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Scheme of a Quantum Well Infrared Photodetector (QWIP) for Astronomical Application

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Abstract— **The 10.5 µm infrared detector has many important applications for astronomical, medical and surveillance requirements including weather forecasting. A theoretical design of GaAs/Al$_x$Ga$_{(1-x)}$As Quantum Well Infrared Photodetector for the above applications has been reported in this paper.**

Present design involves analytical solution of Schrödinger equation, graphical calculation of energy eigenvalues, responsivity and dark current simulation for various temperatures. Our results show that fine tuning of aluminium mole fraction and well width helps in achieving high responsivity for the desired wavelength. Control of these parameters is well within the achievable thin film technological limits of the present time.

Index Terms—**QWIP, 10.5 micron detector, aluminium mole fraction, well width, detector responsivity, dark current.**

I. INTRODUCTION

Astronomical observations show that there is a strong emission of spectrum from certain clusters like the hidden compact radio super-star cluster in NGC5253, C2 in the range of 8 µm to 13 µm region. This spectrum is characterized by a strong [S IV] line at 10.5 µm. Keeping the above spectral range in mind a quantum well infrared photodetector (QWIP) has been designed which is also useful for many other strategic applications.

Existence of subbands in bandgap engineered semiconductor materials allow strong optical transitions at energies far below those allowed in the bulk materials. The large oscillator strengths of these transitions along with flexible material engineering of band gap can be used for designing sensors for very specific wave band with high responsivity. Internal photoemission is the basic principle of operation for this 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 GaAs layer sandwiched between two Al$_x$Ga$_{(1-x)}$As layers gives rise to an offset in the band diagram and hence the quantum well. By knowing this offset the band edge potential can be determined. This well potential is confining potential for electrons in conduction band. There exists quantized energy states inside the quantum well formed due to the offset. The energy difference between the ground state (E_1) and the first excited state (E_2) determines the absorption peak wavelength of intersubband transitions. With the energy eigenvalues E_1 and E_2, eigenfunctions can be evaluated and oscillator strength can further be calculated for bound to bound and bound to continuum transition. Here, a design of GaAs/Al$_x$Ga$_{(1-x)}$As multiple quantum well (MQW) infrared photodetector which operate by photoexciting electrons from localized states in Si doped quantum wells into extended continuum states is presented to have high response in 9.8 – 11.7 µm wavelength range.

II. DESIGN OF QWIP

To design the lattice matched GaAs/Al$_x$Ga $_{(1-x)}$As QWIP, the energy eigenvalues of quantized states inside the wells are calculated by solving the Schrödinger equation graphically. Effective mass approximation is used to compute these energy eigenvalues. The theory of dependence of absorption spectrum and responsivity on the upper state position in QWIPs can be used to calculate detector current responsivity [5]. 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. So only those values of well widths with two bound states are considered that can give a higher responsivity for minimum dark current.

The energy eigenvalues of quantum well are calculated by graphical solution of Schrödinger equation and alternatively confirmed by numerical approach with MATHEMATICA. The graph is shown in fig. 1. These 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.

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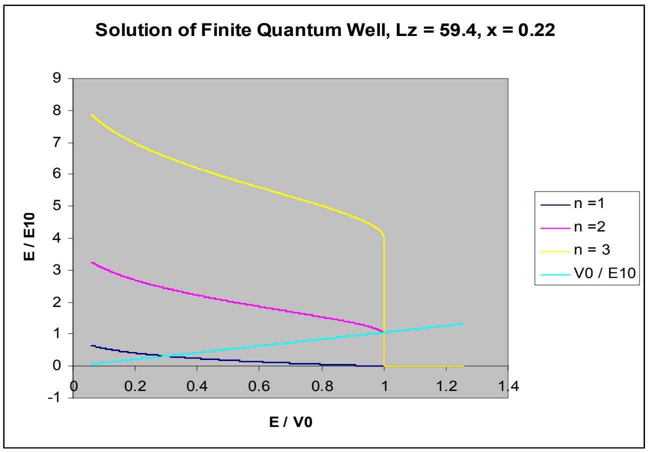

Fig.1. The normalized energy values are taken on both the axes to find the solutions for the well width $L_z = 59.4$ Å and $x = 0.22$.

