Design and Analysis of High Frequency Solar Blind Photodetectors for Communication with Red Signal.

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Abstract. Advantages associated with high-speed communication and data security bolsters the eligibility of Free Space Optical (FSO) and Visible Light Communication (VLC). In this context, characteristics like low noise equivalent power, high frequency response associated with the photodetectors play pivotal roles in determining the performance of the entire communication FSO/RF link. In this study, the authors present the design of detector sensitive to red signal coming from commercial laser with wavelength 650nm (photon energy 1.9eV), while being blind to the rest of sun spectrum. High-sensitivity to signal of commercial laser is provided by double barrier tunnelling p-i-n photodiode made up of Al₀.₅Ga₁₋₀.₅As heterostructure with mildly doped p-type and n-type regions. The photodetector operates as window discriminator. The quantum operation of double barrier tunnelling significantly narrows the band of detectable red light. In addition, all photons with high energy are effectively cut off by p-i-n filter, positioned at the top of the structure. This filtering layer works at the same time as a solar cell and provides reverse bias to the photodetector. Low noise equivalent power on the order of 0.2pW/√Hz and cut-off frequency of 20GHz make this device eligible for FSO communication.

Keywords: Optical, detectors, wireless communication, solar blind

1. Introduction
Recent developments in the area of free space optical and visible light communications [1-3] have opened up new possibilities high speed data transfer and security. In this context, requirement for photodetectors that enable high frequency and less noisy operation has piqued recently. Another facet of merit associated with these sensors is selective sensitivity to the input radiation, which can ensure data security and eliminate chances of intermodulation of input signals. Along this line, recent works [4-6] provide solutions for wavelength selective photodetection for visible, IR and UV segments of the electromagnetic spectrum.

Similar tendencies are observed in R&D of solar blind photodetectors designed to operate in different segments of visible spectrum. Reviewing state-of-the-art solar blind photo-detector technology, we discovered that many novel designs that claim “solar blindness” are not very accurate. We believe that terminology used in description of solar blind photodetectors operation should be corrected. We randomly selected and studied a few [7-12] of the many research studies that appeared in the recent years on the subject. By definition, selection of the semiconductor material in any design with given energy gap $E_g$ makes photodetector automatically blind to all photons from sun spectra with energy $E_{ph}$ smaller than $E_g$ of the material [13]. However, this energy gap $E_g$ is not accurately defined
as threshold barrier and changes with surrounding temperature. Also, no well-defined upper limits of photon energies with which a photodetector is designed to operate, makes it unsuitable for operation with well-defined band of frequencies of the optical signal. That the photodetector designed with no window discriminator would see large part of sun spectra is what makes “solar blind” terminology hardly applicable for these devices.

Significance of low Noise Equivalent Power (NEP) and high frequency response for photodetectors have already been stressed in [14-15]. With high frequency operation being conducive to larger bandwidths and consequently improved data transfer rates, photodetectors capable of responding to high frequency, directly modulated incident radiation have the potential to ensure significant progress in these technologies.

The major challenge of the design of a photodetector for a given wavelength is the necessity to restrict sensitivity of the device to the narrow band of wavelength emitted by commercial laser. We did find the solution to that problem while designing first photodetector, where double barrier tunnelling sorted out and collected the photo carriers with the well-defined energy [16]. This work included an optical photodetector in which selectivity of the device is entirely dependent on quantum alignment of energy of electrons generated by light with energy levels in quantum well of the resonant diode. The proposed structure involved tunnelling of electrons across the potential barrier which enables their separation from the holes that were generated along with them. However, susceptibility of the device to high energy photons in the solar spectrum is quite evident. In current research “solar blindness” is achieved by a much more complex design [17] that offers high value for cut-off frequency and low NEP. Solar Blindness is claimed in our work by restricting the sensitivity of the device to a very narrow band (640nm-650nm) of wavelengths that have negligible footprint in the solar spectrum. The design is supported by filtering layer that keeps high energy photons from irradiating the photodetector and provides the required bias voltage to it.

2. Modelling and Design

As shown in Figure 1, the structure consists of two sections- a filter and a double barrier tunnelling diode. The 0.8µm thick topmost section which is exposed to external illumination, forms a p-i-n solar cell made up of Al_{0.4}Ga_{0.59}As with E_g=1.93eV. It acts as a filter to absorb all photons with wavelengths shorter than 640nm and provides required voltage supply in reverse bias to the lower section. The structure is realized as a 0.5µm thick intrinsic layer sandwiched between equally doped 0.1µm thick positive and negative terminals (N_a=N_d=10^{14}cm^{-3}).

