THE APPLICATION OF PHOTOCONDUCTIVE DETECTORS TO THE MEASUREMENT OF X-RAY PRODUCTION IN LASER PRODUCED PLASMAS*

UCRL--97491
DE88 001630

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ABSTRACT

Photoconductive detectors (PCDs) offer an attractive alternative for the measurement of pulsed x-rays from laser produced plasmas. These devices are fast (FWHM ~100 ps), sensitive and simple to use. We have used InP, GaAs, and Type IIa diamond as PCDs to measure x-rays emission from 100 eV to 100 keV. Specifically, we have used these detectors to measure total radiation yields, corona temperatures, and hot electron generated x-rays from laser produced plasmas.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

INTRODUCTION

Protoconductive detectors can be used to measure pulsed x-ray emission from laser produced plasmas. PCDs are fast, sensitive, very easy to use, and in many instances they offer an attractive alternative to other measurement techniques. A PCD consists of a piece of insulating or semiconducting material whose conductivity is modulated by the radiation absorbed. A bias voltage across the detector drives a current that is modulated by the incident radiation. We have employed these detectors to measure x-ray emission from laser produced plasmas from 100 eV to 100 keV.

METHOD OF OPERATION

A PCD is a block of material with two electrodes and an applied electric field as shown in Fig. 1A. Typically, the dimensions of the detector are approximately 1 mm with applied electric fields of 10,000 V/cm. A leakage current will flow through an unilluminated PCD, typically; 1 μA. When a pulse of radiation excites the detector, i.e., the absorbed radiation creates free electrons and holes, the free carriers drift in the applied electric field and the current through the detector is increased, its resistance has changed (Fig. 1b). A time resolved radiation detector requires that the output current of the detector follow the driving radiation pulse; therefore, the free carriers must either recombine or trap out with sufficient speed so the output current faithfully reproduces the absorbed radiation pulse (fidelity). This characteristic time is the recombination or trapping time, τ (see Fig. 1c). The recombination in a pure material is quite long and would result in a slow detector. The key to high speed PCDs is produced detector material that have short carrier lifetimes.

Ideally, a PCD can be modeled by a simple rate equation

$$\frac{dn}{dt} = f(t) - \frac{n}{\tau} \quad , \tag{1}$$

where n is the electron concentration and f(t) is the time dependent generation rate of free carriers. The generation rate of free carriers is related to the absorbed flux of radiation divided by the average energy to form an electron-hole pair, $\mathcal{Y}$. For monoenergetic radiation (i.e. a laser), Eq. 1 is linear in the incident power and can be used to calculate PCD response very accurately.[1] For broadband excitation, a PCD will measure the incident power if $\mathcal{Y}$ is independent of the photon energy. According to Shockley and Read[2] this is true for photo-excitations that are "far above the bandgap" of the PCD material. Far above bandgap excitation implies that sufficient energy is available so that the partitioning of the incident energy is statistical and that on the average a constant amount of energy is required to form an electron-hole pair. For the material of interest, the average energy to form an electron-hole pair is a few times the bandgap energy of the material, i.e. for InP with a bandgap of 1.4 eV $\mathcal{Y}$ is approximately 5 eV. for photon with an energy greater than 100 eV photoexcitation can be considered to be statistical.

We can compare measurements of gamma to the Shockley and Read theory for InP (see Fig. 2). Agreement is within the errors of the experiments. The details on the region near the bandgap where it takes one photon to create an electron-hole pair and the far above bandgap region have been fit with an arbitrary linear function between the two regions.

For practical applications, the voltage output of a PCD can be described by

$$V = \frac{V_0 e \mu \tau R}{L^2} \int \phi \frac{(E)}{\gamma} \, dE \qquad (2)$$

where V_0 is the applied bias voltage, R is the impedance of the recording system, e is the electron charge, μ is the mobility, $\phi(E)$ is the flux of radiation, and L is the detector length. The integral represents the total number of electron-hole pairs created by the absorbed radiation. The sensitivity of a PCD can be compared to photoemissive device, an x-ray diode.[3] Per unit area PCDs in general are more sensitive than x-ray diodes and are dramatically more sensitive at higher energies. In many applications the flat response of a PCD is a distinct advantage (see Fig. 3).

DETECTORS

The present discussion is limited to three materials InP, GaAs, and Type IIa diamond. The pure semiconductors material (InP and GaAs) are not fast enough to be of interest; therefore, to decrease the recombination time, the crystal lattice is distorted by either doping with a suitable material or damaging it with energetic particles. For example, neutron damaged GaAs samples have been routinely produced with recombination times of less than 60 ps. Type IIa diamond is naturally doped with impurities and has subnanosecond time response. Diamond has a large bandgap (5.5 eV) which makes it very attractive for use as a total power monitor in laser plasma interactions. The large bandgap makes it relatively insensitive to scattered laser light and as a result can be used without filtration.

