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SILICON PHOTODIODE SOFT X-RAY DETECTORS FOR PULSED POWER EXPERIMENTS

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Abstract

Silicon photodiodes offer a number of advantages over conventional photocathode type soft x-ray detectors in pulsed power experiments. These include a nominally flat response, insensitivity to surface contamination, low voltage biasing requirements, sensitivity to low energy photons, excellent detector to detector response reproducibility, and ability to operate in poor vacuum or gas backfilled experiments. Silicon photodiodes available from International Radiation Detectors (IRD), Torrance, California have been characterized for absolute photon response from 1 eV to 10 keV photon energy, time response, and signal saturation levels.

Our calibration measurements show factor of ten deviations from the silicon photodiode theoretical flat response due to diode sensitivity outside the center 'sensitive area'. Detector response reproducibility between diodes appears to be better than 5%. Time response measurements show a 10-90% rise time of about 0.1 nanoseconds and a fall time of about 0.5 nanoseconds.

Introduction

Silicon P-I-N diodes are excellent for use as x-ray detectors due to their high sensitivity, stability, and essentially flat response [1]. Also unlike photoemissive soft x-ray detectors which emit photoelectrons only from the top few angstroms of their surface the silicon photodiodes behave similarly to an ion chamber with the sensitive region being the internal intrinsic silicon layer. Having internal rather than external sensitivity renders the silicon virtually immune to surface contamination. A drawback to older silicon photodiodes has been the doped dead layer which blocked low energy x-ray photons. However, using special doping techniques the International Radiation Detectors (IRD) [2,3] silicon photodiodes are constructed without a doped surface dead layer. For our pulsed power [4] work we have used the IRD type HS-1 diode chips mounted into a custom housing of our design. Despite its small sensitive area of 0.05 mm^2 in the center of the chip we must stand back several meters from typical pulsed power radiation sources to reduce detector signals to usable levels. On the Sandia National Laboratories [5] PBFA-Z pulsed power machine which can output 200 TW our detectors saturate at a distance of 20 meters. These extreme operating conditions motivated us to characterize the HS-1 diode saturation, time, and spectral response.

Diode Construction

The P-I-N diodes used in our detector systems are constructed by epitaxially growing a π-type silicon (equivalent to intrinsic) layer atop a heavily doped p+ silicon wafer substrate. The cathode contact is constructed by heavily n-doping the top of the π-type layer and then a passivating SiO_2 layer is deposited. X-rays must pass through the thin SiO_2 surface passivating layer designed to protect the silicon from atmospheric moisture. Newer designs nitride [6] the SiO_2 window to improve radiation hardness but the x-ray transmission characteristics remain almost the same. By using the minimum thickness SiO_2 entrance window the detector remains responsive through the vacuum-ultraviolet and very soft x-ray region.

Reproducibility

The HS-1 P-I-N diodes we use are mass produced on a 4" or greater diameter silicon wafer. Each wafer can yield over 5000 diodes, all created under identical conditions and therefore should have identical characteristics. As shown in Figure 1., using a visible light monochromator we tested 49 diodes and found response variations with a standard deviation well within the instrumental measurement error bars. The vacuum ultraviolet and soft x-ray response should behave similarly as they too are sensitive only to the upper layers of the diode. Note that the peak response for our 0.05 mm^2 detector is apparently 2.3 A/W which is about four times higher than expected. The reasons for this apparently high response are explained in the 'Spectral Response' section.

