# Development of InP detector for solar pp/$^7$Be neutrino measurement

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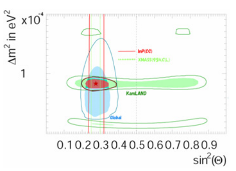
## 1. Introduction

### ◆ Purpose : Precise measurement of ν oscillation mixing angle $\theta_{12}$

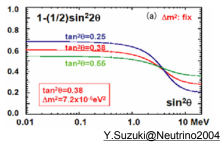
### ◆ Status of determination for ν oscillation parameter



- 96%C.L. allowed region obtained by global fit
  LMA solution (blue) : Cl + Ga + SK (D/N spectrum)
  KamLAND (green) → confirm $\Delta m_{12}^2$

$27^\circ < \theta_{12} < 37^\circ$

mixing angle $\theta_{12}$ is not constrained compared with $\theta_{23}$ (obtained by Atm. ν)
Survival probability tends to increase in 5MeV or less in case of LMA solution, and shapes depend on $\theta_{12}$.



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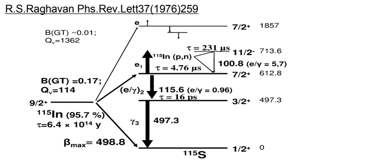
**Amount of pp/$^7$Be ν should be observed**

- **on-going solar pp/7Be experiment**
  - KamLAND (Liquid scintillator, electron elastic scattering (ES))
  - Borexino (Liquid scintillator, ES)
- **future solar pp/$^7$Be experiment**
  - XMASS (LXe, ES, DIRK MATTER)
  - LENS (Liquid scintillator loaded In/Ye, charged current (CC))
  - CLEAN (LNe, ES)
  - MOON ($^{100}$Mo,CC)
  - SIREN ($^{160}$Gd, CC)

### ◆ Technique of low energy solar neutrino detection

R.S.Raghavan Phs.Rev.Lett37(1976)259



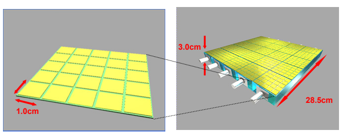
$^{115}$In + $\nu_e$ → $^{115}$Sn* + e$^-$
$^{115}$Sn*(4.76μs) → $^{115}$Sn + $\gamma_1$(115keV) + $\gamma_2$(497keV)

- **Advantage**
  - direct counting
  - sensitive to low energy $\nu_e$ ($E_\nu \geqq$ 125keV)
  - measuring the energy ($E_e = E_\nu$ − 125keV)
  - Triple fold coincidence to extract neutrino signal from huge BG ($e_1 + \gamma_2 + \gamma_3$)
- **Disadvantage**
  - natural β-decay of $^{115}$In ($\tau_{1/2}$ = 6.4 × $10^{14}$ yr)
  - Possible BG due to correlated accidental coincidence by Bremsstrahlung

**●Possible detector with 4tons of $^{115}$In assuming 5 years ope.**

- Number of expected events assuming no ν oscillation → 1885
- Number of expected event assuming LMA solution with Ee≧100keV → 720

Statistical and theoretical error in total → ~3.9 % ⇒ $\theta_{12}$ = 29° - 34°

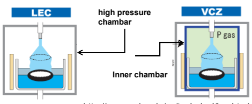


- **Hybrid structure of InP and solid scintillator**
  - InP detector module 10mmX10mmX0.2mm cell
  - Solid scintillator surrounding InP detector to detect γs
- **4tons of $^{115}$In detector for solar ν experiment**
  InP : 5.1tons (2.1X10$^6$ modules)
  solid scintillator (ex. CsI) : 934tons
  total size : 6.3m X 6.3m X 5.3m

## 2. Semi-Insulating(SI) InP semi-conductor

### ◆ InP crystal growth method

**● VCZ (Vapor Pressure Controlled Czochralski)**

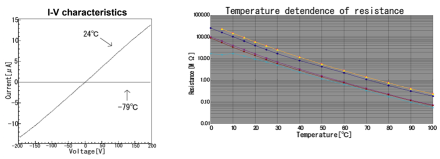


http://www.sei.co.jp/sc/technical/inp.html

- **Product : Sumitomo Electric Industries, Ltd.**
- **Process**
  In inner chamber controlled by steam pressure of As or P, covering material melt by $B_2O_3$ like LEC method and pulling up single crystal growth from it. Because of crystal growth in low temperature gradient, transition density can reduce.

