

KAERI



첨단방사선연구소 검출기 개발 시설·장비 현황

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강창구, 하장호, 김영수, 박정민, 김수진

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PRESENTATION TITLE

CONTENTS



01 방사선 검출기 기술 개요

02 방사선기기팩 시설·장비 소개

03 방사선기기팩 활용 기술

04 방사선기기 클러스터

01 방사선 검출기 기술 개요

01 방사선 검출기 기술

» 방사선기기 원천기술



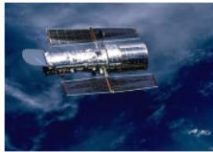
01 방사선 검출기 기술

» 방사선기기 응용분야



보건/의료

- 의료용 CT
- 암진단 PET
- 감마 카메라
- 혈관 조영기
- C-형 중앙치료기
- 골 밀도 측정기
- 방사선치료기
- 사이버나이프
- 하드론치료기



차세대 산업

나노

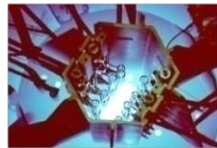
- 전자현미경
- 나노급 세포 CT
- 상온 반도체 센서
- 고온 반도체 센서

우주항공

- X-선 위성 영상
- 감마선 위성 영상
- 외계행성 수분탐지기

바이오

- 동물용 CT
- 동물용 PET



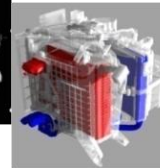
에너지 산업

- 원자력 발전소 방호 계측기
- 연구용 원자로 방호 계측기
- 동위원소 생산평가 계측기
- 핵연료 생산평가 계측기
- 핵융합로 평가 센서
- 원전수거물 센터 방호 계측기
- 차세대 원자로 노심 계측기
- 대기 감시용 계측기
- IAEA 사찰용 센서
- 고방사선용 반도체 센서
- 개인 피폭감시 선량계
- 중성미자 실시간 원자로 감시장치



산업 공정 진단

- 자동차 엔진
- 비행기 엔진
- 전자회로 검사
- 라디오 그래픽용 GEM
- 지하수 탐지용 수분계
- 철강용 콜크 수분계
- 암석 밀도계
- 공전 진단용 밀도계
- 유황 분석기
- 석유/가스 분석기
- 토목용 수분/밀도계
- 공정유체 밀도분포 측정기
- 투과형 강판 두께 측정기
- 반사형 박막 두께 측정기
- 섬유중량측정 시스템
- 필름형 산업용 CT
- 디지털 산업용 3차원 CT
- 나노급 산업용 CT



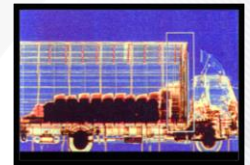
안전 국방 산업

국방

- 핵방호 시스템
- 병사용 선량계
- 화생방 부대용 계측기
- 제논 검출기

보안검색

- 대테러 보안 검색기
- 밀수 방지용 검색기
- 컨테이너 검색기
- 화물 검색기
- 소화물 소형 검색기



통일 산업

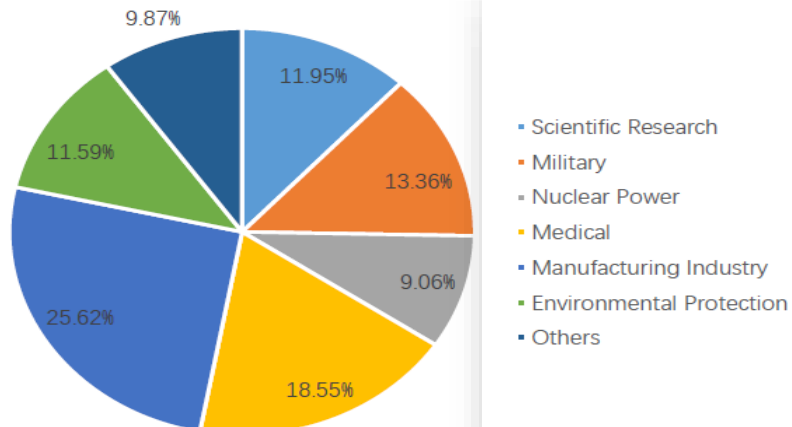
- 무인 폭발물 탐지장치
- 무인 폭발물 제거 장치

01 방사선 검출기 기술

» 방사선 검출기 및 기기 시장현황

<Global Radiation **Detector** Market Size by Type (K Units) & (US\$ Million) & (2020 VS 2026)>

Segment by Type	2020		2026		CAGR (2020E-2026F)
	Production	Value	Production	Value	
Gas Ionization Detectors	683.56	544.32	856.89	565.54	0.64%
Semiconductor Detectors	738.29	720.68	1068.08	868.66	3.16%
Scintillation Detectors	558.72	519.93	823.84	629.52	3.24%
Total	1980.57	1784.93	2748.82	2063.72	2.45%



<Radiation Medical imaging **Equipment** Market>

(단위: 백만달러)

구분	2015	2016	2017	2018	2019	2020	2021	2022	2023	성장률 (%)
핵의학영상 장비	1,797	1,915	2,037	2,166	2,300	2,440	2,586	2,738	2,896	6.1
SPECT	850	877	901	925	947	967	985	1,000	1,014	2.2
PET	947	1,038	1,136	1,241	1,353	1,473	1,601	1,738	1,882	9.0
기타(X-ray, MRI, CT, 초음파)	27,559	29,188	30,915	32,649	34,451	36,246	38,187	40,210	42,409	5.6
합계	29,356	31,103	32,952	34,815	36,751	38,686	40,773	42,948	45,305	5.6

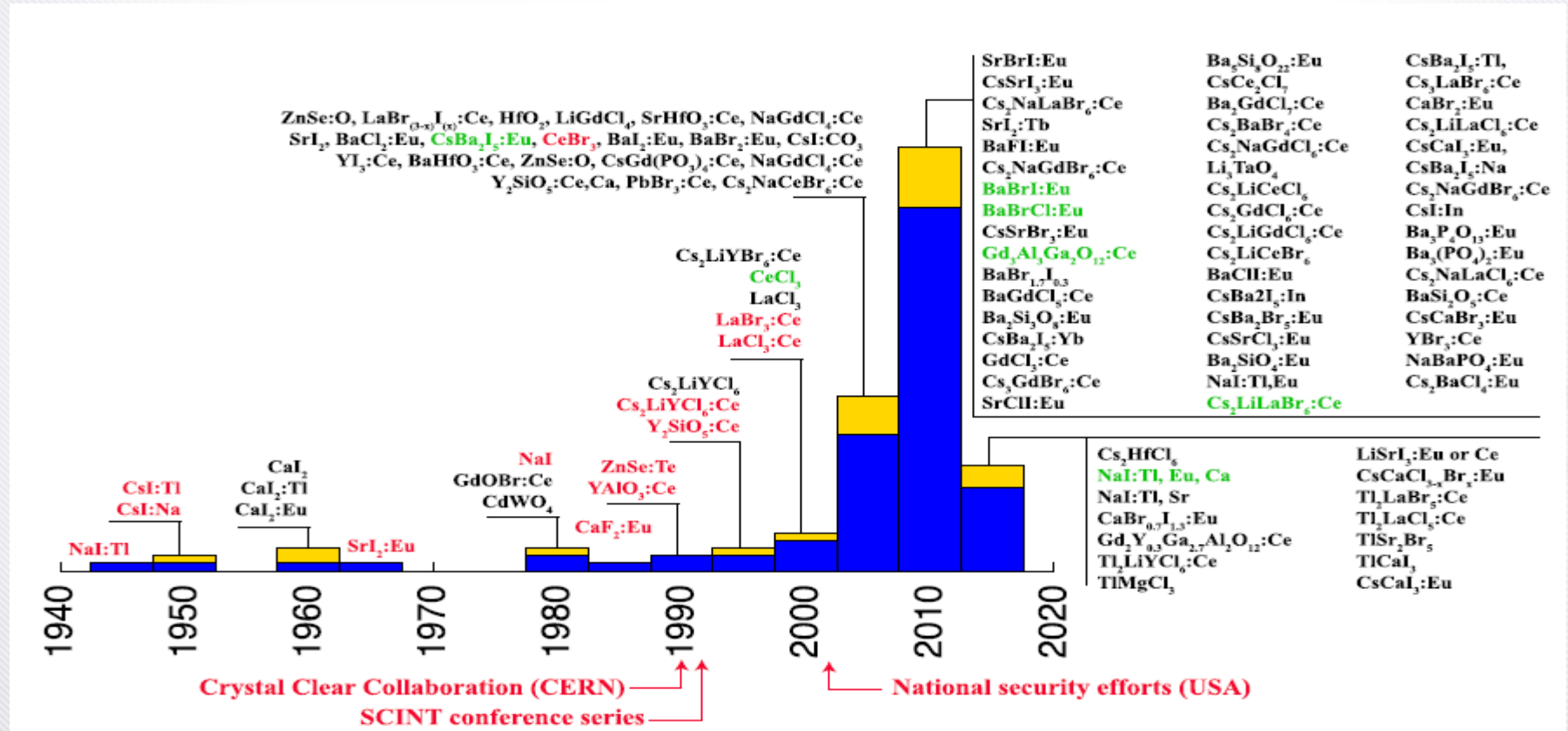
출처: Transparency Market Research Report (2015)

출처: Global Radiation Detector Market Research Report (2020)

01 방사선 검출기 기술

» 섬광체 단결정 현황

<(1940–2017) of first publication of scintillators with light output of >20,000 ph/MeV>



Blue bars: new scintillator compounds

Yellow bars: known compounds with new activator or co-doped

Red letters: commercial products

Green letters: under development

01 방사선 검출기 기술

» 섬광체 단결정 현황

Some Commercial Suppliers of Inorganic Scintillators

- Alpha Spectra (NaI:Tl)
- Detec (NaI:Tl, CsI:Tl, CsI:Na, LuI:Eu, CdWO₄, Bi₄Ge₃O₁₂, PbWO₄)
- Hilger/Dynasil Crystals (Bi₄Ge₃O₁₂, CaF₂:Eu, CdWO₄, CsI:Na, CsI:Tl, NaI:Tl, YAlO₃:Ce, Y₃Al₅O₁₂:Ce, ZnWO₄)
- Hitachi Chemical (Gd₂SiO₅:Ce)
- Radiation Sensors (NaI:Tl)
- Rexion (Bi₄Ge₃O₁₂, Lu₂SiO₅:Ce, LaBr₃:Ce, CsI:Tl, NaI:Tl)
- Saint-Gobain Crystals (BaF₂, Bi₄Ge₃O₁₂, LaBr₃:Ce, CdWO₄, CaF₂:Eu, CsI:Na, CsI:Tl, Lu_{1.8}Y_{0.2}SiO₅:Ce, NaI:Tl, Y₃Al₅O₁₂:Ce, ZnS:Ag)
- ScintiTech/Amcrys (NaI:Tl, CsI:Na, CsI:Tl, CsI:CO₃)
- Scionix Holland (NaI:Tl, CsI:Tl, LiI:Eu, BaF₂, YAlO₃:Ce, Gd₂SiO₅:Ce, Bi₄Ge₃O₁₂, CdWO₄)

Scintillator Cost
(depends on the
size of element)
(\$/cc) [2019]

