

Application of the Barrier Method to Semiconductor Spectrometers for Nuclear Radiation

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High purity semiconductor crystals with low thermal generation rate such as Si and Ge at 77 K have been operated as radiation spectrometer when sandwiched between two thin insulating barrier layers without any preparation besides etching. The working time of such devices is determined by the ratio of the charge on the capacitor formed by the semiconductor surface, the insulating layers and the metal contacts, to the total charge generation rate in the semiconductor volume (thermal generation and absorption of ionizing radiation). Typical working times of 10 h for Si and 1 h for Ge have been obtained with gamma energy resolution comparable to junction detectors. Periodical recharging of the detectors can be performed with light flashes in very short time so that the dead time of a spectrometer incorporating junctionless crystals is negligible. Operation without the presence of an external electric field is possible due to insulator interface charge trapping and was also performed, showing some advantages.

1. Introduction

Considerable effort has been paid to the development of non-injecting galvanic contacts to high purity semiconductor crystals. Diffusion and alloying techniques¹ have been successfully employed together with surface barrier techniques². While the latter one would be preferable for detector fabrication, since it avoids any heat-treatment and results in negligible dead layers, it has often been found instable with time and ambient and difficult to apply to both sides of a crystal, particularly when the semiconductor is close to intrinsic and small variations in the impurity concentrations lead to reversal of the conductivity type. The application of thin layers of insulators forming barrier type capacity contacts has proven to be a useful tool in the investigation of radiation induced dc-currents in inorganic as well as organic crystals, esp. anthracene and tetracene³.

This paper shows that this method can also be applied for the analysis of radiation induced current pulses. Results obtained in the analysis of gamma ray induced pulses from high purity silicon and germanium employing such capacity contacts are given and some further applications of the method are discussed.

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2. Principle of the Method

An n-type Semiconductor with unit area is considered as an example. The crystal is sandwiched between two insulating layers with metal electrodes on the outer sides (Figure 1). l_s and l_i denote the

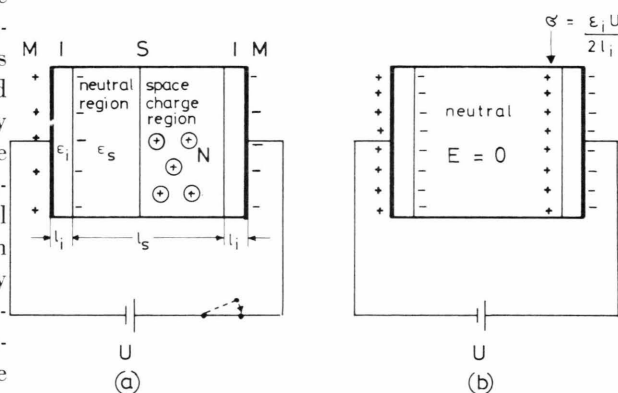


Fig. 1. Schematic arrangement. a) Charge distribution immediately after applying voltage $U < U_0$, b) Thermal equilibrium after generation of σ/e electron-hole pairs.

thickness of the semiconductor and the insulator respectively; ϵ_s and ϵ_i are the dielectric constants.

When voltage is switched on free electrons in the semiconductor are swept to the semiconductor-insulator interface adjacent to the positive electrode within the dielectric relaxation time giving rise to a short charge pulse in the external circuit. This re-



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sults in a positive space charge region near the negative electrode (Figure 1a). For sufficiently high voltage the semiconductor will be totally depleted of free carriers. The voltage necessary for depletion is

$$U_0 = \frac{e N l_s^2}{2 \epsilon_s} \left(1 + \frac{2 l_i}{l_s} \cdot \frac{\epsilon_s}{\epsilon_i} \right)$$

where N is the shallow donor density.

For voltages $U > U_0$ a homogenous electric field is superimposed on the field generated by the fixed donor charges. Electron-hole pairs which are generated by ionizing radiation within the active volume, i.e. the space charge layer for $U < U_0$ and the crystal volume for $U \geq U_0$, induce a current pulse in the external circuit through their motion in the electric field. In other words, the internal ionization current is capacitively coupled to the external circuit via the insulating layers.

