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J.T. Walton

November 1983

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SILICON DETECTORS: NEW CHALLENGES

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SILICON DETECTORS: NEW CHALLENGES

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Abstract

An introduction is given to the areas of current interest in silicon radiation detector design and fabrication. Problems associated with detector grade silicon are reviewed. Passivation of detector surfaces with silicon dioxide or amorphous silicon is described. Two examples of silicon detector applications in x-ray detection and x-ray angiography are presented.

1. Introduction

In the thirteen years since the First European Symposium on Semiconductor Detectors, there has been an incredible increase in the number of semiconductor radiation detector applications. This increase is founded on materials improvements, detector fabrication technology and pulse electronics. High resistivity silicon crystals with diameters approaching 100 mm have become available permitting the fabrication of very large area ($\sim 50 \text{ cm}^2$) detectors, while the development of high-purity germanium has dramatically altered the range of possible applications for germanium detectors.

Concurrent with the material and detector developments have been the innovations and improvements in pulse electronics. X-ray systems with spectral resolutions of the order of better than 100 eV are commercially available and find applications not only in laboratories but also in industrial settings.

While the emphasis in the past decade or so has been on increased semiconductor detector size and improved spectral resolution, there has recently been

a growing interest in detectors with improved spatial resolution. The dedication of this conference, the Third European Symposium on Semiconductor Detectors, to new developments in silicon radiation detectors and in particular, detectors with spatial resolution underscores this shift in interest.

The desire for improved spatial resolution was first formally articulated at the Brookhaven Workshop in 1979 where Sandweiss¹ and his associates detailed a proposal to build a high-energy particle track detector (vertex detector) employing silicon detectors with spatial resolutions of the order of 50 μm or less. Heijne² subsequently demonstrated that high-energy particle tracks could be successfully reconstructed employing, initially, surface barrier strip detectors and then later the excellent ion implanted oxide passivated strip detectors developed by Kemmer³.

With the development of the strip detectors having 50 μm or less strip widths came the challenge of reading the signals from these strips. Proposals for the efficient readout from strip detectors range from discrete amplifiers to entirely novel device structures, one of which has been proposed by Gatti and Rehak⁴. This symposium should provide the synergism for indicating specific avenues to be pursued in this area.

While the principal focus of this symposium is on silicon micro strip detectors--their fabrication, readout and application, we will discuss in this paper results of other work being done on silicon detectors which we believe is important and which will illustrate other challenging areas in silicon detector fabrication. Consequently, we will leave the description of the micro-strip-related activities to the other invited papers.

2. Silicon radiation detectors

Before going into any details of the broad field of semiconductor radiation detectors, it will be useful to briefly summarize the basic features of a semiconductor detector. Figure 1 shows a schematic cross section of a planar $n^+ i p^+$ diode. The incident radiation, gamma rays, x-rays or charged particles produce electrons and holes which are swept by the applied electric field to the n^+ or p^+ contacts respectively. To perform as a high-quality radiation detector, the sensitive region must be free of charge trapping centers. The contacts need to be thin enough to allow the passage of the incident radiation and at the same time remain non-injecting for reverse bias field strengths of 10^2 to 10^4 V cm⁻¹. Finally, the surfaces need to be passivated against changes in the ambients which may produce extensive surface leakage currents.

Single crystal silicon employed in detector fabrication is high-resistivity N or P type (500 - 100,000 ohm-cm) or lithium-compensated P type. In the latter, lithium ions are drifted into P-type silicon to produce compensated material with a net impurity concentration of $2 - 3 \times 10^9$ cm⁻³ (~ 100 K ohm-cm).

As shown in the figure, there are two contacts on the detector. Common practice is to refer to the one with higher electric field as the "rectifying contact" while the other is called the "blocking contact". With a $n^+ \pi p^+$ structure (π refers to high-resistivity p silicon), the n^+ is the rectifying contact and the p^+ is blocking. With high resistivity n material, the roles of contacts are reversed. In the limit of absolutely pure or perfectly compensated silicon, this distinction between the contacts disappears because the electric field strength is equal on both contacts.

