The use of avalanche photodiodes for the detection of soft x rays
J. R. Palmer and G. R. Morrison
Department of Physics, King's College, Strand, London WC2R 2LS, United Kingdom
(Presented on 17 July 1991)

Avalanche photodiodes (APDs) offer an attractive alternative to the gas flow proportional counter (GFPC) for the counting of individual soft x-ray photons. They are reasonably efficient detectors and have the capability of handling higher count rates than a GFPC. With the advent of intense monochromatic x-ray beams from synchrotron radiation sources, the ability to handle high count rates is becoming more important than the need for any energy resolution. Another attraction of using solid-state detectors is the possibility of multielement fabrication of devices: configured detector arrays can then be considered for a number of applications. For example, in the scanning transmission x-ray microscope such a detector system allows much more sophisticated imaging techniques, such as differential phase contrast imaging with a quadrant APD array. In this paper we compare results for several commercially available APDs used as photon counters with a GFPC over the energy range 200-700 eV. APDs operated in the Geiger mode with a simple passive circuit to quench the avalanche current pulses can achieve count rates of the order of $10^6$ s$^{-1}$, and this can be greatly improved upon with the use of an active quenching circuit.

I. INTRODUCTION

Avalanche photodiodes (APDs) are semiconductor p–n junction photodiodes which have been optimized for use under conditions of large applied reverse bias voltage. This results in a device with high internal amplification, important since amplifier noise can often be the limiting noise source. APDs have been seen as the solid-state equivalent of the photomultiplier tube, with the advantages associated with solid-state devices of being rugged, compact, and relatively cheap. Semiconductor processing technology also offers the possibility of fabricating multielement devices with very little dead space between the elements.

Silicon APDs have been used for many years for the detection of visible light, where they have similar characteristics to photomultipliers, and near infrared radiation, where they are superior, with applications in fiber optic communications, remote sensing and, more recently, in astronomy. Their use has also been suggested for x-ray spectroscopy and radiation monitoring, though absorption by the encapsulation precluded their use at energies below 1 keV. Specially fabricated diodes have recently been used for the detection of x rays in the range 500 eV to 15 keV. Efficient use of commercially available APDs in the soft x-ray region is possible if the window of the diode is replaced by a more suitable material, and the main constraint on the lower energy bound will then become absorption in the surface dead layer of the device.

APDs can be operated in a linear mode where the internal amplification is about 100, depending on the reverse bias voltage. It is also possible to use an APD at a reverse bias voltage slightly above the breakdown voltage $V_{br}$ where the internal amplification becomes infinite and a photogenerated free carrier within the depletion region of the diode will cause it to go into catastrophic breakdown. With an appropriate circuit it is possible to "quench" this breakdown current and return it to a stable state, thus yielding current pulses corresponding to the absorption of photons. Operation under these conditions has been likened to that of a Geiger–Müller tube and is generally referred to as the Geiger mode.

II. CONSTRUCTION

All the APDs tested had the so-called “reach through” structure shown schematically in Fig. 1. On the standard device light enters through a window of borosilicate glass and must pass through an antireflective coating of $\approx100$ nm of silicon dioxide on the surface and the p+ layer, of the order of 0.5-$\mu$m thick, which forms the contact. To be detected the light must be absorbed in the low concentration (intrinsic semiconductor) $p$ substrate which is about 100-$\mu$m thick. The p–n junction that creates the avalanche region is adjusted so that the depletion layer of the diode just reaches through to the $p+$ layer when the electric field at the junction is 10%–15% less than that required to cause breakdown; at the breakdown voltage the depletion layer extends out to the $p+$ layer.

![Fig. 1. Structure of a reach-through APD (not to scale).](image)
The voltages required to operate APDs are usually in the range 100–500 V for silicon devices. Device capacitance is related to the size, so for high speed operation the diode area must be as small as possible, of the order of 0.25-mm diameter compared to about 25 mm for a photomultiplier.

### III. OPERATION IN GEIGER MODE

In the Geiger mode the current must be limited to below some small level called the latching current, $I_L$ which is usually around 50 µA. Then, because the number of carriers is fluctuating, the current is unstable and will switch off if the number of carriers in the depletion region fluctuates to zero. A free electron generated in the depletion region, either thermally or by the absorption of a photon, will drift towards the p-n junction with a transit time of about 1 ns, where the large electric field will cause it to gain sufficient energy to generate additional free carriers by impact ionization of valence electrons into the conduction band. These secondary carriers can in turn generate further additional carriers by the same process. This avalanche breakdown pulse must then be quenched and the diode recharged ready for the next event. Since the rise time of a breakdown pulse is short, of the order of 10 ps, as set by the transit time at the high field region at the junction, it is the much longer time taken for the quenching which defines maximum count rate that can be achieved.

