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Optical Characterisation of the Photodetector and Light Emitting Diode over a Wide Range of Temperature

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Abstract: *The influence of temperature on the photo-voltage generated by silicon based photodetector and intensity of light emitted by a high efficiency GaAsP/GaP hetero structure based red light emitting diode has been investigated in the temperature range from 350 to 110 K. Our experimental results show the variation of the photodetector's output from 0.4208 mV to 0.4159 mV whereas the light intensity varies from 0.74 (arb. uni.) to 8.49 (arb. uni.) when the temperature decreases from 350 K to 110 K. The variation of these parameters with temperature is being analyzed by existing theoretical models. The theoretical analysis of the experimental data for the photodetector gives qualitatively the temperature dependence of the product of the carrier mobility (μ) and of its lifetime (τ). The temperature dependence of the product μτ for the present photodetector, shown in our experimental result is $T^{-1.12}$. For the light emitting diode at low temperature the Shockley-Read-Hall (SRH) recombination takes a paramount role along with the radiative recombination. Furthermore, the obtained data for these two important devices will be of help to decide the use of these devices for precision work at different ambient temperatures particularly, at low temperature.*

Keywords: *Si based photodiode, photo-voltage, carrier mobility and lifetime, GaAsP/GaP based LED, light intensity, thermal stress.*

1. INTRODUCTION

The detection and emission of ultra-violate to infrared is an important area in the space and defence research programme. It is needless to mention there are many instruments used in the field of defence and space research programmes which make use of radiation detection and emission. The performance and reliability of these instruments intensely depend on the detectors and emitters of this radiation [1-3]. And to ensure the quality of performance special attention should be paid to design these instruments. It is expected that the performance of these instruments remains stable over a wide range of temperature that may vary from room temperature to temperature far below and above it. It is found that the performance of the sensing parts of these instruments which include different types of photodiodes and solid state high performance light emitting diodes (LEDs) drastically alters with temperature [1, 2]. There is a high possibility that due to lack of information on the changes of the relevant parameters of these optoelectronics devices with the variation of temperature, the operation of these instruments will be unreliable. It is observed that the photodetector's output may reduce drastically, if the temperature of the environment, where the detector is located, decreases even when the incident radiation on the detector remains constant. On the other hand, the emission of a LED will increase for a fixed driving current with the lowering of ambient temperature [4]. And as such for proper choice and appropriate functioning of the optoelectronics devices and to develop instruments based on these devices to operate simultaneously from room temperature to very low temperature region, one requires detailed information on the variation of the device parameters. Without this information it is difficult to design such instruments. There is not enough study on the performance of the commercially available detectors and emitters from room temperature to low temperature area [4-6]; though it has a huge application. Hence, to focus the importance of this particular issue, we propose to study the behaviour of different types of commercially available photodetector and LED in the temperature range from 350 to 110 K.

2. EXPERIMENTAL DETAILS

In our investigation we used one silicon based high photosensitive p-n photodiode (BPW20RF) procured from RS Components, having spectral response peak at 920 nm and chip active area is of 7.5

mm^2. Also, their minimum and maximum wavelength detecting capacities are 550–1040 nm. The photodiode was mounted in a specially designed sample holder having a copper metallic base and arrangement for pressure contact. The LED as a light source will be kept outside of the cryostat with a constant forward current as shown in Fig. 1. The cryostat chamber was evacuated to a pressure 10^{-4} Torr to avoid moisture on the opto-electronics devices by using a high vacuum pumping unit (Model No. PU-2 CH-8, manufactured by- Vacuum Products & Consultants). One voltage source is used for operating photodiode. For temperature measurement in the range 350-110 K one keithley (2000 Multimeter) and a K-type (Chromel-Alumel) thermocouple (TC) are used. The TC output was recorded by a Keithley 2000 multimeter with accuracy of the order of ±0.14 K. Due to the incident of illumination on photodiode it generates the photo-voltage which flows through the sensing resistance connected in series with the photodiode's circuit (see Fig. 1) and it is measured at different temperature by the Philips multimeter. For characterization of LED, it will be placed inside the cryostat and the photodiode will be kept outside. In this investigation we used one GaAsP/GaP based high efficiency red LED namely, L-53ID, having a peak wavelength 627 nm. The details of the experimental set up are also available in our previous work [2].

