HgCdTe Multi-colour Infra-red Detectors

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Abstract

The concept of three-colour detection through a single pixel contact is demonstrated. An intermediate absorber layer is inserted into the centre of the typical back-to-back junction design for two-colour detection. Bias dependent electronic barriers around this intermediate layer control its contribution to the overall signal. One critical parameter for successful operation is low p-doping in these electronic barriers. The sensitivity of device performance to this parameter is demonstrated.

Both FPA's hybridised to read-out chips with switchable inputs, and test diodes for direct assessment, have been produced. This paper concentrates on the test diode assessment, as this provides the greater insight into the operation of the device. It is envisaged that such a device will be used with sequential framing of the different colours to provide quasi-temporal imaging.

Keywords: MCT, multi-colour infrared, FPA, MOVPE, mercury cadmium telluride.

State of current research

HgCdTe (MCT) is often used as the active material for infra-red (IR) detection, due to the wide range over which the band-gap can be tuned. This ternary system also benefits from minimal change in lattice parameter when varying the Cd mole fraction, the x-value in $Hg_{1-x}Cd_xTe$. Owing to these properties, a number of demonstrations of two-colour detection capability using MCT have been reported[1-7]. Two-colour detectors consist of two p-n junctions formed back-to-back. Depending on the number and positioning of the contacts to each pixel, detection can be achieved with spatial and/or temporal coherence. For example, a contact to each of the junctions within the pixel allows temporal coherence in that the two junctions can be read simultaneously. Alternatively, a single contact to each pixel not only allows smaller pitches to be achieved but also offers spatial coherence whereby the colour is selected by the polarity of the applied bias. This route also benefits from a simpler fabrication process.

In a bias-selectable two-colour detector, as in any other such detector, the response is generated by the junction which is in reverse bias. In order that the two junctions are electrically isolated from one another, ie., to prevent transistor action, a high band-gap material is used as a barrier between them. By introducing a third, intermediate band-gap, layer between the junctions, the capability to detect a third colour can be added[8].

The concept of three-colour detection

Bias dependent three-colour detection can be realised by an n-p-n structure consisting intermediate wave (IW) and longer wave (LW) cut-offs. Shown in Figure 1, these three regions are separated by large band-gap, low p-doped, barriers.

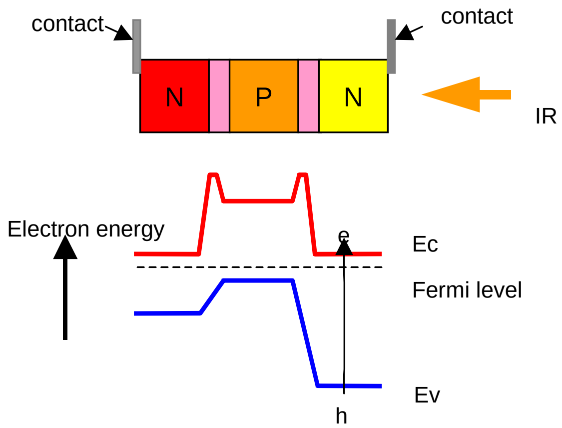

Figure 1: The concept of three-colour detection and a schematic of the energy-band diagram at zero bias.

At low biases, the structure behaves as a two-colour device; the barriers prevent transistor action, but more importantly, they prevent photo-generated carriers in the IW region from contributing to the collected LW or SW currents. As the bias is increased, the majority of the voltage is dropped across the barriers because this side of the junction has the lower doping. The effect of increasing bias is therefore to reduce the height of the barrier. Thus, at a particular bias, the barrier will be reduced sufficiently for photo-generated IW electrons to cross the junction and contribute to the collected current. This is shown in Figure 2, where the case of reverse biasing the SW junction is illustrated.

of three absorbers with, from the direction of incoming radiation, shorter wave (SW),

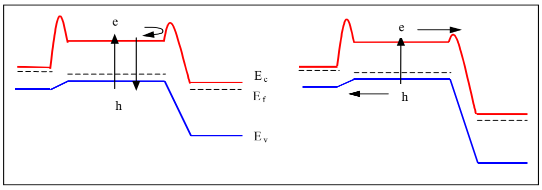

Figure 2: At low negative bias (left) the barrier prevents IW response from contributing to the overall response. Increasing the bias (right) reduces the barrier to enable IW response to be detected.

