Influence of Gold Concentration on the Main Detection Parameters of Ge-Au Photoconductive Detector

B. A. Hasan, M. N. Makadsi and A. F. Abdul-Ameer
Department of Physics, College of Science, University of Baghdad

Abstract:

Ge-Au infrared photoconductive detection was prepared from germanium single crystal which were doped with different gold concentration using thermal evaporation. The spectral resonsivity (R_λ), spectral detectivity (D^*) were determined as function of wavelength, also the resistance, conductivity in dark and with illumination to infrared radiation, the gain and relative photo response have been measured with different gold concentration. Remarkable improvements in the photoresponse gain were observed for the highest resistance specimen at the expense of spectral detectivity values.

تأثير تركيز الذهب على معلمات الكشف الرئيسة لكاشف التوصيل الضوئي Ge-Au

بشرى عباس حسن، متي ناصر مقادسي و أمير فيصل عبد الأمير

قسم الفيزياء / كلية العلوم / جامعة بغداد

الخلاصة:

حضرت كواشف التوصيل الضوئي Ge-Au من بلورات مفردة من الجرمانيوم المطعم بتراكيز مختلفة من الذهب. عين طيف الاستجابية R_λ والكشفية النوعية D^* كدالة للطول الموجي كذلك تم حساب الربح والاستجابة الضوئية النسبية، المقاومة والتوصيلية في الظلام وعند الإضاءة بالاشعاع تحت الأحمر لتراكيز الذهب المختلفة. لوحظ تحسن واضح في الاستجابة الضوئية والربح للعينات ذات المقاومة الأعلى لكن على حساب قيم الكشفية النوعية.

Introduction

Germanium exhibits optical absorption extended to near infrared, which is due to electronic excitation from the filled band to the conduction band [1]. This intrinsic absorption is accompanied by photoconductivity whose long wavelength limit coincides with the intrinsic absorption edge at 1.85μm [2]. This upper limit on wavelength can be extended by adding impurities to germanium crystals, the activation energies of the impurities center then become the determining factor for the maximum wavelength of infrared radiation that can be absorbed[3]. Chemical impurities in the Ge lattice introduce localized energy levels in the energy gap between the valence and conduction bands. Impurities, which have been studied most extensively, are those of columns III and V of the periodic table. The ionization energy values of approximate 0.01eV [4]. More work in past few decades have yielded information concerning localized energy levels introduced into the Ge band structure by Zn [5] Cu [6], Ni [7], Li[8], Au [9] and Pt [10] except Li, the levels introduced by these elements are characterized by ionization energies

that are larger than for elements of columns III and V.

The instruments used for detection of infrared radiation may be divided into two distinct groups, those which are used the heating effect of the radiation and are known as thermal detectors and those which make use of quantum electric effects and are known as photodetectors [11].

The photon effect process that most wildly used Infrared detector is photoconductivity. The term photoconductivity covers all the phenomena by which conductivity changes increases or decreases follow the absorption of light in the considered material [12].

a- Extrinsic infrared photoconductor

Extrinsic infrared photoconductors rely on optical excitation of holes from impurity center such as Au, Cu, Hg or Cd into the valence band of p-type semiconductors. Ge is used principally as the host crystal. In order to keep competing thermal excitation low extrinsic photoconductors are cooled to temperatures between 77 and 4.2K. Since optical absorption constants in the wavelength range of extrinsic carriers excitation are generally low (of order 1 to 10cm^{-1}), the requirement of high quantum efficiency leads to detector dimensions of several millimeter [11].

b- Intrinsic infrared photoconductor

Intrinsic infrared photoconductors utilize band to band excitation. Consequently the light absorption coefficient is high typically (10^3 to 10^4) cm^{-1} so that the dimension of the detector in the direction of incident radiation need only a few micrometer. In addition to the III-V photoconductors, in As, In Sb and narrow band gap intrinsic detectors which had been fabricated from mixed crystal $Hg_{1-x}Cd_xTe$ and $Pb_{1-x}Sn_xTe$ these detectors can be tailored to the desired wavelengths (λ_s) from (1-30) μm. Their importance comes because they can operate at high temperatures that is 77 to 110K.

