UCRL-99555
PREPRINT

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P. T. Springer

This paper was prepared for submittal to
SPIE's O-E/FIBER LASE Boston '88
Boston, MA, September 6-10, 1988

September 9, 1988

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The development and characterization of neutron-damaged GaAs x-ray detectors

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UCRL--99555

DE89 000690

ABSTRACT

Photoconductive x-ray detectors are becoming an important x-ray diagnostic as a result of their small size, fast response time, and high sensitivity. We are developing a discrete array of neutron-damaged GaAs detectors to be used in an imaging x-ray spectrometer, and we describe herein the techniques we use to fabricate and characterize them for an upcoming experiment. Using a 225-ps x-ray pulse from a laser-produced plasma, we measured the sensitivity and time response of the detectors to be 7.1 mA/W and on the order of 150 ps FWHM, respectively. The carrier mobility is $741 \text{ cm}^2/\text{V}\cdot\text{s}$ at a bias of $2 \times 10^4 \text{ V/cm}$.

1. INTRODUCTION

For high-bandwidth detection of photon or charged particle fluxes, photoconductive x-ray detectors offer distinct advantages over other detectors. Photoconductive detectors are typically made of semiconductors or insulators—such as GaAs, InP, and silicon—that can be doped with impurities or damaged with neutrons or charged particles to reduce the carrier lifetime. As in all semiconductor x-ray detectors, radiation entering the detector excites electrons into the conduction band, giving a current related to the exciting intensity. In other solid-state detectors, such as PIN diodes, the electron-hole recombination time is long, and the detector time response is limited by sweepout.

Making detectors thinner not only decreases the sweepout times but also increases the capacitance, which may also limit the response time. In a fast, photoconductive, radiation detector, the response times are determined by carrier recombination rather than sweepout and can be in the range of a few picoseconds. Thus, the time response of the detectors is somewhat adjustable, with a tradeoff in sensitivity.

We are developing an x-ray spectrometer that requires a fast and reliable readout. A spherically curved crystal is used to Bragg-reflect and image x rays from several different sources simultaneously. On the spectrometer output plane, the spectra from the different sources are spaced by only 2 mm, requiring the use of small and finely positioned readout detectors.

The primary means of measuring the x-ray intensity is with a streak camera. The x rays deposit their energy in a subnanosecond phosphor of indium-doped CdS, producing a prompt optical signal that is proportional to x-ray intensity. The signal is transmitted via a quartz optical fiber to the streak camera. An additional, redundant measurement of the x-ray intensity was desired to improve the reliability of the spectrometer.

We chose to use neutron-damaged GaAs detectors because they are small, fast, sensitive, and easy to use. Although only 12 of these detectors will be used in the spectrometer, the ease of microscopic fabrication techniques allowed us to make 200 GaAs chips for use in future experiments.

2. FABRICATION TECHNIQUES

Using techniques developed by Ron Wagner and Bob Hammond of Los Alamos National Laboratory (LANL), Mike Pocha of the Energy Research Division of Lawrence Livermore National Laboratory (LLNL) used 5-cm-diameter, 0.5-mm-thick wafers of undoped GaAs to make the detectors, each of which had a $1 \times 1 \times 2.5$ -mm gap. To produce the ohmic contacts on the detectors, we used microscopic lithographic techniques to deposit 1×1 -mm patterns of layered metal in patterns consisting of 100 Å of gold eutectic (a mixture of 12% germanium and 88% gold), 150 Å of nickel, and finally 1000 Å of gold.

After protecting the patches with photo resist, we etched away the metal between patches and brought the wafer to a temperature of 400°C for 10 s to allow the gold eutectic to alloy with the GaAs. (This is found to produce a good ohmic contact.) We then sawed the wafer into pieces that were slightly larger than 1 × 1 mm.

