GaAs – A VERSATILE PHOTOCONDUCTIVE MATERIAL FOR THE MEASUREMENT OF X-RAYS IN PULSED POWER APPLICATIONS[1]

John E. Rauch[a], Miriam Gersten-Rauch[a,2], Arnold Burger[b], Douglas S. McGregor[c], Alan W. Hunt[d], Randy Spaulding[d], Don King[e], Dave Beutler[e], John Riordan[f], Bruce Failor[f], Jerrold Levine[f], Niansheng Qi[f], Henry Sze[f], Philip Coleman[g], Roman Sobolewski[h], Aleksandr Verevkin[i], Frank Young[j], Frank Davies[k], Chris Delacruz[k], Kelly Campbell[l], and Ajay Verma[m]

[a]Nu-Trek, Inc., 16428 Avenida Florencia, Poway, CA 92064
[b]Fisk University, Center for Photonic Materials and Devices, Nashville, TN 37208-3051
[c]Kansas State University, Mechanical and Nuclear Engineering, Manhattan, KS 66506-5205
[d]Idaho State University, Idaho Accelerator Center, Pocatello, ID 83209
[e]Sandia National Laboratories[3], P.O. Box 5800, Albuquerque, NM 87185-1136
[f]Titan Pulsed Sciences Division, 2700 Merced Street, San Leandro, CA 94577
[g]Alameda Applied Sciences Corp., 626 Whitney St., San Leandro, CA 94577
[h]University of Rochester, Laboratory for Laser Energetics, Rochester, NY 14623
[i]University of Buffalo, Electrical Engineering Department, Buffalo NY 14260
[j]Titan Corporation, 11955 Freedom Drive, Reston VA 20190
[k]K-Tech, 1300 Eubank Blvd SE, Albuquerque, NM 87123-3336
[l]Lawrence Livermore National Laboratory, Livermore, CA 94551
[m]Defense Threat Reduction Agency, Kirtland AFB, Albuquerque, NM 87117-5669

Abstract

We developed four types of GaAs PCDs: bremsstrahlung (two types), soft x-ray, and gamma for pulsed reactors. GaAs PCDs are advantageous in applications that require fast response, high dose rate, and/or neutron insensitivity. Desired detector sensitivity and response were obtained through modification of carrier lifetime by neutron irradiation, size of the sensing element, and orientation of the sensing element. The GaAs PCDs were used to characterize pulsed radiation sources in over 10 different tests and the measured data from these tests are presented.

GaAs PCDs (E7 – E11 rad(Si)/s for use with pulsed bremsstrahlung sources were tested at DTRA Radiation sources, Linac (Idaho Accelerator Center), Linac (White Sands), Hybrid Radiation Source (NRL), GAMBLE II (NRL), and HERMES III (Sandia).

GaAs PCDs for gamma characterization in pulsed reactors (E6 – E7 rad(Si)/s) were calibrated with a Linac (White Sands), checked for high dose rate (E12 rad(Si)/s) response at HERMES III, checked for low dose rate response (5 – 500 rad(Si)/s) and stability at a Co-60 source (Sandia), and checked for stability, sensitivity, and residual radioactivity at the ACCR reactor (Sandia).

Soft x-ray (1 to 15 keV) GaAs PCDs (E2-E6 Watts/cm^2) were used to measure the argon plasma free-bound continuum temperature from a Plasma Radiation Source (PRS) and compared with the plasma temperature obtained from line ratio measurements.

I. GaAs PCD TECHNOLOGY

A. PCD Operation

The GaAs PCDs were designed for applications requiring fast response time, high dose rate, or neutron insensitivity. A broad range of characteristics can be achieved by varying the: (1) Carrier lifetime (via neutron modification); (2) Size of sensing element; and Detector geometry. We developed three detector types: bremsstrahlung (two geometries), soft x-ray, and gamma for characterization of pulsed reactors.

We developed two GaAs PCD types, Parallel and Transverse. The applied electric field is parallel and perpendicular to the direction of applied electric field, respectively. This is illustrated in Fig.1.

Radiation incident on the GaAs generates electron-hole pairs. The GaAs, which is initially a semi-insulator, becomes a conductor. The current is proportional to the conductivity and is given by the formula:

$$I = \frac{q\mu\rho VA}{Wd}\tau\dot{D} \qquad \text{(Eq.1)}$$

where q is the electron charge, μ is the carrier mobility, is the PCD density, V is the bias voltage, A is the detector electrode area, is the carrier lifetime, $\dot{D}$ is the dose rate,

[1] Supported by DTRA01-02-P-0239, DTRA2-04-C-0001, and MDA HQ0006-03-C-0112.

