Preparation and Study of Electrical Characteristics of (n-CdS/p-Ge) Thin-Film Heterojunction

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Abstract

A thin film (400±5 nm) of Germanium was deposited on the slide glass, then another thin film (200±3 nm) of Cadmium Sulphide directly deposited on the Ge thin film, with high purity (99.999%) Aluminum metal was used as O'hmic contact on two sides of heterojunction (n-CdS/p-Ge) by vacuum thermal evaporation technique.

From ideality factor (n) values, the current transporting mechanism in the heterojunction was explained, where three regions in I-V curve were appeared, that is to say, three mechanism of current transportation through the manufactured heterojunction in this research were eventually existed, the saturation current (I_S) was found for each region at different temperature (100, 200, 300) K.

Through C-V measurements we found built – in potential (V_{bi}), the donor density (N_D), the difference between Fermi level and conduction band (Φ_n), the difference between Fermi level and valance band (Φ_p), the conduction and valence bands discontinuity (ΔE_C, ΔE_V), and the depletion regions width (X_n, X_p) of heterojunction (n-CdS/p-Ge) of the frequencies (1, 0.5) MHz.

Keywords: Thin-film Heterojunction; I-V measurement; C-V measurement

الخلاصة

تم ترسيب غشاء رقيق (400±5) نانومتر من الجرمانيوم على شريحة زجاجية ومن ثم ترسيب غشاء رقيق (200±3) نانومتر من كبريتيد الكادميوم على غشاء الجرمانيوم مباشرة ، وقد أستخدم معدن الألمنيوم العالي النقاوة (99.999%) كإتصال أومي على طرفي المفرق الهجين (n-CdS/p-Ge) بإستخدام تقنية التبخير الحراري في الفراغ.

ومن خلال قيم عامل المثالية (n) فسرت آلية إنتقال التيار في المفرق الهجين حيث ظهرت ثلاث مناطق في منحنى التيار – الفولتية مما يستدعي وجود ثلاث آليات إنتقال للتيار خلال المفرق المصنع في هذا البحث ، كما تم إيجاد تيار الإشباع (I_S) لكل منطقة وعند درجات حرارية مختلفة (100,200,300) كلفن .

من قياسات السعة – الفولتية فقد تم إيجاد جهد البناء الداخلي (V_{bi}) وكثافة الشوائب المانحة (N_D) والفرق بين مستوى فيرمي وحافة حزمة التوصيل (Φ_n) والفرق بين مستوى فيرمي وحافة حزمة التكافؤ (Φ_p) واللاإستمرارية في حزمتي التوصيل والتكافؤ (ΔE_C, ΔE_V) وعرض منطقتي النضوب (X_n, X_p) للمفرق المتباين (n-CdS/p-Ge) للترددات (1, 0.5) ميكاهيرتز.

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1. Introduction

The conduction technique between two semiconductors differs in energy gaps and lattice constant was occupied scientists interesting. The heterojunction gives flexibility better than homojunction or even Schottky contact; because by studying properties of each of semiconductor, we easily obtained distinct heterojunction, so we gain numerous of heterojunctions were gives wider field of new applications of semiconductor techniques.

The first advanced step in the study of discontinuity bands was by Anderson's electron affinity rule in 1962[1] who demonstrated the nature of discontinuity bands (ΔE_C, ΔE_V) and fined their values by electron affinity (χ).

2. Theoretical

2.1. I– V Characteristics

Depending on applied voltage polarity, the I-V characteristics were in two types: forward bias and reverse bias, where the heterojunction acting by forward bias when applied voltage polarity is the same polarity of the semiconductor of heterojunction which is lead to decreasing the built – in potential of the heterojunction, and ver-versa for the reverse bias[2,3]. The relation between the current and voltage at forward bias of heterojunction may write as follow[2]:

$$I \propto \exp(AV)\exp(BV) \quad \text{..... .....(1)}$$

hence:
(I): current.
(V): Applied voltage.
(A, B): constant not depending on voltage or temperature.

