Title
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Publication Date
1984-04-01

LBL-17802

Presented at the Third
International Conference on
Semi-Insulating III-V Materials,
Warm Springs, OR,
April 24-26, 1984; and to be
published in the Proceedings

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April 1984

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Prepared for the U.S. Department of Energy
under Contract DE-AC03-76SF00098

Center for Advanced Materials

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ABSTRACT

Using photothermal spectroscopy, we have performed spatially-resolved imaging of LEC undoped GaAs wafers. We report the observation of sub-surface and surface inhomogeneities a few microns in dimensions. Upon heating the wafers to 250 C in a nitrogen atmosphere these inhomogeneities disappear. We conclude from analysis of the photothermal signal that the inhomogeneities are arsenic-rich inclusions. This conclusion is verified by scanned Auger spectroscopy. We have also used photothermal spectroscopy to investigate gap-state absorption (0.5-1.5 eV) of undoped, Cr-, and Si-doped crystals and to study the effect of plastic deformation on the absorption spectrum. In addition to reproducing the known absorption features, we observe in some of the samples a peak at 0.5-0.6 eV which we tentatively attribute to Fe impurities

The small rise in temperature associated with the absorption of electromagnetic radiation has provided the basis for a new spectroscopic tool generally known as photothermal spectroscopy. A characteristic of this type of spectroscopy is its sensitivity and the relative ease with which it can be implemented. Until recently, the more familiar version of this technique has been photoacoustic spectroscopy where the optical heating is converted into sound and is detected with a suitable transducer, e.g., a microphone or a piezoelectric transducer. Although this technique is useful, the ultimate achieved sensitivity is limited by scattering of light on the transducer. Furthermore, for experiments requiring a wide range of temperatures and pressures, or those involving a hostile environment, photoacoustic detection cannot be employed.

To overcome these limitations, the optical heating can be exploited in a different manner. The heating causes a change in the index of refraction of the medium surrounding the sample. This change is probed with a weak laser beam which is deflected as the index of refraction changes. Using phase-sensitive methods, the amplitude and the phase of the deflection can be readily measured with a position-sensitive detector (Fig. 1). Thus by varying the wavelength of the optically-exciting (pump) beam, the deflection of the probe beam is a measure of the optical absorption. This type of spectroscopy is known as photothermal deflection spectroscopy [1].

For thermally-thin materials, the photothermal signal S is quantitatively related to the optical absorption coefficient in the follwing manner [1]

$$S = A\,[1 - \exp(-\alpha \ell)] \qquad (1)$$

where A is a constant which can be determined emprically, α is the

optical absorption coefficient, and ℓ is the sample thickness.

Sensitivities of $\alpha\ell \simeq 10^{-7}$ have been achieved and the superiority of this technique in terms of sensitivity and flexibility has been demonstrated in a recent study of the optical properties of defects in amorphous semiconductors [2].

There exists a class of experimental conditions for which both photoacoustic and photothermal deflection techniques are not suited for studying the optical and thermal properties of matter. Examples of such experiments are those which require vacuum and/or cryogenic temperatures. Such are the conditions encountered in the study of surfaces and interfaces. Similar requirements exist for the task of in situ and real-time characterization of thin-film semiconductors. These conditions motivated the use of optical heating in a yet another manner. Since heating results in the expansion and buckling of the illuminated surface, a measurement of the surface displacement is a means of determining the optical and thermal properties of the illuminated solid. This small displacement can be detected in a variety of ways, the simplest of which is by reflecting a weak probe laser beam off the illuminated surface. As the surface is displaced upon being optically heated, the probe beam will be deflected from its original reflection direction. This deflection is then detected with a position-sensitive detector (Fig. 2). Typically, $\alpha\ell$ of 10^{-6} are readily achievable. This version of photothermal spectroscopy, which is called photothermal displacement spectroscopy [3], has been employed recently to determine unambiguously the nature of the surface reconstruction of Si(111)2x1 [4].