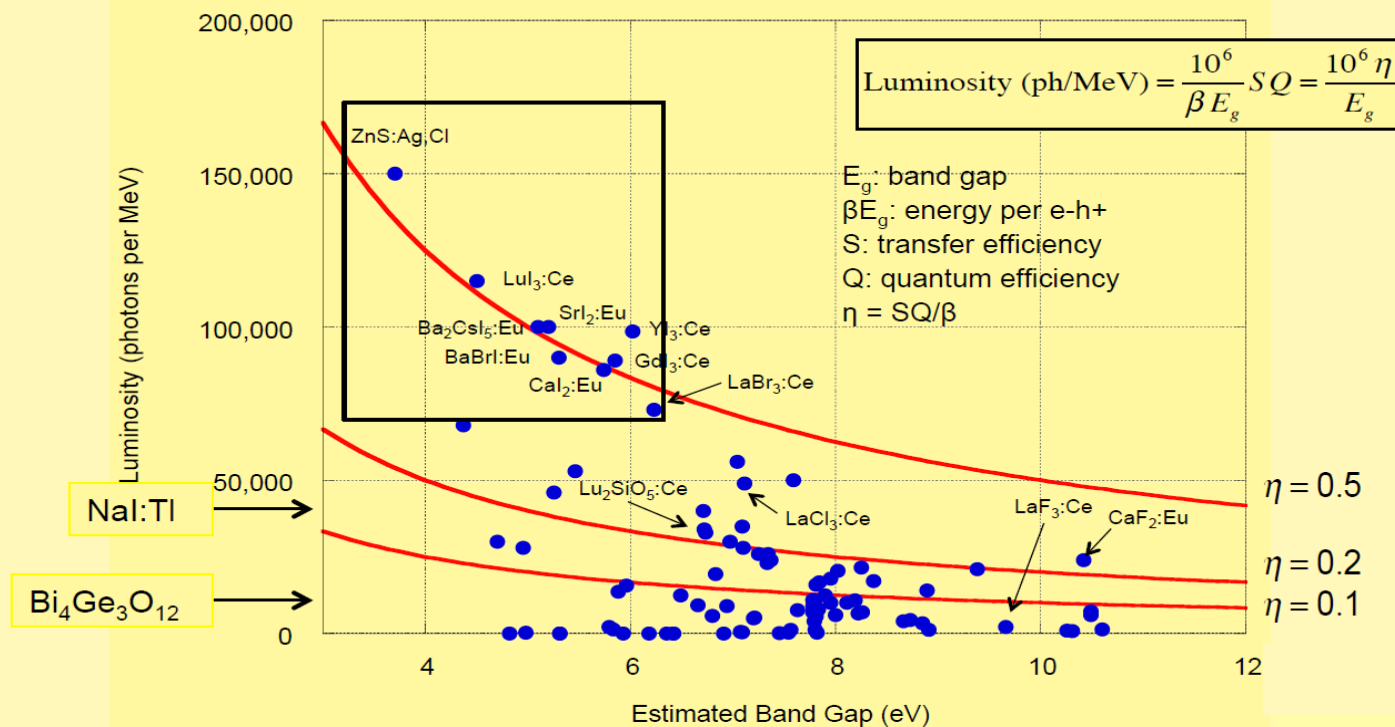
LaBr:Ce	75-150
SrI:Eu	75-150
GAGG:Ce	250-600
NaI:Tl	2
CsI:Tl	4
LYSO:Ce	50-75
BGO	10-15

01 방사선 검출기 기술

» 섬광체 단결정 특성

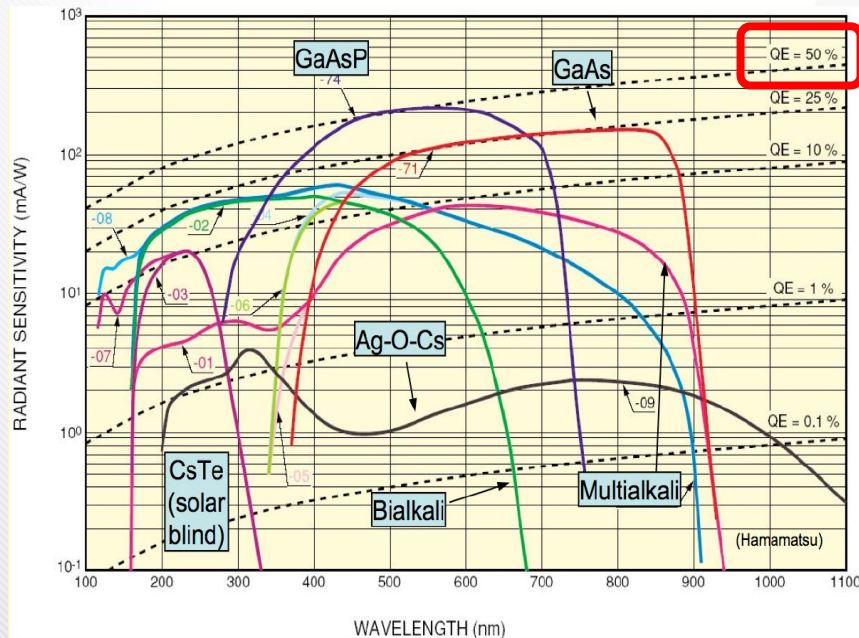
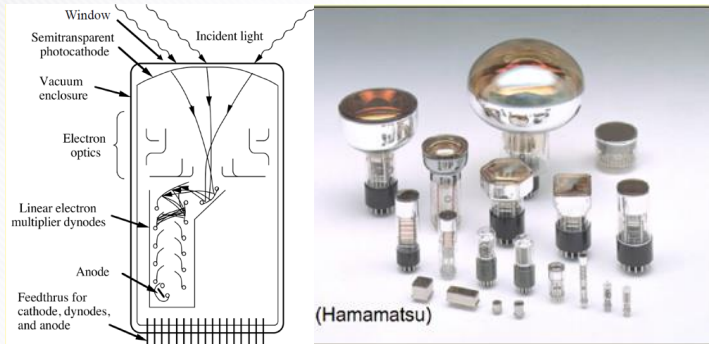
Requirements for High Performance Scintillators

- Good stopping power → density, effective atomic number
- High luminosity → low bandgap, $S \sim 1$, $Q \sim 1$
- Good energy resolution → Luminosity, Proportional Response, Uniform Response
- Decay time → Ce^{3+} 20-60 ns; Eu^{2+} 500-2000 ns

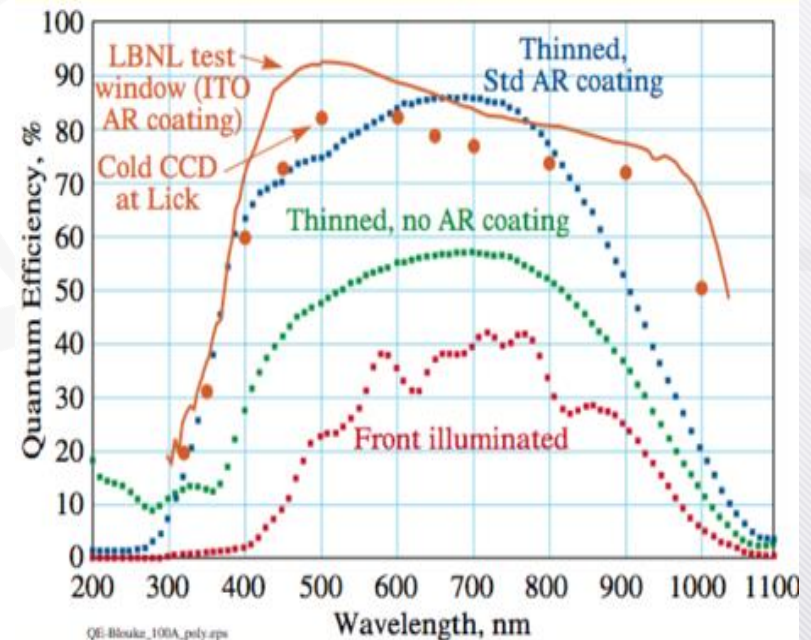
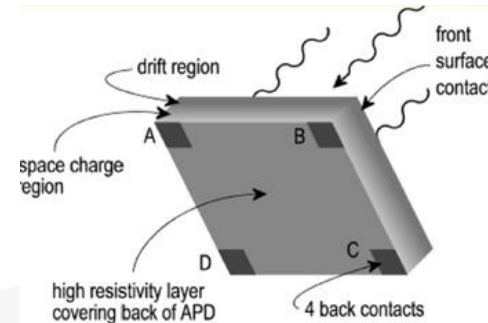


01 방사선 검출기 기술

» 섬광체용 광검출기 특성



Quantum efficiency for photocathode <PMT>



Quantum efficiency for photodiode

01 방사선 검출기 기술

» 화합물반도체 현황 및 특성

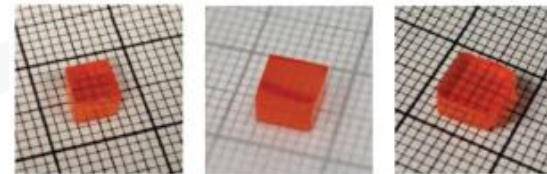
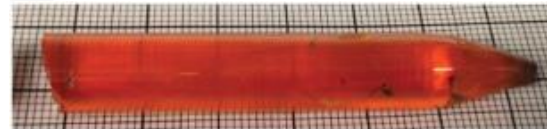
Physical properties of the principal compound semiconductors at $T = 25^\circ\text{C}$.

Material	Si	Ge	GaAs	CdTe	$\text{Cd}_{0.9}\text{Zn}_{0.1}\text{Te}$	HgI_2	TlBr
Crystal structure	Cubic	Cubic	Cubic (ZB)	Cubic (ZB)	Cubic (ZB)	Tetragonal	Cubic (CsCl)
Growth method*	C	C	CVD	THM	HPB, THM	VAM	BM
Atomic number	14	32	31, 33	48, 52	48, 30, 52	80, 53	81, 35
Density (g/cm^3)	2.33	5.33	5.32	6.20	5.78	6.4	7.56
Band gap (eV)	1.12	0.67	1.43	1.44	1.57	2.13	2.68
Pair creation energy (eV)	3.62	2.96	4.2	4.43	4.6	4.2	6.5
Resistivity ($\Omega\text{ cm}$)	10^4	50	10^7	10^9	10^{10}	10^{13}	10^{12}
$\mu_e\tau_e$ (cm^2/V)	> 1	> 1	10^{-5}	10^{-3}	$10^{-3} - 10^{-2}$	10^{-4}	10^{-5}
$\mu_h\tau_h$ (cm^2/V)	~ 1	> 1	10^{-6}	10^{-4}	10^{-5}	10^{-5}	10^{-6}

* The more common growth methods: C = Czochralski, CVD = chemical vapor deposition, THM = traveler heater method, BM = Bridgman method, HPB = high-pressure Bridgman and VAM = vertical ampoule method



