Inherent and additional limitations of HgCdTe heterojunction photodiodes

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The performance of P-on-n double-layer heterojunction (DLHJ) HgCdTe photodiodes at temperature of 77 K is presented. The effect of inherent and excess current mechanisms on quantum efficiency and $R_Q A$ product is analysed. The diodes with good $R_Q A$ operability, high quantum efficiency, and low 1/f noise have been demonstrated at cutoff wavelengths up to 14 μm. The experimental results show that proper surface passivation and low series/contact resistance are major issues relating to fabrication of HgCdTe detectors with high performance.

Keywords: HgCdTe photodiodes, heterostructures, quantum efficiency, $R_Q A$ product.

1. Introduction

HgCdTe is well established as a variable gap semiconductor for fabrication of high-sensitivity detectors over a wide infrared (IR) spectral range. The specific advantages of HgCdTe are the direct energy gap, ability to obtain both low and high carrier concentrations, high mobility of electrons and low dielectric constant. The extremely small change of lattice constant with composition makes it possible to grow high quality layered and graded gap structures. HgCdTe can be used for detectors operated at various modes, and can be optimised for operation at the extremely wide range of the IR spectrum (1–30 μm) and at temperatures ranging from that of liquid helium to room temperature. The back-illuminated mesa P-on-n heterojunction has become the most widely applicable for use in hybrid long wavelength IR (LWIR) focal plane arrays since the larger gap reduces the dark current contribution from the p-type material [1,2]. Although a number of growth techniques are used for device development, most detector materials continue to be grown by liquid phase epitaxy (LPE) because of combination of large wafer area with consistently high material quality [3].

Here we will review the recent trends in the field of Hg$_{1-x}$Cd$_x$Te photodiodes with major emphasis on means to improve the performance of the heterostructure devices operated with cryogenic cooling. More attention is paid to P-n LWIR double layer heterojunction photodiodes (DLHJ) and phenomena connected with the effect of a heterojunction barrier on the quantum efficiency and dynamic resistance of the photodiode. We discuss the primary factors (junction location, compositional gradient, junction architecture) contributing to maximise the detectivity. Finally, the experimental data is presented.

2. Double layer heterojunction photodiodes

High-performance photodiodes can be obtained by successive growth of doped layers using LPE. Doping during growth enables fabrication of multilayer structures. Recently, these techniques are most often used for preparing the backside-illuminated p-on-n HgCdTe heterojunction photodiodes on IR-transparent CdZnTe substrates [4–7]. A schematic of mesa DLHJ P-on-n HgCdTe photodiodes is illustrated in Fig. 1. One important advantage of the p-on-n device is that the n-type Hg$_{1-x}$Cd$_x$Te carrier concentration is easy to control in the $10^{13}$ cm$^{-3}$ range using extrinsic doping – usually indium (for the n-on-p device, the p-type carrier concentration at such low level is difficult to achieve). Compositional control is critical for VLWIR HgCdTe detectors. For photodiodes with the cutoff wavelengths longer than about 14 μm at temperature of 77 K, the composition x of the base layer is 0.20. The absorber layer is grown by LPE from Te-rich solution. The wider band-gap p-type capping Hg$_{1-x}$Cd$_x$Te layer (y = x + Δx) is grown by the vertical-dipper LPE from Hg-rich solution.

Fig. 1. A schematic of mesa DLHJ HgCdTe photodiode.

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and is 0.5 to 1 μm thick. Compositional gradient x between the n-type base and p-type cap layers is within the range of 0.02–0.08. Controlling x requires very good control of x in both layers, in terms of accuracy in producing the given x value and in spatial uniformity. The concentration of As dopant in p-type cap layer is at the level of about 10^{18} cm^{-3}. After growth, the crystals were additionally annealed in saturated mercury vapour at 260°C for further reduction of native point defects by annihilation of Hg vacancies that were previously encountered, revealing the net doping due to n-type background impurity. For fabrication of large diodes (400x400 μm), Au is used as the ohmic contact for p-type side and In for the n-type side. In some cases, the ion milling was applied before In deposition. After p-side contact metallisation, the standard photolithographic techniques are used to delineate the photodiodes by a mesa etch through the thin cap layer. In the work reported here, all diodes have no surface passivation layer applied.

