Progress with Antimonide Based Detectors at SCD

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ABSTRACT
Detectors composed of novel Antimonide Based Compound Semiconductor (ABCS) materials offer some unique advantages. InAs/GaSb type II superlattices (T2SL) offer low dark currents and allow full bandgap tunability from the MWIR to the VLWIR. InAs$_{1-x}$Sb$_x$ alloys ($x$~0.1) also offer low dark currents and can be used to make MWIR devices with a cut-off wavelength close to 4.2$\mu$m. Both can be grown on commercially available GaSb substrates and both can be combined with lattice matched GaAlSbAs barrier layers to make a new type of High Operating Temperature (HOT) detector, known as an XBn detector. In an XBn detector the Generation-Recombination (G-R) contribution to the dark current can be suppressed, giving a lower net dark current, or allowing the same dark current to be reached at a higher temperature than in a conventional photodiode. The ABCS program at SCD began several years ago with the development of an epi-InSb detector whose dark current is about 15 times lower than in standard implanted devices. This detector is now entering production. More recently we have begun developing infrared detectors based both on T2SL and InAsSb alloy materials. Our conventional photodiodes made from T2SL materials with a cut-off wavelength in the region of 4.6$\mu$m exhibit dark currents consistent with a BLIP temperature of ~ 120-130K at f/3. Characterization results of the T2SL materials and diodes are presented. We have also initiated a program to validate the XBn concept and to develop high operating temperature InAsSb XBn detectors. The crystallographic, electrical and optical properties of the XBn materials and devices are discussed. We demonstrate a BLIP temperature of ~ 150K at f/3.

Keywords: Shockley-Read-Hall, Generation-Recombination Current, Diffusion Current, Dark Current, Infrared Detector, High Operating Temperature, Focal Plane Array, Indium Arsenide Antimonide, Type II Superlattice

1. INTRODUCTION

For most of the last decade SCD has been developing new cooled detector designs based on the antimonide family of III-V materials grown by Molecular Beam Epitaxy. The first product to come out of this work is a 480 x 384 epitaxial InSb focal plane array whose dark current is about 15 times lower than in standard ion implanted devices. At 95K this detector currently offers the same radiometric performance as SCD's standard FPAs working at ~80K. The detector is fully qualified and pilot production began in 2008.

We are now working on more advanced devices which incorporate additional features such as tunability of the cut-off wavelength, extremely low dark currents or significantly enhanced operating temperatures. In contrast to InSb, which has a lattice parameter of 6.5Å, our newer devices are all 6.1Å materials and are grown on GaSb substrates. GaSb has a significant advantage in that its bandgap is large enough to be essentially transparent for both MWIR and LWIR devices. Two types of semiconductor system are being evaluated: InAs/GaSb type II superlattices (T2SL) and InAsSb alloys.

Presently, we have achieved T2SL diodes with a cut-off wavelength of ~4.6$\mu$m and with very high BLIP temperatures in excess of 100K. Electrical, optical and radiometric results will be presented in the next section.
Work on InAsSb alloys began in 2008 and has been focused on the development of new InAsSb XBn devices in which G-R currents are suppressed by the incorporation of a wide bandgap AlSbAs barrier in regions of the device where the bands are not flat. The principles of this patented device [1] were presented at last year’s conference where it was shown that operating temperatures as high as 150K may be achievable [2]. Layers with a high crystallographic quality have been grown and processed. Initial structural, optical and electrical measurements are reported in section 3. Our conclusions are summarized in section 4.

