355
10-22-80

h. 1952

DOE/ET/23002-T7

MASTER

**POLYACETYLENE, $(CH)_x$, AS AN EMERGING MATERIAL FOR SOLAR
CELL APPLICATIONS**

Third Quarterly Progress Report for October–December 1979

By
A. J. Heeger
A. G. MacDiarmid

February 14, 1980

Work Performed Under Contract No. AC04-79ET23002

University of Pennsylvania
Philadelphia, Pennsylvania

63,63E

U.S. Department of Energy

Solar Energy

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

"This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy \$6.00
Microfiche \$3.50

TECHNICAL PROGRESS REPORT
(October, November, December, 1979)

(Third Quarterly Progress Report)

POLYACETYLENE, $(CH)_x$, AS AN EMERGING MATERIAL FOR
SOLAR CELL APPLICATIONS

Contract No. DE-AC04-79ET-23002

UNIVERSITY OF PENNSYLVANIA
Philadelphia, Pennsylvania 19104

Date: February 14, 1980

A. J. Heeger

A. G. MacDiarmid

I. Introduction

The electrical and optical properties of the semiconducting polymer, $(CH)_x$,¹⁻³ have recently been of considerable interest. Through chemical doping either p-type or n-type materials can be generated with electrical conductivities which can be varied over the full range from insulator to metal.^{4,5} Optical absorption and reflection studies³ indicate that undoped trans-(CH)_x is a direct gap semiconductor with a band gap of about 1.5 - 2.0 eV. A variety of junctions have been fabricated to elucidate the properties of (CH)_x.⁶ In particular heterojunctions of (CH)_x with either low work function metals or n-type inorganic semiconductors have demonstrated that undoped trans-(CH)_x is p-type, consistent with the observed positive thermopower.⁷ Electron-hole pair generation in the polymer has been demonstrated through photovoltaic response studies of Schottky junctions and p-(CH)_x:n-ZnS heterojunctions.⁶ In the latter case an open circuit photovoltage of 0.8 volt was observed under illumination of 1 sun equivalent. A photoelectrochemical cell has been fabricated utilizing polyacetylene as the active photoelectrode.⁸

In this paper we report initial studies of p-n heterojunctions formed between undoped trans-(CH)_x and n-CdS. The junctions were characterized by measurements of current vs voltage (I-V), capacitance vs voltage (C-V), and photovoltaic response spectra. The results are analyzed in terms of the standard heterojunction equations. We conclude that undoped as-grown films of trans-(CH)_x are p-type with a residual acceptor concentration of

$2 \times 10^{18} \text{ cm}^{-3}$, and that in spite of the complex fibril morphology the semiconductor properties can be inferred by treating $(\text{CH})_x$ as an effective homogeneous medium. Detailed studies of the photovoltaic response at energies below the energy gap for $(\text{CH})_x$ imply the existence of a well-defined deep trapping state in polyacetylene with an energy near the center of the gap.

II. Experimental Details

Undoped trans- $(\text{CH})_x$ films were synthesized using techniques developed by Shirakawa and collaborators.⁹ Two configurations were utilized in these studies:

- i) heterojunctions fabricated by polymerization of a thin (1-10 μm) $(\text{CH})_x$ film directly onto a single crystal n-CdS substrate.
- ii) heterojunctions fabricated by pressure contact of a free-standing $(\text{CH})_x$ film ($\sim 100 \mu\text{m}$) onto a single crystal n-CdS surface.

In both cases, the polyacetylene films were isomerized at 180°C for 2 hours to the thermodynamically stable trans form. Electrodag 502 is known to make good ohmic contacts when painted onto the polymer films and was employed as the electrical contact and carrier collector on the $(\text{CH})_x$ side. The indium doped n CdS was obtained as single crystals from Eagle-Ficher with nominal dopant concentrations of 10 ppm and 50 ppm by weight. Indium was used to make good ohmic contacts to freshly cleaved ($[11\bar{2}0]$ or $[10\bar{1}0]$) CdS.

Routine checks showed that exposure of the CdS crystal to the catalyst caused no harmful effects. For example Au : CdS Schottky diodes were not dependent on previous exposure of the CdS to the catalyst.

