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**Avalanche Photodiodes (APD) as Proportional
Devices**

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Our recent investigations in Bristol have concentrated on the use of APDs in the proportional mode. We have investigated 3 types of APD: an EG&G (RCA) type C30921E, a Hamamatsu type S2382 and one made by the Czech Technical University in Prague. Figure 1 shows that for each type of diode there is a voltage, the breakdown voltage, above which the diode will conduct continuously after it detects a signal.

In most earlier applications APDs were operated in the geiger mode, where the diode is biased slightly above the breakdown voltage. This can give a very large signal initiated by a single photon but must have an external quenching circuit. This geiger mode gives a saturated signal and information about the amount of primary ionization is lost.

If the diode is biased below the breakdown voltage then the avalanches will be limited and the output charge will be proportional to the number of such avalanches and hence to the initial ionization, apart from the inevitable fluctuations in gain.

An APD working in proportional mode may be used to detect light from an external scintillator (Lorenz, 1993) operating as a compact and robust substitute for a photomultiplier which would be insensitive to magnetic fields. It might alternatively be used as a semi-conductor detector for fast charged particle passing through it, with enough gain to enhance the signal and remove the need for very low noise electronics.

The proportional gain in available APDs is rather low. As can be seen from figure 1 the RCA diodes give a maximum useable gain of a few hundred and the Hamamatsu diodes about 100, while the Prague diodes give little proportional gain. Such gains are much less than from a photomultiplier, but still provide a useful increase in signal relative to any noise from electronics. Because silicon and other semiconductors have a low ionization energy in there is a serious background at room temperature which is produced by thermal ionization of the material.

THERMAL EFFECTS

In semiconductor devices the amount of thermal ionization may be reduced by lowering the temperature. In an APD close to breakdown the dark current *rises* dramatically as the temperature is decreased. This is because the *gain* increases as the temperature goes down. The mean free path for the electrons (or holes) increases at reduced temperature, so the electrons gain more energy from the field and ionize more readily at a given field strength. This increase in gain more than compensates for the decrease in the thermal generation of primary electron-hole pairs as the temperature is reduced. At lower temperatures the thermal noise does decrease relative to the signal, but both currents will increase. A change in temperature of 1 °C will give a change of more than 1 % in signal size for a silicon APD operated with a gain of about 100.

The variation of the gain in an APD is unpleasantly large, especially close to breakdown, both as a function of bias voltage and of temperature. It would be useful to have an APD which could be operated with an adequate gain while still biased well below the breakdown voltage. This requires an APD which will not break down until it is biased to a voltage significantly higher than needed to give the required gain.

FEEDBACK AND BREAKDOWN IN APDS

In a silicon diode the ionization coefficient for electrons α_e is appreciably greater than the coefficient for holes α_h , so that avalanches are dominantly due to ionization by electrons. If this were all that could happen the gain would rise exponentially with

the bias voltage without any limit. The limit to the gain attained in practice is caused by some feedback process which means that the generation of one avalanche causes another avalanche to start and so on.

This breakdown condition is very similar to that encountered in the gas-filled multi-gap avalanche chambers developed as particle detectors (Charpak 1978). Here the feedback process is provided by positive ions which return to the electrodes at the start of the avalanche region and release electrons from the metal surface. In multigap chambers it is possible to inhibit the onset of breakdown (Gilmore, 1981) by dividing the gain between two gaps separated by wire mesh electrodes through which some of the charge can pass. The gain in either gap will be too low to produce breakdown. If the transparency of the electrodes for passing positive ions is reduced then the average final charge can be greater before a sufficient fraction is fed back to start a new avalanche.

In a semiconductor both electrons *and* holes may cause ionization, so the feedback process is intrinsic in the material. In silicon the ionization is dominantly by electrons and $\alpha_e \gg \alpha_h$, but at higher field values holes will ionize also. Breakdown results if on average *one* of the holes produced in an avalanche should generate a further electron-hole pair close to the cathode end of the high field region. The gain is very unstable near breakdown. Figure 2 gives a distribution of pulse areas for a Hamamatsu APD operating just below breakdown and shows the tail of abnormally large pulses caused by extra avalanches from ionization by holes.

Figure 2 Pulse size distribution near breakdown.

The standard condition for breakdown in a depletion layer of width W in a semiconductor such as silicon where the ionization is mostly by electrons is (Sze, 1981, p 99)

$$\int_0^W \alpha_e \exp\left(-\int_x^W (\alpha_e - \alpha_h) dx'\right) dx = 1$$

In the case where $\alpha_e = \alpha_h$ this reduces to a limit where the mean number of ionizations per electron is one. This would correspond to a gain of just 2, but when both electrons and holes cause equal ionization it results in breakdown. An APD giving a high gain before break down should have a ratio α_e/α_h as far as possible from unity. In silicon the ratio α_e/α_h is greater at lower fields (Sze, 1981, p 47) so a high gain diode should have a wide depletion layer with a relatively low field. The rate of ionization per unit

length will be lower than at higher field, but in a wide enough layer the same gain could be achieved and if α_h is comparatively low then breakdown will be inhibited. Ideally the material should also have a greater capture cross-section for holes than for electrons, so that holes may be captured before they cause ionization.

The different diodes we have investigated show striking variations in their performance, as summarised by figure 1. The EG&G diodes give a maximum gain in excess of 200 for a bias around 230 volts. The Hamamatsu diodes give gains of around 100, but at a much lower bias, around 100 volts. The diodes built by the Technical University in Prague have a very low breakdown bias, about 30 volts, but give proportional gains of little more than 5.

These results are consistent with the arguments outlined above. The Hamamatsu APD is a comparatively normal diode with the high field in a depletion layer at a junction. The EG&G (ex RCA) diode has a *reach-through* structure where the high field is in a lightly doped region which would tend to give a relatively wide gap with a reduced field. This needs a higher bias voltage to produce the same gain, but the maximum gain which can be obtained before breakdown is the greatest among the three types. The Prague diode contains germanium doped silicon. In silicon the ionization coefficient for electrons is greater than that for holes, whereas in germanium the reverse is true. In a mixture the coefficients may be comparable and breakdown consequently sets in at a very low value of gain. This is advantageous for an APD operated in geiger mode, since it may be operated from a low voltage supply, but is unhelpful for a proportional device.

We are developing a computer simulation of the avalanche process in APDs, for comparison with measured values for the gain and pulse variation. We plan also to measure the linearity and absolute quantum efficiency of the detectors.

CONCLUSION

APDs show promise as particle detectors because they have high quantum efficiency and specific ionization combined with intrinsic gain and the ability to operate in a magnetic field. To obtain reasonably stable operation as proportional detectors the diodes should be biased well away from the breakdown voltage and so it is important to develop diodes which break down at the highest possible gain.

REFERENCES

- Charpak, G. and Sauli, F., 1978, The multistep avalanche chamber: a new high-rate high-accuracy gaseous detector, *Phys. Lett.* **78B**;523.
- Gilmore, R.S., Lavender, W.M., Leith, D.W.G.S. and Williams, S.H., 1981, High gain multigap avalanche chambers for cherenkov ring imaging
IEEE Trans. Nucl. Sci. **NS28**;435-438.
- Lorenz, E., Natkaniez, S., Renker, D., Schwarz, B., 1993, Fast readout of plastic and crystal scintillators by avalanche photodiodes,
Max Planck Institute report MPI-PhE/93-23.
- Sze, S.M., 1981, "Physics of Semiconductor Devices" Publisher, John Wiley.