Development of next generation Far- and Mid- infrared detectors

Development of Germanium blocked-impurity-band (BIB) detector with Molecular Beam Epitaxy (MBE) technique

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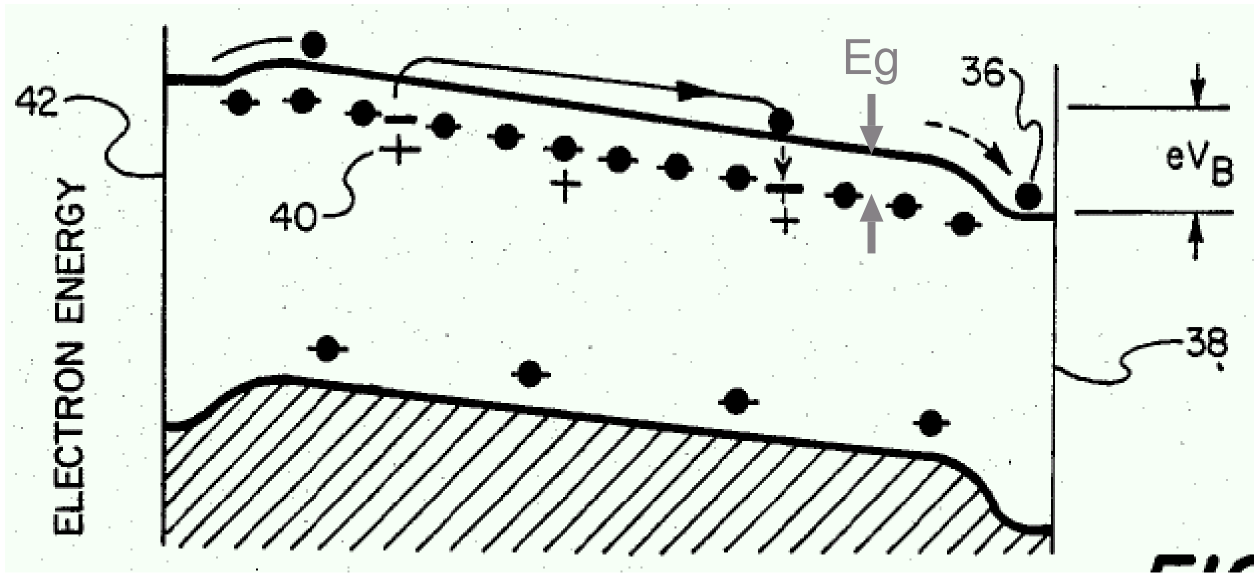
Infrared semiconductor detectors for astronomy

- 1-5um
  - InSb/HgCdTe intrinsic Photo-diode
- 5-36um
  - Si:As/Sb extrinsic photo-conductor
- 50-100um
  - Ge:Ga extrinsic photo-conductor
- 100-200um
  - Ge:Ga extrinsic photo-conductor (stressed)

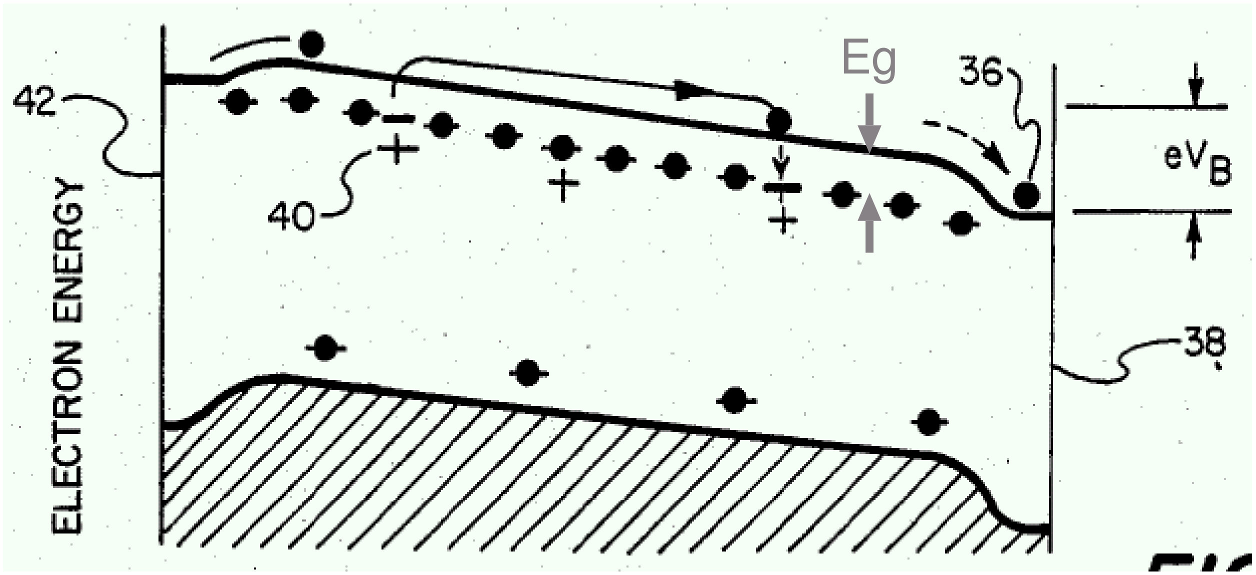
- no good detector 35-50um
- Ge:X blocked-impurity-band (BIB) detector is a candidate which covers 30-200um

extrinsic photo-conductive IR detector



- shallow ionization energies for impurities
  - impurities in GaAs ~ 5 meV ~ 240um
  - impurities in Ge   ~ 10 meV ~ 124um
  - impurities in Si   ~ 50 meV ~ 25um

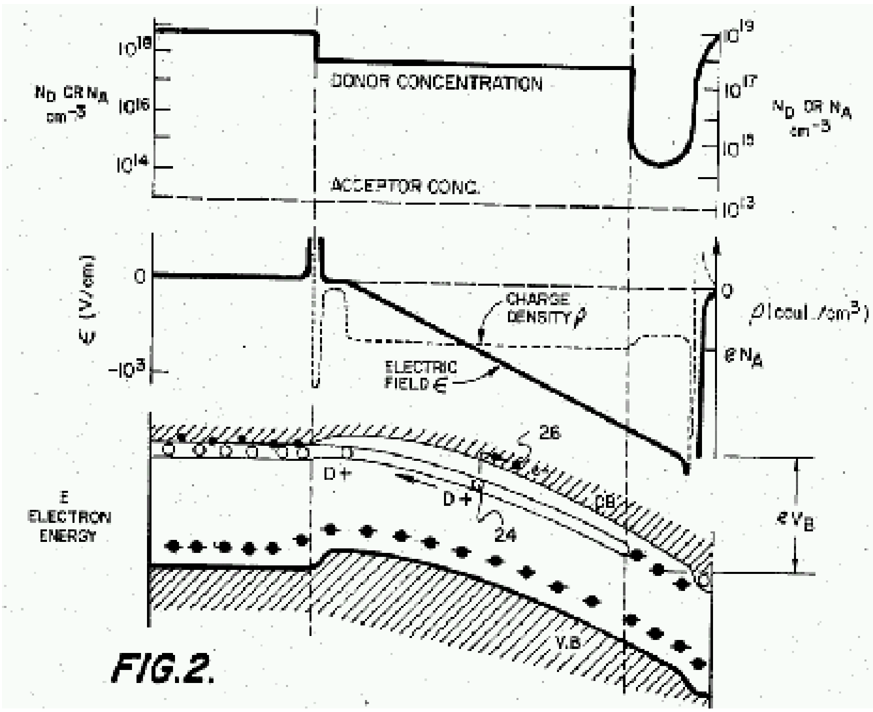
extrinsic photo-conductor



- uni-polar device
  - recombination noise, non-linear response
- hopping current
  - limitation of impurity density
- thick detector for high efficiency (a few mm)
  - higher hitting rate of cosmic rays
  - phonon absorption

    Ge(20-40um; peak at 28um)

extrinsic photo-conductor with BIB structure



Petroff et al.
US patent 4568960 (1986)

epitaxial junction with high dope layer and ultra-pure layer

- highly doped (IR active) layer
  - higher absorption efficiency
    - thin device (a few um)
  - impurity band conduction
    - no recombination noise
    - small non-linear response
    - longer cutoff wavelength
- ultra-pure (Blocking) layer
  - block impurity band conduction
    - smaller dark current

- Si BIB detectors are ready
  - ISOCAM, Spitzer/IRAC, Akari/IRC
- Ge BIB detectors are under development

Key point of BIB detectors

for lower dark current..

