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# Silicon detectors for γ-ray and β-spectroscopy

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**Abstract**

Large active volume Si(Li) detectors were successfully developed for γ-ray spectrometry at room temperature that show a sufficient efficiency and an energy resolution that is better than scintillation detectors. The higher efficiency of the proposed detectors with respect to normal silicon diodes is achieved by increasing the active volume. For this purpose special attention is given to the selection of the initial material which has to show homogeneous electrophysical parameters, low concentration of oxygen impurities and high structural perfection. The technique of using lithium ions is used as these drift into large depths and hence the profile of the impurity distribution is optimized.


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## 1. Introduction

For many applications it is necessary to have portable γ- and β-spectrometers. The definition of type and concentration of β-active radionuclides in samples contaminated during the Chernobyl PS accident is a real problem for Ukraine; together with γ-emitters, they give the greatest contribution to the integral absorbed dose. Inexpensive and practical spectrometers would be extremely useful for fieldwork in Ukraine.

Two types of γ-spectrometer detectors are widely used in practical radiation measurements: NaI scintillators and Ge(Li) semiconductors (or pure Ge). NaI spectrometers have a low-energy resolution; Ge spectrometers have a higher-energy resolution, but they need liquid nitrogen cooling and this is expensive. Many practical tasks would benefit from a cheap spectrometer having good energy resolution without the cumbersome liquid nitrogen cooling.

Silicon detectors operating at room temperature are available for spectrometry of γ-radiation with

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efficiency and energy resolution better than scintillation detectors. The higher efficiency in γ-spectrometry is essentially due to the increased active volume of silicon detectors.

## 2. The influence of initial silicon parameters on mobility of lithium ions

The method of lithium ion drifting in an electric field was used for producing detectors with large active volume [1]. Special attention was given to the selection of an initial material with homogeneous electro-physical parameters and high structural perfection.

The concentration of oxygen in silicon samples was determined with an infrared spectrometer from the adsorption spectrum in the region of 9.1 μm. It was found that the drift mobility of lithium in silicon with a boron concentration of $10^{13}\,cm^{-3}$ and an oxygen concentration of $5\times10^{15}\,cm^{-3}$ is some times higher than in silicon with the same concentration of boron but with an oxygen concentration of $2.5\times10^{16}\,cm^{-3}$. The dislocation-free silicon crystals, due to various conditions of growth and gradients of temperature, may contain various types of microdefects. Three types of native point defects have been identified in silicon grown with the float zone (FZ) technique: A-defects, which are agglomerations of silicon interstitials, B-defects, to be the precursors to A-defects, and D-defects, which are assumed to be vacancy clusters [3,4]. Microdefects of A and B type are found in ingots produced at low and medium crystal growth rates; in these conditions there are excess of silicon interstitial atoms in the FZ, which form microdefects of interstitial type. The size of A-defects is 1–10 μm with concentrations of $10^4$–$10^6\,cm^{-3}$.

The D-defects, observed for high crystal growth rates (>5 mm/min), have been described and identified as vacancy-related structures [2]. They can contain vacancy–oxygen complexes. The size of the D-defects is 40–60 Å and the concentrations are in the range $10^8$–$10^{12}\,cm^{-3}$.

As vacancies have a negative charge, D-defects will be active centers for the capture of the positive lithium ions and will decrease the lithium ion mobility and the size of compensated volume. Therefore, D-defects behave as oxygen atoms, in the sense that they are the centers of lithium capture. D-defects mainly occupy the center of FZ crystals and because of this the size of the sensitive region is decreased.

It is consequently necessary to control the initial silicon material not only for what regards oxygen concentration but also for microdefect distribution.

## 3. Fabrication of Si(Li) detectors

Silicon wafers with a thickness of 5 mm and a diameter of 83 mm were cut from FZ dislocation-free p-type Si crystals. In our measurements the electrical resistivity of the wafers was approximately 4000 Ω cm, the minority carrier lifetime was greater than 500 μs and oxygen concentration was lower than $10^{16}\,cm^{-3}$. In order to form the $n^+-p$ junction, lithium metal was evaporated in a vacuum chamber onto the wafer heated to 450°C for 6 min. The drifting was conducted at 110°C with an applied electric field $>10^3$ V/cm to drive $Li^+$ ions from the $n^+$ lithium diffused region into the p-type bulk. As a result, the $Li^+$ concentration in the bulk will approximately equal to the acceptor concentration. Subsequent fine tuning of the uniformity of the $Li^+$ distribution was carried out (clean up) at 60°C with 400 V reverse bias for period of time less than 1 month.