[2] E-mail: miriam@nu-trek.com.

[3] Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US Department of Energy under Contract DE-AC04-94AL85000.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2005	**N/A**	-

4. TITLE AND SUBTITLE	
GaAs A Versatile Photoconductive Material For The Measurement Of X-Rays In Pulsed Power Applications	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Nu-Trek, Inc., 16428 Avenida Florencia, Poway, CA 92064**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.

14. ABSTRACT
We developed four types of GaAs PCDs: bremsstrahlung (two types), soft x-ray, and gamma for pulsed reactors. GaAs PCDs are advantageous in applications that require fast response, high dose rate, and/or neutron insensitivity. Desired detector sensitivity and response were obtained through modification of carrier lifetime by neutron irradiation, size of the sensing element, and orientation of the sensing element. The GaAs PCDs were used to characterize pulsed radiation sources in over 10 different tests and the measured data from these tests are presented. GaAs PCDs (E7 E11 rad(Si)/s for use with pulsed bremsstrahlung sources were tested at DTRA Radiation sources, Linac (Idaho Accelerator Center), Linac (White Sands), Hybrid Radiation Source (NRL), GAMBLE II (NRL), and HERMES III (Sandia). GaAs PCDs for gamma characterization in pulsed reactors (E6 E7 rad(Si)/s) were calibrated with a Linac (White Sands), checked for high dose rate (E12 rad(Si)/s) response at HERMES III, checked for low dose rate response (5 500 rad(Si)/s) and stability at a Co-60 source (Sandia), and checked for stability, sensitivity, and residual radioactivity at the ACCR reactor (Sandia)

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

W is the energy required to produce electron hole pair (4.3 eV in GaAs), and d is the detector electrode separation. It is because the current is proportional to the conductivity and NOT the collected charge (common misconception) that the very fast response time is possible.

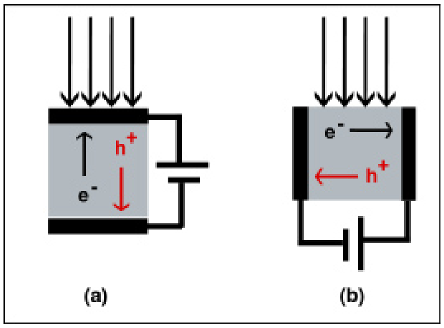

Figure 1. (a) Parallel and (b) Transverse PCDs.

B. Test Overview

Bremsstrahlung PCDs were designed for E7-E11 rad(Si)/s and tested up to 2E12 rad(Si)/s (HERMES III, Sandia). 30 ps response time was also demonstrated. These PCDs were tested on the Fast Linac at the Idaho Accelerator Center (IAC), DTRA simulator (several tests), a Linac at White Sands, HERMES III (Sandia), and GAMBLE (NRL).

Soft x-ray GaAs PCDs (1-15 keV, E2-E6 Watts/cm^2) were evaluated on Ar gas jet experiments. In addition to checking out the PCDs, Phil Coleman compared line ratio temperatures to free-bound continuum temperatures obtained with the PCDs.

Don King (Sandia) characterized the reactor PCDs (5E5-2.5E9 rad(Si)/s). Tests included Linac (calibration), HERMES III (high dose rate), Co-60 (stability), and ACCR reactor (performance, stability, and activation).

II. BREMSSTRAHLUNG AND E-BEAM

A. Sensitivity and Tests

We fabricated/tested Parallel and Transverse PCDs for E7-E11 rad(Si)/s. Nu-Trek tests include: (a) Technology demonstration (Parallel); (b) 30 ps demonstration, Fast Pulse Linac, (with Hunt and Spaulding/IAC); and (c) Calibration, White Sands (with King/Sandia). User/collaborator tests include: (a) Soft/Moderate bremsstrahlung (Riordan/Titan, Delacruz/ K-Tech); (b) 2E12 rad(Si)/s, HERMES III (Beutler); and GAMBLE II (Young/SAIC).

B. Parallel GaAs PCDs

Fifty Parallel biased GaAs PCDs were fabricated and tested using an MBS (Fig 2 and Fig. 3). In Fig. 2 the x-ray pulse recorded with GaAs PCD and facility PIN diode are compared. Note the superior rise time and pulse definition. The GaAs PCD waveform was also a better match with the electrical waveforms.

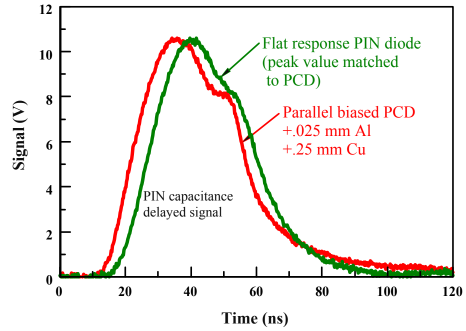

Figure 2. Comparison between Parallel biased GaAs PCD and the facility PIN diode.