Three standard techniques were employed to characterize the heterojunctions: current vs. voltage (I-V), capacitance vs voltage (C-V) and photovoltaic action spectra. The capacitance measurements utilized General Radio 1617 capacitance bridge (120 Hz). For the photovoltaic response, the short-circuit photocurrent was monitored as a function of photon energy using a lock-in amplifier synchronized to a light chopper operating at 27 Hz. A tungsten lamp with a quartz prism monochromator provided adequate intensity over the photon energy range 0.7 eV - 2.5 eV. The source intensity vs. energy was determined by using previously calibrated Si photodiodes and a PbS photoconductive detector. In all cases the light was incident on the junction through the n-CdS ($E_g(\text{CdS}) = 2.42 \text{ eV}$).

To characterize the n-CdS material, Schottky barrier diodes were fabricated by evaporating gold contacts on freshly cleaved surfaces. The C-V characteristics of the Au : n-CdS junctions were used to obtain the donor concentration, N_D , from the slope of the straight line obtained by plotting $1/C^2$ vs V

$$N_D = - \frac{2}{q\epsilon_n} \left[\frac{dC^{-2}}{dV} \right]^{-1} \quad (1)$$

where $q (= 1.6 \times 10^{-19} \text{ Coulombs})$ is the electronic charge and ϵ_n is the dielectric constant of the (n-type) semiconductor. From the Au : n-CdS

(10 ppm) junction we obtained $N_D = 2.7 \times 10^{17} \text{ cm}^{-3}$ (12 ppm) using a value of $\epsilon_n = 10 \epsilon_o$.

III. Discussion of Experimental Results

a. $(\text{CH})_x$ Films Grown on CdS Surfaces

The I-V, C-V and photovoltaic response data for $(\text{CH})_x$:CdS (10 ppm) are shown in Figures 1, 2 and 3. This junction was fabricated by direct polymerization onto the CdS surface with subsequent isomerization. The junction area was 0.105 cm^2 with a $(\text{CH})_x$ film thickness of 4-5 μm . Illumination through the n-CdS with AM2 sun (70 mW/cm^2) produced a short circuit current $I_{sc} = 0.57 \mu\text{A/cm}^2$ and an open circuit voltage $V_{oc} = 0.26 \text{ Volt}$.

The I-V data of Fig. 1 show rectifying behavior characteristic of a p-n junction diode, thus confirming that as-grown polyacetylene is p-type. The series resistance, $\sim 50 \Omega$ for a 1 cm^2 area, is consistent with that expected for undoped trans- $(\text{CH})_x$ with resistivity $\rho \approx 10^5 \Omega\text{-cm}$. As indicated by the C-V data of Fig. 2, the built-in potential ϕ_b was 1.8 V; i. e. very much larger than the observed V_{oc} . The slope of the straight line ($1/C^2$ vs V) was $S^I = 6.7 \times 10^{13} \text{ cm}^4/\text{F}^2\text{-V}$.

The photovoltaic response is shown in Fig. 3 plotted as relative collection efficiency versus photon energy. Since the CdS band gap is 2.42 eV, the observed photoresponse is due to electron-hole generation in the $(\text{CH})_x$; the rapid cut-off above 2.4 eV is due to absorption of the light in the CdS

well away from the junction. The collection efficiency increases dramatically in the region from 1.4 to 2.4 eV, similar to that reported earlier in $(\text{CH})_x$:ZnS heterojunctions.⁶ It is possible that the photocurrent in the region 1.4 - 2.4 eV is limited by a conduction band spike at the interface attributable to the difference in electron affinity of CdS and $(\text{CH})_x$ (see diagram Fig. 3). Such a spike would pose a barrier to collection of photo-generated minority carriers (electrons) from the polymer to the CdS. Alternatively, the relatively low collection efficiency in this range may indicate primary exciton formation, with the actual band gap somewhat larger than 1.4 eV.

The C-V data for a $(\text{CH})_x$:CdS(50 ppm) heterojunction are also shown on Fig. 2. The junction was fabricated in the same manner; direct polymerization on the CdS surface with subsequent isomerization. The junction area was 0.15 cm², and the trans-(CH)_x film thickness was 5 ~ 8 μm. From the C-V data, one finds $\phi_b = 1.9$ volt, and a slope ($1/C^2$ vs V) of $S^{\text{II}} = 1.2 \times 10^{13} \text{ cm}^4/\text{VF}^2$.