CdTe/ CdZnTe



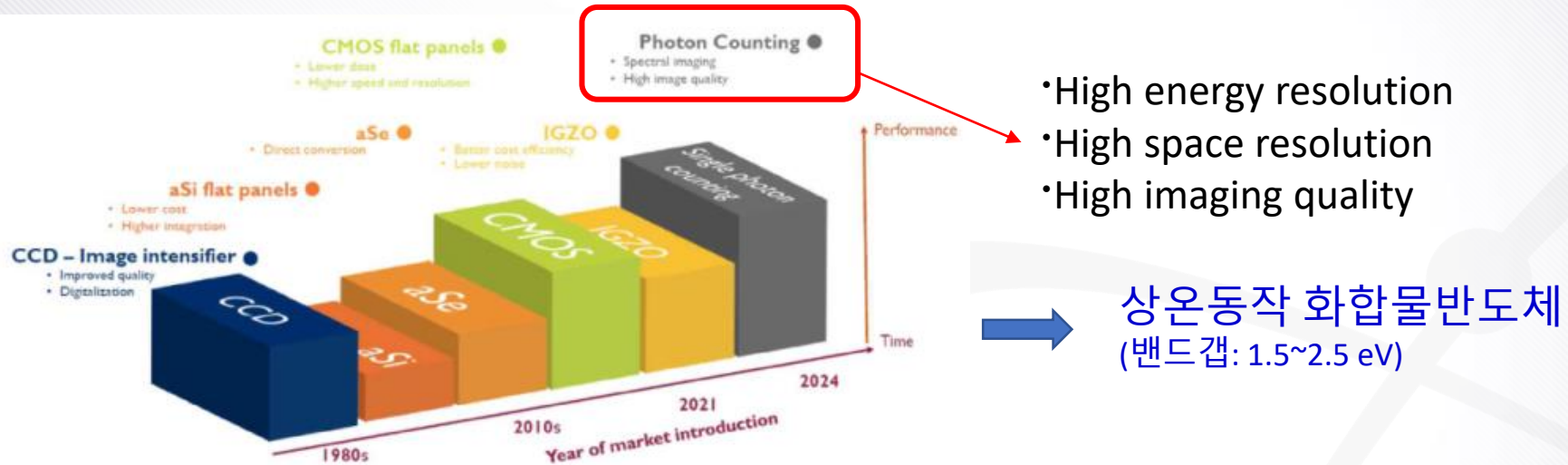
Perovskites



TlBr

01 방사선 검출기 기술

» 방사선검출기 기술 개발 방향 및 화합물반도체 단결정 소재 기업 M&A현황



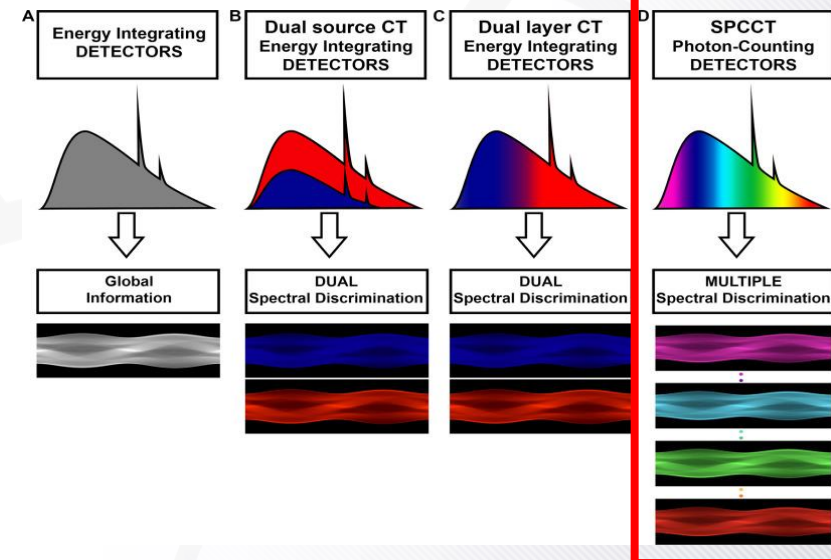
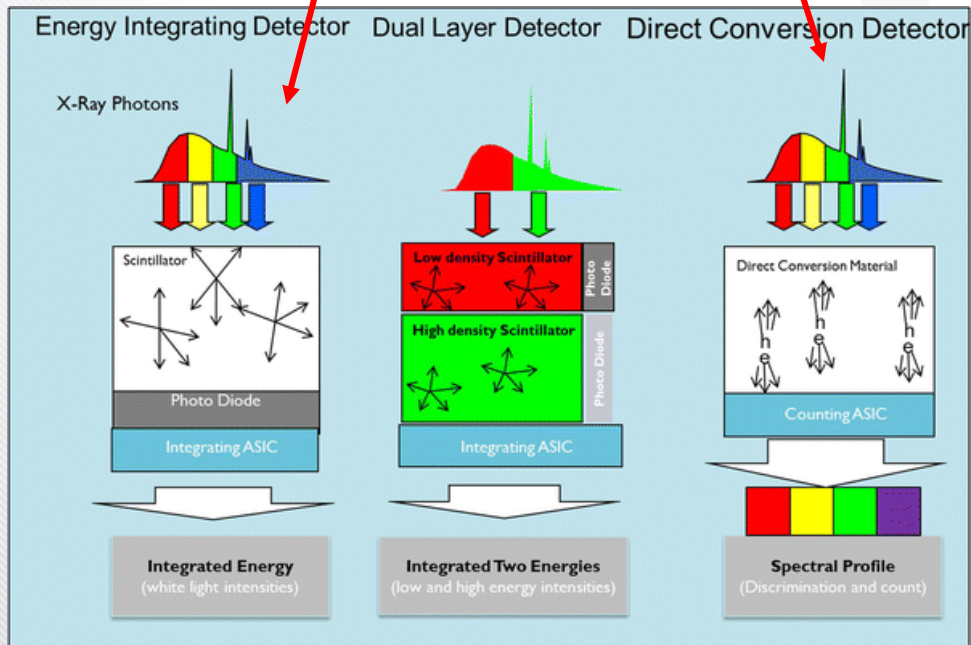
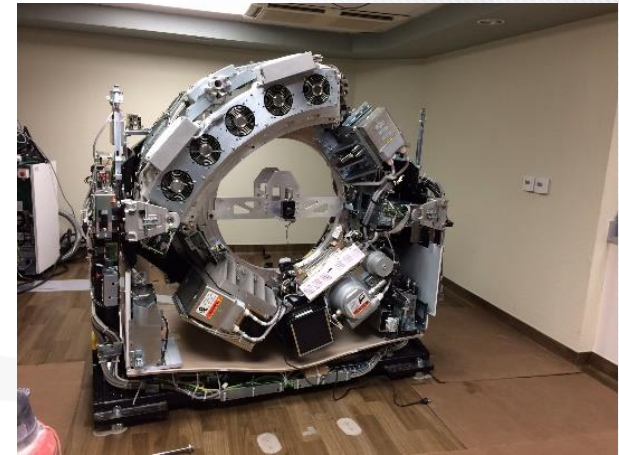
<방사선계측기, 의료기기 글로벌 기업의 화합물반도체 단결정 소재 생산기업 M&A 현황>

	Company	Country	First works	Merged (M&A)
1	eV products Inc.	USA	Detector-grade CdZnTe	Kromek Inc. (UK)
2	Acrorad	Japan	Mass production of CdTe	Siemens (Germany), 2011
3	Orbotech medical solutions Ltd.	Israel	Fabrication of photo-counting CT with GE	GE (USA), 2010
4	Redlen	Canada	Mass production of CdZnTe	Canon (Japan), 2021.09

*출처: Solid State Sensors to shape the future of Medical Imaging, Yole Development (2019)

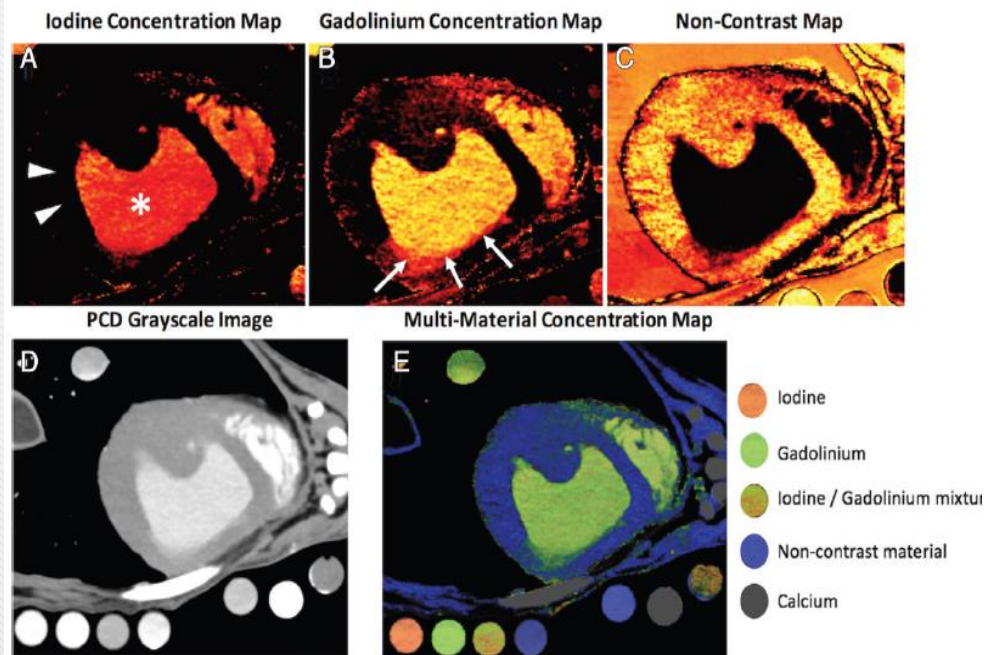
01 방사선 검출기 기술

» Photon-counting CdZnTe detector - Importance and application in Medical CT

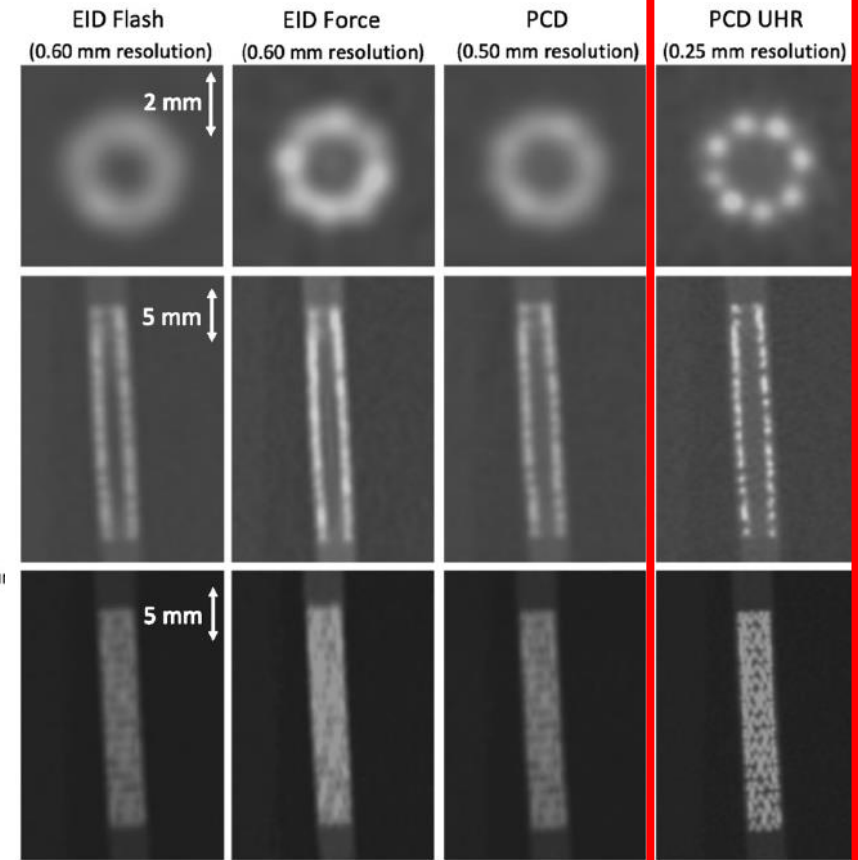


01 방사선 검출기 기술

» Photon-counting CdZnTe detector - Importance and application in Medical CT



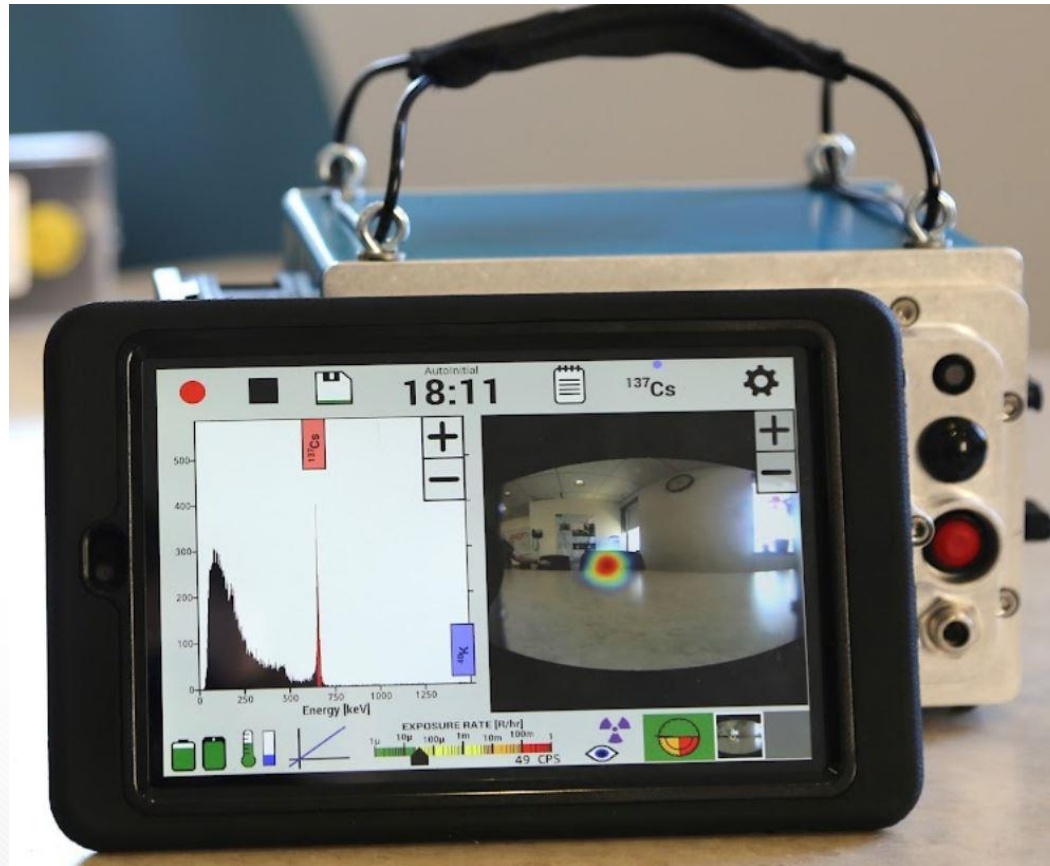
<K-edge images with various contrast agent>