After complete compensation, the wafer was carefully polished with a 10 μm $Al_2O_3$ abrasive and ashed with running distilled wafer. Then copper plating was applied to the $N^+$ surface of the wafer.

Samples were then washed and etched in the usual way and left at room temperature for 2 days. The samples were then mounted on a suitable holder, gold (~30 nm) was evaporated onto the intrinsic face and aluminum (~50 nm) onto the lithium diffused face. These surface-barrier Si(Li) detectors were then stored in a desiccator at room temperature with no bias applied.

## 4. Results and discussion

Surface-barrier Si(Li) detectors with depletion region widths from 3 mm up to 5 mm were

fabricated. The area of the detector sensitive layer was from 3 to 38 $cm^2$. The leakage current was less than 0.1 $\mu A\,cm^{-2}$ at 400 V reverse bias. The detectors have a specific capacity of about 2–3 $pF\,cm^{-2}$. In our experiment standard electronics with 10 μs shaping time constant and equivalent noise of 8 keV were used.

Fig. 1 shows the response of the detector No. 23–1 ($W = 5$ mm, $S = 3\,cm^2$) to $^{137}Cs$ conversion electrons, measured at 400 V reverse bias.

Fig. 2 shows the response of the same detector to the $^{70}Sr + {}^{70}Y$ conversion electrons.

Fig. 3 shows the response of the same detector to the $^{204}Tl$ conversion electrons.

Fig. 4 and 5 show the γ-spectra of $^{137}Cs$ and $^{60}Co$, measured with detector Nos. 1–3 ($W = 5$ mm, $S = 3\,cm^2$) at room temperature. Low-energy tails in γ-spectra are corresponding to Compton electron distribution.

A special program for γ-spectrum processing was developed allowing to identify separate radionuclides in complex spectra. It uses a secondary electron distribution (Compton and photo-effect electrons) to get the peak γ-spectra, Fig. 6, by analogy to Ge spectrometer and the continuous energy γ-spectra. To get the continuous energy γ-spectra we developed an unfolding technique based on a differentiation method which uses a specific matrix that takes into account the detector response function dependence on the γ-radiation energy.

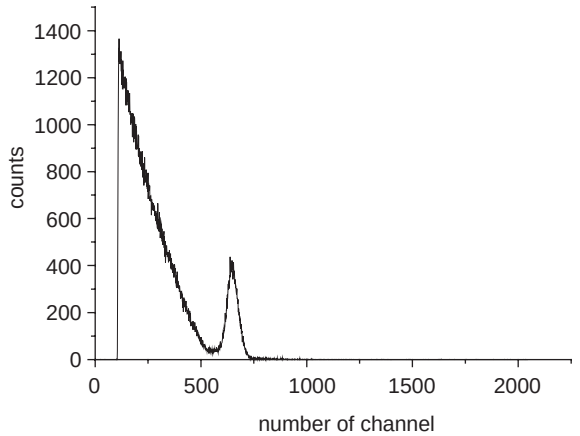


Fig. 1. $^{137}Cs$ conversion electron spectrum measured with detector No. 23-1 ($W = 5$ mm, $S = 3\,cm^2$) at a bias of 400 V.

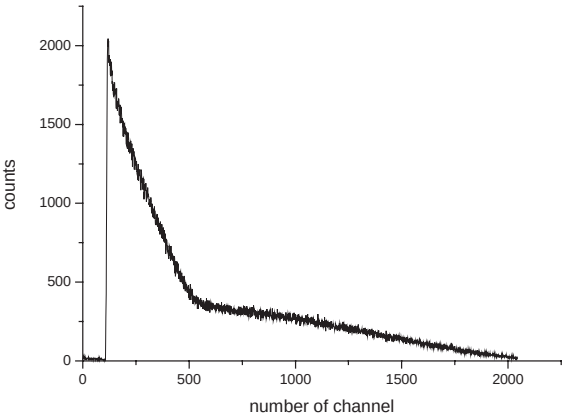


Fig. 2. $^{90}Sr + {}^{70}Y$ conversion electron spectrum measured with detector No. 23–1.

