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Applications of drift photodiodes in future experiments

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Abstract

Recent developments of low capacitance photodiodes are discussed, with emphasis on future applications in high luminosity collider experiments.

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Applications of drift photodiodes in future experiments

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Abstract

Recent developments of low capacitance photodiodes[1] are discussed, with emphasis on future applications in high luminosity collider experiments.

Introduction

In recent years silicon photodiodes have become essential devices in particle physics; several large experiments currently use them for scintillating crystal readout. Their pros and cons are now well known - the advantages include low cost, robustness, immunity to magnetic fields, a high quantum efficiency over a wide spectral range and, because of the unity gain, no sensitivity to bias voltage variations. However they require a low noise amplifier for read out, which to date has been a relatively expensive item, and to achieve a satisfactory signal to noise ratio a pulse shaping time of a few μsec is required. This comes about [1] because the electronic noise depends mainly on three parameters: the total input capacitance (C_{in}), diode dark current (I_{dark}) and amplifier time constant (τ). This can be expressed by the Equivalent Noise Charge (ENC) which has the dependence

$$ENC^2 \sim a\, C_{in}^2/\tau + b\, I_{dark}\tau + c$$

Thus, for a diode with a large capacitance, a long time constant is required to reduce the contribution from the first term which originates in thermal noise in the first transistor of the preamplifier. Typically in high energy physics applications ENC values of ~400 electrons can be achieved with $1cm^2$ photodiodes of 80pF capacitance and very low leakage current, ~1nA.

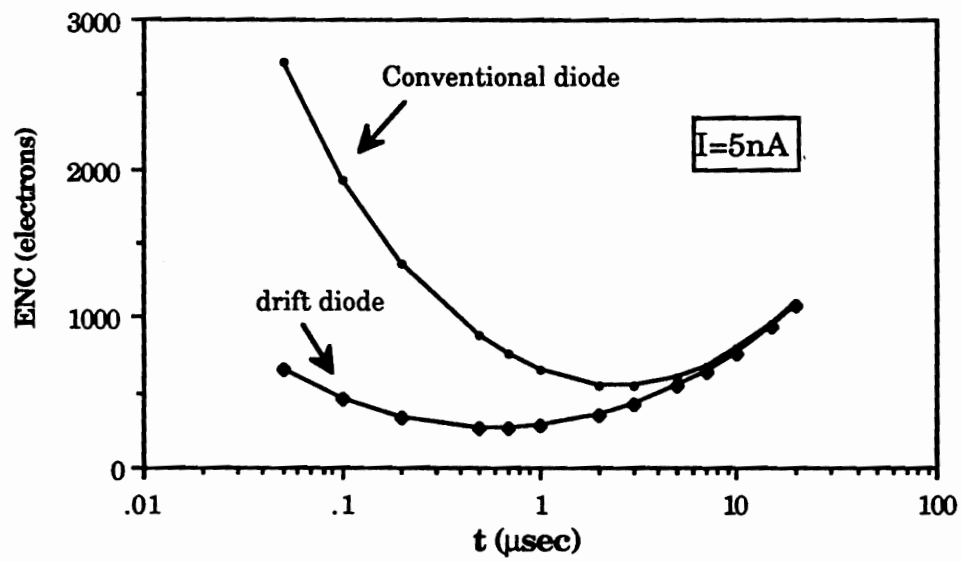

Fig.1. Comparison of the likely performance of a conventional photodiode, C~80pF, read out by a high quality JFET preamplifier and a drift photodiode, C~4pF, read out by matched CMOS electronics. The pulse shaping is assumed to be a CR-RC filter.

[1] *The work described here has been carried out by a collaboration between Imperial College, the Senter for Industriforskning, Postboks 124 Blindern, 0314 Oslo 3, Norway and AME A/S, Horten, Norway [5].*

It is hard to see how long shaping times could be tolerated in an SSC or LHC environment, even in a heavily segmented system with low occupancy. A reduction in time constant leads to an increase in noise and, eventually, loss of peak signal since the preamplifier rise time is ultimately limited by the input capacitance. Fig. 1 shows what might be achieved with a conventional diode and high quality amplifier.

Thus, although silicon is often cited as an intrinsically fast detection medium, it is usually difficult to take full advantage of its speed because of signal processing limitations. A possible way is to exploit alternative detector designs which trade off some of the detector speed against capacitance to reduce signal processing times.