<Comparison of images with different CT detectors>

01 방사선 검출기 기술

» Room-temperature RI identifier - Importance and application in Radiation Monitoring Field



<Polaris from H3D®>

02 방사선기기팍 시설·장비

02 방사선기기팹 소개

» 시설소개

방사선기기 팹(FAB) 센터
(70 여종 연구/제작 장비, 2017년 운영 개시)

방사선 센서 및 계측기 FAB

- 단결정 성장실
- 단결정 가공실/평가실
- 반도체형 방사선센서 제작실
- 방사선 센서 성능평가실

발생장치 및 융복합 기기 FAB

- 전자총/가속관 조립실
- 고/저에너지 가속기시험실
- 고주파 발생장치 시험실
- 대형기기 시험검사실



단결정 성장실



- 항온항습실
- 정제로 (2)
- 초클라스키 (2)
- 일방향 응고로 (8)
- 시료 보관함 (1)
- 석영관 보관함 (1)
- 소형 밀링 (1)

반도체 공정실



- 크린룸 (Class 100, Class 1,000)
- 마스크 제작장비 (1)
- 리소그래피장비 (2)
- 스피너 (2)
- 습식에칭장비 (2)
- 화학증착기 (3)
- 열증착기 (2)
- 에칭기 (2)
- E-beam 장비 (1)

단결정 가공실



- Polisher (4)
- Wire Saw (5)
- Glove box (3)
- Wet bench (2)
- 시약장 (4)
- 석영관 가공장비 (2)
- 탄소코팅로 (4)

센서 성능평가실



- 적외선 분광기 (1)
- 자외선 분광기 (1)
- 전기특성분석기 (1)
- 오실로스코프 (4)
- 방사선 스펙트럼 분석기 (4)
- 고도장치 (1)
- 탁상형 SEM (1)
- 표면 분석기 (1)

9 MeV 시험실



- 컨테이너 검색기 시험
- 항공용 복합방사선 보안검색기 시험
- 9MeV 전자가속기
- 15 MeV 전자가속기
- 9 MeV X-선 차폐
- 14 MeV 중성자 차폐

15 MeV 시험실



- 미사일 비파괴검사 시험
- 15MeV 전자가속기
- 15 MeV X-선 차폐
- **DT generator**

02 방사선기기팸

» 반도체 공정실 / 소재 성장실

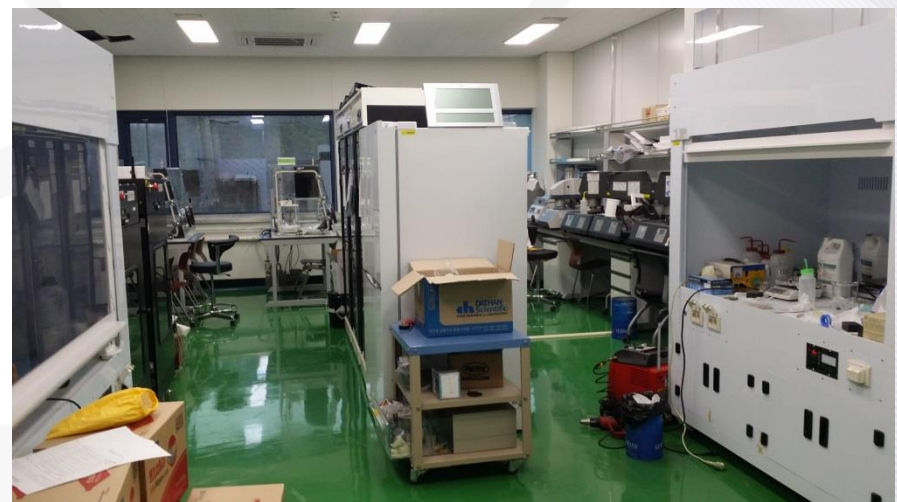
실험실명	사용 용도	배치된 주요 장비명
반도체형 공정실 (100 class)	리소그래피 공정	Laser Mask Maker , Mask Aligners , Mask Spin Coaters, Hot Plates, Wet Station, Spin-Rinse-Dry
	증착 공정	Furnaces (Oxide, POCl), Low-pressure CVD, Plasma-enhanced CVD, Thermal Evaporator E-beam Evaporator, Sputter, Rapid Thermal Annealer, Plasma Asher
	에칭 공정	Deep Reactive-Ion Etcher, Wet Stations, Spin-Rinse-Dry
소재 성장실 (항온/항습)	정제로	High-vacuum Purification Furnace, Zone refining furnace
	섬광체 성장	Czochralski Furnace (2", 3")
	화합물 반도체 성장	Low -pressure Bridgeman Furnace, Travel Heat Method Furnace, Zone Melting Furnace, Sublimation Furnace



01 방사선기기팸

» 성능평가실 / 소재 성장 준비/가공실

실험실명	사용 용도	배치된 주요 장비명
방사선 센서 성능 평가실	방사선센서 특성 평가	Ellipometer, Infra-red Mapper, UV Measurement Equipment, I-V, C-V Measurement Equipment, NIM Modules, 4GHz Oscilloscope, Electrometer, Charge Mobility Measurement System
	방사선센서 패키징	Flip-Chip Bump Bonder, Wire Bonder, Ball Bonder
방사선 센서 소재 준비/가공실	Quartz 튜브 가공	Quartz Tube Sealing System, Quartz Tube Cutting System
	센서 재료 가공	Carbon Coating Furnace, Automatic Polishers, Diamond Wire Saws



03 방사선기기팩 활용 기술

03 방사선기기팩 활용기술

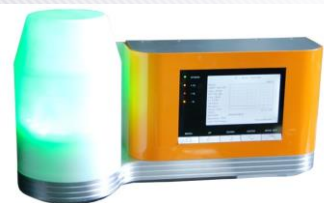
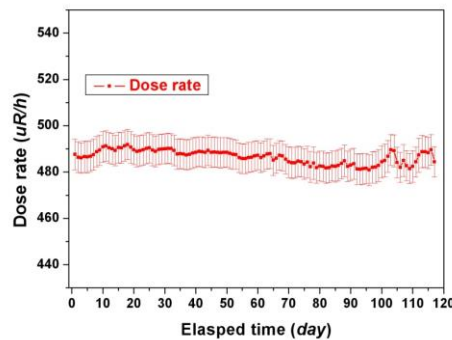
Cylindrical 이온챔버

- 방사선 시설 모니터링



<I.C. for RMS>

- ◆ Active vol.: 11.8 L
- ◆ Filling Gas: Dried Air
- ◆ Sensitivity: $4.0 \times 10^{-10} \text{ A/R/h}$ @ ^{226}Ra
- ◆ Range: $10^{-2} \sim 10^7 \text{ mR/h}$
- ◆ Application : Radiation monitoring for nuclear facility



<I.C. for RMS>

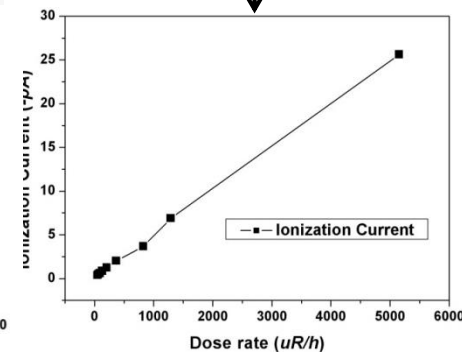
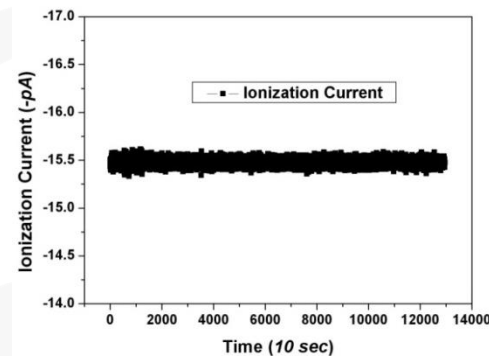
고압 이온챔버

- 환경방사능 모니터링



<I.C. for Proton Beam Intensity>

- ◆ Active vol.: 8.5 L
- ◆ Filling gas : Ar, 25 atm
- ◆ Insulator : ceramic
- ◆ Sensitivity:
 $2.6 \times 10^{-14} \text{ A/R/h}$ @ ^{226}Ra
- ◆ Shadow shielding tech.



03 방사선기기팩 활용기술

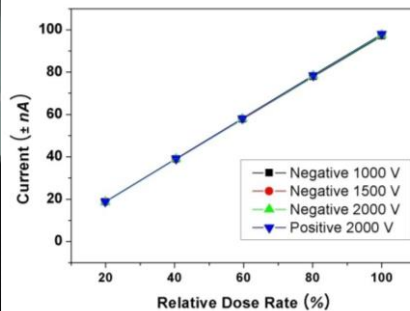
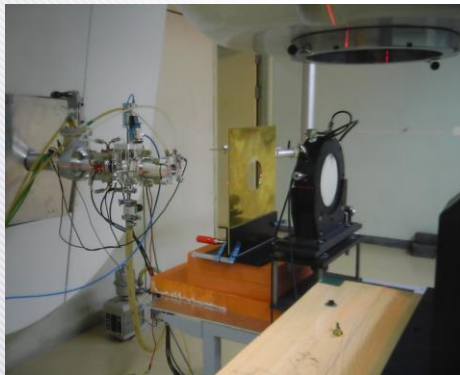
평판형 이온챔버

- 230 MeV proton beam intensity monitor



<I.C. for Proton Beam Intensity>

- ◆ Electrode :
Aluminized Mylar
- ◆ Filling gas :Ar
- ◆ Insulator : G-10
- ◆ Energy loss @ 230 MeV : 0.045% (~100 keV)



<linearity>

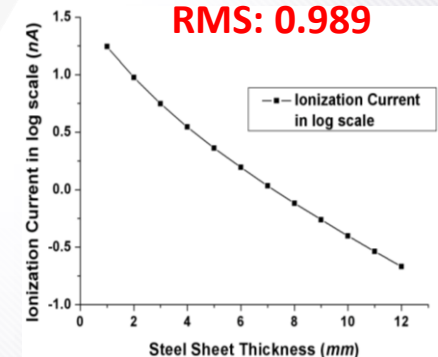
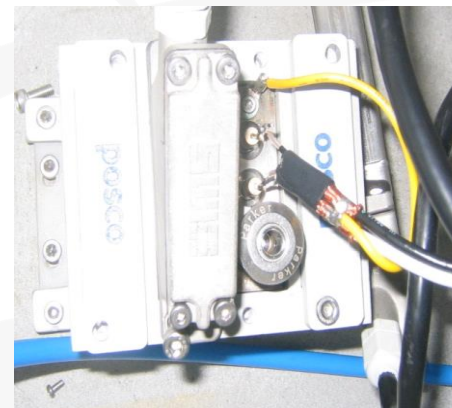
(Industrial Appl.) 철판두께 측정 이온챔버