Gold doped germanium

Gold in germanium Ge can occur in four states of ionization, which can be represented by four levels in the energy gap as shown in Fig. (1). The lowest level is 0.05 eV above the valence band but is a donor level [13]. The other three are acceptors. The first of these is 0.6 eV above the valance band while the other two are 0.20 and 0.05eV below the top of the conduction band respectively. In specimen of Ge contains no other impurity but gold the behavior at low temperatures would be determined by the formation of holes in the valence band as a result of electron capture in to the 0.16eV level. If some group III impurities are present, then the 0.05 donor level will become ionized, the electron falling in to the group III levels. If the concentration of group III impurities is smaller than that of Au, holes will be created by capture of electrons from the valence band into the empty donor levels. The presence of upper acceptor levels is revealed by introducing group V impurities. The electrons from these impurities will fill the successive acceptor levels permitting electrons to be excited from the upper acceptor levels to the conduction band. Photoconductor transitions can occur from all four levels [14, 15].

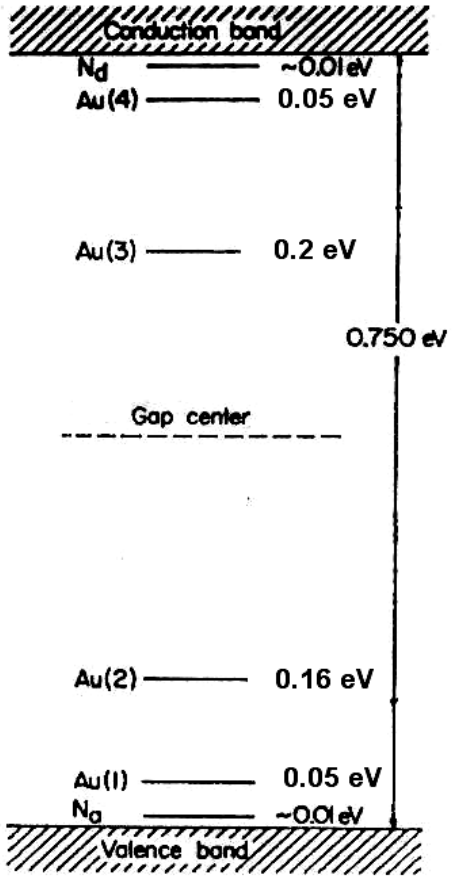


Fig.(1): Energy levels produced by gold impurity in germanium

Most transitions have are from 0.16eV level which has a photocond-uctive threshold at about 9μm. Photoconductivity of 0.05eV donor impurities have been studied by Schlitz, Harty and Rowley [16]. In their system Ga was used to soak up the Au donor electrons. As soon as radiation is applied some the Ga centers will be emptied and the electrons are lift back to Au atoms. At about 15 Kº the Ga levels will become thermally ionized and the photoconductive response in the (15-20)μm region render this system look promising but further work is needed.

Basic consideration

To point out the influence of the material parameters on the detector performance we apply the definition of spectral responsively and spectral detectivity of Ge-Au photoconductive detector (PC).

The spectral responsively, R_λ [17] is given by:

$$R_\lambda = \frac{\lambda P^2_D \tau_n}{hcw\, t^{3/2} n_o^{3\backslash 2} e^{1/2} \mu_n^{1/2}} \qquad (1)$$

Where (λ) is the wavelength (either the cut off or the peak value, τ_n and μ_n the electron lifetime and mobility respectively, e the electron charge, no is the free electron concentration, h the Planck constant, c the speed of light P_D the Power density.

w,t the width and thickness of the sample respectively. The spectral detectivity, D^*_λ is defend [18] as:

$$D^*_\lambda = \frac{R_\lambda}{I_N}(A_D \Delta f) \qquad (2)$$

Where A_D is the detector element area and Δf is the frequency band width, and I_N is total noise. The total noise includes both the thermal and generation-recombination noise [10, 20].

