Development of Double-Sided Microstructured Si(Li) Detectors

D. Protić, T. Krings, and R. Schleichert

***Abstract*—A new technique for manufacturing double-sided structured Si(Li) detectors has been established. The position-sensitive structure on the implanted p^+–contact can be made smaller than 100 μm by photolithography followed by plasma etching of grooves to separate the position elements. By modifying this technique position-sensitive structures on a thin (~30 μm) Li-diffused contact were created. Areas of 50 mm × 50 mm were divided into 50 or 100 strips with a pitch of 1 mm or 500 μm, respectively. The strips were separated by ~35-μm-deep and ~50-μm-wide grooves. Measurements of the electrical resistance of the grooves and reverse current of the strips are presented. Charge splitting on the adjacent strips shows practically no charge loss through the groove. Small pixel effects are demonstrated on a Li-diffused contact (100 strips with the pitch of 500 μm) and on the first double-sided Si(Li) detector (50 × 50 strips with a pitch of 1 mm). By measuring the relative time distribution of the signal from both contacts it is possible to obtain some three-dimensional imaging capability.**

***Index Terms*—Double-sided microstructured Si(Li) detectors, position-sensitive Si(Li) detectors, silicon radiation detectors, thin Li-diffused contacts, three-dimensional position sensing.**

I. Introduction

POSITION-SENSITIVE Si(Li) detectors of the digital type, mostly as an array of strip elements, have been well known for many years [1]–[5]. In nearly all cases, the position-sensitive structure is one-dimensional and created by strips of evaporated gold on Li-compensated silicon. This structure is sometimes realized on boron-implanted p^+-contacts by etching grooves between position-sensitive elements [2], [5].

A Si(Li) detector with strips on both contacts was reported as early as 1973 [1]. Thin window p^+–surface-barrier contacts were evaporated through a photochemically produced mask. The Li-diffused contact was about 0.2 mm thick and was subdivided by sawing grooves (orthogonal to the strips on the p^+-contact) with a width less than 0.3 mm and a depth of about 0.5 mm with a wire saw. Using appropriate electronics, 64 position elements of 2 mm × 5 mm could be defined [1].

During the last few years, several Si(Li) detectors about 5 mm thick with various strip patterns on the p^+-implanted contacts were successfully used in the ANKE experiments at the COoler SYnchrotron COSY Jülich [5]. However, for a correct reconstruction of particle paths and simultaneous energy measurement, especially for spectator protons in p,d-experiments, Si(Li) detectors with position elements smaller than 1 mm on both contacts would be very helpful. Additional motivation for the development of double-sided structured Si(Li) detectors arose from their possible application in medicine, for example, as a component of the Compton camera for the imaging of positron emitters [6], and in astrophysics, such as the Compton Telescope and Advanced Compton Telescope [7].

A relatively fine position-sensitive structure on the p^+-contact can be realized by various techniques in many laboratories. Structures with a pitch smaller than 2 mm or with a somewhat complicated pattern on the standard Li-diffused contact (100–500 μm thick) obviously cannot be prepared by sawing grooves. Our goal has been to develop the technique for producing proper Li-diffused contacts with a thickness of 10–30 μm and then modify our plasma-etching method to be able to produce grooves more than 30 μm deep and as narrow as possible.

Thin Li-diffused contacts on Si(Li) detectors have already been fabricated by a low temperature diffusion (453 K for 30 min) [8]. The contact thickness was determined with the help of alpha particles and amounted to 13 μm. Lithium diffusion inside the contact tends to increase its thickness during the storage of the detector at room temperature. After four years, the measured thickness amounted to about 30 μm [9]. A lower concentration of lithium ions inside the thin contact should significantly reduce this effect and perhaps decrease the probability of precipitation of electrically active lithium ions. Low-temperature diffusion of lithium combined with removal of a silicon layer with higher lithium concentration could enable the preparation of thin and stable Li-diffused contacts (n-contacts).

