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SILICON RADIATION DETECTORS

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1. FOREFORD

What we mean in terms of "radiation detection" or "radiation measurement" is extremely wide. The radiations to be detected or to be measured are He atomic nuclei (α-rays), electrons (β-rays), light (x-rays radiated from atoms and γ-rays radiated from atomic nuclei), neutrons (n-rays), protons and other atomic nuclei (light ions or heavy ions). The rate at which these radiations penetrate through the matter differs by more than several orders of magnitude depending on the sort of radiation. It also differs by more than several orders of magnitude for the same type of radiation depending on the energy value.

There are cases when their energy value is the order of 0.01eV (thermal neutrons) or 10^7eV. There are also cases where the precise energy (precision of better than $1/10^4$) is demanded and cases when a certain output regardless of the energy value is demanded, for example, the case of radiation control. Especially, the new revision of the regulations specifies that personal dosimeters shall display the output which is equivalent to the effect on the human body, that is, the effective dose equivalent (Sievert Sv).

From the standpoint of radiation "intensity", there are cases where measurement of 10^{-5} R/h is demanded and cases where measurement of 10^{+7} R/h is demanded.

What should be emphasized here is "to satisfy simultaneously two or more of the above specifications. For instance, the detector of X- and γ-rays for personal radiation control is required to give a constant output regardless energy within ±10% to ±20% in the range of 60keV to 6MeV (10^3 range) as well as a linear output to dose rate in the range of 10^{-4} to 10^2 R/h (10^6 range).

Because of the items outlined above the technique of the radiation detection is applied to a lot of fields. Recently, for a possible measurement which can be achieved without radiation, the measurement method is to be replaced by the method where radiation is not used. The cases where radiation must be used are, however, increasing. The new methods of radiation measurement are also increasing due to the recent development of the accelerators. The future increase of nuclear power plants and nuclear fuel reprocessing facilities will expand the radiation measurement application field or market.

Among many detectors used in atomic-power plants and in other radiation control equipments, we describe here the silicon (Si) semiconductor detector which has been developed by Fuji and which is steadily capturing a large share of the market in recent years.

This Si detector is composed of a Si detection element which is based on the use of an amorphous Si (a-Si) layer formed by the plasma CVD method, a preamplifier which amplifices the small amount of electric charge generated in the detection element with a good S/N ratio, a main amplifier and a discriminator. They are made on one board as a hybrid IC (HIC).

Compared to the GM counter and other detectors, its features are small size, light weight, excellent environment-resistance, long life, etc., as well as the radiation detection characteristics and low detector-bias voltage, which are described later. Because of these features, it replaces the GM counter or other detectors in fields where the GM counter is ordinarily used. The Si detector will be further used in new application fields.

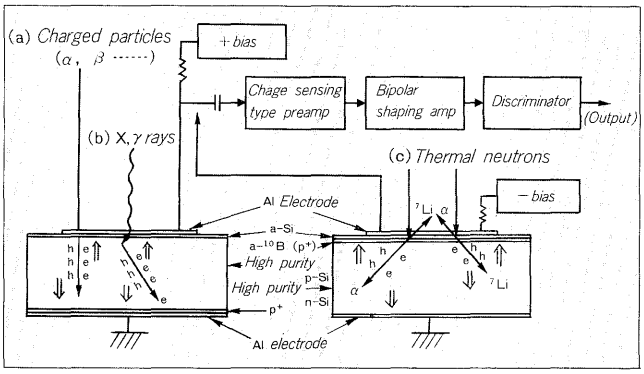
2. DETECTION PRINCIPLE OF Si SEMICONDUCTOR DETECTORS AND COMPARISON WITH OTHER DETECTORS

The Si detector developed by Fuji is outlined in *Fig. 1*. The Si detection element (the left side of the figure) is made by forming an a-Si layer and p^+ layer of about 1μm thickness with the plasma CVD method on both sides of a ultra high-pure p type Si wafer whose acceptor-ion density is lower than 10^{-10} of Si atoms.

