Novel Broadband Photodetector for Optical Communication

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ABSTRACT

Broadband photodetector having detection capability ranging from visible to near infrared can be useful as a common detector for both data and transport applications. The capability of using single detector for all application in optical communication as the receiver, not only makes the total system cost lower, but it also makes easier the system vendors to reduce the inventory. We proposed detector having the detection capability ranging from 650 nm to 1750 nm, wavelengths that covers all optical communication wavelengths application. This invited paper has two-fold objectives: (a) provide a comprehensive overview of conventional photodetectors and their types, being used in today's optical communication and (b) introduce a development of multi-wavelength photo detector which authors pioneered. The features of proposed multiwavelength detector are simple structure, low-cost, high quantum efficiency, high sensitivity, and high speed.

KEYWORDS: Broadband, multiwavelength, optical communication, detectors, data-communication

I. INTRODUCTION

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Broad spectral detectors are required for various optical communications ranging from access to long-haul applications where wavelengths of *0.65-μm*, *0.85-μm*, *0.98-μm 1.3-μm*, and *1.5-μm* are used. To date, several detectors covering different spectral ranges are used for this purpose. Next generation communication receiver requires single detector that can detect multiple spectral bands (*0.6* to *1.5 μm* of wavelengths) and could be used for multiple optical communications. Using of single receiver having broadband detection capability can not only make the instrument unusually small, light and low-power requirement, but it can also help to reduce the inventories helping to reduce the total system cost.

As the detectable spectral ranges of Silicon (*Si*) are limited to the wavelengths below 1 μm (where *Si* exhibits absorption), *Si* based detector is usually used for detecting *0.65-μm* and *0.85-μm* wavelengths, frequently used for plastic fiber based private networks and access networks, respectively *[1]*. This Si- based detector has been extensively studied for its applications for shorter wavelengths (*0.6 μm* to *0.85 μm*). On the other hands, $In_{0.53}Ga_{0.47}As$ 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]*. Photodetectors especially of $In_{0.53}Ga_{0.47}As$ based *p-i-n* 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 as close to 1 *[5]* are available for optical communication. *InGaAs* material is usually used as absorption material, and the diode is fabricated on the *InP* wafer. None of the current solution can provide broad spectral detection capability ranges from *0.6 to 1.7 μm* of wavelengths, necessary for various optical communication applications. It is highly desirable to design a photodetector having broader spectral detection ranges (*0.6 to 1.7 μm*) and that could replace multiple detector usages in optical communication.

For covering broad spectral ranges especially from *0.6 to 1.7 μm*, conventionally two photodetectors 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 photodetector, which could offer high bandwidth (GHz and above) combined with high quantum efficiency over a broad spectral ranges (*0.6 to 1.7 μm*).

We propose a photodetector for broad spectral detection ranges (*0.6 to1.7 μm*), and estimate their key performances including quantum efficiency, bandwidth, and noise equivalent power. We believe the proposed photodetector could be used as a standard detector in next generation receiver for multipurpose optical communication.

II. TECHNICAL APPROACH

We will explain technical approach for achieving broad spectral ranges, high efficiency, and high-speed photodetector for various optical communication applications.

A. PHOTODETECTOR STRUCTURE

For designing a photodetector having broad spectral detection capability, we mainly focus on to the photodetector structure and its material system. First, conventional photodetector structure and its material systems are explained to have a clear view of our idea, based on which the main technical approach is made. This subsection covers only the structure of single photodetector, and the following subsection covers the proposed photodetector.

a. *Conventional Photodetector and Material Systems*

Figure 1 shows the dependence of the absorption coefficient on the wavelength for different semiconductors used in photodetectors. Absorption has asymptotic behavior near bandgap wavelength λ_g where the material is transparent, and there is a strong dependence of the absorption on the wavelength shorter than λ_g. Silicon and Ge have indirect bandgaps. For detecting 0.65-μm wavelength (plastic fiber based network) and 0.85-μm (short distance data communication), Si and GaAs are used as the photodetector materials, respectively. The absorption-coefficient dependence of Ge on the wavelength is fairly similar to that of direct-transition materials because of the narrow bandgap and narrow displacement between Γ and L in the momentum space. However, Ge is not very effective in detecting light with a loss-minimum wavelength of 1.55-μm. This is because a depleted absorption region of at least a few tenths of micron is needed to obtain a 90% optical-to-electronic conversion efficiency. In contrast, a 3-4-μm InGaAs layer thickness can enable high conversion efficiency in the 1.3-1.55-μm wavelength region, frequently used for medium and long-haul optical communication.