**● Characteristic table**

| | |
|---|---|
| EPD | ~5,000cm$^{-2}$ |
| Conduct | Semi-insulation |
| Dopant | InP(Fe) |
| Resistivity | (4.9~5.2)×10$^7$Ωcm |
| Mobility | (2.8~2.7)×10$^3$Ωcm |
| Thickness | 456~459μm |
| Diameter | 50.00mm |
| Orientation | (100)±0.03° |



$I\,[A] \propto T^{2/3} \exp(-E_g/2k_\beta T)$

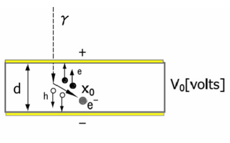
$E_g$ : band gap (1.29eV)
$k_\beta$ : Boltzmann constant
T : element temperature

Dark current could be reduced by lowering temperature

● Characteristic of SI InP semi-conductor is both target and detector

## 3. Test Module with the SI InP

### ◆ Detection of radiation with SI InP solid state detector



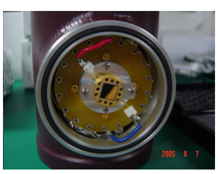
μ : mobility [$m^2 v^{-1} s^{-1}$]
v : carrier velocity [$ms^{-1}$]
E : electric field [$vm^{-1}$]
d : thickness of SI InP
$x_0$ : range of electron

$E = V_0/d \quad v = \mu E = \mu V_0/d$

drift length : $L_d = \tau v = \mu\tau V_0/d$ τ : carrier lifetime [s]
e/h creatrion energy : $\varepsilon_{eh}$
charge $Q_{total}[C] = (\text{electron energy})/\varepsilon_{eh} \times e$
$L_d \fallingdotseq \infty \quad Q_{obs}[C] = \int_0^R (dE/dx)/\varepsilon_{eh}\, e^{-r(x)/L_d}\, dx \times e$

- Produced electron loses its energy, and creates electron-hole pair as carrier.
- Carrier moves along electric field.
- If drift length is enough to the thickness, charge collection efficiency achieves 100%.
- If the drift length is not enough, the carrier might be trapped by the impurity before the collection.
- Drift length is proportional to carrier mobility and electric field.