- ultra-pure layer for the block layer

for higher quantum efficiency (thick depletion layer)

- thinner blocking layer
- lower concentration of minor impurity in the active layer

$$w = \sqrt{\frac{2\kappa_0\varepsilon_0}{qN_A}|V_b| + t_B^2} - t_B$$

(higher Bias voltage leads break down of the detector.)

History of Ge BIB detector development

- Wu et al (1991)
  - Iron implantation into pure bulk wafer

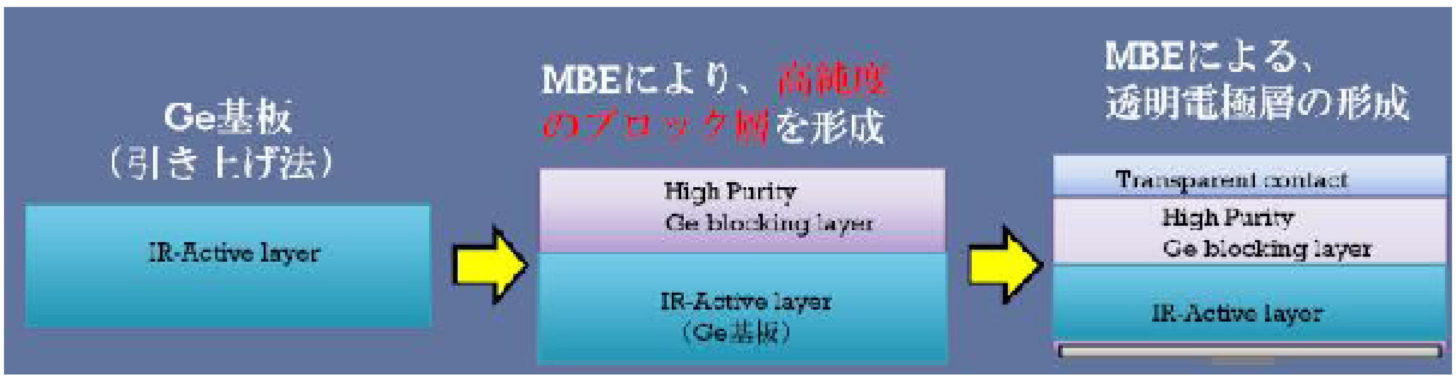
- Watson et al (1993)
  - Chemical Vapor Deposition (CVD) growth of blocking layer on high doped wafer

- Bandaru et al (2002)
  - Liquid Phase Epitaxy (LPE) growth of high dope layer on pure wafer

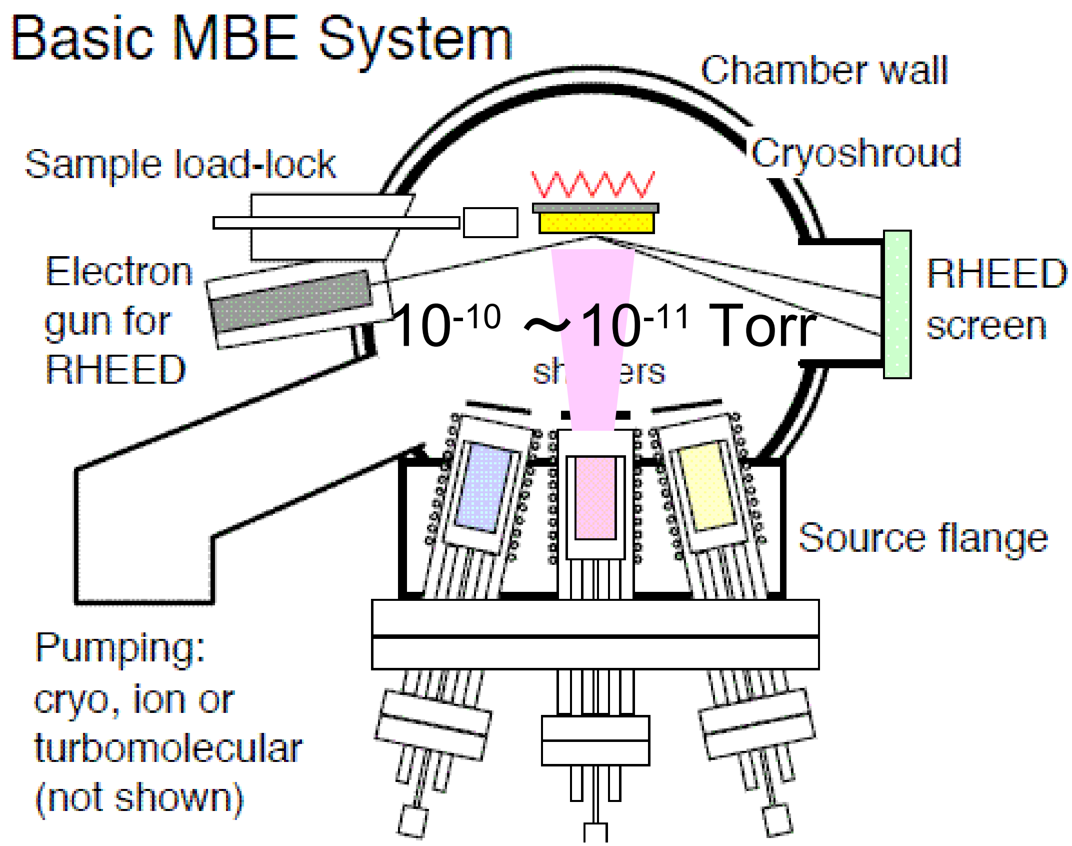
Our approach

- high quality bulk wafer for the high dope layer
  - smaller minor impurity concentration

- epitaxial growth of the block layer on the high dope layer by the MBE technique
  - purer block layer compare to CVD or LPE
  - thinner block layer



Molecular Beam Epitaxy (MBE)



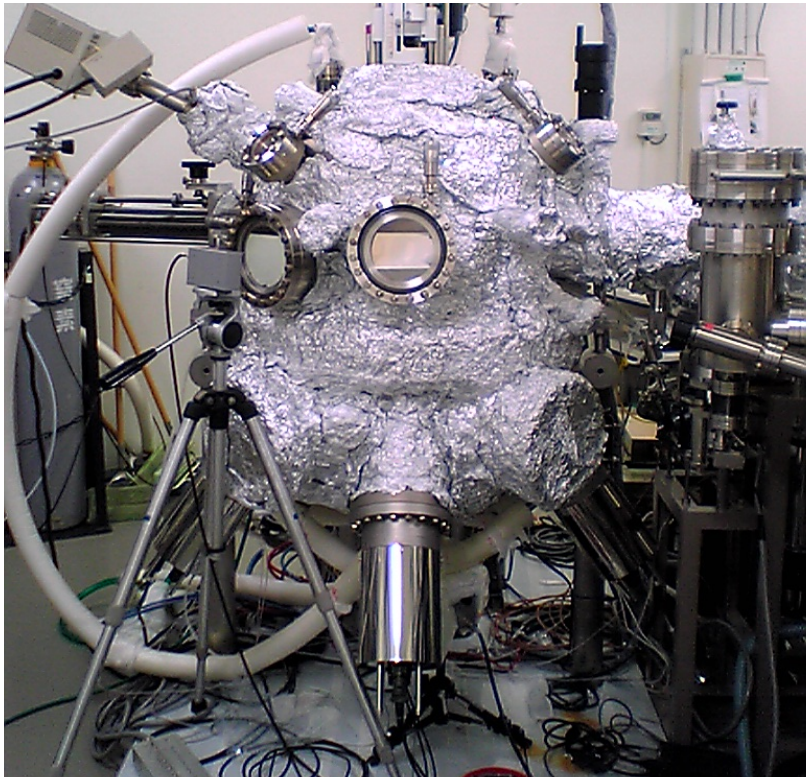
Molecular Beam Epitaxy (MBE)

