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Synthetic diamond-based position-sensitive photoconductive detector development for the Advanced Photon Source

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A novel X-ray beam-position detection device that we call a position-sensitive photoconductive detector (PSPCD) is designed to have synthetic diamond as its substrate material. We proved that it is feasible to use synthetic diamond to make a hard X-ray position-sensitive detector based on the photoconductivity principle and that it acts as a solid-state ion chamber. Experiments on different PSPCD samples using synthetic diamond with a high-heat-flux white undulator beam, as well as with monochromatic hard X-ray beams, have been performed at the Advanced Photon Source. Recent test results with the PSPCD in the quadrant configuration as an X-ray beam-position monitor and in a multipixel array as an X-ray beam profiler are presented in this paper.

Keywords: beam-position monitors; beam profiler; images; X-rays; CVD diamond.

1. Introduction

Natural diamonds as photoconductive radiation detectors (PCDs) have been studied since 1956 (Cotty, 1956). It has been found that only certain diamonds, those with low impurity concentrations (specifically nitrogen), are suitable for use as radiation detectors (Kozlov *et al.*, 1975). Natural diamonds have been used as PCDs for soft X-ray detection with a laser-produced plasma soft X-ray source and a synchrotron radiation source (Kania, Pan, Kornblum *et al.*, 1990; Kania, Pan, Bell *et al.*, 1990). Insulating-type (type II*a*) synthetic diamond (from high-pressure cells) as solid-state ionization-chamber radiation detectors have been studied for biological applications with α particles and γ radiation (Keddy *et al.*, 1987). Compared with other photoconductors, diamond is a robust and radiation-hardened material with high dark resistivity and large breakdown electric field, and is sensitive to hard X-rays (Kozlov *et al.*, 1977).

At the Advanced Photon Source (APS), synthetic diamond, especially CVD diamond, has been studied as a blade material (coated by gold or other metal) for high-heat-flux photoelectron emission-type X-ray beam-position monitors (XBPM) (Shu *et al.*, 1992). CVD diamond offers superior thermal–physical properties, such as high thermal conductivity, a low thermal expansion coefficient, and good mechanical strength and stiffness under heat, which are critical for the APS insertion-device beamline XBPM design. An X-ray transmitting beam-position monitor (TBPM) using CVD diamond has also been developed for combining filter/window and XBPM functions (Shu *et al.*, 1994). In February 1996 a sample for a PSPCD-type TBPM, which was designed and prepared at the APS, was tested at the European Synchrotron Radiation Facility (ESRF) beamline ID-6 (Shu *et al.*, 1997). The results showed that it is feasible to use a single CVD-diamond disk to make a hard X-ray position-sensitive detector based on the photoconductivity principle and that it acts as a solid-state ion chamber (Shu & Kuzay, 1996*a*). In this paper recent test results with a PSPCD in a quadrant configuration as an X-ray beam-position monitor and in a multipixel array as an X-ray beam profiler are presented.

2. PSPCD as an X-ray transmitting beam position monitor

The basic concept of the X-ray TBPM is to mount the monitor blade perpendicular to the synchrotron radiation beam and to design the blade and its sensor coating in such a way that most of the X-ray beam will be transmitted through the blade. Thus, the total absorbed photon power cannot cause thermal damage to the blade.

There are two different types of the TBPM designed at the APS, as shown in Figs. 1(*a*) and 1(*b*). Fig. 1(*a*) shows a photoemission-type TBPM, in which the CVD diamond is acting as an electrical insulating heat sink for the aluminium coating, which is the photoemission sensor material. Four current amplifiers measure the photon–electron return current from the quadrant aluminium sensor to obtain the beam position information. For a PSPCD-type TBPM, shown in Fig. 1(*b*), the quadrant patterns of the aluminium coating were applied on both sides of the diamond disk. A d.c. bias voltage was used to generate the current signal, which is based on the photoconductive properties of CVD diamond. With X-ray illumination, electron–hole pairs are generated, which changes the conductivity of the diamond in the region where the X-ray penetrates. By measuring the current in