The silicon drift diode

A natural way to achieve this is based on the idea of the silicon drift detector [2] whose principles are explained more fully elsewhere [3]. Briefly, a detector is constructed by implanting p-type electrodes into both surfaces of an n-type silicon wafer. The devices are fully depleted and a field is set up inside the detector which transports electrons liberated by ionisation to a readout electrode some distance away. These devices were originally proposed and demonstrated as position sensitive detectors and drift times of many μsec have been observed. However, perhaps the most interesting property of such detectors is their low intrinsic capacitance, independent of area, since the device capacitance is essentially defined by the geometry of the read out electrode alone.

A photodiode based on the same principle can be constructed by a modification to the design of a conventional diode. A uniform p-type implant forms the photosensitive surface in the usual way; the surface that is implanted to make the ohmic contact is instead subdivided into several cells as shown in fig 2. Each cell comprises a central n-type anode surrounded by a rectangular array of p-type cathodes. In our designs the cells are all connected together by the outermost cathode so that biasing becomes quite simple. A sufficiently large reverse bias is applied to the outermost cathode to fully deplete the detector. The anodes are connected to ground at the preamplifier and intermediate cathodes and the photosensitive surface float to their operating voltages. Electrons drift within each cell, in a direction orthogonal to the electrodes, to the anode.

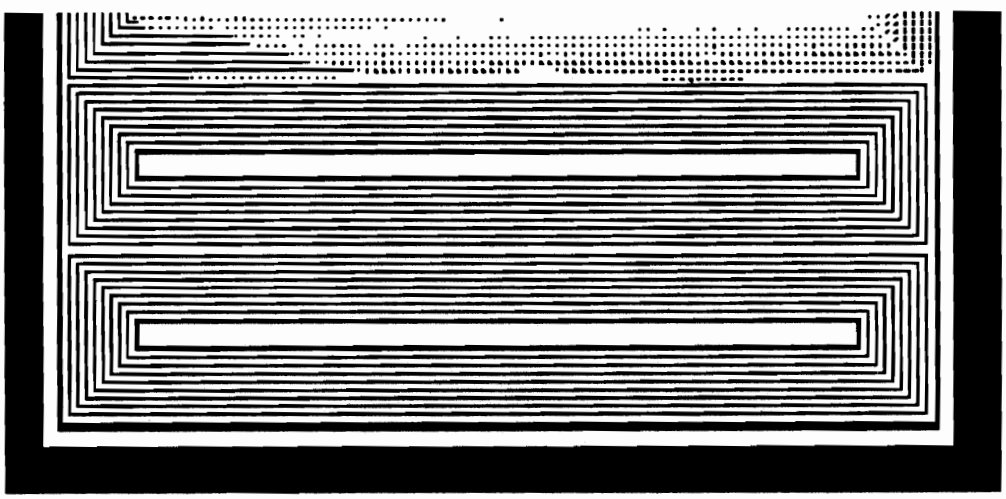

Fig.2 A section of one surface of a drift photodiode, showing two cells of the device. The photosensitive surface is opposite this one. Each of the five cells is 2mm by 10mm laid out so that a central anode is surrounded by field shaping cathodes to provide the drift field. The total active area is $1cm^2$

The principle of the detector was first demonstrated in 1985 [4] and, indeed, many drift detector designs have been demonstrated by a collaboration between Kemmer, MPI (Munich) and others. Other manufacturers who have attempted to make drift detectors have rarely been successful. In

our own case several attempts have produced working detectors with readily observed drift properties but with leakage currents much higher than would normally be considered useful. This originally surprised us since the process being used to fabricate the detectors is a well established one which produces very low leakage microstrips and large area diodes, recently as low as 50pA/100μm/cm^2.

This year, after some research on the gettering processes responsible for reducing leakage currents in diode detectors, we succeeded in producing very high quality drift photodiodes [5]. Devices with leakage currents as low as ~2nA, at the operating voltage of ~90V, have been tested and the yield of the very best detectors is promising enough to believe that further optimisation can be achieved. The total capacitance for the 1 cm^2 area is ~4pF. Some results obtained are shown in fig. 3. The roughly parabolic time distance relationship is a characteristic of this design; the maximum drift time can be altered by material resistivity as well as design.