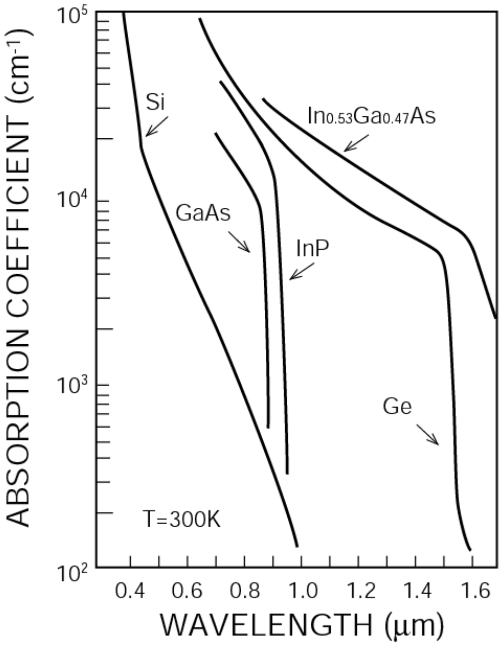


Figure 1: Dependence of the absorption coefficient on the wavelength for different semiconductors used in photodetectors

Indium phosphide (*InP*) based photodetectors especially of p-i-n type have been studied extensively over the last decade for its application in optical communication. These photodetectors are based on the structure and material system, which can detect the wavelengths covering from 0.9 to 1.7 μm. Figure 2 shows a cross-sectional view of a typical commercial photodetector. In most cases a thin layer of *InGaAs* acting as the absorption region, is sandwiched between two layers of doped *InP [8]*. These two materials (*InGaAs* and *InP*) combination used in the photodetector determine mainly photodetector's spectral detection region.

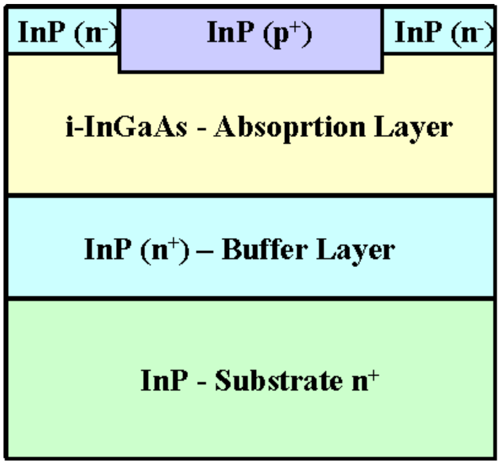
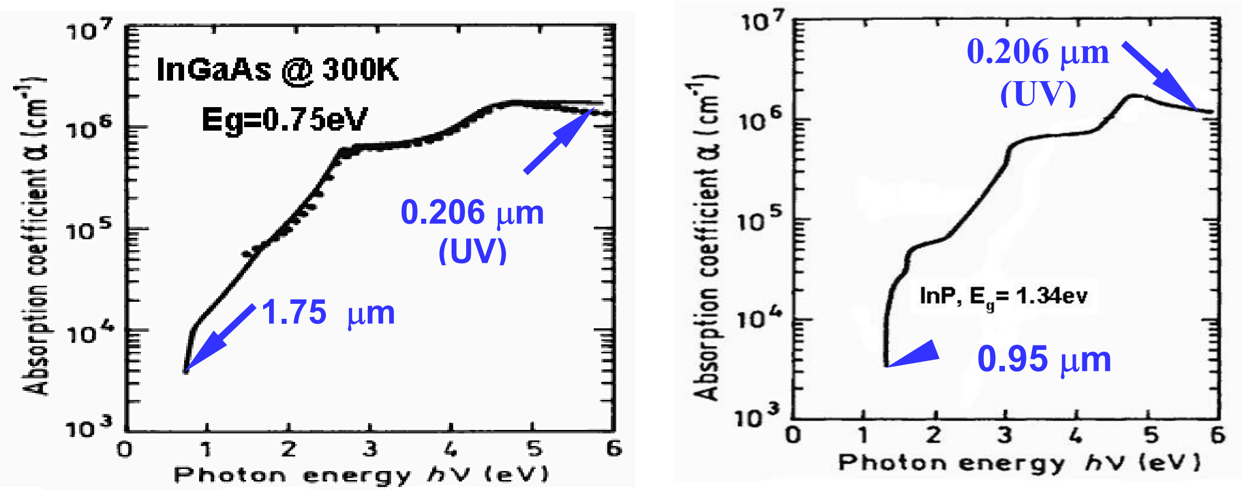