The a-Si layer serves as a surface protective film and simultaneously forms and a/c hetero junction on the p-Si substrate (crystal). Aluminum (Al) is evaporated on the both sides of the element to the thickness of about 1μm. These form the (n^+) and p^+ electrodes. The high purity Si turns to a depletion layer (state in which there are no carriers – e and h –) by applying a reverse bias-voltage.

The α-rays, β-rays, and other charged particles injecting into the detection element from the outside of the detector create e–h pairs by losing their energy in the Si depletion layer (sensitive part) as shown in *Fig. 1* (a).

Fig. 1 Detection principle



The number of these e-h pairs is proportional to the energy lost by the charged particles.

The energy value *W* necessary to create one pair is 3.8eV for silicon. The e and h created are collected at the anode (n^+) and at the cathode (p^+), respectively. The charge (pulse) induced at the anode at this time is converted to a voltage by a charge-sensitive preamplifier and is further amplified with a good S/N ratio by a bipoplar-shaping type amplifier.

To achieve a good S/N ratio, the signal component is sufficiently amplified and the noise component distributing over a wide band is attenuated by pulse shaping with a time constant matched to the time necessary to collect e and h at the electrodes.

Since a proportional counter, GM counter, and other gas detectors have a gas multiplication, the output from the detector itself is large. On the other hand, since the semiconductor detector does not have this multiplication (same as ionization chamber), special innovations of the amplification circuit are necessary to improve the S/N ratio. It is necessary to develop an amplifier system appropriate for the size of detector (sensitivity) as well as for the operating temperature, depending on the purposes. It is as important as the development of the detector element.

Since the *W* value of Si is lower than that of CdTe (4.6eV), S/N ratio of Si detector is much better. Because the life of h in CdTe is very short, the signal contribution of h is almost zero. Therefore, the S/N ratio of CdTe is further worse than that of Si.

The main source of noise is the leakage current (reverse current). It depends on the type of semiconductor material and on the operating temperature. A semiconductor with a small band gap has a large reverse current and a small *W* value. Ge has a low *W* value of 2.9eV and hence a good S/N ratio can be expected. However, unless Ge is cooled to near the liquid-nitrogen temperature, its reverse current is too high to get a good S/N ratio. This is the reason why Ge can not be applied for the purposes discussed in this article. Due to the similar arguments, the operating temperature of the Si detector is limited to about 60°C.

Detection of X-ray and γ-ray is based on the some what different principle as the charged-particle detection, as conceptionally shown in *Fig. 1* (b). The X-ray or the γ-ray incident into the detector transfer its energy to the electrons via one or two of three elementary processes, and then the electrons are detected in the same manner as the charged particles. The efficiency of the energy transfer to the electrons is complicatedly dependent on the energy of the γ-ray (X-ray)

For the various detectors described here, we demand the output responding to the dose or equivalent of independent of the radiation energy. It is thus very important although difficult for us to achieve a good characteristic of energy. In this development, good energy characteristics were obtained through many experimental trials, for example, by placing the appropriate materials before, behind or surrounding the detector, or by adjusting the level of discrimination, for each detector.

The principle of the semiconductor detector for thermal neutron detection developed by Fuji is shown in *Fig. 1* (c). A 1μm thick boron (B) film is formed on the surface of a high purity n-type Si wafer by plasma CVD method. This B film contains a large amount of ^{10}B (enrichment of 90% or more), and acts not only as a p^+ electrode but also generates α particles and ^7Li ions via the nuclear reactions with the thermal neutrons. These α particles and ^7Li ions, which are incident into the depletion layer of n-Si formed by the reverse bias, produce e and h. The thermal neutrons are detected by collecting these e and h. Neutrons of a high energy than thermal neutrons are detected by counting the thermal neutrons, which are generated by a polyethylene modulator of hemisphere shape surrounding the detector. Neutrons of a still higher energy, i.e. MeV or more, are detected by measuring the recoiled protons, which are generated in a polyethylene disk (radiator) placed inside the case of the Si detector element.