As stated above, the APD will only continue to be conducting if a current greater than $I_L$ is flowing, to ensure that there is always an electron in the avalanche region. Thus a breakdown pulse can be passively quenched simply by limiting the current that can flow through the diode to below $I_L$ by means of a sufficiently large load resistor, $R_L$. Alternatively the bias voltage can be removed electronically upon detection of an avalanche discharge, a process known as active quenching.

When a breakdown occurs the diode will conduct causing the voltage across it to drop from very close to the reverse bias voltage $V_r$ to just below the breakdown voltage $V_b$. In passive quenching $R_L$ is chosen such that the resultant current flow $(V_r - V_b)/R_L$ is less than the latching current. Following this the diode recharges to the reverse bias voltage with a time constant $C R_L$ where $C$ is the combined capacitance of the diode and any stray capacitances. Operating at 10 V above $V_b$ and taking $C$ as 1.6 pF from the manufacturer’s data sheet for a typical device, then the recharge time constant of about 0.3 µs is obtained, though in practice this will be increased due to the capacitances of the leads and resistors. This pulse fall time will be followed by a recovery time of several microseconds before reaching the quiescent condition, though retrigging can occur during this time. During the recovery period the device operates under perturbed conditions with lower detection efficiency and lower multiplication, though with amplification of the pulses to a set level the reduction in pulse amplitude will not be apparent. This gives a maximum possible count rate of the order of 3 MHz, but with increasing nonlinearity as this is approached, due to a combination of the photon statistics and the changing detection probability.

The dead time can be significantly reduced by recharging the device through a small resistance of the order of 100 Ω, which involves using an active quenching circuit. If the avalanche pulse is used to trigger a fast comparator, the output of the comparator can be used to superimpose a negative pulse on the bias voltage (that reduces $V_r$ below $V_b$ so quenching the avalanche. The maximum count rate is now set by the propagation delays in the quenching circuit. This will be the sum of the time taken for the comparator to switch on, send the quenching pulse, and for this to propagate through the feedback to switch off the comparator. Pulse widths of 320 ps have been achieved using this method with the RCA C30902S and new types of APD are expected to do better still.

The overall detective quantum efficiency (DQE) is the product of the probability of producing a photoelectron by absorption of a photon in the depletion region (a function of the wavelength of the illumination) and the probability that a breakdown will be initiated, termed the photoelectron detection probability (PDP). The PDP will increase with reverse bias, but so will the number of dark counts that are caused by thermally generated free electrons. If the diode is cooled then the number of dark counts will be reduced, improving the signal-to-noise ratio and also making it possible to increase the PDP by increasing the reverse bias.

However, cooling can have the added consequence of increasing the amount of afterpulsing that occurs. Electrons generated by the avalanche can become trapped in the crystal lattice and are released after various time intervals causing false avalanches. These afterpulses can occur up to 5 min after the real pulse though most will occur within 1 ms. The generation of afterpulses increases with excess reverse bias voltage, and when the device is cooled to reduce the number of dark counts become the limiting factor on the bias level, so there must be some tradeoff between the amount of afterpulsing and the quantum efficiency. An overall DQE of 30% is thought to be the best that can be achieved with commercially available diodes before afterpulsing becomes a significant problem.

### IV. RESULTS

Initial tests were performed with Hamamatsu type S2382 and RCA types C30607E and C30902S. The glass window on the front of each diode was removed by turning off the top of the metal casing, and was replaced with a 100-nm-thick silicon nitride membrane coated with 100 µm of aluminium to exclude visible light. The opacity of this thickness of aluminium was found to be insufficient to exclude all the visible light but the count rate could be reduced to the dark count rate with simple baffles: total darkness was unnecessary. Increasing the thickness of the aluminium coating would also attenuate the x rays at the wavelengths of interest.

The passive quenching method was used with a load resistor of 200 kΩ, allowing operation at excess reverse bias voltages of up to 10 V; above this level the current flowing...
on quenching exceeded the latching current and caused the diode to stay conducting for longer. However, since these tests were done without cooling the diode the amount of dark signal precluded operation above this level of overbias. The breakdown current pulses were amplified using a fiber optic receiver IC operating as a current to voltage converter to give 5-V output pulses, which were turned into square pulses by the on-chip comparator. It was the inherent hysteresis of this comparator, giving a minimum pulse width, and hence deadtime, of 1.2 µs, which set the maximum possible count rate to $8 \times 10^5$ s$^{-1}$, though due to the nonlinearities mentioned above the practical limit was about half this. Using the pulses direct from the current to voltage converter, which showed a deadtime of 270 ns, enabled a greater linear region to be achieved, but noise on the signal caused some pulses to be counted more than once. It is clear that even using a passive quenching circuit it is possible to achieve near-linear count rates approaching $10^6$ s$^{-1}$.

