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Self-adjusting resistor unit in the detector-voltage supply of a charge-sensitive pre-amplifier for an ionization detector

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ABSTRACT:
A self-adjusting resistor unit is described which stabilizes the bias voltage of a detector for ionising particles, while always keeping the parallel thermal noise of the bias resistor significantly below the detector shot noise. The user is exempted from adjusting the bias resistor to the detector leakage current for achieving optimum operation conditions. Moreover, the unit avoids the drop of the operation voltage on the detector when the reverse current increases up to several orders of magnitude without any further intervention. The self-adjusting unit leads to an extension of the time of operation of the detector under stable conditions by up to several orders of magnitude.

Keywords:
Voltage stabilisation
Charge-sensitive pre-amplifier
Electronic noise
Detection of ionizing particles

1. Introduction

Detectors for ionizing particles are most often operated with charge-sensitive pre-amplifiers [1,2]. Figure 1 shows the main elements of a charge-sensitive pre-amplifier connected to a silicon detector. The diode *D* denotes the silicon detector. The operation voltage of the detector is inserted from an external power supply at the point HV and applied to the detector via the resistors R_1 and R_2. R_1 and *C* form a filter to reduce the noise from the power supply. R_f and C_f form the feedback network of the operational amplifier.

The properties of the pre-amplifiers need to be carefully adjusted to the characteristics of the detector and the operation conditions of the measurement [3]. Particularly critical parameters are the resistors R_1 and R_2. E.g. if R_2 is chosen too low, the resolution of the set up is not optimum [4]. If the value of $R_1 + R_2$ is chosen too high, the operation conditions of the detector are unstable, because only a small fraction of the voltage of the power supply is applied to the detector. Thus, the polarisation voltage of the detector is strongly modified if the reverse current varies. In any ionization detector, the DC current depends on the load of ionizing particles seen by the detector. Moreover, the reverse current in semi-conductor detectors strongly depends on temperature. An additional difficulty arises from the fact that silicon detectors are subject to radiation damages when they are bombarded with heavy ionizing particles [5,6] or with neutrons [7]. As a consequence, the reverse current increases. Thus, the values of R_1 and R_2, which were chosen to have optimum values at the beginning of a measurement, gradually become inappropriate. This can be a severe problem, since the reverse current may increase by several orders of magnitude in a rather short time. It is in principle possible to adapt the values of these two resistors to the actual operation conditions of the experiment, but this is very cumbersome and time consuming. If a large number of channels is used, e.g. in the case of silicon-strip detectors, such an adjustment during the experiment is even practically impossible. Any adjustment becomes inconceivable in the case of modern, highly integrated pre-amplifiers. The series resistance in the bias chain may be avoided by a DC-coupled detector, applying the bias voltage from the backside of the detector. However, in this case the detector current may produce an offset in the preamplifier output that is impractically high. Moreover, this method is not applicable for double-sided Si strip detectors.

In the following, we will propose a technical solution of this problem, which works as a self-adjusting system, assuring always optimum operation conditions without any further intervention.

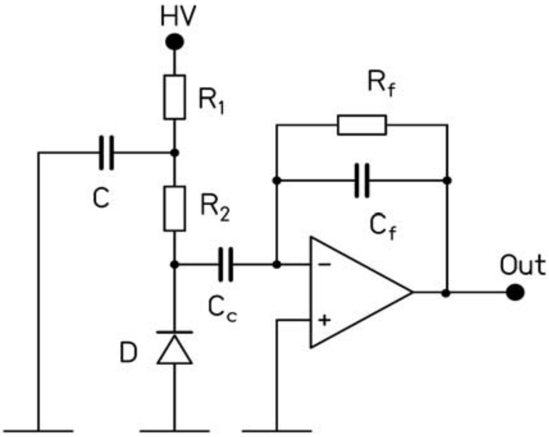

Fig. 1: The main elements of a charge-sensitive pre-amplifier. See text for details.