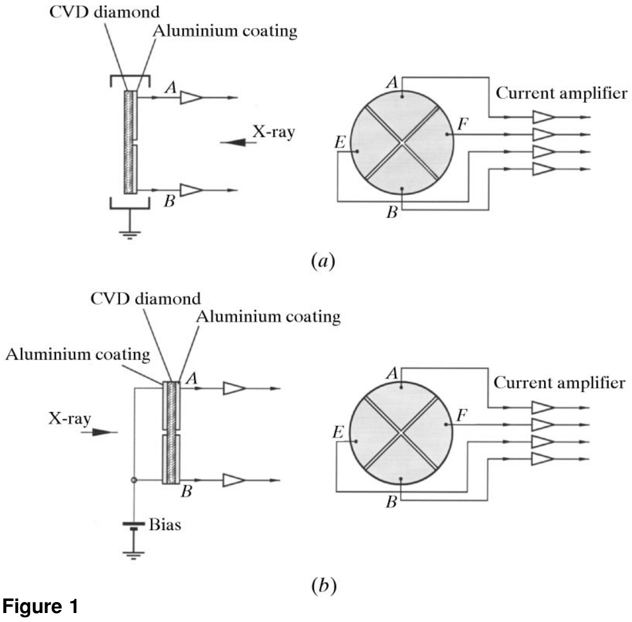

Figure 1
(*a*) Schematic of the photoemission-type TBPM, where the CVD diamond acts as an electrical insulating heat sink for the aluminium coating, which is the photoemission-sensor material. (*b*) Schematic of the photoconductive-type TBPM, where the quadrant patterns of the aluminium coating were applied on both sides of the diamond disk.

different quadrant areas, the X-ray beam position can be determined.

According to a simple carrier model, the photogenerated carriers, electrons and holes, are treated as a single charge carrier and the carrier density can be determined from the equation (Kania, Pan, Bell *et al.*, 1990)

$$\mathrm{d}n/\mathrm{d}t = [P(t)/\gamma V] - (n/\tau),$$

where $P(\tau)$ is the absorbed X-ray power, τ is the carrier lifetime, n is the carrier density, γ is the average energy to form an electron–hole pair, and V is the excited volume.

From the test results we have learned that, compared with a photoemission-type TBPM, the beam-position signal from a PSPCD-type TBPM has less ID-gap dependence. This is caused by the higher sensitivity of the PSPCD-type TBPM to the hard X-ray radiation, so that less bending-magnet radiation contamination contributes to the beam-position results from the PSPCD-type TBPM (Shu *et al.*, 1997).

A total of 11 PSPCD-type TBPMs have been installed on the APS front-end commissioning filter/mask/windows assemblies. The thickness of the 25 mm diameter insulating-type CVD-diamond disk is 150 µm; the CVD-diamond disk is coated with four electronically isolated aluminium quadrant patterns. The thickness of the aluminium coating is ~0.2 µm. The PSPCD-type TBPM is located 25 m from the source and downstream of a 300 µm thick graphite filter. During typical operating conditions at the APS (7 GeV and 100 mA with undulator gap 11 mm), the PSPCD-type TBPM transmits more than 3 kW undulator white-beam power with ~300 W mm^{-2} power density. The power absorbed by the TBPM is 84 W, with 3.6 W mm^{-2} power density (Kuzay *et al.*, 1996). When the beam is centered, each quadrant area of the PSPCD-type TBPM provides a ~300 µA signal with 1.5 V bias supply. The X-ray transmission with this assembly at 10 KeV is ~78% (Shu & Kuzay, 1996*b*).

Unlike the photoemission-type TBPM, a vacuum is not necessary for the operation of the PSPCD-type TBPM. It can be operated in an atmospheric environment as well as in a vacuum. It also shows a good response to the monochromatic hard X-ray. Fig. 2 is a plot of PSPCD output response *versus* X-ray energy. The experiment was performed at APS undulator beamline 1-ID with a cryogenically cooled Si(111) double-crystal monochromator. The PSPCD was set in an atmospheric environment during this experiment. The PSPCD output *versus* bias voltage was also measured, as shown in Fig. 3.