For a heterojunction¹¹

$$S = \frac{d(1/C^2)}{dV} = 2 \frac{(\epsilon_p N_A + \epsilon_n N_D)}{q N_A N_D \epsilon_p \epsilon_n} \quad (2)$$

where ϵ_n (ϵ_p) is the dielectric constant of the n-type (p-type) material and N_A (N_D) is the acceptor (donor) dopant concentration. For CdS, $\epsilon_n = 10 \epsilon_0$ (ϵ_0 is the free space permittivity; for $(\text{CH})_x$ we use the average value,

$\epsilon_p^{ave} = (\frac{1}{3}\epsilon_{||} + \frac{2}{3}\epsilon_{\perp}) \approx 6$.^{12, 13} Thus the acceptor concentration in the polymer may be obtained from the expression

$$N_A = \frac{2 \epsilon_n N_D}{(S q N_D \epsilon_n - 2) \epsilon_p} \quad (3)$$

Using the experimental values for S^I (Fig. 2) we obtain $N_A = 1.6 \times 10^{18} \text{ cm}^{-3}$ for the $(\text{CH})_x$ films.

With an impurity concentration of 50 ppm CdS may no longer be characterized as a non-degenerate semiconductor with the dielectric constant of the intrinsic material.¹³ Therefore $\epsilon_n N_D \gg \epsilon_p N_A$ and the heterojunction equation (2) reduces to the Schottky formula

$$N_A = \frac{2}{q \epsilon_p S^{II}}$$

Using the experimental value for S^{II} we obtain $N_A = 2 \times 10^{18} / \text{cm}^3$ in good agreement with the value obtained from S^I and consistent with the results of analysis of the thermopower data.⁷

In the limit when diffusion toward the depleted region is unimportant, the collected current will result only from carriers generated near the junction and carried to the junction by the internal electric field; i. e. I_{sc} will be proportional to the product $E\mu\tau$ or d_p whichever is greater (where E is the electric field, μ is the mobility and τ is the minority carrier lifetime). In either case one would expect an increase in photoresponse by back biasing the junction since the depletion depth and the electric field in the

polymer can be increased by reverse biasing the junction. The photo-response was therefore examined under reverse bias conditions. The results are shown in Fig. 4 for $V = -1$ Volt and -2 Volts. No significant increase was observed for photon energies below approximately 2.0 eV, whereas at higher energies the collection efficiency increases sharply under reverse bias conditions. Increasing the reverse bias (and the field strength in the junction) yields a nonlinear increase in response; at higher fields the increase is larger and onsets at a lower photon energy. The nonlinear increase observed under reverse bias suggests that $E_{UT} < d_p$ with the recombination lifetime field dependent and increasing with increasing field strength in the polymer, perhaps as a result of geminate recombination. The existence of a threshold energy for the enhancement of the collection efficiency with back biasing could be related to the conduction band interface spike (inset of Fig. 3).

b. Pressure Contact $(CH)_x$: CdS Heterojunctions

The C-V characteristic of a heterojunction produced by a pressure contact between n-CdS (N_D^I) and a free-standing trans-(CH)_x film is shown in Fig. 5. As indicated, the heterojunction built-in potential was $\phi_b = 1.94$ Volt; nearly the same as that obtained from the film grown directly on the CdS surface. From the slope (1.4×10^{17} V/F²) we obtain an estimate of the junction area, $A = 0.03$ cm². Since the apparent contact area (the area of the CdS surface) was $.09$ cm², the fractional active area, A_F , was one-third. Evidently the relatively soft mechanical properties and/or rough

surfaces of the trans-(CH)_x films lead to unexpectedly good pressure contact junctions. The photoresponse of this heterojunction is shown in Fig. 6; the large increase in quantum efficiency in the range 1.4 eV - 2.4 eV is again evident. For freshly made junctions a shoulder was observed in the photovoltaic response as shown in Fig. 6a. This shoulder disappears after exposure of the (CH)_x to air for a period of one or two days (Fig. 6b). Similar effects have been observed for the grown junctions.

Since the catalyst used in the (CH)_x polymerization is extremely air sensitive, the possibility that the 1.4 eV shoulder is due to trace amounts of residual catalyst must be considered. In an attempt to check for such an effect, a pressed contact junction was fabricated in a dry box with a drop of catalyst purposely added to the junction region. No effect on the photoresponse was observed. We conclude that the structure in the photoresponse near 1.4 eV is intrinsic to the polymer; the air sensitivity is probably due to the slow reaction with oxygen known from infra-red and magnetic resonance studies.