Surface passivation or protection of silicon detectors has been accomplished through the use of silicon dioxide, organic coatings or semiconductor films.

Silicon dioxide is commonly used to passivate integrated circuits and is also used in detector fabrication. However, the high temperature processing typically employed to grow silicon dioxide precludes its use with silicon lithium-compensated [Si(Li)] detectors due to rapid redistribution of the lithium at high temperatures. Consequently, organic coatings and, more recently, semiconductor films have been employed to passivate the surfaces of Si(Li) detectors. A special class of organic coatings are epoxy resins which have been used for many years in the assembly of surface barrier detectors. The details of the various fabrication techniques employed with silicon detectors were reviewed recently⁵ and need not be considered in detail here. However, some specific comments on the availability of detector grade silicon and detector passivation will be made in the following sections.

3. Semiconductor detector silicon

It is encouraging that the symposium organizers have arranged for a representative of a major silicon supplier to address this meeting. The supply of high-quality silicon for detector fabrication has at best been tenuous over the years and improvements in the situation would be most welcome. Unlike germanium which has benefitted from a close collaboration between the crystal grower and detector fabricator, detector grade silicon has been available for detector fabrication as a byproduct. Most of the high-resistivity silicon is neutron transmutation doped for use in high power devices. The differences in the availability of these two elemental semiconductors is due in part to the strong interest over the past twenty years by nuclear chemists and physicists in gamma ray spectroscopy which has been revolutionized by the use of lithium-compensated and, subsequently, high-purity germanium detectors. A second aspect in the availability of silicon and germanium crystals for detectors is

the fact that germanium technology is both cheaper and easier because of its substantially lower melting point ($T_{Ge} = 936^{\circ}C$, $T_{Si} = 1412^{\circ}C$). Detector grade silicon has not experienced the in depth spectroscopic interest enjoyed by germanium. Silicon used for detector fabrication has been obtained from commercial suppliers whose interest in detector grade silicon is, for the most part, peripheral, with the result that the understanding of the silicon crystal growth parameters affecting detector performance is fragmentary.

Illustrative of the problems which can occur between the silicon crystal supplier and detector fabricator is the experience we had when our supplier changed their crystal growing conditions and we suddenly found that the silicon could no longer be lithium ion compensated by our techniques. A subsequent study⁶ suggested that micro defects (pre B swirls) produced by the modified crystal growth conditions might have been responsible for the low lithium ion mobility which we observed. The new growing conditions improved the silicon for its use in the electronics industry, but made the material practically useless for detector fabrication.

While we have had our difficulties with commercial silicon suppliers, we have also obtained some very remarkable material. For example, shown in Fig. 2 is the capacitance-voltage (C-V) characteristic for a small x-ray detector we recently made with high-purity N-type silicon. From the C-V data, we can estimate the net impurity concentration, $|N_D - N_A|$, as:

$$|N_D - N_A| = \frac{2\epsilon V}{qw^2} = 3 \times 10^9 \text{ cm}^{-3} \quad (1)$$

where V is the voltage at which total depletion occurs (~ 300 V) $q = 1.6 \times 10^{-19}$ C, $\epsilon = 8.85 \times 10^{-14}$ F cm^{-1} and w is the detector thickness (0.33 cm).

This crystal is intrinsic at room temperature since $|N_A - N_D| < n_i(T) = 1.45 \times 10^{10} \text{ cm}^{-3}$ ($T = 20^{\circ}C$) where n_i is the intrinsic carrier concentration.

The ^{55}Fe spectrum shown in Fig. 3 for this high-purity detector is comparable to that which we obtain with similar sized Si(Li) detectors. However, the performance on higher energy x-rays indicates the presence of charge trapping centers in this crystal. We found an effective Fano factor of 0.17 instead of 0.11 which we commonly obtain with Si(Li) detectors⁵. Nevertheless, the impurity level of 3×10^9 is impressive and we are presently investigating whether we can improve the crystal performance through passivating the deep traps with atomic hydrogen.

