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An optimized Design, Fabrication and Characterization of Quantum Well Infrared Photodetector

Celine Joseph[1], Harvey Beere[2], David Ritchi[3], A.K. Saxena[4]

[1]*Dept. of Physics, College of Science, King Faisal University, Kingdom of Saudi Arabia*
[2,3]*Cavendish Laboratory, SP, Cambridge University, Cambridge, U.K.*
[4]*Indian Institute of Astrophysics, Bangalore, India*

[1]cantony@kfu.edu.sa, [2]heb1000@cam.ac.uk, [3]dar11@cam.ac.uk, [4]saxenaak@iiap.res.in

***Abstract*— This paper reports an optimized design and development and characterization of Quantum Well Infrared Photodetector(QWIP). GaAs well superlattice is embedded between AlGaAs barriers. This design involves analytical solution of Schrodinger equation, numerical calculation of energy Eigen values, calculation of absorption coefficient, quantum efficiency, responsivity, dark current and detectivity. The results show that fine-tuning of aluminium mole fraction and well width helps in achieving high responsivity for the desired wavelength. The design shows a measured high detectivity and a diminished dark current. The paper also shows the growth, fabrication and characterization of QWIP.**

***Keywords*— QWIP, well width, responsivity, dark current, detectivity.**

I. INTRODUCTION

Internal photoemission is the basic principle of operation for QWIP detection. Based on this fact several QWIP designs have been proposed for wavelength range of 8.0 - 12.0 μm [1-4]. The 10.5-μm infrared detector has many important applications for astronomical, medical and surveillance requirements including weather forecasting. The QWIP design presented in this paper is based on following conditions:

1) The value of aluminium mole fraction (x) should be below 0.45 to have a direct bandgap semiconductor material (AlGaAs) [4].
2) Only those values of well width and x are considered for which there lies two bound states (one bound and another quasi-bound state) inside the well in order to have high absorption.
3) Barrier thickness is optimized and chosen to be six-seven times of the well to avoid tunneling and kept low enough so that device thickness is not too large keeping in mind to increase number of wells[5] .
4) The energy eigenvalues of quantized states inside the wells are calculated by solving the Schrödinger equation. Effective mass approximation is used to compute these energy eigenvalues.
5) Using these eigenvalues E1 = 40.5 meV, E2 = 158.8 meV which corresponds to 10.5 μm wavelength of interest, Lw,x, n and Lb for the optimized voltage, the device parameters absorption like coefficient, quantum efficiency, responsivity, dark current and detectivity were calculated.

II. DESIGN OF QWIP

The theory of dependence of absorption spectrum and responsivity on the upper state position in QWIPs is used to calculate detector current responsivity [7]. In the present analysis it was found that a fine tuning of well width and aluminium mole fraction may result in quite high detector responsivity. It was verified that by decreasing the width or barrier height of a quantum well that contains two bound states, the excited bound state can be pushed into continuum. Although this gives rise to larger escape probability but can result in unwanted dark current. Hence, only those values of well widths with two bound states are considered that can give a higher responsivity with minimum dark current. The energy eigenvalues are then used to calculate absorption efficiency. The values of absorption efficiency along with other material parameters are used to calculate detector responsivity.

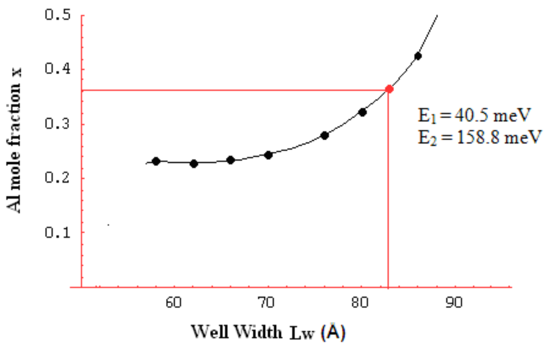

Figure 1. Well width versus aluminium mole fraction to detect a peak wavelength of 10.5 µm with two bound states inside the well

The results are shown in as the above figure 1.which gives variation of well width versus wavelength for various aluminium mole fractions. Two bound state conditions peaking at 10.5 µm starts at 58 Å with mole fraction 0.23. Beyond the well width of 86 Å, the aluminium mole fraction 0.425 the engineered material gets into indirect band gap. Fig. 2 shows the value of responsivity at 83 Å with mole fraction 0.365 which is well within the limit of being a direct band gap semiconductor material (AlGaAs). This set of values has been chosen for present QWIP design.