Both the pressure contact junctions and the direct surface polymerized junctions exhibit short on-off photovoltaic response times. Although previous measurements on (CH)_x:ZnS heterojunctions indicated a long (~ 15 sec) response time, the (CH)_x:CdS junctions as well as (CH)_x:ZnS junctions studied subsequently all have response times less than 0.1 sec.

c. Deep Trapping State in Polyacetylene

Fig. 7 shows the photoresponse of a junction fabricated by direct

polymerization of $(\text{CH})_x$ onto CdS (10 ppm); the data were obtained immediately after first irradiating the junction with radiation at 2.0 eV. The photovoltaic response peak at 0.9 eV was observed only after previously pumping the system by illumination at frequencies above 1.4 eV; moreover the effect could be bleached by irradiation at $\hbar\omega \approx 0.9$ eV. Both the pumping and bleaching occurred reversibly. The threshold photon energy for pumping is shown in Figure 7. To obtain the data of Fig. 8 the junction was first illuminated for 10 sec. at frequencies above 1 eV, then the photoresponse at 0.9 eV was recorded. The threshold pumping energy is clearly evident at $E_{th} = 1.45 \pm .05$ eV.

The decay of the 0.9 eV photoresponse peak was monitored both in the dark and in the presence of bleaching radiation at 0.9 eV (all measurements were taken at room temperature). When measuring the dark decay, the junction was first pumped for 10 sec at $\hbar\omega_p = 2$ eV ($80 \mu\text{W}/\text{cm}^2$ or 2.6×10^{14} photons/ cm^2 -sec.); the system was then kept in the dark for a time t after which the response at 0.9 eV was recorded. The dark decay was extremely slow; as shown in Fig. 9a the characteristic dark decay time is about $4\frac{1}{2}$ hours. The bleaching decay (Fig. 9b) under illumination of 0.9 eV radiation ($.5 \text{ mW}/\text{cm}^2$ or 3.6×10^{15} photons/ cm^2 -sec.) was about 40 seconds. Note that the photoresponse peak measurement could be done in a few seconds so that any effect of bleaching during measurement was small, and corrections for this were made in all measurements.

C-V measurements of the heterojunction of Figs. 6 and 7 yielded $\phi_b = 2.1$ eV and a slope ($1/C^2$ vs V) of $6.12 \times 10^{13} \text{ cm}^4/\text{V-F}^2$ consistent with values from other grown $(\text{CH})_x$:CdS (10 ppm) junctions. The 0.9 Volt response peak has been observed with junctions using both CdS (10 ppm) and CdS (50 ppm). We have thus far observed the 0.9 eV peak only in junctions fabricated by direct polymerization onto the CdS surface. However, we note that the peak signal at 0.9 eV is only about a factor of ten above the limiting noise of our measurement system. Thus, since I_{ac} is typically at least an order of magnitude smaller for the pressed contact junctions, the 0.9 eV peak would be unobservable.

The long dark decay time is indicative of a meta-stable deep trapping state in or near the junction. The traps are efficiently filled by pumping electron-hole pairs at frequencies $\hbar\omega_p \geq E_{th} = E_g$ where E_g is the energy gap in $(\text{CH})_x$. Thus, from Fig. 7, we conclude $E_g = 1.45$ eV. The relatively slow bleaching rate (compared to the filling rate) indicates a quantum efficiency much below that of e-h pair creation for $\hbar\omega > E_g$; the bleaching transition is evidently highly forbidden.

IV. Summary and Conclusion

Heterojunctions have been fabricated between undoped polyacetylene and n-CdS. The I vs V data show rectifying behavior characteristic of a p-n junction diode, thus confirming that as-grown polyacetylene is p-type. Depletion has been studied in the polymer by using CdS of different doping concentrations. From C-V characteristics we infer a residual acceptor

concentration in as-grown films of p-(CH)_x of $N_A \approx 2 \times 10^{18} \text{ cm}^{-3}$, in agreement with that inferred from analysis of the thermopower data, and a junction built-in potential of 1.8 - 2.0 eV. Studies of these junctions imply that the depletion of (CH)_x can be predicted from the simple diode equations in spite of the complex fibril morphology of the polymer. From the point of view of its semiconductor properties (depletion, etc.) (CH)_x can be viewed as an effective homogeneous medium.