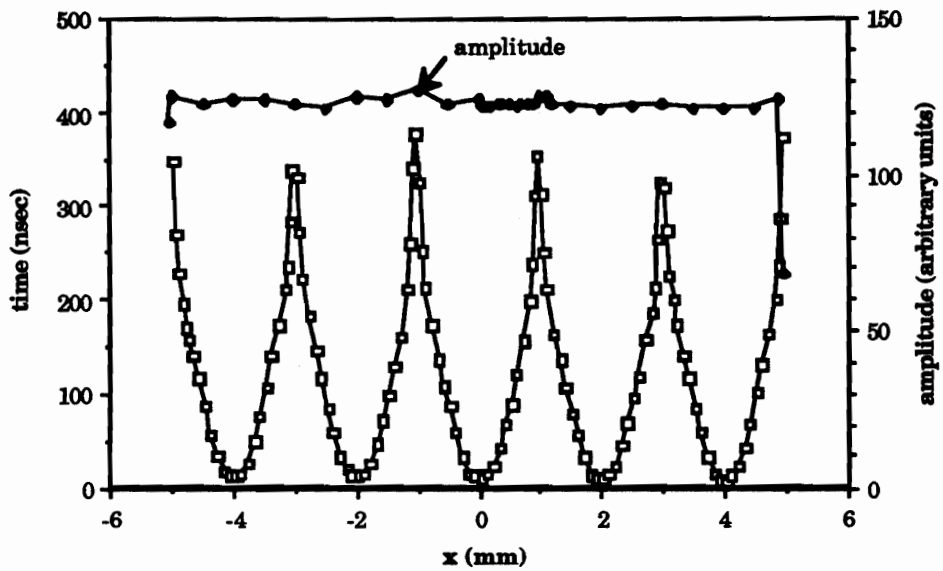

Fig.3. Variation of the drift time and amplitude with position of one of the drift photodiodes described. The detector was scanned with a 50μm diameter light spot at 850nm wavelength in a direction orthogonal to the anodes.

Immediate requirements

To demonstrate the full potential of drift photodiodes some further work is needed. A reduction in maximum charge collection time by reduction of cell width seems rather easy to achieve and optimisation for specific areas could be undertaken. More important are longer term studies of stability and radiation hardness and optimisation of the process to improve production yields. So far the detectors tested have shown pleasing behaviour since they appear to be very stable with no special attention paid to humidity, temperature,etc. More long term observations are certainly required. Radiation damage effects can be predicted as far as bulk leakage current changes; more subtle effects affecting charge collection as a consequence of both bulk and surface damage must be examined. Because of the simple design and the absence of detailed position measurements drift photodiodes are expected to be more radiation tolerant than complex drift devices.

Future developments

The results shown in fig. 1 could be obtained with a good quality preamplifier using a monolithic JFET as the input device. For large scale future applications these amplifiers are not likely to be suitable unless integrated devices can be produced. For photodiode read out the JFET is usually operated with a drain current of at least several mA to produce the high transconductance needed for low noise and the preamplifier is usually produced in hybrid (surface mount) technology. In con-

trast,a drift diode, with a capacitance of, say, 4pF could be easily matched to an MOS transistor produced on a CMOS chip. This is a major advantage for large scale applications - yet the system performance should be better than currently possible in several ways. Fig. 1 compares the performance that might be achieved with a CMOS circuit [6] and a drift diode assuming a transistor drain current of only 100μA. A very low power system could be implemented on a large scale. Jarron [7] has pointed out that lower detector capacitance also enables one to trade power consumption at the front end, signal processing time, segmentation and noise to achieve the required system performance. It is clearly possible to consider instrumenting individual cells using integrated circuit technology; this could lead to additional possibilities such as the local rejection of anomalously large signals caused by the passage of a charged particle through the diode.

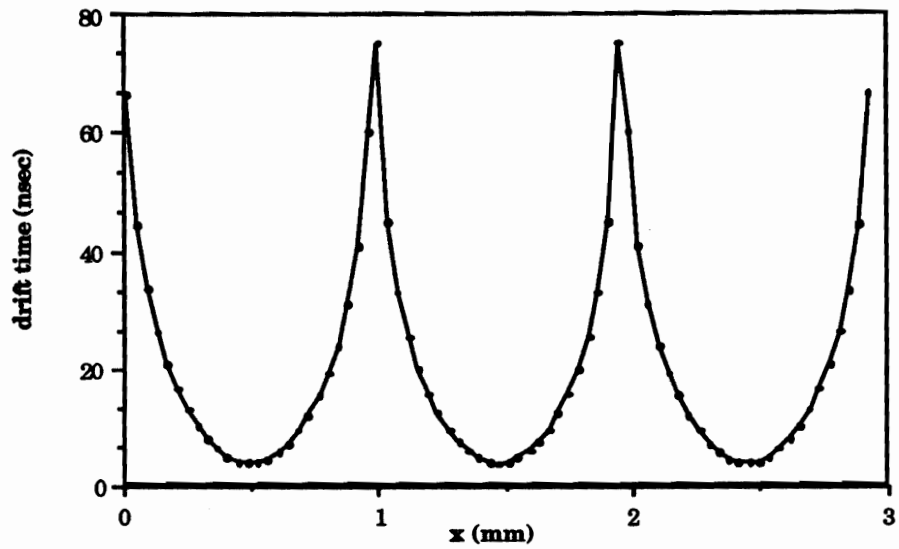

Fig.4. A simulation of three 1mm wide cells of a drift photodiode assuming similar properties to actual photodiodes tested. The reduction in the cell width leads to a significant reduction in collection times.

