High Speed pin Photodetector with Ultra-Wide Spectral Responses

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ABSTRACT

We report the design and fabrication of a high speed surface illuminated *pin* photodetector with a wide spectral response. An InGaAs based detector was grown lattice matched to InP and the device was fabricated using a novel technique to facilitate the direct absorption of incoming photons in the InGaAs layer without being absorbed by any other wider bandgap material. The absorption of a wide spectrum of wavelengths was achieved by recess etching almost all of the InP contact layer above the InGaAs absorption layer of a *pin* photodiode subsequent to ohmic contacts formation. Theoretical simulation shows responsivities above 0.6 A/W between 900 and 1600 nm and a linear reduction to 0.3 A/W at 650 nm. This makes the detector operational in both visible and near-infrared spectrum. The responsivities are 0.50, 0.77, and 0.67 A/W for 840, 1310 and 1550 nm respectively. These values confirm the potential of the device to be effective in all of the optical fiber communication wavelengths. Our calculations also show that the device can operate above 10 GHz throughout the spectrum.

Keywords: high-speed photodetector, pin photodiode, wide spectrum of wavelengths.

1. INTRODUCTION

Broad spectral image sensors are required for various ground-based, air-borne, space-borne military applications, including the atmospheric properties measurement, surface topography and remote sensing. To date, several sensors covering different spectral ranges are used for this purpose. Next generation instruments require single sensor (or its array) that covers multiple spectral bands (0.3 to 2.5 μm of wavelengths) and could be used for different applications.

Solid-state image sensors with higher resolution are used in many commercial applications and also for other light imaging uses. Such imaging sensors typically comprise of CCD (charge coupled device) or CMOS (complimentary metal oxide semiconductor) image sensors with associated switching elements, and address (scan) and read out (data) lines [1]. Both CCD and CMOS image sensors are used in silicon technology which is so matured that nowadays millions of pixels and surrounding circuitry can be fabricated. As today's CCD and CMOS image sensors technology are based on Si-technology, the detectable spectral ranges are limited to the wavelengths below 1 μm where Si exhibits absorption. Besides, CCD and CMOS image sensors have also other shortcomings such as low frequency response combined with low quantum efficiency over broad spectral response.

Absorption coefficient of various semiconductors used in the optoelectronic devices are shown in Figure 1. It is seen that $In_{0.53}Ga_{0.47}As$ (InGaAs) and Ge are two materials whose absorption spectrum covers both the visible and the near infrared spectrum. Ge can not be used to get heterostructure photodetectors. Any *pin* type photodetector based on Ge will have significant amount of absortion in either p+ or n+ layer, which will lower the responsivity and the speed of the photodetector. InGaAs based detector on InP substrate is used for detecting the light with wavelength range from 0.9 to 1.7 μm which is widely used in the optical communication [2]-[6]. Photodiodes especially of InGaAs *pin* type have been studied extensively over the last decade for its application in optical communication. Now a day, the photodetector speed as high as 40 Gb/s [6], and quantum efficiency close to 100% [5] are available for optical communication. InGaAs material is usually used as absorption material, and the diode is fabricated on the InP wafer. For detection of radiation having shorter wavelengths (300 nm to 980 nm), Si based photodiodes are used and that has been also extensively studied. None of the current solution can provide broad spectral detection capability ranges from 0.3 to 2.5

μm of wavelengths. It is highly desirable to design the photodetector (array) having broader spectral detection ranges (0.3 to 2.5 μm) for various military's applications including remote sensing, surface topography etc.