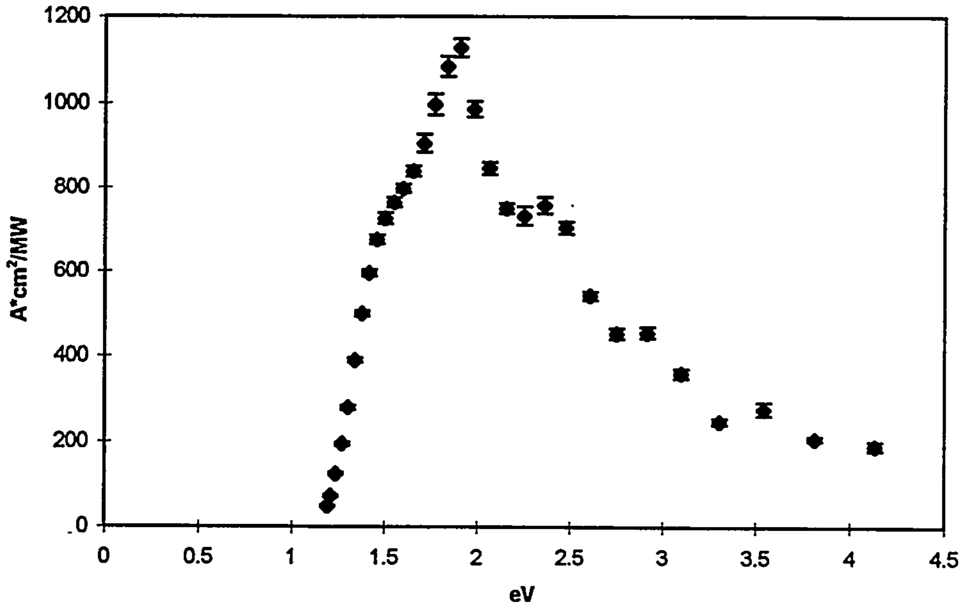

Figure 1. Average response and 1-σ error bars for 49 HS-1 silicon diodes.

Time Response

The factors contributing to detector response time are the resistances and capacitances present in the detector and measuring circuitry and the charge carrier transit times.

In conventional p-n diodes if the bias voltage isn't high enough to fully deplete the lightly doped p-type or n-type silicon or if the photogenerated charge reduces the effective bias then the undepleted lightly doped silicon behaves as a series resistance. However, in epitaxially grown detectors the cathode (n+) and anode (p+) contacts are heavily doped silicon with essentially zero resistance and the intrinsic (π-type) epitaxial layer provides a well defined fully depleted active region. Therefore the resistance contribution for our P-I-N diodes is dominated by the 50Ω measuring circuit load impedance.

Capacitance (**C**) of the diode can be well approximated by the silicon permittivity (ε), area (**A**), and the epitaxial layer thickness (**D**). For the HS-1 diodes:

$$C = \varepsilon A/D = 10^{-12} \text{ x } (5\text{x}10^{-4}) / 10^{-3} = 0.5 \text{ pF}$$

Using the 50Ω impedance and 0.5 pF capacitance the RC rise time (t_{RC}) would be 2.2RC which equals 55 ps. Worst case carrier transit time is a hole traveling across the entire depletion layer thickness. The time is given by the thickness (**D**) divided by the product of the hole mobility (μ) and electric field strength(**E**). For the HS-1 diodes at 50 volt bias (**V**):

$$t_c = D / \mu E = D^2 / \mu V = (10^{-3})^2 / 480(50) = 42 \text{ ps}$$

Adding the times in quadrature yields a theoretical rise time of 70 ps. In practice the rise time will be longer due to space charge effects. As the x-rays are absorbed the photogenerated charges distort the electric field thereby changing the carrier transit time. The situation is worsened because soft x-rays are absorbed at the surface of the depletion layer causing a non-uniform distortion of the field that is a function of both photon energy and intensity. Because the HS-1 diode is sensitive to visible light a fast pulsed laser is a convenient rise time measuring instrument.

Using a visible (600 nm) laser with a Gaussian pulse shape and a FWHM of 50 picoseconds we tested the response of the HS-1 diode chip as a function of bias voltage. The four plots show diode signal rise time, the FWHM, peak current, and total collected charge as a function of bias voltage.