Figure 2: A commercial *InGaAs* photodetector. The contact layers are highly doped *p*- and *n*- *InP* layers.

The absorption spectra of *InGaAs* (lattice matched to *InP*) and *InP* materials are shown in Figs. 3(a) and 3(b). The bandgaps of *InGaAs* and *InP* are 0.75 eV and 1.34 eV, which correspond to wavelengths of ~1.7 μm and ~0.95 μm, respectively, since $\lambda_c = 1.24/E_g$, where E_g is the bandgap. The absorption coefficient of these material increases with increasing of photon energy. *Any photodetector made using InGaAs as the active absorption layer is expected to absorb all the wavelengths from UV (ultraviolet) to 1.65 μm unless some photons are selectively blocked.*



(a) (b)

Figure 3: The absorption coefficient of (a) *InGaAs* of bandgap 0.75 eV *[9]* and (b) *InP* of bandgap 1.34 eV *[10]* versus photon energies. These are the enlarged portion as shown in Fig. 1.

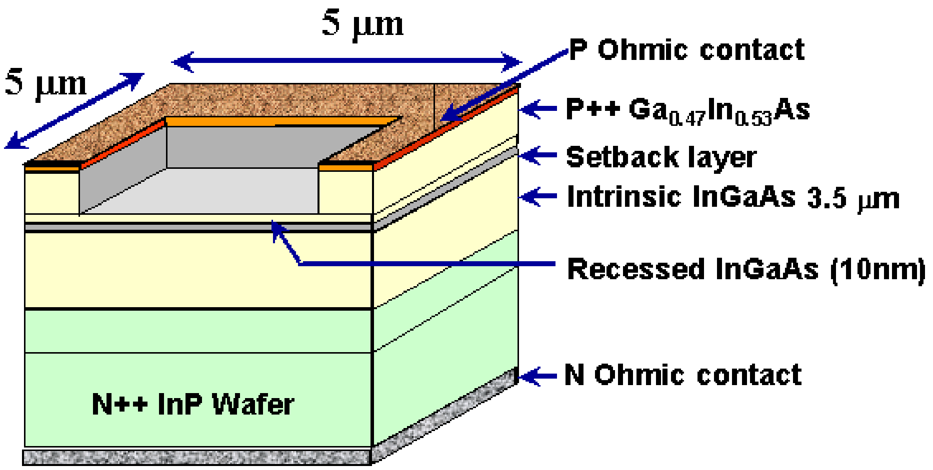
After carefully looking at Figs. 2 and 3, one can understand why conventional device structure as shown in Fig. 1 cannot respond to any photon with a wavelength below 0.95 µm. The reason is that the *InP* contact layer absorp the light of wavelengths below 0.9 µm. Any photon absorption in doped *InP* contact layers doesn't generate any electrical response in the device (if carrier diffusion is neglected). Thus, commercially available photodetector based on $In_{0.53}Ga_{0.47}As$ are not suitable for broad spectral ranges covering from 0.3 to 2.5 µm, but only limited to 0.9 to 1.7 µm.