2. Thermal noise and shot noise

When choosing the value of R_2, one should take care that the parallel thermal noise is small compared to the unavoidable shot noise of the detector. Detailed considerations lead to a very simple rule of thumb, which can be used to realize this condition: Thermal noise due to R_2 and shot noise due to the reverse current are equal if the voltage drop on R_2 is about 50 mV [8]. Appreciably larger voltage drops on R_2 should be avoided in order to assure that the operation voltage on the detector stays approximately constant. A decreased operation voltage has very negative consequences, because the depletion depth of the detector decreases, causing a more or less drastic decrease of the ionization charge provided by the detector. In addition, the effective capacity of the detector increases, leading to a loss of charge collection in the feed-back capacity C_f. These arguments lead to a very simple rule of operation: Since the thermal and shot noise add up quadratically, there is no gain in electronic resolution if the voltage drop on R_2 exceeds a few hundred mV. An excessive voltage drop can only be avoided if the value of R_2 is adjusted more or less continuously to the variation of the total current through the detector.

3. Self-adjusting resistor unit

Figure 2 shows the proposed self-adjusting resistor unit connected to the silicon detector, which is denoted by *D*. The section on the left of the capacity *C* replaces R_1, and the section on the right of the capacity *C* replaces R_2 in figure 1. In this example, the following values of the resistors are chosen: R_1 and R_4 = 10 MΩ, R_2 and R_5 = 1 MΩ, R_3 and R_6 = 100 kΩ. The series can easily be extended for smaller or larger currents. One silicon diode limits the voltage drop on the resistor mounted in parallel to 700 mV. The diodes D_1 to D_4 of the self-adjusting resistor unit should have the following properties: The effective resistance of the diode below the forward bias and in reverse direction should be large compared to the resistance of the Ohmic parallel resistor, so that the DC current through the diode remains small compared to the current through the respective Ohmic parallel resistor. It should be assured that their capacities are small compared to the capacity of the detector and that they are suited for frequencies comparable to those of the operational amplifier.

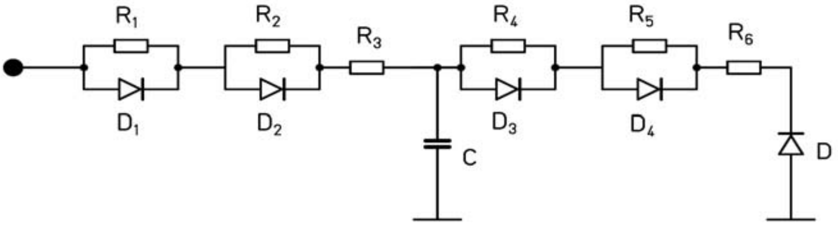

Fig. 2: The proposed self-adjusting resistor unit.

The voltage drop over the proposed self-adjusting resistor unit of figure 2 as a function of the reverse current of the detector is shown in figure 3. In this example, the reverse current causing a voltage drop of ΔV=10 V is increased by a factor of 100 due to the function of the diodes.

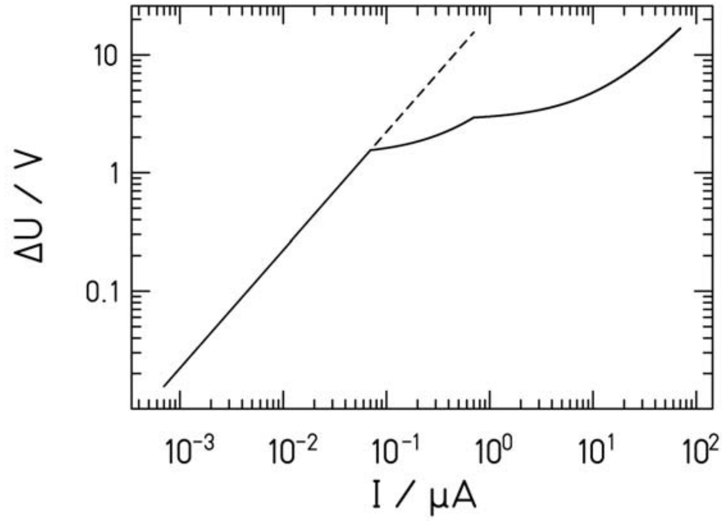

Fig. 3: Voltage drop between the voltage supply and the detector as a function of the reverse current. The dashed line indicates the voltage drop without the self-adjusting resistor unit and $R_1 = R_2 = 11.1$ MΩ (see figure 1).