The presence of trapping centers in the high-purity crystal and of micro-defects in the crystal employed in Si(Li) detector fabrication clearly serve to illustrate that the measurement of resistivity and minority carrier lifetime are insufficient for characterizing silicon for detector fabrication. Photo-thermal Ionization Spectroscopy and Deep Level Transient Spectroscopy are employed in the evaluation of high-purity germanium⁷ and to obtain a better understanding of the problems in detector grade silicon techniques such as these should be more commonly employed. Darken⁸ in a recent review on the characterization of semiconductors strongly emphasized the absence of defect characterization in silicon intended for radiation detection. Therefore, a challenge on the path to more complex silicon detectors would appear to be better characterization of silicon crystals for detector applications.

4. Silicon detector technologies

4.1. Contacts

While silicon detector fabrication has survived or prospered employing what might be called nonstandard crystals for the semiconductor industry, the processes used in making these detectors have benefitted greatly from the technological advances made by the electronics industry. For example, the

early semiconductor radiation detectors used metal Schottky barrier contacts. The development of the first diffusion processes and subsequently ion implantation techniques by the semiconductor industry have been exploited in detector fabrication to make contacts much more rugged than the metal contacts. Furthermore, it is to be expected that ion implantation will be employed to an even greater extent in the fabrication of the more complex devices proposed, since the impurity concentration and location can be easily controlled.

4.2. Surface passivation

4.2.1. Silicon dioxide - Industry's interest in the silicon/silicon dioxide interface has resulted in this system being the most thoroughly studied and perhaps understood solid phase system. A model for this system is shown in Fig. 4⁹. While a detailed review of this model is beyond the scope of this paper, the major features can be highlighted. There are four types of charge: mobile ionic charge, oxide trapped charge, fixed oxide charge and interface trapped charge. Of these, the fixed oxide charge and the interface trapped charge are of most interest in detector fabrication assuming that the processing is sufficiently well controlled that the concentrations of mobile ions and oxide trapped charge are insignificant. The fixed oxide charge is positive and is assumed to be produced by structural defects in the oxide layer adjacent to the silicon/silicon dioxide interface. The interface trapped charge can be either positive or negative and, unlike the fixed oxide charge, it can flow to or from the underlying silicon. Consequently, the amount of interface charge can be changed. Furthermore, this charge center can be neutralized by low temperature annealing in a 10% hydrogen atmosphere. After neutralization, we find that the positive fixed charges are the dominant species in high quality silicon dioxide. These positive charge centers play

an important role in device performance since they will attract electrons to the interface. In the case of high-purity silicon, the density of electrons can be large enough to invert the surface region of the p-type silicon under the silicon dioxide. The consequence of this is shown in the cross sections of a p^+n and a n^+p diodes shown in Fig. 5. With the p^+n diode, the n surface should have little influence on the device leakage current at low reverse bias voltages. However, with the n^+p diode, the inverted n surface can act as an extension of the n^+ contact thereby increasing the diode leakage current. Consequently, from this simple model it would be expected that silicon n^+p diodes will have higher leakage currents than p^+n . This model has been demonstrated experimentally¹⁰.

Methods for measuring the charge center densities at the Si/SiO_2 interface are well developed. These measurements typically involve the use of a metal oxide semiconductor (MOS) structure with high (10 kHz) and low (quasi-static) frequency capacitance measurements¹¹. Representative results for these measurements are given in Fig. 6 along with typical values of the parameters. The MOS measurement technique is readily performed and provides a convenient monitor on silicon dioxide passivated device processing. A concern with this technique in the past has been its application to high resistivity silicon since the device resistance, with certain capacitance meters, can obscure the capacitance measurement. With recently available impedance bridges, capacitance measurements can be performed in the presence of high series resistance. The results given in Fig. 6 were obtained with 2 $k\Omega cm$ n -type silicon and similar values have been obtained with 8 $k\Omega cm$ p -type silicon. We have successfully used this technique to monitor improvements in our oxide growth conditions and also in subsequent device processing.