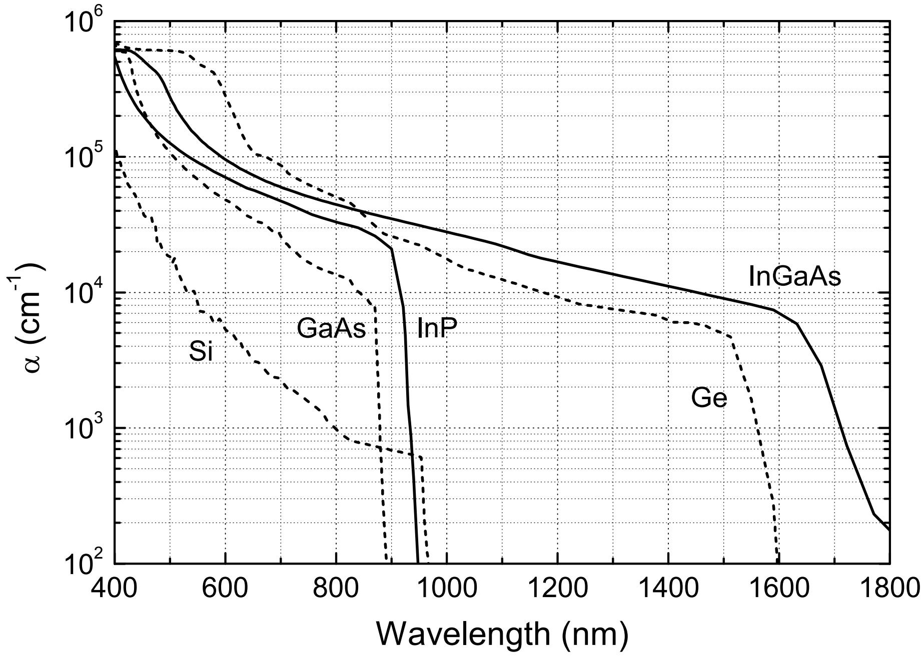


Figure 1. Absorption coefficient of various semiconductors used in optoelectronic devices. [8]

For covering broad spectral ranges especially from 0.3 to 1.6 μm, conventionally two photodiodes fabricated from Si and InP technology, discretely integrated [7], are usually used. Although wafer bonding can be used to bond Si and InP to cover longer wavelengths, the reliability of wafer bonding over wide range of temperature is still an unsolved issue and a high-speed operation is not feasible with a wafer bonding approach. It is highly desirable to design a monolithic photodiode array, which could offer high bandwidth (GHz and above) combined with high quantum efficiency over a broad spectral ranges (0.3 to 2.5 μm), and the possibility to rapidly and randomly address any pixel.