LASER PRODUCED PLASMA MEASUREMENTS

Diamond PCDs have been used in disk experiments to measure the total radiation yield from a variety of targets. These experiments were performed with an unfiltered detector utilizing its relative insensitivity to scattered laser light (0.35 μm on the Nova laser). The experiments include x-ray conversion efficiency measurements on gold and uranium and Au:Be mixtures.

At the Naval Research Laboratory, using the Pharos III laser, we studied the effects of induced spatial coherence (ISI) on the conversion of 1.05 μm light to soft x rays using a PCD filtered to look at 600 eV photons.[4] Figure 4 is a summary of the results for 300 J of laser radiation in a 2 ns pulse focused to 10^{14} W/cm^2 on gold. A statistically significant improvement in the x-ray conversion efficiency was observed between the ISI and the non-ISI beam.

High energy x rays produced in laser-plasma interaction from hot electrons can also be measured with PCDs. A direct comparison was made between a single channel PCD measurement of hot electron yield and a multichannel filter, scintillator, and photomultiplier detector covering the energy range from 20 to 60 keV was made. The two systems agreed within the uncertainties of the measurement.

The sensitivity of the PCDs to visible light can be exploited to provide a timing fiducial for laser based experiments. The Nova laser 2ω optical fiducial has been fiber optically coupled into the PCD. By controlling the relative timing of x-ray signals and the optical fiducial, a single oscilloscope trace can provide an accurately timed piece of the time resolved x-ray emission (see Fig. 5). Modern high speed single shot recording systems have permitted measurements to be made with 150 ps time resolution.

CONCLUSION

PCDs have found a variety of applications in the measurement of x rays from laser produced plasmas from 100 eV to 100 keV. The detectors are fast and simple to use. Their sensitivity to visible light permits accurate timing in laser based experiments.

REFERENCES

1. A. E. Iverson and D. L. Smith, IEEE Trans. Elec. Dev., (1987).
2. W. Shockley and W. T. Read, Jr., Phys. Rev. 87, 835 (1952).
3. D. R. Kania, et al., Jour. Appl. Phys. 60, 2596 (1986).
4. D. R. Kania, et al., 17th Annual Anomalous Absorption Conference, Tahoe City, CA 1987.

FIGURE CAPTIONS

1. An overview of the operation of a PCD: a) biased but unilluminated detector results in a small leakage current, b) illumination creates free electrons and holes that produce a current by drifting in the applied electron field, and c) recombination of the free carriers with a characteristic time, t.
2. A comparison of the Shockley theory of the average energy to form an electron hole pair to a variety of experiments for InP (see Ref. 3 for details).
3. A comparison of the response of an InP:Fe photoconductor of various lengths, L, with three common x-ray diode photocathode materials versus photon energy.
4. A filtered PCD measurement of the x ray yield from the interaction of 2 ns pulses containing 300 J of 1.05 μm laser light focused to 10^{14} W/cm^2 with and without induced spatial incoherence (ISI).
5. A sample measurement demonstrating the use of optical fiducial (0.53 μm mixed with a measurement of 50 to 100 keV x rays from a laser produced plasma.

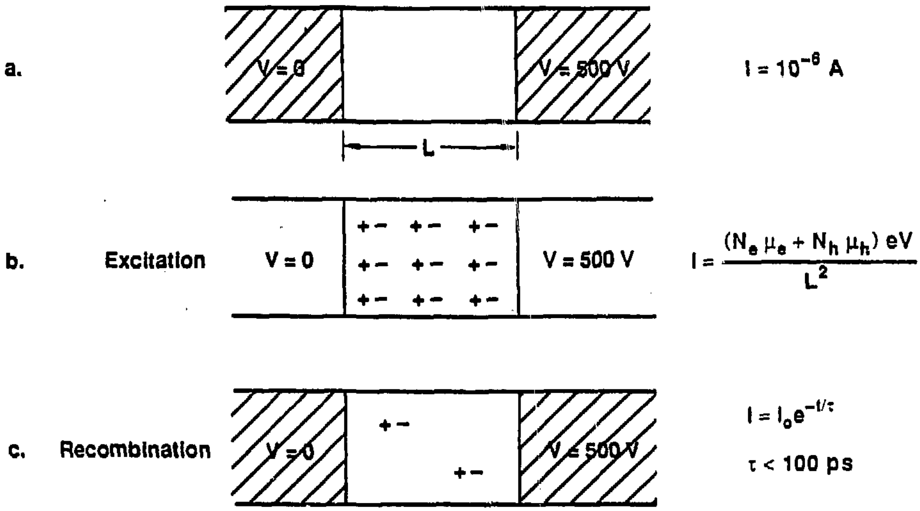

a.
V = 0
V = 500 V
$I = 10^{-6}$ A
L
b.
Excitation
V = 0
V = 500 V
$I = \frac{(N_e \mu_e + N_h \mu_h) eV}{L^2}$
c.
Recombination
V = 0
V = 500 V
$I = I_o e^{-t/\tau}$
$\tau < 100$ ps