The bias dependence of the spectral response is shown in Figure 3. When looking at the SW response, increasing the bias has the effect of shifting the cut-off to that of the IW. In the case of the LW junction, the cut-on at low bias is determined by the IW cut-off. At higher bias, when the IW response begins to contribute, the cut-on shifts to the cut-off of the SW absorber. One significant departure from ideality comes from the fact that the IW is unlikely to be thick enough to absorb all of the IW radiation. Some IW radiation will be absorbed in the LW layer resulting in an IW tail in the spectral response which cannot be turned off, even at low biases.

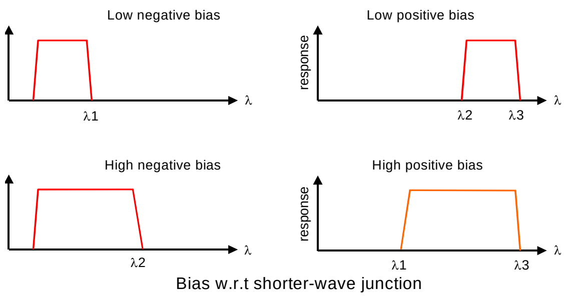

Figure 3: Idealised spectral responses of a three-colour detector at various biases. λ_1, λ_2 and λ_3 refer to the cut-offs of the SW, IW and LW absorbers respectively.

Scope of this paper

Following on from an earlier successful demonstration of three-colour detection[8], further iterations studied the effect of lowering the p-doping in the barrier to increase sensitivity. However, devices often appeared blind in the SW at 77K, ie., there was no response. This could be remedied by increasing either the temperature or the bias. One explanation was that incorrect doping in the barrier itself resulted in the electronic barrier being not in the conduction band as intended but in the valence band. The SW carriers could only overcome this barrier if, for example, given increased energy by a higher measurement temperature.

As was pointed out above, it is critical in the n-p-n structure that the barrier contains only a low p-doping, in order that the applied bias is dropped predominantly across itself. As the success of the structure as a whole hinges on correct doping of the barrier, this has lead to two issues: the proportion of the arsenic p-doping that is activated and the level of intrinsic background n-doping.

In order to evaluate the relevance of these factors to the performance of the barrier, a number of experimental structures were grown and characterised. Two p-undoped-p (P-U-P) structures of differing x-values and one structure with a gradient in x-value were characterised by SIMS and differential Hall to give an indication of arsenic activation as a function of x-value. One undoped homolayer was used to determine background n-doping by the differential Hall method. These results are discussed below. A series of three-colour device structures were grown, which took account of the results obtained from the experimental structures. Their fabrication and characterisation are also discussed.

All growth was performed by MOVPE on GaAs substrates with an orientation off (100) and a CdTe buffer layer to absorb the mismatch in lattice parameter between GaAs and MCT[9]. Iodine and arsenic were used as the n- and p- dopants respectively.

Experimental structure study

P-U-P structures

To assess the activation of arsenic at different x-values, two structures were grown which consisted of an undoped layer sandwiched between p-doped layers (P-U-P structure). One was a mid-wave structure with an x-value around 0.28, the other was short-wave with an x-value around 0.52. It was expected that the arsenic from the p-layers would diffuse into the undoped layer. A SIMS profile, which gives the amount of arsenic present, and Hall measurements, which can give the amount of charge generated by this arsenic, were compared to extract the level of arsenic activation for a given x-value in diffused regions.

