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THE ELECTRICAL PROPERTIES OF $Hg_{1-x}Cd_xTe$/Si DIODES

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ABSTRACT

n-type $Hg_{1-x}Cd_xTe$ films of 1 μm thickness with various Cd content (16,18,20,22)% have been deposited on p-type wafer Si Substrate by using thermal flash evaporation technique to fabricate p-n heterojunction.The electrical properties of this junction which include the capacitance-voltage and current-voltage were studied . The C-V characteristic which studied at frequency equal to 10 kHz gave an indicated that these diodes are abrupt type. The capacitance decreases with increasing the reverse bias voltage and Cd content, and the width of depletion layer increases with increasing Cd content. The value of built-in potential varies from 0.11 to 0.19 V when x value change from 16 to 22%.

The current-voltage characteristic for $Hg_{1-x}Cd_xTe$/Si diodes show that the forward current at dark condition varies approximately exponentially with applied voltage and the mechanism of transport current coincide with recombination-tunneling model. The rectification coefficient and ideality factor increases with increasing Cd content and reduce the temperature, while the tunneling constant decreases with increasing Cd content and the tunneling current increases when the temperature drops to 77 K. From the I-V measurements under illumination, the photocurrent increases with decreasing Cd content.

Key Words: $Hg_{1-x}Cd_xTe$ alloys and films, flash evaporation technique, C-V characteristics of $Hg_{1-x}Cd_xTe$/Si heterojunction, I-V characteristics of $Hg_{1-x}Cd_xTe$/Si heterojunction.

I. INTRODUCTION

In the recent several years, the unquestionable leader among semiconductor materials applied in production of infrared detectors has been mercury-cadmium telluride (MCT).particular interest in this material result, first of all from its fundamental physical properties. It is characterized by variable, composition- dependent energy band gap, demonstrates high mobility of electrons in relation to the mobility of holes, has low permittivity, as well as it is possible to produce both low and high concentrations of majority carriers [1].The extremely small change of lattice constant with composition makes it possible to grow high quality layers and graded gap structures [2].

HgCdTe was first synthesized in 1958 by a research group led by Lawson at the Royal Radar Establishment in England, this work was the successful out come of a deliberate effort to engineer a direct- band gap, intrinsic semiconductor for the long wavelength infrared spectral region(8-14 μm)[3].So that its regarded fundamental interest material since few decades owing to its widespread applications in industrial, space and military systems[4].

The narrow gap semiconductor alloy $Hg_{1-x}Cd_xTe$ is the dominant material for the fabrication of high performance infrared photon detectors and detector arrays used in night vision, thermal imaging and ballistic missile defense due in part to its variable direct band gap [5].

The lattice constant of MCT is weekly changed for different compositions between CdTe and HgTe. This is very important for using complex MCT heterostructutres (HS's) for a new generation of IRD. Using different physical processes enables us to design different types of IRD operating in a wide temperature range (from liquid nitrogen temperature to room one)[6]. The market demand as well as other competitive technologies make higher

requirements for improving the HgCdTe heterostructure parameters [7]. 145The efforts have been focused on the development of third generation devices, which are multicolor devices and large focal plane array detectors for which high-quality, large and homogenous active layers are necessary[8].
In this paper ,we have studied the electrical properties of $Hg_{1-x}Cd_xTe$ films which prepared by flash evaporation because the preferential evaporation in the conventional method would lead to non stoichiometric films on Si substrate. The advantages of Si substrate for HgCdTe , include the ability to make large area single color LWIR detectors.

II. EXPERIMENTAL PROCEDURE

$Hg_{1-x}Cd_xTe$ alloys of different x value (16,18,20,22)% were prepared from their high purity elements (purity 99.999%). An isotype HgCdTe/Si heterojunctions were made by depositing n-type $Hg_{1-x}Cd_xTe$ films of thickness equal to 1 µm on p-type single crystal Si of (111) orientation at 473 K and the rate fixed at (1/30) µm/min by thermal flash evaporation technique with vacuum pressure below 10^{-5} mbar.
The capacitance-voltage characteristics measurement made by using LRC apparatus type (Agileut 429 uA Precision Impedance Analyzet) at frequency 10 kHz .
Capacitance at different reverse bias voltage at the range (0-1) volt was measured to determine the type of the heterojunction (abrupt or graded).
The value of built-in voltage (V_D) was obtained from the plot of inverse capacitance squared versus reverse bias voltage, and then the interception of the straight line with voltage axis represents the built-in voltage. Also the width of the junction can be deduced from the flowing equation