Hammond and Wagner then neutron-damaged the GaAs pieces in LANL's Omega west reactor. After surrounding the pieces with boron carbide and indium foil to capture thermal neutrons, they placed them near the reactor core for 1000 to 2000 s, producing detectors with response times of 100 to 200 ps. (Although we have not measured the curve of response time vs neutron dose, it can be said that higher neutron doses result in faster response times but lower sensitivities. With lower neutron doses, the time response is degraded, showing a long-lived tail. Because a 200-ps response time is adequate and the highest sensitivity is desired, heavy neutron-damage is not desirable for the x-ray spectrometer application.) The chips were allowed to "cool" until they were safe to handle, and then the side into which the x rays enter was polished.

3. ASSEMBLY, CHECKOUT, AND RESULTS

The 1 × 1 × 0.5-mm, neutron-damaged GaAs detectors are mounted in an endcap that fits at the end of a 5-cm piece of 0.141-in.-diameter copper coaxial cable (141 Cu-jack). Connections to the GaAs crystal are made with silver epoxy. One side of the crystal is connected, by means of a spring bellows, to the center conductor of the coaxial cable. The other side of the crystal is connected to ground through a protecting endcap. The 141 Cu-jack terminates at an SMA connector.

After assembly, as a check to verify that the detectors function and have adequate time response, we applied a 1-kV bias to them through a high-bandwidth coupling can and excited them with 55-ps pulses of 800-nm light from a GaAs laser diode. Figure 1 shows the measured signal for a detector that had been irradiated for 2000 s. The signal from the detector irradiated for 1000 s was similar. The detectors show a time response of approximately 150 ps FWHM and exhibit no long-lived tail.

To date, we have calibrated the detectors for sensitivity by using pulsed x rays from a laser-produced plasma. These x rays have a mean energy of 2 keV, a pulse duration on the order of 200 ps, and a peak intensity of 1.1×10^4 W/cm². We also plan to use dc x-ray sources to calibrate the detectors in order to obtain the correct range of x-ray energies of interest in the spectrometer application.

Figure 1. The 150-ps FWHM time response of the photoconductive detector is measured by using a 55-ps pulse of 820-nm light and a 25-ps sampling oscilloscope. The carrier recombination time of 120 ps is determined from the exponential falloff of the signal once the exciting pulse stops.

3.1 Pulse calibration

We used the Janus laser facility at LLNL to produce a 200-ps pulse of x rays. The neodymium glass laser was frequency-doubled and operated with a pulse duration of 100 ps. We focused the laser to a spot size on the order of 30 μm onto a titanium foil. We placed a 127- μm filter of beryllium on a 50-ps, 8201 XRD, and a 50-ps Tektronix 7250 oscilloscope recorded the 225-ps FWHM x-ray pulse (see Fig. 2). The photoconductive detector then measured the x-ray pulse, and two silicon PIN diode detectors determined the energy deposition of the x-ray pulse.

We placed the photoconductive detector, with a 127- μm beryllium x-ray filter, 11.4 cm from the target. The two PIN diodes were each 30.5 cm from the target and had defining apertures of 2.17 mm^2 . One of the PIN diodes, with a filter identical to that of the photoconductive detector, measured the x-ray intensity behind 127 μm of beryllium. The other PIN diode, with an x-ray filter of 50.8 μm of beryllium, determined the mean energy of the x rays.

Figures 3, 4, and 5 show the oscilloscope traces from a 2.64-J laser shot, as measured by the photoconductive detector and two PIN diode detectors. The photoconductive signal has an FWHM of 475 ps, which is close to the bandwidth limit of the Tektronix 7104 oscilloscope used to record the signal. We used the oscilloscope to record a 60-ps pulse from a pulse generator, and the trace is shown in Fig. 6. The observed FWHM of the trace shown in Fig. 6 implies an oscilloscope response time on the order of 400 ps. The 475-ps width of the observed photoconductive signal is a combination of the photoconductive response time, the 225-ps time duration of the x-ray pulse, and the 400-ps oscilloscope response time. The observed trace is consistent with a photoconductive time response on the order of 150 ps, as was seen using the GaAs laser diode.