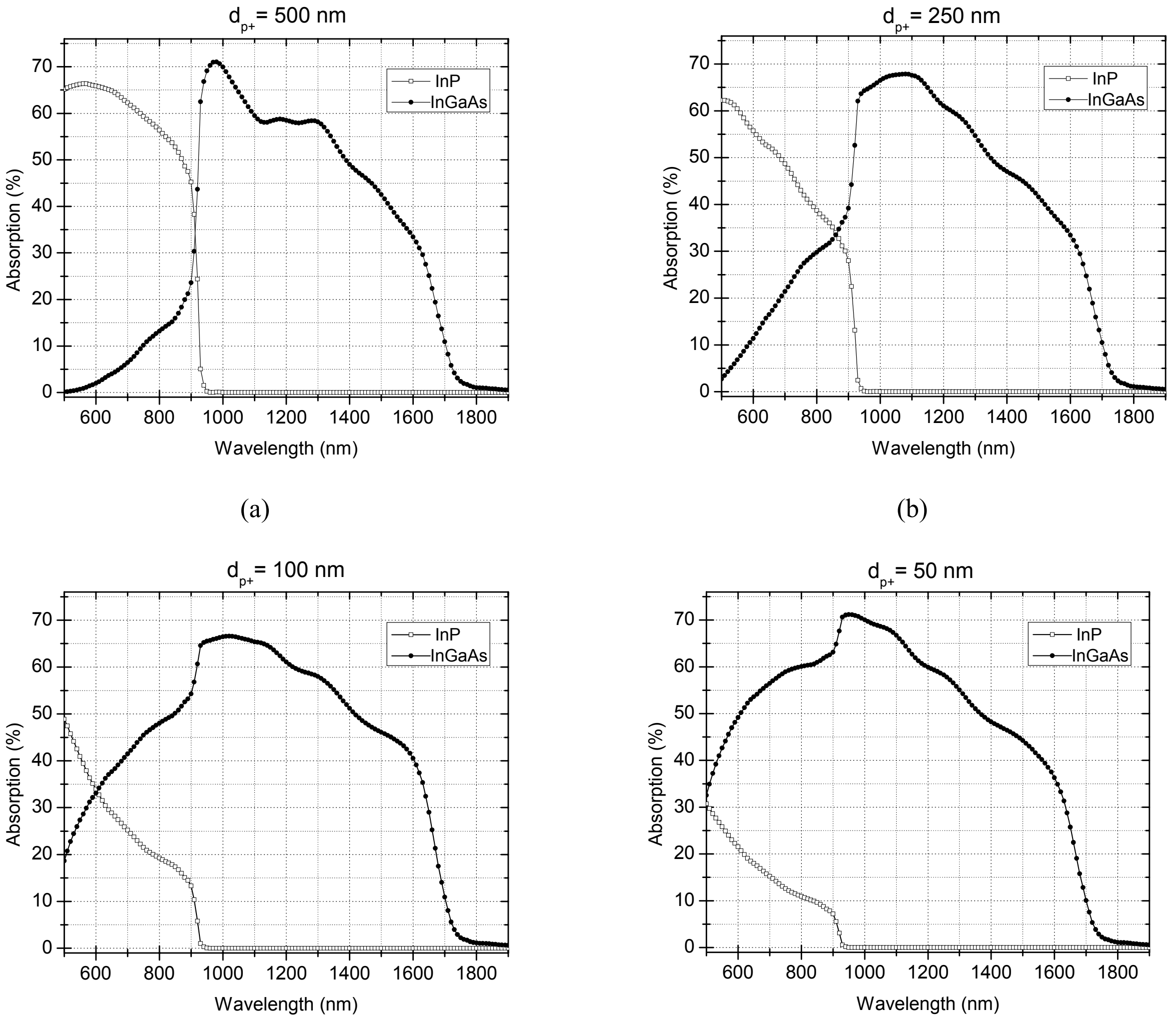
2. DESIGN

We designed an InP based *pin* type photodetector with a 1μm intrinsic InGaAs layer lattice matched to InP. The InGaAs layer thickness was chosen to be 1μm in order to get high responsivity through out the spectral range of operation. The layer structure of the grown wafer is shown at Table 1.

The structure was grown on semi-insulating InP substrate. Initially highly Si doped InP layers were grown. The dopant concentration was grades as the thickness increased to prevent the dopant migration to the intrinsic InGaAs layer. The n+ layers also has a thin undoped InGaAs layer which is used as the etch stop layer. After the n+ layers, intrinsic InGaAs layer was grown. This layer was not doped. But the background doping is n-type in the order of 10^{15}. Then the top p+ layers were grown with a similar dopant profile; starting from 5×10^{17} to 10^{20} at the topmost InGaAs layer. This InGaAs layer is used to get ohmic contacts with lower resistance. It is etched away after the fabrication to prevent loss of the optical power.

Table 1. Epitaxial layer of the grown wafer.

Type of Layer	Material	Thickness (nm)	Dopant	Concentration (cm^{-3})
p+	InGaAs	60	Zn	1×10^{20}
p+	InP	300	Zn	1×10^{20}
p+	InP	100	Zn	5×10^{18}
p+	InP	100	Zn	5×10^{17}
i	InGaAs	1000		Undoped
n+	InP	200	Si	1×10^{18}
n+	InP	500	Si	5×10^{18}
	InGaAs	60		Undoped
n+	InP	250	Si	5×10^{18}
		Semi Insulating InP Substrate		



(a) (b)