4.2.2. Amorphous semiconductor films - For a variety of reasons, passivation coatings other than SiO_2 have been employed over the years both in the semiconductor industry and in radiation detector fabrication. Recently amorphous semiconductor films have been introduced to passivate the surfaces on high-purity germanium¹² and $\text{Si}(\text{Li})$ ¹³ detectors. These films are interesting in that it is possible to tailor the film properties with the introduction of suitable gases during deposition to produce a neutral surface on high-purity germanium as opposed to the n-type surface produced by SiO_2 on silicon.

In Figs. 7 and 8 the results are shown of scans down the sides of n-type and p-type high-purity germanium detectors with a collimated gamma source. If there is a net surface charge present on the detector, the field lines near the surface will not reach from the n^+ to the p^+ contact and consequently over regions near either the n^+ or p^+ contact, the signal charge will not be collected within the measurement time. However, if the net charge is zero, the Fermi level will be flat at the surface (flat band condition), the surface can be considered neutral and the field lines near the surface will reach from the n^+ to the p^+ contact. As seen in Fig. 7, the 17.5% hydrogenated amorphous germanium (a-Ge:H) coating provides a neutral surface on the n-type germanium detector, while in Fig. 8, both the 7% and 17.5% a-Ge:H films are equally effective in producing a neutral surface on the p-type device.

The reverse leakage currents on the same high-purity germanium detector with and without a-Ge:H coatings are shown in Fig. 9. The activation energy, E_A , for the leakage currents, I_L , given in the figure were derived assuming that:

$$I_L \propto e^{-\frac{E_A}{kT}} \quad (2)$$

For an intrinsic semiconductor diode at low temperatures:

$$I_L \propto e^{-\frac{E_g}{2kT}} \quad (3)$$

where E_g is the semiconductor bandgap energy¹⁴. Therefore it would be expected that $E_A \approx E_g/2$, which is in fact observed for the bare detector ($E_g \approx 0.73$ eV for Ge).

The activation energy measured for the a-Ge:H coated device was found to be independent of the hydrogen concentration (0.5, 7.0 and 17.5%) present in the argon atmosphere during the sputtering of the a-Ge:H coating. The lower activation energy of the leakage current for the device coated with a-Ge:H could be explained by: 1) the a-Ge:H coating shunting the detector junction, 2) a lower bandgap energy for a-Ge:H than for Ge, or 3) the presence of a high density of neutral states at the Ge/a-Ge:H interface. Since the detector leakage current showed little sensitivity to variations in voltage, the shunting of the junction is unlikely. Second, a-Ge:H has a higher bandgap than Ge¹⁵. Consequently, the density of states must be the contributing factor to the leakage current.

Application of hydrogenated amorphous silicon (a-Si:H) to Si(Li) detectors suggests that the situation may be somewhat more complex with silicon than germanium. Leakage current measurements on devices coated with different hydrogen concentrations present during the film deposition are shown in Fig. 10 where it can be seen that unlike germanium, the activation energies of the leakage currents are dependent on the hydrogen concentration. However, the leakage current for the bare Si(Li) detector, like germanium, has $E_A \approx E_g/2$ ($E_g \approx 1.1$ eV for Si). Again, for the same reasons as with germanium, the observed activation energy of the leakage current is related to the density of states at the Si/a-Si:H interface. The increase in the activation energy for

the Si(Li) detectors is consistent with the reported decrease in the density of states with increasing hydrogen concentration in a-Si:H¹⁶. While we do not fully understand the results on silicon, we have employed these films on a number of Si(Li) x-ray detectors. These results are reported in the next section.

In summary, the leakage currents achieved by Kemmer³ with oxide passivated detectors are outstanding and unchallenged, demonstrating that high quality oxidation can produce almost defect-free diodes. The use of materials other than silicon dioxide in the fabrication of high voltage silicon rectifiers, etc., would suggest that surface passivants other than silicon dioxide might also be successfully employed in silicon detector fabrication. Chemical vapor deposition of polysilicon films, for example, has long been used on high voltage devices to overcome the problems of the positive oxide fixed charge and interface trapped charge, characteristic of thermally-grown silicon dioxide¹⁷. High voltage integrated circuits, which share the problem with radiation detectors of fabrication on high resistivity silicon are becoming of increased commercial importance. Consequently, improvements are to be expected in passivation techniques and the challenge will be to successfully incorporate these improvements into the planned more complex radiation detectors.