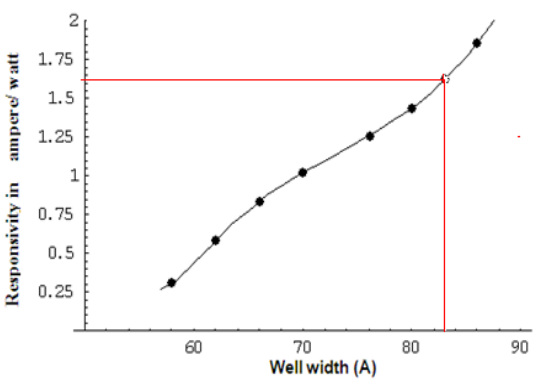

Figure 2. Well width versus responsivity for peak wavelength of 10.5 micron. Lb=550A, λ = 10.5 micron, V = 2.1V

The detectivity of the device for silicon dopant level of 0.7 x 10^{24} atoms/ m^3 at device operating temperature, 180K, is 1.95×10^8 $mHz^{1/2}$/Watt and the dark current 3.8×10^{-4} Ampere .

An increase in the dopant level will not add much difference to the figure of merit and at the same time increases the dark current. Hence the optimized silicon dopant concentration is chosen to be 0.7 x 10^{24} atoms/ m^3.

The value of photoconductive gain was calculated to be 0.323 for 2.1 Volt using the formula

$$g = \frac{\tau_d + \tau_c}{N\tau_d}$$; where $\tau_d = \frac{L}{v_d}$ is drift time ,where

$$v_d = \frac{\mu|\vec{E}|}{\sqrt{1+\left(\mu|\vec{E}|/v_s\right)^2}}$$ [1] (1) is the drift velocity

$\tau_c -$ capture time ,v_s is saturation velocity and μ is mobility; these values are taken from Andrews & Miller,1991.

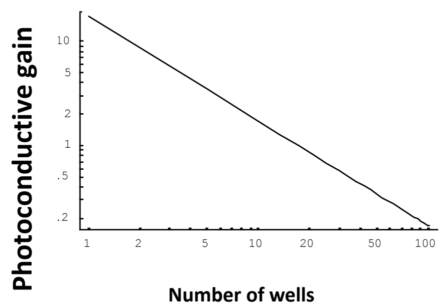

Figure 3. Variation of photoconductive gain with number of wells

Fig. 3 Shows the variation of photoconductive gain with number of wells. The experimental value of photoconductive gain for 30 wells is calculated as 0.5236 from H.C.Liu, 1992 [6]. Fig.4. shows the variation of responsivity for the above said values of well width and mole fraction but with different barrier widths (varying from 200 Å to 800 Å). Considering the profitable responsivity and the diminished dark current the barrier width was chosen as 550 Å Based on all of the above parameter considerations, the 10.5µm QWIP was designed which is suitable for Astronomical applications.

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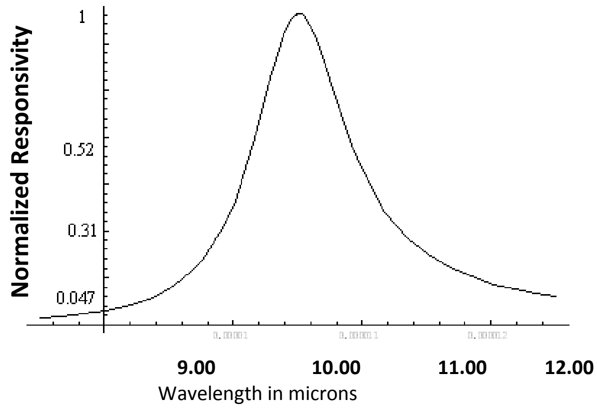