The quantum well stack of fig. 2, consists of GaAs quantum wells and $Al_xGa_{(1-x)}As$ barriers. The combination of well and barrier layers is repeated for thirty times as shown in fig. 3. The well width is chosen to be equal to 59.4 Å and barrier width is chosen to be equal to 300 Å with aluminium mole fraction x as 0.22. This choice is the result of so many calculations done for this purpose. The design consists of deposition of repeated sequence of $Al_{0.22}Ga_{0.78}As$ /GaAs (59.4 Å)/$Al_{0.22}Ga_{0.78}As$ up to thirty times. The silicon doping concentration in GaAs well is assumed to be 1.53×10^{18} cm^{-3}, which is derived from two dimensional carrier density given in [5]. Taking the possible effects of error in the aluminium mole fraction and well width during deposition into consideration the responsivity was calculated for various combinations of the same. We calculated responsivity for these possibilities and it is assumed that this design will produce a combined effect to give a broadband detection effect. Assumptions include the operating temperature of 77 K and an applied operating field of 25 kV/cm (corresponds to an applied bias of $\simeq$ 2.8 V) to the quantum well stack. The schematic band diagram for our simple design of GaAs based broadband detector is shown in fig. 3.

The design stated above can be realized practically at our laboratory with available coating facility. With our existing facility we are capable of depositing GaAs/$Al_{0.22}Ga_{0.78}As$ thin films with an accuracy $\simeq \pm 1.0$ Å in well width and in aluminium mole fraction $\simeq \pm 0.01$. Precise control over process parameters e.g. temperature, pressure etc. is speciality of the available coating plant.

The material parameters taken in to consideration to come up with the results presented here are listed in table 1.

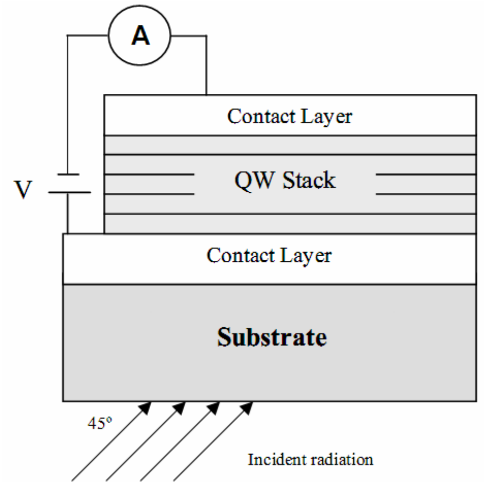

Fig. 2. Schematic diagram of a stacked quantum well photodetector with readout circuit

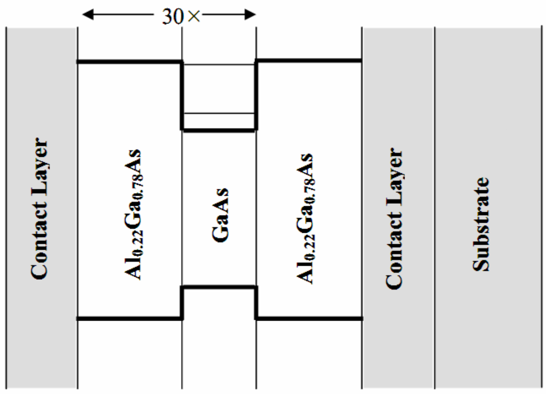

Fig. 3. Schematic band diagram of the GaAs based QWIP sample with confined energy levels shown in the well.