- Steel sheet thickness Monitor (POSCO Kwangyang)



<I.C. for Steel sheet thickness>

- ◆ Electrode: Stainless steel
- ◆ Insulator : ceramic
- ◆ Thickness of an incident window : 0.5 mm
- ◆ Filling gas: Xe @ 6 atm

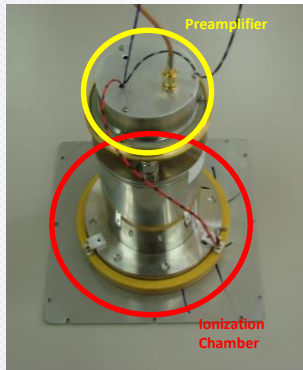


<linearity>

03 방사선기기팩 활용기술

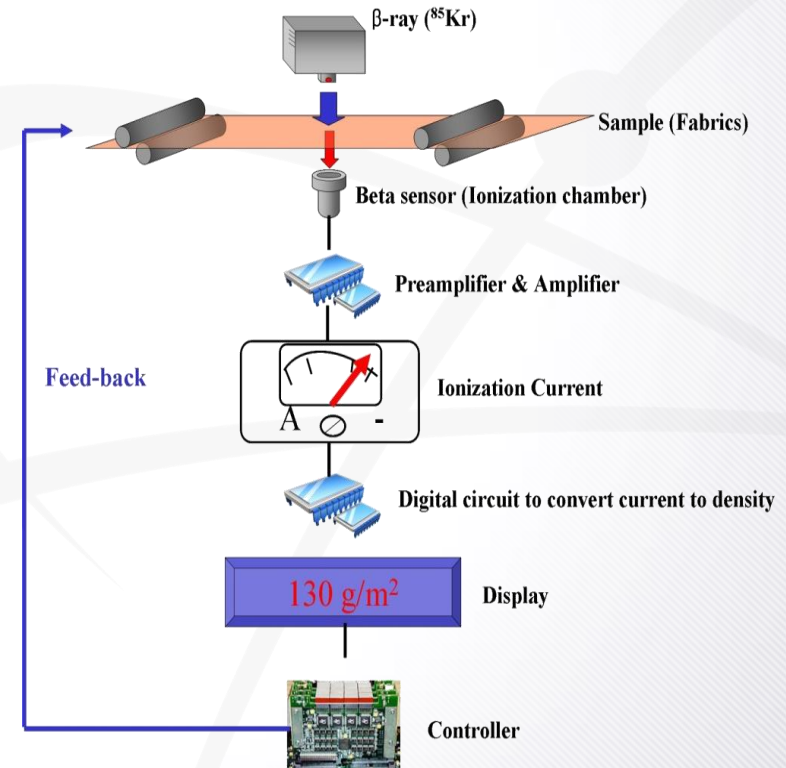
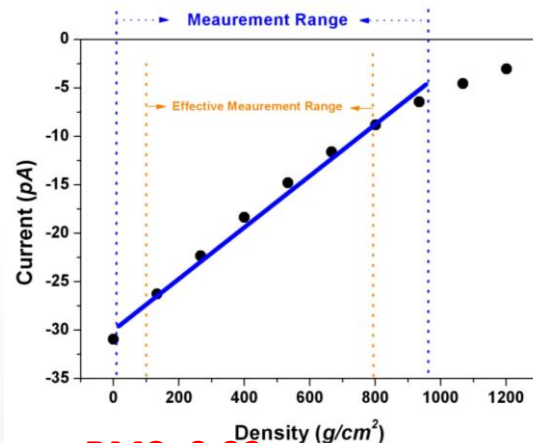
(Industrial Appl.) 섬유 밀도 측정 이온챔버

- 베타선 (Kr-85) 이용



<I.C. for fabric density>

- ◆ Incident window : Al Mylar
- ◆ Guard electrode
- ◆ Filling gas: Xe @ 1 atm
(W-value : 21 eV/ion pair)

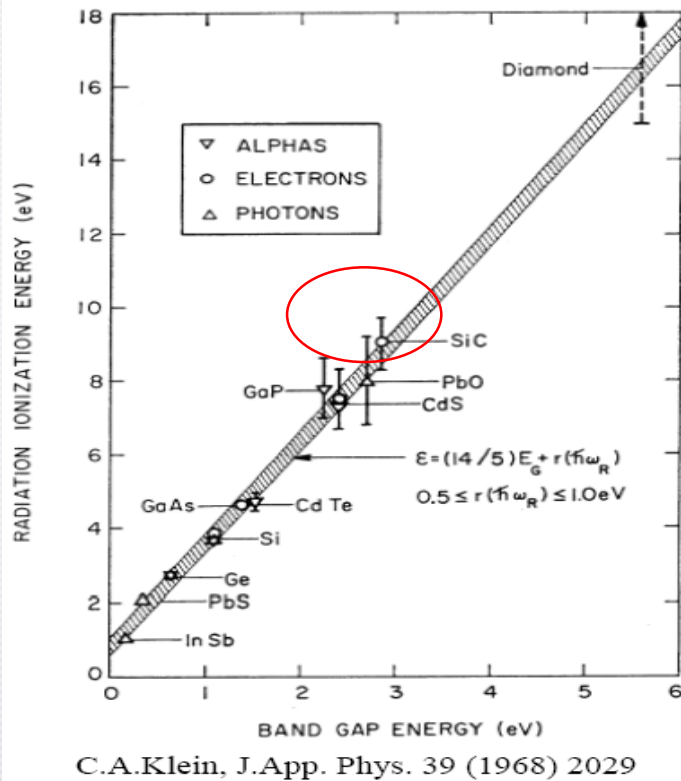


<섬유 밀도 측정 시스템>

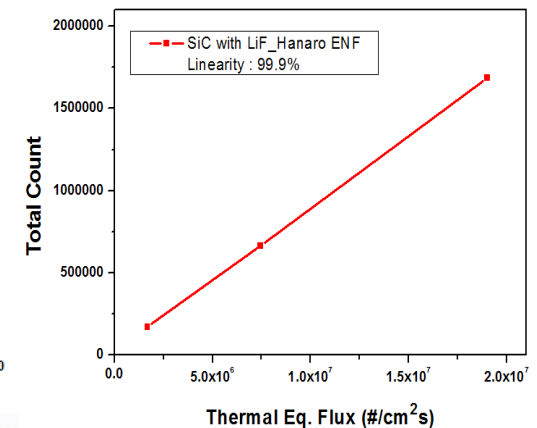
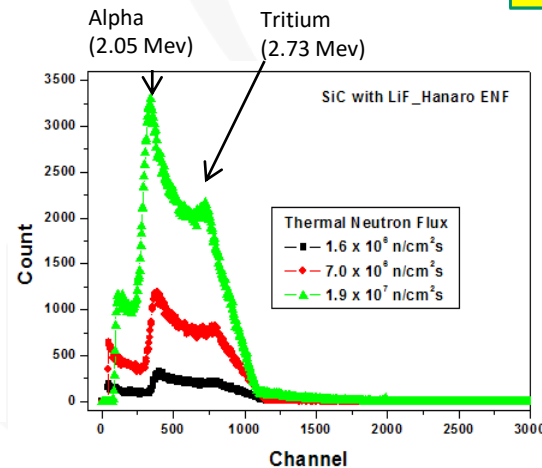
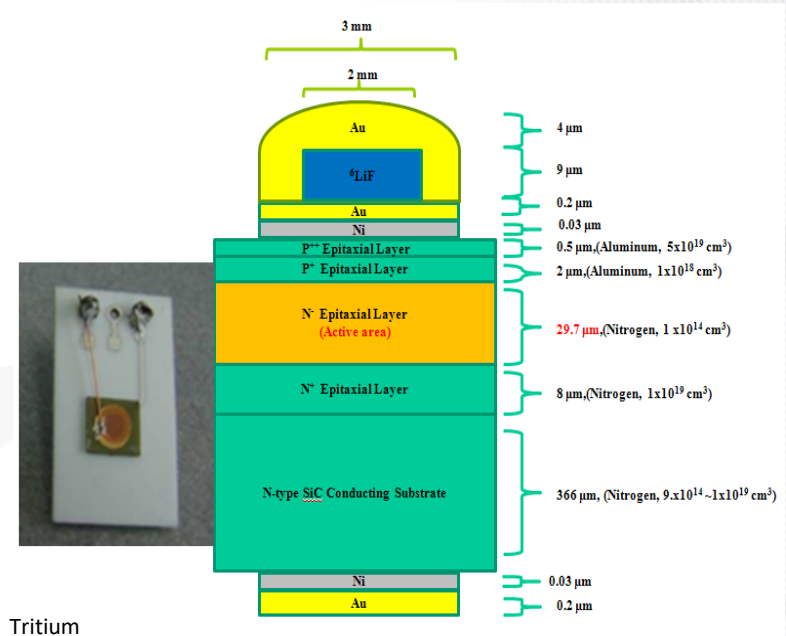
03 방사선기기팩 활용기술

SiC 기반 중성자 센서

- Development of SiC neutron detector by using ^6LiF .



- Wide band-gap
- High radiation resistance and thermal conductivity ($\sim 800\text{K}$)
- High physical and chemical stability



03 방사선기기팩 활용기술

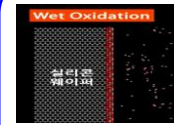
Si PIN 센서 제작기술개발

섬광체 결합형 Si PIN 광센서 개발

- 고효율 광센서 설계/제작기술 개발

저에너지 X-ray 및 Gamma-ray 검출용 Si PIN 센서 개발

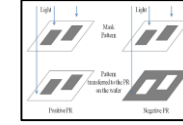
- 저노이즈, 고분해능 Si 반도체센서 설계/제작기술 개발



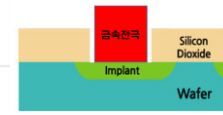
<성막공정>



<식각공정>



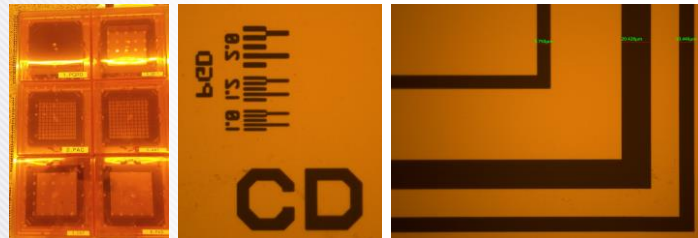
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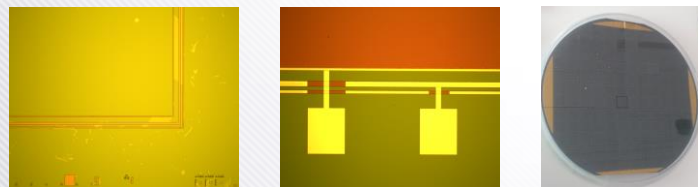
<전극공정>

Si PIN 센서 제작공정
(Fabrication process of Si PIN)

단위공정결과물 (Process results of Si PIN)



<포토마스크제작_6mask 공정>

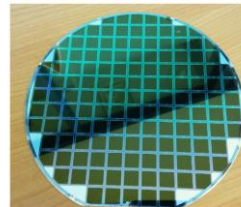


<가드링 에칭>

<전극형성>

<다이싱>

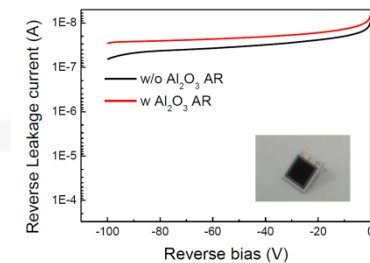
Si PIN센서 특성 (Characteristics of Si PIN)