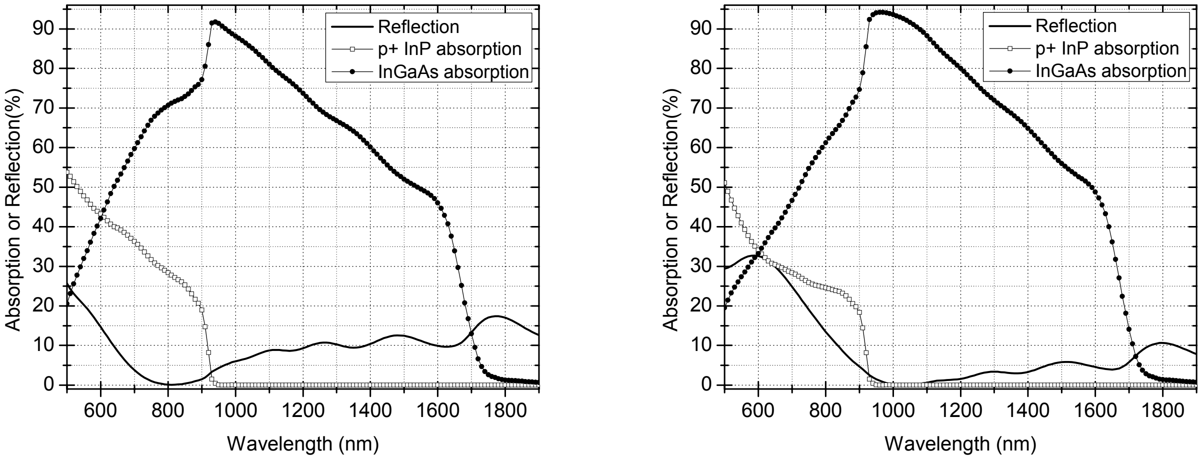
(c) (d)

Figure 2. Absorption in the p+ InP (□) and intrinsic InGaAs (•) layers for the detector structure with 500nm (a), 250nm (b), 100nm (c), and 50nm (d) p+ InP layers.

Optical properties of the photodetector were obtained with a transfer matrix method (TMM) based calculations. We calculated the reflected power and the absorbed optical power in the p+ InP and intrinsic InGaAs layers. Without the anti-reflection coating, 30% of the optical power is reflected from the top semiconductor layer. Figure 2 shows the absorbed optical power in the p+ InP layers and InGaAs layer after the topmost InGaAs layer was etched away. Here we can see the effect of the InP layer thickness on the optical power absorbed in the InGaAs layer. Around 920 nm, the optical power absorbed in the InGaAs layer drastically decreases with 500 nm p+ InP layer as shown in Figure 2(a). Above 920 nm, the absorbed power decreases gradually due to decrease of the absorption coefficient of the InGaAs. As the top p+ InP layer is etched away and become thinner, the absorption in the InGaAs layer increases below 920 nm, while it is almost same above this wavelength. The absorption in the p+ InP and intrinsic InGaAs layers were calculated for p+ InP layer thicknesses of 250, 100, and 50 nm and shown in Figure 2(b), (c), and (d) respectively.

The absorption in the active layer can be increased by depositing anti-reflection coating, which increases the power coupled to the photodetector layers. After etching the InP layer to desired thickness, single or multi-layer antireflection coatings are deposited on the active area. As the number of layers used in the coating increases, the spectral range which the reflection is minimized increases. But adding more layers increases the complexity.

We calculated the reflected power and the power absorbed in the p+ InP and intrinsic InGaAs layers for different coating layer thicknesses. We have chosen silicon nitride layer with a refractive index of 1.85. With this dielectric coating, zero reflection can be achieved for a semiconductor with refractive index of 3.42. Figure 3(a) and (b) shows the reflection, absorption in p+ InP layer and intrinsic InGaAs layers as a function of wavelength for 108nm and 149nm thick coatings respectively.