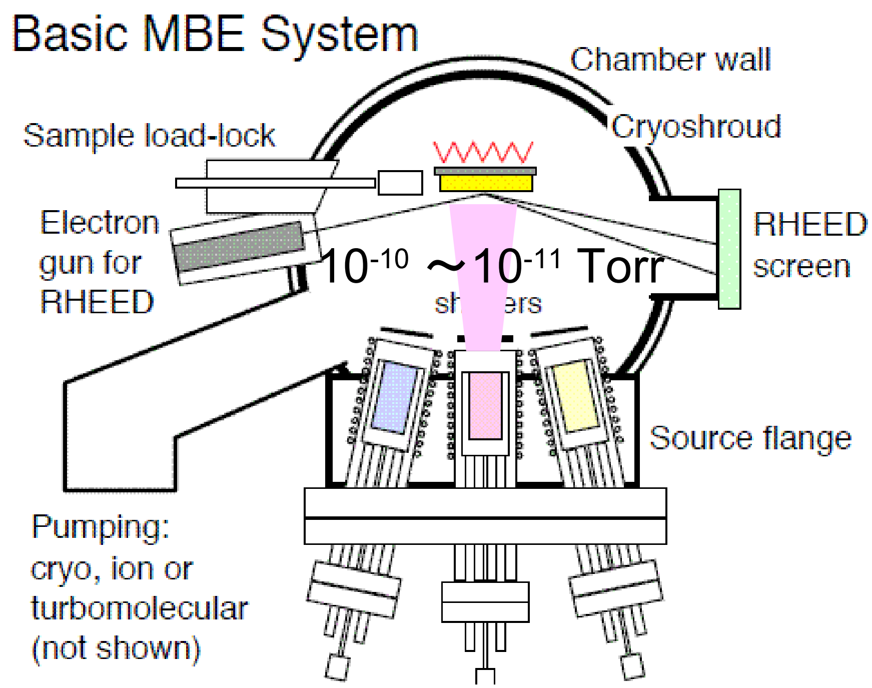
- epitaxial growth in the ultra high vacuum chamber
  - high purity can be achieved
- easy to control the growth
  - in-situ monitor of the growth of the crystal layers

    Reflection High Energy Electron Diffraction (RHEED)
  - easy to control the thickness of the layer at atom level
- non-thermal equilibrium growth of the crystal
  - crystal growth at low temperature can be done
  - small diffusion of impurity at the interface

- slower speed of the growth of the crystal (1 um/hour)
  - thick layer deposition is difficult
- high vacuum chamber
  - exchanging the wafer is difficult
  - mass production is difficult (cost is high)

MBE system at ISAS/JAXA Hirose Lab.

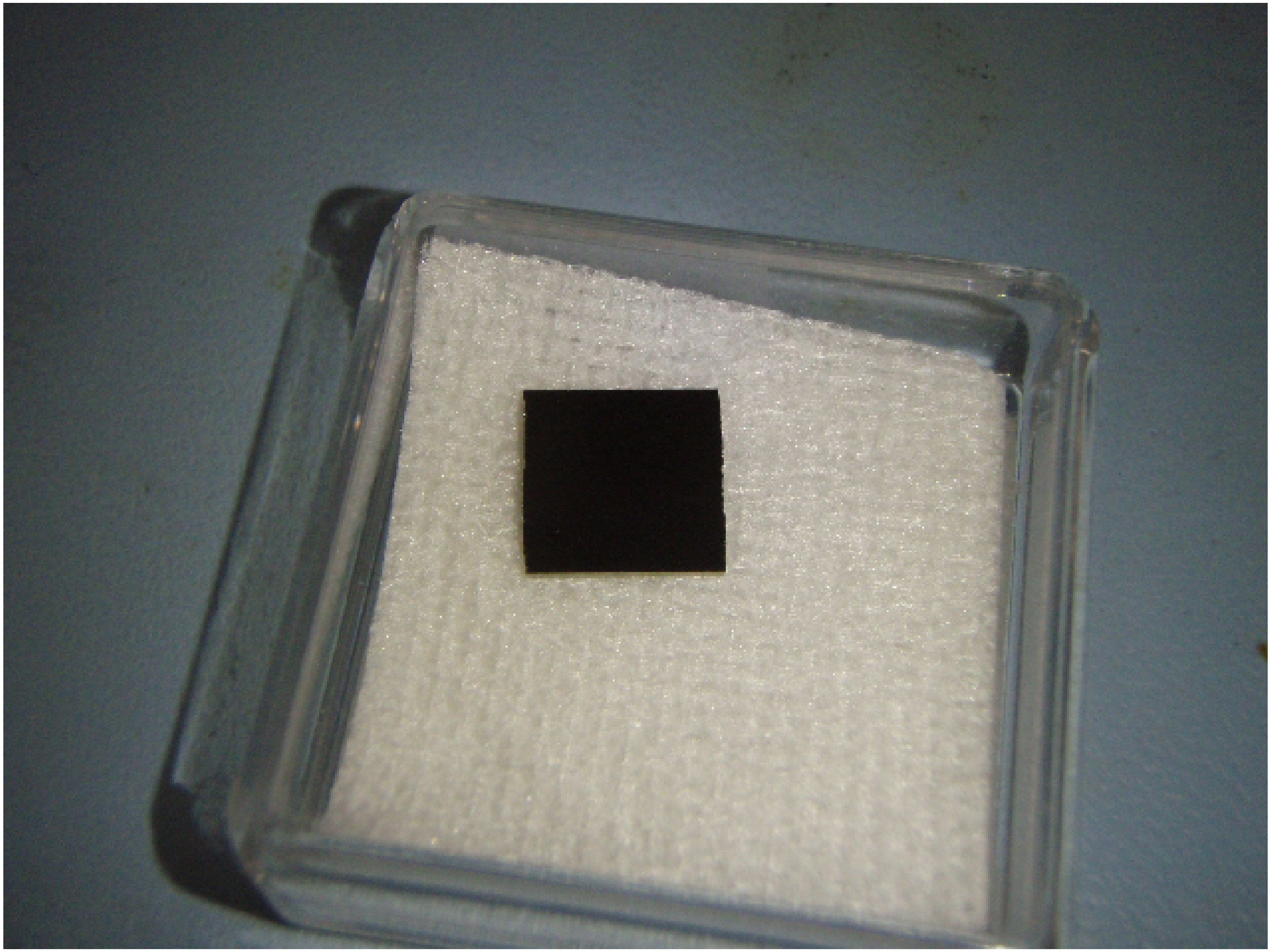




We will use the MBE system for this purpose only

(No high vapor pressure material such as Ga or As are used to keep cleanness)

