Detector developments and investigation of radiation damage in semiconductor detectors in the Institute of Nuclear Research of HAS (ATOMKI), Debrecen

Gabor Kalinka

**Semiconductor detector** development between 1971-90 concentrated around Si(Li) X-ray detectors and complete X-ray spectrometers. Nowadays - in collaboration with Japanese partners - Si pin and SDD detectors, and HgI₂ planar detectors, all for X-ray detection, are under construction.

**Scintillation charged particle** detector systems using CsI(Tl) crystals coupled to Si pin photodiodes has been developed for nuclear physics (European, Japanese and South-African collaborations), while systems using LSO/LYSO crystals combined with Position Sensitive Photoelectron Multipliers are being developed for **gamma-ray** detection in Positron Emission Tomography (PET).

Detector **radiation damage** studies started very recently in ATOMKI with the increased use of Si pin photodiodes in conjunction with particle accelerators.
Semiconductor detector development

ionizing radiation: e-h pair creation in reverse biased diode structures, charge collection, integration, signal shaping (noise filtering), amplitude measurement

P-N detector
Thin sensitive volume:
• low X/gamma efficiency
• large capacitance → noise

P-I-N detector, e.g. Si(Li)
Thick sensitive volume:
• higher efficiency
• lower capacitance
• better energy resolution
High vacuum dewar Si(Li) detectors (1988) in cooperation with Tesla, Brno (Czechoslovakia)

136 eV FWHM

1986: XRF laboratory, Havanna
1990: Detector laboratory, Osaka
1991: end of Si(Li) era, ATOMKI “detector clinics”
Microelectronics: advanced p-n or p-i-n detector (photodiode)
3-4 orders of magnitude (!) lower current → moderate cooling
~ 100-800 µm thickness, X-ray energy 1-20 keV
Good Si(Li) detectors have still been the standard!

Hamamatsu S1223 photodiode
2.4 x 2.8 x 0.2 mm³
Room temperature X-ray detection with Si-pin photodiodes

**FWHM=440 eV @ 5.9 keV**

Fe-55

**FWHM=580 eV @ 60 keV**

Am-241
Semiconductor Drift Detector (SDD)
1984, Gatti, Rehak
very small anode, very small capacitance, excellent resolution

Principle of the sideward depletion

Partial depletion

Full depletion
Realization of a circular drift detector
AMPTEK (USA) pin detector
-30 °C, 150 eV, 3000 USD

KETEK (Germany.) drift-detector
-30 °C, 125 eV, 10000 EU

Aim: construction of similar pin/SDD detector units
International collaboration with Osaka Electro-Communication University and a Japanese Semiconductor Company
Prototype Si pin/SDD detector
(radiation entrance side)
HgI$_2$ detector development

- HV side irradiation
  Electron traversal

+ HV side irradiation
  Hole traversal
Scintillation detector developments (1991-)
- CsI(Tl) scintillator (550 nm) + Si pin photodiodes
- LSO scintillator (420 nm) + PMT
Scintillation charged particle detector systems developed by ATOMKI using multilayer polymer mirror reflector wrapping based on Giant Birefringent Optics

100 element CsI(Tl) + Si pin photodiode detector system (DIAMANT + ChessBoard) for EUROBALL, (France, Italy) EXOGAM (Ganil, France) AFRODITE (iThemba, South Africa) Collaboration with CENBG, Bordeaux; MSI, Stockholm; INFN, Napoli scintillator : 14 x 14 x 3 mm³ photodiode : 10 x 10 mm² for ~ 30 MeV/amu particles Dedicated preamplifiers and highly integrated dedicated electronics in VXI-standard Excellent energy- and particle-resolution (~ 2 times better than that of counterpart Microball at Gammasphere)

300 element CsI(Tl) + Si pin photodiode detector system (GRACIA) for RIBF at RIKEN (Japan) Collaboration with Riken and Rikkyo University scintillator : 16 x 16 x 55 mm³ photodiode : 10 x 10 mm² for ~ 130 MeV/amu particles Dedicated preamplifiers, (yet) standard signal processing electronics Performance is only a little bit inferior to the DIAMANT system (det. size 24x larger !)
The DIAMANT charged particle detector system built into the target chamber of the EUROBALL gamma-detector system (Strasbourg, 2004)