It is also known that by increasing the content of Indium x of $In_xGa_{1-x}As$, the detectable wavelength range can be extended beyond 1.7 µm. $In_{0.8}Ga_{0.2}As$ material has a bandgap of 0.47 eV and can detect the wavelength range of 0.8-2.6 µm. *[11]*. In this case, the lattice mismatch is increased with *InP* materials and substrate, and this could be alleviated using of the $InAs_yP_{1-y}$ in between absorption layer $In_{0.8}Ga_{0.2}As$ and the substrate *InP [12]*.

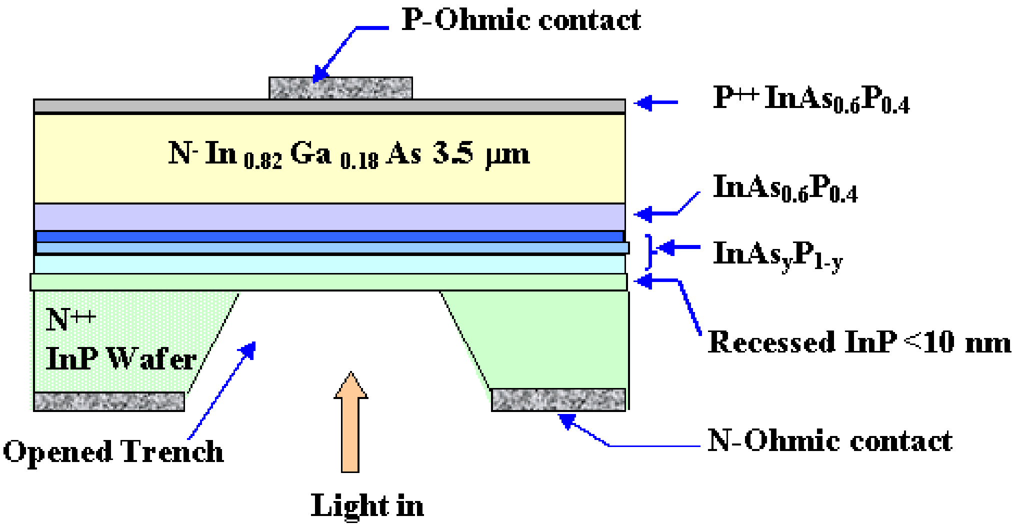
Conventionally, a wafer bonding technique is also used to design a photodetector with wide spectral response. In such devices, longer wavelengths are absorbed by a device structure shown in Fig. 1, while shorter wavelengths are detected by a Silicon photodetector, wafer bonded to an *InP* based structure. As the linear coefficient of thermal expansion (CTE) of *InP* and *Si* are $4.60\text{x}10^{-6}\,C^{-1,}$ and $2.6\text{x}10^{-6}C^{-1}$, respectively, the CTE mismatches cause stress in a wafer-bonded structure in wide temperature ranges operation. In addition, making an array with a wafer bonded structure poses a great challenge in designing interconnect with the aim of addressing individual pixels.

b. ***Proposed Photodetector Structure***

If the photodetector structure consists of *InGaAs* (lattice matched to *InP*) as a absorption layer, and an ohmic contact layer which does not absorb significant number of photons, the photodetector can be used in wide spectral regions covering from UV to 1.7 µm, and can be extended its detection capability to 2.5 µm by varying the *InGaAs* composition. *The detector can be top-illuminated type or bottom-illuminated type.* Figures 4(a) and 4(b) are the cross-sectional views of the top-illuminated and bottom-illuminated type photodetectors, respectively. The proposed device has a thick absorption layer of 3.5 µm *Ga0.47In0.53As* that ensures a quantum efficiency (QE) of more than 90% at 1600 nm wavelength and much higher QE for shorter wavelengths as suggested by Figs. 3.



(a) Top-illuminated type photodetector



(b) Bottom-illuminated type photodetector

Figure 4: The schematics of a pin photodiode with recessed (a) top contact layer and (b) bottom contact layer for allowing penetration of incoming photons.