II. Detector Fabrication

A. *P^+-Contact*

Several 5 and 6 mm thick silicon slices of the p-type ($\rho = 4000\ \Omega$cm), with a diameter of 3 in (supplied by TOPSIL, Denmark), were lapped and chemically polished before ion implantation. Boron implantation was then performed at 20 kV with a dose of 10^{14} cm^{-2}. The implanted surface was covered with a ~300-nm-thick evaporated aluminum layer before annealing at 673 K.

B. *Lithium Diffusion and Drift*

Lithium diffusion was carried out in an inert gas atmosphere by decomposing $LiAlH_4$ [10]. A ~70-μm-thick diffused layer was produced after diffusion (performed for 30 min at 523 K). The chemically polished or lapped surface of this layer was also covered with a ~300-nm-thick evaporated aluminum layer. To achieve a good diode characteristic the rim of the slice had to be chemically etched.

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For the drift of the lithium ions, the diode was placed on a hot plate (373 K) and gradually biased up to 1000 V. About 30 days were needed to compensate the originally p-type region of a 5-mm-thick diode. The very high concentration of the boron ions in the p^+-contact prevents the drift of the lithium ions through it.

Not all diodes could sustain the relatively high bias voltage during the drift process without a considerable increase of the reverse current. For these diodes a new lithium diffusion had to be performed after removing the "poor" Li-diffused layer.

C. Thin Diffused Layer

The lithium distribution inside the diffused contact changes more or less with time, depending on the temperature and the gradient of the concentration. Decreasing concentrations of the lithium ions at the surface and a continuous increase of the layer thickness are the result. By successive removal of the surface layers and measurement of their sheet resistivities one can reconstruct the lithium concentration in the removed layers [10] and determine the number of the lithium ions per cm^2 in the rest of the contact. This number N_S [cm^{-2}] is given by

$$N_S = 4.63 \cdot 10^{15} \cdot \rho_S^{-1} \qquad (1)$$

with ρ_S expressed in $\Omega/\Box$.

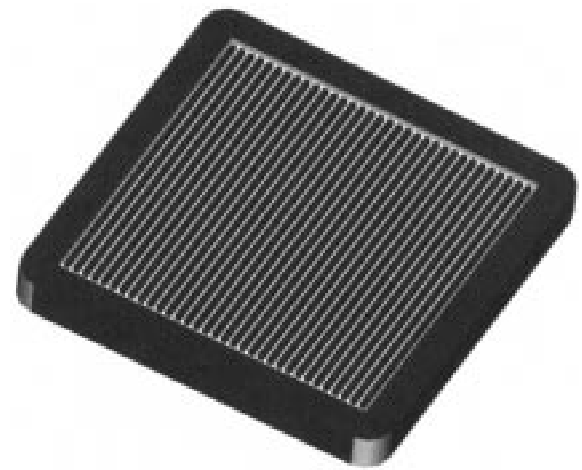
The lithium distributions were measured on several test pieces with the same diffusion parameters (30 min at 523 K), but with different thermal treatment after the diffusion. From these measurements we provisionally concluded that the sheet resistivity of a layer with about $5 \cdot 10^{14}$ lithium ions per cm^3 at the surface and a thickness of about 30 μm should be higher than 5000 $\Omega/\Box$. Further experiments are planned to find procedures which could enable even thinner n-contacts to be made by lithium diffusion.

After completion of the drift process sheet resistivities of the Li-diffused contacts were measured applying the four-point method. Each of the contacts was then thinned by lapping. The sheet resistivity and the thickness of a removed layer were successively measured. Depending on the thermal history of the diode the procedure was stopped after reaching the values of 5000–10 000 $\Omega/\Box$. The lapped surface was chemically polished before the evaporation of a 300-nm-thick aluminum layer. The diodes were then ready for producing position-sensitive structures on both contacts.