And the equation above was derived depending on tunneling – recombination theory.

By the forward bias characteristics of heterojunction, it noticed that the curve is divided into two distinct regions, high voltage and low voltage region, in low voltage region which less than (0.3V) were the lost of the current resulted by the following equation[2]:

$$I_f = I_S \exp(qV/nkT) \quad \text{..... ..... (2)}$$

hence:
(I_f): the current at forward bias.
(q): electron charge.
(k): Boltzmann's constant.
(T): temperature.
(I_S): saturation current, (n): ideality factor, where their value ranged (1-2) in this region, and may calculated by the following equation[4]:

$$n = (q/kT)\cdot\left[dV/d\ln(I_f/I_S)\right] \text{.....(3)}$$

While at the high voltage region the current established by the tunneling processes through junction which gives by equation [1].

In the reverse bias the relation was linear ($I \alpha V$) at low voltage, on the other hand, the relation is exponential ($I \alpha V^m$ hence m>1) at high voltage[2].

2.2. C–V Characteristics

C-V characteristics were used to fined the carriers concentration, built – in potential, depletion region and give a clear picture of the charge distribution of the heterojunction[5].

In anisotype heterojunction, we fined the capacity of junction would appear when two semiconductors were contact possessing different types of conductivity; the capacity per area at reverse bias may represented by[5]:

$$\frac{C}{a} = \frac{dQ}{dV} = \frac{\epsilon_S}{W} \text{.....(4)}$$

hence:
(C): junction capacitance.
(a): junction area.
(Q): interface charge.
(V): applied voltage.

($\in_s$): permittivity of semiconductor.
(W): width of the depletion region, which found by following[1,5]:

$$(X_0 - X_1) = [\frac{2N_A \in_{S_1} \in_{S_2} (V_{bi} - V)}{qN_D(\in_{S_1} N_D + \in_{S_2} N_A)}]^{1/2} ...(5)$$

$$(X_2 - X_0) = [\frac{2N_D \in_{S_1} \in_{S_2} (V_{bi} - V)}{qN_A(\in_{S_1} N_D + \in_{S_2} N_A)}]^{1/2} ...(6)$$

$$W = (X_2 - X_0) + (X_0 - X_1) = (X_2 - X_1)$$

$$= \left[\frac{2 \in_{S_1} \in_{S_2} (V_{bi} - V)(N_A + N_D)}{q(\in_{S_1} N_D + \in_{S_2} N_A)}\right]^{1/2} .....(7)$$

The equation (4) could rewrite by:

$$\frac{C}{a} = \left[\frac{qN_D N_A \in_n \in_P}{2(\in_n N_D + \in_P N_A)(V_{bi} - V)}\right]^{1/2} .....(8)$$

hence:
($\in_n$, $\in_p$): permittivity of the donor (n-type) and acceptor (p-type) semiconductor respectively.

The equation (8) could be written by:

$$\frac{1}{C^2} = \frac{2(\in_n N_D + \in_P N_A)(V_{bi} - V)}{a^2 qN_D N_A \in_n \in_p} .....(9)$$

From the equation above, we fined the relation between ($1/C^2$) and voltage is linear, and the slope of straight line would equivalent for equation (9) derivative:

$$\frac{d(1/C^2)}{dV} = \frac{2(\in_n N_D + \in_P N_A)}{a^2 qN_D N_A \in_n \in_P} .....(10)$$

From the equation above, we could fined the donor or acceptor density were used to calculate the difference between Fermi level and valance band (Φ_P) for p-type semiconductor or conduction band (Φ_n) for n-type semiconductor according to the following equation[6]:

$$\Phi_P = (kT/q)[\ln(N_V/N_A)].....(11-a)$$

$$\Phi_n = (kT/q)[\ln(N_C/N_D)].....(11-b)$$

hence:
(N_C, N_V): effective density of state in conduction and valance bands respectively.

