InP solid state detector for measurement of low energy solar neutrinos

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Abstract

A large volume radiation detectors using a semi-insulating Indium Phosphide (InP) wafer have been developed for Indium Project on Neutrino Observation for Solar interior (IPNOS) experiment. The volume has achieved to $20mm^3$, and this is world largest size among InP detector observed γs at hundred keV region. Although the depletion layer, most of charge generated by electron hole pair production are collected by an induction, and the charge collection efficiency and the energy resolution are obtained by 60% and 25%, respectively. We measured actual backgrounds related to ^{115}In β decay, and no significant background was found.

Key words: solar neutrinos, neutrino oscillation, stellar evolution
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1. Introduction

Super-Kamiokande and Sudbery Neutrino Observatory experiment has established ν_e oscillation in their solar neutrino data in 2001[1, 2], and a long way problem so called Solar Neutrino Problem in past 30 years was almost solved by the LMA oscillation. Independently, KamLAND experiment confirmed the oscillation using reactor $\overline{\nu_e}$ in sense of Δm^2 [3]. However, the oscillation mixing angel (θ_{12}) was not pointed out as well as θ_{23} observed in the atmospheric neutrino data. Next step of neutrino physics should measure both precise oscillation parameter and CP phase. For the future solar neutrino experiment, a precise θ_{12} measurement would be done with 1% accuracy. In this point of view, new experimental technique to measure not only flux but also energy of solar $pp/^7$Be neutrinos will be necessary due to direct observation of upturn of the neutrino energy spectrum.

Helioseismology shows us the information of the interior of the Sun using observations of motion on the surface. Most of analytic results are consistent with predictions of the standard solar model, however, still small difference of frequency less 0.5% in the intrinsic mode between the observation and the model remains. Therefore, low energy neutrinos from not only $pp-chain$ but CNO cycle are also important for direct investigation of solar interior on the stellar evolution theory. We are going to plan the experiment of low energy solar neutrino observation, so called, Indium Project on Neutrino Observation for Solar interior (IPNOS), for these objects.

2. Low energy solar neutrino experiment using ^{115}In

In 1976, R.Raghavan proposed new technique for the measurement of low energy $pp/^7$Be solar neutrinos [4] via following reaction;

$$^{115}\mathrm{In} + \nu_e \rightarrow ^{115}\mathrm{Sn}^* + e^-. \quad (1)$$

The prompt electron has an energy with $E_\nu - 118$ keV, here E_ν is an energy of incident neutrinos. Therefore the neutrino spectroscopy can be realized. An excited state of ^{115}Sn shown in Eq.(1) decays into the ground state with a lifetime of 4.76μs, and emits two γs (116 keV and 497 keV). This signature is also able to use for a triple-coincidence to extract neutrino signal from huge backgrounds. However, ^{115}In itself has natural β decay into the ground state of ^{115}Sn with a lifetime of 4.4×10^{14} years and maximum β energy of 495keV. The radiative Bremsstrahlung could produce fake coincidence for the neutrino signal. In order to avoid this, a fine segmented with well energy resolution detector is necessary [5].

Many possible detectors using indium were designed in last few decade, however, no realistic detector has been made. In 1988, Suzuki and Fukuda developed the InP solid state detector ($1mm^2 \times 10\mu m$) using the pn-junction and the detector observed the γs from the radioactive sources

[6]. For large volume detector, a liquid scintillator solved indium was developed by Suzuki [7] and LENS project [8]. Recently LENS group presented the feasibility of realistic way to build a big scale detector [9], but there still exist some difficulties of the transparency with respect to the weight of solvent.

New detector using InP semi-conductor has been re-evaluated for last several years. The semi-insulating (SI) InP wafer is commercially produced for the optical devices. Typical dopant is Fe and the crystal is usually grown by the liquid encapsulated Czochralski (LEC). Some radiation detectors have been developed for X-ray detector. The ESTEC group have characterized a 0.18 mm thick of InP at -60 °C achieving 8.5 keV FWHM at 60 keV[10], and Italy group obtained 11 keV FWHM at 122 keV with 0.25 mm thick SI InP at -60 °C[11]. There is other crystal growth method, namely the Vertical Gradient Freeze (VGF), which is relatively higher resistance and naturally smaller EPD than LEC. A radiation detector using the VGF SI InP wafer is developed by UK group[12], and our group. Most of developed detectors by UK group, however, have a small volume of the order of $1mm^3$ or less, and it seems to hard to use for solar neutrino experiment. On the other hands, our group tried to produce $7mm^3$ size InP detector, however, no clear peak from γs was found.