An important and characteristic parameter in photothermal spectroscopy

is the thermal diffusion length L_{th} which defines the depth from which the photothermal signal originates. L_{th} , which is also called the thermal wavelength, is given by

$$L_{th} = (K_{th}/\omega\rho C)^{\frac{1}{2}} \qquad (2)$$

where K_{th} is the thermal conductivity of the sample, ω is the modulation frequency of the light, ρ is the density, and C is the heat capacity.

The modulation dependence of the thermal diffusion length is what is exploited to perform non-destructive depth profiling and imaging of solids. The higher the modulation frequency , the shorter the thermal length, and the closer to the surface the information is derived from. On the other hand, for low modulation frequencies, the photothermal signal is a probe of the bulk. Furthermore, by focussing the pump and probe beams, scanned microscopy can be performed. The achieved spatial resolution is a function of the size of the focal spot of the pump beam as well as the thermal diffusion length. Resolution of 1 micrometer has been attained.

We have performed scanned photothermal microscopy of semi-insulating LEC undoped GaAs wafers. The pump beam was an Ar- ion laser focussed to one micron on the wafer. The probe beam was a 0.5 mW HeNe laser. Both the deflection and the displacement schemes were used and yielded identical results. As can be seen (Fig. 3), both the phase and the amplitude of the photothermal signal exhibit small features which are due to the scattering of the thermal wave by thermal inhomogeneities in the wafer. By varying the modulation frequency, we were able to determine that these features lie on

and near the surface. By analysing the photothermal signal using the theory described in Ref.[1], we were able to deduce that the inhomogeneities are arsenic-rich inclusions. Our preliminary estimate of the degree of arsenic enhancement in these inclusions is approximately 14% averaged over the one micron pump-beam diameter. To test the validity of our conclusion, scanned Auger spectroscopy (2 micron resolution) was performed on these inclusions. The Auger spectra verified our conclusion and gave an arsenic enhancement of 12%. Upon heating the wafers in a nitrogen atmosphere at 250 C, the arsenic- rich inclusions were no longer observed in the photothermal scans. This could be due to the arsenic diffusing into the matrix or evaporating out of the wafer. It should be noted that anion inclusions have been observed in cleaved III-V surfaces using scanned Auger spectroscopy [5].

We have also investigated the optical absorption spectra of undoped, Cr-, and Si-doped GaAs crystals in the 0.5-1.5 eV range. In Fig. (4) we compare the photothermal deflection spectra of Cr- and Si-doped materials. As can be seen, the semi-insulsting Cr-doped sample reproduces the main features obtained using conventional techniques [6]. In addition, we observe a small peak at 0.5-0.6 eV which we tentatively attribute to Fe impurities. The Si-doped sample exhibits a qualitatively different spectrum. The absorption coefficient does not drop at photon energies lower than 0.9 eV as is the case for the Cr-doped material. The spectra of two Si-doped n-GaAs samples are shown in Fig. (4). While both are from the same boule, sample A is from near the top of the boule, whereas sample B is from near the center. The larger thermal gradients and stresses expected near the top end of the boule may account for the increased defect density in sample A.

In Fig. (5) we show spectra of semi-insulating LEC GaAs and of the same material after being plastically deformed at 400 C. It is clear that the deformation increases the deep-level defect density. This is in agreement with results obtained by other methods such as ESR [7] and conventional infrared absorption [8].

In conclusion, the preliminary results reported here indicate that photothermal spectroscopy and imaging appear to offer a potentially powerful tool for the study and characterization of GaAs and other III-V materials.

Acknowledgements: We thank D. Wei, D. Ripple for technical assistance, G. Elliott of Hewlett-Packard for the GaAs wafers, and K. Gaugler for the scanned Auger spectra. This work was supported by the Director, Office of Energy Research, Materials Science Division, US Department of Energy under contract No. DE-AC03-76SF00098.