And the extension of straight line is represent built-in potential of junction, so the value of discontinuity in valance and conduction bands could be calculated by the following equations[7]:

$$\Delta E_C = -V_{bi} - \frac{\Delta E_g}{2} + \frac{kT}{q}\ln\left(\frac{N_A N_D}{p_i n_i}\right) + \frac{kT}{2q}\ln\left(\frac{N_{C1}N_{V2}}{N_{C2}N_{V1}}\right) .....(12)$$

$$\Delta E_V = \Delta E_g - \Delta E_C .....(13)$$

hence:
(n_i, p_i): intrinsic carrier concentration in both types of semiconductors.

3. Experimental

Germany slide glass was cut with dimensions (1.5cm x 3cm) and cleaned with distilled water and placed in ultrasonic bath for 20min. then dried by hot air current and placed inside thermal vacuum evaporation system directly; hence the deposition processes were done.

3.1. Thermal Vacuum Evaporation

Thermal vacuum evaporation system type (BALZARS-BAK640) was used; the system was cleaned enough by alcohol. The system containing of two types of pumps, the first one is (Rotary Pump) which rising the pressure to (10^{-3}Torr), the second is (Diffusion Pump) which rising the pressure to (10^{-6}Torr).

To conducting the back contact, Aluminum with (99.999%) purity was deposited by (100nm) thickness on the surface of slide glass, after Aluminum thin film rigged, p-type Germanium (400±5 nm) thickness deposited on the Aluminum which deposited on the slide

glass, then the thin film left to be rigged, after that, n-type Cadmium Sulphide deposited on the Germanium thin film by (200±3 nm) thickness, after the thin film rigged, the front contact was deposited, hence Aluminum deposited in a (2mm) diameter circle and with (100±2 nm) thickness on the thin film of Cadmium Sulphide, then the samples left to dried, it important to mention that after each evaporation the formed thin film left for 30min. under the same conditions of vacuum (10^{-6}Torr) to avoid the oxidation of depositing thin film. Then the samples were lifted and the system cleaned again.

The thickness of the thin films was choose depending on characteristics of each of them at used thickness[5,8,9,10,11,12]. Type of metal and thickness of O'hmic contact, were choose depending on experimental conditions, it was noticed that increasing of the thickness of contact due to improvement of the contact activity.

In general the thickness was measured by weight method according of the following equation[6]:

$$t = m / 2\pi\rho r^2 \quad \text{..... ....(14)}$$

hence:

(m): evaporated material mass.

(ρ): evaporated material density.

(t): depositing layer thickness

(r): distance between substrate and Boat.

3.2. I – V Measurement

I-V characteristics could be obtained by applied voltage on both sides of heterojunction, when positive voltage on Cadmium Sulphide side was connected, and negative voltage on Germanium side, we obtained heterojunction characteristics at forward bias and ver-versa, we obtained of reverse bias of the heterojunction (n-CdS/p-Ge). These characteristics were measured at different temperatures (100,200,300K) by putting the sample inside Cryostat system, which demonstrated in figure (1).

3.3. C – V Measurement

C-V characteristics were measured by using multifrequency LCR meter type (hp) to measured the capacitance at frequencies (0.5,1MHz) in the reverse bias, the built – in potential was found, and so the concentration of charge carriers from the relation ($1/C^2$) and reverse bias voltage.

4. Results & Discussion

4.1. I – V Characteristics

Figure (2) shows the characteristics of heterojunction (n-CdS/p-Ge) at room temperature for the forward and reverse biases, it could be seen that the heterojunction like any diode starting with slight increasing at forward bias to reach the built – in potential value (V_{bi}) which is equal (0.3Volt) approximately, were the current started to increase directly after this value while the voltage still increasing. In the case of the reverse bias the current still very weak until it reach the break down voltage value which equal (3.7Volt) approximately, were the current is starting to increase after this point while the voltage still constant.