III. THEORETICAL RESULTS

A. Calculation of responsivity

The absorption efficiency (η) is plotted against wavelength (λ) as shown in fig. 4 (A). To plot this graph we have used the equations and parameters listed in table 1. This graph shows high absorption efficiency of 6.5×10^{-3} at a wavelength of 10.635 μm. Experimental uncertainties in the value of aluminium mole fraction and well width will lead to an unavoidable uncertainty in the value of responsivity. We studied theoretically the effect of these errors which arise due to experimental constraints during deposition of the active layers. This experimental limitation would give rise to a broader band detection. The responsivity (R) is plotted against wavelength (λ) in fig. 4 (B), taking experimental error into account. The actual detector response will depend upon individual experimental conditions achieved.

Table 1: Parameters and references used to design a QWIP and to calculate responsivity of the same.

Parameter	Analytical expression	References
Solution of Schrödinger equation	For even parity: $\frac{kL_z}{2} = n\pi + \text{atan}\left(\frac{m_w^*}{m_b^*}\frac{\alpha}{k}\right)$, n = 0,1,2 … For odd parity: $\frac{kL_z}{2} = \frac{\pi}{2} + n\pi + \text{atan}\left(\frac{m_w^*}{m_b^*}\frac{\alpha}{k}\right)$, n = 0,1,2 … $k = \sqrt{2m_w^* E}/\hbar$ and $\alpha = \sqrt{2m_b^*(V-E)}/\hbar$	Self consistent
Effective mass in well and barrier region	$m_w^* = 0.067m_0$ $m_b^* = (0.0665 + 0.0835x)m_0$, m_0 is rest mass of electron.	[6], [7]
Barrier height	$\Delta E = V = 0.76x$, x represents Al mole fraction	[6]
Chosen Well, Barrier width & mole fraction	L_z = 59.4 Å L_b = 300 Å x = 0.22	-
Energy eigenvalues	E_1 = 49.93 meV, E_2 = 166.82 meV	-
Carrier density in well region	1.53×10^{18} cm^{-3}	-
Angle of incidence	θ = 45°, p – polarized	-
Absorption efficiency	$\eta = \frac{e^2 h}{4\varepsilon_0 n_r m_w^* c}\frac{\sin^2\theta}{\cos\theta} n_{2D} \frac{1}{\pi\Delta E}\left[\frac{1}{1+[(E_2-E_1-\hbar\omega)/\Delta E]^2} f_{B-B} + \frac{L\sqrt{2m_w^*}}{2\pi\hbar} \times \int_V^\infty \frac{dE_z}{\sqrt{E_z-V}} \frac{1}{1+[(E_z-E_1-\hbar\omega)/\Delta E]^2} f_{B-C}\right]$ f_{B-B} & f_{B-C} are oscillator strengths, B – Bound, C – Continuum, ω is the angular frequency of incident light n_{2D} can be calculated from carrier density in well region	[5]
Lorentz lineshape function	$\Delta E = 5.0meV$	[5]
Photoconductive gain	g = 0.5745, chosen for 30 wells	[8]
Responsivity	$R = \frac{eg\eta\lambda}{hc}$; e, h, c & λ having their usual meanings	[5]
Assumed operating temperature and field	T = 77 K E = 25 kV/cm	-

Table 2: Values of well width (L_z) and aluminium mole fraction for plot in fig. 4 (B)

L_z (Å)	x	λ_{peak} (μm)	R (A/W)
58.2	0.23	10.145	98.0
58.8	0.225	10.382	97.8
59.4	0.22	10.635	96.3
60.1	0.215	10.896	98.98
60.78	0.21	11.173	99.3

The values of well width and aluminium mole fraction for which the graph in fig. 4 (B) is drawn are listed in table 2.

The above calculation on responsivity for varied mole fraction and well width has been considered based on our experience on control of these parameters in our coating facility. Using Sigma automatic deposition controller well width can be controlled to better than 1.0 Å accuracy and mole fraction by prior calibration can also be controlled to an accuracy of 0.01 or better. We may expect a root mean square average of the responsivity as shown in fig. 5. From the above theoretical design it is imperative that high order of responsivity can be achieved with fine control of these parameters.

Thus the above detector design will be able to give better than 60% of the peak responsivity for a flat spectral range of 10.4-11.4 μm. The full width at half maximum of 0.35 lies between 9.8-11.7 μm with the peak value at ≃ 10.5 μm.