3. Si SEMICONDUCTOR DETECTORS FOR VARIOUS MEASURING INSTRUMENTS AND METERS

The Si detectors and their characteristics, when applied to various radiation control apparatus, are described in this section.

A plenty of the personal dosimeters (roentgen R display) and the γ-ray surveymeters described in section *3.1* and *3.2* have already been sold and their high reliability has been proved.

The personal dosimeter (Sv display) for the 1cm depth dose equivalent (section *3.1*) and the area monitor (section *3.3*) have already been successfully developed and was placed on sale in September 1988.

The β-ray detector for dust monitors, the α-ray detector for surveymeters (section *3.4*) and the neutron personal desimeter (section *3.5*) have already been successfully developed and are expected to be placed on sale in 1989.

3.1 Si detector for pocket alarm dosimeter for personal radiation control

Pocket dosimeters using Si, CdTe, and other semiconductor detectors are on sale in recent years. These are gradually replacing the GM counter type in the atomic power plants, etc. for the following reasons. The possibility of replacing other types (film badge, pocket chamber, TLD, etc.) with the semiconductor detectors is also increasing for the application to the conventional personal radiation control.

(1) Compared to the dosimeter of GM counter type
  (a) Long life and high reliability. Low maintenance cost.
  (b) High voltage power supply unnecessary.
  (c) Wide range of dose rate based on capability of high-counting-rate measurement.
  (d) Light, thin, and small.
  (e) Good energy characteristic.
(2) Compared to the conventional type mentioned above, in addition to item (1) above,
  (a) Direct, prompt reading of dose and dose rate.
  (b) Sound and display outputs for alarm and monitor.
  (c) Setting and reading of various data are possible by one-chip microcomputer control and by optical communication function.
  (d) Various self-diagnostic functions.
(3) The superior points of the Si detector as compared to the CdTe and other semiconductor detectors were described in *Section 2.*

Besides the above, Fuji has successfully developed a pocket dosimeter using a Si semiconductor with a good energy characteristic for the 1cm depth dose equivalent (Sv) ranging from 60keV to 6MeV to meet the revision of the law to SI units. This section outlines the new products whose performance has been improved compared to the conventional ones.

Fig. 2 Block diagram of Si semiconductor detector Hybrid IC for pocket dosimeter

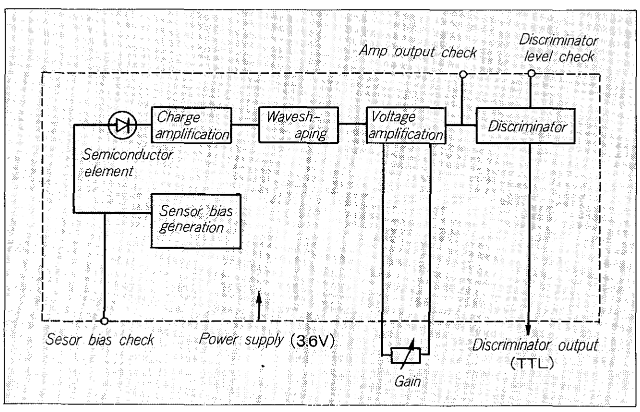
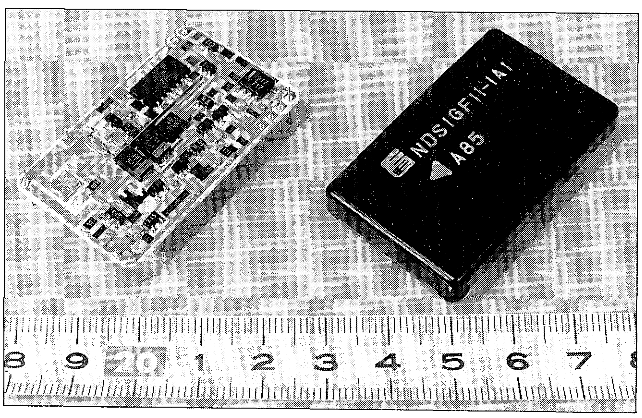