Detailed studies of the photovoltaic response at energies below E_g for (CH)_x imply the existence of a meta-stable trapping state 0.9 eV below the conduction band. We note that similar results were reported earlier for (CH)_x:ZnS junctions where a photovoltaic response peak was observed at 0.90 V only after previous irradiation at higher frequencies. Thus, although interface states must be considered, the precise similarity of results with ZnS ($E_g = 3.6 \text{ eV}$, electron affinity = 3.0 eV) and CdS ($E_g = 2.42 \text{ eV}$, electron affinity = 4.5 eV) implies that the meta-stable deep trapping level is in the polymer. In this context we note that the neutral soliton defects proposed for (CH)_x would act as electron (or hole) deep traps with energy near the center of the gap.

The clearly defined threshold for pumping into this deep level provides perhaps the best indication to date of the onset of electron-hole pair generation, $E_{th} = 1.45 \pm .05 \text{ eV}$. Although a shoulder is observed in the photovoltaic response at this energy, the collection efficiency is very small at

1.4 eV. If we identify E_{th} with the energy gap, E_g , then the small photocurrent in the region 1.4 eV - 2.4 eV might be due to the spike formed in the conduction band, at the interface, as a result of the electron affinity mismatch. Alternatively, the relatively low collection efficiency in this range may indicate primary exciton formation, with the actual band gap somewhat larger than 1.4 eV. Since there is no major structure in the optical absorption coefficient at 1.4 eV, we favor the identification of $E_{th} = E_g = 1.45 \pm .05$ eV. However, there is conflicting evidence regarding the precise value of E_g so that additional experiments are in order.

References:

1. C. K. Chiang, C. R. Fincher, Jr., Y. W. Park, A. J. Heeger, H. Shirakawa, E. J. Louis, S. C. Gau, and A. G. MacDiarmid, Phys. Rev. Lett. 39, 1098 (1977).
2. C. K. Chiang, Y. W. Park, A. J. Heeger, H. Shirakawa, E. J. Louis, and A. G. MacDiarmid, J. Chem. Phys. 69, 5098 (1978).
3. C. R. Fincher, Jr., D. L. Peebles, A. J. Heeger, M. A. Druy, Y. Matsumura, and A. G. MacDiarmid, Solid State Commun. 27, 489 (1978).
4. H. Shirakawa, E. J. Louis, A. G. MacDiarmid, C. K. Chiang, and A. J. Heeger, Chem. Commun. 578 (1978); C. K. Chiang, M. A. Druy, S. C. Gau, A. J. Heeger, H. Shirakawa, E. J. Louis, A. G. MacDiarmid, and Y. W. Park, J. Am. Chem. Soc. 100, 1013 (1978).
5. C. K. Chiang, S. C. Gau, C. R. Fincher, Jr., J. W. Park, A. G. MacDiarmid, and A. J. Heeger, Appl. Phys. Lett. 33, 181 (1978).
6. M. Ozaki, D. L. Peebles, B. R. Weinberger, C. K. Chiang, S. C. Gau, A. J. Heeger, and A. G. MacDiarmid, Appl. Phys. Lett. 35, 83 (1979).
7. Y. W. Park, A. Denenstein, C. K. Chiang, A. J. Heeger, and A. G. MacDiarmid, Solid State Commun. 29, 747 (1979); J. F. Kwak, T. C. Clarke, R. L. Greene, and G. B. Street, Bull. Am. Phys. Soc. 23, 56 (1978).
8. S. N. Chen, A. J. Heeger, Z. Kiss, A. G. MacDiarmid, S. C. Gau, and D. L. Peebles, Appl. Phys. Lett. (Jan. 1980).

9. H. Shirakawa and S. Ikeda, Polym. J. 2, 231 (1971); H. Shirakawa, T. Ito, and S. Ikeda, Polym. J. 4, 460 (1973); T. Ito, H. Shirakawa, and S. Ikeda, J. Polym. Sci., Polym. Chem. Ed. 13, 1943 (1975).
10. S. M. Sze, Physics of Semiconductor Devices (Wiley-Interscience, New York, 1969) p. 21.
11. Ref. 10, p. 143.
12. C. R. Fincher, Jr., M. Tanaka, D. Peebles, L. Lauchlan, A. J. Heeger, and A. G. MacDiarmid, Phys. Rev. 20, 1589 (1979).
13. Mihály, G., Vancsó, G., Pekker, S., and Jánossy, A., J. of Synthetic Metals (in press).
14. W. Sasaki, J. Phys. Soc. (Japan) 21 (supplement 1966) p. 543; F. D. Adams, D. C. Look, L. C. Brown, and D. R. Locker, Phys. Rev. B 4, 2115 (1971).
15. I. B. Goldberg, H. R. Crowe, P. R. Newman, A. J. Heeger, and A. G. MacDiarmid, J. Chem. Phys. 70, 1132 (1979).
16. W. P. Su, J. R. Schrieffer, and A. J. Heeger, Phys. Rev. Lett. 42, 1698 (1979); M. J. Rice, Phys. Lett. 71A, 152 (1979); B. R. Weinberger, E. Ehrenfreund, A. Pron, A. J. Heeger, and A. G. MacDiarmid, J. Chem. Phys. (to be published, May, 1980).
17. J. Ritsko, E. Mele, A. J. Heeger, A. G. MacDiarmid and M. Ozaki, (to be published).