5. Applications

5.1. Six-detector x-ray spectrometer

Applications involving semiconductor detectors are employing increasingly complex detectors and detector systems. An example of the increased complexity is the x-ray spectrometer with six Si(Li) detectors which we are currently assembling at LBL¹⁴.

Interest in improving the monitoring capabilities for trace radioactive nuclides in the environment has prompted our development of these specialized x-ray spectrometers (shown schematically in Fig. 11) which are characterized by having a close sample-detector geometry and Si(Li) detectors with thin entrance contacts on both sides. The six-detector spectrometer is designed to use Si(Li) detectors 9 cm^2 in area, 7 mm thick, and a lithium contact thickness of $\sim 20 \text{ }\mu\text{m}$ versus 100 - 150 μm for standard Si(Li) detectors. Mounted in a liquid-nitrogen-cooled cryostat, these detectors which are surface passivated with 7% a-Si:H gave the system noise performance shown in Fig. 12. Also shown in this figure is the expected noise contribution due to a detector leakage current of 1 pA. However, the measured leakage currents of those detectors with 800 V bias were typically $\sim 0.1 \text{ pA}$ and consequently, the noise due to the detector leakage current is negligible in these measurements. There are, however, differences in the detector noise performance at the longer amplifier time constants which may be due to the a-Si:H coating or other factors. At long measurement times, the system becomes very susceptible to extraneous noise sources such as mechanical vibrations and $1/f$ noise. While considerable care was taken to exclude such sources from our system, we are not certain whether the variations in noise performance of the various detectors are due to the surface coating or to external factors.

Spectra of N_p L x-rays from ^{241}Am incident on the lithium and gold barrier contacts of one of these detectors are shown in Figs. 13a and b, respectively. A careful comparison of the two spectra show that the peak-to-valley ratio of the L x-rays is only slightly smaller for photon incidence on the lithium contact than on the gold contact (6.5 versus 7.6). The stability of these a-Si-H coated detectors to date has been excellent and the use of a-Si:H has greatly facilitated the assembly of the six-detector spectrometer.

5.2. Strip detectors--multielement detectors

While we have not discussed micro strip detectors, we have been active in this area by fabricating devices and assisting others with their designs. The detectors to be reported on by Bosisio¹⁵ and Rehak¹⁶ at this symposium were fabricated at LBL. Furthermore, we are working with Parker¹⁷ to interface micro strip to an integrated circuit readout multiplexer.

In addition to micro strip detectors, we have fabricated multielement detectors with strip widths (~ 1 mm) as shown in Fig. 14. These Si(Li) detectors have been used in studies at SLAC with the synchrotron x-ray source aimed at reducing the risk in producing heart angiograms¹⁸. The individual detector elements are coupled to current sensing amplifiers to measure the changes in the x-ray intensity. More recently, this detector design has been used in experiments on computed tomography (CT) scans¹⁹. The experimental arrangement is shown in Fig. 15 where the sample, an excised pig heart into which iodinated vaseline has been placed into the cardiac chambers and arterial tree, is incrementally rotated in the x-ray beam. The x-ray beam energy is switched above and below the K absorption edge of iodine at each position with the variations in the x-ray intensity being detected by the detector. From those incremental views the composition of the heart can be reconstructed by first taking the difference between the two absorption measurements and then employing various algorithms and a high speed computer to produce the cross sectional views of the heart shown in Fig. 16. The arteries are approximately 1 - 2 mm in diameter and the ventricle is approximately 3 x 4 cm.

The multielement detectors used in these experiments and in performing the earlier angiography experiments were approximately 1.5 x 4 cm and had 60 strips. We are currently fabricating Si(Li) detectors that are 15 cm long and have 300 strips. When used with the new x-ray beam line planned at SLAC,

these latter devices will permit scanning of the heart to be accomplished in one pass taking 1 - 2 seconds, thereby reducing the radiation exposure to ~ 1/100 now required to produce a heart angiogram.