Fig. 3 Pocket dosimeter Si semiconductor detector HIC (NDSI)



The block diagram of the Si semiconductor detector is shown in *Fig. 2*. All components are combined on one PC board constructing a 46.5 x 28.5 x 6(mm) HIC as shown in *Fig. 3*. The HIC is operated with a 3.6V battery power supply. The detection element was originally developed by Fuji. Its dimensions are 3 x 3 x 0.4(mm). An amorphous thick film (~1 μm) and p^+ layer are formed on both sides of a 40mmϕ or 50mmϕ high purity Si single crystal wafer by the plasma CVD method. The wafer is chopped into pieces after the Al electrodes are formed by vacuum evaporation. It has been proved that this detection element does not deteriorate even at 150°C. The detector bias voltage is 15V. The preamplifier is of a charge sensitive type. The amplifier is of a bipolar type and the signals are shaped with a time constant of 0.5μs. A discriminator puts out a TTL waveform for a pulse with pulse height equivalent to 50keV or more. The linearity to dose rate obtained is better than 10% up to 0.5Sv/h (50R/h) and 20% up to 1.0Sv/h (100R/h). The range of dose rate measurement is a magnitude of 5 orders. This detector can be used at temperature of –20 to +50°C. Energy characteristic tests were repeatedly performed with the standard X-ray and γ-ray fields at Electrotechnical Laboratory (MITY) and the Institution of Radiation Measurements by changing the detector discriminator and filter conditions. *Fig. 4* (a) shows the final results obtained, which shows the ratio of the displayed dose value (Sv) to the irradiated dose (Sv) as a function of phantom energy where the dosimeter was placed 2cm apart from a phantom [acryl, 400 x 400 x 150(mm)] for calibration of personal dosimeters and was irradiated perpendicular to it. The phantom below 0.2MeV is X-ray. The quality index (QI) is 0.8. Since the standard field is defined in R units, the Sv

Fig. 4 Energy characteristic and mSv-R conversion coefficient of pocket dosimeter

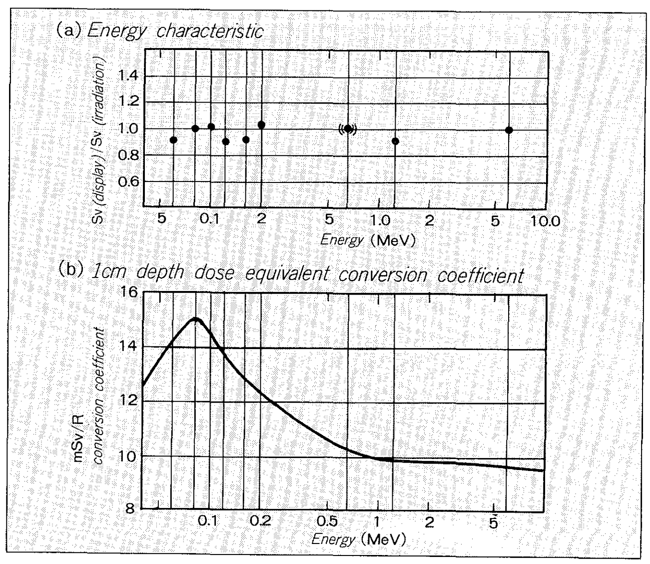


Fig. 5 Exterior view of pocket alarm dosimeter (NRQ4)