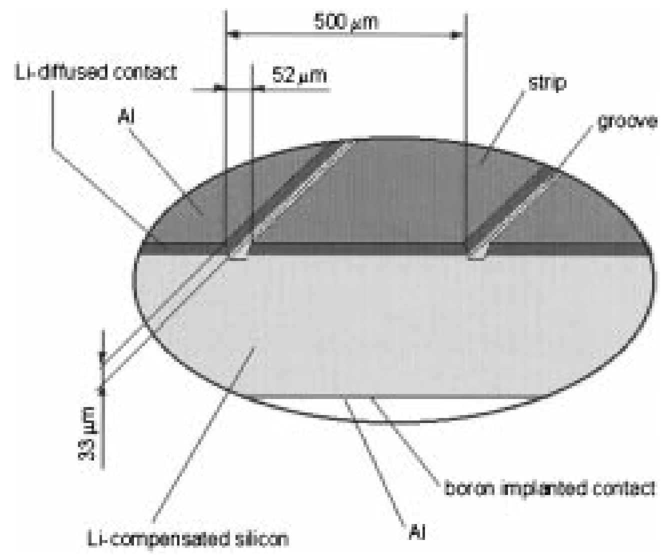
D. Position-Sensitive Structure on n-Contacts

The same well-established photolithographic process combined with plasma etching (SF_6 or 80% CF_4 + 20% O_2) of the grooves can be used to create a position-sensitive structure [3] on either contact. Because the n-contact is thicker ($\sim$30 μm) than the p^+-contact (5–10 μm), deeper grooves are required on the n-contact. For the assumed $\sim$30 μm thick n-contact the depth of the grooves must be more than this figure.

Two different photolithographic masks fabricated at ISG, Forschungszentrum Jülich, were used to define a 50 mm × 50 mm area containing 50 or 100 strips with a pitch of 1 mm or 500 μm, respectively. In both cases, the opaque strips were separated by 15-μm-wide transparent areas. The whole pattern was surrounded by a guard ring.



(a)



(b)

Fig. 1. Schematic view of (a) the Li-diffused contact divided into strips surrounded by the guard-ring and (b) strips with a pitch of 500 μm separated by 33 μm deep and 52 μm wide plasma-etched grooves.

All diodes were cut to form a 60 mm × 60 mm square with slightly rounded corners. The pattern of a mask was transferred to the n-contact by the photolithographic process. The strips, separated by about 17-μm-wide openings, were covered with the photoresist. To enable plasma etching of the grooves the aluminum layer in the openings had to be removed.

During plasma etching the depth of the grooves defined by the openings increases, but, unfortunately, so does their width. The schematic view of the n-contact showing strips with the 500-μm-pitch and the corresponding grooves is given in Fig. 1.

Up to now position sensitive structures have been realized on n-contacts of four diodes (a patent has been filed). Two of them have 50 strips with the 1-mm pitch, another two 100 strips with the 500-μm pitch. One of the 50 strip diodes also received the same structure (orthogonally oriented) on the implanted p^+-contact with about 5-μm deep grooves.