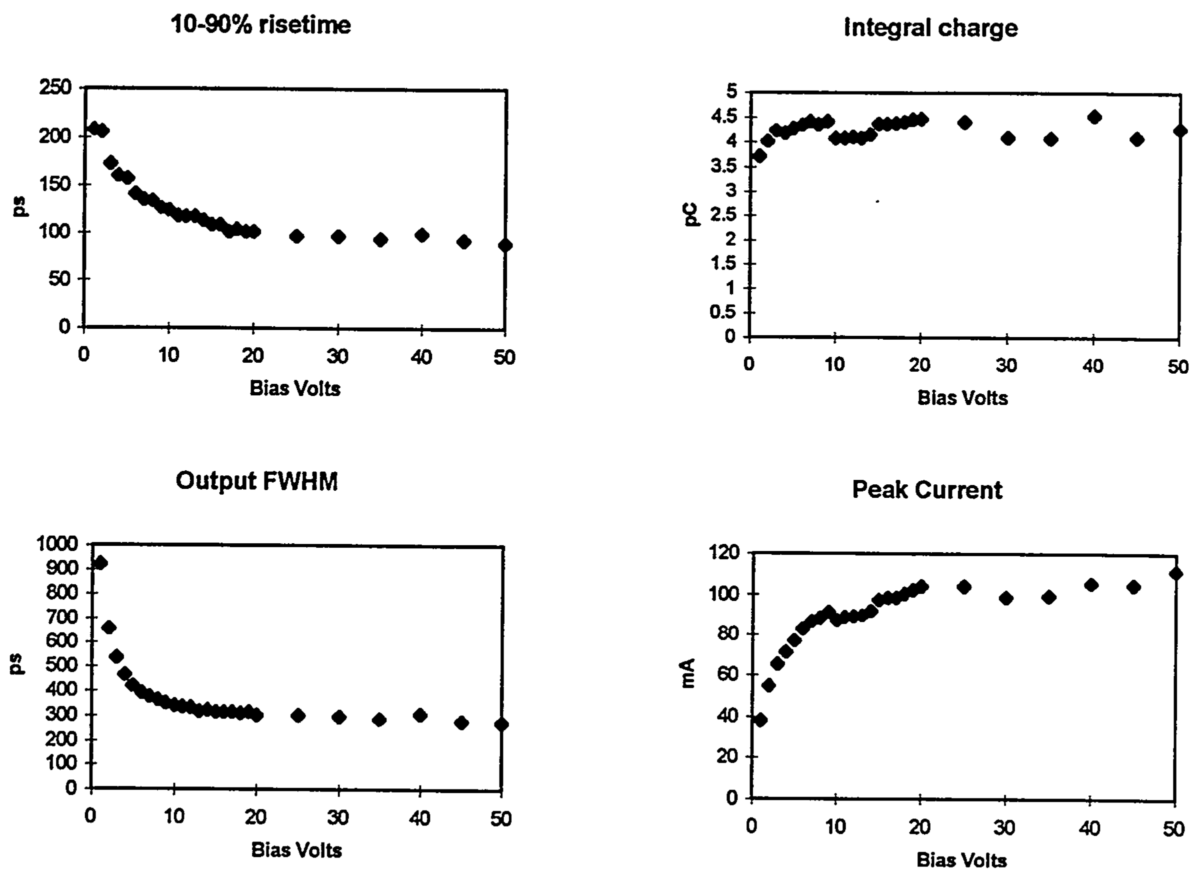

Figure 2. HS-1 silicon diode response as a function of bias voltage for a fast visible laser input pulse.

The scarcity of trapping sites due to the high purity silicon in the depletion layer leads to long recombination times so almost all the ion pairs generated should be collected. Variation in the integral charge plot is within the pulse-to-pulse stability of the laser used. As the internal electric field is reduced at lower bias voltage the charges move more slowly resulting in slower risetime and wider output pulses as shown in the risetime and FWHM plots. However because the integral charge is constant a wider output pulse requires a reduced peak current. The resulting interdependence of the variables can lead to misinterpretation of fast filtered diode signals. Generally the higher energy filtered detectors will have smaller signal levels and may accurately track the plasma radiation output whereas the lower energy filters generally will have the largest signals and may be distorted. The ratio of the detectors will then be weighted towards the higher energy photons and imply a higher plasma temperature than is actually present. It should be noted that the plots shown are valid only for the given signal input. A different radiation input resulting in a different space charge profile in the silicon will alter the drift velocities and change time response.
However the asymptotic portion of the risetime plot gives the minimum risetime of the HS-1 diode. The net effect is that as bias voltage is decreased the risetime increases and peak current decreases causing a smearing in time of the input signal.

Spectral Response

HS-1 diode spectral calibrations from 50 eV to 6 keV were performed at our x-ray synchrotron beamlines located at the National Synchrotron Light Source (NSLS) [7], Brookhaven National Laboratory, Long Island, NY. The units of response are quoted in terms of A*cm^2 / MW instead of the more usual A / MW because of signal collected from portions of the chip outside the center "sensitive area". The HS-1 is constructed with an 8000 angstrom SiO_2 protective layer surrounding the center sensitive area which has a 60 angstrom SiO_2 coating. At visible wavelengths the outer region is transparent causing an apparent increase in response. Likewise at x-ray energies above 600 eV the outer region becomes partially transmitting. The effect is the true sensitive area of the HS-1 diode changes with photon energy hence the sensitive area cannot be divided out during the calibration measurements as is standard practice. Overlaid upon the plot are two simple models of the HS-1. The light dashed line assumes a silicon response of 2.70 x 10^5 A / MW and then calculates photon absorption in 15 microns of silicon and the transmission through a 60 angstrom window with an area of 0.05 mm^2 using SiO_2 tables from the Handbook of Optical Constants [8]. The solid line uses elemental absorption tables [9] and adds signal from the outer region 8000 angstrom windowed area assuming a decreasing charge collection efficiency away from the center region due to the poor electric field geometry.