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FIGURE CAPTIONS:

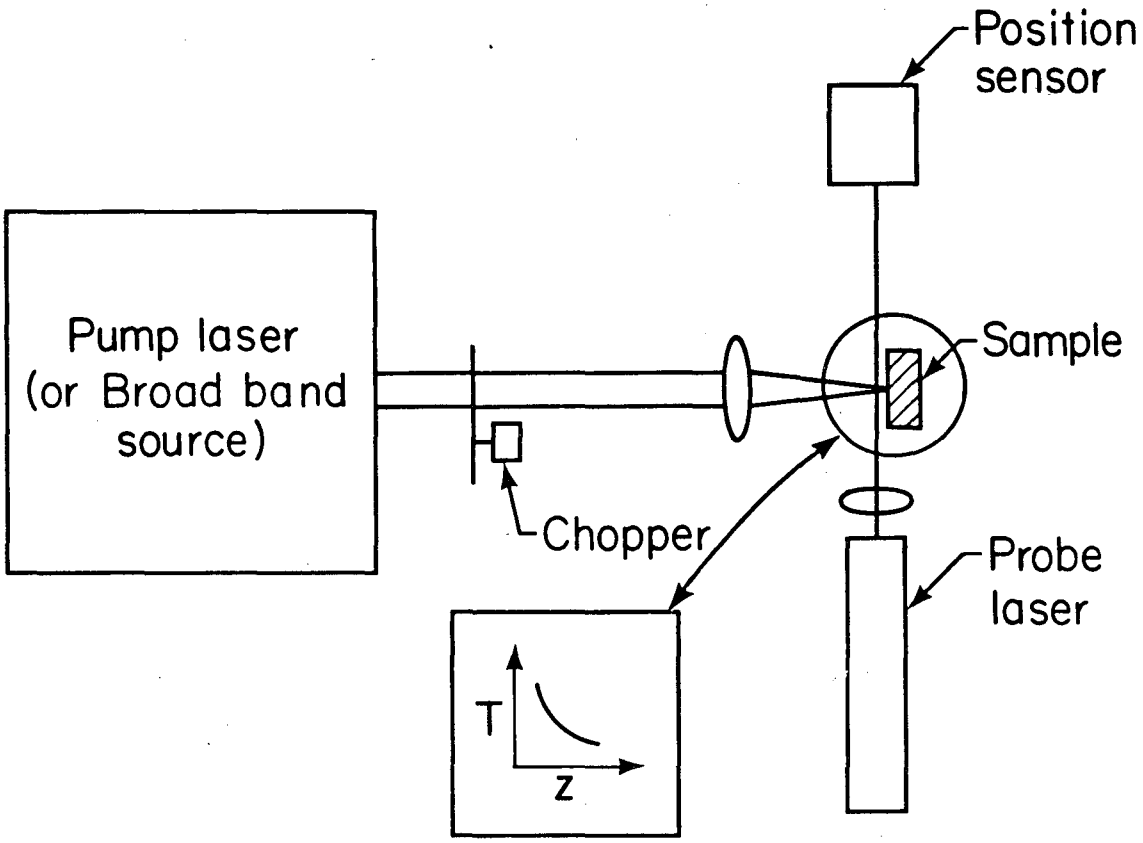
Fig. (1): Schematics of the experimental setup for photothermal deflection spectroscopy.

Fig. (2): Schematics of the experimental arrangement for photothermal displacement spectroscopy.

Fig. (3): Spatially-resolved photothermal scans of LEC undoped GaAs wafers.