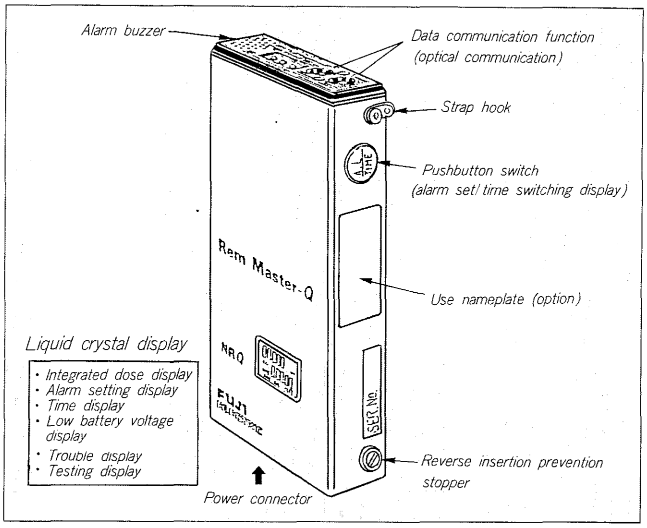
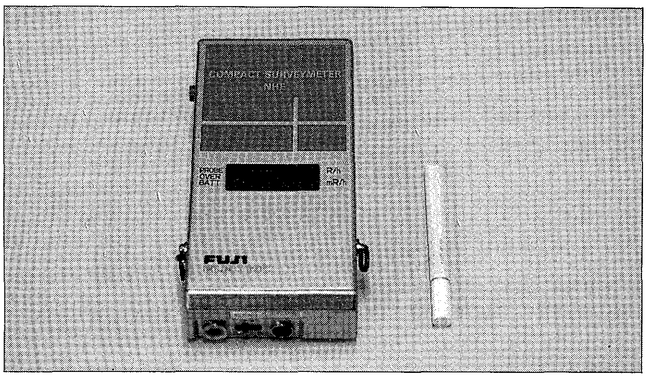


Fig. 6 Exterior view of semiconductor type surveymeter (NHE)



(irradiated) value was calculated by using the 1cm depth dose equivalent conversion coefficient (mSv/R) of *Fig. 4* (b).

Fig. 4 shows that the agreement (energy characteristic) within ±10% is obtained for the separation of 2cm. The maximum deviation between the value for the 2cm separation from the phantom and the value for the close contact case was 3% and occurred at 200keV.

Fig. 5 shows a new pocket alarm dosimeter (NRQ4), which can respond to the 1cm depth dose equivalent by mounting the detector HIC described above.

3.2 Si semiconductor detector for surveymeter

This section describes the characteristics of the detector itself and the surveymeter, which were developed for a small, lightweight, and long life surveymeter replacing the GM counter.

An exterior view of the semiconductor surveymeter is shown in *Fig. 6*. The objective is 80keV to 6MeV γ(X)-rays. Wide range measurement of dose rate of 0.1mR/h to 30R/h is possible of γ and X-rays from 80keV to 6MeV. The detector electrode area is approximately 300mm^2. An obvious peak was obtained with a low bias (60V) for the ^{241}Am 59.5keV γ-ray. The dependence of the detection

Fig. 7 Surveymeter energy characteristic

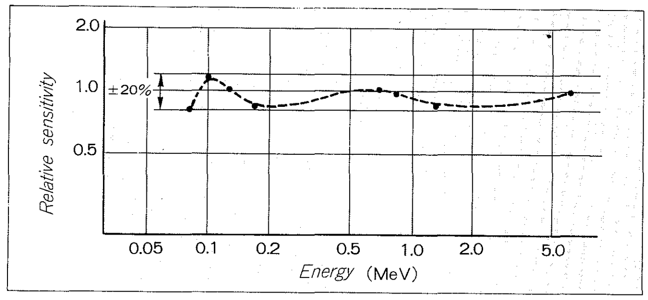
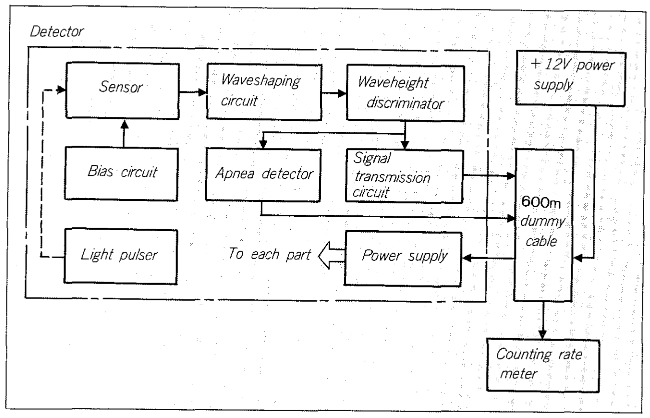