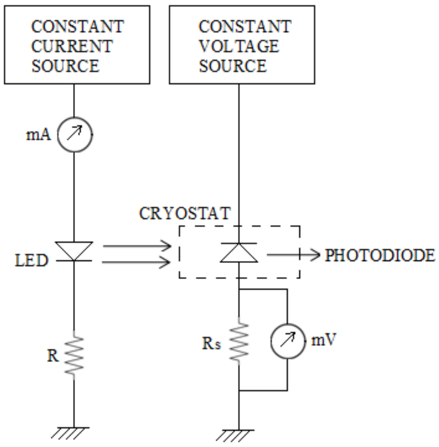

Fig1. *Schematic diagram of the experimental set up used for the photo-voltage (V_{ph}) measurement*

3. Results and Discussions

3.1. Temperature Characteristics of Photo-Voltage

The variation of photodiode's output voltage at different temperatures is shown in Fig. 2 and listed in Table 1.

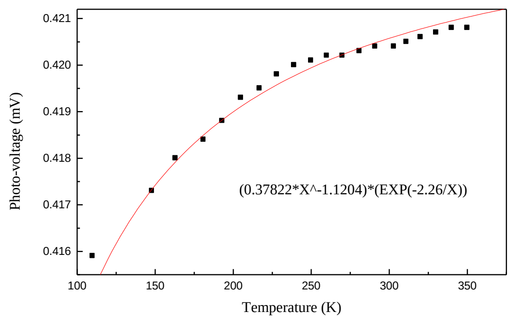

Fig2. *Variation of the photodiode's output with temperature for fixed illumination incidents on it. Numerical fit, continuous line according to Eq. (3). The solid square indicates the experimental points*

In order to understand the effect of lowering of temperature on the optical performance of the photodetector, we consider only the photons that produce the electron-hole pairs (g_{op}). Hence, due to incident of photon on the photodiode, the change in excess electron or hole concentration Δn and Δp becomes as [7]

$$\Delta n = g_{op}\tau_n \; ; \quad \Delta p = g_{op}\tau_p \qquad (1)$$

where, τ_n and τ_h are the excess charge carrier lifetimes. Due to incident of photon on the photodiode its photoconductivity must be changed and is turned into [7]

$$\Delta\sigma \approx q g_{op}(\tau_n\mu_n + \tau_h\mu_h) \tag{2}$$

where, μ_n and μ_h are the mobilities of electrons and holes respectively. For Si based device we assume a simple non-radiative recombination which implies the lifetime of electrons and holes are almost equal and hence the variation of photocurrent as a function of temperature is given by

$$I_{ph} \approx AT^{-2}exp\left(-\frac{E_g}{KT}\right)V \tag{3}$$

where, A (= WD/L; W = chip width, D = thickness, L = length) is a temperature independent constant and V is the applied voltage across the electrodes. In Eq. (3) we assume that the temperature dependence of μ is $T^{-3/2}$ and g_{op}~$\exp(-E_g/KT)$, respectively and E_g is the bandgap of Si [4]. In our previous work we have observed that for a package device temperature dependence of τ is quite complex and a strong temperature dependence is found at lower temperature region rather than high temperature. Manik et al. [4] assume temperature dependence of τ is $T^{-3/2}$, but in Eq. (3) we assume $T^{-1/2}$ for τ. However, to get only the dominant effect, Eq. (3) may be simplified by neglecting the temperature dependence of the product $\mu\tau$ as [4]

$$I_{ph} \sim exp\left(-\frac{\gamma}{T}\right) \tag{4}$$

where, γ is a temperature independent constant. The current according to Eq. (4) is allowed to pass through a sensing resistance R_s which is connected in series with the photodiode's circuit. Equation (4) implies that if we plot $\ln V_{ph}$ versus 1/T curve it should be a straight line (actually we measure the photo-voltage (V_{ph}) which is proportional to the current in the photodiode). To check the validity of Eq. (4) we plot $\ln V_{ph}$ against 1/T which is shown in Fig. 3 and found that our experimental data qualitatively corroborate with the above relation of photocurrent. Figure 3 clearly shows that it exhibits two linear regions with different slope and a major deviation from linearity at the lower temperature region which suggests the exact temperature dependence of product $\mu\tau$ is needed to include in the temperature dependent photocurrent relation specially at low temperature.