$$W = \in_S / C_o \quad \ldots\ldots\ldots \quad (1)$$

where C_o is the capacitance at zero biasing voltage, and

$$\in_S = \frac{\in_n \in_p}{\in_n + \in_p} \quad \ldots\ldots\ldots \quad (2)$$

Where ϵ_s is the semiconductor permittivity for the two semiconductor materials.
The concentration of carrier was calculated from the relation

$$\frac{1}{C^2} = \left[\frac{2(\in_1 N_{A1} + \in_2 N_{D2})}{q N_{D2} N_{A1} \in_1 \in_2} \right] . (V_D - V_a) \quad \ldots\ldots\ldots \quad (3)$$

where $[2(\epsilon_1 N_{A1}+ \epsilon_2 N_{D2})/qN_{D2}N_{A1}\epsilon_1 \epsilon_2]$ represent the slope, N_{A1} and N_{D2} are the accepter and donor concentrations, and ϵ_1, ϵ_2 are the dielectric constant of p-type and n-type semiconductor respectively. V_D is the built-in potential, V_a is the applied voltage.
The response and rise time can be found from the flowing equations

$$t_{response} = t_r / 2.2 \quad \ldots\ldots\ldots \quad (4)$$

where

$$t_r = RC \quad \ldots\ldots\ldots \quad (5)$$

Also the current-voltage measurement in the dark and light were performed by using Keithley 616 digital electrometer and d.c power supply , the bias voltage was varied (0-2) Volt in the case of forward and reverse bias.
From the plot of the relation between forward current and bias voltage in the dark the ideality factor was determined from the relation

$$\beta = \frac{q}{k_B T} \frac{V}{\ln(I_f / I_{S1})} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

The tunneling constant Ą was deduced from equation:

$$Ą = [d \ln (I_f/I_{S2})]/dV \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

In the light condition, the optoelectronic measurements of diodes were made, the samples were exposed to IR source (SiC) at intensity equal to (26) mW/cm^2.

The open circuit voltage (V_{oc}) and short circuit current (I_{sc}) measurement also were done for $Hg_{1-x}Cd_xTe$/Si heterojunction for different value of x under illumination by (SiC) source at range of power intensities (6-120) mW/cm^2.

III. RESULTS AND DISCUSSION

The junction capacitance variations as a function of the reverse bias (0-2) Volt of $Hg_{1-x}Cd_xTe$/Si diodes at different x values are shown in Fig. (1) in order to get an idea about the impurity distribution in the vicinity of the junction. This measurement was achieved in frequency equal to 10 kHz. It is clear that the capacitance decreases with increasing the reverse bias. This behavior was due to the increasing in the depletion region width, which leads to increase the value of built in voltage.

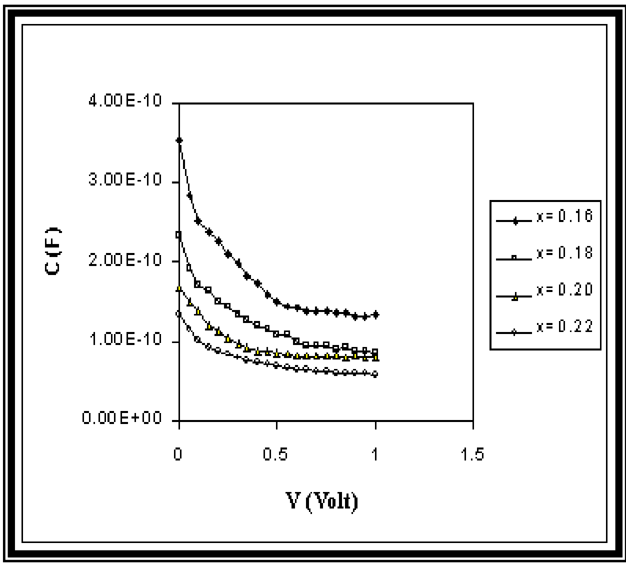

Figure 1: Capacitance vs. reverse applied voltage for $Hg_{1-x}Cd_xTe$/Si diodes of different Cd content.