Sample of MBE growth



Key point of MBE

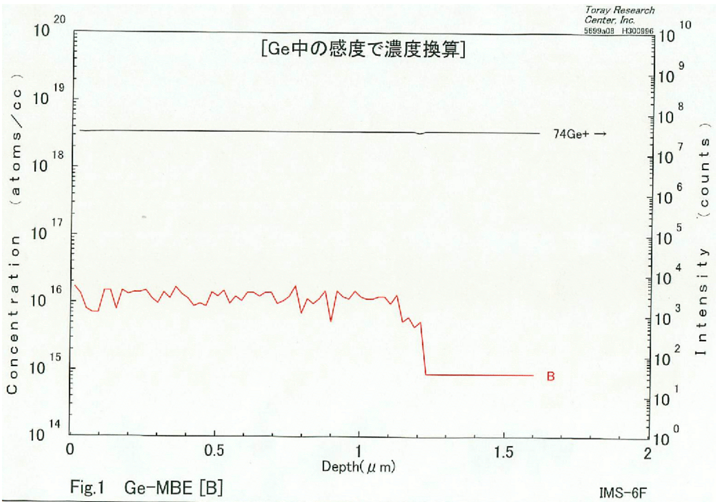
- ultra-pure Ge wafer and the source material
- physical condition of growth of crystal
  - temperature of the wafer
  - temperature of the source material (kinetic energy and flux of the molecules)
- high purity of vacuum chamber

History of our project

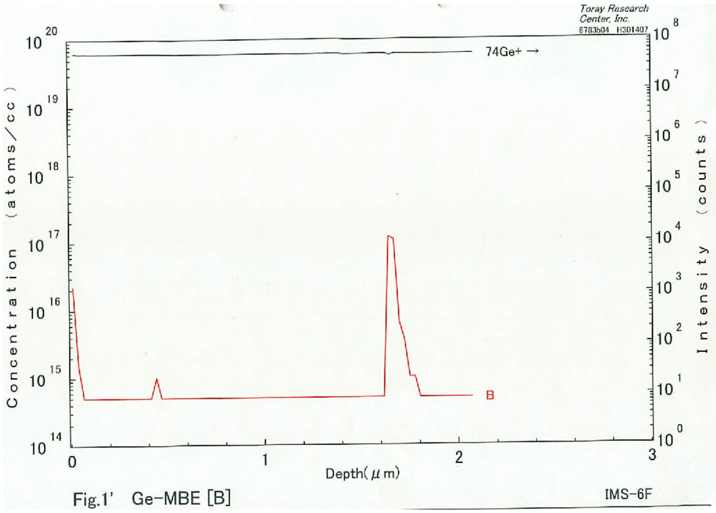
- 2003-2004: development of high quality Ge ingot
- 2005 MBE on pure Ge wafer
  - Use of Pyrolytic Boron Nitride (PBN) crucible makes large contamination of Boron
- 2006 MBE on pure Ge wafer
  - Use of Pyrolytic Graphite (PG) crucible suppress contamination
  - Find a condition which enables epitaxial growth of Ge on Ge
- 2007 MBE on pure Ge wafer
  - Temperature control of Cryo Shroud (Liquid Nitrogen) realize MBE growth in ultra high vacuum condition
  - replace (upgrade) of ion vacuum pump
- 2008 MBE on high dope wafer
  - demonstrate high contract dopant profile

Suppression of contamination

Boron profile from Secondary ion mass spectrometry (SIMS) analysis



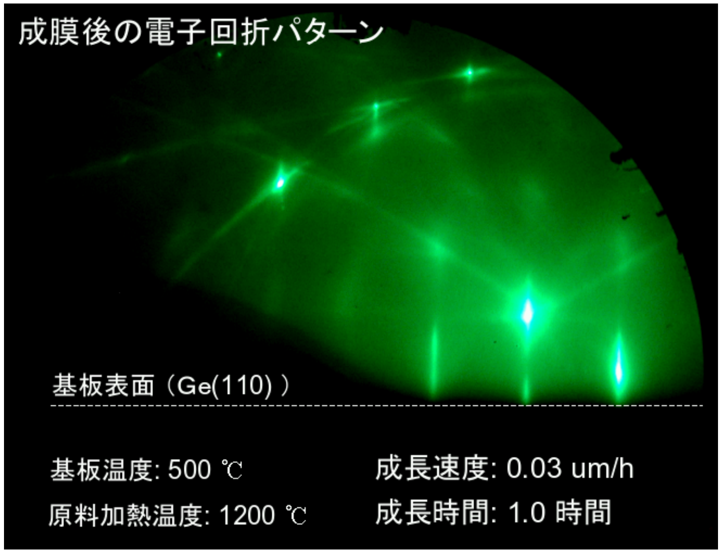
pBN(Pyrolytic Boron Nitride)

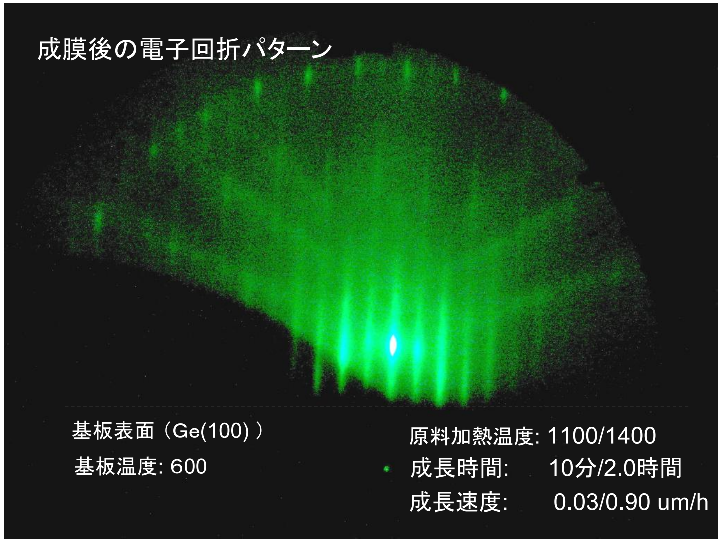


pG(Pyrolytic Graphite)

improvement of melting pod material suppress B concentration below the detection limit (<10^14/cc)

Improvement of the structural quality





Reflection High Energy Electron Diffraction (RHEED)

Starting crystal growth with

- higher wafer temperature
  - 500 C =>600 C
- lower Ge source temperature
  - 1200 C=>1100 C

single crystal mode to layer-by-layer mode

Vacuum control

Supply Liquid Nitrogen for Cryo Shroud is very important

- high vacuum (contamination to the crystal growth)
- prevent overheat (safety)