The electronic units for processing scintillation detector signals synchronously with Germanium detector signals has also been developed in ATOMKI (not shown in the photo).
The forward hemisphere of **DIAMANT** detector system together with mounted preamplifiers inside the target chamber
Energy resolving capability of DIAMANT scintillation detectors (low energy alpha spectrum of U-232)
Particle resolving capability of DIAMANT scintillation detectors (low energy region < 50 MeV)

EUROBALL + DIAMANT with VXI
Commissioning Experiment; April 2000
$^{170}\text{Er} + ^{30}\text{Si} (165 \text{ MeV})$

- PROTONS
- DEUTERONS
- ALPHAS
- Pulses from PIN-diodes
Part of the 300 element (detectors packed in quad units) CsI(Tl)+Si pin photodiode charged particle detector system GRACIA at RIKEN RARF
Detector blocks for small animal PET systems

- Crystal type: LSO scintillator
- Crystal size: 2x2x10 mm³
- 8x8 crystal matrix unit
- Lumirror light reflector
- Position Sensitive PhotoMultiplier Tube
- Recently: 33x33 matrix unit of 1.4x1.4x12.5 mm³ LYSO crystals
- 16x16 anode PSPMT
Radiation damage research

Detector radiation damage studies started very recently in ATOMKI with the increased use of Si pin photodiodes in conjunction with particle accelerators. Preliminary results have been obtained with 5.5 MeV alpha particle irradiation from Am-241 isotope, with 6.5 MeV oxygen, 2.15 MeV lithium, 0.43 MeV hydrogen ions (both with 5 um range in Si), and 2 MeV protons (50 um range). Photodiodes irradiated uniformly were characterized by I-V and C-V techniques and charge collection measurements with 5.5 MeV alpha particles. Diodes irradiated with a patterned way were evaluated with Ion Beam Induced Charge (IBIC) method, using \( \mu m \) focussed beam of the same particle at the same energy as during irradiation either online or offline.
Summary of I-V plots versus 5.5 MeV alpha fluence up to $1 \times 10^{11}$ cm$^{-2}$ (generation centers)

S5821 diode at 22 degrees centigrade
C-V plots versus fluence of 5.5 MeV alpha (ionized impurity centers)

\[ C = \varepsilon_S \frac{A}{W} \]

if \( N_d = \text{const.} \)

\[ W = \sqrt{\frac{2\varepsilon_S}{qN_D} \left( U_R + U_{bi} \right)} \]
CCE measurement with 5.5 MeV alpha particles after different fluences of 5.5 MeV alpha particles (trapping and/or recombination centers)

S58F diode measured with Am241 alpha following Am241 irradiation

- Virgin
- $5 \times 10^9$ cm$^{-2}$
- $1 \times 10^{11}$ cm$^{-2}$

Graph showing peak amplitude vs. $1/(\text{Reverse bias voltage}) [1/V]$.
2 MeV H\(^+\) irradiation (50 \(\mu\)m range) of 3x3 squares of 100x100 \(\mu\)m\(^2\) area in logarithmically evenly spaced fluence steps from 0 to 5\(\times\)10\(^{11}\) cm\(^{-2}\)
2 MeV H\textsuperscript{+} IBIC scan of the irradiation site prior to irradiation at $U_d=0$ V

Detector material nonuniformity (growth striations)
Results relevant for detector applications: degradation for the $U_d \geq 10$ V case

\[ \delta(CCE)_{rad} = (2.2 \pm 0.5) \times 10^{-15} [cm^2] \Phi [cm^{-2}] + (-3.3 \pm 0.5) \times 10^{-13} [cm^2 V] \frac{\Phi [cm^{-2}]}{U [V]} \]

\[ \Delta_{rad} [keV] = (4.0 \pm 1.5) \times 10^{-5} \sqrt{\Phi [cm^{-2}]} \frac{\Phi [cm^{-2}]}{U [V]} \]

\[ \Delta = \sqrt{\Delta_0^2 + \Delta_{rad}^2} \]