In an extended version shown in figure 4, the diodes D_3 and D_4 might be replaced by two diodes in series, each. The limiting voltage drop on the resistors R_4 and R_5 mounted in parallel is now 1.4 V. When the diodes parallel to R_4 (R_5) become conductive, the voltage drop on R_5 (R_6), which is the main source of thermal noise in this case, is 140 mV. In this version, the contribution of thermal noise to the resolution is certainly negligible. Furthermore, the extended version is suited for positive and negative polarisation voltages due to the additional diodes mounted in inverse direction. In the extended version, the effective resistivity $R_{eff}=dU/dI$ between C and the detector is 11.1 MΩ if the current stays below 140 nA. For a current between 140 nA and 1.4 µA, the effective resistivity reduces to 1.1 MΩ. If the current exceeds 1.4 µA, the effective resistivity drops to 100 kΩ. Up to a current of 50 µA, the total voltage drop in the unit does not exceed 10 V, which is still smaller than the operation bias of most silicon detectors. Of course, one could also extend the unit by sets of diodes in parallel to R_3 and R_6 and two additional resistors of 10 kΩ following R_3 and R_6, reducing this voltage drop further for higher reverse currents.

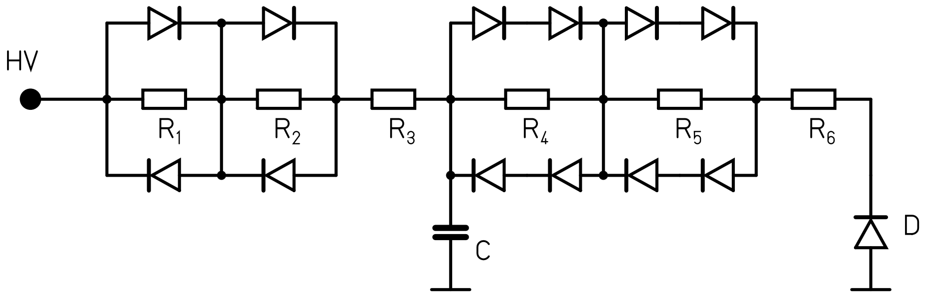

Fig. 4: Extended version of the proposed self-adjusting resistor unit.

While the most drastic failure of the equipment, the drop of the operation voltage on the detector, which leads to a drastic reduction of the signal height, is avoided by the described self-adjusting resistor unit, there are still two unavoidable effects that lead to a deterioration of the pre-amplifier response. The most direct effect is the unavoidable increase of the shot noise. If the resolution drops below the value that is necessary for the intended measurement, the detector must be exchanged. Also cooling is a very efficient mean to reduce the reverse current, but it might not always be applicable. In addition, the function of the pre-amplifier begins to deteriorate if the resistivity given by the effective detector resistivity and the resistivity between the capacity *C* and the detector become too low. E.g. some loss of charge occurs if the discharge current of the detector becomes comparable with the current from the output of the charge-sensitive amplifier loading the feed-back capacity. This effect can be reduced by a proper choice of the operational amplifier, but finally it is unavoidable. As a consequence, the calibration of the detector response changes. However, a constant survey of the pulse height of a pulse-generator signal, inserted to the test input of the pre-amplifier, may be used to correct for this effect.

4. Test measurements

A test measurement has been performed in order to study the modification of the electronic response of a pre-amplifier, equipped with the proposed self-adjusting resistor unit, when the detector current increases. For this purpose, the resistor R_2 in figure 1 of a Canberra 2003 BT pre-amplifier with R_1= 10 MΩ [9] was replaced by the right half of the self-adjusting resistor unit in figure 2. Therefore, the total bias resistor was 22.1 MΩ. The detector was replaced by a capacity of 150 pF and a variable resistor in parallel. This way we exclude from the measurement any modification of the charge collection in the detector itself due to radiation damages, which may be very complex and rather specific for a certain kind of detector. The measurement is certainly not fully representative for the effect of an increased reverse current with a real detector, but it accounts for the fact that the charge collection is almost unaffected due to the stable bias voltage and it correctly measures the increase of the shot noise due to the increased reverse current. Thus, the most important effects are considered. Figures 5 and 6 show the pulse height and the noise at the output of the pre-amplifier. The noise is given in equivalent ionization energy in a silicon detector. Thus, the energy scale corresponds to the deposited energy of a light ionizing particle in a silicon detector.