The analysis of the mid-wave P-U-P structure is shown in Figure 4. The results from differential Hall measurements are displayed as lines of average across each layer that is removed, rather than a single point for each layer. The final measurement is shown as the value for the remaining thickness of material. The values for carrier concentration throughout the mid-wave structure indicate an activation value of 70%, which is the value commonly assumed when designing structures.

The SIMS / Hall comparison for the short-wave structure is shown in Figure 5. The method used to determine depth within the Hall technique is subject to quite large errors, which can then lead to some uncertainty in the determination of carrier concentration. However, it is quite clear that activation is significantly reduced, to around 30%.

In view of a drastic reduction in arsenic activation at high x-values, there are two methods by which to achieve the required doping. The level of applied doping can be increased to compensate for a 70% loss in active arsenic. However, it is not known what determines the exact value of activation, ie., whether the figure can be affected by factors such as temperature during processing. The second solution to the problem of low activation is to avoid altogether the use of such high x-values. In order to accommodate a lower barrier, this may necessitate the shifting of the whole structure to longer wavelengths.

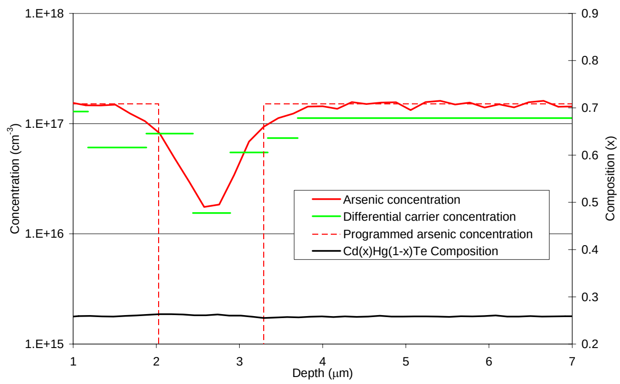

Figure 4: Mid-wave P-U-P structure; SIMS and Differential carrier concentration from Hall measurements.

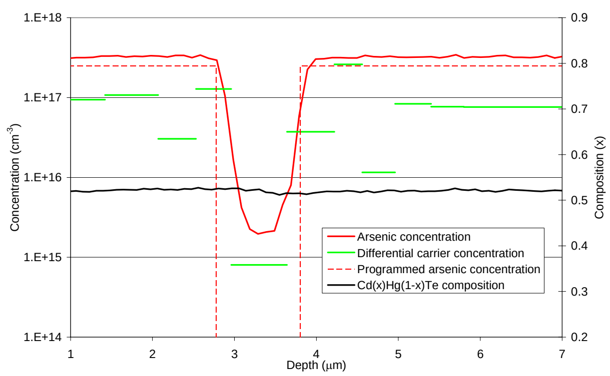

Figure 5: Short-wave P-U-P structure; SIMS and Differential carrier concentration from Hall measurements.

Varying composition structure

As a further investigation into the activation of arsenic at high x-values, a structure was grown with a constant applied doping across a region where the x-value rises steadily from around 0.35 to around 0.7. Again, SIMS analysis is compared to differential Hall measurements and these are shown in Figure 6. In this case, differential resistivity has been plotted, rather than carrier concentration, as it shows more clearly the point at which the falling activation begins to affect the results. An x-value of 0.5 appears quite clearly to be the point at which the activation of the arsenic begins to decrease. The results also indicate that rather than a gradual decrease in activation, there is a sharp drop at x = 0.5. This would strongly suggest that the problem of reduced activation can be alleviated by simply avoiding x-values above 0.5.