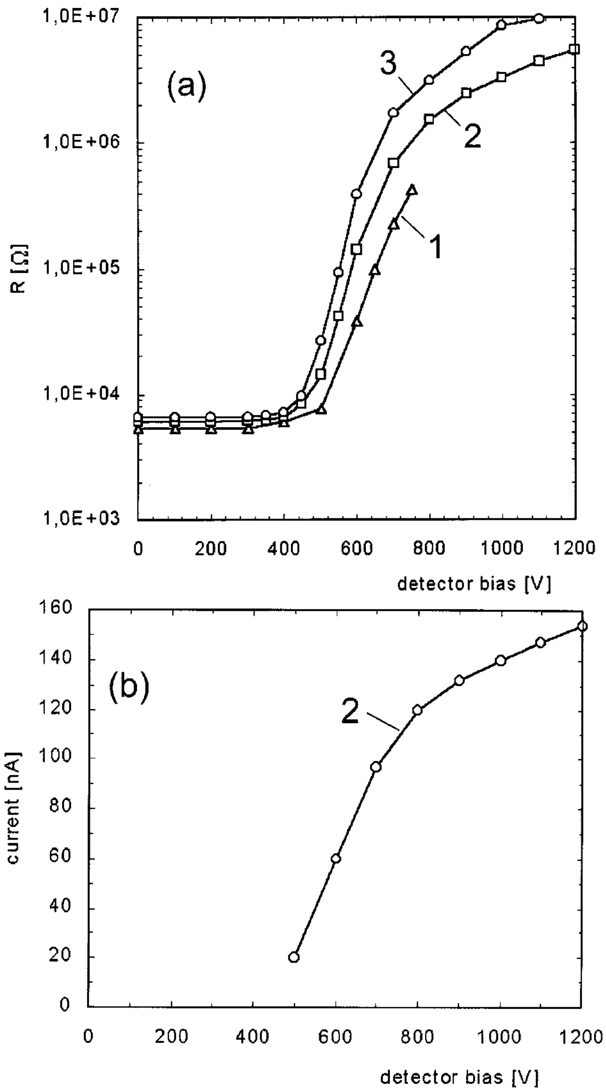


Fig. 2. (a) The resistance between an n-strip of the 100-strip structure and its neighbors: 1) six days after fabrication under a bias of 600 V; 2) after an additional ten days under 800 V; 3) after an additional four days under 800 V. (b) The reverse current of the same strip as a function of the detector bias.

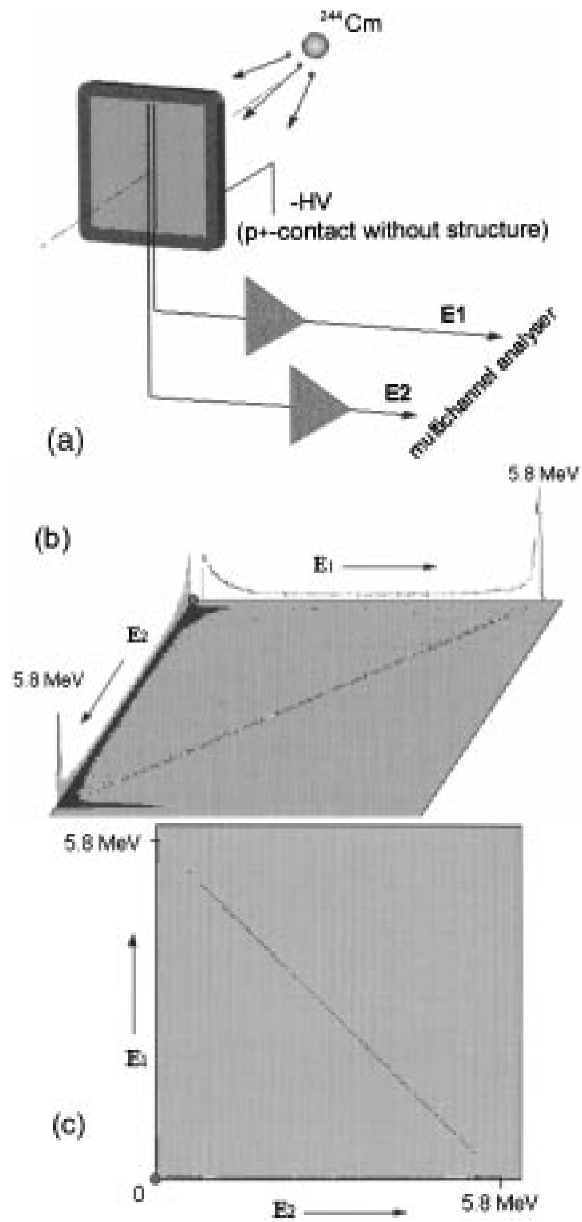


Fig. 3. Measurement of the charge splitting on two adjacent n-strips. (a) Schematic view of the measurement. (b) Two-parameter energy spectrum (three-dimensional presentation) showing single events detected with energies E_1 or E_2 and coincident events presented on the straight line between the two 5.8 MeV peaks. (c) The same spectrum, but in two-dimensional presentation (detector bias 1000 V).

E. Detector Mounting

All four diodes, 3.5–5.5 mm thick, were placed on metal frames with the help of indium wires. Several adjacent strips in the middle of the structure were connected to the printed boards by bonded aluminum wires. The rest of the strips were connected to the guard ring, also by bonding. No passivation was applied to the open surfaces of the Li-compensated silicon or grooves.