Experimental details

Five sample are cut from Ge single crystal in dimension of about $(3\times8\times1)mm^2$ rectangular slabs. These specimens were polished and etched in a mixture of [5 volume HNO_3+3 volumes of HF+5 volumes of CH_3 COOH]. Specified percents of Au are evaporated on samples using thermal evaporation in Argon ambient. The samples are led in furnace in an argon ambient temperature at nearly melting point of germanium 1173K, this perform diffusion of Au in Ge single crystal [21]. Silver paste contacts had been soldered to the slabs in an inert atmosphere. Spectral responsivity measurements were conducted using the detector test system type: DSR 500 from Optronic Inc. which has monochrometor. type (0-0.5-1200) in the rang (0.1-30)μm, power supply (0-60)Volt, and HP millimiters. Potoconductivity measurements were carried out at 77K using Tungsten

lamp with suuphair window emitted in the range (0.2-6)μm supplied with D.C power supply (15 Ampere). The dark conductivity and with illumination were measured by applying the following equation:

$$\sigma = \frac{L}{R.A_D} \quad (3)$$

Where A_D is the detector area, R is the detector resistance, L is the distance between the electrodes.

Samples were in good contact to copper block to provide good thermal flow and the assembly was mounted in the cavity fitted with Ge window. A copper cylinder served as radiation shield. The temperature was measured by Au, Co-Ag, Au thermocouple attached to one contact point of the sample. I-V characteristics are measured for every sample in dark and under illumination. Current and voltage have been read using digital multimeters. Spectral responsively measurements were performed for all sample detectors, the data were analyzed with the following equation:

$$R_\lambda = \frac{I_{ph}}{P} \quad (4)$$

Where I_{ph} is the photocurrent and P is the corresponding emitting power from IR source which was obtained using standard calibrated detector type PbS model 740-6 from Optronic Inc. The spectral detectivity D* was obtained from equation (2) with the measured values of $R\lambda$ and I_N The total noise was measured using the following equation:

$$I^2_N = (4qI_D G_{ph} \Delta f) \quad (5)$$

Where I_D is the dark current, Gph is the photoconductive gain which is measured by applying the equation:

$$G_{ph} = \frac{I_{ph}}{I_D} \quad (6)$$

Results and Discussion:

The plots of dark and under illumination current as function of applied voltage are shown in Fig. (2a, b, c, d, e, f). For different C_{Au} one can notice the photocurrent explicitly higher than dark current for all doping concentration. Moreover the photocurrent and dark current get to rise together with applied voltage. Another observation is the equating of photo and dark current at high bias voltage as shown in Fig. (2a) this may be attributed to saturation effect, morever an interesting result when gold is added to Ge is that the dark current in Fig. (2, b, c, d, e, f) is lowered three orders of magnitudes comparing with Fig.(2a). This explains the main purpose of gold addition to Ge such that by proper impurity compensation the high conductivity of Ge (high carrier concentration which produce dark current) has been hindered through increasing its resistively. One can observed that dark current was usually linear with voltage. The non linearity appeared for large photocurrent.

The current voltage characteristics were done for C_{Au}=0.1, 0.15, 0.2, 0.25, 0.3, the electrical resistance were obtained using Ohms Law at room temperature and at 77K. One can observed from Table(1) that with gold concentration C_{Au}=0.2 the sample resistance exceeded 10 MΩ while other samples reveal lower increase in resistance at the same temperature, however the resistance of all samples increase three order of magnitude. This fact confirms the work of workers Wood [22], Crigrescu [17], Lasseretal [3], McCubbin [23] who obtain resistance $5x10^6$ Ω for Ge-Au at 77K while Newman [24] indicated that the sample resistance exceeded 10MΩ. Dunlap [25] pointed out that gold doped germanium samples may be high or low resistance and the resistivity may be as high as 10^8 Ω.cm.