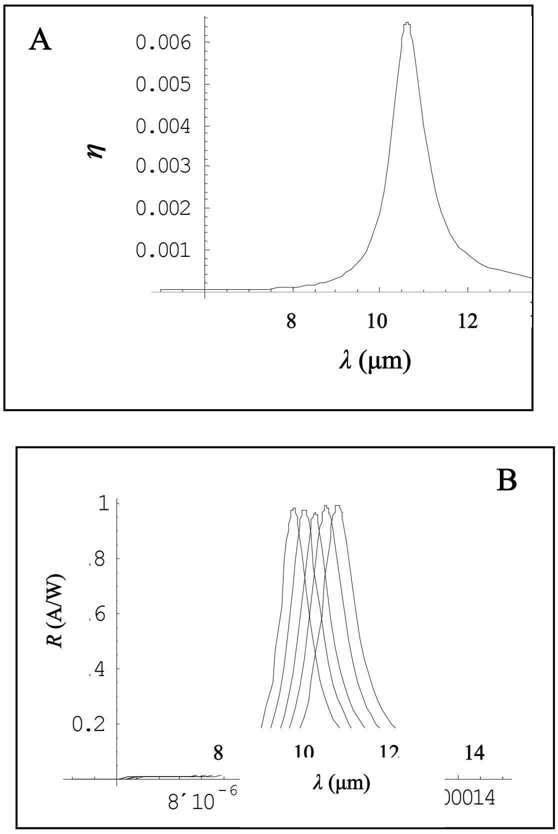

Fig. 4 (A) Absorption efficiency (η) plotted against wavelength (λ), (B) Responsivity (R) plotted against wavelength (λ).

B. Calculation of dark current

The dark current of the detector designed in this paper is calculated by considering the model presented by Andrews and Miller [9]. The graph in fig. 6 for dark current is plotted for varied mole fraction and well width listed in table 2, considering possible accuracy of well width by 1.0 Å and mole fraction by 0.01 or better. We may expect a root mean square average of the dark current for various temperatures as shown in fig. 7. Present calculation involves variation of dielectric constant with temperature as well as image charge barrier lowering has also been taken into account. The calculations use a mobility of 1000 $cm^2V^{-1}s^{-1}$, a saturation drift velocity of 5×10^6 cm s^{-1} and the nominal sample parameters shown in table 1. At assumed bias voltage 2.8 volts the values of dark current for various temperatures is listed in table 3. When applied voltage increases the barrier potential decreases and hence the electron in the well can very easily escape to the continuum which increases the conductivity.

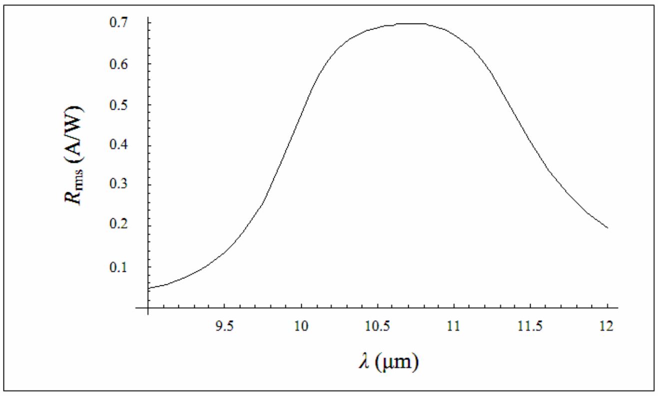

Fig. 5 Root mean square responsivity (R_{rms}) plotted against wavelength (λ)