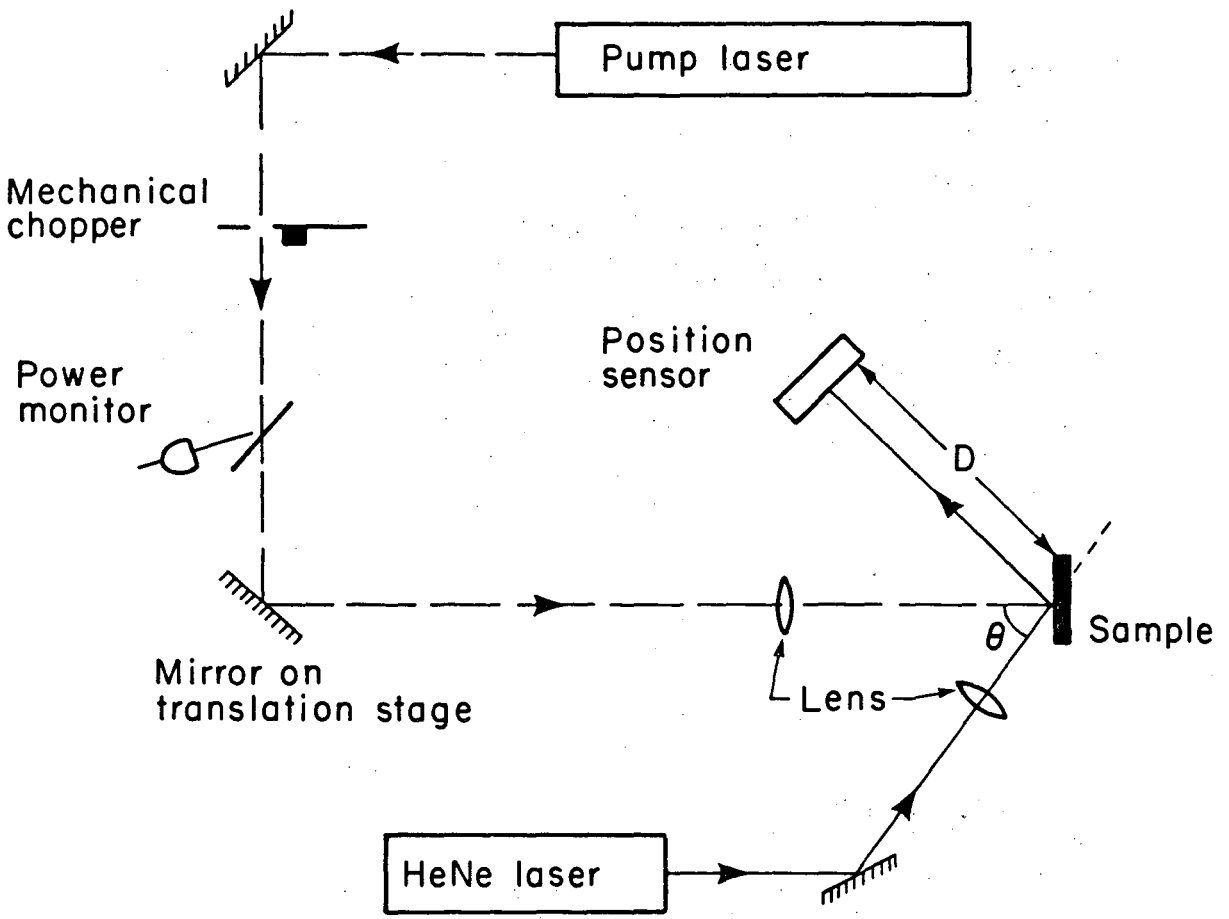
Fig. (4): Photothermal absorption spectra of Cr- and Si-doped GaAs.

Fig. (5): Photothermal absorption spectra of LEC semi-insulating as grown and plstically deformed GaAs.



