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Section A

Letter to the Editor

Report on the X-ray efficiency and time response of a 1 cm^2 reach through avalanche diode ☆

A.Q.R. Baron *

Stanford Linear Accelerator Center, Stanford Synchrotron Radiation Laboratory, Stanford, Ca 94309, USA

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Abstract

We report the time response and efficiency of a 1 cm^2 reach through avalanche photodiode used for direct detection of X-rays. The efficiency varies from ~ 70% at 8 keV to ~ 15% at 16 keV, consistent with an active thickness of more than 90 μm of silicon. The time resolution, full width-at-half-maximum, is 0.8 ns.

The use of large area avalanche diodes for direct X-ray detection has been discussed in the context of X-ray spectroscopy [1–3] with an emphasis on the gain uniformity of the diodes and noise sources. This paper, however, is concerned with X-ray scattering experiments in which the efficiency of the diode, the time resolution and the dynamic range are of primary importance. Work with avalanche diodes along these lines was done as early as 1966 [4], and, recently, several types of avalanche diodes have been investigated [5,6]. Here we present the efficiency and time response for a 1 cm^2 reach through avalanche diode manufactured by EG & G Optoelectronics [7].

The reach through diode [8] has a wide depleted π region in which the creation of electron–hole pairs will result in electron amplification. This means that the efficiency of the device for direct X-ray detection may be large, simply because the active thickness of silicon, where an X-ray can be absorbed with subsequent amplification of the electrons so generated, is large. In addition, the high field in this depleted region means that electrons will be transported quickly to the gain region of the device. Thus, a reach through device may have high efficiency and retain sub-nanosecond timing capability.

Measurements were done on beamline 2-3 of Stanford Synchrotron Radiation Laboratory (SSRL). Monochromatic X-rays collimated to a 50 μm^2 spot were allowed to fall on the diode, after passing through an ion chamber used to monitor the incident flux. The time structure of the X-ray pulses arriving at the detector is just that of the electrons circulating in the synchrotron. This, in turn, is determined by the radio frequency (rf) acceleration of the electrons, which, at SSRL, confines electrons to bunches of Gaussian shape and full width at half maximum (FWHM) of 0.13 ns, separated by integer multiples of 2.8 ns = 1/358 MHz (the radio frequency of the accelerating field).

Fig. 1 is a schematic of the electronics used in these measurements. The diode was biased at positive high voltage (480 V), with the signal lead isolated from guard ring by a 10 MΩ resistor. The signal was capacitively coupled into a Phillips 6954 (×100) pulse preamplifier through a 4700 pF capacitor. The signal out of the preamplifier, averaged over many single 14 keV events, is shown in Fig. 2. The initial fall time is 2.4 ns, followed by a slower rise of 7.3 ns, for a FWHM of 7 ns.

The output of the preamplifier was further amplified (×20) by a fast timing amplifier (EG & G Ortec FTA 420) before being sent to a constant fraction discriminator (EG & G Ortec 934). The time response of the diode was measured using the output of the constant fraction discriminator to start a time to amplitude converter (TAC), while the ring timing signal, locked to the revolution period of electrons in the synchrotron, was used as a stop. The output of the TAC was then fed into a multichannel analyzer. The electronics in this configuration had a jitter of less than 0.2 ns.

Fig. 3 shows the efficiencies measured for X-rays between 8 and 16 keV. These were calculated by dividing the pulse rate from the constant fraction discriminator by the incident flux rate, as measured by the ion chamber (calibrated against a NaI detector). A correction has been included for the thin Al window used to prevent detection

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* Tel. +1 (415) 926 4000, fax +1 (415) 926 4100.

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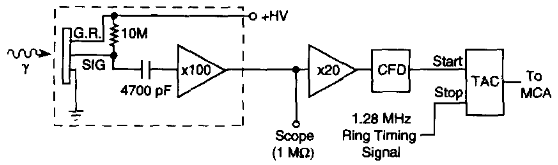

Fig. 1. Schematic of electronics used in the experiment. Components are described in the text.

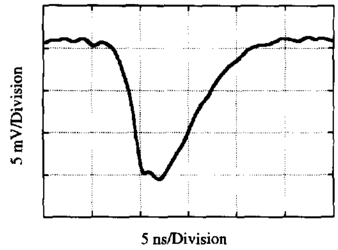

Fig. 2. Pulse shape as measured out of the ×100 preamplifier using a Tektronix 620A Oscilloscope (500 MHz, 2 Gs/s). Average over many 14 keV events, diode operated at 480 V.

of visible light, so efficiencies are for photons falling normally on the surface of the silicon. The error in the efficiency measurements was dominated by the uncertainty in the incident flux. The solid line is a fit assuming that all X-rays absorbed within a 94 μm "active" thickness of silicon are detected. Note that measurements at several locations on the diode gave similar results, with the best fits corresponding to 91, 94 and 98 μm.