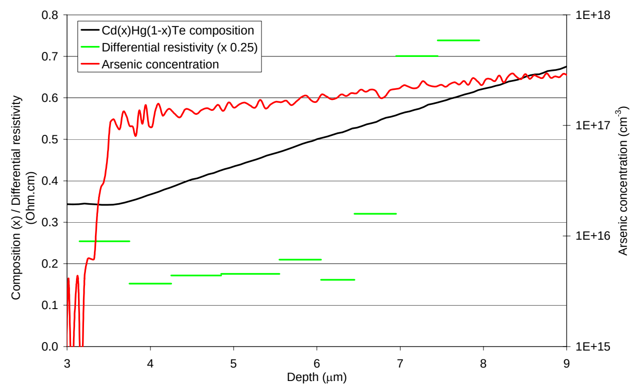

Figure 6: Structure with x-value gradient; SIMS and differential resistivity from Hall measurements.

Undoped homolayer

An undoped homolayer with an x-value of 0.44 was grown and analysed by differential Hall. The measurements indicated an n-type background with an average carrier concentration of around 1.4×10^{15} cm^{-3}. Clearly, to create any p-type layer, its p-doping must exceed this value. Doping the barrier p-type to only a low level would be made more difficult if the background n-doping is variable.

Three-colour devices

Fabrication

Focal plane arrays (FPA) of size 320×256 on a 30 μm pitch were fabricated using mesa etching for pixel isolation. The mesas were etched to a depth of 8 μm, through both junctions, using a mixture of Br and HBr with bubble agitation. The diodes were passivated by electron beam evaporated CdTe followed by annealing to aid inter-diffusion into the MCT. Hybridisation to the CMOS read-out chip (ROIC) was achieved by flip chip bonding using evaporated indium bumps on both components. The pixel input is switchable between an NMOS and PMOS input to allow both diode polarities in alternate frames. After hybridisation the GaAs growth substrate can be removed to reduce thermal stresses. Removal of the growth substrate also eliminates optical cross-talk which would otherwise occur from internal reflections.

In addition to the 320 x 256 arrays, test-arrays are produced for hybridisation to lead-out discs. Variable mesa sizes within these arrays enable bulk and surface leakage currents and noise sources to be isolated. These test arrays are used for I-R-V, and spectral response assessment. This paper concentrates on the results from these test diodes as opposed to the ROIC hybrids, as this gives greater insight into the operation of the detectors.

Details of grown structures

Three separate three-colour structures have been grown, 2vg2026, 2vg2031 and 2vg2054. In view of the results discussed above, only x-values below 0.5 were used. Cut-off wavelengths of the three absorber layers were chosen to be around 4, 5.5 and 9 μm. Low p-doping in the SW barrier is achieved not by directly doping it but by diffusion of arsenic from the IW absorber. The main difference between the three structures is the thickness of the 'spacer' layer, which is the undoped layer between the intermediate layer and the SW barrier which it is doping. It is clearly to be expected that the wider spacer will result in the lowest level of p-doping in the SW barrier. 2vg2054 has the narrowest spacer while 2vg2031 has the widest.

To illustrate the structures grown for this paper, Figure 7 shows the predicted profiles and the measured SIMS profiles of 2vg2054. The lower detection limit for arsenic in SIMS is around 10^{15} cm^{-3}, which is why the measurement appears to suggest a high arsenic background. A lower detection limit is also visible for iodine. Apart from the width of the spacer, the other two structures are as 2vg2054.