The photodiode performance was established by measurements of the current-voltage (I-V) characteristics, capacity-voltage (C-V) characteristics, and spectral responsivity at 77 K. The photodiodes were mounted in a liquid nitrogen cooled cryostat system and temperature dependencies of the characteristics were measured in the temperature range between 77 K and 300 K. The relative photoresponse spectra were measured with an FTIR spectrometer. The absolute photoresponse was determined using a calibrated blackbody test set, which is composed of a blackbody source, preamplifier, lock-in amplifier, and a chopper system. The two essential detector performance parameters on which detectivity depends: R_pA – the zero bias impedance-area product, and quantum efficiency were described and analysed.

3. Inherent junction current mechanisms for DLHJ photodiodes

The junction current mechanisms in HgCdTe photodiodes can be classified into two groups: fundamental mechanisms, which depend only on the inherent HgCdTe material properties and device design, and excess mechanisms, which require a surface or bulk defects [3]. Among these mechanisms, the most fundamental is diffusion current due to Auger or radiative recombination. Let us consider the P-on-n heterojunction photodiode in the back-illuminated configuration (Fig. 1). To achieve high quantum efficiency, the n-type absorber layer thickness is designed to be large enough to provide high absorption. The thickness of about 15 μm is optimal for a 14-μm cutoff detectors operated at 77 K. The band gap of the p-layer is made sufficiently large, so that diffusion current from this layer is negligible compared to that from the n-type absorber layer. In VLWIR HgCdTe heterojunctions, there is a tendency to form a barrier in the valence band that prevents migration of photoinduced charge to the junction depletion region. Barrier formation is related to the alloy composition step across the heterojunction – Δx, and the p-n junction location with respect to the graded region. A band profile for the P-on-n photodiode for different Δx is shown in Fig. 2(a). In all cases, the p-n junction is located in the 0.5-μm-wide graded region – near the wide-gap area. The influence of composition gradient on photodiode parameters has been estimated in Fig. 2(b). The minimum Δx of about 0.03 is needed to suppress diffusion current from the P-type cap layer. However, the large Δx does not improve the R_pA but decreases the quantum efficiency.

The position of p-n junction, relative to the compositionally graded region at the cap-base interface, is also an important inherent effect. It is critical for high quantum efficiency of the P-on-n LPE heterojunction. In our earlier paper [8], we apply a simple numerical model that shows the connection between photodiode parameters, base region geometry, and position of a heterojunction barrier. For the best photodiode performance a P-n junction should be located in the graded-gap region near its centre. In such case a barrier in the valence band does not arise.

4. Properties of VLWIR HgCdTe photodiodes – excess mechanism

One of the important issues that plays a major role in practical realisation of LPE grown VLWIR HgCdTe photodiodes exhibiting high performance is reduction of excess junction current mechanisms. Figure 3(a) displays the rep-
representative I–V and \( R_{O}A \) curves versus bias voltage for a 14 \( \mu \)m cutoff detector operating at 77 K. Figure 3(b) compares the measured I–V curves of the device to ideal diffusion model. Theory fits the data very well from -20 mV to +40 mV. At larger forward bias, the data can be fitted by adding a series resistance of 60 \( \Omega \). The reverse bias characteristics beyond -50 mV are dominated by a shunt current. The shunt resistance of about 1300 \( \Omega \) is connected with surface effects. The \( R_{O}A \) data (after subtracting the shunt impedance) for this device is plotted versus reciprocal temperature in Fig. 4, along with the \( R_{O}A \) calculated for one-dimensional diffusion current for an n-type absorber layer with only radiative and Auger 1 recombination. Detectors have theoretical diffusion limited performance down to 100 K but are limited by the surface or tunnelling currents even near zero bias for temperatures 90 K and lower. For very long cutoff wavelengths, interband tunnelling currents could cause a serious problem forcing development of doping techniques to reproducibly grow/anneal base layers to yield \( N_{D}/N_{A} \) less than \( 10^{15} \) cm\(^{-3}\). Tunnelling is generally seen for junctions under reverse bias. The measured I–V characteristics at high reverse bias voltage, as shown in Fig. 5, has not been determined by tunnelling current. The surface-related current mechanisms, termed surface leakage, with ohmic and breakdownlike behaviour, are probably dominating the reverse current at low temperatures. Thus, the correct passivation is still a major problem.