Figure 1

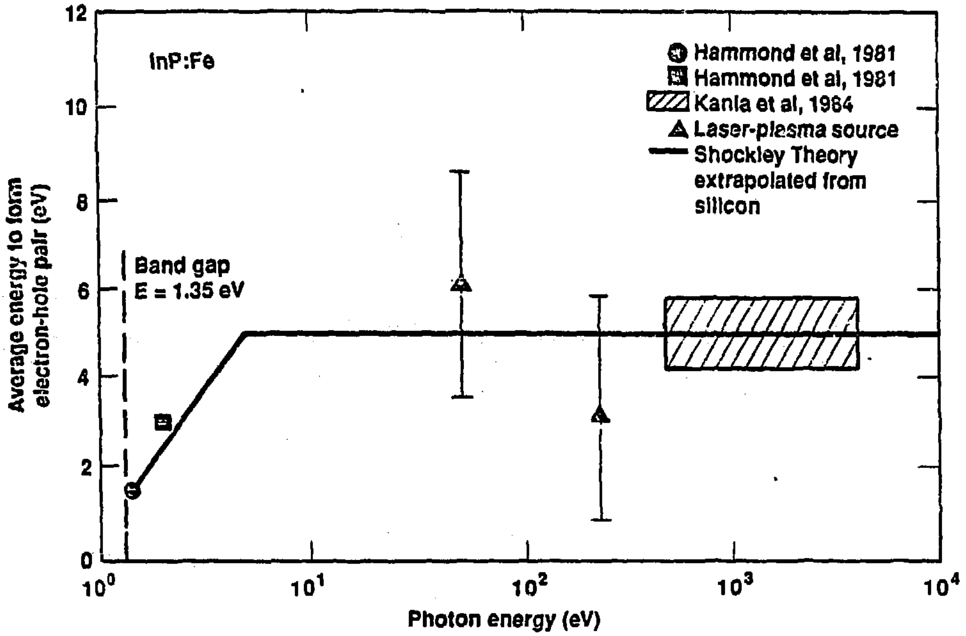

12
10
8
6
4
2
0
InP:Fe
Hammond et al, 1981
Hammond et al, 1981
Kania et al, 1984
Laser-plasma source
Shockley Theory extrapolated from silicon
Band gap
E = 1.35 eV
Average energy to form electron-hole pair (eV)
10^0
10^1
10^2
10^3
10^4
Photon energy (eV)

