure 10 shows an FPA image registered at 150 K in accordance with all of the above requirements, apart from the AL thickness, which, in this device, was 1.3 \( \mu \text{m} \). Because of the thinner AL, the QE in this case was \( \sim 35\% \). Semiconductor Devices’s (SCD’s) Blue Fairy (BF) read-out integrated circuit (ROIC) was used, which has a 320 \( \times \) 256 format and a 30-\( \mu \text{m} \) pitch. The nominal capacitor size was 5 Me. Images from detectors with a thicker AL and a higher QE will be reported shortly. The image in Fig. 10 was made under BLIP conditions at \( f/3 \). The FPA had an NETD of 16 mK with a 20-ms integration time (measured with a blackbody temperature of 35°C). The operability was 98.8%, based on the same criteria for defining defective pixels as in SCD’s standard production line of InSb FPAs. The image was captured after performing a two-point nonuniformity correction procedure.

**8 Summary and Conclusions**

Detectors based on the XBn\(_p\_n\) architecture offer the possibility of very low dark currents and very high operating temperatures. This is achieved by excluding the depletion region of the device from the narrow-bandgap AL and, instead, confining it to a much wider bandgap barrier material (Fig. 2). Under these conditions, the bulk G–R current should be suppressed and the device current becomes essentially diffusion limited. In this work, we have demonstrated the expected suppression of the G–R current in lattice-matched \( nBn \) structures with an InAsSb AL and an AlSbAs BL. When the BL is \( p \)-type, the active layer must be doped very high, in the region of \( n \sim 1.5 \times 10^{17} \text{ cm}^{-3} \), in order to exclude most of the depletion region (\( nB_p\_n^+ \) architecture). This has the detrimental effect of shortening the device cutoff wavelength significantly, due to the Moss–Burstein effect. The preferable BL doping is therefore \( n \)-type (\( nB_n\_p \) architecture), because there is then no lower limit to the AL doping and a cutoff wavelength of \( \sim 41 \mu \text{m} \) is achievable. We have demonstrated a dark current at 150 K close to \( 3 \times 10^{-7} \text{ A/cm}^2 \) in \( nB_n\_p \) devices with a low AL doping of \( 4 \times 10^{15} \text{ cm}^{-3} \). For an AL of thickness 1.3 \( \mu \text{m} \), the measured QE of such a back-illuminated detector was \( \sim 35\% \). It is expected to increase to \( \sim 70\% \) when the AL thickness is increased to 4 \( \mu \text{m} \). In both cases, BLIP operation can be achieved at 150 K and \( f/3 \), and is still estimated to be maintained at 160 K.

The high performance of our \( nB_n\_p \) detectors is due in part to the very high material quality of our MBE grown structures. At 150 K, we have estimated a minority carrier lifetime of \( \sim 670 \text{ ns} \) and a bulk diffusion length of \( \sim 50 \mu \text{m} \) in \( n \)-type InAsSb with a doping of \( n \sim 4 \times 10^{15} \text{ cm}^{-3} \), based on an analysis of the temperature dependence of the diffusion limited dark current. The large value of the bulk diffusion length for low AL doping is also consistent with the variation of the measured photocurrent with device mesa size. It may be noted that a large diffusion length enhances detector performance by suppressing the diffusion limited dark current. It should not lead to enhanced optical cross talk, since the cross talk in a high-performance array detector is determined by the thickness of the photon-absorbing layer. This should be significantly smaller than the diffusion length if high quantum efficiency is to be achieved.

FPA detectors have been made with a 320 \( \times \) 256 format and a 30-\( \mu \text{m} \) pitch, using SCD’s Blue Fairy ROIC. These FPAs have a high operability and an NETD at 150 K of 16 mK, using \( f/3 \) optics and a 20-ms integration time. Excellent image quality has been achieved based on SCD’s standard two-point nonuniformity correction procedure.

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**Appendix: Effect of AL Doping on the Dark Current Temperature Dependence of XBn Devices**

XBn detectors are photovoltaic devices; thus, the diffusion current density in our devices is given by the standard photovoltaic formula: \( J_{\text{diff}} = \frac{qR_{\text{in}}}{L_0} \tanh(L_0/L_p) \), where \( L_0 \) is the width of the AL, \( p_{\text{eq}} \) is the equilibrium hole concentration, and \( L_p \) and \( L_n \) are the hole diffusion length and lifetime, respectively. The hyperbolic tangent term is included because, in all the cases considered in this work, the AL was grown on a buffer layer that was designed to have a negligible surface recombination velocity (SRV). The low SRV is confirmed by the high values obtained for the internal QE in Sec. 6, demonstrating that no carriers are lost.
In samples A1, B1, and B2, the AL doping is high (≥ 3 × 10^{16} \text{cm}^{-3}) and there is a measurable Moss–Burstein energy shift, $E_{MB}$, in the optical absorption edge, with $E_{MB} > k_{B} T$ (see Table and Sec. 6). This means that the Fermi level in the AL lies an energy, $E_{GR}$, above the conduction band edge, and the usual expression for the equilibrium hole concentration deduced from the law of mass action, $n_{p0} = n_{i}^2/N_{D}$, does not hold.

Here, $N_{D}$ is the doping and $n_{i}$ is the intrinsic carrier concentration. Instead, it can easily be shown that the equilibrium hole concentration is given by $n_{p0} = n_{i}^2 e^{-E_{MB}/kT}/N_{C}$, where $N_{C} = 4.8297 \times 10^{22}(m_{e}^*/m_{0})^{3/2} T^{3/2}$ m^{-3}, and $m_{e}^*$ is the conduction band effective mass. In contrast, samples A2 and A3 have low AL doping (4 × 10^{15} \text{cm}^{-3}). For these samples, the Fermi level should lie below the conduction band edge and the law of mass action can be applied. When the appropriate formula for the equilibrium hole concentration is substituted into the above expression for the diffusion current density, it is found that for the case of high doping, $J_{diff} \propto T^{3/2}e^{-E_{MB}/kT}$, whereas for low doping $J_{diff} \propto T^{3}e^{-E_{MB}/kT}$. Here, $E_{GR}(n)$ refers to the zero-temperature extrapolation of the bandgap, including the Moss–Burstein energy, which is a function of the electron concentration, $n$. For the low-doped samples, $E_{GR}$ is the zero-temperature extrapolation of the intrinsic bandgap energy.

In devices that exhibit a bulk G–R current, the standard treatment gives $J_{GR} \propto T^{3}e^{-E_{MB}/kT}$ (see Ref. 16). For G–R limited behavior, the activation energy is thus about half that for diffusion limited behavior. The G–R activation energy is independent of AL doping because the G–R current originates from the depleted part of the AL.

References

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