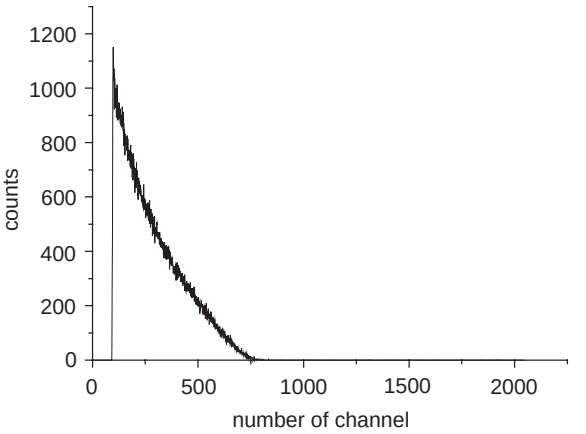


Fig. 3. $^{204}Tl$ conversion electron spectrum measured with detector No. 23–1.

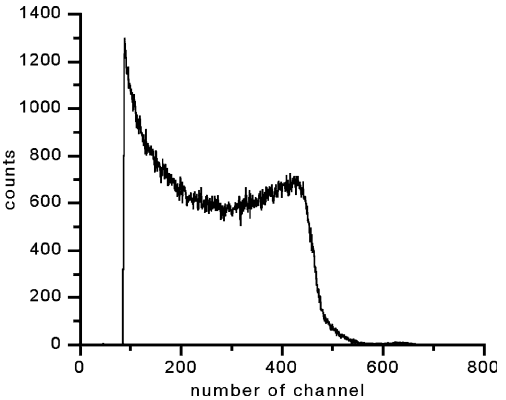


Fig. 4. $^{137}Cs$ γ-spectra measured with noncooling Si(Li)-detectors.

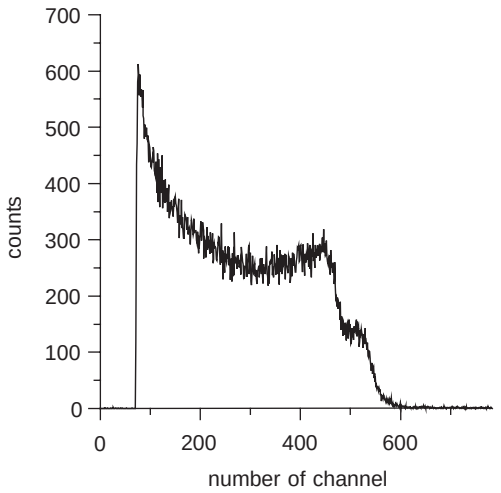


Fig. 5. $^{60}$Co γ-spectra measured with noncooling Si(Li)-detectors.

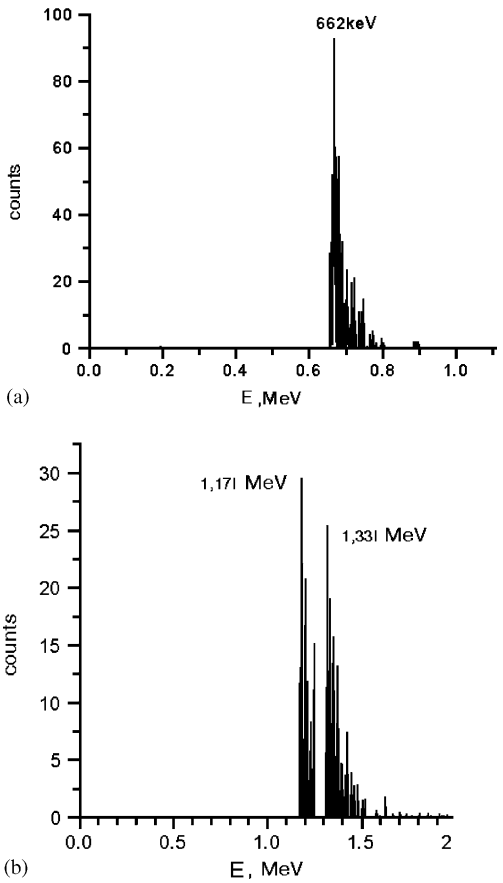


Fig. 6. (a) $^{137}$Cs γ-spectra and (b) $^{60}$Co after a special program processing.

The efficiency for γ-rays was stated at irradiation by $^{137}$Cs source ($E_\gamma = 662$ keV). As known, the efficiency has strong reverse dependence on the energy of γ-rays. The detectors have approximately a 3% detection efficiency for the γ-radiation and a sensitivity of 0.03 pulse/(s Bq). At room temperature, the energy resolution of the detectors is 25–30 keV.

The possibility of operation at normal room temperature with a rather good energy resolution, a low reverse voltage and small sizes allow one to state that these Si(Li) spectrometers look promising for use in many problems of γ- and β-radiation measurement.

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