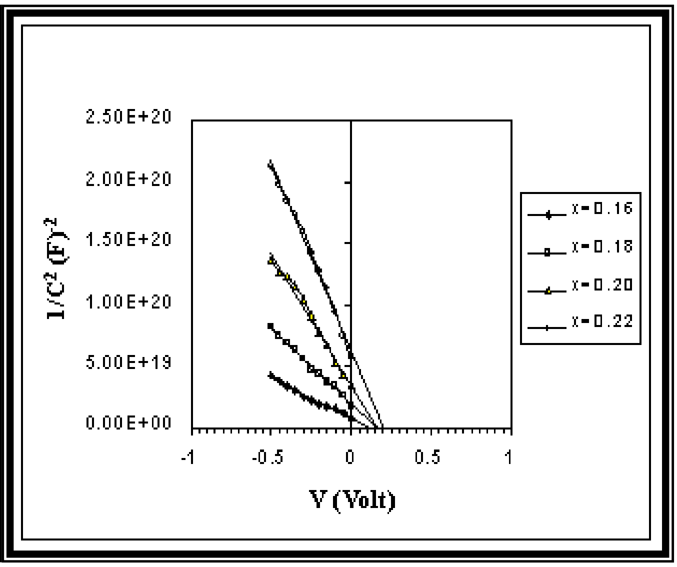

Figure 2: The variation of $1/C^2$ as a function of reverse bias voltage for $Hg_{1-x}Cd_xTe$/Si diodes of different Cd content.

We can observe from the same figure that the capacitance increases approximately two times and half when x content decrease from 0.22 to 0.16. This behavior was attributed to increase the carrier concentration when the Hg content increases in the $Hg_{1-x}Cd_xTe$ composition, which leads to increase the capacitance and as a result the W decreases. This result is in agreement with Foyt et al [9] where they found the capacitance increases from 25 pF to 120 pF when the value decrease from 0.5 to 0.25.

The width of the depletion layer (W) can be calculated by using equation (1). We can see that the depletion layer increases from 0.482 μm to 1.27 μm with increasing x value from 0.16 to 0.22.

The C (V) curve of $Hg_{1-x}Cd_xTe/Si$ diodes follows a square root law (i.e a linear dependence of C^{-2} versus V) as shown in Fig. (2) which indicates that the impurity profile near the junction is abrupt. From the intercept and the slope of the best fit straight line, one obtains a built in voltage and an impurity concentration.

Table (1) illustrates all the parameters that are calculated from this measurement. It is clear that the value of built in voltage increase from 0.11 to 0.19 Volt with increasing the Cd content from 0.16 to 0.22. This occurs as a result of the decrease in capacitance and the increasing in depletion width.

The carrier concentration of $Hg_{1-x}Cd_xTe/Si$ heterojunction which is deduced from the slope and by using equation (3) increases from $0.380X10^{14}$ to $1.644X10^{14}$ cm^{-3} when x changes from 0.22 to 0.16.

From the value of zero bias capacitance (C_o) the response time ($t_{response}$) and rise time (t_r) can be calculated from the equation (4) & (5) respectively. We can notice that the rise and response time increases from 6.7 and 3.045 to 17.7 and 8.04 nsec respectively, when the value of x decreases from 0.22 to 0.16 as shown in Table (4-10). Similar results have been obtained by Cohen & Riant [10], they observed that the rise time is in the range 2-5 nsec.

Table 1: The parameters which obtained from C-V characteristics for $Hg_{1x}Cd_xTe/Si$ diodes with different Cd content.

x	V_D(Volt)	C_o (nF)	W (µm)	$N_D X10^{14}$ (cm^{-3})	t_r (nsec)	$t_{response}$ (nsec)
0.16	**0.110**	**0.354**	**0.482**	**1.644**	**17.7**	**8.04**
0.18	**0.140**	**0.234**	**0.729**	**1.146**	**11.7**	**5.32**
0.20	**0.165**	**0.170**	**1.004**	**0.570**	**8.5**	**3.86**
0.22	**0.190**	**0.134**	**1.274**	**0.380**	**6.7**	**3.05**

The current- voltage characteristic in the dark condition in forward and reverse bias is considered one of the most parameters of detector measurement by which the mechanism of the current transport can be estimated.