2. TYPE II SUPERLATTICE DIODES

(a) Optical and electrical properties

Standard p’/n’/n” diodes have been fabricated from an InAs/GaSb type II superlattice with a bandgap close to 0.28eV at 10K. The superlattice had a total thickness of 3μm and was grown at SCD using a Veeco Gen III MBE machine. Nominal InAs and GaSb widths were 9 and 12 monolayers respectively. The interfaces were biased to be "InSb-like"[3]. Several more superlattice wafers grown in the same way show an extremely high degree of reproducibility and uniformity across the wafer as determined by X-ray, FTIR optical absorption and photoluminescence measurements. The variation in the cut-off wavelength between growths is typically <0.05 μm, and the splitting between the zero-order X-ray satellite of the superlattice and the GaSb (004) substrate peak is typically in the range 0-150 arcsec. Figure 1 shows the temperature dependence of the photoluminescence (PL) peak measured from the superlattice wafer used to make the diodes that are reported below. We have compared the PL peak energy and the position of the absorption edge at 77K in similar wafers and they have been found to agree to better than 0.03μm. Therefore the PL peak position can be taken as a reasonable measure of the bandgap. From figure 1 it can be deduced that between 80 and 180K the bandgap varies almost linearly as $E_G(\text{meV}) = 284 - 0.114T$ where $E_G = 0.114 \text{eV/K}$ and $T$ is the temperature in Kelvin. This formula is used below to interpret the dependence of the diode dark current on temperature.

Diodes, with side dimensions of 30 to 300μm, were made by mesa etching, followed by surface passivation and contact metallisation. Figure 2 shows the logarithm of the current density as a function of inverse temperature between 80 and 210K in a 100 x 100μm diode made from the wafer of figure 1, for reverse bias values of -0.1V and -1V. The temperature dependence at a reverse bias of -0.1V (solid points) shows two essentially straight portions with different slopes joined at the crossover temperature, $T_0\sim 135K$. The slopes of these regions correspond to activation energies of 178 and 252 meV respectively. Diodes from other superlattice wafers with similar bandgaps showed very similar results. This type of behaviour is usually associated with diffusion limited currents at high temperatures (small 1/T) and G-R limited currents at low temperature (large 1/T), with activation energies and hence slopes roughly in the ratio 2:1. The activation energy of the steeper portion is usually slightly greater than the zero temperature band gap, (it is actually the zero temperature extrapolation of the variation of the bandgap with temperature in the relevant temperature range). Behaviour of this type was reported for In$_{0.99}$Al$_{0.01}$Sb diodes in ref. [4] and for InAs diodes in ref. [5]. While the general behaviour of refs. [4] and [5] is reproduced here by our superlattices, the slope values in the superlattice deviate quite significantly from the simple 2:1 relation. Also they do not correspond very closely with the extrapolated zero
temperature bandgap of 284 meV for this superlattice. We have fitted the results to a "two trap model" which may explain these slight discrepancies. The model is discussed below.

(b) Two trap model of dark current

The standard model for G-R and diffusion limited behaviour is based on a continuum of G-R centres close to the midgap energy [6]. It gives a low temperature G-R limited current with an activation energy of half the bandgap, and a high temperature diffusion limited current with an activation energy of the whole bandgap, regardless of the precise ratio of the electron and hole lifetimes or the band-edge densities of states. We define the temperature \( T_0 \) as the temperature below which the current is G-R limited and above which it is diffusion limited. Since the activation energies in the two temperature regions differ significantly, in the present case, from those expected from the standard model, we suggest that this may be indicative of additional G-R centres localized at specific energies, and with short lifetimes, that dominate the continuum contribution.

The current below \( T_0 \), due to a specific G-R centre or trap, \( t_1 \), located at an energy \( \Delta E_v = \Delta E_{v1} - \alpha_v T \) above the valence band edge and \( \Delta E_c = \Delta E_{c1} - \alpha_c T \) below the conduction band edge, may be written [6]:

\[
J_{GR} = \frac{en}{N_e \tau'_p} \left( \frac{\Delta E_v}{kT} + \frac{\Delta E_c}{kT} \right) L_{dep}' \]