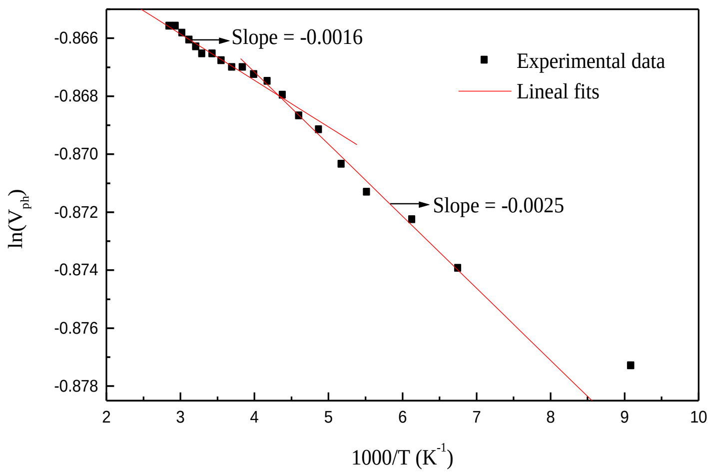

Fig3. *Plot of $\ln V_{ph}$ versus 1000/T*

Since, in Eq. (3) the temperature dependence of $\mu\tau$ is assumed then the experimental data is fitted according to this relation (see Fig. 2). From Fig. 2 it is evident that Eq. (3) shows an improvement at low temperature and the best fit parameters suggest temperature dependence of $\mu\tau$ is –1.12. Moreover, such analysis can give qualitatively the temperature dependence of $\mu\tau$ and help to know the inside physics of the device.

3.1. Variation of LED Intensity with Temperature

The variation of light intensity with temperature is shown in Fig. 4 and listed in Table 1.

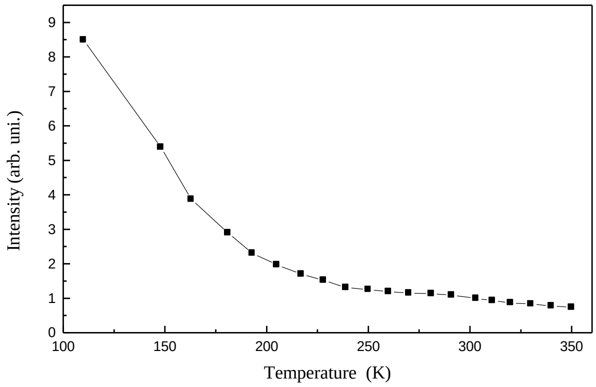

Fig4. *Variation of LED intensity with temperature at a driving current of 15 mA*

Variation of LED intensity with temperature curve shows that the LED is extremely sensitive to temperature. Figure 4 shows that the light intensity increases rapidly within the range of temperature 217 K to 148 K whereas it further goes lower when the temperature level is below 148 K. It is also to note that the obtained results have good reproducibility and consistency. However, the variation of intensity of an LED as function of temperature may be described by the following relation given by [4]

$$L_{T'} = L_{T_0} exp[-C(T' - T_0)], \quad (5)$$

where $L_{T'}$ and L_{T_0} are the luminous intensities of LED at temperature T' and at some other reference temperature T_0 respectively, and C = lnά$L_{T'}$ where ά is the temperature coefficient of the intensity. Generally, the photocurrent is generated in the photodiode due to the incident of radiation from the LED which is allowed to pass through a sensing resistance. Actually the voltage drop across the sensing resistance of the photodiode is measured which is in turn assumed to vary linearly with the light intensity of LED incident on the photodiode, given by Eq. (5). In terms of voltage, Eq. (5) may be rewritten as

$$V_{Out} = C' L_{T_0} exp[-C(T' - T_0)], \quad (6)$$

where C', which is assumed for simplicity, a temperature independent constant. To get only the dominant effect, Eq. (6) may be simplified by assuming that the temperature coefficient of the intensity ά is independent of temperature, and then Eq. (6) yields

$$lnV_{Out} \approx \frac{lnA}{T} - lnB, \quad (7)$$

with A = $C' L_{T_0}$, B = ά/C', and $T = T' - T_0 \gg 1$.

Equation (7) is a straight line equation with decay character.