The efficiency measured depended on the discriminator threshold, with higher thresholds leading to lower measured efficiencies, as is shown in the inset to Fig. 3. This results from variation in the pulse height for different events. Sources for this variation include noise from the diode dark current, noise from the preamplifier, statistical variations in the diode gain from event to event, and variations in the diode gain as the X-ray absorptions occur at different locations. At higher X-ray energies, the last probably dominates: the X-rays are highly penetrating (the 1/e absorption length at 14 keV is 350 μm) so that some of them will be absorbed inside the avalanche gain region of the diode, and only be partially amplified. At lower energies, the noise from the 6954 amplifier became a problem, and prevented setting the discriminator threshold below 40 mV. The data presented in Fig. 3. were collected using a discriminator threshold that increased linearly with the incident photon energy (from 40 to 80 mV), in an attempt to compensate for the variation in signal size with energy.

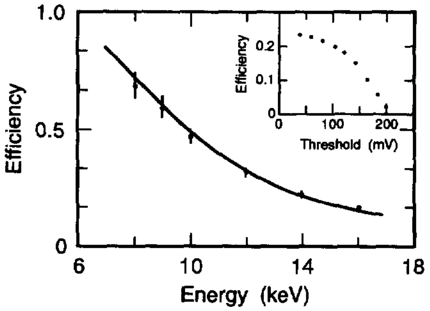

Fig. 3. The efficiencies (points) of the diode measured at different photon energies (diode operated at 480 V, gain approximately 150). The discriminator threshold was linearly scaled with photon energy from 40 to 80 mV. The solid line is a fit assuming detection of all X-rays photo-electrically absorbed in a 94 μm "active" thickness of silicon. The inset shows the effect of raising the discriminator threshold on the measured efficiency at 14 keV.

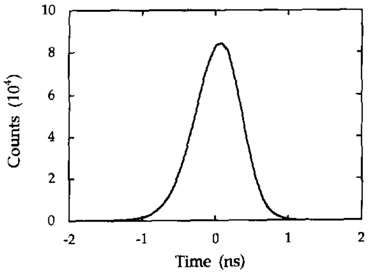

Fig. 4. Linear plot of the time response of the diode operated at 480 V with 14 keV X-rays incident and a discriminator threshold of 104 mV (20% efficiency).

Fig. 4 shows the time response of the diode for 14.0 keV incident radiation and a discriminator threshold of 104 mV. The full width at half maximum is 0.77 ns, which confirms that the drift velocity must be nearly saturated ($\sim 10^7$ cm/s) over the entire active thickness of silicon.

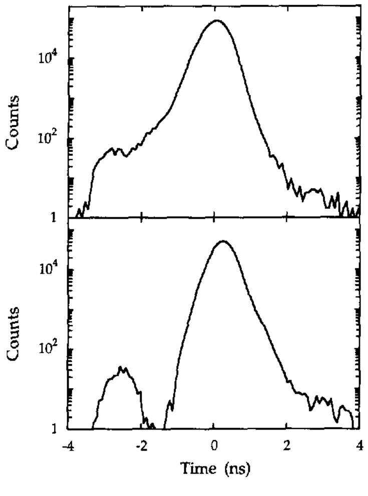

Fig. 5. Logarithmic plot of the time response at 14 keV for two different discriminator settings: (a) 104 mV = 20% efficiency and (b) 164 mV = 10% efficiency. Note the resolution of the mini-bunch at higher threshold.

Fig. 5 shows the time response on a logarithmic scale, for two different discriminator thresholds. The time resolution of the diode improves at higher thresholds, and the "tail" at early times in Fig. 5a is revealed in Fig. 5b to be a small bunch of electrons in the synchrotron, reduced from the main bunch by a factor of 10^3 (note the 2.8 ns separation). The improved time resolution at higher threshold is primarily the result of the reduced influence of the preamplifier noise on the triggering time of the constant fraction discriminator.

Large area reach-through diodes are promising candidates for time resolved detection of X-rays. When comparing them with other large area diodes, in particular those of a beveled edge design [6], one finds that they have comparable time resolution but enhanced efficiency, due to their larger active thickness of silicon. They also operate at lower voltages, less than 500 V as opposed to ~ 2 kV. However, reach-through diodes also have lower gains and hence, when operated in a fast pulse timing mode, preamplifier noise becomes more of a consideration.

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[7] EG&G Optoelectronics Division, EG&G Canada LTEE/LTD, 22001 Dumberry Road, Vaudreuil (Quebec) Canada J7P 8P7. Tel: +1 (514) 424-3300. The diode used here is a prototype for a 1 cm^2 device soon to be marketed by EG&G.

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