A shaping time constant of 0.2μs might well be acceptable for most calorimeter type applications at SSC, given likely occupancies, provided the time development of signals at the amplifier outputs are recorded. However it is still desirable to minimise charge collection times. This can certainly be done by optimising the cell design; fig. 4 shows what is expected for a cell width of 1mm compared to the 2mm used so far. A current pulse from uniform illumination of the surface will have the usual fast rise but an extended tail compared to a conventional diode. There are likely to be other geometries which can made just as simply for specific requirements.

The original motivation for the development of drift photodiodes was for scintillation light detection with improved resolution. This is expected to be of even greater importance in future with the use of faster scintillators. Some important materials, such as barium fluoride, have relatively low light output [8] and they also radiate at short wavelengths where conventional diodes are insensitive because of surface coatings. However previous work by one of us [9] has shown that high quantum efficiency at wavelengths as short as 200nm can be obtained with optimised processing; preliminary measurements indicate that our drift diodes show similar behaviour. It is not clear whether the spectral response can be extended further to the region of interest for liquid xenon scintillation; wavelength shifter coatings may be required.

Further improvements in charge collection speed can be obtained by cooling detectors and this can have a marked effect on leakage currents too. Electron mobilities are known to increase as $T^{-2.42}$ and leakage currents decrease as exp(-E/kT), with E≈0.5eV in the case of ideal, bulk-dominated currents. Fig. 5 shows some recent examples of our detector behaviour. Operation at liquid xenon temperature should lead to a further gain in speed of a factor ~3. We plan to verify this expecta-

tion using some of the present devices in the near future.

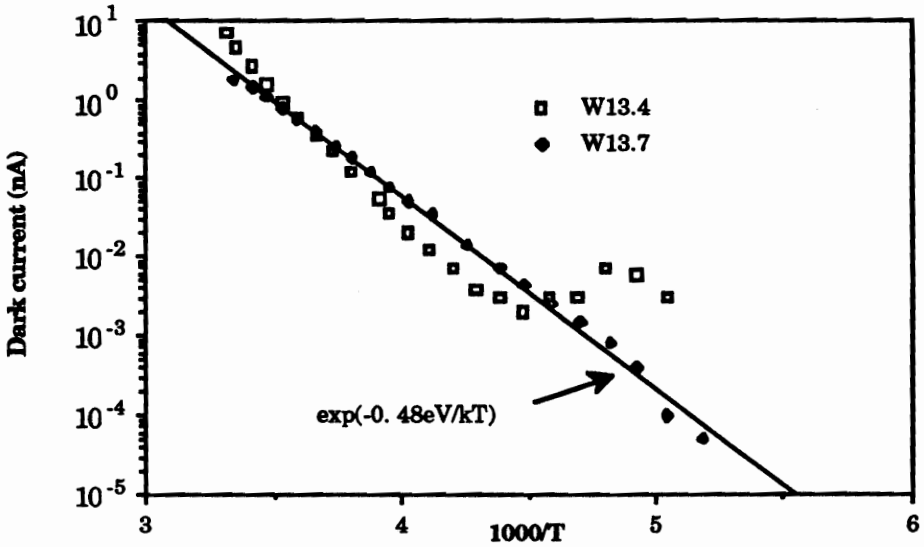

Fig. 5. Recent results for two photodiodes showing the reduction in leakage current with temperature. The line is a fit to the form shown for the diode W13.7.

Price is likely ultimately to be a major concern but at present it is too soon to estimate the economies of scale likely to be applicable in future. Any simplification of the design will certainly lead to eventual cost reduction. One might hope that simple drift devices like those described here could be produced for little more than conventional diodes. In addition one should not forget that the cost of the amplifier usually represents a major contribution to the total system; a device using a VLSI amplifier can contribute a major saving, as well as simplifying construction.

Conclusions

Low leakage current drift detectors have been produced for the first time in a commercial process. They offer the possibility of high rate readout of scintillators with better noise performance than obtained with conventional photodiodes and with the additional advantage of a low power large system when matched to integrated electronics. Further optimisation is required to improve yields and study the long term behaviour of the detectors but many promising applications can be foreseen. Although the technology is already fairly advanced to realise them on the scale of an LHC/SSC detector will require a sustained R&D effort. Such an effort would seem well justified given the potential.

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