Figure 2

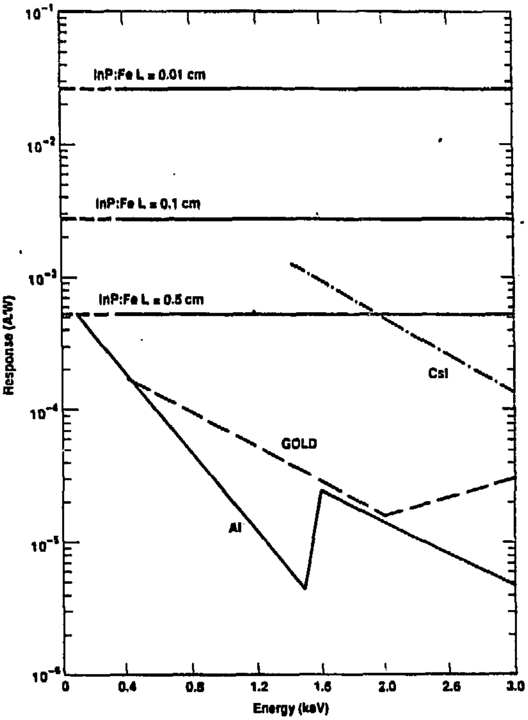
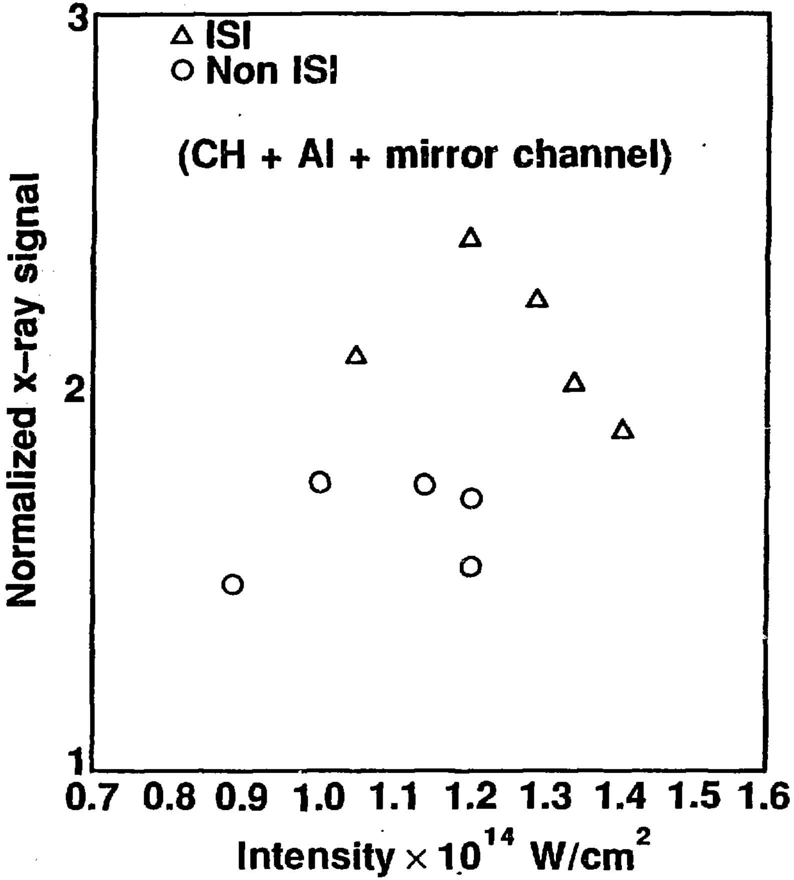

10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
InP:Fe L = 0.01 cm
InP:Fe L = 0.1 cm
InP:Fe L = 0.5 cm
CsI
GOLD
Al
Response (A/W)
0
0.4
0.8
1.2
1.6
2.0
2.6
3.0
Energy (keV)

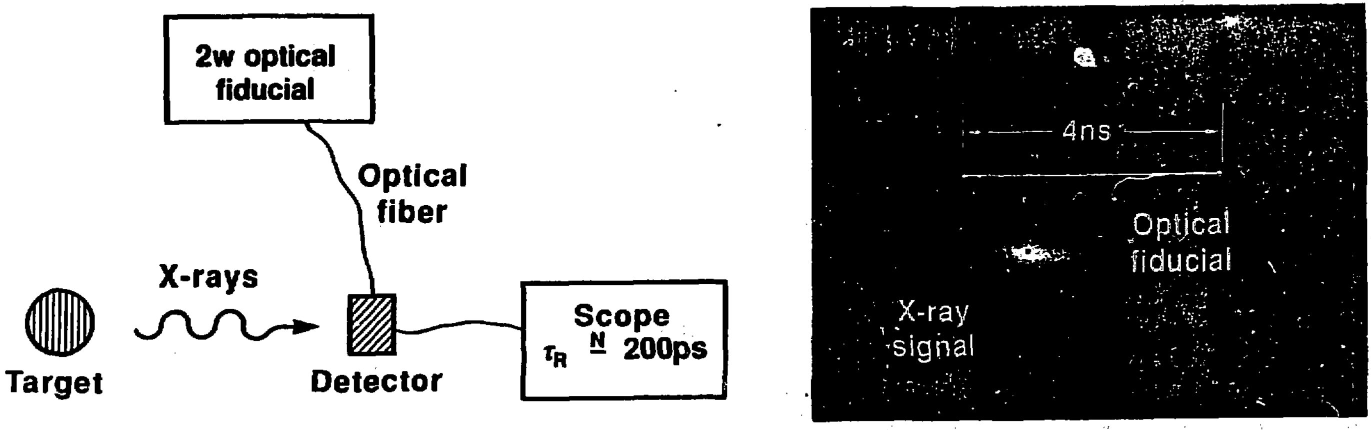
Figure 3



3
2
1
△ ISI
○ Non ISI
(CH + Al + mirror channel)
Normalized x–ray signal
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
Intensity × 10^{14} W/cm^2

Figure 4

Figure 5


2w optical fiducial
Optical fiber
X-rays
Target
Detector
Scope
τR ≅ 200ps
4ns
Optical fiducial
X-ray signal