![Figure 1](image)

**Figure 1.** a) Positive terminal of solar cell b) Intrinsic region of solar cell c) Negative terminal of solar cell d) Insulating contact e) p-type electrode of photodetector f) Lightly doped barriers g) lightly doped well h) n-type electrode of the photodetector
The photodiode having $E_g=1.9\text{eV} \ (\lambda=0.65\mu\text{m})$ which comprises the lower section operates on the basis of double barrier tunnelling phenomenon. It consists of 3nm thick n-type doped quantum well made of Al$_x$Ga$_{1-x}$As ($x=0.38$), housed between two 3nm thick (each) n-type doped barriers of AlAs ($E_g=2.16\text{eV}$). The 0.66µm thick top and bottom electrodes in the photodiode, made of Al$_x$Ga$_{1-x}$As ($x=0.38$) are p- and n-type doped respectively. The acceptor doping in the top electrode $N_a=12\times10^8 \ \text{cm}^{-3}$ while n-type doping in bottom electrode $N_d=10^4 \ \text{cm}^{-3}$. Figure 2, depicts the energy levels (in eV) associated with finite quantum well and conduction band at different depths plotted on x-axis within the photodetector. The confined discrete energy levels which can modulated by varying the thickness of the well and the height of the potential barrier, are highly sensitive to energy of photo-carriers and very efficient in selection and tunnelling of incoming electrons.

By reducing the number of discrete energy levels to one, the device is designed to conduct photoelectrons on application of a small reverse bias voltage of 1V between the emitter and the collector. The reverse bias on the p-side brings the highest energy level down for the electrons to tunnel through. The negative terminal of the solar cell and p-type doped electrode of the photodetector are shorted by an aluminium contact extending along the rim of the device which forms ohmic contacts at these terminals. Ohmic contacts made of aluminium at the positive terminal of the solar cell and bottom electrode of the photodetector are shorted in a similar way. A 0.1µm thick intrinsic layer of Al$_{0.38}$Ga$_{0.62}$As, shown in Fig.1, acts a non-opaque insulating layer between these terminals. Taking into consideration the analysis pertaining to the gaussian intensity profile of the laser beam conducted in [18], the dimension of the device is finalized at 1mm×1mm.

![Figure 2. Energy profile within the finite quantum well formed by AlAs/Al$_x$Ga$_{1-x}$As heterojunctions.](solid line: conduction band, dashed line: discrete energy level within the quantum well)

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### TABLE I

**CALCULATED VALUES OF CURRENT DENSITIES WITHIN THE SOLAR CELL AND PHOTODETECTOR FOR VARIOUS SOURCES.**

| Device     | Source       | $\lambda, \text{nm}$ | $\Phi_0(\lambda)$, photons cm$^{-2}$s$^{-1}$ | Current Density, $J_l$, mA/cm$^2$ |
|------------|--------------|-----------------------|---------------------------------------------|----------------------------------|
| Solar Cell | Sun Spectrum | 500-600               | $1.65\times10^{17}$                         | 38                               |
| Photodetector | Sun Spectrum | 639-650             | $5\times10^{15}$                             | 1.148                            |
| Photodetector | Laser      | 650                   | $10^{18}$                                   | 755                              |

To assess the overall impact of the red band within the solar spectrum and the red colored laser beam in terms of output current density, on the device and the solar cell following formuleae sourced from [18] were used-

$$G_L = \alpha(\lambda)\Phi_0(\lambda)[1 - R(\lambda)]e^{-\alpha(\lambda)x} \quad (1)$$
\[ J_L = eG_L \tau_p (\mu_n + \mu_p) \]  \hspace{1cm} (2)

Where \( \alpha \) is the absorption coefficient, \( \Phi_0(\lambda) \) is the intensity of photon flux (having wavelength equal to \( \lambda \)) falling on the surface of the device, \( \mu_n \) and \( \mu_p \) are electron and hole mobilities, \( \tau_p \) is minority carrier lifetime for holes, \( G_L \) is the electron hole pair generation rate at depth \( x \) into the device and \( R(\lambda) \) is the fraction of photons reflected at certain depth in the device.

Since, the evaluated current density (depicted in table1) for the photodetector associated with 640nm-650nm band of the sun spectrum is negligible compared to that produced by same band from a red laser beam, the design can rightly be inferred as being blind to solar irradiance falling within this band of wavelengths.