The signals shown in Figs. 3 and 4 are used to determine the sensitivity of the photoconductive detectors. The PIN diodes were calibrated and shown to have a flat response. The sensitivity of the PIN diodes is 0.2 C/J. The signal shown in Fig. 4 shows 1.84 nC of charge collected, implying a total of 293 $\mu\text{J}/\text{sr}$ of x rays behind the 127- μm beryllium filter for the 2.64-J laser shot. Integrating the photoconductive signal gives 80 pC of charge for the 11.2 nJ of incident x rays. This implies an efficiency of 7.1 mC/J.

The theoretical efficiency of the photoconductive detector is given by

$$\eta_{\text{pcd}} = e v \tau / w E_{\text{ch}} \quad (1)$$

Here, e is the electron charge, v is the carrier drift velocity, τ is the carrier recombination time, $w = 0.5 \text{ mm}$ is the gap width, and $E_{\text{ch}} = 5 \text{ eV}$ is the energy per electron-hole pair in GaAs. The measured efficiency implies a value of

Figure 2. The Janus laser focused onto a titanium target produces a 225-ps x-ray pulse, as measured by a 50-ps 8201 x-ray diode and recorded by a 50-ps Tektronix 7250 oscilloscope.

Figure 3. The PCD signal from the Janus x-ray pulse, as recorded by a Tektronix 7104 oscilloscope.

Figure 5. Another PIN diode is used to measure the total energy in the x-ray pulse that passes through a 51- μm beryllium filter. The PIN diode gives 4.06 nC of charge. Using the detector sensitivity and solid angle implies a filtered x-ray pulse strength of 648 $\mu\text{J}/\text{sr}$ for the 2.64-J laser shot. Based on the differential attenuation, the mean x-ray energy is about 2 keV.

Figure 4. A PIN diode is used to measure the total energy in the x-ray pulse that passes through a 127- μm beryllium filter. The PIN diode gives 1.84 nC of charge. Using the detector sensitivity and solid angle implies a filtered x-ray pulse strength of 294 $\mu\text{J}/\text{sr}$ for the 2.64-J laser shot.

Figure 6. The Tektronix 7104 oscilloscope response time, as measured by a 60-ps pulser, is 400 ps FWHM.

17.8 μm for the product $v\tau$. The detector has only 3.6% of the intrinsic efficiency because of the neutron-damaging. With an estimated $1/e$ recombination time of 120 ps, the drift velocity is on the order of 1.48×10^7 cm/s. This value is below that of intrinsic GaAs biased at 20,000 V/cm. The carrier mobility, μ , is 741 $\text{cm}^2/\text{V}\cdot\text{s}$ at this bias level.

3.2 Dc calibration

The second method for calibrating the detectors is by the use of x rays from standard x-ray tubes. When biased, the GaAs detectors have a leakage current of about 1 μA , which is caused by the resistance of the GaAs. This leakage current far exceeds the typical currents induced by laboratory x-ray tubes. To measure the smallest x-ray induced currents, we balance the leakage current of one photoconductive detector against that of another that is biased with a voltage of the opposite polarity. The leakage currents are combined and measured with a

sensitive electrometer. The bias voltage of the compensating PCD is adjusted to zero the reading when no x rays are applied. Differential leakage currents as low as 1 nA are obtained. The stability of the differential leakage current is about 1 nA/s, which is sufficient to allow a determination of the x-ray-induced current. At the time of this writing, however, these calibrations have not yet been performed.

4. ACKNOWLEDGMENTS

I would like to thank Mike Pocha for his help in the detector fabrication and Ron Wagner and Bob Hammond for their help in the detector irradiations. I thank George Wells for his help in the detector assembly. Russell Benjamin operated the x-ray diode and fast oscilloscope for the Janus run.

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.