Fig. 8 Semiconductor type area monitor (NDM) measurement system



sensitivity on the incident direction is constant within ±11% at angles of +60° to −60° when the surveymeter was irradiated with the ^{137}Cs γ-rays. The dose rate displayed was independent of temperature within ±5% at −5° to 50°C. The energy characteristic is shown in *Fig. 7*. The figure shows the excellent energy characteristic 80keV to 6MeV. The dose-rate linearity obtained is within ±10% for the dose rate of 5mR/h to 10R/h and within ±20% for the dose rate of 1mR/h to 30R/h by means of the automatic compensation function of the built-in CPU.

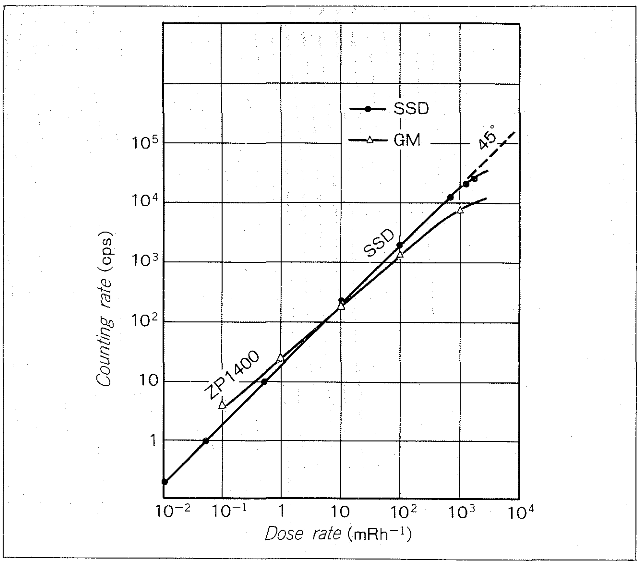
Because this semiconductor type of the γ-ray surveymeter mounting the Si detector has advantages of long life, small size, light weight, high performance and high reliability, it is expected for the semiconductor surveymeter to replace the conventional GM counter type of surveymeter for the measurements of medium and high dose rates in future.

3.3 Area monitor using a semiconductor detector

A semiconductor detector element for the γ-ray area monitor has been developed to improve the reliability and to reduce the size of the conventional area monitor, which uses a GM counter, an ionization chamber or a scintilation detector, and is so far used in the atomic power plants and various radiation handling facilities.

The sensitivity to γ-rays, the linearity to dose rate, the energy dependence, the temperature dependence and so on were measured by using a system shown in *Fig. 8*.

Fig. 9 Area monitor dose rate linearity



The senser part is integrated with a charge amplifier and with a detector element made by forming an a-Si layer on a p-type high-purity Si substrate.

A light pulser feeds periodic light pulses having a Si sensitive wavelength to the detector element. The pulser is a unit replacing the conventional radiation source.

An saturation detecting circuit outputs a signal when the counting rate exceeds a certain preset value. The energy characteristic was measured mainly at the Electrotechnical Laboratory (MITY) except for the point of 6.1MeV energy, which was measured at the Institution of Radiation Measurements.