4.2. I – V at Different Temperatures

I-V characteristics at forward bias of heterojunction (n-CdS/p-Ge) were studied, three regions could be seen, each region appeared as straight line with determined range of voltage as showed in figures (3,4,5), were I-V characteristics measured at different temperatures (100, 200, 300)K for the forward bias these regions represented according to the applied voltage value on heterojunction, the first region was determined at the voltage less than (0.3Volt), the second region was determined when the voltage ranged (0.3-0.75)Volt and the third region was

determined when the voltage greater than (0.75Volt). Table (1) shows saturation current values and ideality factor at temperatures above for the three regions.

The current transporting mechanism could be determined by knowing the ideality factor values, it's appeared that the ideality factor values of the first region at different temperatures was ranged between (1.69-2.85) which revealed that the dominant current transporting mechanism in this region was the emission and tunneling mechanisms may be starting with increasing as the temperature decreasing[1,13,14]. While in the second region in which the ideality factor values starting with high increasing, the current transporting mechanism was depending on the recombination between electrons and holes for current transporting[1,13,14], on the other hand, while in the third region which appeared as increasing in the current values, the tunneling mechanism starting to increase with eclipse of recombination mechanism[1].

These three cases were basically depending on the applied voltage on junction, depending on temperature also, where the three cases appeared slight differences in the ideality factor, but these differences will look greater if we see the saturation current were gained from the three cases, were the current value which passed through the junction depending on the temperature directly[1], since with temperature decreasing, the energy gap was increasing[1,2,5,6], and according to the equation (13), the discontinuity of the valance and conduction bands starting to increase, so the passed current was decreased.

4.3. C – V Characteristics

When reverse voltage applied on heterojunction (n-CdS/p-Ge), the depletion region thickness would extended, and the thickness was reduced when the forward voltage applied, so it can be consider the heterojunction as a capacity in which the first semiconductor represented one side and the other side represented by the second semiconductor and the depletion region represented isolated region of the capacity, so any change in the thickness of the depletion region would affect the junction capacitance according to equation (4).

Figure (6) shows the capacitance as a function of reverse bias voltage for heterojunction (n-CdS/p-Ge) at room temperature and for two frequencies (0.5,1MHz). It was notice that the capacity was decreased as the reverse bias voltage decrease, and this leads to increasing the thickness of the depletion region and the capacitance decreased with increasing of frequency.

The built – in potential values of the heterojunction (n-CdS/p-Ge) were calculated by the relation of ($1/C^2$) with voltage as showed in figure (7), and finding donor density (N_D) after finding of straight line slope from equation (10), and finding the difference between Fermi level and conduction band (Φ_n) and the difference between Fermi level and valance band (Φ_p) from equations (11), and when the values of donor and acceptor densities were known at both sides of heterojunction, the discontinuities values in valance and conduction bands could be calculated from equations (12,13) respectively, and finding the depletion region both sides of heterojunction by the equations (5,6) respectively, table (2) showed all the obtained values from the results of C-V characteristics of heterojunction (n-CdS/p-Ge).

The discontinuity values of heterojunction (n-CdS/p-Ge) could be theoretically calculated by the following equations[15].

$$\Delta E_C = E_{C2} - E_{C1} = \chi_1 - \chi_2 \text{.....(16)}$$

$$\Delta E_V = E_{V2} - E_{V1} = (E_{g_1} - E_{g_2}) - (\chi_1 - \chi_2) \text{.(17)}$$

When we know that the energy gab (E_g) and electron affinity (χ) of Cadmium Sulphide where (2.42eV, 4.5eV) respectively[5,8,10], while (E_g) and (χ) of Germanium where (0.66eV,4eV) respectively[5,9,13], so (ΔE_V=1.26eV, ΔE_C=0.5eV), the results of this research relativity compatible with the theoretical values of discontinuity bands heterojunction.

5. Conclusions

The temperature difference would effect directly on the current values and ideality factor, so it would effect on the current transporting mechanism of heterojunction (n-CdS/p-Ge), it was noticed that the current would decrease with decreasing of temperature and by studying the results of C-V characteristics it revealed that the frequency is proportion equivalent with built – in potential, discontinuity in valance band and thickness of depletion region in donor side, while the frequency is proportion inversely with donor density, discontinuity in conduction band and thickness of depletion region in acceptor side.