The detectors were tested in groups of 10. Figure 3 illustrates the excellent consistency on a detector-to-detector and shot-to-shot basis. This data is for 10 shots (x10 detectors). Standard deviation was 4-8 %.

Although the Parallel PCDs were very reliable, we decided to focus on the Transverse PCDs. This is because they are capable of substantially faster response times and are equally applicable to soft and hard spectra.

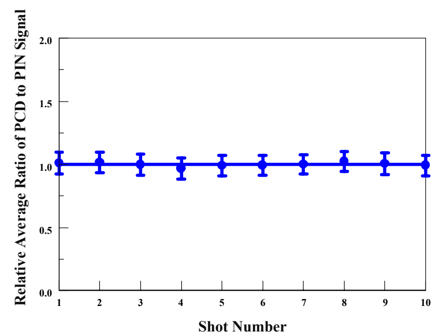

Figure 3. Excellent repeatability; 4-8% standard deviation in absolute response (10 shots, 10 detectors/shot).

C. Fast responding Traverse PCDs/IAC tests

Testing was performed at the IAC using the Fast Pulse Linac (***bunched*** mode of operation). It has a pulse width of ~ 50 ps. PCD response time is ~ 30 ps (Fig. 4).

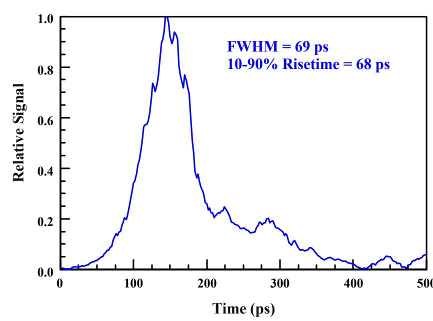

Figure 4. Fast Pulse Linac (***bunched***), IAC. Pulse width is ~ 50 ps and PCD response time is ~ 30 ps.

We proceeded to use the same GaAs PCD to resolve the Linac fine structure. (Fast Pulse Linac, ***un-bunched*** mode of operation.) The PCD waveform is compared to the facility PIN diode. Actual dose rate is 3.5X than measured with facility PIN diode.

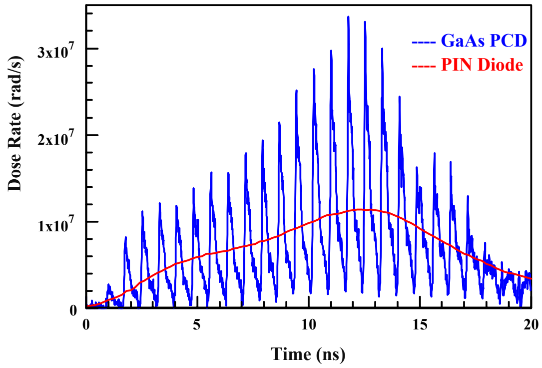

Figure 5. Linac pulse as recorded with GaAs PCD and facility PIN diode. Actual dose rate is x3.5 higher than normally reported. (Fast Pulse Linac, ***un-bunched***, IAC)

Figure 6 was also recorded with the Fast Pulse Linac and illustrates the diversity of time response possible with the GaAs PCD. Each PCD had a different active area and/or neutron modification.

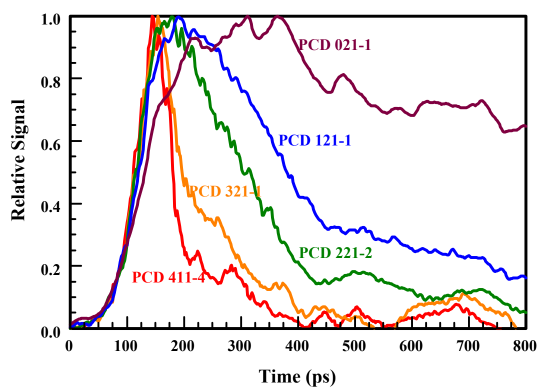

Figure 6. Waveforms corresponding to 5 different neutron modification levels and a number of different sensing areas.

D. Titan and Sandia Tests

John Riordan (Titan) and Dave Beutler (Sandia, HERMES III) evaluated the GaAs PCDs. The data is shown in Fig. 7 and Fig. 8 respectively. Similar tests were performed at NRL on GAMBLE and by K-Tech.