The intention is to use an APD in place of a gas flow proportional counter (GFPC) on a scanning transmission x-ray microscope (STXM). In these tests an APD was used as direct replacement for the GFPC on the King's College STXM on-line 5U1 at the Daresbury SRS, U.K., and the STXM on line X1 at the National Synchrotron Light Source, Brookhaven, U.S.A. Synchrotron radiation, after monochromation, was directed through a silicon nitride vacuum exit window, through a pinhole, and on to the detector. The space between the exit window and the detector was flushed with helium to eliminate the attenuation by air. The thickness of aluminium on the APD window was about ten times that on the GFPC window, and there was 1–2 mm of air trapped in front of the active volume of the APD, but otherwise there was direct correspondence between the two detectors.

As the excess reverse bias is increased the number of counted photons increases, but so does the dark count. Figure 2 shows that above a certain level the dark count becomes so high as to reduce the signal count rate. The RCA C30902S is the only diode specifically recommended for use in Geiger mode and has been specially selected to have a low dark count rate. The other diodes were found to have a dark count rate which rose more rapidly with reverse bias.

Figure 3 shows a comparison between two of the diodes and the proportional counter, over the energy range 200–700 eV. The overall shape of the spectrum is determined by the efficiency of the soft x-ray monochromator, not the detectors, but it is clear that the performance of the APDs is very similar to that of the GFPC. In each case the dominant features introduced are of the nitrogen and oxygen absorption edges associated with the detector window materials. The dark count rate for the APDs is higher than the GFPC when operated at the bias required; the GFPC dark count rate can be reduced to virtually zero by pulse height discrimination. At the higher x-ray energy end of the graphs the response of the APDs seems to be better than that of the GFPC, perhaps due to the increased penetration of the x-ray photons into the active volume of the APD.

V. CONCLUSIONS

APDs have been shown to detect soft x rays satisfactorily, with a similar response to that of a GFPC. However, they must be shielded from visible light and at room temperature they have a higher dark count. This could be reduced by cooling and it is likely that this would increase the counting efficiency could be improved. The maximum count rate of APDs exceeds that of most GFPCs even with a simple passive quenching circuit. It seems likely that as more intense synchrotron radiation sources become available it will be necessary to use detectors which operate at higher speeds than GFPCs.

Already it has proved possible to record images using a single element APD as the detector in a STXM, but an important reason for using a solid-state detector in the STXM is the possibility of introducing multispectral devices, to allow new more sophisticated STXM imaging modes to be realized. For example, a detector with concentric annular elements would allow simultaneous bright-field and dark-field imaging, while a detector split about the optical axis and used for differential phase contrast (DPC).
imaging yields phase gradient information by responding to the deflection of the beam by the specimen. A system is currently under development that uses a quadrant array of APDs which will enable DPC images to be recorded with four directions of differentiation simultaneously with the normal amplitude contrast image.\(^{26}\)

Although it is possible to make position sensitive proportional counters with multiwires\(^{27}\) or resistive wires\(^{28}\) they are difficult to fabricate and have low spatial resolution compared to that possible with solid-state devices. To use an APD in linear mode for this type of imaging it would be essential for the avalanche gain to be uniform over the active area,\(^{29}\) a very stringent requirement, whereas by operating in Geiger mode it is sufficient that all the active area be biased above \(V_b\) when enabled and below \(V_b\) when quenching.\(^{30}\)

It has been suggested\(^{6}\) that photons are generated by the avalanche breakdown process, which would militate against the use of APD arrays operated in Geiger mode because of crosstalk caused by such light leaking into adjacent elements. However, recent experiments\(^{31}\) have shown that this is not a measurable effect, probably because the distance travelled by such photons is very small.

**ACKNOWLEDGMENTS**

We wish to acknowledge the financial support of U.K. SERC and NATO (Grant No. CRG910276) for this work. We are particularly grateful to Chris Jacobsen, Janos Kirz, and Shawn Williams of SUNY at Stony Brook for the assistance and advice they provided at Brookhaven National Laboratory. J.R.P. is supported by a SERC studentship.

25. Optical communications receiver LH0082 from RS Components Ltd., U.K.