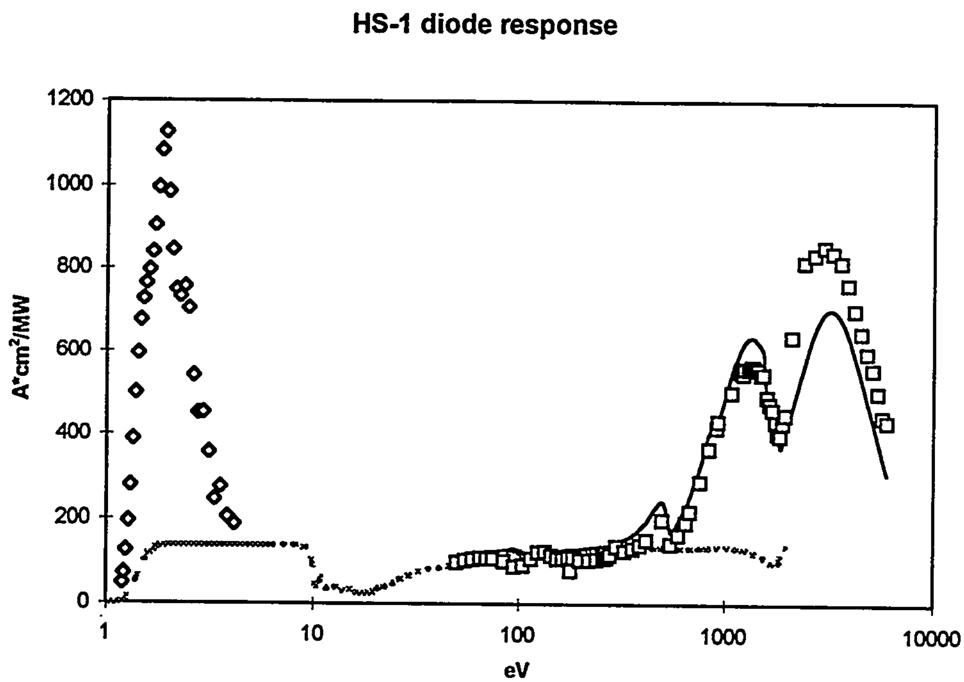

Figure 3. HS-1 silicon diode spectral response . Overlaid curves show two different physical models of behavior.

Spectral calibrations of a type AXUV-100 silicon photodiode were performed at the National Institute of Standards Technology (NIST), our Bechtel Nevada laboratories, and the NSLS at Brookhaven National Laboratory. The AXUV-100 diode is covered with a 60 angstrom SiO_2 window over its entire surface. The higher response lobes in the visible and at higher x-ray energies seen by the HS-1 are absent in the AXUV-100 calibrations. The two model calculations assume 2.73 x 10^5 A / MW silicon sensitivity, 60 micron depletion depth, and a 60 angstrom window. The dashed curve uses the Handbook of Optical Constants SiO_2 tables and the solid line uses free atom elemental absorption coefficient tables. The divergence of the two models at 30 eV is probably due to molecular effects invalidating the free atom assumptions. The assumption of a constant W value of 3.66 eV / ion pair (0.273 A / W) also breaks down at low photon energies.[10]