Fig.(3a,b) show the different typical relation between photocurrent

response and photon energy for Ge-Au photoconductors with different C_{Au}. The valley in the photocurrent response in the energy range (0.3-0.45)eV are clearly observed for C_{Au}=0.15,0.2,0.25. This may represent the combined effect of the absorption by the adhesive material on the back of the sample and to condensed contamination (e.g water vapor on its front [30]. The same feature was observed by Haller [26] who attributed to photothermalionization process. The same observation of valley in spectral response has been indicated by Perera and Matick [27] who explained the phenomena at the result of two phonon absorption. On the other hand the photocurrent response for 0.15 C_{Au} analogous to the response for 0.2 C_{Au} and 0.1 C_{Au} analogous to the response of 0.25 C_{Au}. While at 0.3 C_{Au} the photocurrent response shows two drops region at the response curve. From the photocurrent response on can deduce an interesting result that the five detector samples have cutoff wavelength at 77K corresponding to 0.155eV such result was indicated by Lesser *et al.* [3] for germanium doped with Au and antimony. Spectral responsivity measurement were performed, and the data were analysis using equation (4). The experimental results for R_λ are shown in Fig. (4) obvious that the higher R_λ corresponding to C_{Au}=0.1. This is similar to that obtained by Dunlap[9]. While the low R_λ can be observed at C_{Au}=0.2 which attributed to high compensation. Since Hiromoto et al [28] sugegested that photoconductors made of Ge single crystal with lower compensation declared higher responsivity to step change in photon flux. Another observation from Fig. (4) is the R_λ peak of C_{Au}=0.1,0.15,0.3 have the the same values at λ=2.8μm while at C_{Au}=0.2 R_λ attain the maximum value at 2.4μm or lower wavelength this is ascribed to compensation effect leads to high resistance Ge-Au detector. Newman [24] pointed out that the high resistance Ge-Au detector show responsivity peak at shorter wavelength. At 0.25 C_{Au} R_λ peak shifted to longer wavelength (4μm), however the responsivity declare very low value in lower wavelength. Indeed the R_λ at (0.2, 0.25) C_{Au} get to vanish with λ in contrast with behaviour of the R_λ of (0.1,0.15,0.3)% C_{Au}. On the other hand the wavery in the plot of R_λ, or one can see more than one peak is attributed to two phonon absorption of germanium [27].

The values of D* were calculated from the measured values of R_λ an I_N the total noise current using equation (4) and (5). The spectral detectivity values are drown as function of wavelength for different gold concentration in Fig.(5). As we expected the performance is high for the lower gain and associated noise at C_{Au} 0.15 and 0.3 at wt%. Our D* value for Ge-Au detector at C_{Au}=0.15 is similar to that obtained by Beyen *et al.*[29]. The D^* were measured to be 4.3×10^{10} $(cm/W)(Hz)^{-1/2}$ for sample resistance $(1\times10^6)\Omega$ at 77K and sensitive area $(2\times2)mm^2$. Our D* value is $2.38\times10^{10}(cm/W)Hz^{-1/2}$ at the mentioned gold concentration. It was found that for optimum current gain, the minimum detectable power will be lowered as compared to the case without gain. If the gain exceeded the optimum value the sensitivity decreases more because of excess noise associated with carrier multiplication.

Table (2) illustrates the main results of photoconductivity measurements of five samples. One can observe that there is no systemic variation of dark resistance with different C_{Au}. This deduction is in agreement with that obtained by Dunlap [25] who had found that Ge-Au