III. Measurements

A. Electrical Characteristics

The four fabricated detectors could be operated up to a bias of 1200 V. Different total reverse currents ranging from 20–50 μA were measured at this bias depending on the environment (air or vacuum). The reverse currents through the strips amounted to 80–120 nA at 1000 V. A very important aspect concerning the use of the strips as detector elements is their electrical resistance to their neighbors. As an example, this resistance is presented for an n-strip of the 100-strip structure in Fig. 2(a). Additional "clean-up" drift at room temperature increases this resistance due to lithium ions leaving the contact. From this picture, one could conclude that the Li-diffused n-contact extends deeper than the grooves. But applying biases of more than 400 V the resulting electrical field penetrates deeper and deeper into the n-contact causing higher resistances between the strip and the surrounding elements. Another conclusion could be that the Li-compensated region (very slightly n-type) is completely depleted at 400 V. For the 4.7-mm-thick detector one can then calculate the donor concentration of $2.4\cdot10^{10}$ cm^{-3}. This means that a maximum concentration of $2.4\cdot10^{10}$ cm^{-3} donors is present in the compensated region compared to $3.5\cdot10^{12}$ cm^{-3}

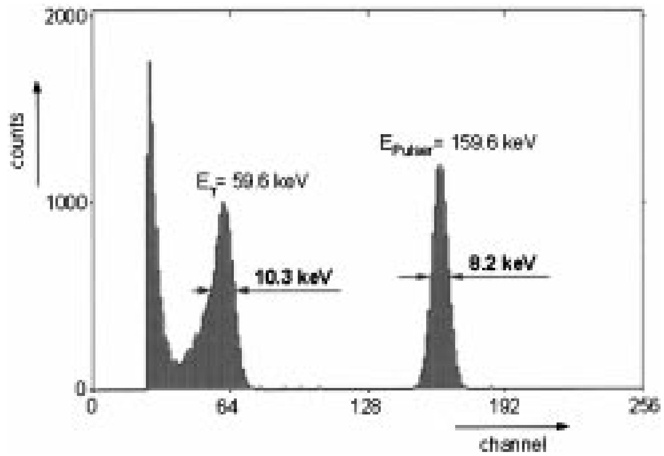


Fig. 4. Energy spectrum of ^{241}Am taken at room temperature with a strip of the 50-μm pitch structure on the n-contact (detector bias 1000 V).

acceptors in the starting material. Additional information can be obtained from the capacitance versus voltage measurements.

In Fig. 2(b) the reverse current of the same strip is shown as a function of the detector bias.

B. Charge Splitting Between Two Adjacent n-Strips

Two adjacent n-strips of the detector with 100 strips (500 μm pitch) were connected to amplifier chains to measure the energy of 5.805 MeV alpha particles (^{244}Cm) irradiating the p$^+$-contact (without structure). The output signals E_1 and E_2, shaped with a time constant of 2 μs were fed to a dual-parameter analyzing system [Fig. 3(a)]. Incident α-particles produced electron–hole pairs just below the p$^+$-contact. The electrons were moved over a distance of 4.7 mm toward the n-contact. During this time the electron cloud also expands laterally due to diffusion. Only part of these clouds completely reaches a strip. The other part shares its charge between neighboring strips. The spectra shown in Fig. 3(b) and (c) indicate that practically no charge losses were caused by the existence of the groove between the adjacent strips. Especially from Fig. 3(c) , in which the straight line connects two 5.8-MeV α-peaks, one can conclude that the possible charge losses must be below 1%. All points on this straight line represent events coincidently detected in the adjacent strips with the summed energy amounting to 5.8 MeV.

C. γ-Ray Spectra

γ-ray spectra of ^{241}Am were measured at room temperature with the strips of the n-contact using three of the fabricated detectors. Energy resolutions ranging from 10 to 14 keV were achieved for the 59.6 keV γ-line and 8–12 keV for the pulser line. One of the better spectra, taken while the 500 μm pitch structure was irradiated, is shown in Fig. 4.