Now, we draw a curve between ln($L_{T'}$) and inverse temperature 1/T to check the validity of the Eq. (7) which is shown in Fig. (5)

A close observation reveals that Fig. 5 exhibits three linear regions with different slope values, though the first and the second slopes are quite closer. The value of the third slope is far distinct from previous two due to the occurrence of a sharp break below 148 K which suggests that Eq. (7) evaluates a satisfactory range of temperatures to some extent and ά may also vary with temperature. If we relate ά to inverse characteristic temperature then it is more reasonable to assume that it has weak temperature dependence [8]. Mainly, the characteristic of ά is influenced by the SRH recombination rate, that is, not by the radiative recombination and Auger recombination rates [8]. Our experimental results represent that the light intensity increases rapidly for lowering of temperature and as result the radiative recombination is proved more effective rather than two recombination mechanisms. But at low temperature the SRH recombination again plays a paramount role along with the radiative recombination and creates a weaker temperature dependence of the emitted intensity. However, it has to be pointed out that the above relation describes only the gross feature of the effect of temperature on the performance of the device.

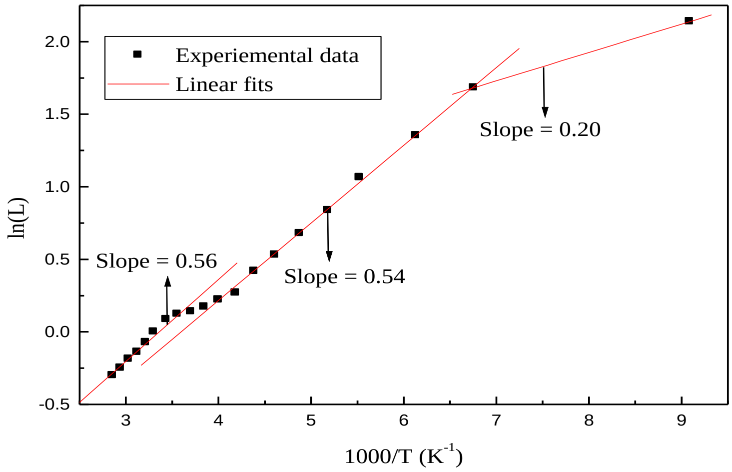

Fig5. *Experimental fit of the ln(L_T') with inverse temperature 1/T*

Table1. *Experimental values of photo-voltage (V_{ph}) of BPW20RF photodiode and light intensity (L_T') of L-53ID LED at different temperatures.*

Temperature (K)	V_{ph} × 10 (mV)	Intensity (arb. uni.)
350	4.208	0.74
340	4.208	0.78
330	4.207	0.83
320	4.206	0.87
311	4.205	0.93
303	4.204	1.0
291	4.204	1.09
281	4.203	1.13
270	4.202	1.15
260	4.202	1.19
250	4.201	1.25
239	4.20	1.31
228	4.198	1.52
217	4.195	1.70
205	4.193	1.97
193	4.188	2.31
181	4.184	2.9
163	4.18	3.87
148	4.173	5.38
110	4.159	8.49

4. Conclusions

In conclusion, the optical studies of available optoelectronics devices at different ambient temperatures are necessary to use them in this temperature range. Since these data are not available, in particular, for such commercial photodiodes and LEDs, the present measurements on these devices provide new information which will be proved to be beneficial to make the design as well as the execution of the application. According to Eq. (3) the variation of photo-voltage of the present device with temperature demands that the temperature dependence of carrier mobility as well as lifetime are should be known because these parameters have an effect on V_{ph}, in particular at low temperature. For the present photodiode theoretical analysis of its experimental data seems to imply that the product $\mu\tau$ depends on the temperature as $T^{-1.12}$ which helps us to know the important physics within the device. However, further studies in this direction are required on the various types of photodiodes for acquiring a better insight and to substantiate the scientific views of the actual temperature dependence of $\mu\tau$.

The plot between lnL_T' versus 1/T, shows a sharp break in the curve below 148 K i.e. the gradient is different which suggests that Eq. (7) satisfies a limited range of temperatures and the characteristic of ά is mainly influenced by the SRH recombination rate. The intensity of the LED increases with lowering of temperature which improves visual perception is a distinct advantage for low temperature application of the device. However, this is proved to be futile by increasing the forward voltage which ultimately leads to breakdown. Hence, for designing the device, the execution of the application should have to address these competing effects.

This work is expected to stimulate further theoretical and experimental study to achieve better understanding of the carrier transport mechanism in such devices and the obtained results can be used to get a deep insight into the optical characteristics of photodiode and LED to improve the device performance.

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