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Table [1] Results of (I-V) characteristics

	Region 1		Region 2		Region 3	
T (K)	I_{S1} (μA)	n_1	I_{S2} (μA)	n_2	I_{S3} (μA)	n_3
300	2.5	1.69	440	6.39	0.18	2.32
200	0.043	1.99	49.4	9.97	0.021	3.52
100	0.0003	2.85	7.6	18.14	0.41	11.07

Table [2] Results of (C-V) characteristics

F(MHz)	1	0.5
V_{bi}(V)	0.341	0.264
N_D(cm^{-3})	$2.41x10^{13}$	$3.38x10^{13}$
F_p(eV)	0.128	0.128
F_n(eV)	0.258	0.249
DE_C(eV)	0.13	0.22
DE_V(eV)	1.63	1.54
X_p(cm)	$1.76x10^{-7}$	$1.83x10^{-7}$
X_n(cm)	$4.16x10^{-7}$	$3.66x10^{-7}$

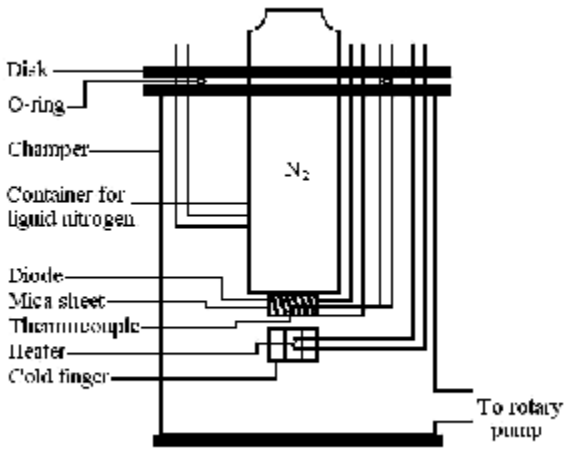

Figure (1) Cryostat system.

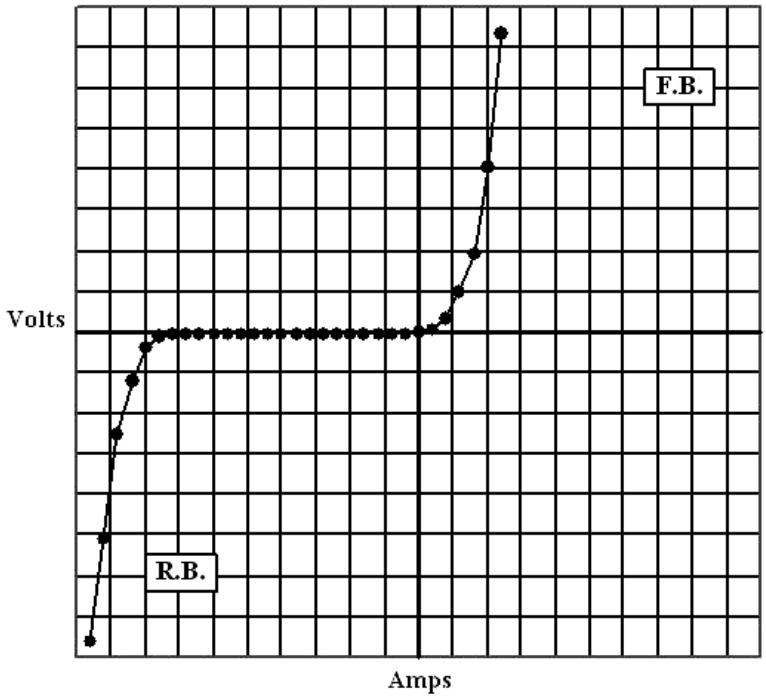

Figure (2) I-V characteristics of (n-CdS/p-Ge) heterojunction.
The ordinate scale is (1mA/div) while the abscissa scale is (0.5V/div).