John Riordan compared a Si PIN diode, photo diode and a GaAs PCD (Fig. 7). He is considering using the GaAs PCDs for the construction of a near-field voltage monitor for use on the source-side of the Reflex Triode and as detection elements in the Time-resolved Differential Absorption Spectrometer (TDAS), which presently uses diamond PCDs. In comparison to the other two detector types, the GaAs PCDs can operate at higher dose rates and hence are suitable for near field applications in which the dose rate is high. The PIN diode and photo diode are too sensitive for near field applications.

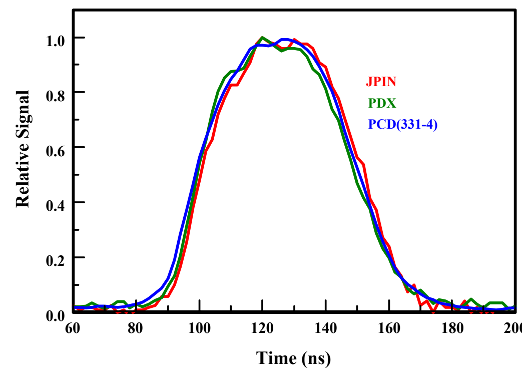

Figure 7. PIN diode, photo diode and GaAs PCD comparison. Excellent match was obtained.

Dave Beutler (Sandia) compared a GaAs PCD (PCD 411-7) to a diamond PCD (PCD 415). Dose rate was 2E12 rad(Si)/s, a factor of 20 higher than the design goal. The GaAs PCD had a faster rise time and a truer late time response. The waveforms had "ripples" at the high dose rates that were result of using the PCD at dose rates much higher than their design. Lower sensitivity models that will work well at these dose rates are being fabricated.

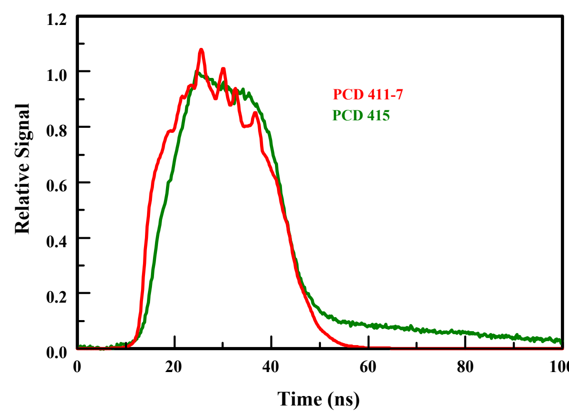

Figure 8. Comparison of GaAs PCD (411-7) and diamond PCD (415) at high dose rate (2 E12 rad(Si)/s).

III. SOFT X-RAY

A. Overview

These GaAs PCDs are Traverse and have high field magnets (5600 Gauss) to suppress photoelectron emission. We checked out the PCDs in an Argon PRS (Plasma Radiation Source) test. On the same test Phil Coleman (AASC) used the GaAs PCDs to measure the plasma temperature from the free bound continuum. We also checked out the PCDs at White Sands using a Linac. A previous generation of GaAs PCDs was calibrated at the Brookhaven Cyclotron, (Campbell, Livermore) and these PCDs will be calibrated in the fall.

B. PRS Tests

Test objective was characterization of the 12 cm Ar gas puff that was developed by AASC. A typical argon spectrum is presented in Fig. 9. The He-like free-bound continuum starts around 4.1 keV. For the line ratios we used the Ly-alpha and the He-alpha (+IC line).

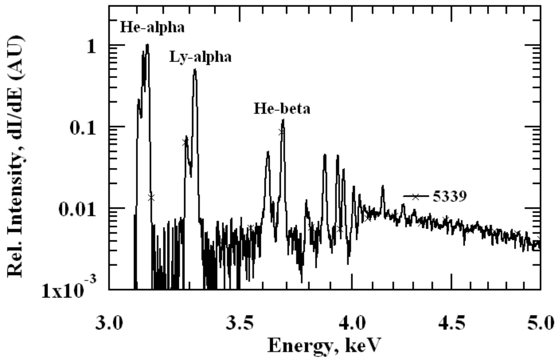

Figure 9. Typical Ar K-shell spectrum. The temperatures derived from the free-bound continuum and the ratio between the He-alpha and Ly-alpha were compared.