XBL 836-2666

Fig. (1)



XBL-831-22

Fig. (2)

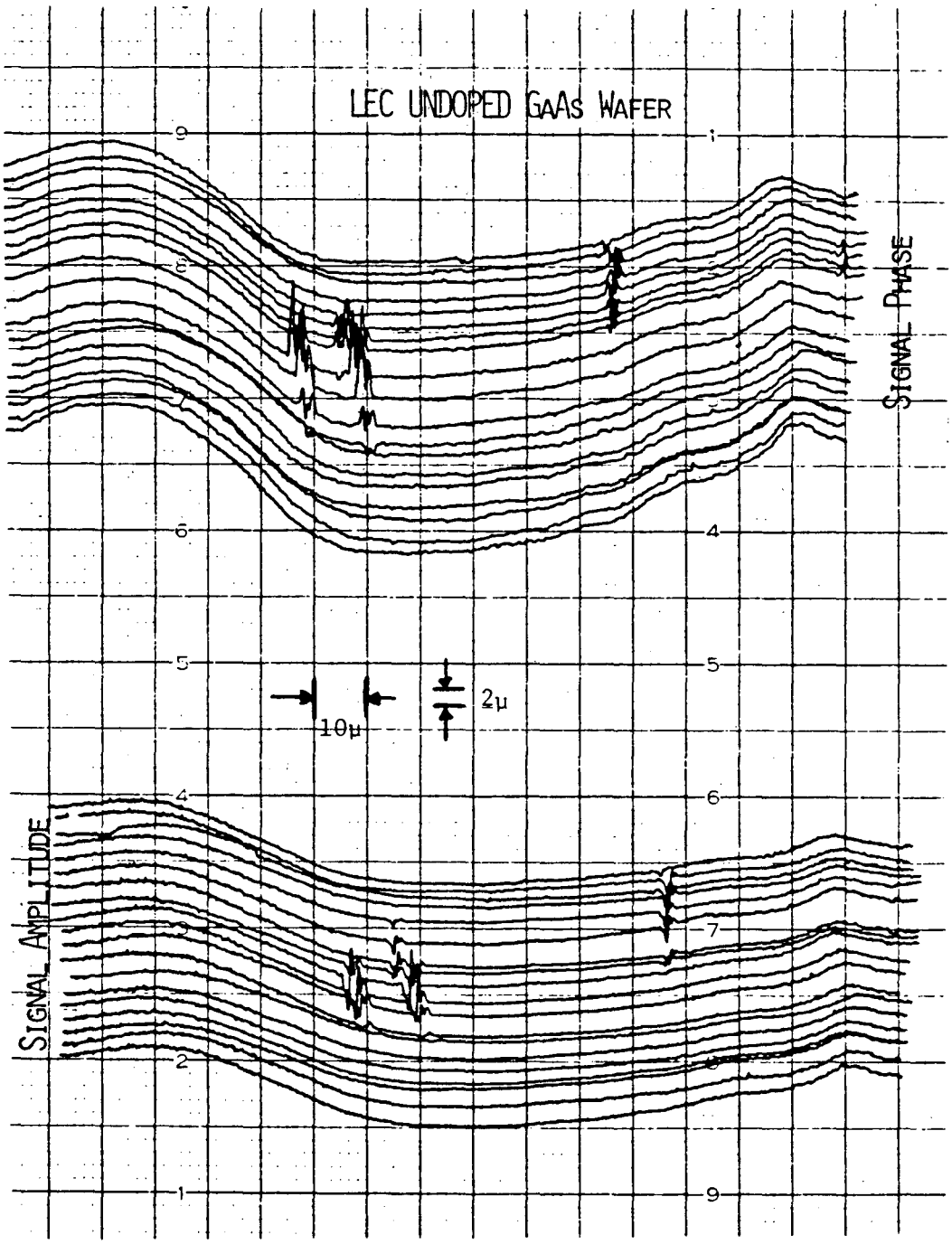

LEC UNDOPED GaAs WAFER
SIGNAL PHASE
SIGNAL AMPLITUDE
10μ
2μ
XBL 845-1701

Fig. (3)