By thermal generation of electron-hole pairs in the depleted volume the thickness of the space charge layer shrinks and finally the system returns to thermal equilibrium which is characterized by the fact that the applied voltage drops across the insulating layers alone while the bulk of the semiconductor is field-free with the equilibrium electron concentration $n_0 = N$. Therefore the breakdown voltage of the insulators sets an upper limit for the voltage which can be applied. The total charge σ of either sign to be generated until equilibrium is established is thus given by

$$\sigma = \epsilon_i U / 2 l_i \quad (\text{see Fig. 1 b}).$$

This charge is trapped at the semiconductor-insulator interfaces or it gives rise to very thin accumulation respectively inversion layers at the surfaces. For an applied voltage of 1000 V,

$$\epsilon_i = 4 \cdot 10^{-13} \text{ C V}^{-1} \text{ cm}^{-1} \quad \text{and} \quad l_i = 10^{-4} \text{ cm}$$

σ becomes $2 \cdot 10^{-6} \text{ C cm}^{-2}$.

The thermal generation rate has a surface component and a bulk component. While generation in the bulk can be evaluated from the minority carrier lifetime and the intrinsic carrier density the surface generation depends very sensitively on the etching procedure and the ambient for a given material. It is, however, generally the surface which determines the total pair generation with cooled Si and Ge. From the leakage currents obtained with junction detectors in the order of 10^{-11} A for Ge and 10^{-12} A for Si at 77 K the relaxation time to thermal equilibrium

may be estimated to 10^5 s (Ge) and 10^6 s (Si) for a system in the conditions given above. At constant generation the voltage drop across the semiconductor decreases linearly with time. Therefore, the periods of time given should be reduced by a factor of ten, if considered as working times for a detector, since a reduction of not more than ten percent in the voltage is tolerable with regard to constant charge collection.

If the carriers are generated by the absorption of gamma quanta the total dose corresponding to the charge $2 \cdot 10^{-7} \text{ C}$, i.e. a voltage reduction from 1000 V to 900 V will be about $3 \cdot 10^6$ quanta of 1 MeV energy for a detector area of 1 cm^2 .

For reestablishment of the original field strength the electrodes must be first short circuited and the charge carrier stored at the surfaces must recombine and then the voltage is reapplied again. In the case that the charges are stored near the insulators in accumulation layers in the crystal, the carriers are ready to move and therefore neutrality is established within the dielectric relaxation time and equilibrium is reached with the minority carrier lifetime as time constant.

Quite a different situation, however, prevails when the charges generated during the application of the external field are trapped at the semiconductor insulator interfaces^{4,5} as it is the case e.g. with mylar layers. This case is of particular interest, because semiconductors with charges fixed at the interfaces cannot return immediately to neutrality after short-circuiting the electrodes; rather an internal electric field of opposite sign as the originally applied external field will persist in the semiconductor for long periods of time. It will have almost the strength of the applied external field, when the insulator interfaces were charged to saturation. Again, thermal equilibrium will be eventually established by generated carrier pairs swept by the internal field to the interfaces and neutralizing the charges trapped there. With the aid of light sources neutralization can be performed in very short times.

With interface trapping not only voltage-on but also short-circuit operation is possible. A short circuit operation cycle consists in the following steps:

- a) Voltage is applied for very short time; thereby light is shining on the crystal to charge the insulators to saturation.

b) Light is switched off and the circuit is shorted. The crystal is then in a similar condition as during voltage-on operation for the same period of time except for the polarity of the field.

Short circuit operation is also possible with voltages smaller than U_0 . In this case the short-circuit shifts the space charge region from the side of the formally negative electrode to the opposite electrode. Advantages of the short-circuit mode of operation are discussed in section 4. Charge trapping at interfaces has been observed e. g. with mylar insulators. The mechanism involved is interpreted as transfer of carriers from the semiconductor to the insulator where a charge density of more than 10^{13} cm^{-2} was demonstrated to exist.

Since electron-hole pairs generated in the semiconductor are stopped at the interfaces the charge signal Q_m measured in the external circuit will be smaller than the generated charge Q_0 :

$$Q_m = Q_0 \cdot \left(1 + \frac{2l_i}{l_s} \cdot \frac{\epsilon_s}{\epsilon_i} \right)^{-1}.$$

In a not fully depleted crystal the thickness of the crystal l_s must be replaced by the length of the space charge region in the above formula. The length of the space charge region is a function of time through its connection with the voltage drop and therefore the measured charge decreases with time. As a result a peakshift toward lower energies is observed in a recorded spectrum when the voltage across the semiconductor drops below depletion voltage.