Figure 4. Variation of responsivity with wavelength for optimized design

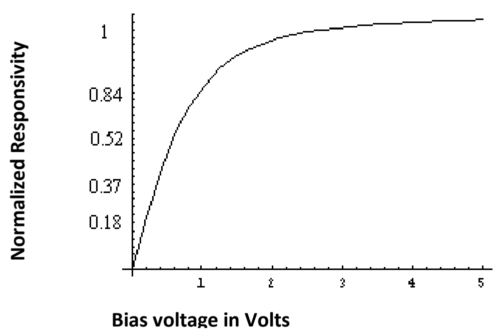


Figure 5. Variation of Responsivity with applied voltage for optimized design

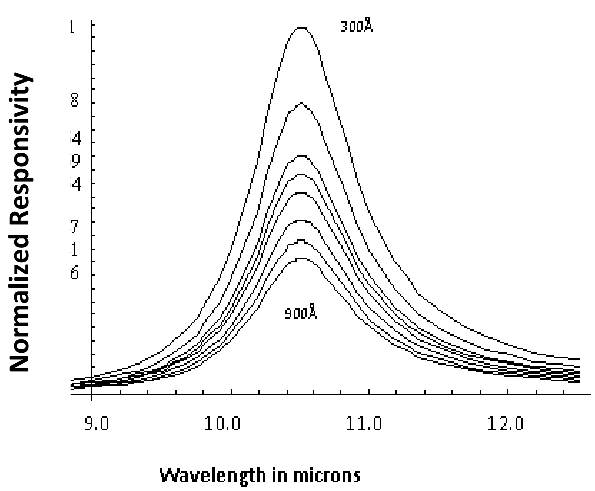


Figure 6. Normalized Responsivity of the detector for well width 83Å, x = 0.365, with variable barrier widths, dopant 0.7x10^{18}/cm^3 at 2.1Volt

The design consists of deposition of thirty times repeated sequence of $Al_{0.365}Ga_{0.635}As$(550Å) /GaAs(83 Å)/$Al_{0.365}Ga_{0.635}As$ (550 Å) Fig.7.. The silicon doping concentration in GaAs well is assumed to be 0.7x10^{18} cm^{-3}, which is chosen from the reference [6] as it is shown therein that a high detectivity can be obtained for this doping concentration.

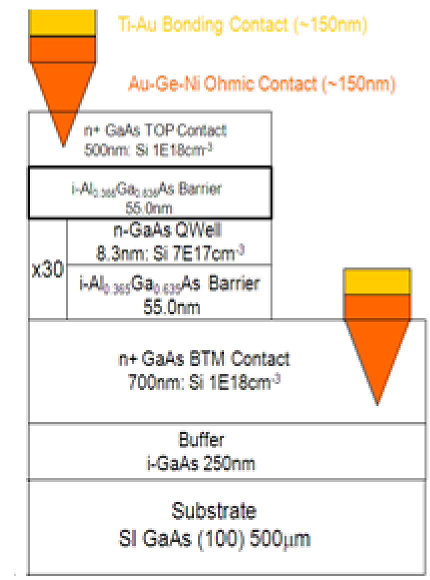


Figure 7. Design picture

Insulation of top and bottom layers was done by spinning an uniform polyimide insulating film on top of the chips 4000 rpm for 60 seconds.Finally Ti/Au (20/100nm) metallization for the external contact pads was accomplished through a lift-off process. The devices are gold bonded for characterization.

Table 1.
The optimized design 10.5-micron QWIP outcomes

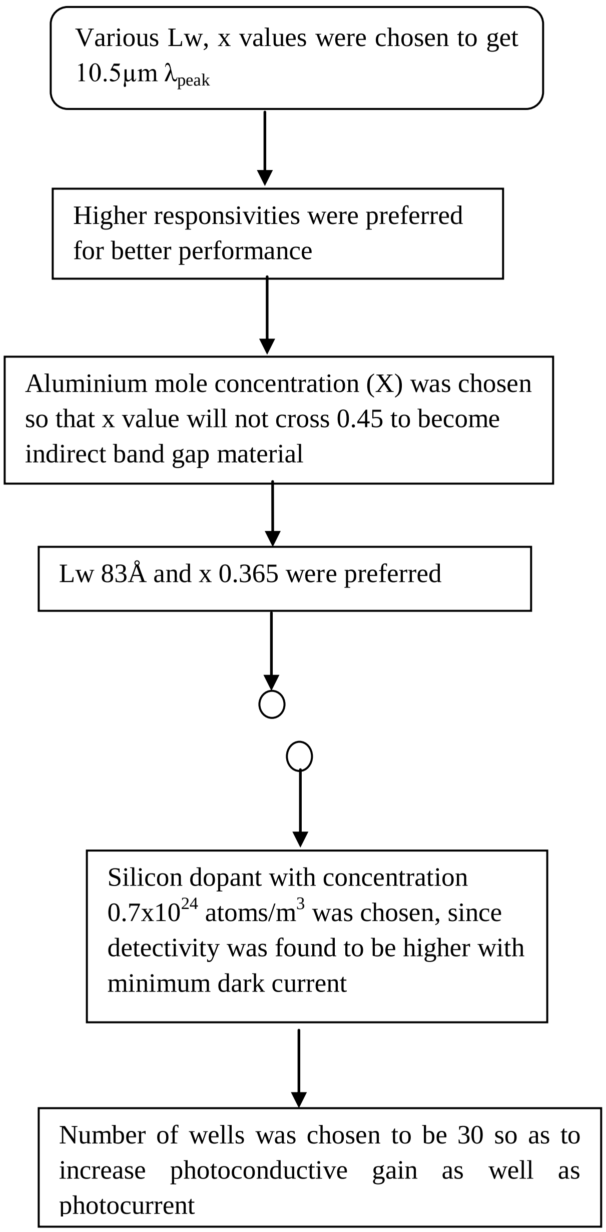
Parameters: λp = 10.5µm, Lw = 83 Å, x = 0.365, Lb =550Å,1000x1000µm^2, 0.7x10^{18}/cm^3, Bias = 2.1 Volts, T1 =120K, T2 = 140K, T3 = 160K, T4 = 180K.