**●InP detector with cooling dewar**

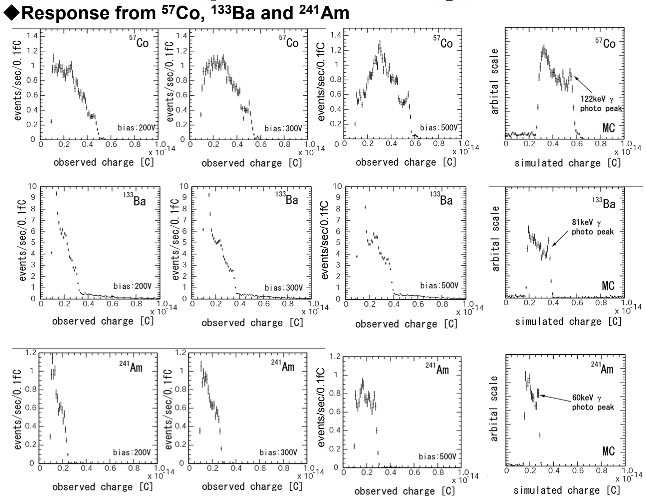


Size:
7mm×7mm×0.2mm
Electrode :
- Ohmic contact
- Vacuum evaporation of Au base

**Schematic view of InP detector**

## 4. Spectrum analysis

### ◆Response from $^{57}$Co, $^{133}$Ba and $^{241}$Am



**γ spectrum obtained by InP detector**

- Photo electric peak for 81keV ($^{133}$Ba), 122keV ($^{57}$Co) and 60keV($^{241}$Am) were observed,
- However, two peaks were found.
- Higher peak corresponds to photo electric peak with charge collection efficiency (CCE) 100%.
- Average energy of electron/hole pair production is obtained by 3.5eV.
- Lower peak obtained by carrier drift is equivalent to CCE 56%($^{57}$Co) and 72%($^{133}$Ba), respectively
- Intrinsic energy resolution σ=5%@122keV

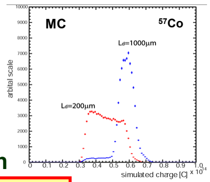
**Spectral analysis with MC**

- Assuming charge collection due to both depletion layer formed at the ohmic contact between electrode and InP and drift of carrier in remaining region
- Input parameter : thickness of depletion layer : 30μm
  Drift length:250μm, e/h production energy : 3.5eV
- MC reproduces spectral shape of data well

**Carrier drift length $L_d$ should be longer**

Low CCE signal improved by increasing carrier drift length

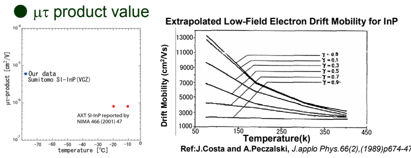
**Assuming Ld ~1000mm, photo electric peak will be single peak with good energy resolution**



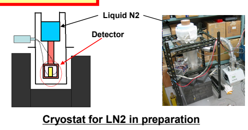
### ◆ How to increase the carrier drift length

**1. Increasing mobility (μ)** — **Temperature → lower**

● μτ product value



Ref:J.Costa and A.Peczalski, J.applo Phys.66(2),(1989)p674-479



Crystat for LN2 in preparation

Drylce (-79 ℃) → Liquid $N_2$(- 186℃)

- Increasing μτ product value at lower temperature
- Increasing mobility by cooling

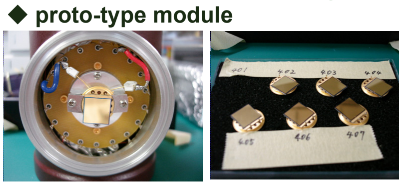
**Direct measurement of mobility using Hall Effect will be done by Semiconductor Research Institute.**

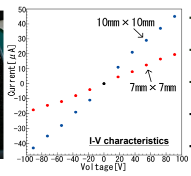
**2. Higher bias voltage ($V_0$)** — **Change electrode material (Au → Pd or Ag)**

- Avoid electric noise due to dark current
- Schottky barrier height: 0.37eV(Au) / 0.41eV(Pd) / 0.54eV(Ag) Ref: J.Phys.III 1(1991) 749-758

## 5. Prototype detector

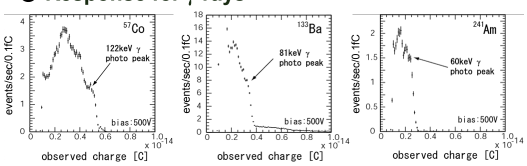
### ◆ proto-type module





- size:
  10mm X 10mm X 0.2mm
- same structure as test module
- current is proportional to electrode area.
- just delivered since 12th of July !
- first data has been taken with DryIce cooling.

**● Response for γ-rays**



- **No. of Events have been increased by 3.1 times as compared with 2.8 times larger electrode area($^{57}$Co).**
  ⇓
  **Effective area spread.**
- **Proto-type module has same performance as test module.**

### ◆ Prototype detector for solar neutrino experiment

- proto-type detector consists of 4 modules
- **Measurement of $^{115}$In β-decay spectrum and bremsstrahlung in Kamioka mine**
  - estimate effect of accidental coincidence due to backgrounds.
  - establish counting methods.
  - Kyoudou-riyou program of ICRR, Univ. of Tokyo
  - experiment will start at the end of this year or early of next year