may be high or low resistance as well as could be p or n type depending on the presence of acceptor or donor impurity respectively (i.e. degree of compensation). Indeed the dark resistances of our sample are in the normal range obtained by other workers like Kaiser and Fan [30]. Johnson and Levinstien [15], and Newman [24]. However our Ge-Au samples are good photoconductors as a result of having high resistance at 77K and this makes them easy to detect small current. The fraction change in conductivity concentration produced by incident radiation $\Delta\sigma/\sigma$ and reveal the doping ratio C_{Au}=0.1 is the most sensitive sample because it gave the high photoresponse ($\Delta\sigma/\sigma$=9.43) while other sample gave lower photo response. Our data are compatible with that obtained by Kaiser an Fan [30] for Ge-Au at 77K. The decreasing in $\Delta\sigma/\sigma$ as C_{Au} increases is attributed to onset of impurity conduction or increasing Au concentration increase the thermal charge carriers which in turns increases the noise. The photocurrent gain G_{pc} has been measured through applying equation (6) for the five Ge-Au detectors. The G_{pc} values are listed in table (3). The G_{pc} reach maximum value (40) at C_{Au}=0.2 and decreasing with increasing bias voltage due to increasing dark current. The high G_{pc} for this sample is due to very low dark current since it exhibit very high resistance at 77K. The lower G_{pc} at C_{Au}=0.25 is may be ascribed to low mobility due to high concentration of impurity.

Conclusions

Gold doped germanium photoconductor may be high or low resistance depending on the presence of the donors and acceptors impurities naturally exist in Ge and thus the purity of single crystal germanium used as starting material and the contamination arising in furnace during preparation process of Ge-Au samples are responsible for determining the properties of Ge-Au samples. Introducing gold in Ge is governed by the low solubility of it in the host crystal. Our Ge-Au. Samples are an infrared photoconductors with response to about 6μm. An enhancement in the performance (i.e. the high spectral detectivity values) can be obtained with suitable ratio of gold concentration which leads to low noise or high dark resistance . At 77K Ge-Au detectors samples the generation recombination noise will be dominated.

Table(1) Illustrate the values of dark resistance at room temperature and at77K of gold doped Ge single crystal with different gold concentrations

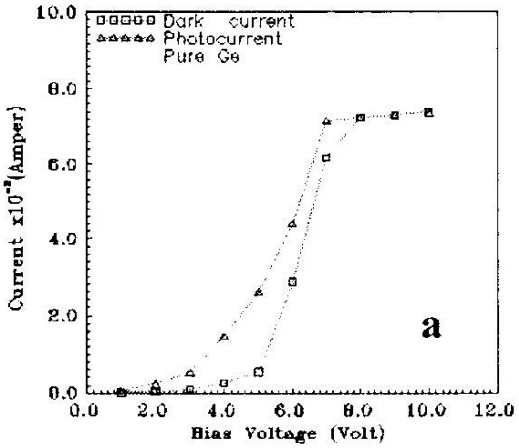
Doping ratio at.wt.%	0.1	0.15	0.2	0.25	0.3
R (at R.T)KΩ	1.33	0.9	1.38	1.616	7.0
R (at 77K)MΩ	24	2.27	90	0.303	0.9

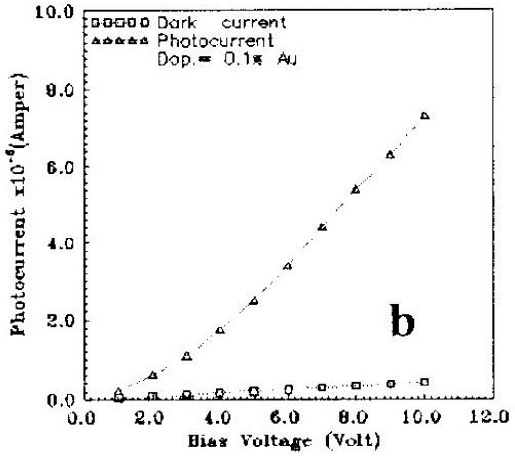
Table(2) Illustrate the values of resistance, conductivity in dark and with illumination with IR radiation and the relative photoresponse of gold doped Ge single crystal at 77K with different gold concentrations