Temperature monitoring at the end of LN2 line

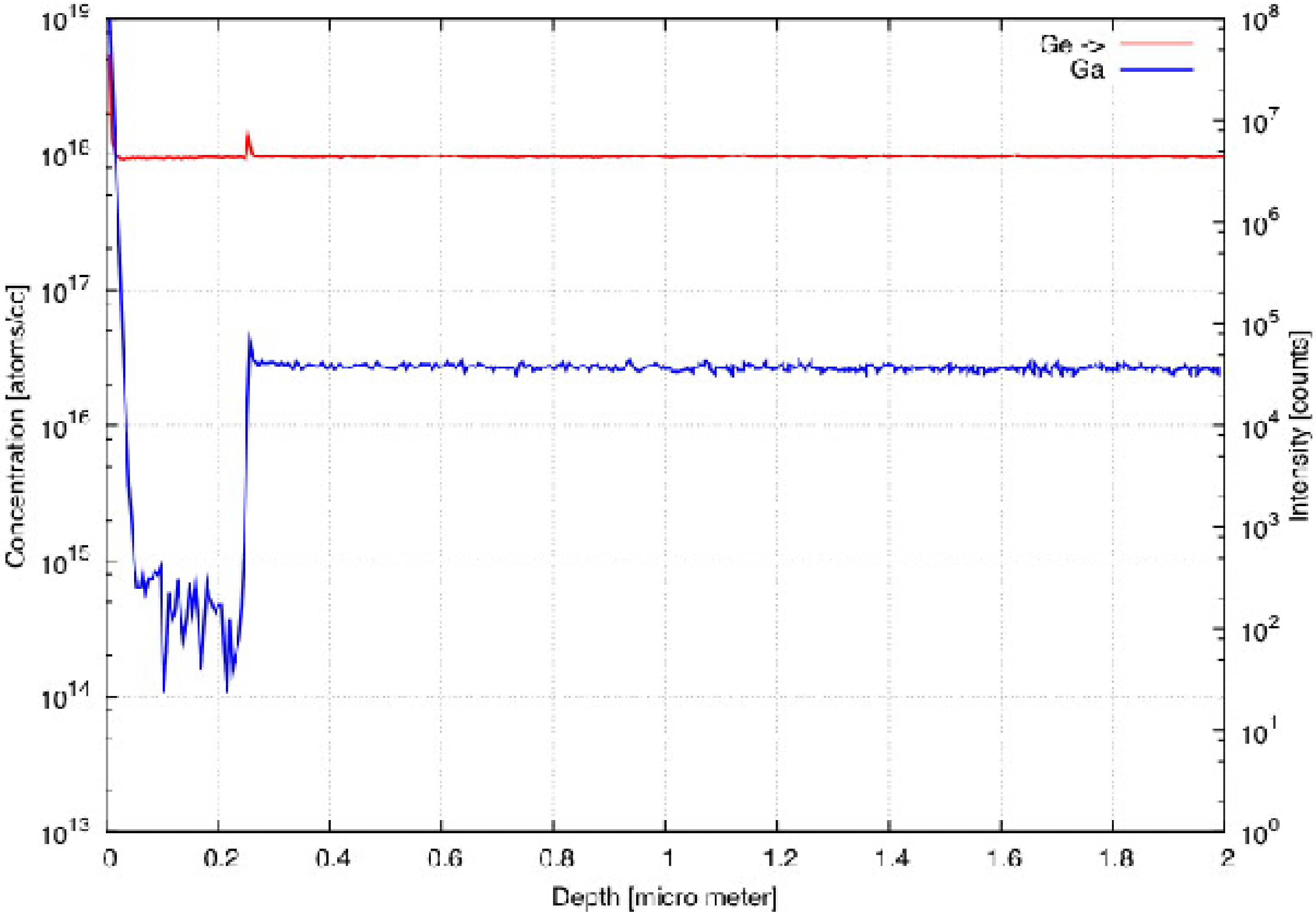
Automatic pressure control device is install to the LN2 tank

pressure in the vacuum chamber is reduced from 10^-9 to 10^-10 (torr).

Now we have learn the Ge MBE technique.