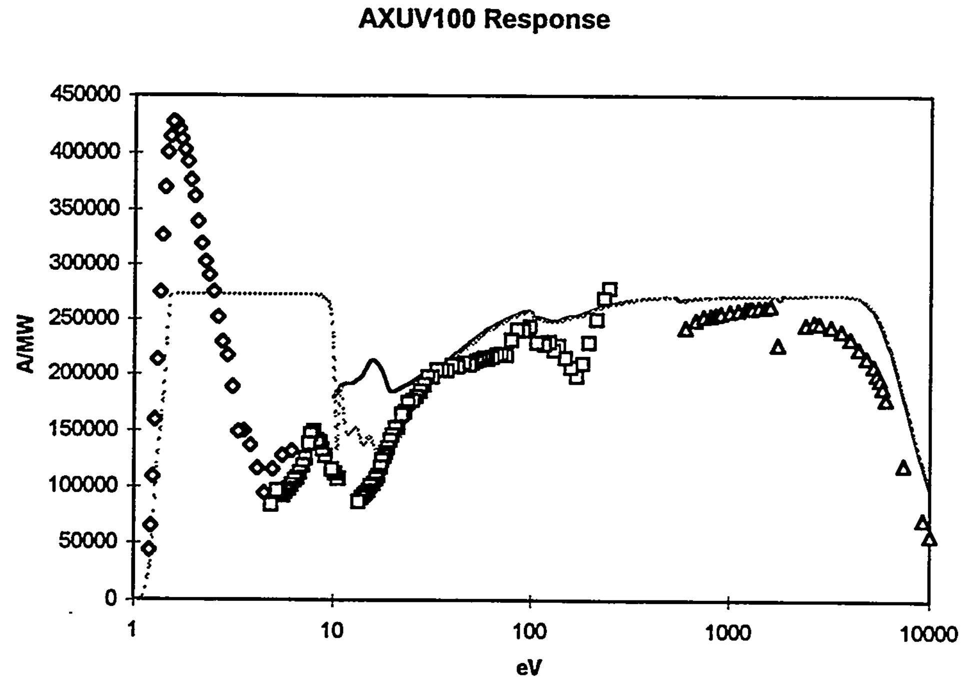

Figure 4. Large area AXUV100 silicon diode response. Measured visible data and x-ray data curves overlap nicely at 6 eV. Modeled data diverges at 30 eV depending on whether Handbook of Optical Constants (dashed line) SiO_2 or free atom absorption coefficients are used.

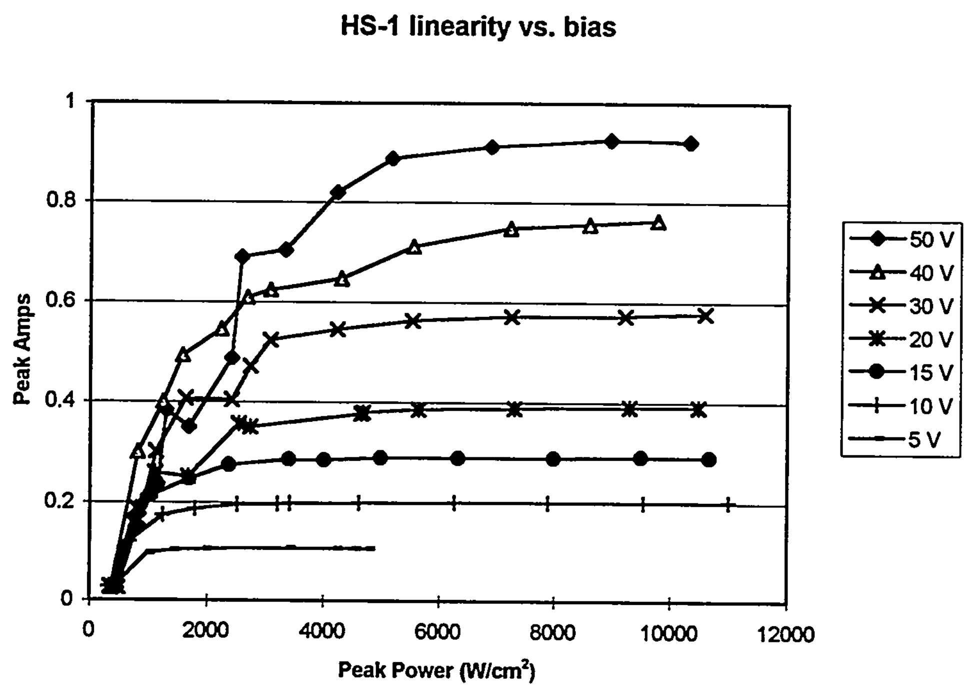

Figure 5. HS-1 silicon diode saturation response as a function of bias voltage.

Linearity Response

An important practical consideration in the use of diodes for pulsed power measurements is the linearity of signal output and/or the shape of the power input versus signal output curve. Using a pulsed ruby laser we irradiated the HS-1 diodes with several intensities while biased at voltages from 5 to 50 volts. Figure 5. shows 'hard' saturation at approximately the bias voltage for our 50Ω system. Unfortunately the data are too noisy to extract the linear range of the diode. However based upon this data and some laser produced plasma data we feel the HS-1 diode biased at 50 volts is linear up to 200 mA and possibly as high as 400 mA output.

Conclusions

Silicon photodiodes have proven to be a versatile and useful complement to our standard photocathode detectors for soft x-ray measurement and are very competitive with diamond for a number of applications. Silicon mass production provides an unlimited supply of identical detectors at low cost of a few dollars per diode as opposed to roughly $1000 / diamond detector. With a nominal response of 0.27 A / W silicon photodiodes are about 400 times more sensitive than diamond. At a 50 volt bias HS-1 silicon diodes have risetimes of 100 ps and linear range of several hundred milliamperes. The ~100 ps recombination time of diamond still yields the best time response. However for bolometric measurements silicon has an advantage in millisecond recombination times allowing all the photogenerated charges to be eventually collected even when the detector is saturated. These characteristics make silicon P-I-N diodes ideal detectors for soft x-ray plasma measurements in harsh pulsed power environments.

Acknowledgments

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