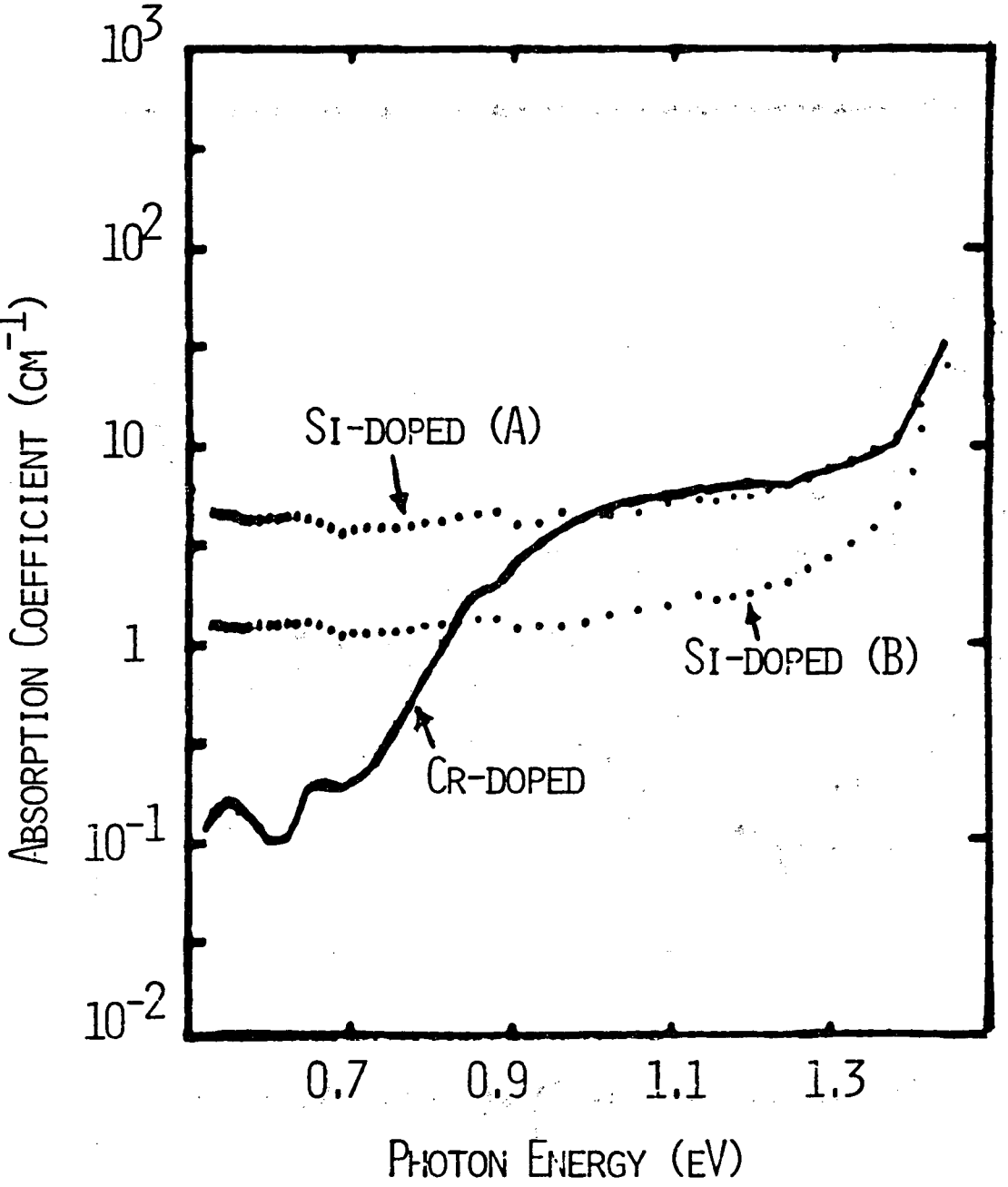


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Fig. (4)