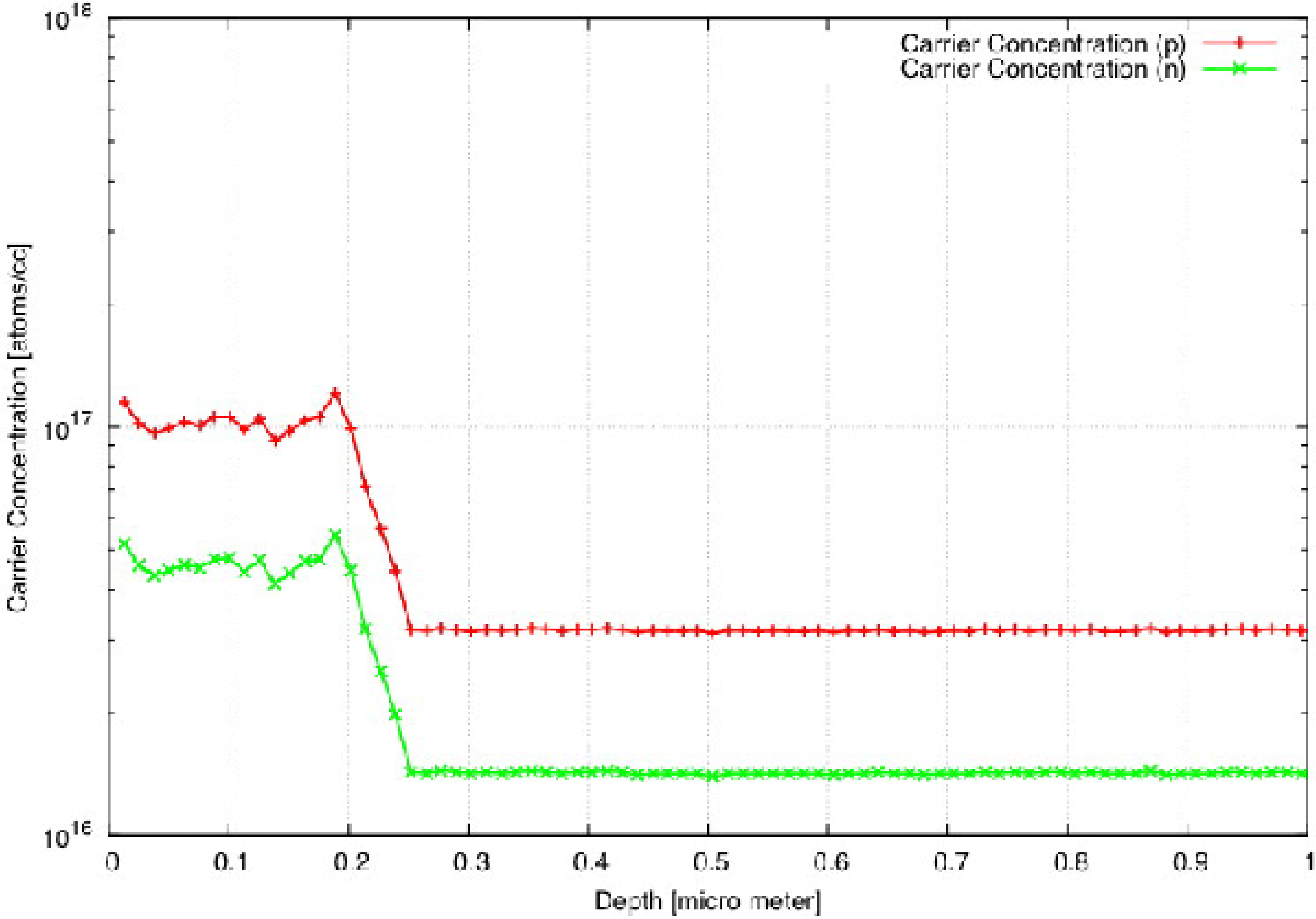
We will start Ge BIB devices

No diffusion of major dopant into blocking layer



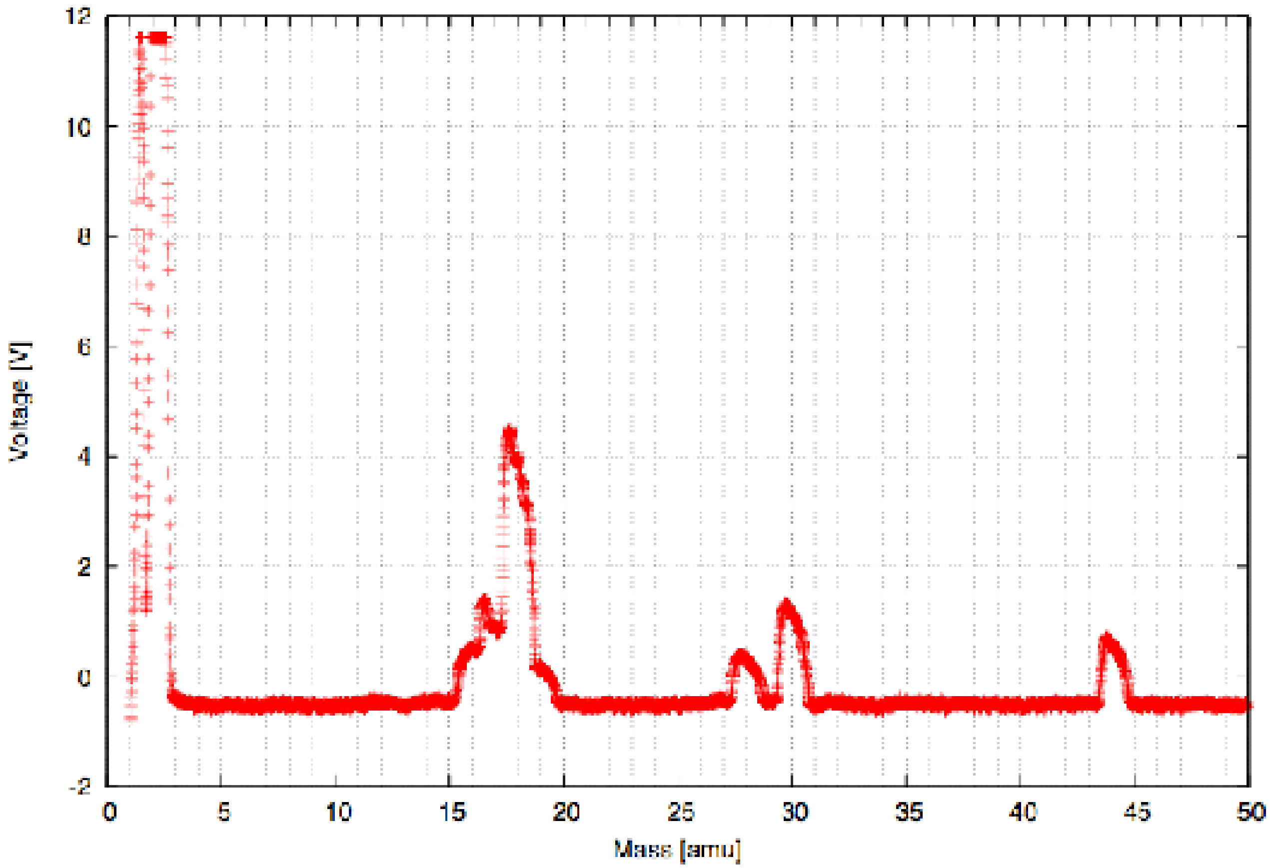
Gallium profile from Secondary ion mass spectrometry (SIMS) analysis

purity of blocking layer is not enough



Carrier concentration profile from Spread Resistance Analysis(SRA)

What is contamination source? Vacuum?



Quadrupole Mass Spectrometer (QMASS) analysis results

H_2(2), O(16), OH(17), H_2O(18), N_2/CO(28), NO/C_2H_6(30), CO_2(44)

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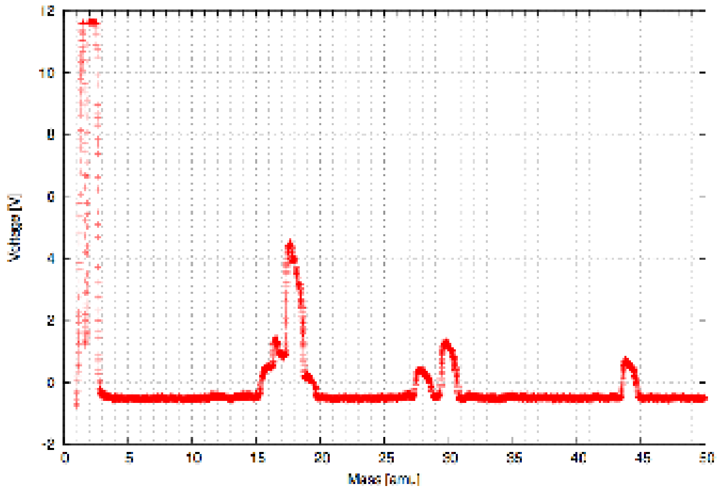

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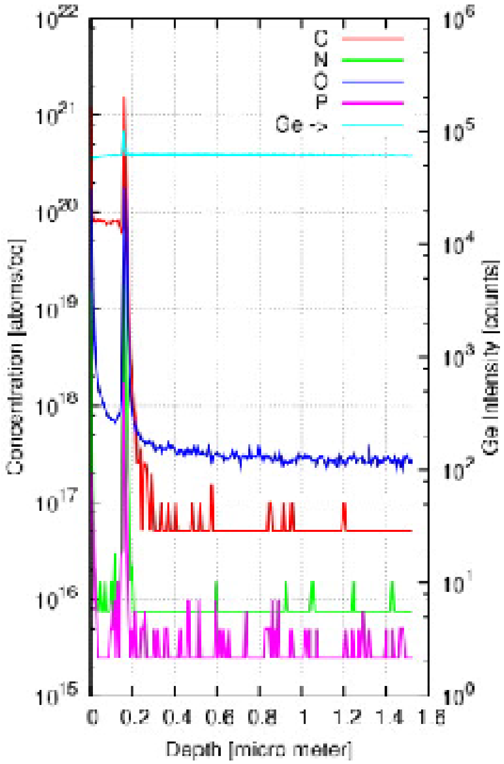
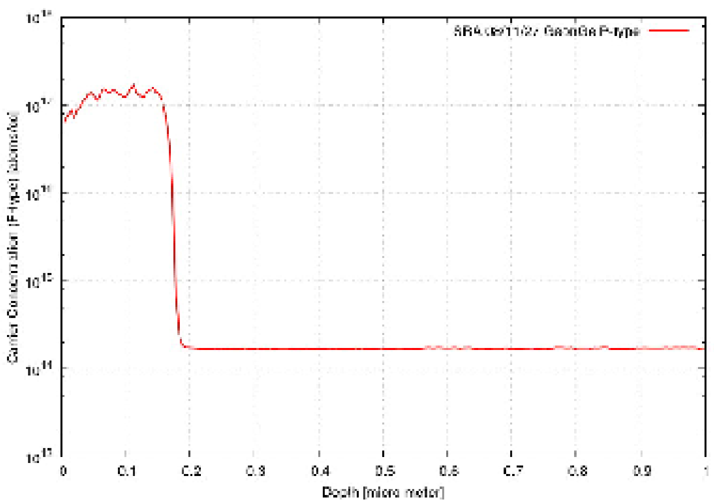
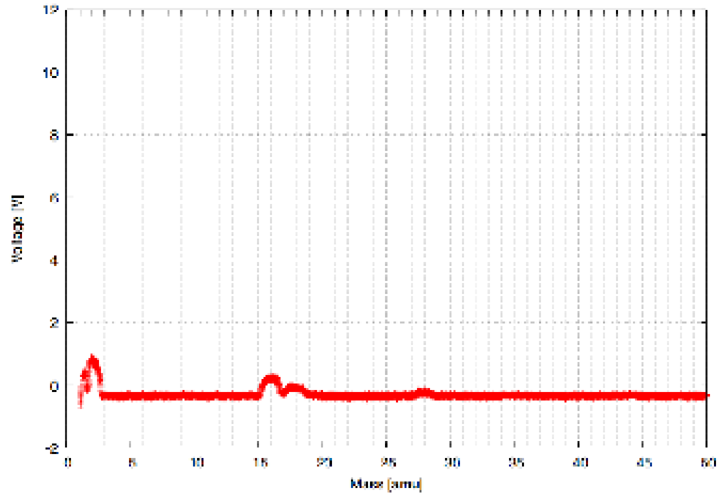




Carrier concentration profile from Spread Resistance Analysis(SRA)

- QMASS predict contamination of N, O, C and N from vacuum.
- SRA shows carrier concentration of 10^17/cc
- Non of them shows corresponding concentration in SIMS result.