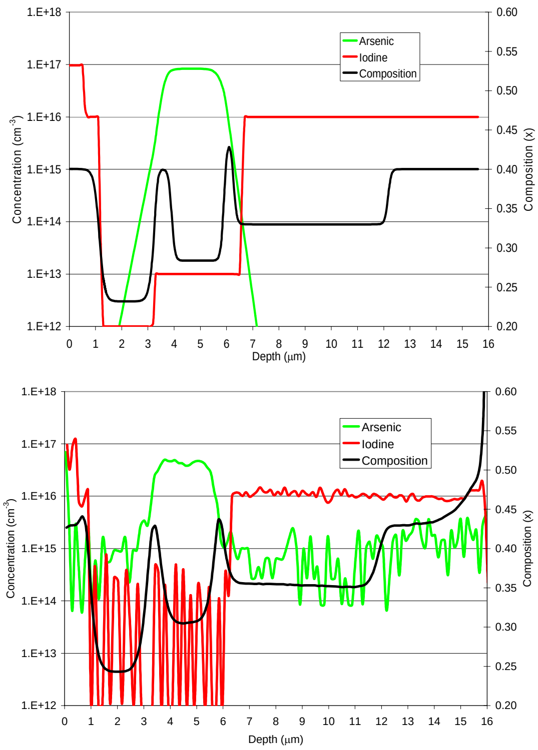

Figure 7: Predicted (left) and measured SIMS (right) profiles of 2vg2054.

R-V characterisation

I-R-V assessment of diodes can be performed at three temperatures below room temperature: 77K, 145K and 192K. The system including a source-measure unit and a switch box allows 64 diodes to be tested sequentially. The diodes view a room temperature scene in F/1.5. The R-V curves of the 60 x 60 µm diodes from 2vg2054 are shown in Figure 8. The $\sim 10^8 \Omega$ maximum resistance shown is the limit of the measurement equipment, and as such is a lower limit for the diodes. The SW junction appears hard in reverse bias (negative bias in the figures) and does not show signs of breakdown up to at least -1.6V. The LW diode is much softer, with a lower maximum and clear breakdown. The R-V curves from the other structures are very similar and are not presented.

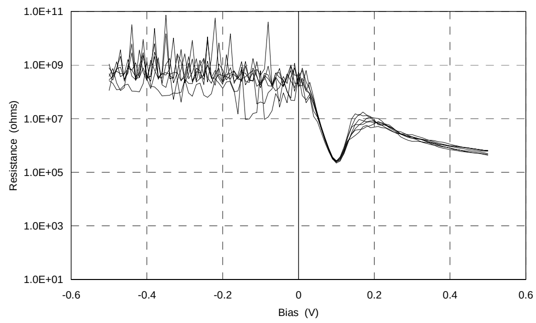

Figure 8: R-V curves of 60 x 60 µm test diodes from 2vg2054.

Spectral Response

The spectral response as a function of bias is measured using an FTIR instrument with a transimpedance amplifier. Apart from a coated Ge window, no filters were used and the reference spectrum was taken before starting the device measurements.

As an example of what is obtained by the three structures, Figure 9 shows the 77 K spectral response of 2vg2054 at various biases. Two-colour performance is demonstrated, as either the LW or the SW response can be removed by choosing the polarity of the bias. The first point to note is the presence of SW response at 77 K, which means that the issue of excessive n-doping in the barrier has been resolved. There is also IW and SW response present when the LW junction is reverse-biased, due to either incomplete absorption of these wavelengths in their respective absorbers or photon-recycling[1]. However, the structure was designed specifically to investigate the performance of the SW junction and as such the measurements of interest, and all results discussed from this point, are those where the SW junction is reverse-biased.

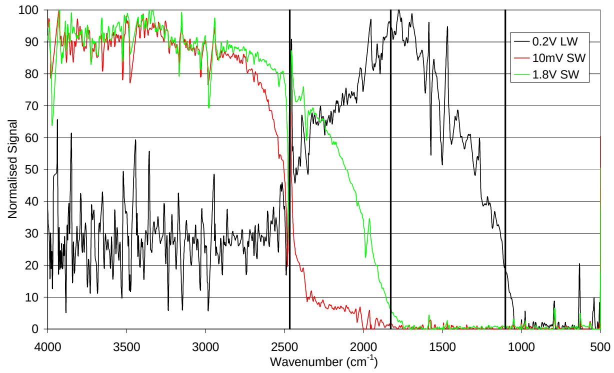

Figure 9: Bias dependent spectral response of 2vg2054. LW and SW refer to the junction which is in reverse bias. The vertical lines show the predicted cut-offs of the three absorbers.