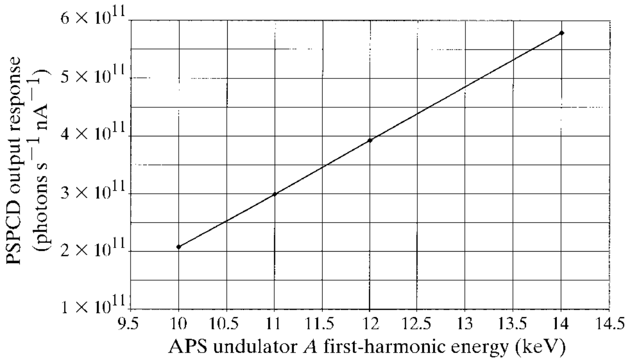

Figure 2
A plot of the PSPCD output response *versus* X-ray energy.

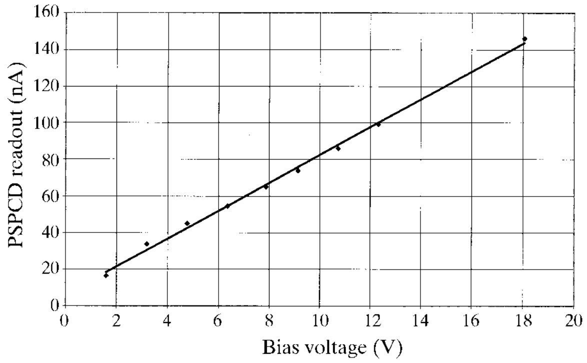

Figure 3
A plot of the PSPCD output *versus* bias voltage.

3. PSPCD as an X-ray transmitting beam profiler

An X-ray transmitting beam profiler system using two linear-array PSPCDs has been designed for the APS undulator beamline commissioning. The same insulating-type CVD-diamond disk was used as the linear-array substrate. On each disk 16 0.2 µm thick, 175 µm wide aluminium strips were coated on one side and an orthogonal single 175 µm wide strip on the other. Hence, looking through the disk, a linear array of 16 pixels is created as the photoconductive-sensor elements, with 175 × 175 µm pixel size.

A schematic of the profiler system is shown in Fig. 4. During the measurement, two sets of 16-pixel linear-array PSPCDs are placed into the hard X-ray beam, perpendicular to each other. Transmitting by the hard X-ray beam, the two arrays readout the beam vertical and horizontal profile information simultaneously. To obtain a complete beam 2D (two-dimensional) profile one can scan the linear array across the beam. Fig. 5 shows a set of APS undulator white-beam profiles directly measured by a 16-pixel linear-array PSPCD scanning across the beam with two different

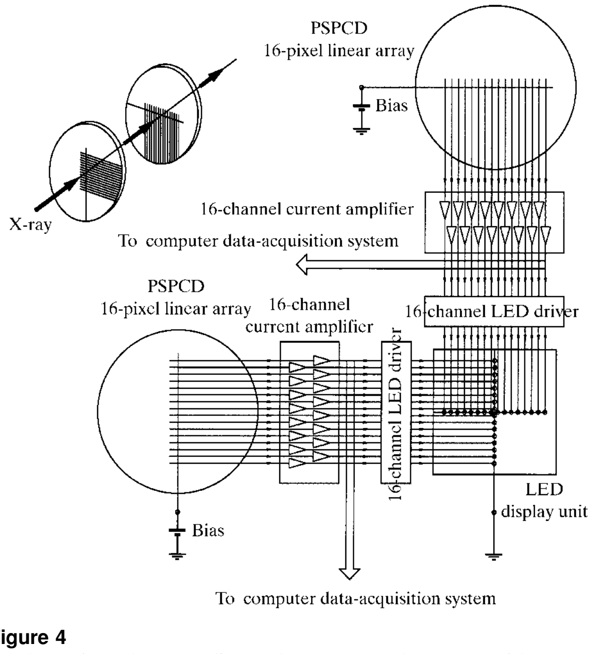

Figure 4
A schematic of the CVD diamond PSPCD profiler system with two sets of 16-pixel linear-array PSPCDs and read-out electronics.

