Performance of silicon PIN photodiodes at low temperatures and in high magnetic fields

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Abstract

The performance of a Si PIN diode (type Hamamatsu S3590-06) as an energy sensitive detector operating at cryogenic temperatures (\(\sim 10\) K) and in magnetic fields up to 11 T was investigated, using a $^{207}$Bi conversion electron source. It was found that the detector still performs well under these conditions, with small changes in the response function being observed in high magnetic fields, e.g. a 30% to 50% decrease in energy resolution. A GEANT4 Monte Carlo simulation showed that the observed effects are mainly due to the modified trajectories of the electrons due to the influence of the magnetic field, which changes the scattering conditions, rather then to intrinsic changes of the performance of the detector itself.

Key words: PIN-Diode; $\beta$-particles; magnetic field; low temperatures; resolution

1 Introduction

Si PIN photodiodes, originally designed to detect photons, have over the years found more and more applications in nuclear and particle physics. Nowadays they are used in a wide variety of experiments for the detection of X-rays\textsuperscript{[1]}, electrons\textsuperscript{[2, 3, 4]}, or $\alpha$-particles\textsuperscript{[5, 6, 7]}, but they have up to now always been used in rather low magnetic fields. Solid state detectors like avalanche photodiodes and silicon drift detectors have already been tested in high magnetic fields up to respectively 7.9 T\textsuperscript{[8]}.
and 4.7 T (9) to be used in tracking devices at collider experiments. However, these detectors were not used for spectroscopic purposes. With Penning ion traps becoming more widespread in nuclear physics (10), and now also being used for in-trap and trap-assisted spectroscopic measurements (e.g. (11)), an increasing need for solid state state detectors that can operate in even higher magnetic fields (up to 11 T) has emerged. For α-particles and low energy electrons a Si PIN diode is a good option provided it performs well in such extreme conditions.

Here we present the results of measurements to test the performance of a Si PIN diode at a temperature of ∼ 10 K and in magnetic fields up to 11 T using conversion electrons from a $^{207}$Bi source. A series of GEANT4 (16) simulations was performed as well to get a better understanding of these results.

## 2 Experimental setup

The performance of a Si PIN diode at about 10 K and in high magnetic fields was measured using a Brute Force Low Temperature Nuclear Orientation setup (4). The apparatus is equipped with a superconducting solenoid providing a magnetic field up to 17 T.

The detector was a Si PIN photodiode produced by Hamamatsu Photonics (type S3590-06). This is a 500 μm thick fully depleted windowless PIN diode with a sensitive area of 10 x 10 mm$^2$. It allows to fully stop electrons with energies up to 350 keV, while the sensitivity for γ radiation is still very low. The insensitive SiO$_2$ surface dead layer has a thickness of 270 nm (13) which is thin enough to allow to use this PIN diode also for the detection of α particles. The housing consists only of ceramic material and non-magnetic metals, rendering this detector well-suited for operation at cryogenic temperatures and in magnetic fields. The detector was previously already commissioned and used in experiments at a temperature of ∼10 K and in a magnetic field of 0.6 T, showing good behaviour in these conditions (4).

The electron source used was a commercially available $^{207}$Bi conversion electron source. The decay of this isotope proceeds mainly via three γ lines with energies of 539.7 keV, 1063.7 keV and 1770.2 keV, respectively, each of them being converted for a couple of percent yielding several conversion electron lines. Only the conversion electrons of the two lowest energetic transitions were used here because of the thickness of the detector. The $^{207}$Bi activity is sandwiched between two 2.4 mg/cm$^2$ thick titanium windows supported by an aluminium ring. A GEANT4 simulation showed that energy loss in these windows shifts the full energy peak of the 481.7 keV and 975.7 keV K conversion electrons by 2.3 keV respectively 2.0 keV to lower energies and causes an additional energy spread of 1.9 keV and 1.7 keV, respectively.