3. Results of simulation and analysis of noise and frequency response

Two separate analyses were conducted on SILVACO to evaluate performances of photodetector and the solar cell. The output current density of the photodetector when reverse biased with a voltage of 1V and irradiated with a 650nm laser beam with intensity=1W/cm\(^2\) turns out as 136mA/cm\(^2\) which is of the same order as the assessed value in table1.

![Figure 3. I/V characteristics of the solar cell (x-axis presents anode voltage in Volts; y-axis presents output current density in A/cm\(^2\))](image)

As expected, negligible values of current on the order of 2.5pA/cm\(^2\) (dark current) are obtained when the reverse biased photodetector is operated in the absence of laser radiation. Since the output current density of the photodetector is obtained at a bias voltage of 1V, the responsivity of the device has been evaluated as 0.136A/W.

![Figure 4. Circuit diagram explaining joint operation of the solar cell and the photodetector](image)
The performance characteristics of the solar cell depicted in Figure 3, have been obtained through simulations with solar spectrum. The open circuit voltage $V_{oc}$ was obtained at 1.04V. Simulated value of short circuit current density (11.5mA/cm$^2$) is also comparable with the theoretically evaluated value in table 1.

Joint operation of the solar cell and photodetector is realized through a circuit similar to the ones presented and analysed [19] and [20] since the difference in magnitudes of current from the solar cell and photodetector continues to be the same, when load resistance is connected between the top electrode of the photodetector and ground. The circuit is depicted in Figure 4. Availability of solar radiation and/or high energy radiation enables reverse biasing of the photodetector by the voltage that is generated across its terminals. As a result, the radiation availed at the top electrode of the photodetector is depleted of high energy photons ($E_g$=1.94eV).

Presence of laser radiation falling within band of wavelengths associated with photon energies ranging from 640nm (1.93eV) to 650nm enables outward flow of current (given by the reverse biased direction) from the top electrode of the photodetector. The output current from the photodetector, depicted as $I_{photo}$, is too high to be supported by the solar cell which enables short circuit of 11.5mA/cm$^2$ and inhibits current flow from the photodetector. As a result, $I_{photo}$ is driven towards ground by the “LOAD”, which may comprise of impedance matching circuits, amplifiers or other such RF interfaces.

Figure 5. Signal to noise ratio in dBs plotted along y-axis against incident optical power in pW (pico-Watts) plotted in logarithmic scale along x-axis.

By definition, Noise Equivalent Power (NEP) of the photodetector is the optical power input that produces output current equal to dark current output of the photodetector. This value was extracted by simulating the device with decreasing intensity of 650nm laser.

Figure 6. Output current in A/cm$^2$ of the photodetector along y-axis plotted against frequency of small magnitude radiation along logarithmic x-axis.
Since the output current decreased linearly with intensity, 0.2 × 10^{-10} \text{W/cm}^2 of incident intensity produced total output current in the order of 2.5pA/cm², to realize the signal to noise ratio (SNR) of 1 as shown in Figure 5. The value of incident power was scaled down to the proposed are of cross-section of the device to pitch the NEP of the device at 0.2pW/\sqrt{\text{Hz}} of incident bandwidth.

Small signal AC analysis of photodetector was carried on SILVACO by initially irradiating the device a 650nm beam having intensity of 1W/cm². Leveraging the linearity between intensity of incident radiation and total output current (evident from Figure 5.), frequency response of the photodetector to directly modulated (at source) incident beam was carried out by superimposing solution of another small signal variable optical input of the same wavelength on the existing response. The small signal input had intensity peaking at 1mW/cm² with frequency of oscillations varying from 100KHz to 110GHz. From the obtained results depicted in Figure 6. The 3dB power cut-off frequency of the photodetector can be approximated at 20GHz.

4. Conclusion

Through this work, apart from the ability of achieving solar blindness by ensuring sensitivity only to a 10nm wide band of wavelengths, we have enabled high frequency operation. Low value of NEP associated with our design is also in compliance with current standards of industry.

Significance of window discrimination-based design used for achieving solar blindness is underlined by current study. Another important feature of our design is the solar cell (top layer of the structure) that solves two purposes as at the same time by simultaneously functioning as cut off filter, and collector of solar energy for providing bias of about 1V to the photodiode. As a result, sensitivity to a very narrow band (640nm–650nm) bolstered by double barrier tunnelling is the most important feature of our work which accurately implies window discrimination. As stated in [1-3] prospective applications of this device include under water communication, information processing and satellite to ground station high speed data transfer.

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