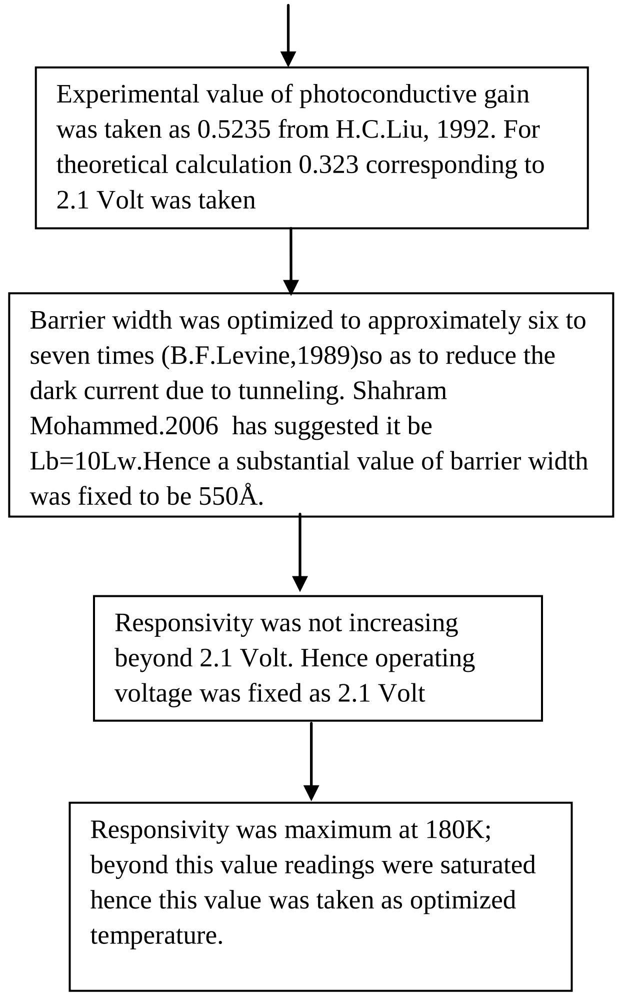
Absorp. Coefficient in / m (α)	Absorp. Efficiency (η)	Norm. Respons. (R)	Detectivity In cmHz$^{1/2}$/Watt (120K)	Dark Current in (120K)	Noise Current in A (120K)	Detectivity in cmHz$^{1/2}$/Watt (140K)
1.76x10^6	0.0207	1.00	5.63x10^{11}	3.8x10^{-7}	2.7x10^{-13}	1.32x10^{11}

Dark Current in A (140K)	Noise Current in A (140K)	Detectivity in cmHz$^{1/2}$/Watt (160K)	Dark Current in A (160K)	Noise Current in A (160K)	Detectivity in cmHz$^{1/2}$/Watt (180K)	Dark Current in Ampere (180K)	Noise Current in Ampere (180K)
7.07x 10^{-6}	5.15x 10^{-13}	4.44x10^{10}	9.02x10^{-6}	9.39x10^{-12}	2.26x10^{10}	1.09x10^{-5}	1.35x10^{-12}

Table 1 shows the theoretical values that are calculated for the desired wavelength of interest, 10.5 µm QWIP with the device parameters: Lw=83Å, x= 0.365, n=$0.7x10^{18}$ /cm^3, Lb= 550Å, N=30 wells and with operating bias voltage 2.1 Volts. Figure 5.11 to Figure 5.17 shows the various outcomes of the optimized design. The responsivity shown by the optimized design is 1.66A/watt