The source was placed at a distance of 8 mm from the Si PIN diode with a
7 mm long, 10 mm diameter Al collimator in between and a 1 mm thick, 9 mm diameter Cu collimator on top of the detector. The Cu collimator served to limit the active area of the detector as it is known that the charge collection efficiency for this kind of detectors degrades at the edges of the sensitive surface (15). The system was installed in the bore tube of the superconducting magnet as shown in fig. 1. The positioning is such that the magnetic field lines are perpendicular to the surface of the detector. The signal is led through the 4 Kelvin, 77 Kelvin and room temperature radiation shields to a charge collecting pre-amplifier (Canberra 2001) outside the cryostat. It was further processed by standard NIM electronics and a PC based data acquisition system.

![Diagram of experimental setup](image)

**Fig. 1.** Sketch of the experimental setup. The Si PIN photodiode and the $^{207}$Bi source are placed inside the bore tube of the 17 T superconducting magnet. The signal from the detector passes through the 4 K, 77 K and room temperature radiation shields before reaching the pre-amplifier.

### 3 Measurement and results

First the detector was cooled to $\sim 10$ K in the absence of a magnetic field. In accordance with previous measurements (4) no significant difference between
the $^{207}$Bi spectra measured at room temperature and at cryogenic temperatures was observed. Nevertheless it is well known that cooling solid state detectors generally improves the energy resolution since the leakage current of the detector significantly decreases when cooling it below 0°C ([14]). The fact that the performance of the diode at room temperature and at cryogenic temperatures was similar in our setup then indicates that the major contribution to the noise is in this case not coming from the detector itself but from the signal processing. Indeed, the complexity of a cryogenic setup requires to lead the unamplified signal from the detector through three radiation shields (i.e at 4 K, at 77 K and at room temperature) to the preamplifier. One has to try to avoid that this wiring acts too much as a heat bridge between the room temperature parts and the 4 K cooled parts of the system, leading to a wire length of about 30 cm and increased pick-up of noise. The energy resolution (FWHM) of the detector in this configuration was, both at room temperature and at $\sim$10 K, 6.4(1) keV and 7.5(2) keV for the 482 keV and 976 keV conversion electron lines, respectively. A spectrum obtained at $\sim$10 K and without magnetic field is shown in figure 2. The two sets of conversion lines are clearly visible above the background of scattered electrons. The behavior of the conversion electron peaks at 482 keV and 976 keV was monitored throughout the different measurements that were performed.

Fig. 2. Conversion electron spectrum of $^{207}$Bi measured with the Si PIN diode operating at $\sim$10 K in 0 T. The reverse bias was 140 V.
During a first series of measurements the field at the position of the detector was gradually increased from 0 T to 11 T. No major changes in the performance of the detector were observed. Between 0 T and 2 T the count rate increased roughly by a factor of 10 due to the focussing of the electrons by the magnetic field. This resulted in a $2\pi$ effective solid angle at about 2 T for the 482 keV electrons and at somewhat higher magnetic field also for the 976 keV electrons. This is illustrated in figure 3. Note that the initial count rate was sufficiently low so that the dead time, even at the highest field values, did not get larger than a few percent. In addition to the overall change in count rate

![Fig. 3. Conversion electron spectra ($^{207}$Bi) obtained with the Si PIN diode operating at $\sim$10 K and in magnetic fields of 0 T, 0.5 T, 2 T and 11 T. The most important change is the counting rate due to the focussing of the electrons while, in addition, the shape and the position of the full energy peaks also change slightly (see text).](image)

a clear change in the shape of the peaks as a function of the magnetic field is observed; with the magnetic field increasing the resolution worsens somewhat, while the peaks get a tail on the low energy side and also move slightly to lower energies (i.e. about 2.5 keV). When the field was lowered back to 0 T the spectrum was again identical to the one observed before the field was raised. The effects observed in high magnetic fields were thus clearly due to the presence of the field and no damage was caused to the detector.