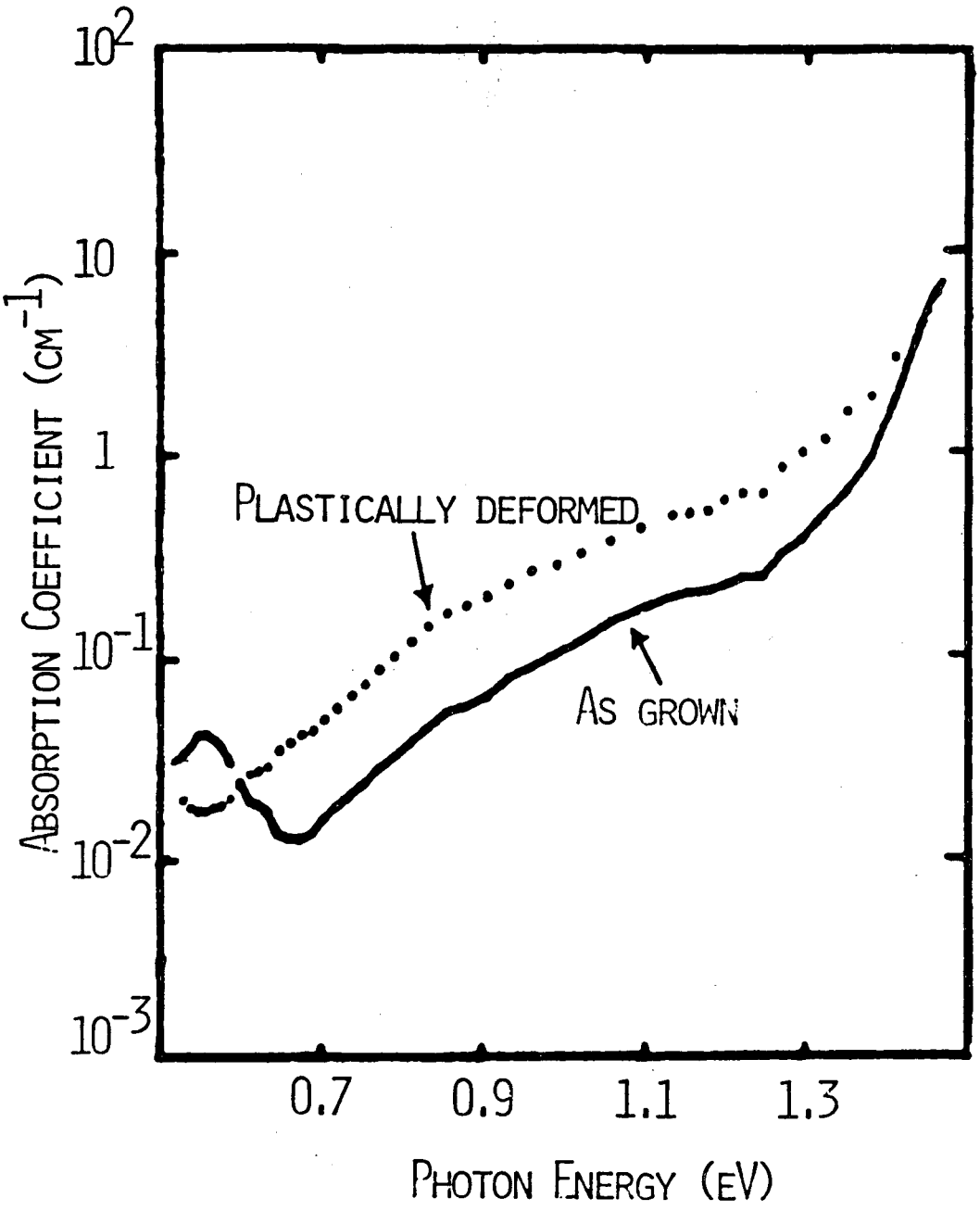

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Fig. (5)

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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