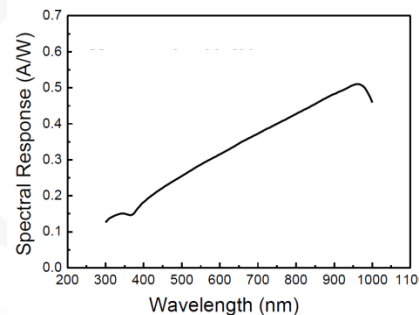
Si PIN Device Array



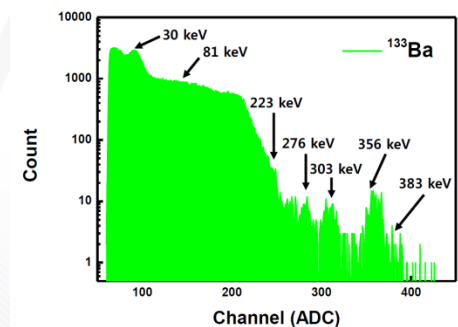
Wire bonding된 Si PIN



<전기적 특성>



<광 특성>

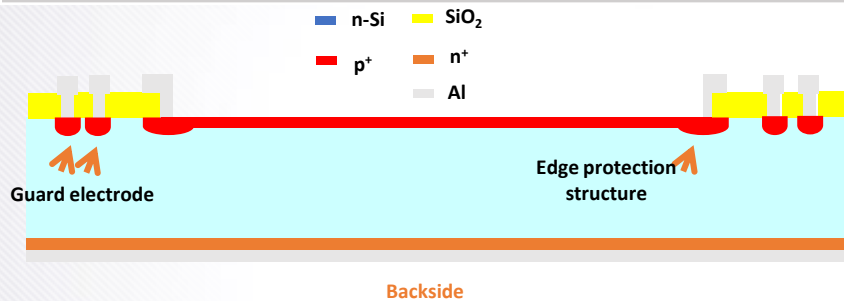


<방사선 반응>

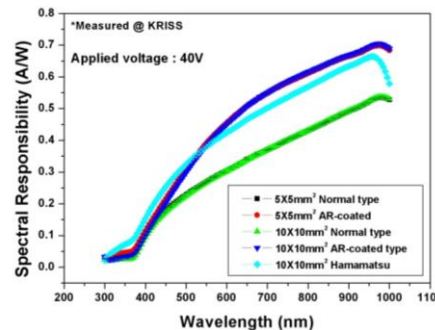
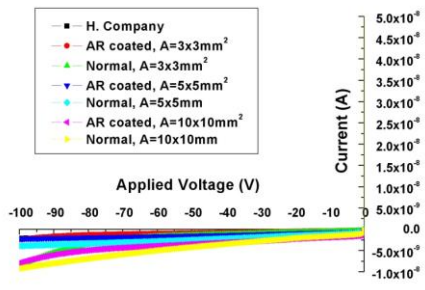
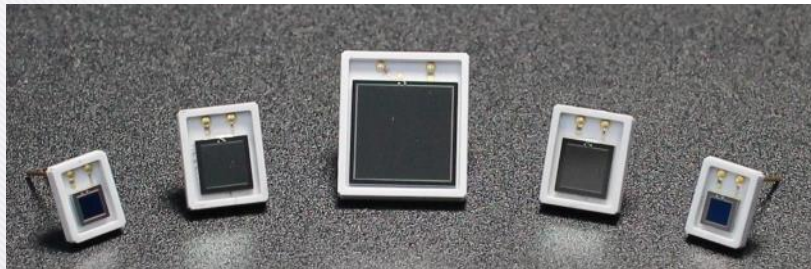
03 방사선기기팩 활용기술

PIN photodiode 반도체 센서

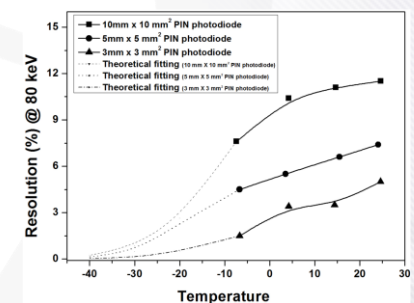
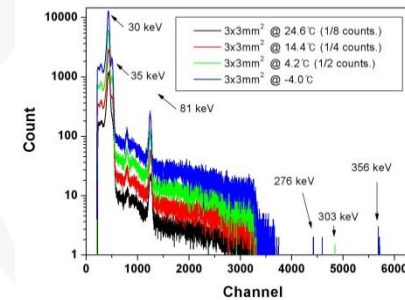
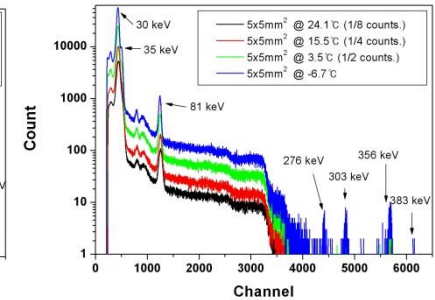
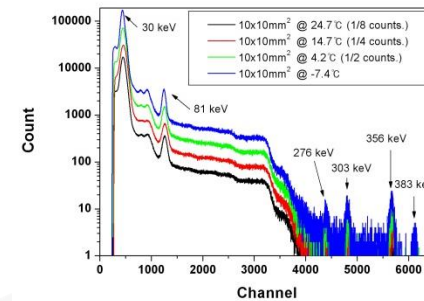
- Active area
10mm X 10mm, 5mm X 5mm, 3mm X 3mm
- TEM(Thermo-electric Module)



- A Basic Structure of a design of a PIN-type radiation detector-



Ba-133



<Pulse Height Spectra with respective to Temp.>



<Prototype of a portable XRF>

03 방사선기기팩 활용기술

(Appl.) PIN photodiode 반도체 센서

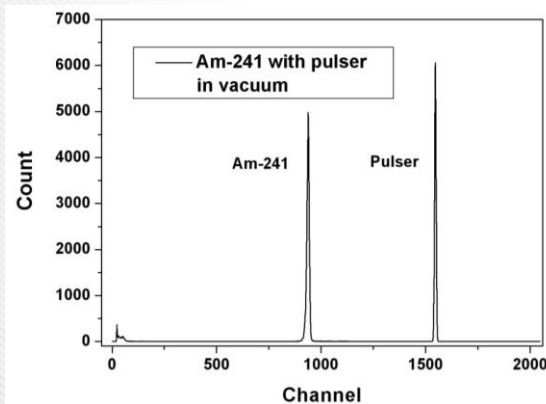
- Radon detector

* Uranium concentrated soli source (from KRISS)

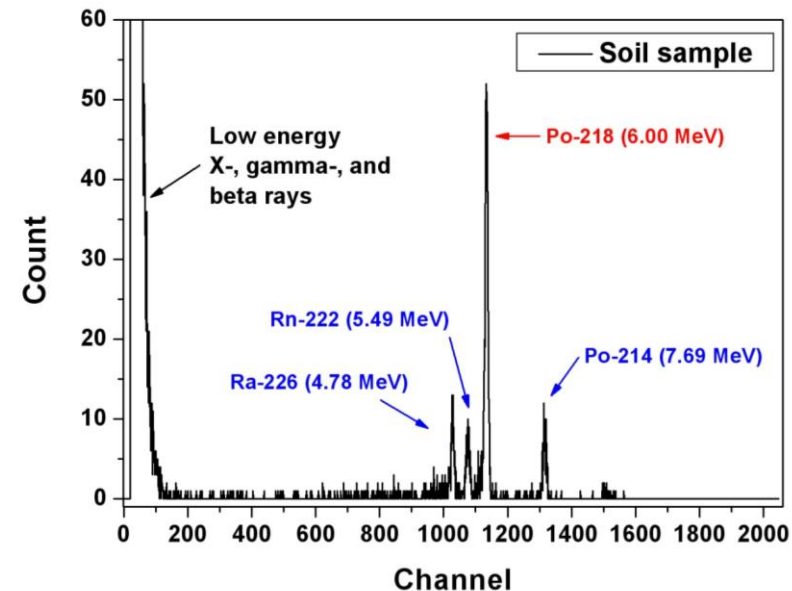
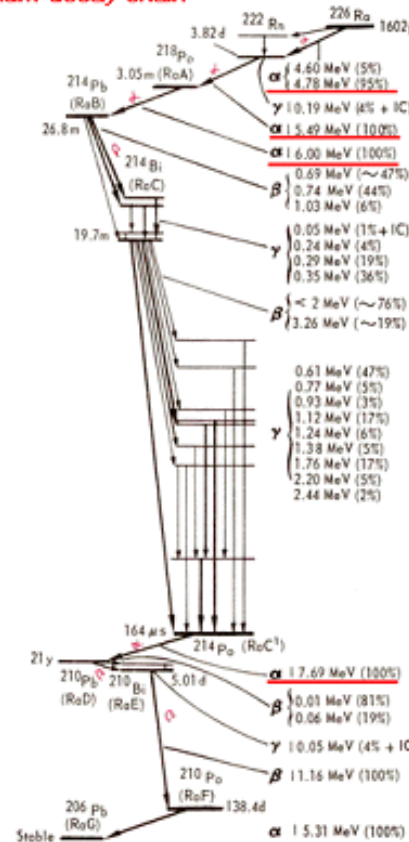
- ^{226}Ra concentration : 5.6 Bq/g

- Emanation rate : 25%

R = 0.9% @ 5.49 MeV



- Radium decay chain-



- 40 V @ 5.49 MeV alpha particle in vacuum-

- Sensitivity: 0.3 (cpm/pCi/L) -

03 방사선기기팩 활용기술

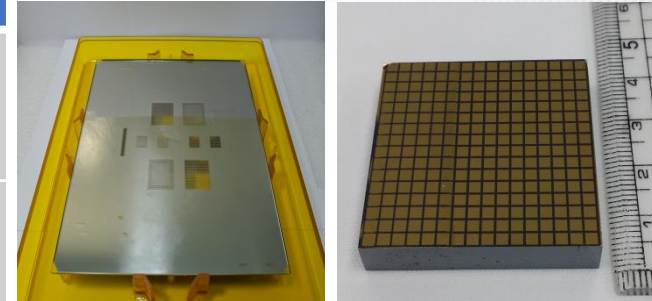
Cd(Zn)Te 핵분광용 대구경 단결정 성장

Cd(Zn)Te 단결정 성장기술 개발

- Cd(Zn)Te 단결정 성장을 위한 전처리 기술개발
- Cd(Zn)Te 단결정 성장 및 재료특성평가 기술개발

16X16 픽셀급 CdZnTe 영상센서 모듈 설계/제작기술개발

- Cd(Zn)Te 화합물반도체 단결정 방사선 성능평가 기술개발
- Lithography법을 이용한 CdZnTe 영상센서 설계/제작



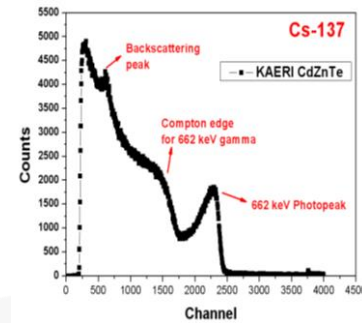
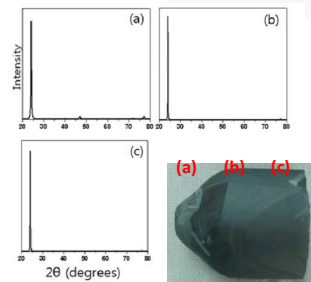
Lithography법을 이용한 영상센서 제작



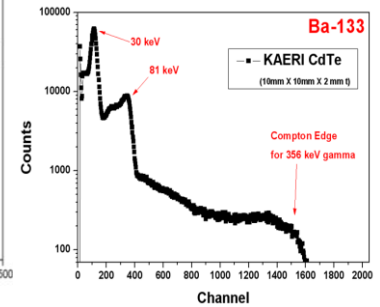
고순도 CdZnTe 성장을 위한 carbon coated quartz tube