In a second series of measurements data were taken with the detector subjected to a field of 5 T for two full days. The operation of the detector was
observed to remain stable and no change in the spectra was seen during this entire period, showing that stable, long-term operation of the detector at low temperatures and in high magnetic fields is possible. Finally, spectra were again recorded while the field was changed in steps, now decreasing it from 11 T down to 0 T. Smaller steps were taken in the region where the changes to the spectra seemed to be largest, i.e. between 1 T and 5 T. No differences compared to the first sweep, where the field was increased from zero field to 11 T, was observed. This can be seen in figure 4 where the energy resolution (FWHM) of the 482 keV and the 976 keV conversion electron peaks as a function of the magnetic field for the two field sweeps is shown. The resolution of the pulser peak, present during the entire experiment, was 2.0 keV and stable within 0.1 keV.

Fig. 4. Energy resolution of the full energy peaks of the 482 keV and 976 keV conversion electron lines of $^{207}$Bi observed with a Si PIN diode operating in different magnetic fields and at a temperature of $\sim$10 K.

4 Discussion and interpretation

Although the Si PIN diode tested here still works well in high magnetic fields, a clear dependence of the spectrum shape on the magnetic field strength was
nevertheless observed (see Fig. 3). This is important for the use of this detector as a spectroscopic device.

To investigate the origin of these changes in more detail a series of GEANT4 (version 4.90) Monte Carlo simulations were performed. The routine that was used was developed to track electrons and reproduce experimental spectra for the real experiment (17). A detailed geometrical description of both the detector and the source, including also the piece supporting them, as well as the collimators, were included. For ease of interpretation mono-energetic electron lines of 500 keV and 1000 keV were included instead of implementing the full $^{207}$Bi decay scheme. Further, different homogeneous magnetic fields, comparable to the ones used in the experiment, were applied in these simulations, while for every emitted electron both the emission angle and the energy deposited in the sensitive area of the detector were recorded. Figure 5 shows, for different magnetic fields, the initial emission angle relative to the vertical axis for the electrons that are detected in the full energy peak. It is seen that from 2 T upward the detector indeed has almost a 2$\pi$ effective solid angle.

![Graph showing the number of 500 keV electrons that end up in the full energy peak as a function of their initial emission angle for different applied magnetic fields.](image)

Fig. 5. The number of 500 keV electrons that end up in the full energy peak as a function of their initial emission angle (defined relative to the vertical axis and corrected for the solid angle) for different applied magnetic fields. Already at 2 T about 46% of the emitted electrons end up in the detector, while in a field of 11 T about 50% do so. The events to the left of the vertical solid line are backscattered electrons that still reach the detector.
In figure 6 the simulated detector response to 500 keV mono-energetic electrons is shown for different fields. It must be stressed that the Monte Carlo simulation only registers the energy which the electrons deposit in the detector and that effects of charge collection and signal processing, which also contribute to the energy resolution in a real experiment, are not included in the simulations.

Fig. 6. The simulated detector response to 500 keV electrons for applied magnetic fields up to 11 T. Note that the spectra are rescaled so that the peak shapes can more easily be compared.