D. Small Pixel Effect

The output signals of a charge-sensitive preamplifier connected to a strip of the position-sensitive detector increase significantly only when electrons or holes come into the vicinity of the strip. Such a response is commonly referred to as the “small pixel” effect [11]. This effect was demonstrated on the 4.7-mm-thick detector with 100 strips on the n-contact (500 μm pitch)

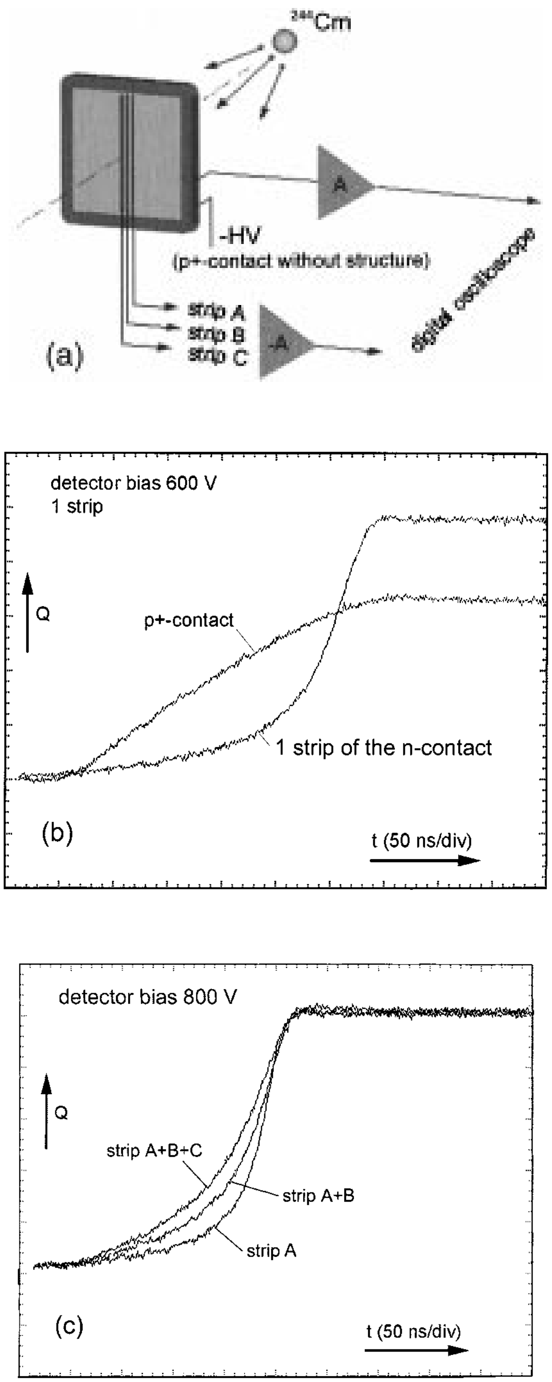


Fig. 5. (a) Schematic view of the setup for demonstrating the small pixel effect. (b) Coincident output signals of the charge-sensitive preamplifiers induced by an α-particle incident on a p$^+$-contact against the strip. (c) Output signals coming from one strip and two or three strips connected together, corresponding to pitches of 0.5, 1, and 1.5 mm, respectively.

and the p$^+$-contact without structure [Fig. 5(a)]. One, two, or three neighboring strips were connected to one charge-sensitive preamplifier and the p$^+$-side to another. Electron–hole pairs were created by α-particles (^{244}Cm) irradiating the p$^+$-contact. The holes reached the p$^+$-contact very soon and electrons had to move toward the n-contact. The outputs of the preamplifiers were monitored with a digital oscilloscope so that the signal from the p$^+$-contact served as the trigger. Fig. 5(b) clearly shows the difference in the shape of the coincident signals coming from