with \( \tau'_p = e^{\alpha_v/kT} \tau_p \sim 2 \tau_p \) and \( \tau'_n = e^{\alpha_c/kT} \tau_n \sim 2 \tau_n \), where \( \tau_p, \tau_n \) are the usual hole and electron capture lifetimes (\( \alpha_v \) and \( \alpha_c \) are taken to be equal to \( \alpha / 2 \), when \( e^{\alpha_v/kT} = e^{\alpha_c/kT} \approx 2 \)). Note that \( E_G = \Delta E_v + \Delta E_c \) where \( E_G = E_0 - \alpha_g T \), is the bandgap. \( L_{dep}' \) is the portion of the depletion region that contributes to the G-R current, for which an approximate expression is given below. Since there is a very high density of states at the valence band edge due to the low dispersion of the first superlattice mini-band based on heavy hole states (\( N_v >> N_c \)), then if \( \tau'_p << \tau'_n \), the maximum contribution to the G-R current will occur for values of \( \Delta E_v, \Delta E_c \) significantly above midgap. If this maximum falls fairly close to the specific trap energy, \( t_1 \), then \( t_1 \) will make a large contribution and equation (1) can be used directly to express the G-R current. It gives an apparently steeper slope on the plot of log (current) vs. reciprocal temperature, close to the value of \( \Delta E_v \), which is larger than the half bandgap slope obtained from the standard continuum model.

We next assume that the high temperature, diffusion-like, portion of figure 2 is dominated by G-R centres, \( t_2 \), whose energy separation from the valence band, \( \Delta \alpha \), is \( \sim 235 \) meV (this value is chosen because it turns out to give the best fit) where \( \Delta \alpha \) varies only weakly with temperature (e.g. \( t_2 \) may be a deep acceptor state linked to the valence band of the bulk GaSb). Based on the measured doping level (\( n \sim 2 \times 10^{15} \) cm\(^{-3} \)), the Fermi-level in the photon absorbing layer is estimated to be more than 400 meV below the conduction band at a temperature of \( T_0 \), and even further below at higher temperatures. The bandgap at \( T_0 \) is 270 meV. Therefore this centre lies significantly above the Fermi level at all
temperatures above $T_0$ and so is active. Formally the denominator in the expression for G-R current is equal to 

$$N_c \tau_p e^{-|E_G-E_{V0}|/kT} \times e^{-|E_G-E_{V0}|/kT} \sim N_c \tau_p e^{-|E_G-E_{V0}|/kT}$$

where $\tau_p$ is the lifetime of the G-R centre and the first term in the square brackets is dominant (when the second term is dominant, the usual diffusion limited behaviour is obtained with the activation energy of the full bandgap). The G-R current at temperatures above $T_0$ exhibits an activation energy of $\Delta E_{V0}$ and varies as:

$$J_{GR} = \frac{e}{\tau_p} \bar{L}_p \times N_v e^{-\Delta E_{V0}/kT}$$

where $\bar{L}_p = L_p \left(\tau_p'/\tau_p\right)$ is an effective diffusion length for the holes and $L_p$ is the actual hole diffusion length. Equation (2) contains the diffusion length, because G-R centres, $t_2$, in the flat band region of the active layer contribute to the current at distances of up to one diffusion length from the edge of the depletion layer.

The solid line in figure 2 shows the fitted current $J_{GR} + J_{GR}$ at low bias (-0.1V), using equations (1) and (2), taking the electron and hole effective masses (which appear in the standard expressions for $N_C$ and $N_v$), the activation energy $\Delta E_{V0}$, and the effective diffusion length $\bar{L}_p$ as fitting parameters, and using the formula for $L'_{dep}$ given below. In the fit, the variation of the bandgap with temperature given above (see figure 1) has been taken into account. The separation from the valence band used for the G-R centres, $t_1$, that dominate the low temperature behaviour comes out to be $\Delta E_{V0}=174$ meV which is quite close to the activation energy deduced from the slope of the low temperature portion in figure 2. The reason that the fitted activation energy for the high temperature portion of the fit, $\Delta E_{V0}=235$ meV is significantly less than the value of 252 meV measured directly from the data is that the high temperature portion does not follow a simple exponential dependence but actually varies with temperature as: $\sim T^{3/2} \exp(-\Delta E_{V0}/kT)$. The electron and hole lifetimes deduced from the fit shown in figure 2 are $\tau_p'=17$ nS and $\tau_n'=610$ nS. However these values, especially $\tau_n'$, can vary over quite a wide range depending on the values of the fitting parameters used, in particular the effective masses and the effective hole diffusion length, so they can only be taken as indicative of a short hole lifetime. A very similar fit with almost identical values of the activation energies and lifetimes was obtained for another sample with a bandgap 5 meV smaller than the bandgap of the sample in figure 2.