Figs. (3 a & b) show the I-V characteristics in the forward and reverse bias voltage of $Hg_{1-x}Cd_xTe/Si$ Heterojunctions for different Cd content are achieved at R.T and 77 K respectively. The striking feature of these figures is the non-ohmic behavior where it is very clear. Current flows relatively freely in the forward direction of the diode, but very low current flows in the reverse direction. In general the forward dark current is generated due to the flow of majority carriers and the applied voltage inject majority carriers which leads to decrease the value of built in potential, and decrease the width of the depletion layer.

From Fig. (3a) we can notice two regions in the forward current for all samples. The first is the generation- recombination current dominated at low bias voltage lower than 0.15 Volt. This current is developed because the number of charge carriers generated is greater than that of the intrinsic carrier (n_i), i.e $np > n_i^2$ to reach equilibrium there should be generation-recombination [11]. This result is agreement with Becla & Popko result [12], who found that the I-V characteristic is given by the generation- recombination current for mesa $Hg_{0.58}Cd_{0.42}Te$ junction at room temperature, where β equal to 2.6.

The increase of bias potential to a value greater than 0.15 Volt made the forward bias current deviation from the exponential dependence occurs. This excess current can be attributed to a tunnelling mechanism [13].

Where as recombination- tunnelling in the depletion region plays an increasing role at lower temperatures (77 K) and as shown in Fig. (3 b).

The reverse bias current comprises two regions. The first is the generation current, which depends on the bias voltage. The increase in the bias voltage leads to an increase in depletion layer width (W), which in turn increases generation current.
The second region appears after the voltage increases. Where the reverse bias current stabilizes and becomes independent of the bias voltage. This is called the diffusion current [14].

From the same figures we can see that the current increases with decreasing x value, this may be due to improve in the crystal structure that implies the increase in the grain size with decreasing the value of x, and to decrease in the depletion layer as shown in C-V characteristics.

The rectification Coefficient ('B), which represents the ratio between forward and reverse current at certain applied bias voltage has been determined at 1.5 Volt that are listed in Table (2), we can observe that the rectification Coefficient increases, considerably with increasing the Cd content (x value) and with decreasing the temperature. This occurs due to increase the junction resistance (increase the depletion width) when the value of x increase and when the temperature drops. Similar results were obtained by Becla & Popko [10],they observed that the rectification Coefficient of $Hg_{0.82}Cd_{0.18}Te$ junction is rather small and amounts to 5 at 77 K and to about 6.5 at 4.2 K.

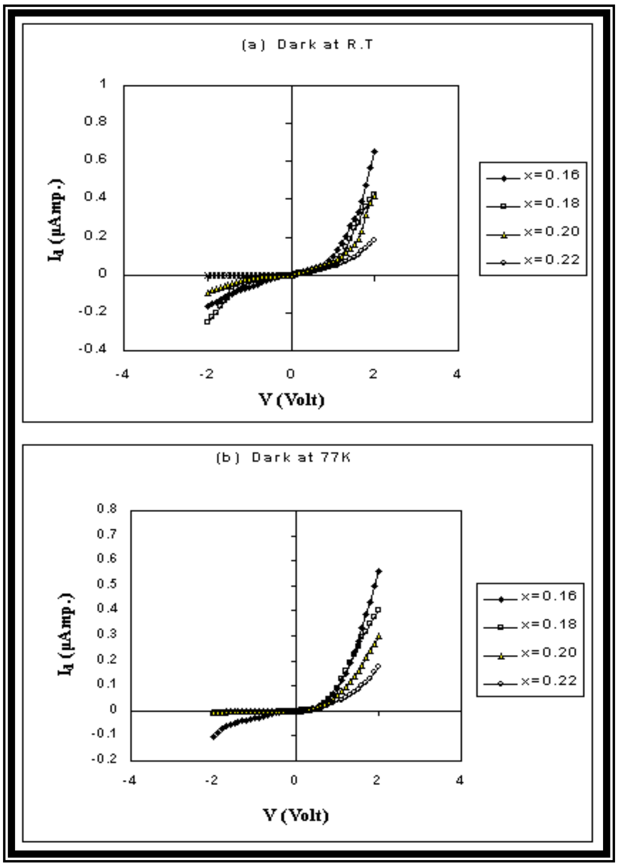

Figure 3: I-V Characteristics for $Hg_{1-x}Cd_xTe/Si$ diodes at forward and reverse bias voltage of different Cd content at (a) R.T and (b) 77 K.