III. Optimization Flowchart





IV. Growth, Fabrication And Characterization Of 10.5 Micron QWIP

The device was grown, fabricated and electrically characterized at the Cavendish Laboratory, Cambridge University, UK.The sample V601 contains thirty 83Å n-GaAs quantum wells (7E17cm^{-3}) positioned between thirty-one 550Å $Al_{0.365}Ga_{0.635}As$ barriers, sandwiched between two n^+ GaAs top and bottom contacts (1E18cm^{-3}). Pre-growth rate calibrations are done using optical pyrometery oscillations, measured the GaAs and AlAs growth rates to be within ±1% tolerances expected.

High-resolution diffraction shows, Fig 8. clear satellite structure from sample V601, confirming excellent crystal quality and growth uniformity. There is good agreement between the measured sample (black trace) and the simulation of the structure (red trace).

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Analysis of the separation of the high order super lattice (SL) peaks gives a repeated period thickness of 637.2Å, which is slightly thicker than the intended structure thickness of 633Å (+0.67%). The slight difference between the zero-order SL peaks between the measured and simulation traces suggests that the Aluminium concentration is slightly higher than intended in the grown sample.

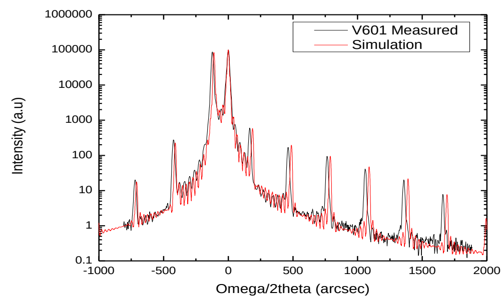

Figure 8. High-resolution Diffraction spectrometry graph of the sample.

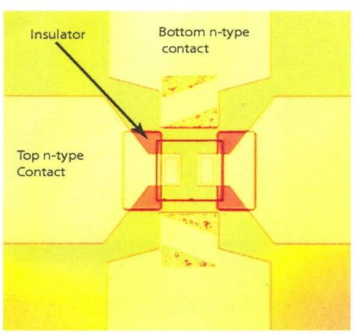

Figure 9. Fabricated device

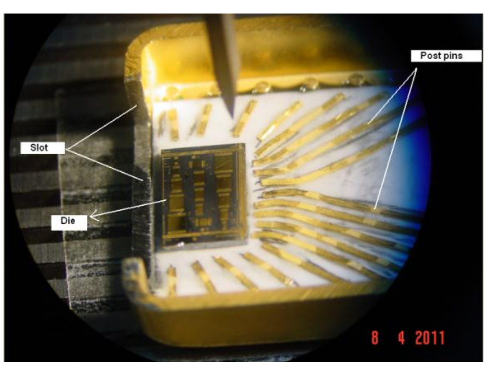

Figure10. Packaging of the device with slot

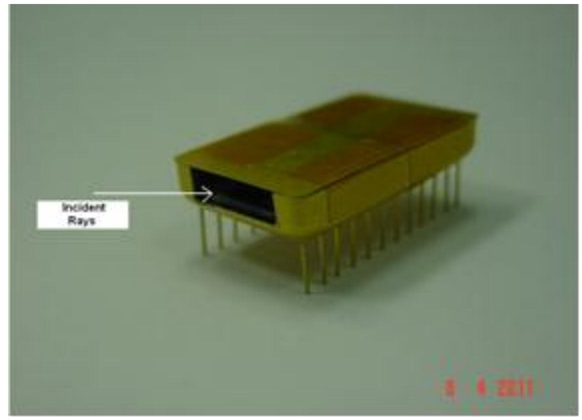

Figure 11. Final Packaged device

Figure 9 shows actual size of the packaged device and Figure 10 shows the slot given for incident rays to enter through the window. Figure 11 shows the final packaged device.

Table 2:
Dark current values for various temperatures

Temperature (K)	Dark Current at 2.1 V (in A) 40µm x 40 µm		Dark Current at 2.1 V (in A) 60µm x 60 µm	
	Theoretical	Experimental	Theoretica l	Experimental
120K	$4.6x10^{-10}$	$1.09\ x10^{-9}$	$1.44x10^{-9}$	$1.7\ x10^{-9}$
140 K	$1.07x10^{-8}$	$2.9x10^{-8}$	$2.88x10^{-8}$	$6.6\ x10^{-8}$
160 K	$9.12x10^{-8}$	$3.4\ x10^{-7}$	$2.34x10^{-7}$	$7.9\ x10^{-7}$
180 K	$4.89x10^{-7}$	$2.4\ x10^{-6}$	$1.34\ x10^{-6}$	$5.5\ x10^{-6}$

Table 2 shows the dark current values for various temperatures.