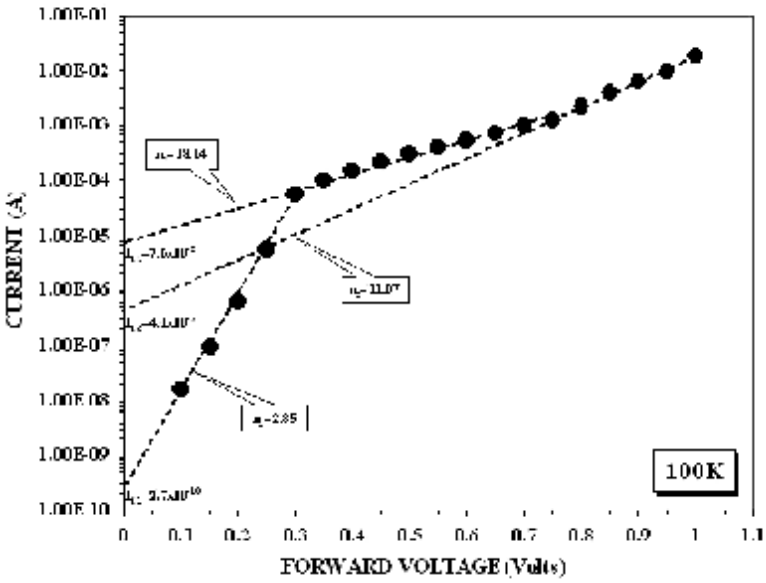

Figure (3) Forward I-V characteristics at (100K) of (n-CdS/p-Ge)

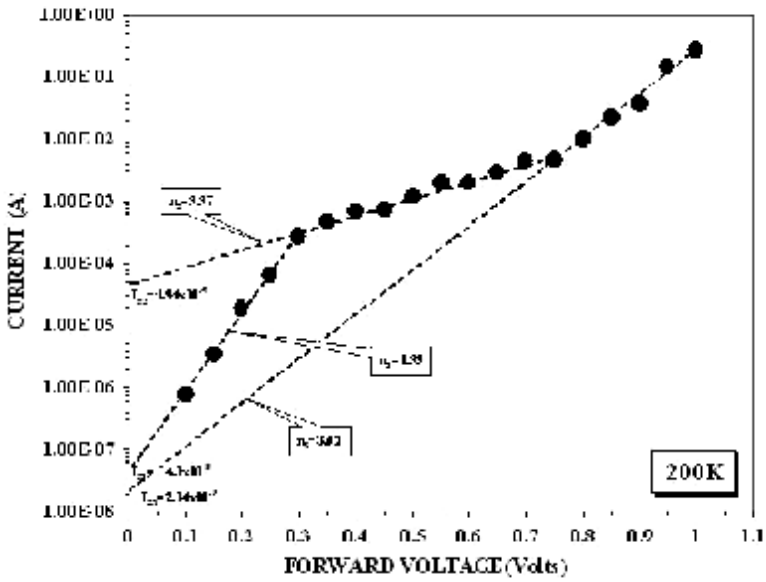

Figure (4) Forward I-V characteristics at (200K) of (n-CdS/p-Ge)