In support of the PRS tests we fabricated a vacuum mounting plate that accommodated 4 GaAs PCDs. It also included filter mounts. After PCD checkout we selected 4 Level 2 detectors, who's sensitivity was ~ 8E-6 A/W/cm^2. Two PCDs were filtered with 4 mil Kapton + 2 mil aluminum and the other two PCDs were filtered with 4 mil Kapton + 5 mil aluminum. The continuum temperatures varied between 1.5 and 2.4 keV (Fig. 10). The continuum temperatures correlated well with the line temperatures, but were consistently higher and increased more rapidly. This can be explained by the different origin of the lines and the continuum, the continuum originating from a hotter core that is optically thin for these wavelengths. There where a number of shots with H_2S. On these shots there was a substantially better match (Fig. 9). In addition, the continuum yield as estimated from the GaAs PCDs tracked the total K-shell yield.

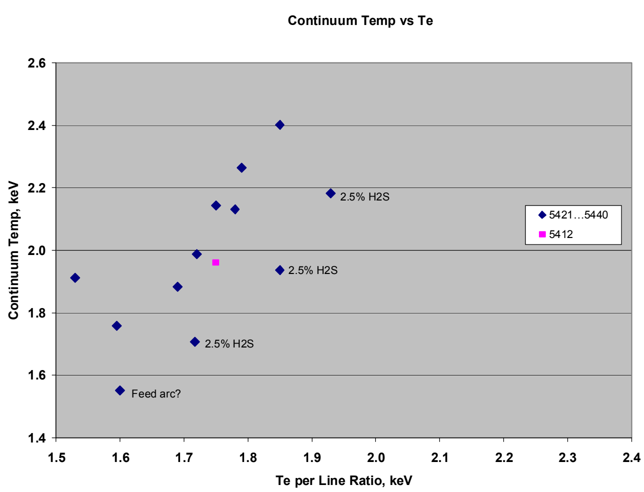

Figure 10. A good correlation was demonstrated between the continuum and line temperatures.

VI. REACTOR GAMMAS

The FWHM of the reactor signal is ~ 120 ms and there is a high neutron background. The design was adapted to the challenges of the environment. In particular, the detector was double ended as opposed to single ended and low activation materials, such as aluminum, were used if possible. The area of the GaAs was relatively large (5 mm x 5 mm), to provide adequate sensitivity in a relatively low dose rate (2E6 rad(Si)/s) environment. Don King (Sandia) tested the detectors. This included: (a) Calibration, Linac (White Sands); Stability, Co-60; High dose rate, HERMES III; and Response, sensitivity, and residual radioactivity, ACCR reactor (Sandia).

Reactor parameters were: Peak power, 96.3 MW; FWHM, 115.86 ms; Total yield, 19.5 MJ; Total gamma, 2.069E5 rad(TLD); Total nvt, 1.58E14 n/cm^2 1MeV(Si); GaAs PCDs with a 50 ohm load. The GaAs PCD waveforms are presented in Fig. 11. The higher and lower sensitivity traces were obtained with Level 3 and Level 4 GaAs PCDs, respectively. These detector types have a sensitivity of 3.6E-8 V/rad(Si)/s and 2E-8 V/rad(Si)/s. Hence, the different is response is exactly as expected.

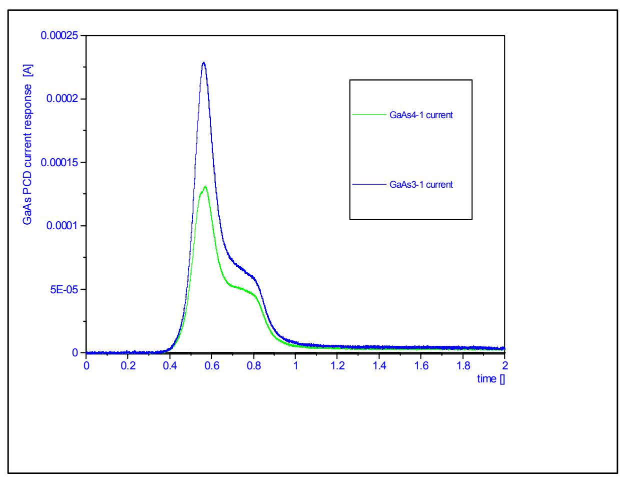

Figure 11. Reactor data. The higher and lower sensitivity traces were obtain with a Level 3 and Level 4 GaAs PCDs, respectively.

V. SUMMARY

Four types of GaAs PCDs, bremsstrahlung (Traverse and Parallel), soft x-ray, and reactor gammas were developed and tested. The GaAs PCDs exhibited outstanding time response and compared favorably to facility detectors. The GaAs PCDs provide substantial advantages in applications for which a fast response time is needed, in high dose rate/flux environments, and when a high neutron background is present. Scientists that are active in these fields evaluated the GaAs PCDs and the feedback was for the most part very positive. Some fabrication issues were identified and will be corrected in the next iteration, which is presently in progress.