Figure 4(a) is a top surface illuminated pin photodetector with a 100Å thin highly doped InGaAs layer as the top contact. The doped InGaAs thin layer will absorb less than 1% of the input power at 1600 nm wavelength and less than 5% at 400 nm wavelength. Incorporating a thin spacer layer in between intrinsic absorption layer and p-ohmic contact layer will prevent the p-dopant from diffusing to absorption layer. The photodiode is 5 μm x 5 μm with an opening of 3 μm x 4 μm or less for receiving light. The photodetector can be designed in circular or square in shape. The epi-layer is grown on a highly doped n-InP wafer and the n-ohmic contact is placed at the bottom of n+ InP wafer. The p-ohmic contact is a thin ohmic contact on a highly doped InGaAs layer with a dopant concentration of $>10^{20}/cm^3$. Figure 4(b) is a back-illuminated *p-i-n* photodetector with a <100Å thin highly doped *InP* layer as the bottom contact. The doped *InP* thin layer will absorb less than 1% of the input power at 2.6 μm wavelengths and less than 5% at 0.3 μm wavelengths. The photodetector can be made to 5 μm x 5 μm or less opening for receiving light. The diode can be designed in circular or square in shape. The buffer layers with graded composition of $InAs_yP_{1-y}$ are placed between absorption layer $In_{0.8}Ga_{0.2}As$ and the substrate *InP*. This dislocations bend at step interface of each graded layer and are disturbed to enter into the next layer. So it is very effective to reduce the dislocation density in the lattice mismatch materials [13], [14]. The epi-layer is grown on a highly doped *n-InP* wafer and the n-ohmic contact is placed at the bottom of *n+ InP* wafer. Thin layer of highly doped *InGaAs* layer of $>10^{20}/cm^3$ can be used on *InAsP* for the P-ohmic contact layer.

Broad-Spectral (UV to 2.5* μm*) and High Quantum Efficiency (>95%) Capability

The proposed device has a thick absorption layer of 3.5 μm $In_{0.8}Ga_{0.2}As$ that ensures quantum efficiency (QE) of more than 95% at 1.65 μm wavelength and much higher QE for shorter wavelengths as suggested by Figs. 3.

With varying the *InGaAs* composition, the proposed detector's sensitivity can be extended to UV to 2.5 μm. If we consider absorption of $In_{0.8}Ga_{0.2}As$ material is 5000 /cm at cut-off of 0.47 eV, like others low band gaps materials having cut-off band gap of below 0.5 eV, such as *InGaSb*, *InGaAsSb* etc, the quantum efficiency of the proposed photodetector structure is estimated to be > 80% at 2.5 μm of illumination for 3.5 μm thick absorption layer. The proposed photodetector not only can be made to high speed but also can be made to have high quantum efficiency at 2.5 μm of wavelength illumination.

High Speed* (<10 ps*)

The capacitance of the device is estimated to be in the range of sub femto-Farad due to the small junction area, and thick absorption layer. Overall frequency response is mainly limited by the transit time response. The 3 dB frequency f_t for the vertical detector can be expressed by $f_t = 3.5\nu/(2\pi x)$, where ν is the saturation velocity which is $\nu = 5.3\times10^6$ cm/sec for *InP [8]* and *x* is the absorption layer thickness. The frequency response of the proposed structure is estimated to be

10 GHz @ 3dB. The quantum efficiency greater than 95% for any wavelengths from UV up to 1.65 μm is also estimated.

Noise (Temporal)

Shot noise in detector is mainly determined by detector dark current which is mainly dependent on the type of detector material and its quality. As we propose to use well-matured *InGaAs* materials, in our proposed structure, we expect to have very low dark current and thereby very low noise. We would also use well-defined/matured process technology, which would allow us also to reduce the noise, induced due to the higher operating temperature.