Figure Captions:

Figure 1: I-vs-V characteristic of trans-(CH)_x:n-CdS (10 ppm) p-n heterojunction; (CH)_x film polymerized directly on CdS surface.

Figure 2: C-vs-V characteristic of trans-(CH)_x:n-CdS p-n heterojunctions; (CH)_x film polymerized directly on CdS surface. The two lines are for CdS with different doping levels: • • • 10 ppm and x x x 50 ppm.

Figure 3: Photoresponse of trans-(CH)_x:n-CdS (10 ppm) p-n heterojunction; (CH)_x film polymerized directly on CdS surface.

Figure 4: Photoresponse in the presence of reverse bias.

• • • V = -1 Volt

o o o V = -2 Volts

The junction was fabricated by direct polymerization of (CH)_x onto CdS (10 ppm) surface. The data are normalized to the response at zero bias.

Figure 5: C-vs-V characteristic of a free standing film of trans-(CH)_x:n-CdS (10 ppm) p-n heterojunction (pressure contact).

Figure 6: Photoresponse of a free standing film of trans-(CH)_x:n-CdS (10 ppm) p-n heterojunction (pressure contact).

(a) a fresh trans-(CH)_x film

(b) after exposure for four days.

Figure 7: Photoresponse of trans-(CH)_x:n-CdS(10 ppm) p-n heterojunction

• • • Before illumination with $\hbar\omega = 0.9$ eV

x x x After illumination with $\hbar\omega = 0.9$ eV for 20 minutes

The bleaching effect is clearly evident.

Figure 8: Threshold photon energy for pumping effect at 0.9 eV photo-response peak.

Figure 9: Decay of 0.9 eV photoresponse peak.

(a) dark decay

(b) in the presence of illumination at $\hbar\omega = 0.9$ eV

Figure 1: I-vs-V characteristic of $\text{trans}-(\text{CH})_x$:n-CdS (10 ppm) p-n heterojunction; $(\text{CH})_x$ film polymerized directly on CdS surface.

Figure 2: C-vs-V characteristic of trans-(CH)_x:n-CdS p-n heterojunctions; (CH)_x film polymerized directly on CdS surface. The two lines are for CdS with different doping levels: ••• 10 ppm and x x x 50 ppm.

Figure 3: Photoresponse of trans-(CH)_x:n-CdS (10 ppm) p-n heterojunction; (CH)_x film polymerized directly on CdS surface.

Figure 4: Photocurrent in the presence of reverse bias

••• V = -1 Volt

ooo V = -2 Volts

The junction was fabricated by direct polymerization of $(CH)_x$ onto CdS (10 ppm) surface. The data are normalized to the response at zero bias.

Figure 5: C-vs-V characteristic of a free-standing film of trans-(CH)_x: n-CdS (10 ppm) p-n heterojunction (pressure contact).

RELATIVE COLLECTION EFFICIENCY

Figure 6: Photoresponse of a free standing film of $\text{trans}-(\text{CH})_x:\text{n-CdS}$ (10 ppm) p-n heterojunction (pressure contact).
 (a) a fresh $\text{trans}-(\text{CH})_x$ film.
 (b) after exposure for four days.

Figure 7: Photoresponse of $\text{trans}-(\text{CH})_x:\text{n-CdS}$ (10 ppm) p-n heterojunction
 ••• Before illumination with $h\nu = 0.9$ eV
 x x x After illumination with $h\nu = 0.9$ eV for 20 minutes
 The bleaching effect is clearly evident.

Figure 8: Threshold photon energy for pumping effect at 0.9 eV photoresponse peak.

RELATIVE PHOTOCURRENT AT 0.9 eV

Figure 9: Decay of 0.9 eV photoresponse peak.
 (a) dark decay.
 (b) in the presence of illumination at $\lambda_i = 0.9$ eV.