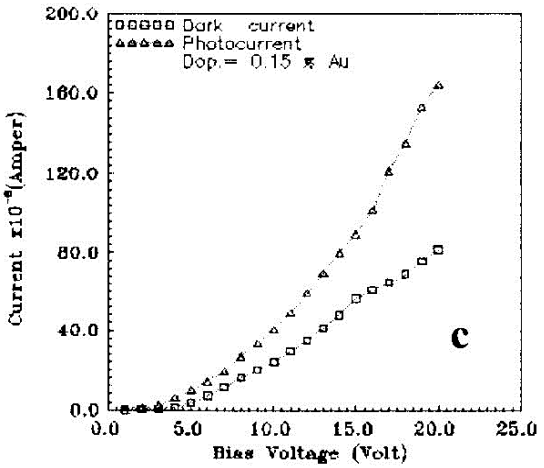
Doping ratio at.wt.%	R_d Ω	R_{ph} Ω	R_{ph}/R_d	σ_d $(\Omega.cm)^{-1}$	σ_{ph} $(\Omega.cm)^{-1}$	$\Delta\sigma/\sigma$
0.1	24×10^6	2.32×10^6	10.43	0.55×10^{-6}	5.74×10^{-6}	9.43
0.15	2.27×10^6	0.667×10^6	3.4	6.16×10^{-6}	20.98×10^{-6}	2.405
0.2	90×10^6	19.54×10^6	4.6	0.22×10^{-6}	1.023×10^{-6}	3.65
0.25	0.303×10^6	0.29×10^6	1.04	66×10^{-6}	68.72×10^{-6}	0.0412
0.3	0.9×10^6	0.4×10^6	2.12	22.28×10^{-6}	47.28×10^{-6}	1.12

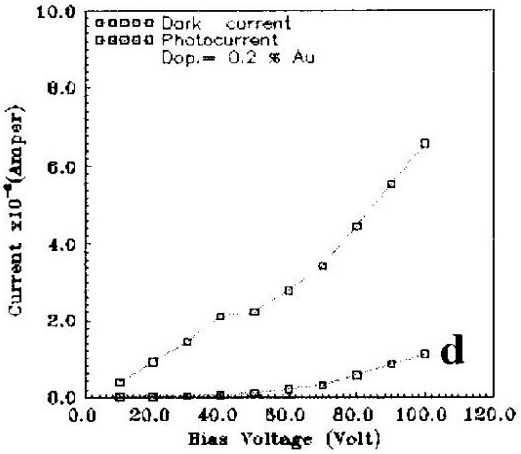
Table (3) Illustrate the photoconductive gain values of the gold doped Ge single crystal at 77K with different gold concentrations

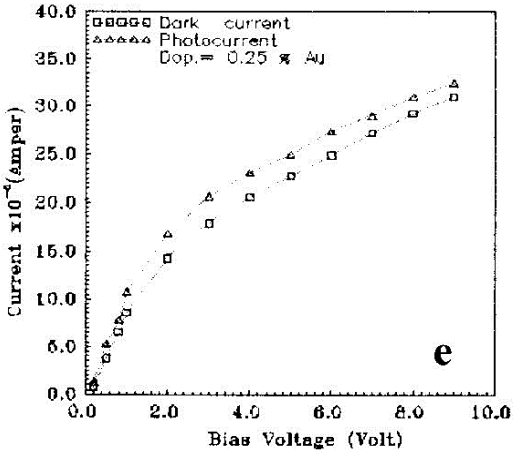
Doping ratio at.wt.%	Gain at Bais Voltage(5 Volt)	Gain at Bais Voltage (10 Volt)
0	4.66	1
0.1	12	17
0.15	2.82	1.67
0.2	50	40
0.25	1.13	1.1
0.3	4.37	4.8