Figs. (4 a, 4 b) show the a semi- log relation between dark forward current and bias voltage (0-0.25)Volt for $Hg_{1-x}Cd_xTe/Si$ diodes at different x value. We can recognize two regions in these figures, we can say the first one represents the recombination current, while the second region represents tunneling current. Therefore the mechanism of the forward current coincides to the recombination- tunneling mechanism. Such data is in agreement with result of Migliorato et al [13]. The mechanism of transport current is estimated from the value of ideality factor (β) which can be calculated by using equation (6) after determining the reverse saturation current of the first region from intercept the straight line with the current axis at zero voltage bias. It is clear that the saturation current (I_{S1}) increase from 1.659X10^{-13}A to 81.20X10^{-13}A,while it increases from 0.954X10^{-13}A to 28.8X10^{-13}A with decreasing x value from 0.22 to 0.16 at R.T and 77 K, respectively.

The increase of I_{S1} with decreasing x value may be due to the increase of the carrier concentration when the Hg content increases. While the I_{S1} decreases when the measurement achieved at 77 K, this occurs as a result of increase the resistivity and the decrease of the carriers mobility when the temperature drops to the 77 K.

From Table (2) we can see that the value of ideality factor changes from 1.373 to 1.781 at R.T, while it varies from 2.037 to 2.78 at 77 K when x decreases from 0.22 to 0.16. This means that the value of β increases when the temperature decreases to 77 K. This is expected because such temperature drop means vanishing the diffusion mechanism where β equals to 1.0, therefore β takes higher value at 77 K.

This result is in agreement with results of Migliorato et al [13], where the ideality factor varies from 1 at 180 K to 1.7 at 77 K.

From the second region in Figs. (4 a&b) we can calculate the tunneling constant (Ą) by using equation (7).

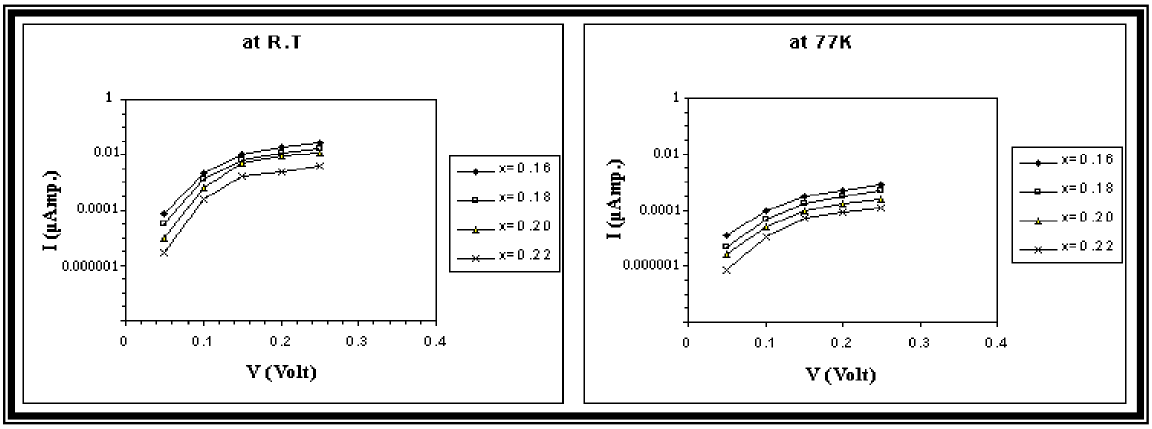

Figure 4: I-V characteristics at forward bias voltage on semilogarithm scale for $Hg_{1-x}Cd_xTe/Si$ diodes of different Cd content at (a) R.T and (b) 77 K.

The tunneling constant increases from 3.297 to 4.149 V^{-1} at R.T and from 3.415 to 4.290 V^{-1} at 77 K when x decreases from 0.22 to 0.16 as shown in Table (2). This coincides with the results of Becla & Popko [12], they found that the contribution of tunnel current increases when x is reduced and the effect of tunneling current increases in the junction when the temperature drops.