C. Feasibility Check by Experimentally

To check the validity of our idea as explained in *Section a*, single conventional photodetector (as shown in Fig. 2) having ~0.8 μm thick top-*InP* contact layer, was fabricated, and its spectral response was measured. Noted here that $In_{0.53}\ Ga_{0.47}\ As$ layer having spectral response up to 1.7 μm is used as the absorption layer in the fabricated device. The main objective is to see whether the spectral response can be extended to the near ultra violet without using the *InP* as mentioned in Figs. 3. Figure 5 shows its spectral response of fabricated detector element (conventional type) of *1.0 mm diameter*. As depicted, the spectral response has a cut-off near 0.9 μm wavelengths, which is common for conventional *InP* based detector, which uses $In_{0.53}\ Ga_{0.47}\ As$ as the absorption layer.

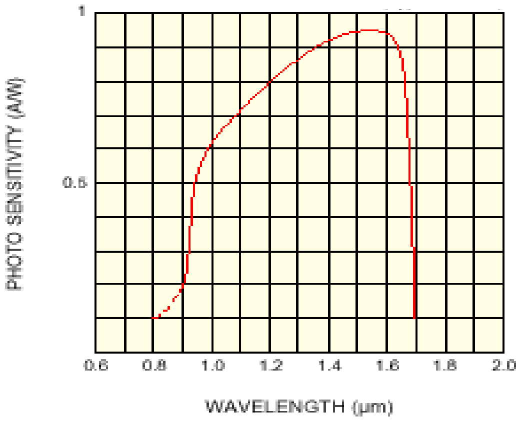


Fig. 5: Spectral response of conventional fabricated photodetector.

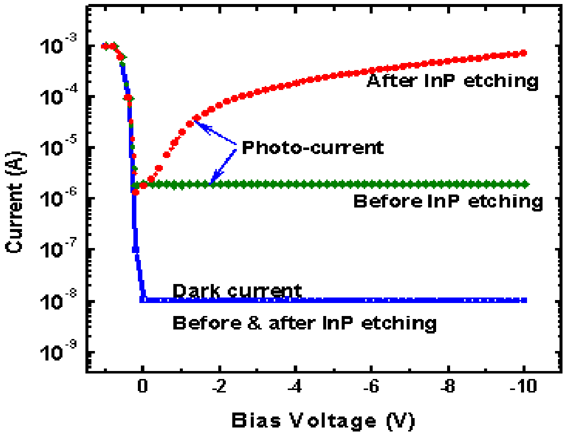


Fig. 6: I-V characteristics at different conditions

To check our idea, we measured its dark and photocurrent under white light illumination before and after *InP* etching. Approximately < 10 nm thick *InP* layer was kept to spread the field. The white light lamp, a combination of spectral wavelengths ranging from UV to near infrared was used for optical current measurement. Figure 6 shows the I-V characteristics at different conditions. It is clearly seen that, before etching the *InP* contact layer, detector's response is close to dark current under visible illumination. Once the *InP* was etched out (keeping ~ 10 nm for spreading), detector started to show its response under visible illumination. Figure 6 shows almost three order of magnitude increases in the photocurrent level. Combining Figures 5 and 6, it can be concluded that a similar structure with $In_{0.8}Ga_{0.2}As$ active region is expected to detect all the wavelength from <0.3 nm to 1.7 μm.

We plan to fabricate the proposed detector covering these wavelengths (<0.6 nm to 1.7 μm) using InGaAs on InP. As *InGaAs* is matured material, the dark current for 10 μm diameter is expected to be < 1 pA (from Fig. 6) without improving the process and the material quality. The proposed sensor is expected to offer frequency response of 10 GHz and above bandwidth, and high quantum efficiency over 95% over the entire wavelength region.

III. CONCLUSION

We propose a novel photodetector having broad spectral bandwidth ranging from *0.6 to 1.5-μm* for optical communications. Today, from short distance to long-haul optical communication, various wavelengths such as 0.65-*μm, 0.85-μm, 0.98-μm, 1.3-μm, and 1.5-μm* are used, and proposed photodetector could be used as a common detector for all wavelengths being used for optical communication and could replace multiple detector usages. Initial experimental results and estimated results indicate that proposed detector could be made to high speed, high quantum efficiency, and low noise. More work is underway and would be presented in near future.

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