At low bias, less than 20% of the depletion region contributes to the G-R current. Very roughly speaking, this is the region where the conduction band bending on the $n$-side and the valence band bending on the $p$-side are each greater than half the bandgap. This is based on the assumption that the G-R trap energy is at mid-gap while in the present case it turns out to be about 10% above mid-gap. However the simpler case is sufficiently accurate for purposes of estimation and leads to an approximation for the effective part of the depletion region as:

$$L'_{dep} \sim L_{dep} \left[1 - E_G/4(V_{bi}-V) - \sqrt{E_G/2(V_{bi}-V)}\right]$$

where $V$ is the forward bias, $V_{bi}$ is the built-in voltage of the junction, $E_G$ is the bandgap and $L_{dep}$ is the depletion width. At a reverse bias of -1V, the contributing part of the depletion region increases by a factor of about 6.5. This results in a substantial increase in the G-R contribution to the dark current while the diffusion part remains unaffected because the diffusion length for holes is bias independent. Hence as can be seen from figure 2, $T_0$ increases rapidly with bias. The fit to the high bias results of figure 2 was obtained simply by taking the G-R contribution at low bias and increasing the effective depletion width according to equation (3). The bandgap was taken to be 0.274 eV (the value in figure 1 at 100K, which is in the middle of the G-R limited temperature range) and the built in voltage was 0.25 eV. The fit at high bias has no other adjustable parameters and agrees well with the measurements.

(c) Radiometric analysis

Using the results of figure 2, the potential operating temperature of a detector based on our superlattice diodes can be estimated. The horizontal broken line in the figure is the photocurrent density at $f/3$ for a cut-off wavelength of 4.56μm
(which corresponds to the bandgap of the superlattice at ~120K), a cut-on wavelength of 3 μm, and a quantum efficiency of 70%. This line intercepts the curve of the current measured at a reverse bias of -0.1V at a temperature of 129K, which is the Background Limited Performance (BLIP) temperature for the device. A similar analysis of dark current measurements on diodes made from another superlattice wafer with a cut-off wavelength of 4.65μm yields a BLIP temperature of 120K. Reducing the quantum efficiency to a value of 40% reduces both of the above temperatures by about 3K.

We have made several 320 x 256 element Focal Plane Arrays (FPAs) from the second superlattice wafer. The FPAs were bonded to SCD's Blue Fairy signal processor [7]. The FPAs were characterized in a test Dewar at liquid Argon temperature. They exhibited reasonably good image quality and a residual non-uniformity of <0.07%.

3. InAsSb XBn DEVICES

By introducing a wide bandgap n-type AlGaSb barrier layer between the n- and the p-layers of a standard type II superlattice diode, a so called pBn structure is created, in which all of the band bending is confined to the barrier layer, thereby suppressing the G-R current. A number of variations can be made, known in general as XBn structures, in all of which the G-R current is suppressed. [1,2]. A variation known as an nBn structure, in which both superlattice layers are doped n-type has recently been attempted at the University of New Mexico [8, 9]. However, the polarity of the barrier doping in their structures was not defined and it is not clear whether they succeeded in suppressing the G-R current. The significance of the barrier doping type is discussed further below. In a superlattice device without G-R current, the dark current should follow the straight dotted line in figure 2 at all temperatures, increasing the BLIP temperature and making the BLIP temperature independent of bias.

In this section we describe our efforts to demonstrate the suppression of the G-R current in nBn devices based on InAsSb nearly lattice matched to GaSb, which has a cut-off wavelength close to 4.0μm. The design and expected performance of XBn devices was discussed in detail at last year's conference [2] where it was predicted that operating temperatures as high as 150K may be possible in InAsSb based devices.