3. Experimental Set Up and Results

Mylar foils with $2.5 \cdot 10^{-4} \text{ cm}$ thickness, one side aluminized, were used as insulating layers. The dielectric constant of this material is about $4 \cdot 10^{-13} \text{ CV}^{-1} \text{ cm}^{-1}$ and the breakdown voltage is in the order of 500 V per 10^{-4} cm thickness. The foils were cut to slightly larger diameters than the crystals to avoid edge breakdown. The crystals with mylar on both faces were pressed between indium foils to ensure good thermal and mechanical contact.

Silicon detectors: At room temperature, intrinsic Si ($250 \text{ k}\Omega \text{ cm}$) with 20 mm diameter and 3 mm thickness was investigated. This material has been tried for detector fabrication in the usual technique (lithium diffusion for n^+ together with Au surface barrier) without success due to high leakage currents. Unprepared slices were etched in 3:1 HF:

HNO_3 (cooled) and mounted between mylar foils. In this way, detectors with good resolution and working times in the order of 10 h were obtained without difficulty. Furthermore it could be shown that the high leakage currents observed in the surface barrier detectors originated from carrier injection from the evaporated gold contact: When the gold was removed and replaced by the mylar again working detectors resulted with the n^+ side in galvanic contact to ground. No particular interest has been paid up to now to ultimate resolution. Gamma ray resolution at 122 keV was in all cases limited by the external preamplifier to about 1,5 keV fwhm.

Germanium detectors: High purity germanium, both n-type and p-type, with impurity concentrations ranging from 10^{10} to 10^{11} cm^{-3} was tested. The diameter of the slices was about 4 cm and their thickness 4 to 5 mm. As is known from the junction detectors, germanium is more difficult to etch and to mount for low leakage currents at 77 K than silicon and therefore several trials were necessary to obtain working times in the order of 1 h. With detectors of 10^{11} cm^{-3} impurity concentration peakshift to lower energies could clearly be observed with still good resolution for the 662 keV line at the end of the working period due to the voltage across the detector falling below the depletion value.

Due to carrier trapping at the mylar surface the detectors worked in voltage-on and short circuit mode of operation for the same periods of time. Recharging of the traps was performed with a light bulb.

4. Discussion

The detector working time limit connected with the barrier method may be reduced to some minor scale by the use of a periodical recharging circuit incorporating a light source. Short-circuit mode of operation seems to be advantageous for the following reasons:

No special requirements are to be imposed on the HV supply, since HV is applied only during the dead time of the spectrometer.

For the same reason a reduction in microphony is accomplished.

Excess noise of connector leakage currents can be eliminated.

Energy resolution, pulse rise time and detector working time remain the same in short-circuit operation as with an externally applied voltage.

Although the application of the barrier method to cooled Si and Ge displays some definite advantages in spite of some change in resolution due to the small decrease of the collecting field during operation time and has in some cases proven to be essential for counter operation of quasi-intrinsic material, the main purpose of this work with Si and Ge is to demonstrate the capabilities of the insulator method with material of well known spectrometer properties.

Investigations of other materials with up to now poor detector performance, esp. wide band gap semiconductors such as CdTe, CdS or ZnS with the aid of the barrier method seem to be promising. Besides of the simplicity of the procedure the following aspects should be considered:

The problems connected with the bulk material can be separated from the influence of current injection from metallic contacts on noise and trap population.

Materials with strong trapping of radiation released free carriers can be operated at higher temperatures if contacted with insulating layers to reduce the detrapping time, if the thermal pair generation is determined by the band gap energy E_g and not by generation centers in the forbidden gap: Since the Schottky-barrier height for current injection from contacts is always smaller than E_g and in many cases approximately $E_g/2$, one can go to considerably higher temperatures with insulating layers before the thermal pair production in the bulk sets a limit to detector performance due to increasing dark current noise and decreasing working time.

The operating voltage is not limited by local contact breakdowns.

Current pulse measurements with organic crystals and liquids⁶ for neutron or beta counting using insulating contacts are also of interest.

A further application of the barrier method beyond the field of nuclear detectors may be in the non-destructive measurement of semiconductor parameters such as doping profiles. The versatility of the contact geometry provides for local resolution.

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