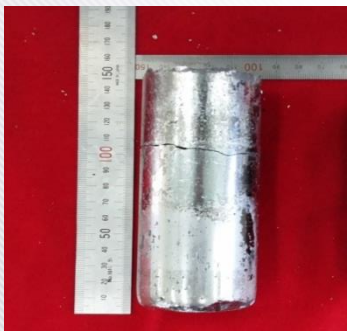
브릿지만법을 이용한 3\"/>



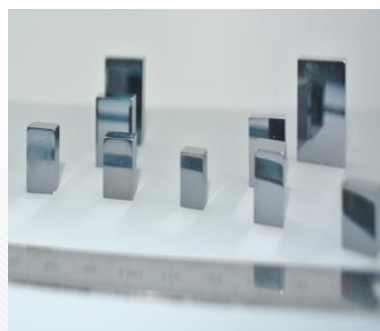
Planar-type CdZnTe



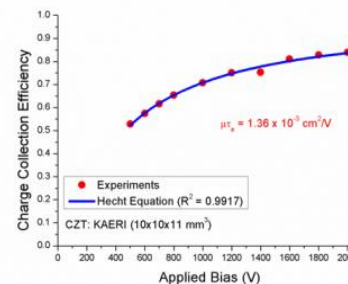
Planar-type CdTe



THM법을 이용한 CdZnTe 단결정

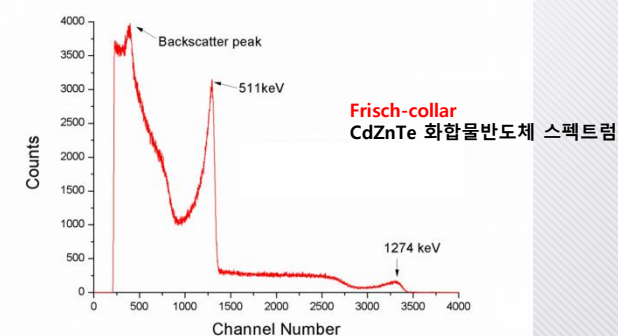


CdZnTe 단결정



전자 이동도 특성평가

<CdZnTe 단결정 재료 특성평가>



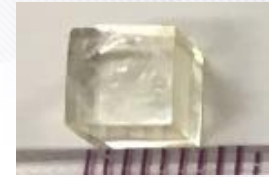
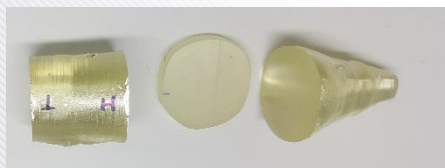
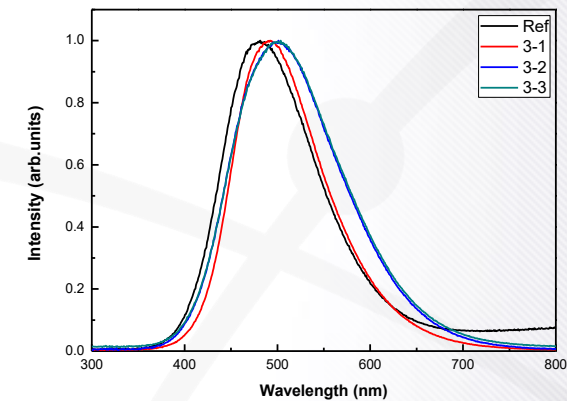
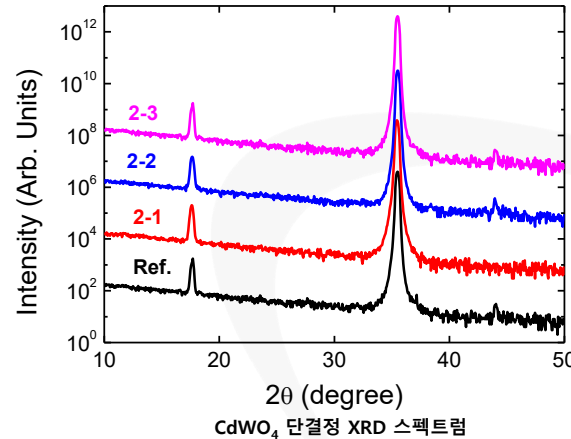
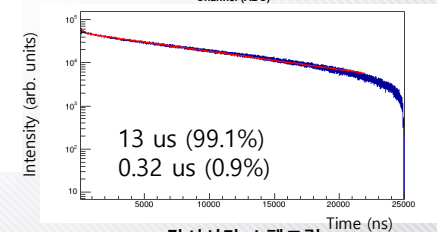
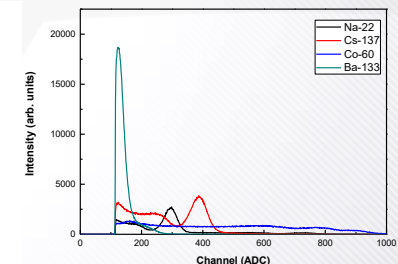
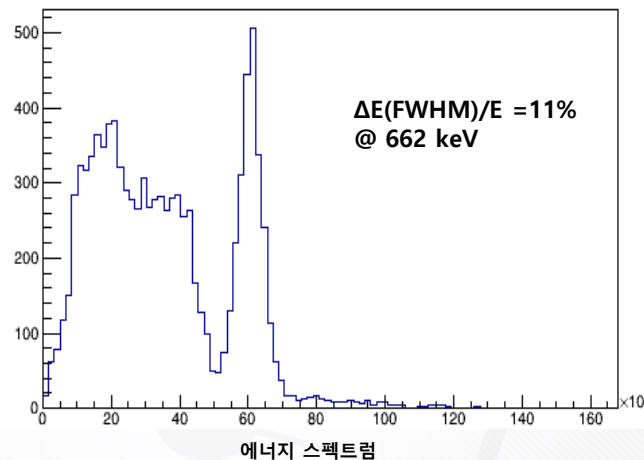
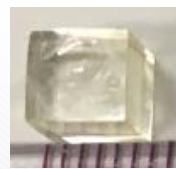
<CdZnTe 단결정 방사선 특성평가>

03 방사선기기팩 활용기술

CdWO₄ 핵분광용 단결정 성장

CdWO₄ 단결정 성장기술 개발

- CdWO₄ 단결정 성장을 위한 전처리 기술개발
- CdWO₄ 단결정 성장 및 재료특성평가 기술개발

초크랄스키법을 이용한 CdWO₄ 성장초크랄스키법을 이용한 CdWO₄ 단결정열처리 된 CdWO₄ 단결정가공된 CdWO₄ 단결정 샘플<CdWO₄ 섬광체 단결정 성장><CdWO₄ 단결정 특성평가>

03 방사선기기팩 활용기술

감마선 3차원 위치추적형 감마선 영상장치 개발 및 특성평가

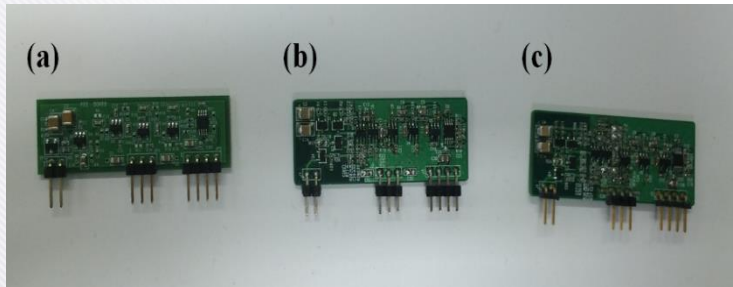
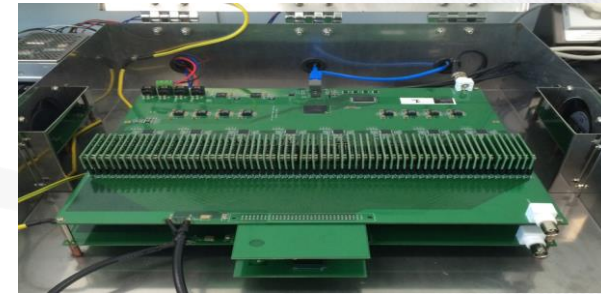
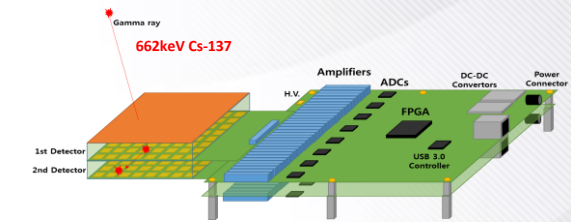
256 픽셀급 아날로그 신호처리 및 영상처리모듈 개발

- 잡음/이득 향상 및 선형성 확보 설계/제작기술 개발

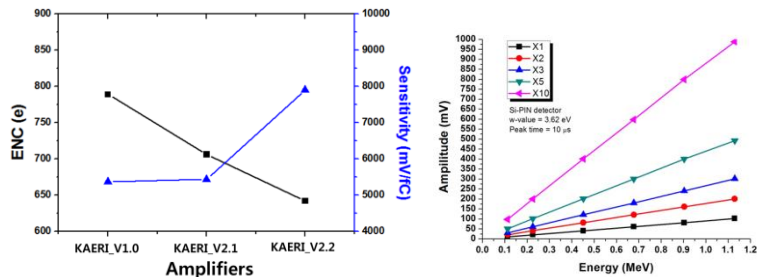
감마선 3차원 위치추적형 영상 센서 모듈 개발

- CdZnTe 화합물반도체 기반 256 픽셀급 영상센서 설계/제작기술 개발

감마선 3차원 위치추적형 감마선 영상장치 및 영상획득



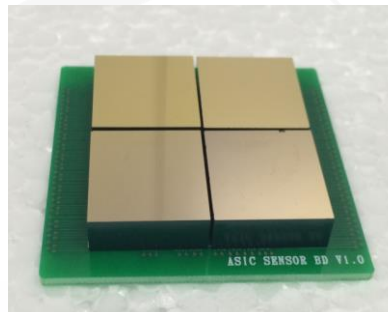
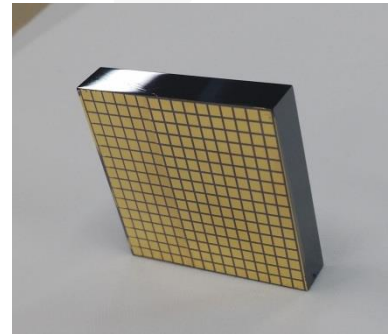
개발된 아날로그 신호처리 회로



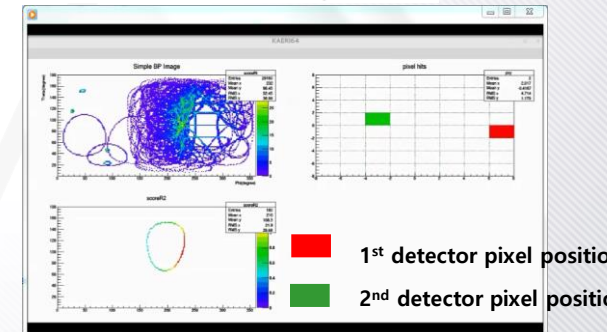
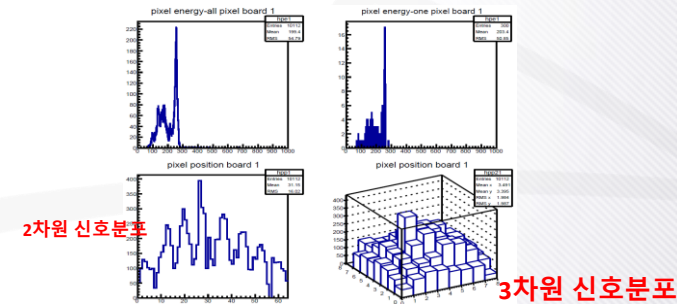
잡음 및 이득 비교