Table 2: The parameters which obtained from I-V characteristics for $Hg_{1-x}Cd_xTe/Si$ diodes with different Cd content.

x	0.16		0.18		0.20		0.22	
Temp.	R.T	77K	R.T	77K	R.T	77K	R.T	77K
I_{S1}X10^{-13} (A)	81.20	28.8	30.60	9.610	6.020	4.780	1.659	0.954
I_{S2}X10^{-10} (A)	26.91	0.690	16.55	0.425	14.42	0.242	5.68	0.171
β	1.781	2.780	1.665	2.483	1.417	2.442	1.373	2.037
Ą $(V)^{-1}$	4.149	4.290	4.054	4.263	3.753	4.054	3.297	3.415
˙B	2.771	5.936	2.008	31.310	3.336	132.56	154.33	143.22

The relation between the photocurrent (I_{ph}) and the reverse bias voltage (V_r) of the $Hg_{1-x}Cd_xTe$/Si diodes with different Cd content are presented in Fig. (5), the measurements are carried out under illumination power density equal to 120 mW/cm^2 at R.T and 77 K, respectively.

From this figure we observe that the photocurrent increases with increasing the bias voltage, i.e I_{ph} increases with increasing the depletion region width (W) this is due to reduction of the concentration of carriers. This is because increaseing the electric field sweeps the carriers out of the depletion region and with existing illumination, electron-hole pairs are created near the junction. If the e-h pairs is generated within a diffusion length (L_n, L_p) of the transition region, the electrons can diffuse to the junction and swept down the barrier to the n side.

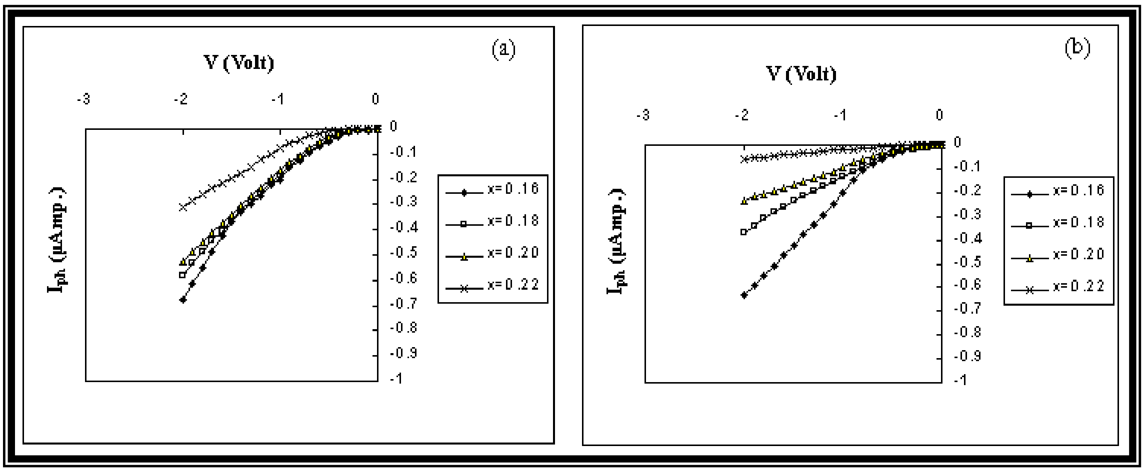

Figure 5: The relation between I_{ph} and reverse bias voltage for $Hg_{1-x}Cd_xTe$/Si diodes of different Cd content at (a) R.T and (b) 77 K.

The resulting current is called the generation current since its magnitude depends entirely on the rate of generation of e-h pairs. So that the photocurrent is expressed as function of generation and diffusion mechanism as in the following equation [15].

$$I_{ph} = q\, a\, G_{ph} (L_p + L_n + W) \quad \ldots\ldots(8)$$

Where G_{ph} generation rate of photocarriers, L_p and L_n are the diffusion length of holes and electrons, respectively.

From the same figure we can see the photocurrent increases with decreasing x value this is attributed to the decrease of the energy gap with decreasing x value as presented in optical properties. The short circuit current (I_{Sc}) is measured, presumably when the terminals of photodiode are shorted. It is proportional to the light intensity and if the circuit is open, an open circuit voltage (V_{oc}) will be generated with the positive polarity at the anode. Therefore these two parameters regarded a distinction feature for photovoltaic detectors, where these detectors can separate the generated pairs without the need to apply any external field.