What is contamination source? Vacuum?



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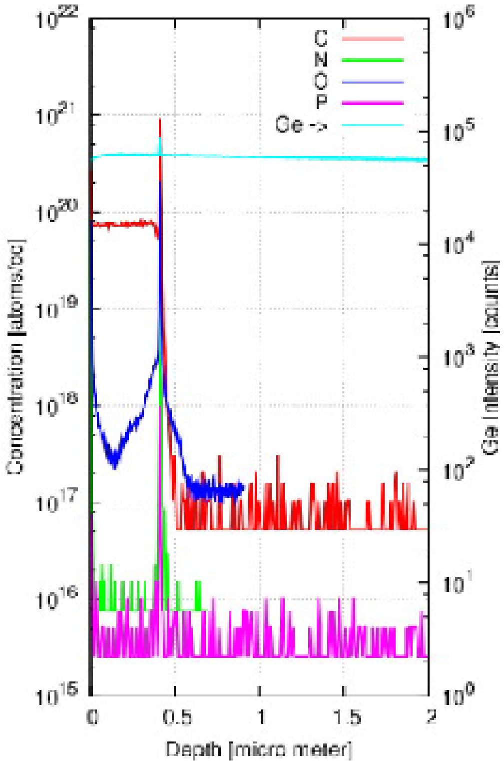
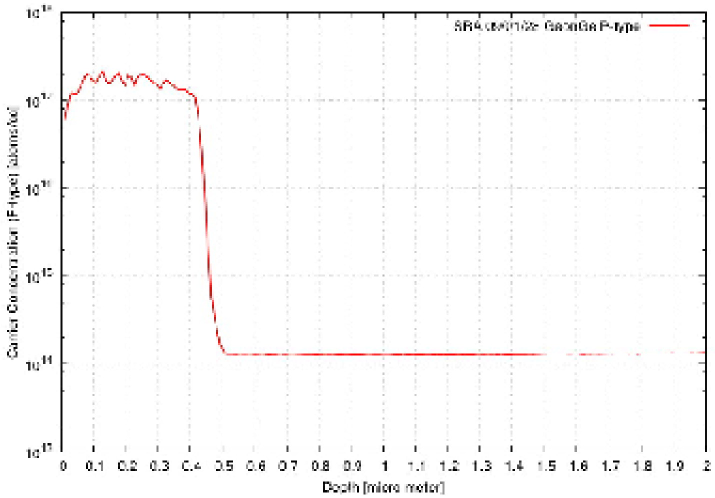
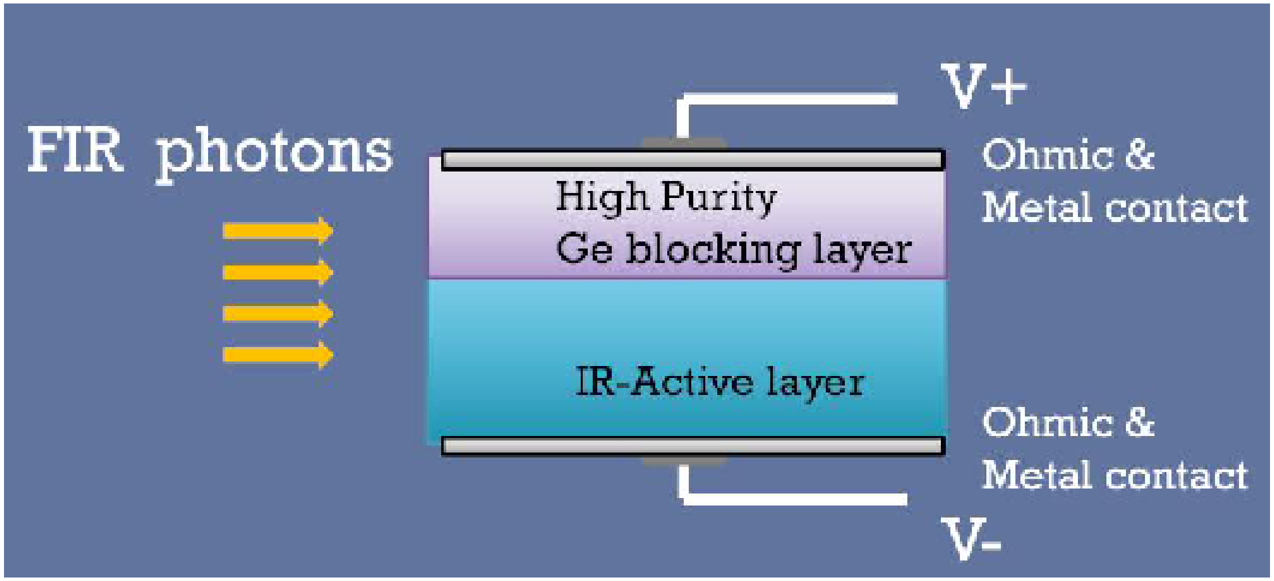




Carrier concentration profile from Spread Resistance Analysis(SRA)

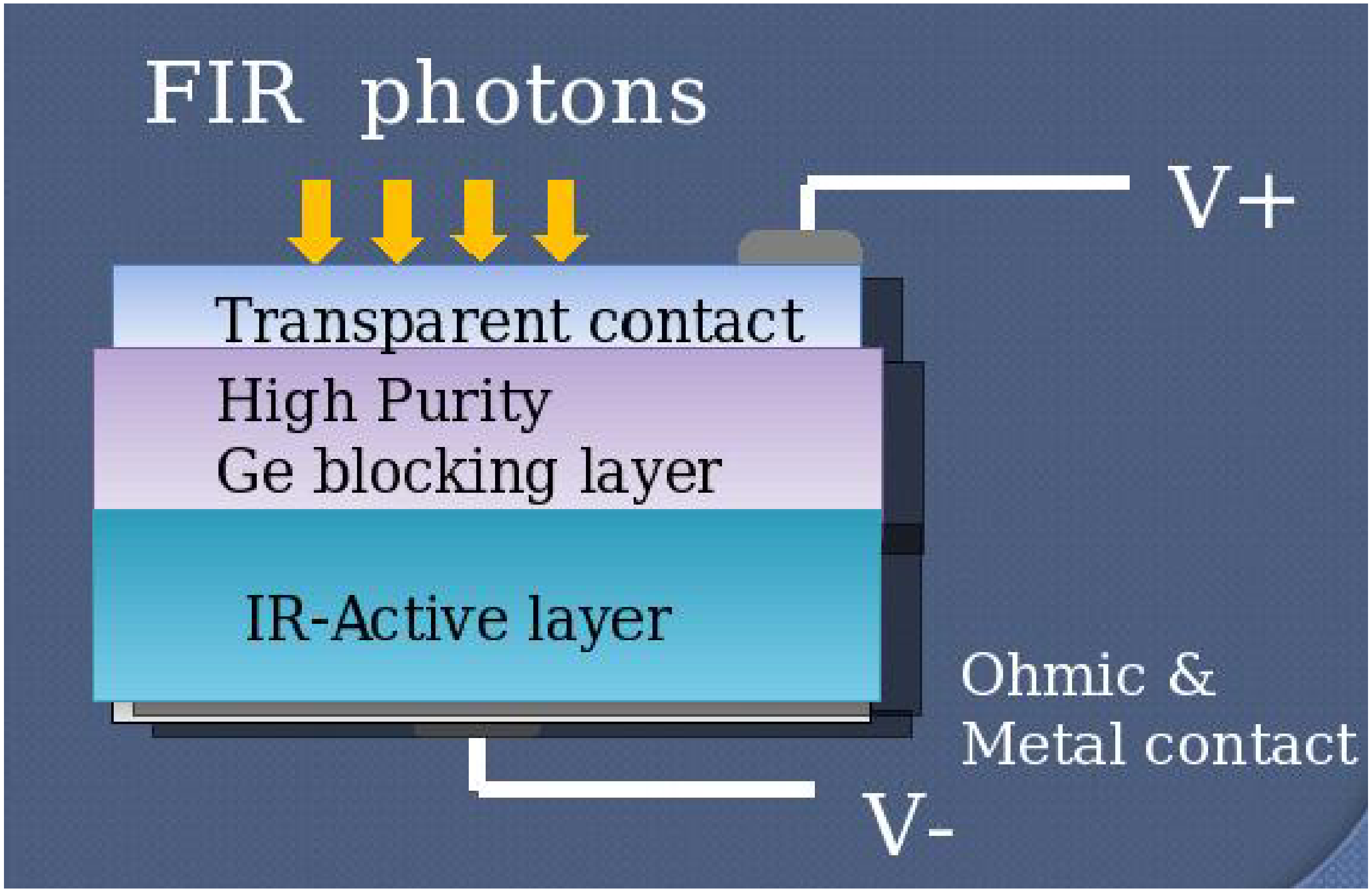
- reduction of residuals in vacuum does not improve purity in the Epitaxial layer
- Carbon contamination from graphite crucible is one possibility.
- try crucible made from other material
- defect in crystal growth may produce carrier
- try slower growth rate