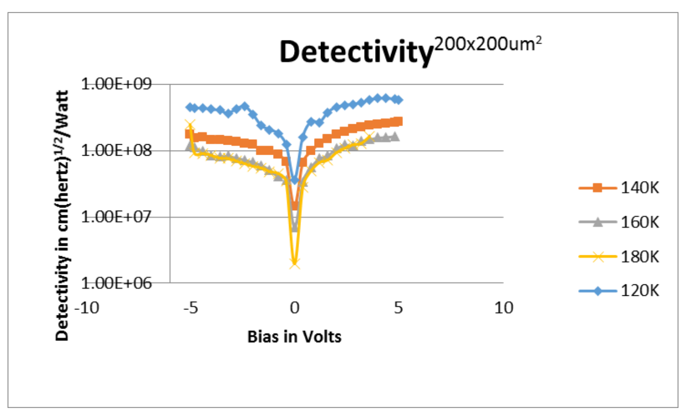

Figure 12. Measured detectivity for 200x200µm^2 device with 5.81x10^{11} cm^{-2} doping for various temperatures

Detectivity is basically the signal to noise ratio of a radiation detector normalized to unit area and operating bandwidth of the detector. Detectivity can be determined from the measured responsivity and noise of the detector. Detectivity is calculated using the formula

$$D^* = \frac{R\sqrt{AB}}{i_n} \quad \text{Amp(Hz)}^{1/2}\text{/Watt [2]} \qquad (3),$$

Where R is the responsivity, A is the area of the detector and B is the operating bandwidth of the detector and i_n is the noise current due to the generation recombination of carriers. I_{noise} is the measured noise current.D* Fig.12 is a function of operating temperature, detector bias and the cutoff wavelength.

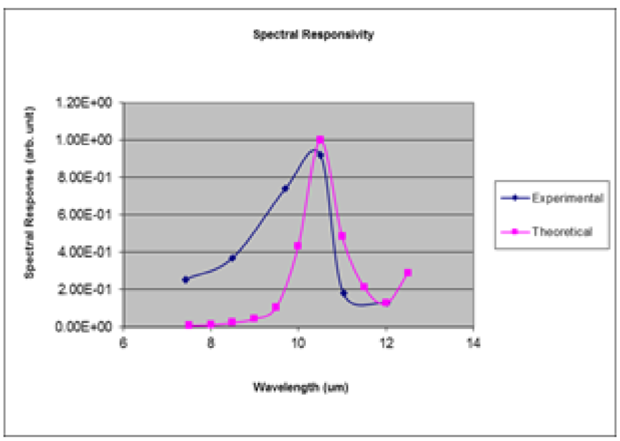

Figure 13: Spectral response curve at 180K for bias voltage 2.1V of 1000x1000µm^2 device with doping density 5.81x10^{11} cm^{-2}.

The spectral responsivity of the QWIP device is shown in figure 13. Normalization was done according to the flux spectral transmission of INSAT 3D filters. Extrapolating and suitable fitting of the experimental values the spectral responsivity is found to be peaking at 10.45 µm. The normalized value of responsivity is 0.95 against the normalized value of unity. The FWHM lies between 9.2 µm to 11.4 µm .

V. Conclusion

The design and analysis of quantum well infrared photo detector has been proposed to detect a band of wavelength from 10.1µm -11.0 µm with peak at 10.5 µm which is of astronomical importance. To optimize the design, experimental control of parameters such as well width, aluminium mole fraction, silicon dopant concentration and barrier thickness are taken into consideration. Study reveals that a fine tuning of well width and aluminium mole fraction is required to get a high response from GaAs/$Al_xGa_{(1-x)}As$ detectors. The stacked design has given improved detector performance in terms of absorption efficiency and responsivity. The optimization of device parameters like bias voltage and operating temperature have yielded a measured high detectivity with minimum dark and noise current. The device shows a measured detectivity 6.8 x 10^9 cm (Hz)$^{1/2}$/Watt a diminished dark current 6.08x10^{-5} Ampere at 180K at 2.1V .

Acknowledgment

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