The dose rate linearity observed for the range of 10^{-2} to 10^3 m/R/h is shown in *Fig. 9*. The average γ-ray sensitivity is 22.5cps/mRh^{-1}. The counting loss is less than 7% at the dose rate of 1Rh^{-1}. The performance of this Si area monitor is therefore superior to the monitors using a GM counter. The energy was confirmed to be constant within ±18% in the energy range of 80keV to 6.1MeV, where the data were normalized to the ^{60}Co standard. The QI of the X-ray source used is 0.8. The γ-ray sensitivity was stable within ±5% for temperatures ranging from $-10°$ to 60°C.

As discussed above, the present device satisfies the basic specifications demanded for the area monitor. The size of the area monitor has been sufficiently reduced by adopting the Si detector element compared to the monitors using the ionization chamber or the scintilation counter.

3.4 Large area semiconductor detector for dust monitor

The main β-ray detectors used for dust monitors are so far the GM counter of an end-window type and the scintilation counter. These two detectors require a high voltage higher than several hundred volts. The GM counter of the end-window type has a disadvantage of the limited lifetime. The scintilation detector is limited with its size.

In this development, we have intended to make a compact dust monitor by combining the semiconductor detector, which can operate at a low voltage of several ten volts and has a long lifetime, with the electronic circuit as the HIC. As a β-ray counter, we have fabricated a semiconductor detector with a 2,000mm^2 sensitive area and performed fundamental experiments about this detector. We have also developed a small HIC circuit.

The detector element was manufactured by forming a thick a-Si layer on a p-type high-purity Si wafer of 60mmϕ by means of the plasma CVD. The a-Si layer acted also as a passivation layer. The leakage current and the noise level were reduced by fabricating a guard ring electrode. The detection efficiency (counts/no. of decays) for a source-to-detector distance of 1cm was measured to be 22% for a U_3O_8 source, where a Myler foil of 12μm was used as entrance windows. This observed efficiency is comparable to that of a GM counter of end window type. The same value as with the GM counter was also obtained for a ^{60}Co source.

It is possible to raise the sensitivity of this semiconductor detector, which is expected to be used in place of the GM counter as the β-ray detector for a small, low-bias, long-life dust monitor. A large number of Si semiconductor detectors are expected to be used as a α-ray surveymeter or as various other monitors, especially, at the fuel reprocessing facilities.

3.5 Semiconductor detector for personal neutron dosimeter

We are developing a personal neutron dosimeter by applying the semiconductor detector in order to control the neutron exposure at atomic power plants, nuclear fuel reprocessing facilities, high-energy accelerator facilities, etc.