With the self-adjusting resistor unit the output signal only reduces by about 10 percent when the reverse current increases up to a value of 120 μA, see figure 5. For comparison, the response of a standard detector – pre-amplifier unit (without the self-adjusting unit) as a function of the reverse current has been simulated and is represented by the dashed line in figure 5. For this purpose, the 5.48-MeV alpha particles from a ^{241}Am source were recorded with a Passivated Implanted Planar

Silicon (PIPS) detector from Canberra [10] (active area 300 mm^2 and thickness 150 µm) connected to an unmodified pre-amplifier (Canberra 2003 BT), corresponding to the electric circuit of figure 1 with R_1=10 MΩ and R_2=100 MΩ. The reverse current in the Si detector at the nominal bias voltage (+50 V) was les than 10 nA. The most important effects of an increased reverse current and the corresponding reduction of the bias voltage are the reduced charge collection in the detector due to the decreased depletion depth and the reduced charge extraction by the pre-amplifier due to the increased detector capacity. These effects were simulated by applying a reduced bias voltage. The nominal bias voltage was reduced by the voltage drop in a resistor of 110 MΩ, which is equal to the value of the total bias resistor ($R_1 + R_2$). A drastic drop of the response signal at a reverse current of about 450 nA appears. Thus, the self-adjusting unit provides dramatic improvement compared to the situation of a fixed resistor of 110 MΩ, which would have limited the operation to a reverse current of a few hundred nA.

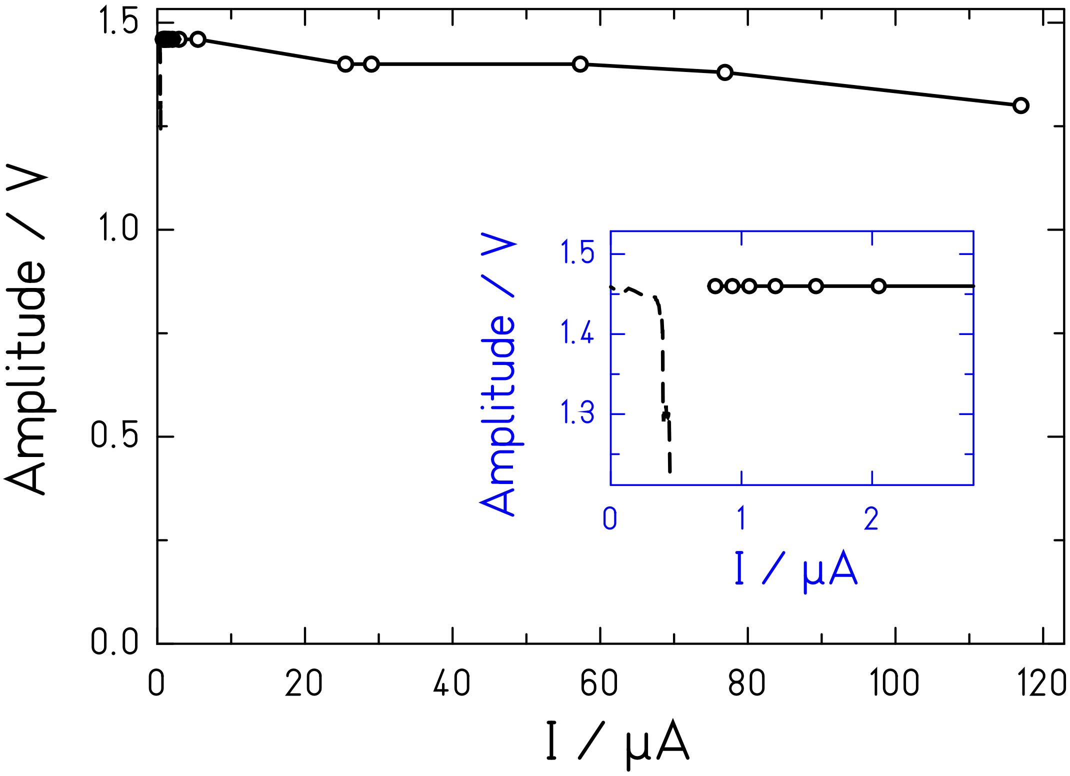

Fig. 5: Amplitude of the output signal of an amplifier (0.5 µs shaping) corresponding to the ionization signal of 5.48 MeV in a silicon detector as a function of the detector current. The data points, connected by the full line, were measured using a preamplifier with the self-adjusting resistor unit proposed in this work. The “reverse current” was adjusted by varying the resistance mounted in parallel to the capacity, representing the detector. For comparison, a measurement with an alpha source (5.48 MeV) and a Si detector connected to the unmodified pre-amplifier (figure 1) was performed. The dashed line depicts the response of the detector - pre-amplifier set-up as a function of the simulated reverse current. For this purpose, the nominal detector voltage (+50 V) was reduced by the voltage drop on 110 MΩ, which is equal to the value of the total bias resistor ($R_1 + R_2$). In the inset, the same curves are shown for currents of few µA.