아날로그 신호처리회로의 선형성

<256 픽셀급 아날로그 신호처리 및 영상처리 모듈개발>



<영상센서 모듈>

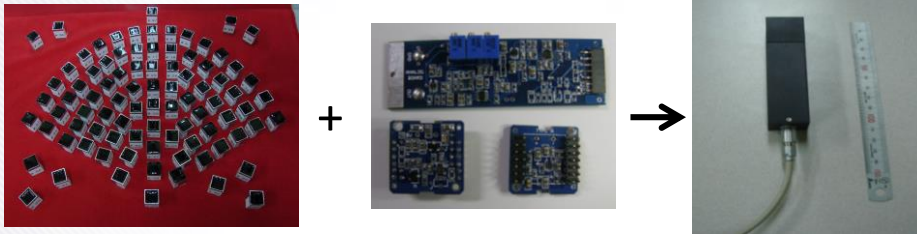


<3차원 위치추적 영상획득>

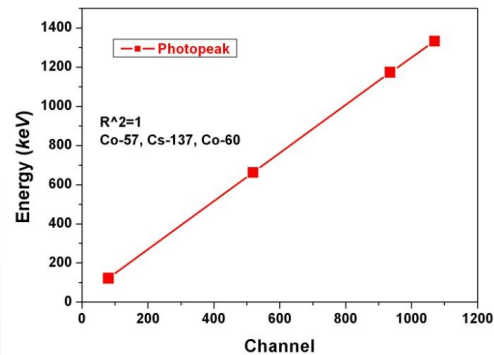
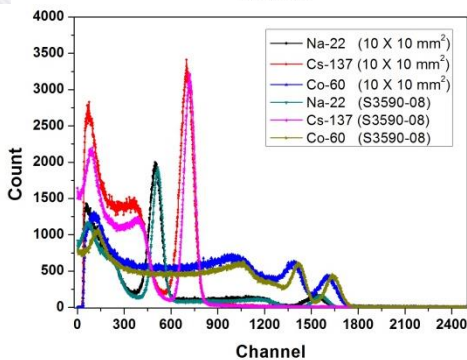
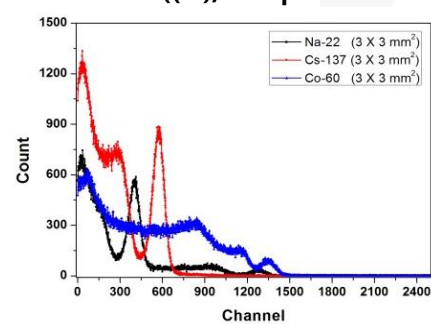
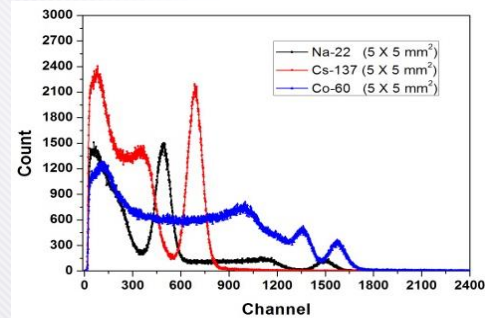
03 방사선기기팩 활용기술

(Appl.) CsI(Tl)/PIN photodiode detector

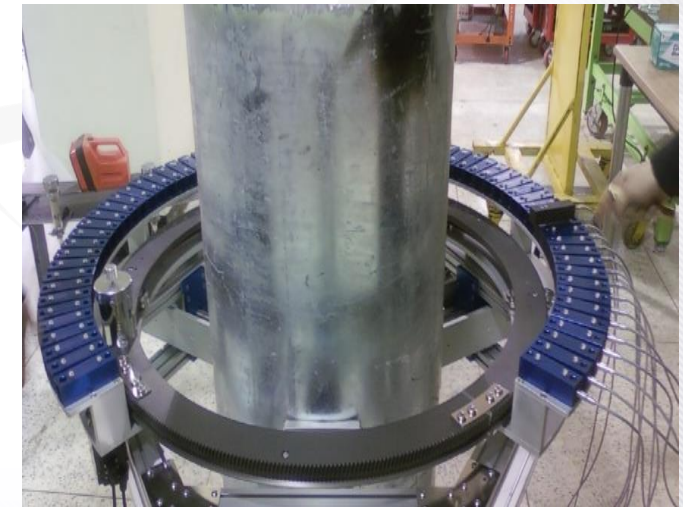
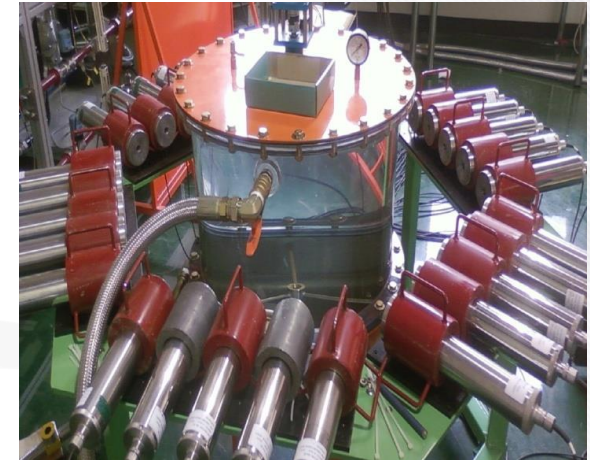
- CsI(Tl)/PIN photodiode + Preamplifier + Shaping Amplifier



<CsI(Tl)/PIN photodiode>



<Comparison of pulse Height spectra>



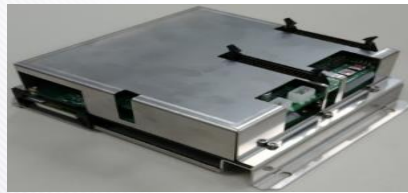
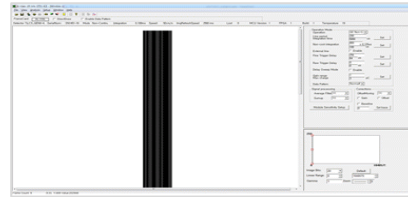
<Industrial CT>

03 방사선기기팩 활용기술

비파괴 검사용 이중에너지 x-선 및 고속중성자 영상모듈

➤ x-선 검출용 신호처리모듈 제작 및 시험

✓ 6 MV X-선을 이용한 팬텀 영상획득 예비 시험

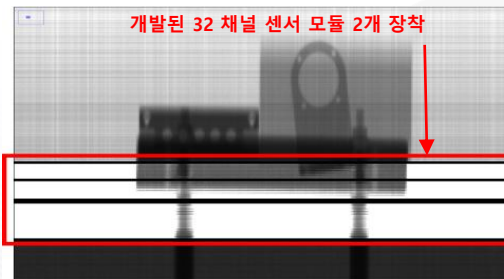


x-선용 영상센서 모듈

32채널 가시광 영상 획득



x-선 영상 획득용 팬텀



6 MV X-선 팬텀 영상

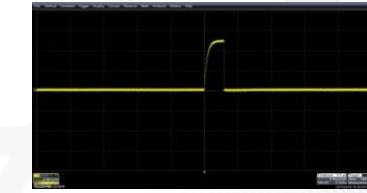
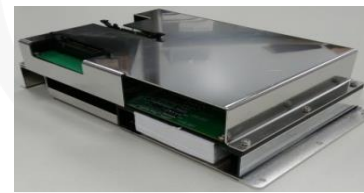
이중에너지 x-선 영상 획득 예비 시험

➤ 중성자 검출용 신호처리모듈 제작 및 시험

✓ 14 MeV 중성자 스펙트럼 획득

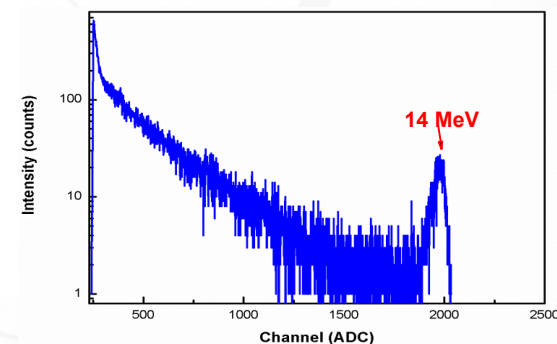


32채널 readout shaping amp 출력



32채널 readout discriminator 출력

중성자용 영상센서 모듈



14 MeV 중성자 에너지 스펙트럼

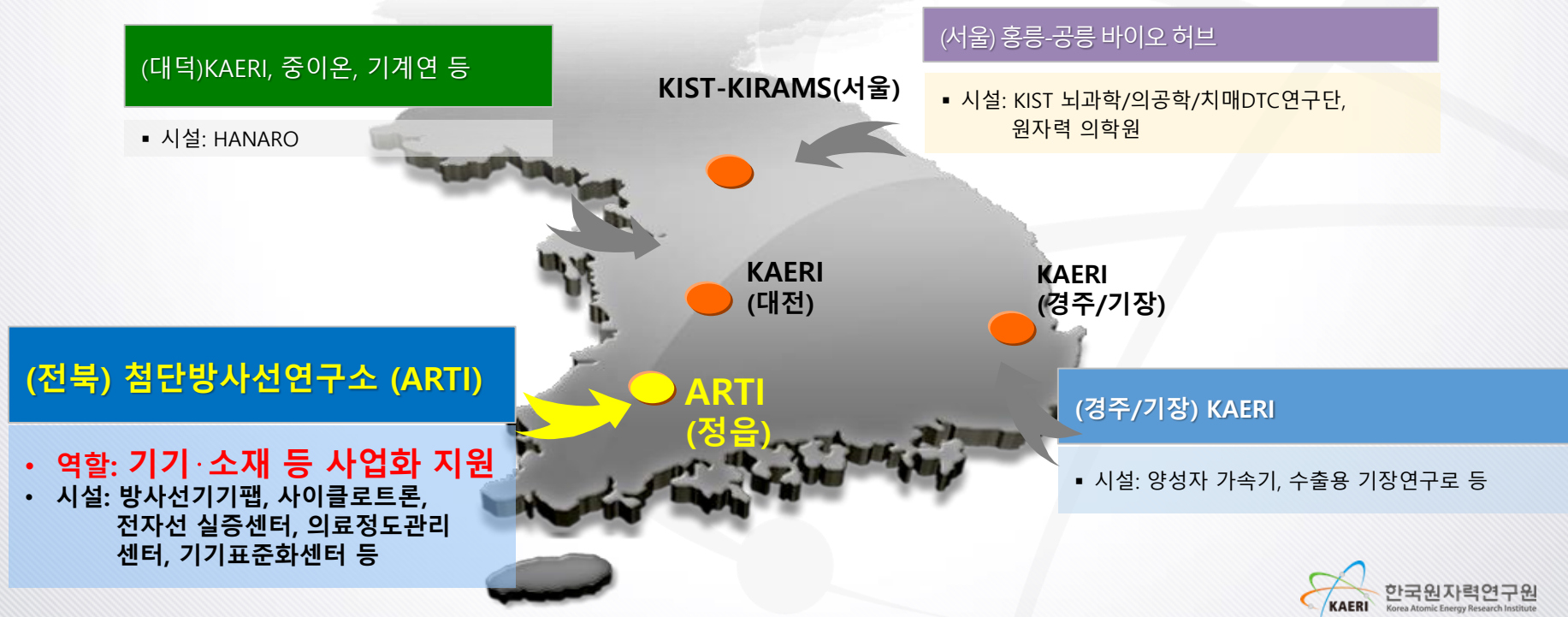
04 방사선기기 클러스터

04 클러스터 개요

- » 과기정통부는 국가균형발전의 일환으로
- 지역혁신체계 구축 → 지역별 대형 연구 인프라 중심 융복합 클러스터
 - 지역별 특화서비스 제공 → **방사선기술 기술사업화**

[추진근거] 과기정통부 “미래방사선 산업창출 전략(‘19)”, 신정부 정부-지역 R&D 강화

<4대 권역별 방사선 클러스터>



04 방사선기기 클러스터



감사합니다