6. Discussion

Pointing out new challenges and directions in an area which changes as rapidly as silicon device technology is difficult. However, some of the problems facing silicon detector fabrication have been present for a long time and have yet to find a satisfactory solution. Two of these have been mentioned in this paper--silicon detector grade material and silicon detector passivation.

In fabricating the new generation of silicon detectors, additional challenges are evident in incorporating detector and integrated circuit technologies, and insights into the melding of these will be presented at this symposium by Hosticka²³ and Zimmer²⁴. It would appear, however, that the fabrication of these new devices will employ techniques not traditionally associated with silicon detector fabrication. The required merging of detector, integrated circuits and materials is beyond the prevalent arrangements where relatively small individual groups excel at one particular detector fabrication technique. This will have to change if the new silicon detector designs are to be realized. Hopefully, this symposium will provide the impetus for making these changes to meet the challenges ahead.

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Figure Captions

- Fig. 1. Cross section of an idealized semiconductor radiation detector.
- Fig. 2. Capacitance-voltage characteristic of a high-purity silicon detector.
- Fig. 3. ^{55}Fe spectrum obtained with the detector of Fig. 2 with 1000 V bias and 17 μsec amplifier peaking time.
- Fig. 4. Model for the charge centers⁹ present in SiO_2 .
- Fig. 5. Cross sections of p^+n (A) and n^+p (B) structures indicating the presence of electrons attracted to the Si/SiO_2 interface causing this region to be in accumulation or inversion.
- Fig. 6. (A) The low frequency/high frequency capacitance measurements on a MOS structure on 2 k Ω cm n-type [1,1,1] orientation silicon. The interface state density (D_{it}) derived from the capacitance measurements as a function of the silicon bandgap energy is shown in (B) along with representative values of D_{it} , the fixed oxide charge, N_f , and the flat band voltage, V_{fb} .
- Fig. 7. Results of scanning with a collimated gamma source along the surface of a n-type germanium detector coated with different surface passivants. A neutral surface is indicated by a flat response along the surface.
- Fig. 8. Similar to Fig. 7 but showing that the a-Ge:H coatings are equally effective in p-type germanium detectors in producing neutral surfaces.
- Fig. 9. Reverse leakage currents on a high-purity Ge detector with and without a-Ge:H coating.
- Fig. 10. Reverse leakage currents on Si(Li) detectors with and without a-Si:H coating.

- Fig. 11. Simplified cross section of an x-ray detector system intended for soil sample analysis.
- Fig. 12. Noise performance as a function of amplifier peaking time constant for the Si(Li) detectors coated with 7% a-Si:H.
- Fig. 13. N_p x-ray spectra obtained for photon incidence on the thin lithium contact (A) and on the gold barrier contact (B) of a Si(Li) soil analyzing detector.
- Fig. 14. Schematic of the multielement detector employed in producing the cross-sectional angiograms of Fig. 16.
- Fig. 15. Experimental arrangement for the production of the cross-sectional angiograms of Fig. 16.
- Fig. 16. Cross-sectional angiograms of an excised pig's heart. The arteries and ventricle are indicated.

Figure 1.

XBL 8311-4653

Figure 2.

Figure 3.

XBL 8312-4708

Figure 4.

Figure 5.

XBL 8311-4652

OXIDE GROWTH CONDITIONS	Dit	N_f	V_{fb}
STEAM (1050°C)	2.5×10^{11}	3.3×10^{11}	-13.5V
OXYGEN + Cl ₂ (1070°C)	4×10^{10}	2.2×10^{11}	-2.0V

XBL 8311-4651

Figure 6.

Figure 7.

Figure 8.

XBL 7910-12224

XBL 8311-4650

Figure 9.

XBL 8311-4649

Figure 10.

XBL 834-9247

Figure 11.

XBL 839-11422

Figure 12.

XBL 834-9248

Figure 13.

GEOMETRY

Figure 14.

COMPUTED TOMOGRAPHY USING SYNCHROTRON RADIATION

XBL 8210-2908

Figure 15.

VERTICAL ARTERIES
(1×2 mm)

VENTRICLE
(3×4 cm)

b)

XBB 830-9219A

a)

Figure 16.

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