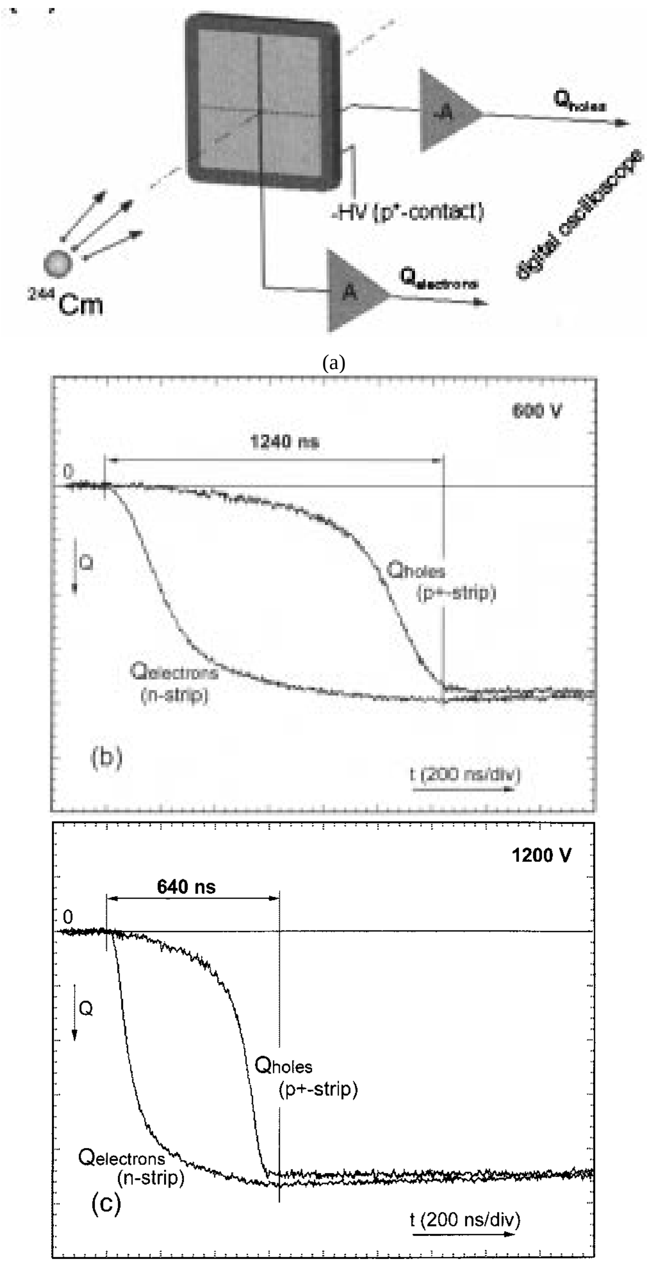


Fig. 6. (a) Schematic view of the setup for demonstrating the small pixel effect on the 50 × 50 strip detector, 5.5 mm thick; one strip of each side connected to a charge-sensitive preamplifier; coincident output signals of the charge-sensitive preamplifiers for a detector bias of (b) 600 V and (c) 1200 V.