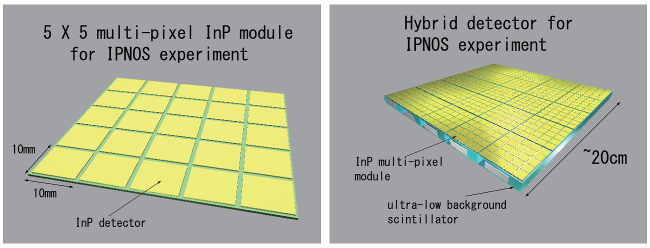

Figure 1: Possible detector design for IPNOS experiment. Left figure shows the multi-pixel InP detector, and right figure shows the hybrid structure which consist of multi-pixel module and scintillator.

It is possible to be real solar neutrino detector, if InP solid state detector has a massive. Assuming a mass of InP detector to be order of 1g, which corresponds to $10mm \times 10mm \times 0.2mm$, then 10^6 order of detector are necessary for the actual detection of solar neutrinos. We need to combine such even small detector as multi-pixel as shown in left side of Fig.1. According to this idea, 5×5 detectors are combined as one module, so same bias voltage should be applied in each detector and the signal line also should be unified. Another feature is the detection of γs from ν_e capture process by ^{115}In nuclei. These 116 keV and 497 keV γ could escape from the original InP wafer, so other detector should observe them efficiently. Therefore the IPNOS detector will have a hybrid structure of InP multi-pixel modules surrounded by low background (solid) scintillator as shown in right side of Fig.1.

3. Performance of InP detector

We have chosen another wafer produced by Sumitomo Electrical Industry Co. LTD with the method of Vapor Pressure Controlled Czochralski (VCZ). Hamamatsu Co. LTD developed InP detector with $10mm \times 10mm \times 0.2mm$. The electrodes consist of Cr-Au with $1\mu m$ thickness for top and Au-Ge/Ni/Au with 0.13/0.015/0.5 μm thickness for bottom as shown in Fig.2. The junction between electrode and InP are ohmic contact in room temperature, however actually a Schottky barrier could be formed at low temperature, because of the rectification in the measurement of Hall effect.

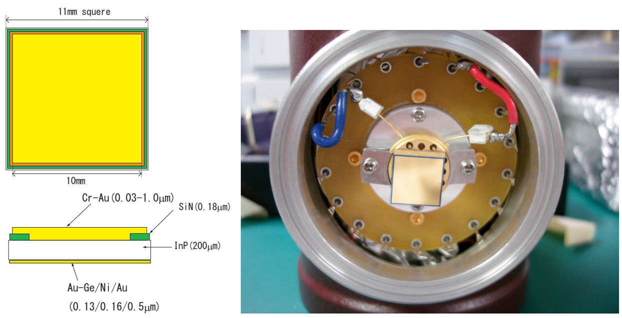

Figure 2: Left figure shows the schematic view of the InP detector. The detector size is $10mm \times 10mm \times 0.2mm$.

The performance of InP detector was measured by using γs emitted by usual radio active sources. Carriers generated by the energy deposit of an electron via photoelectric process or Compton scattering are drifted along to electric field. As usual solid state detector, the charge could be induced by the polarized carrier at the surface of electrode. The induced charge is evaluated by

$$Q[C] = \int_0^R \frac{dE/dx}{\epsilon} \frac{L_d}{d} dx. \tag{2}$$

Here, L_d is the carrier drift length, ϵ is an average energy for electron/hole pair production, R is the carrier range, and d is thickness of InP detector. Generally speaking, the carrier drift length is expressed by $L_d \equiv \mu\tau\frac{V_0}{d}$, here μ is the carrier mobility, τ is life-time of the carrier trapping and V_0 is the bias voltage. In order to get longer life time, the detector should be cooled.