The devices had classical spectral response curves, as shown in Fig. 6. Quantum efficiencies were bias dependent. A consequence of having the series and contact resistance comparable to the junction impedance is a decrease in the injection efficiency leading to severely reduced quantum efficiency. At forward bias the \( \eta \)-value decreases to zero and then the photocurrent changes its sign and suddenly increases due to domination of photodetection effect over the photovoltaic signal (gray line for +60 mV). It can be
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Fig. 7. Quantum efficiency as a function of bias voltage for photodiode E18 (T = 77 K).

clearly seen in Fig. 7 where quantum efficiency is plotted versus bias voltage. At reverse bias voltage quantum efficiency was about 70% and nearly independent of bias. The decrease of η-value at the forward bias is connected with valance band barrier formation. Schematic representation of the conduction and valence band energies with respect to the Fermi level vs. position for two different voltage biases are shown in Fig. 8. The plots illustrate the dramatic difference between the case with no barrier, and the case with a barrier where the carriers “pile up” in the base and η-value decreases abruptly due to the retarding field in the barrier region. This effect is more significant where contact resis-

tance is comparable to junction impedance. Figure 9 shows the dark and illuminated I-V and R_d-V curves for the device with the dynamic impedance dominated by series/contact resistance at zero bias. Therefore, the quantum efficiency at zero bias is almost zero, and the detector needs to be operated in reverse bias, where the junction impedance is significantly higher (8 times). The optimum bias to operate this detector is 50 mV reverse bias, where the detector dynamic impedance R_dA = 2.4 Ω cm^2 and quantum efficiency η = 70% are maximum.

Stronger background illumination caused a significant decrease in quantum efficiency and dynamic resistance, es-

Fig. 8. Schematic representation of the conduction and valence band energies with respect to the Fermi level vs. position for two different voltage biases.

Fig. 9. The dark and illuminated I-V (a) and R_d-V (b) characteristics for photodiode E13b (A = 0.2 mm^2, T = 77 K).

pecially in the presence of the valence band barrier. Figure 10 presents the inverse of the zero-bias resistance as a function of the measured photocurrent I_b, with a fit to a parameterised version of the illumination-dependent shunt resistance [9]

\[
\frac{1}{R_0} = \frac{I_b}{IR_b} + \frac{1}{R_d(0)}
\]

Clearly, the fit is very good, using a value for the barrier-induced IR product IR_b of 50 mV. Smaller values of IR_b correspond to larger decreases in the total diode resistance for a given illumination level. Figure 10 shows that the “dark” resistance R_d(0), estimated to be about 320 Ω is comparable with the real dark resistance for zero-back-

Fig. 10. The inverse of the zero-bias resistance as a function of measured photocurrent (T = 77 K).
ground (equal to 330 Ω). The effect of the barrier on the background-induced shunt resistance is much stronger than the effect on the quantum efficiency.

Finally, the current noise was measured as a function of frequency to confirm that the illumination-dependent shunt resistance does not generate additional noise itself. Figure 11 illustrates the current noise spectra for f/8 cold shield at 77 K taken at biases 7, 0, and −40 mV. The noise is dominated by the zero-bias background shot noise and by detector diffusion current terms. The noise in Fig. 11 is higher at forward bias than at reverse bias. For the frequency below 800 Hz, the 1/f noise is observed. The source of 1/f noise is rather surface leakage current. By improvements in materials and processing, the surface leakage currents may be reduced and the 1/f noise, due to these currents, will not cause a significant decrease in photodiode performance.

![Current noise vs frequency for DLHJ photodiode at 77 K, f/8 cold shield for three applied voltage biases.](image)

Fig. 11. Current noise vs frequency for DLHJ photodiode at 77 K, f/8 cold shield for three applied voltage biases.

5. Conclusions

The last decade has seen significant advances in the LPE HgCdTe material growth and detector fabrication. Device quality LPE material is being grown routinely for application in the 8–14 µm spectral region. Excellent control of the composition, growth rate, layer thickness, doping concentration, dislocation density and transport characteristic made possible to obtain high performance VLWIR detectors operated at 77 K. The inherent limitations of DLHJ HgCdTe photodiodes are very well recognisable, but some additional limitations are still important. Unsuitable surface passivation results in increase of the shunt resistance, surface tunnelling current and 1/f noise. Series and contact resistance comparable to junction impedance causes a significant decrease in quantum efficiency. Minimisation of series/contact resistance and good passivation of the junction can eliminate these excess effects.

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References