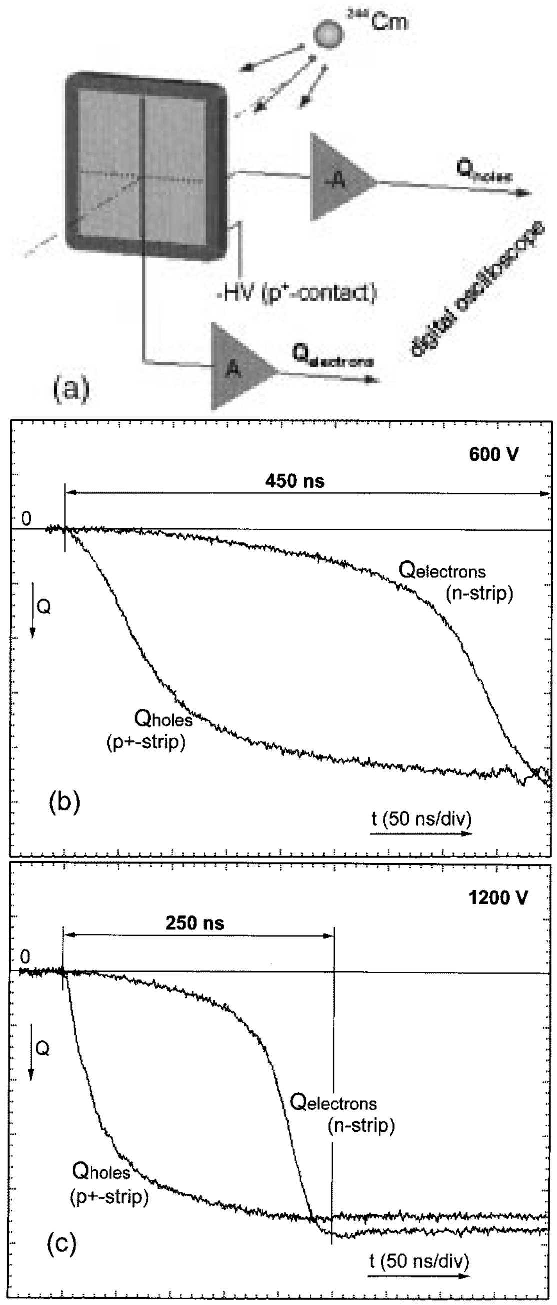


Fig. 7. (a) Schematic view of the same setup as in Fig. 6(a), but with α-particles impinging on the p^+-contact; coincident output signals of the charge-sensitive preamplifiers for a detector bias of (b) 600 V and (c) 1200 V.

the nonstructured p^+-contact and a strip of the n-contact. Furthermore, as shown in Fig. 5(c), different shapes result for one, two or three strips connected to the preamplifier, corresponding to pitches of 0.5, 1.0, and 1.5 mm, respectively. For this measurement the detector bias was increased to 800 V.

An even better understanding of the "small pixel" effect can be obtained by similar measurements but using the double-sided structured Si(Li) detector. Either the p^+- or n-contact of the 50 × 50 strip detector with a pitch of 1.0 mm was irradiated with α-particles of ^{244}Cm. One n-strip and one p^+-strip were connected to charge-sensitive preamplifiers.

The schematic view of the measurement set-up, for α-particles impinging on the n-contact, is shown in Fig. 6(a). The estimated effective thickness of this n-contact ranged from $\sim$5 μm at a detector bias of 600 V to less than 1 μm at 1200 V so that the energy losses in the dead layer were surprisingly small. Coincident signals induced by an α-particle incident on the area defined by the crossing of the two strips are shown for detector biases of 600 and 1200 V in Fig. 6(b) and (c), respectively. Relatively long collection times were measured because the signals on the strips were induced to a great extent by holes moving from the n- toward the p^+-contact.

The results of the measurements with the same setup, but with α-particles impinging on the p^+-contact, schematically shown in Fig. 7(a), are presented for the two bias voltages in Fig. 7(b) and (c). Due to the higher velocity of electrons, which, in this case, mainly contributes to the collected charge on the n-strip, the collection time is significantly shorter than that shown in Fig. 6. For the detector bias of 600 V the ratio of the collection times t_e/t_h amounts to 2.76. This ratio is more or less equal to that of the mobilities ($\mu_e/\mu_h = 2.81$). At higher electric fields the electron and hole velocities tend to the same value of 10^7 cm/s. This is the reason for the lower value of the collection time ratio of 2.56 at 1200 V.

IV. Conclusion

The experimental results achieved during the development of the position-sensitive structures on the Li-diffused contact clearly show the possibility for fabricating double-sided microstructured Si(Li) detectors. There are also certain indications that the effective thickness of the Li-diffused contacts could be minimized. This means that also thick transmission Si(Li) detectors, with or without position-sensitive structures, could probably be realized.

But the most exciting result of the measurements seems to be the capability to find the depth of photon or to some extent charge particle interaction inside the compensated region of the two-dimensional Si(Li) detectors by exploiting the "small pixel" effect. The difference of the collection times for n- and p^+-strips can be used to determine the depth of an interaction, as proven for a Ge-strip detector [11].

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