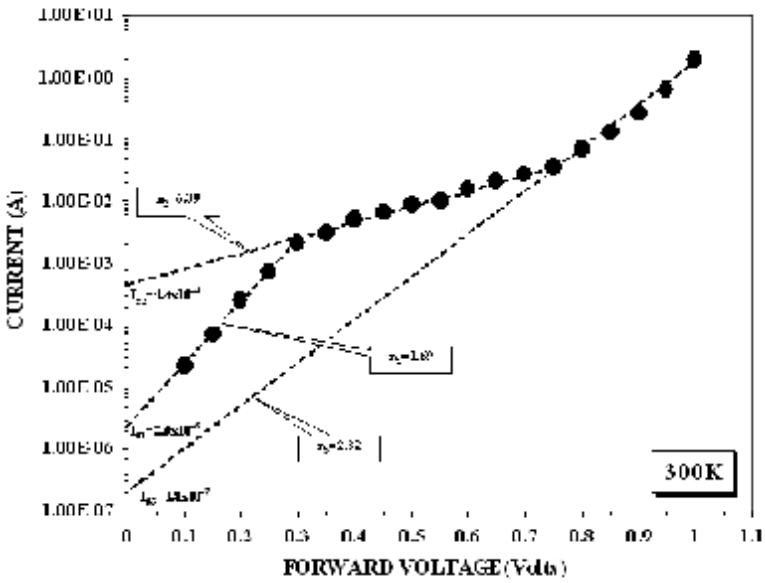

Figure (5) Forward I-V characteristics at (300K) of (n-CdS/p-Ge) heterojunction.

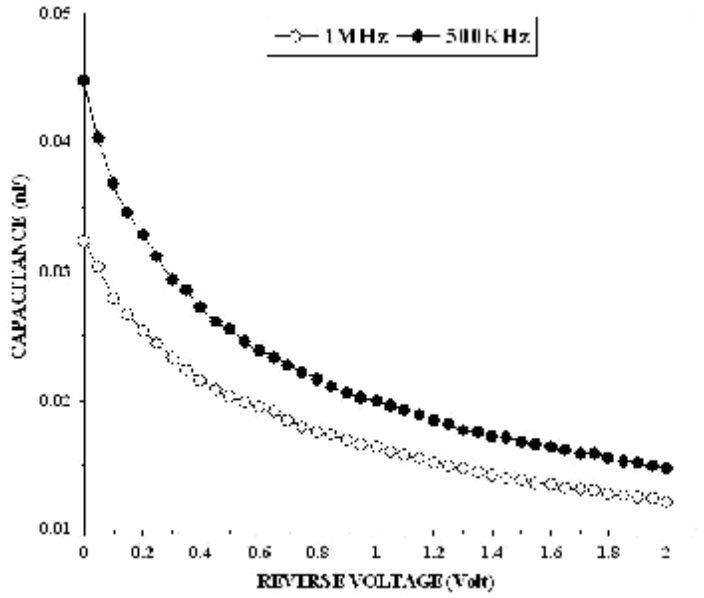

Figure (6) C-V characteristics of (n-CdS/p-Ge) heterojunction.

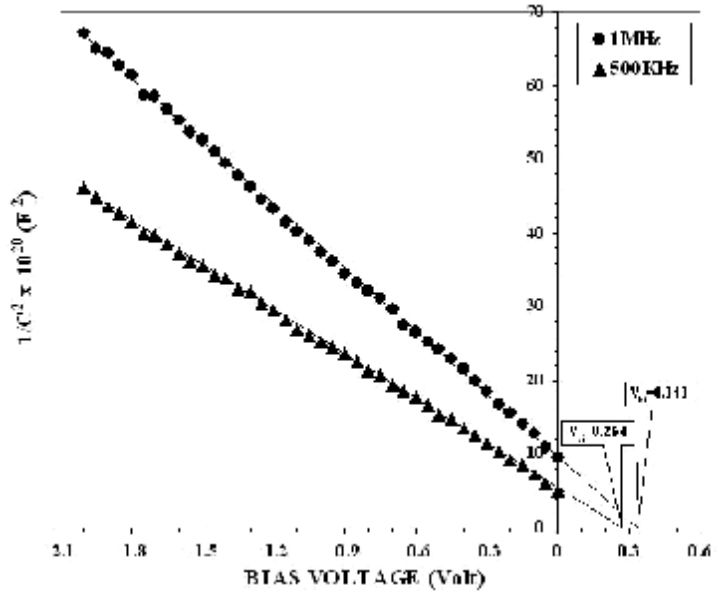

Figure (7) ($1/C^2$-V) characteristics of (n-CdS/p-Ge) heterojunction.