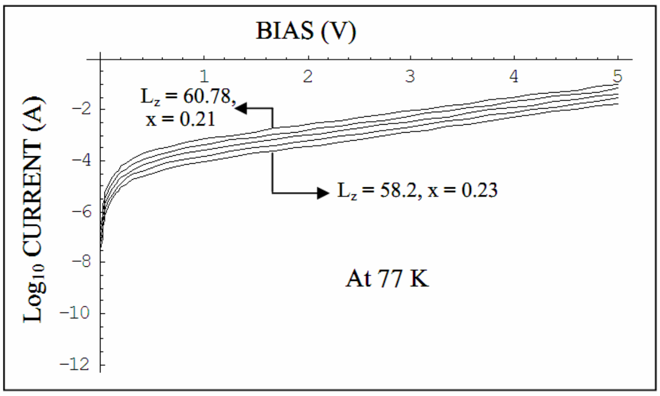

Fig. 6: Theoretical dark current-bias characteristics at 77 K for values of L_z and x listed in table 2

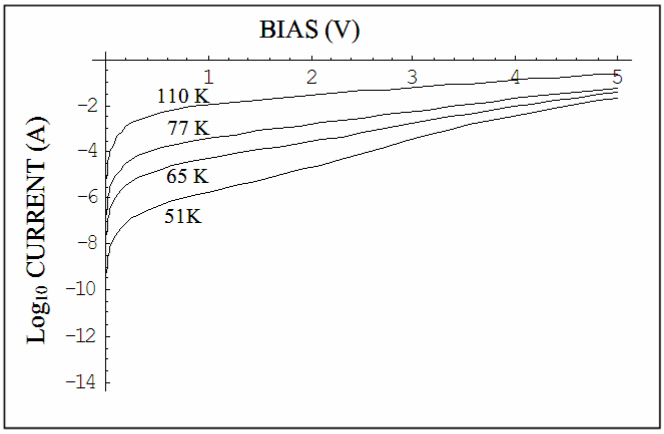

Fig. 7: Theoretical dark current-bias characteristics at various temperatures (in K)

Table 3: RMS Dark current values for various temperatures

Temperature (K)	Dark Current at 2.8 V (in mA)
51 K	0.257
65 K	1.44
77 K	5.49
110 K	66.06

IV. CONCLUSION

The design and analysis of quantum well infrared photo detector has been done theoretically to detect a band of wavelength from 9.8-11.7 μm with peak at 10.5 μm. To analyze the design, experimental control of parameters such as well width and aluminium mole fraction are taken into consideration. The 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 good insight into the detector performance in terms of absorption efficiency and responsivity. Fig. 7 shows that dark current value is increased when the applied voltage is increased. The present design will show quite a high response and minimum dark current subject to the applied bias voltage and operating temperature.

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REFERENCES

[1] Fabio Durante P. Alves, G. Karunasiri, N. Hanson, M. Byloos, H. C. Liu, A. Bezinger, M. Buchanan, Infrared Physics & Technology 50 (2007) 182-186.

[2] M. Jhabvala, K. K. Choi, C. Monroy, A. La, Infrared Physics & Technology 50 (2007) 234-239.

[3] N. Cohen, R. Gardi, G. Sarusi, A. Sa'ar, M. Byloos, A. Bezinger, A. J. SpringThorpe, H. C. Liu, Infrared Physics & Technology 50 (2007) 253-259.

[4] H. C. Liu, D. Goodchild, M. Byloos, M. Buchanan, Z. R. Wasilewski, J. A. Gupta, A. J. SpringThorpe, G. C. Aers, Infrared Physics & Technology 50 (2007) 171-176.

[5] H. C. Liu, J. Appl. Phys. 73 (6), pp. 3062-3067 (1993)

[6] SameerShah, M Thirumavalavan, Ranjay Laha, A. T. Kalghatgi, S. B. Krupanidhi, "Detection Wavelength Tuning and Dark current modeling for GaAs/AlGaAsQuantum Well Infrared Photodetectors using MATLAB and Synopsys ISE TCAD".

[7] Eoin O'Reilly, Quantum Theory of Solids (2002).

[8] H. C. Liu, Appl. Phys. Lett. 60 (12), pp. 1507-1509 (1992).

[9] S. R. Andrews, B. A. Miller, J. Appl. Phys. 70 (2), pp. 993-1003 (1991).