Figure.3 shows that the observed charge distribution measured at -79 °C for several radio-isotopes. There found two peaks in each spectra. For instance, photo peak for 122 keV γ of ^{57}Co appears around 0.3×10^{-14} C and 0.55×10^{-14} C. Higher peak is produced by the charge collection which the carrier reaches at the electrode, and it is consistent with an average energy for electron/hole pair production to be 3.5 eV. This assumption is also confirmed by the fact that the higher peak position was not changed as increasing bias voltage. On the other hands, lower peak moves to higher position as increasing bias voltage. This is naturally explained by Eq.(2). The collection

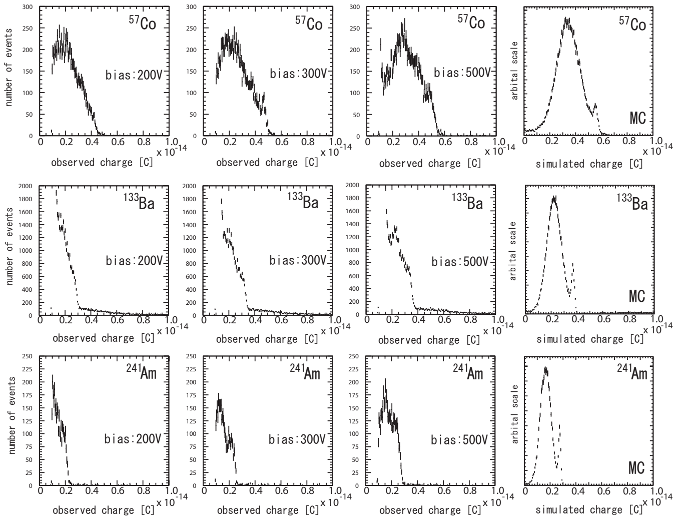

Figure 3: Observed and simulated charge distributions for several γs obtained by the InP detector.

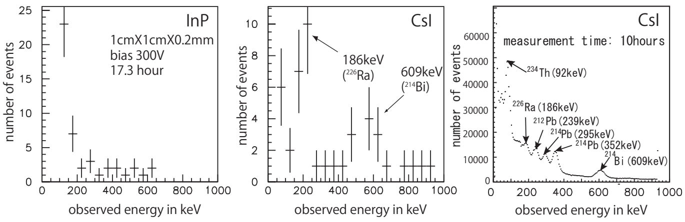

Figure 4: Energy spectrum of coincidence events for CsI and InP detector for 17 hour data, and U/Th background observed in CsI detector by self trigger.

efficiency for lower peak corresponds to 60%. According to a simulation with the energy resolution of 20% at 122 keV for a lower peak, the spectral shape could reproduce assuming both $L_d \sim 120\mu m$ as shown in most right of Fig.3. An intrinsic energy resolution for a higher peak was also assumed by 3% at 122 keV in this simulation.

4. Measurement of backgrounds

As described in section 2, ^{115}In decays naturally with β emission, and the radiative Bremsstrahlung might be possible background in the observation of solar neutrinos. For the measurement, we used InP detector for measurement of β event and CsI(Tl) scintillator for the measurement of radiative Bremsstrahlung. The CsI size was $50mm \times 50mm \times 20mm$. These two detectors are located by face to face and set inside of radio-active shield which consist of the lead in 5cm thickness and the oxygen free copper in 1cm thickness. The 4-π active veto plastic counter surrounded the shield rejected backgrounds due to the cosmic ray. The energy threshold for InP and CsI detector was 100keV and 50keV, respectively.

In order to detect the radiative Bremsstrahlung, we took coincidence between InP and CsI detector within 10 μsec. In case of 17.3 hours measurement, 46 events were observed. Before concerning of the coincidence events, it is necessary to take into account U/Th natural backgrounds. According to measurement of U/Th activity using ultra-low background germanium detector located in Kamioka mine, the InP wafer contains them as order of 10^{-11}g/g. Also right figure of Fig.4 shows the energy spectrum of CsI detector obtained by self trigger. It is clearly seen that the photo-electric peak due to some nuclei in the U/Th decay chain such as ^{214}Bi. The amount corresponds to order of 10^{-10}g/g in the CsI scintillator or surrounded material. According to Fig.4, most of coincidence events between InP and CsI detector looks consistent with β-γ coincidence of U/Th backgrounds in those detectors as indicated by ^{214}Bi γ observed in CsI, and no clear evidence for the effect of radiative Bremsstrahlung was found. This scheme was also confirmed by Si instead of InP detector. Moreover, an accidental triple coincidence between InP detector and the solid scintillator was evaluated by 5×10^{-6}events/day/1 hybrid detector, which corresponds to 10 events/day/4ton detector using this data. This means that we need to reduce the amount of U/Th contamination in the detectors or surrounded materials only 1/10, if S/N ratio will be assumed by an order of 1.

5. Conclusion

An InP solid state detector has been developed and obtained suitable performance. Observed charge spectra could be explained by induced charge, and the collection efficiency is achieved by 60%. No significant background was found in the actual setup for solar neutrino observation. This is the first time to demonstrate InP detector with a bulk size crystal.

Acknowledgments

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