It is seen that the effects that were observed when the field was increased, i.e. the fact that the full energy peak broadens, gets a tail at the low energy side and also slightly shifts to lower energies, are all reproduced by the simulation. This indicates that these changes are mainly caused by the magnetic field that modifies the trajectories of the $\beta$-particles so that they deposit different energies in the sensitive volume of the detector, rather than being due to an intrinsic change in the performance of the detector itself. This can be rather easily understood. With no field the majority of the detected $\beta$ particles follow a straight trajectory from source to detector and pass almost perpendicular through the source window and through the detector front dead layer. In the presence of a magnetic field they spiral from source to detector thereby arriving at a rather shallow incidence angle on the surface of the detector. This causes a longer and more varying path length in the source window as well as
| B(T) | Resolution increase at 485 keV (keV) exp. | Resolution increase at 976 keV (keV) sim. | Simulated effective solid angle |
|------|------------------------------------------|------------------------------------------|-------------------------------|
| 0.5  | -0.2(3)                                  | -0.3(3)                                  | 0.10(14) exp.                 |
| 0.5  | 0.10(14)                                 | 0.10(14)                                 | 0.10(14) sim.                 |
| 0.5  | 0.03π                                    | 0.06π                                    | 0.16π                         |
| 1    | 0.4(3)                                   | 0.4(3)                                   | 0.8(3) exp.                  |
| 1    | 0.90(14)                                 | 0.90(14)                                 | 0.90(14) sim.                 |
| 1    | 1.4(3)                                   | 1.4(3)                                   | 1.4(3) sim.                  |
| 1    | 1.40(14)                                 | 1.40(14)                                 | 1.40(14) sim.                 |
| 1    | 1.9(3)                                   | 1.9(3)                                   | 1.9(3) sim.                  |
| 1    | 1.73(14)                                 | 1.73(14)                                 | 1.73(14) sim.                 |
| 6    | 2.9(3)                                   | 2.9(3)                                   | 3.5(3) exp.                  |
| 6    | 1.91(14)                                 | 1.91(14)                                 | 1.91(14) sim.                 |
| 6    | 2.40(14)                                 | 2.40(14)                                 | 2.40(14) sim.                 |
| 11   | 2.2(3)                                   | 2.2(3)                                   | 3.6(3) exp.                  |
| 11   | 1.90(14)                                 | 1.90(14)                                 | 1.90(14) sim.                 |
| 11   | 2.40(14)                                 | 2.40(14)                                 | 2.40(14) sim.                 |
| 11   | 2.0π                                     | 2.0π                                     | 2.0π                          |
| 11   | 1.9π                                     | 1.9π                                     | 1.9π                          |

Table 1

Comparison between the experimental and simulated increase in energy resolution, relative to the value at 0 T, in the presence of different magnetic fields. The experimental error bars are extracted from the variation of the resolution at 0 T in time. The error bars on the simulated data are coming from the statistics of the simulation.

Table 1 lists the experimentally observed as well as the simulated change in energy resolution (FWHM), together with the simulated effective solid angle, for different magnetic fields and for electron energies of 500 keV and 1 MeV. As can be seen, both the field and the energy dependence of the FWHM is rather well reproduced by the simulations, but the exact change in energy resolution is underestimated by about 1 keV for the larger magnetic fields. Also the observed shift of the full energy peak to lower energies (see Figs. 3 and 4) is underestimated by the simulations. It is impossible to say whether this discrepancy is due to imperfections of GEANT4 when handling the altered scattering conditions due to the presence of large magnetic fields, or to an effect of the magnetic field on the signal processing that is not included in the simulations, as e.g. the charge collection process.

More detailed discussions on how well GEANT4 handles these altered scattering conditions can be found in references [17][18][19].

Finally, a remark has to be made here about the long term use of this Si PIN diode as a charged particle detector. It is well known that the performance of semiconductor detectors degrades when exposed to α-radiation, which causes lattice damage in the Si, and to cryogenic temperature cycles. We have performed the same magnetic field tests at ~10 K with a detector that had earlier been used for α particle detection. This detector performed similar as to energy resolution and scattered events in high magnetic fields, but in fields
higher than 1 T a series of satellite peaks often appeared in the spectrum. The appearance of these peaks did not seem to be correlated with any special event, while they could be made to disappear by inducing a small mechanical vibration to the system (e.g. by filling cryogenic liquids). In order to avoid these unwanted peaks that are thought to be related to lattice damage caused by the previously detected $\alpha$ particles we always use new detectors in our experiments.

5 Conclusions

The Si PIN diode tested here showed good behavior while operating at a temperature of $\sim 10$ K in magnetic fields up to 11 T. The response to electrons was found to change slightly, mainly due to the influence of the magnetic field on the trajectories of the $\beta$-particles. For mono-energetic electrons slightly (i.e. $\sim 30\%$) broadened full energy peaks were observed. The fact that this detector works well both at cryogenic temperatures and in high magnetic fields makes it ideally suited to be used as an energy sensitive detector for low energy electrons and positrons as well as for $\alpha$ particles in experimental setups where such conditions are encountered, e.g. (cryogenic) penning traps or low temperature nuclear orientation set-ups.

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