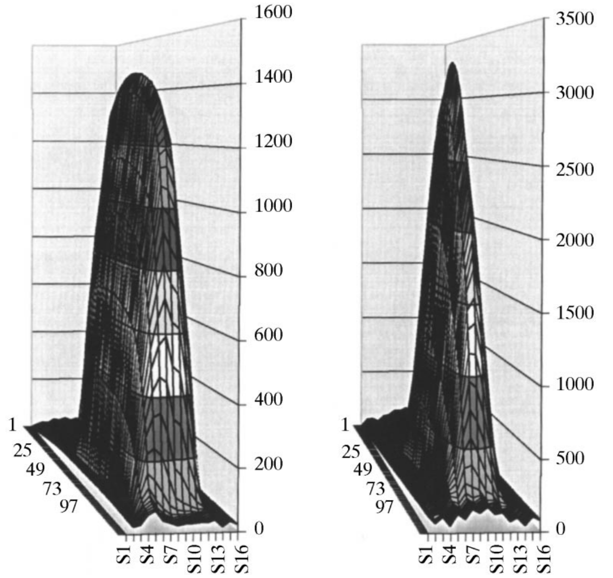

Figure 5
A set of APS undulator white-beam profiles directly measured by a 16-pixel linear-array PSPCD scanning across the beam with two different undulator magnet gap settings of $G = 15$ mm (left) and $G = 30$ mm (right).

undulator magnet gap settings. A 12.7 mm thick aluminium filter was used for these measurements to eliminate most of the soft X-rays.

A prototype of 2D imaging PSPCD has been built at the APS. As shown in Fig. 6, 16 aluminium strips are coated on both sides of the CVD-diamond disk creating a 16 × 16 pixel two-dimensional array with 175 × 175 µm pixel size. Preliminary tests proved that a 2D hard X-ray beam profile image could be read by a multichannel current amplifier with pulsed bias electronics. We have tested the single-pixel response of this 2D imaging PSPCD using an undulator white beam with a 150 × 150 µm aperture. It was found that the pixels in this 2D array PSPCD do not cross talk.

4. Conclusions

We have developed a novel position-sensitive photoconductive detector using insulating-type CVD diamond as its substrate material. Several different configurations, including a quadrant pattern for an X-ray transmitting beam-position monitor, and 1D and 2D arrays for PSPCD beam profilers, have been developed. Tests on different PSPCD devices with a high-heat-flux undulator white beam, as well as with monochromatic hard X-ray beams, have been performed at the APS. It was proven that the insulating-type CVD diamond can be used to make a hard X-ray position-sensitive detector based on the photoconductivity principle and that it acts as a solid-state ion chamber.

A total of 11 CVD-diamond PSPCD-type TBPMs have been installed on the APS front end for commissioning use. The linear-array PSPCD beam profiler has been routinely used for direct measurements of the undulator white-beam profile. More tests with hard X-rays and γ-rays are planned for the CVD-diamond 2D imaging PSPCD. Potential applications include a high-dose-rate beam profiler for fourth-generation synchrotron radiation facilities, such as free-electron lasers.

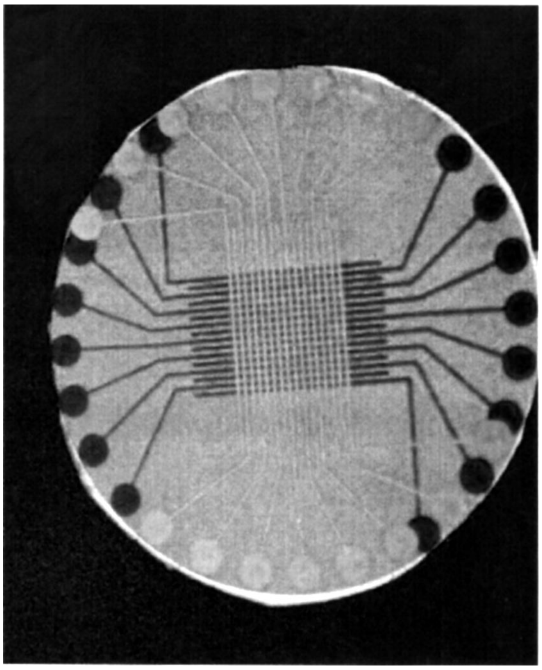

Figure 6
Photograph of the APS prototype 2D imaging PSPCD.

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