Figure 3 shows the absorption and photoluminescence (PL) spectra, both measured at 150K, in an almost perfectly lattice matched InAsSb alloy sample. There is excellent agreement between the PL peak position and the absorption edge. Figure 4 shows the tunability of the cut-off wavelength that we have observed without significant loss of PL intensity, in InAsSb layers up to 3.5μm thick. In figure 4 the observed PL peak position is plotted at temperatures of 8K and 150K vs. the splitting between the zero order substrate and alloy [004] peaks in the X-ray diffraction (XRD) spectra. A lattice mismatch of 500ppm corresponds to a splitting of 126s if the alloy is fully strained or 60s if the alloy is fully relaxed. At 150K the longest wavelength that we observed in a thick layer was 4.13μm which corresponds to an XRD splitting of ~300s.

In figure 5 the dark current is shown as a function of temperature and bias in a 300×300μm mesa device made from an nBn structure which comprised InAsSb layers, 2μm and 0.8μm thick, grown either side of a an undoped AlSbAs barrier layer, of thickness 0.6μm. The InAsSb layers were both n-type with n~8 ×10^{15} cm^{-3}. X-ray measurements showed that the [004] peaks of the two InAsSb layers were split by less than 250s from the GaSb substrate peak. In figure 5, negative bias corresponds to the 2μm thick InAsSb layer acting as the active layer and the 0.8μm thick InAsSb layer acting as the contact layer. The mesa devices were fabricated by wet selective etching of the nBn wafers down to the
AlSbAs barrier. Metal was deposited on the top of the mesas and the devices were wire bonded for the electrical measurements.

In figure 6 the logarithm of the dark current is plotted as function of inverse temperature at a representative bias of -0.4V. Similar behaviour was observed at both smaller and larger bias values. It can be seen that there are two straight portions of the curve with a crossover temperature of $T_0 \approx 180K$. These linear regions have been fitted to a dependence of the form $i \propto kT^n e^{-\Delta / kT}$. In standard diodes, such a dependence with $n=1.5$ corresponds to G-R limited behaviour, and with $n=3$, to diffusion limited behaviour. In the present case, we obtain $\Delta_1 = 280\text{meV}$ for $n=3$ at high temperatures and $\Delta_2 = 160\text{meV}$ for $n=1.5$ at low temperatures ($\Delta_2 = 0.57 \Delta_1$). These activation energies correspond approximately to the bandgap and to half the bandgap, respectively, as expected for diffusion and G-R limited behaviour. Thus, in this device, the behaviour is identical to that in a normal diode, and the G-R current has not been suppressed. This result also shows that the background doping in the undoped barrier layer is $p$-type: at zero bias, electrons transfer from donors in the active and contact layers to acceptors in the barrier layer, resulting in significant depletion of the active layer, even at zero bias. As the negative bias is increased, the depletion width in the active layer increases. In order to remove the G-R current and realize the advantage of the XB$n$ architecture, this depletion must be eliminated. A way to do this is by doping the barrier $n$-type. Then, electrons will transfer from donors in the barrier layer to accumulation layers which form next to the barrier in both the active and contact layers. The active layer will thus no longer be depleted, so the dominant dark current will be that due only to the diffusion of holes.

Figures 7 and 8 respectively show the dark current at 150K and its temperature dependence from 77K to room temperature, at bias values of -0.4V and -1.4V in a 200 × 200µm $nBn$ structure with an $n$-type barrier. The device had
an active layer thickness of 1.3 μm, a barrier thickness of 0.21 μm, and a contact layer thickness of 0.22 μm. All layers in the device are n-type. It can be seen that at the low bias value, the logarithm of the dark current exhibits a linear dependence on reciprocal temperature over a wide temperature range from ~120K up to room temperature. Below 120K, the device resistance becomes very high and the device current falls below that which can be measured reliably. The activation energy obtained from the plot is \( \Delta_1 = 290 \text{meV} \) for \( n = 3 \) which corresponds well with the bandgap of the active layer, as expected for diffusion current. For the higher bias, it can be seen that the G-R current has returned, with two straight portions of the curve and a crossover temperature of \( T_0 \sim 180K \). The activation energy of the higher temperature portion is the same as at low bias, corresponding to diffusion limited behaviour. The lower temperature portion has an activation energy for \( n = 1.5 \) of \( \Delta_2 = 140 \text{meV} = 0.48 \Delta_1 \), which is clearly G-R limited behaviour, activated by approximately half the bandgap energy. The crossover temperature increases with bias as expected, since the G-R contribution increases with bias. The diffusion only behaviour seen down to 120K at a reverse bias of -0.4V, persists up to a reverse bias of about -0.7V, before the G-R contribution sets in. At this bias the electron accumulation layer next to the barrier/active layer interface is removed, so that at higher bias values the active layer starts to be depleted. Note that the current is almost bias independent between -0.2V and -0.7V, as expected for diffusion limited behaviour. At a smaller reverse bias than -0.2V, the electron accumulation layer next to the barrier is so deep that it creates an effective barrier in the valence band which prevents holes from passing easily across the barrier layer and into the contact layer. Hence the current falls sharply at reverse bias values smaller than -0.2V.