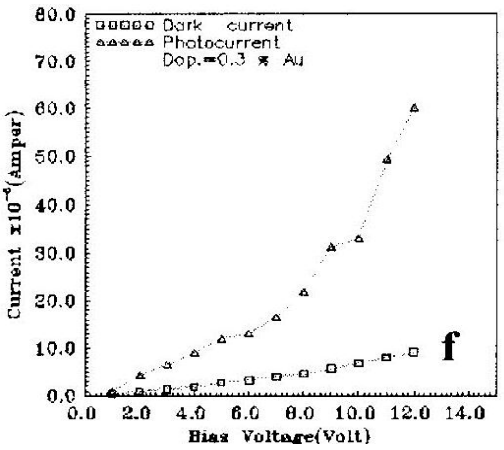
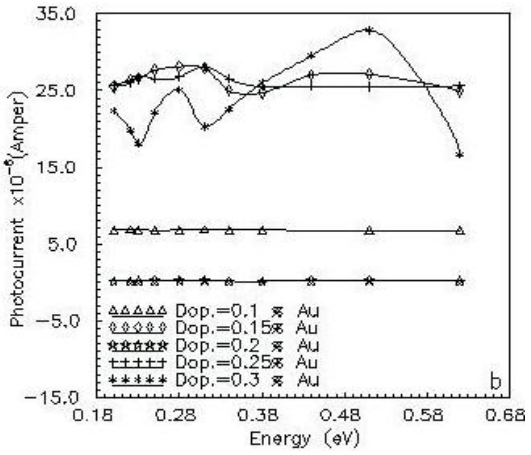


Fig. (2a, b, c, d, e, f) I-V characteristics in dark and with illumination of gold doped Ge single crystal at 77K with different gold concentration



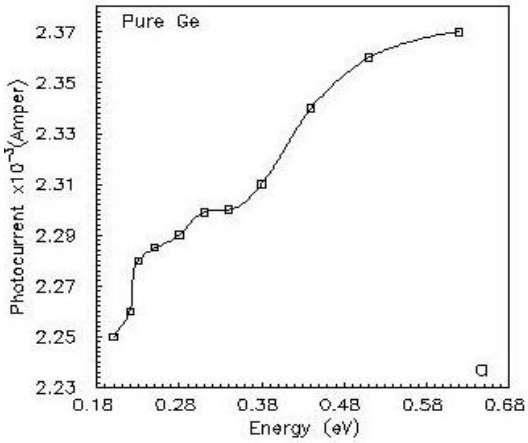


Fig. (3 a, b) Photocurrent response of gold doped Ge single crystal at 77K with different gold concentrations at bias voltage =6Volts

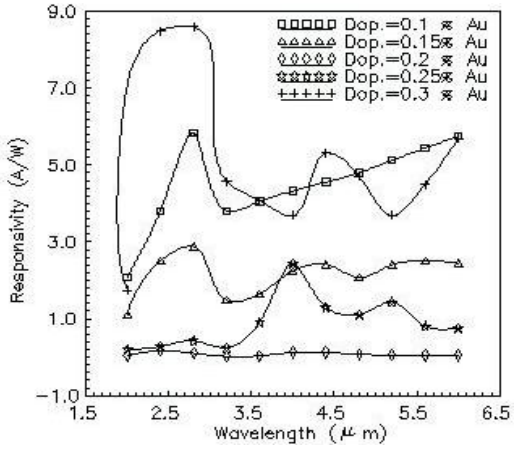


Fig. (4) Responsivity versus wavelength of gold doped Ge single crystal at 77K with different gold concentrations

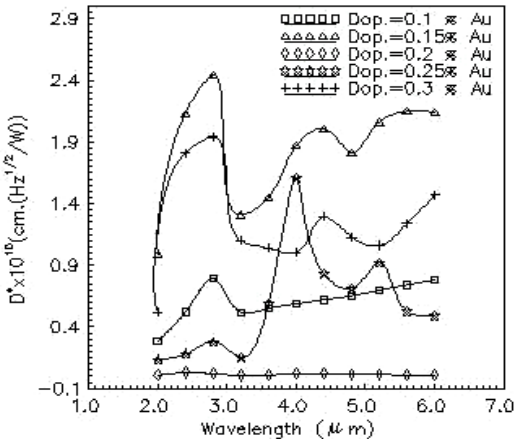


Fig. (5) Detectivity versus wavelength of gold doped Ge single crystal at 77K with different gold concentrations

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