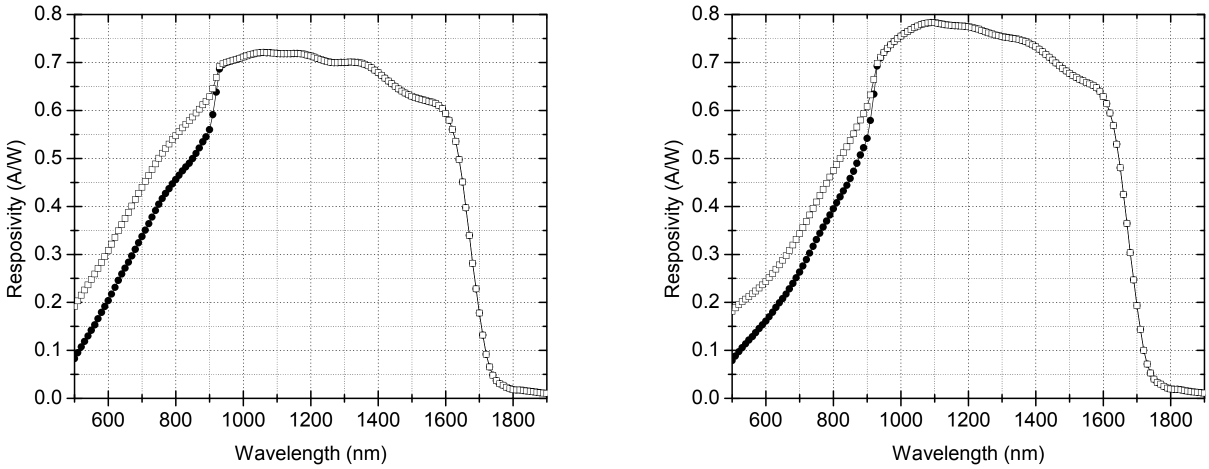


(a)

(b)

Figure 3. Reflection (-), absorption in the p+ InP (□) and intrinsic InGaAs (●) layers for the detector structure with 100 nm top p+ InP layer with 108 nm (a) and 149nm (b) thickness anti-reflection coating.

After calculating the spectral absorption in the photodetector layers, we can calculate the responsivity (or quantum efficiency) of the photodetector. The intrinsic layer is thin enough to collect all the photogenerated carriers. We know that each absorbed photon will generate one electron hole pair which contributes to the photocurrent. So above 920nm wavelength, the quantum efficiency will be equal to the absorbance of the intrinsic InGaAs layer. Below 920nm wavelength, photogenerated carriers will be present in the heavily doped layers. Electrons within the diffusion length of the p+ InP layer will diffuse slowly to the intrinsic layer, which finally contributes to the photocurrent. This extra current must be included during the calculation of the quantum efficiency (or responsivity).



(a)

(b)

Figure 4. Responsivity calculation of the photodetector when the diffusion of electrons from p layer was included (□) and not included (●) for the detector with 108 nm (a) and 149nm (b) thickness anti-reflection coating.

We calculated the responsivity of the photodetector for two anti-reflection coating layers mentioned in Figure 3. Figure 4 shows the results of these calculations. We show the responsivity when the diffusion current included and not included in the calculations, which gives the upper and lower limit. As we have absorption in the InGaAs layer above 920nm wavelength, the results for both cases are identical. Below 920nm, we see a significant difference. Based on these results, this photodetector can be used between 500nm and 1700nm spectral range, which covers the most of the visible and near-infrared spectrum.

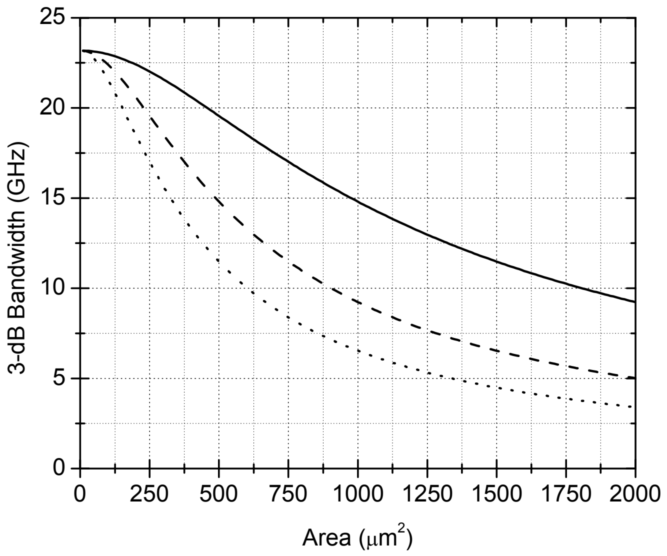


Figure 5. Calculated 3-dB bandwidth of the photodetector with the load resistance of 50Ω and for serial resistance of 0Ω (solid line), 50Ω (dashed line), and 100Ω (dotted line).