Fig. 10 Configuration of detector for neutron personal exposure dosimeter

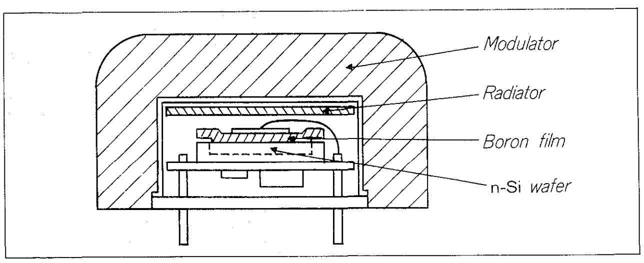


Fig. 11 Puluse-height spectrum at thermal neutron irradiation

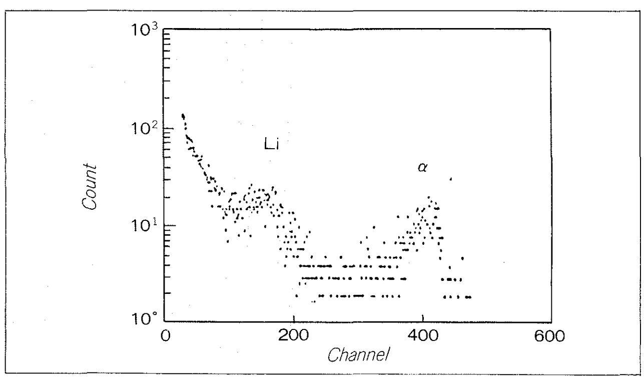


Fig. 12 Pulse-height spectrum at fast neutron irradiation

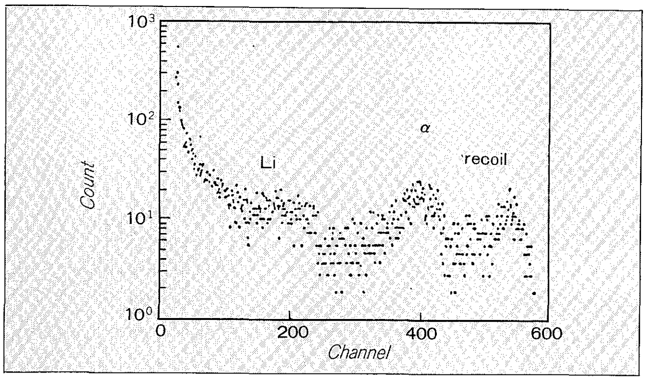
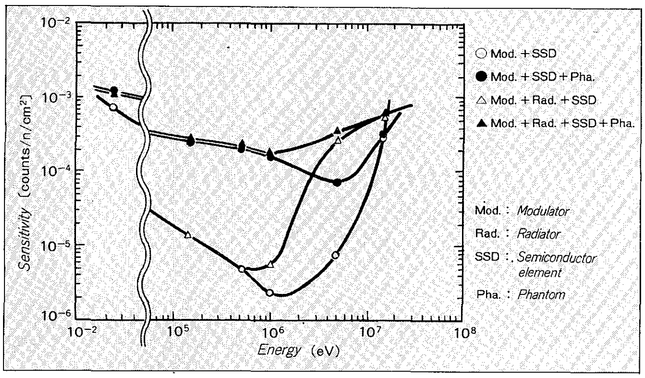


Fig. 13 Energy characteristics of semiconductor neutron detector



This section outlines the development result of the semiconductor neutron detector which can be applied to the neutron dosimeter.

The configuration of the semiconductor neutron detector developed is shown in *Fig. 10.* The neutron detector element is based on an amorphous boron-10 film formed on an n-type Si substrate. This element is combined with a head amplifier and sealed in a TO-8 case. The sensitivity for medium to fast neutrons was increased by placing a polyethylene disk radiator for generation of recoil protons, and by surrounding the element case with a polyethylene moderator of semisphere shape.

Fig. 11 shows a pulse-height spectrum observed by irradiating the detector with thermal neutrons. Two components corresponding to the α- and Li particles, which are generated in the ^{10}B (n, α) reaction, are clearly seen in the figure. *Fig. 12* shows a pulse-height spectrum for irradiation with fast neutrons. The increase of the sensitivity is confirmed for the fast neutrons, because the recoil protons from the radiator have been observed.

Fig. 13 shows the energy characteristics measured by applying monochrome neutrons to this detector. This measurement was performed for four cases: with and without a polyethylene radiator, and with and without a water phantom which simulates the state in which the dosimeter is worn on the body. The measurements using the radiator and the phantom shows that the sensitivity is increased by several to several ten times in the medium to high-energy region and that a fairly flat response is hence obtained. The sensitivity is ten to hundred times compared to that of conventional neutron film badge.

4. CONCLUSION

Since a manufacturing system for the Si detector elements of small area (about $10mm^2$) was established at Tokyo Factory in 1985, the manufacturing technology has been considerably developed to be able to produce the detector elements of large area ($2{,}000mm^2$). The HIC circuit technology has been also progressed and many products described above are being developed. We are expecting a revolution in the radiation-detector market by new further developments.

We acknowledge many people outside the company, who have kindly permitted us to use various facilities and also have provided fruitful discussions. Of these, we wish to thank the relevant people of Electrotechnical Laboratory (MITY), the Institution of Radiation Measurements, Japan Electronic Industry Development Association, Tohoku University, Musashi Institute of Technology, Rikkyo University and Kyushu University.