The noise, shown in figure 6, shows a linear increase in double-logarithmic scale with an exponent of about 0.36. Thus, the increase is a bit less steep than the expected increase of shot noise, which should vary in proportion to the square root of the current. This graph can be used in order to determine the limit of operation under the condition of a specific measurement that a certain resolution has to be met.

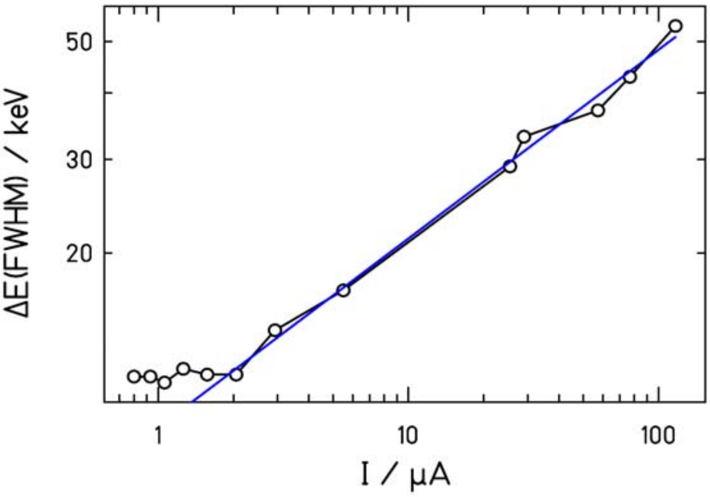

Fig. 6: Simulation measurement of the equivalent noise ionization signal in a silicon detector as a function of the reverse current. See text for details.

We would like to remind that there are many experiments where the requirement on the electronic noise is rather modest. E.g. the fluctuations in energy or energy-loss measurements of heavy ions are governed by incomplete charge collection and atomic collisions and often amount to several 100 keV or even a few MeV. In this case, reverse currents in the order of 100 µA are not yet critical at all, see figure 6. But it should also be considered that the detector might suffer from other kinds of damage in addition to the increased reverse current like a change in the effective doping concentration in silicon detectors, if the detector is subject to very high doses of heavy charged particles or neutrons, which might induce an additional deterioration of the detector response.

The previous results show that the use of the proposed self-adjusting resistor unit allows one to extend the operation domain of the detector by about three orders of magnitude with a rather moderate modification of the electronic response. It can be argued that the bias resistor can be adapted in advance to the critical requirements of the measurement. However, this is often not possible. For example, a specific problem appears if a strip detector is subject to an unexpected inhomogeneous load of ionizing particles. The self-adjusting unit will automatically provide operation conditions which are best adapted to the different parts of the detector, assuring in any case that the detector is fully depleted over the whole area. Parts of the detector which are less damaged even keep their low electronic noise. Such a flexible condition cannot be realized by reducing the bias resistor over the whole detector in advance.

5. Conclusion

The ionization current and the reverse current of ionization detectors can vary appreciably in an experiment as a function of time or from one detector to another. The increase of the reverse current of the detector due to radiation damage can be as high as several orders of magnitude. This leads to a loss of operation voltage on the detector and a drastic reduction of pulse height if the resistor in the voltage supply is not adjusted. These effects can be almost completely avoided by using a self-adjusting resistor unit as proposed in this work, which stabilizes the bias voltage of the detector, while always keeping the parallel thermal noise of the bias resistor significantly below the detector shot noise. Using the proposed self-adjusting unit, the operation limit is mainly given by the unavoidable shot noise, which grows approximately with the square root of the detector current. In many applications, the resolution is initially not governed by electronic effects. In these cases, the self-adjusting resistor unit may lead to an extension of the life time of the detector under stable conditions by up to several orders of magnitude. In any case, the user is exempted from adjusting the bias resistor to the detector leakage current for achieving optimum operation conditions.

A French patent application (N°FR1058804) extended by an international PCT application (n°PCT/EP2011068791) claiming this invention has been filed by the CNRS on October, 26th 2010.

Acknowledgement

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