It can be seen in the figure that the SW response is largely independent of bias, whereas the IW response can be adjusted by changing the bias. This trend is repeated in the other two structures. A rudimentary figure of merit (FOM) can be defined to assess the responsiveness of the IW to bias when the SW junction is reverse-biased. It is defined as the proportional increase in the IW signal between the biases of 0.4V and 1.6V. The wavelength is chosen to be the wavenumber equidistant between the SW and IW cut-offs for each structure. The values of the FOM for the three structures are as follows:

2vg2031:	1.72 (wide spacer)
2vg2026:	2.46 (medium spacer)
2vg2054:	2.92 (narrow spacer)

The increasing value for the FOM with narrower spacer is predominantly due to falling IW signal at low bias, rather than increasing IW signal at high bias. This indicates that narrowing the spacer has increased the effectiveness of the barrier to the IW electrons.

It can be assumed in broad terms that, for the structure to operate correctly, the p-doping in the barrier must fall between two limits: it must be high enough to overcome activation and/or background n-doping problems such that the electronic barrier sits in the conduction band; and it must be low enough for the depletion region to extend across the whole barrier at higher biases. The immediate issue which arises is that the barrier is doped by diffusion from the IW absorber. Therefore the doping level will vary across the barrier itself and be higher on the IW side. A highly non-ideal situation is illustrated in Figure 10, where arbitrary minimum and maximum limits are shown to be exceeded by the outer regions of the barrier.

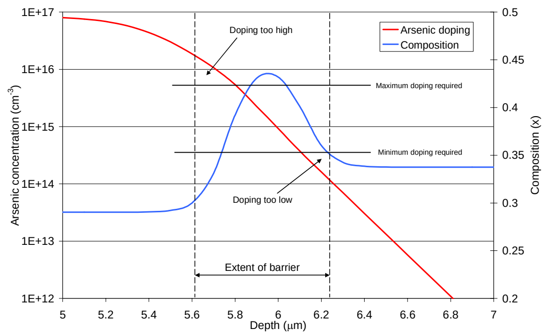

Figure 10: In this example, incorporating arsenic by diffusion can lead to excessive and insufficient doping in the parts of the barrier closest to and furthest from the dopant source respectively.

The narrower spacer raises the doping level across the whole barrier and therefore increases the proportion of the barrier with at least the minimum level of doping. This explains the reduced IW signal at low bias. However, at the same time, the proportion of the barrier with too much doping may also be increasing. If a part of the barrier has too much p-doping then it will be rendered less sensitive to applied bias. This is seen in Figure 9, where the biases required to turn the barrier 'on' and 'off' are almost 2V apart. Increasing the proportion of the barrier with excessive doping will only widen the bias range needed to control the IW signal.

Therefore, the solution to the problem of excessive doping in the barrier cannot be solved by simply reducing the applied doping level: the wider spacer has already been seen to produce a less effective IW barrier. A future structure is planned which will include a doping 'shoulder' in the barrier. The intention here is to maintain the doping level in the SW half of the barrier (right-hand half in Figure 10), whilst reducing the level in the IW half.

Conclusion

The principle of three-colour detection using a two terminal device has been demonstrated. Array results have been produced which display three separate cut-off values, selectable by the polarity and magnitude of the applied bias. This is achieved by introducing an intermediate absorber layer into a conventional two-colour device, where the cut-off is given by whichever junction is in reverse bias. This intermediate layer is flanked by barriers which act to prevent intermediate response at low biases, but which are lowered at higher biases to allow intermediate response to be detected.

The critical factor in the performance of the detector is the doping level in the short-wave barrier and its subsequent response to applied bias. The barrier must be p-doped to a low level, a parameter which can be affected by both the composition of the barrier and the background doping achieved during growth. The sensitivity of the device performance to this parameter has been demonstrated.

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