Other important property of a photodetector is the speed. In our detector, the speed will depend on different factors in different wavelength range. Below 920nm, the diffusion from the heavily doped layers will affect the speed of the photodetectors, while above 920nm, the speed will depend on the transit time of the photo-generated charges and the RC constant of the photodetector.

When a reverse bias of 10 V is applied, the electric filed in the intrinsic layer is 10^5 V/cm. At this electric field, the velocity of electrons and holes are 9.5×10^6 and 6×10^6 respectively. The time it takes all the photo-generated carriers in the intrinsic layer to reach the highly doped layers is around 10.5 psec and 16.7 psec for electrons and holes respectively. Our calculations show that small area photodetectors have transit time limited 3-dB bandwidth of 23 GHz. As the area increases, the capacitance of the photodetector increases and starts to limit the bandwidth of the photodetector. Figure 5 shows the calculated 3-dB bandwidth of the photodetector with the load resistance of 50Ω and for serial resistance of 0Ω, 50Ω, and 100Ω. Below 920nm wavelength, the diffusion current will degrade the 3-dB bandwidth significantly.

3. FABRICATION

The fabrication of the photodetectors starts with the p+ ohmic contact formation. Sample is patterned with photoresist and Ti/Pt/Au metals are deposited on the p+ InGaAs layer. After cleaning the sample, lithography is done for the n+ ohmic etch. All the layers down to the InGaAs etch stop layer inside the n+ InP layers are etched with wet etch solutions. H_3PO_4:H_2O_2:H_2O solution is used to etch InGaAs, HCl:H_2O solution is used to etch InP. After the desired depth is reached, Ge/Ni/Au metals are deposited. After the lift-off and the cleaning, the sample is processed at high temperatures to decrease the resistance of the contacts. Then, all the layers outside the mesa of the photodectors are etched down to the semi-insulating InP layer to isolate the photodetectors electrically from each other. The detectors are ready to the tests and post processing steps. The active area of the photodetector is patterned and etched gradually to see the effect of the thickness of the p+ InP layer on the responsivity and the speed of the photodetectors. Finally anti-reflection coating is deposited for the optimized structure.

4. CONCLUSION

The calculations show that the photodetector is capable of operating between the 500nm and 1700nm wavelength range, which covers the most of the visible and near-infrared spectrum. Also the photodetector has 3-dB bandwidth of 23 GHz for optical signals in the 920 nm to 1700 nm range. The bandwidth is lower below 920nm, but the expected bandwidth is above 10 GHz. With these properties, the photodetector shows high speed and wide bandwidth properties.

REFERENCES

1. B. Ackland and A.Dickinson, “Camera on a chip,” ISSCC Dig. Tech. Papers, pp. 22-25, 1996.
2. G. Lucovsky, R. F. Schwarz, and R. B. Emmons, “Transit-time consideration in p-i-n diodes.” J. Appl. Phys., 35, pp.622-628, 1964.
3. R. G. Smith and S. D. Personick, “Receiver design for optical communication systems,” in Semiconductor Devices for Optical Communication, 2nd ed., pp.89-160, H.Kressel-Springer-Verlag, New York, 1982.
4. T. Mikawa, S. Kagawa, and T. Kaneda, “InP/InGaAs PIN photodiodes in the 1 µm wavelength regio.” Fujitsu Sci. Tech. J., 20, pp. 201-218, 1984.
5. M. K. Emsley, O. Dosunmu, and M. S. Ünlü, “Silicon substrates with buried distributed Bragg reflectors for resonant cavity-enhanced optoelectronics,” IEEE J. Selected Topics in Quantum Electron., 8(4), pp. 948-955, 2002.
6. A. K. Dutta, M. Takechi, R. S. Virk, M. Kobayashi, K. Araki, K. Sato, M. Gentrup, and R. Ragle, “40 Gb/s Postamplifier and PIN/preamplifier Receiver Moduled for Next Generation Optical Front-end System”, IEEE J. Lightwave Technology, 20, pp. 2229-2238, 2002.
7. Hamamatsu, Optoelectronics Catalog, 2003.
8. Edward D. Palik, Handbook of Optical Constants of Solids, Academic Press, Orlando, 1998, Vol. 1.