In figure 7, a horizontal line has been included corresponding to the photocurrent expected at \( f/3 \), an overall quantum efficiency of 70% and a wavelength range of 3<\( \lambda <4 \)μm. This line intersects the dark current curve at a reverse bias of ~ -0.8V, which is slightly beyond the maximum bias at which the device is still diffusion limited at 150K. By operating at a reverse bias of ~ -0.4V a device with BLIP performance at >150K can be achieved. It is expected that further improvement of the device can be realized by optimization of the active, contact and barrier layer dopings and widths.

4. SUMMARY AND CONCLUSIONS

New results were presented for the temperature dependent dark current in standard diodes made from type II superlattice wafers grown by MBE at SCD with cut-off wavelengths close to 4.6 μm at 120K. A plot of the logarithm of the current vs. reciprocal temperature shows two straight portions with different slopes, corresponding to a low
temperature G-R limited region and a high temperature diffusion-like region. The activation energy of the diffusion-like region appears to be slightly lower than expected from direct measurements of the bandgap vs. temperature. From this difference it was deduced that the high temperature region may be influenced by a trap located a few tens of meV below the conduction band edge. By considering the type II alignment of the bulk band edges in the superlattice, this conclusion is consistent with a trap level located in the GaSb layers about 100 meV above the bulk GaSb valence band edge. A similar trap location of ~80 meV above the AlSb valence band edge was proposed by Fuchs et al. to explain their photoluminescence results in InAs/AlSb quantum wells [10]. The superlattice diodes exhibit BLIP temperatures in the range 120-130K at $f/3$ and -0.1V reverse bias, assuming a quantum efficiency of 70%.

In order to strive for higher operating temperatures we have investigated $nBn$ devices based on an InAsSb alloy, lattice matched to GaSb. Photoluminescence measurements of the InAsSb cut-off wavelength at 150K, as a function of lattice mismatch, showed that perfectly lattice matched material has a wavelength of 4.0µm, and we have obtained good PL signals to wavelengths of at least 4.13µm.

In $nBn$ devices with an $n$-type barrier the depletion region may be confined to the wide bandgap AlSbAs barrier layer and the bands in the InAsSb active layer are then flat or accumulated. Under these conditions the G-R current is suppressed and only the much smaller diffusion limited component of the dark current remains. On the other hand, if the barrier is doped $p$-type, the depletion region extends into the active layer and the G-R current is significant. Mesa devices were fabricated with both $p$-type and $n$-type barriers by selective etching down to the barrier layer. In a device with a $p$-type barrier, the dark current showed behaviour similar to that in standard $p$-$n$ junction diodes with a G-R limited current below a crossover temperature $T_0 \sim$180K, and a diffusion limited current above. However, in a device in which the barrier was doped $n$-type, the G-R current was totally suppressed at reverse bias values up to -0.7V. In this bias range, the depletion region was excluded from the InAsSb active layer and at all temperatures between 295K and 120K the dark current showed thermally activated behaviour, with an activation energy close to the InAsSb bandgap, as expected for a current that is only diffusion limited.

At a reverse bias of -0.4V, our $nBn$ device with an $n$-type barrier exhibited a BLIP temperature at $f/3$ and 70% quantum efficiency of more than 150K. We believe that this type of $nBn$ device can be further optimized and that even higher BLIP temperatures may be possible in the future.

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