Fig. (6) shows the dependence of short circuit current (I_{Sc}) on the power intensity of the light for different x content, it is clear that the curve can be divided into two regions, in the first region I_{Sc} is nearly linear with respect to the amount of incident light, while the second region represents the saturation region with increasing the power intensity to a limit range.

Our interpretation for this behavior is that, the incident light excite the carriers and separate the electrons from their atoms, i.e create electron-hole pairs which leads to increase I_{Sc} and then the saturation occurs due to the recombination effect.

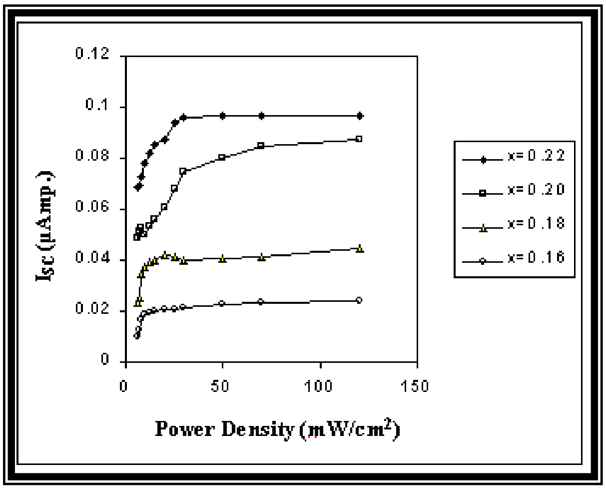

Figure 6: The variation of I_{Sc} as a function of power intensity for $Hg_{1-x}Cd_xTe/Si$ diodes of different Cd content.

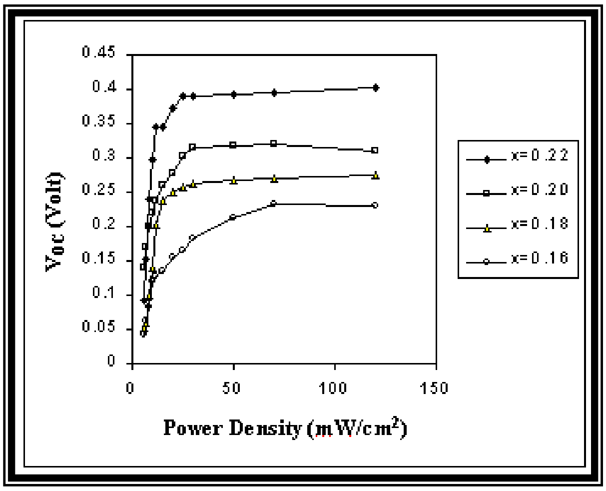

Figure 7: The variation of I_{Sc} as a function of power intensity for $Hg_{1-x}Cd_xTe/Si$ diodes of different Cd content.

The variation of open circuit voltage (V_{oc}) as a function to the Cd content with the light power intensity is shown in Fig. (7). We can see that the V_{oc} varies logarithmically with respect to the change of amount of light.

It is clear that the I_{Sc} and V_{oc} increase with increasing x from 0.16 to 0.22 content by a factor of 4&1.75 respectively. This is due to increase the built in voltage when the Cd content increases.

IV. CONCLUSIONS

The electrical properties of $Hg_{1-x}Cd_xTe/Si$ diodes which include C-V and current-voltage measurements shows that capacitance decreases and the width of depletion layer increases with increasing Cd content.The relation between inverse capacitance square and the reverse bias voltage for $Hg_{1-x}Cd_xTe/Si$ heterojunction of different Cd content reveal a straight-line relationship, which means that the junction was an abrupt type.When the Cd content increases the built-in voltage increases as a result of decreasing the capacitance value and increasing depletion width. The donor carrier concentration of $Hg_{1-x}Cd_xTe/Si$ heterojunction increases with decreasing Cd content. The mechanism of the current transport in the forward condition coincides with recombination-tunneling mechanism. The tunneling current plays an increasing role at lower temperature (77 K).It is found that the rectification coefficient increases with increasing Cd content and when the temperature drops.

The value of ideality factor increases with increasing Cd content at room and liquid nitrogen temperature . Under illumination condition, the photocurrent increases with decreasing Cd content.

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