2009: side illuminated BIB device



develop ohmic contact by AuGe deposition

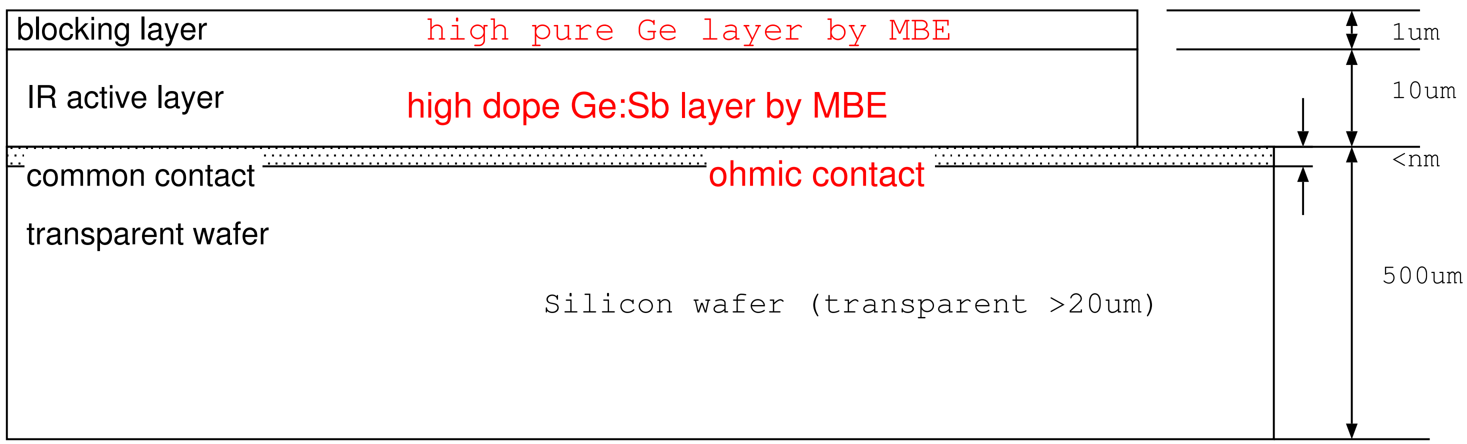
2010: front illuminated BIB device



develop transparent contact by MBE (very thin high dope layer)

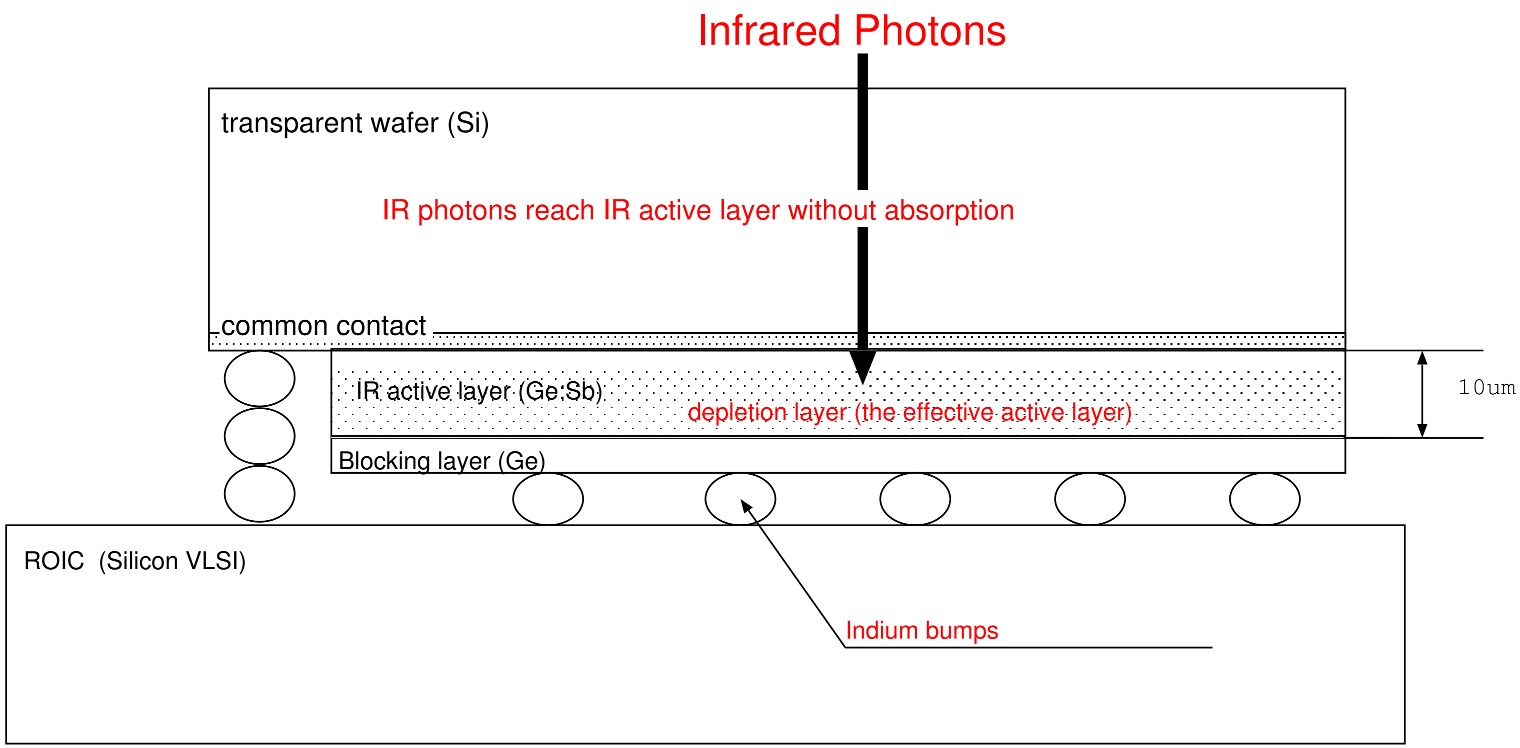
200X: Ge BIB detector on Silicon Wafer

BIB structure fabrication with MBE



200X: Ge BIB detector on Silicon Wafer

flip detector wafer and bump it with Silicon ROIC

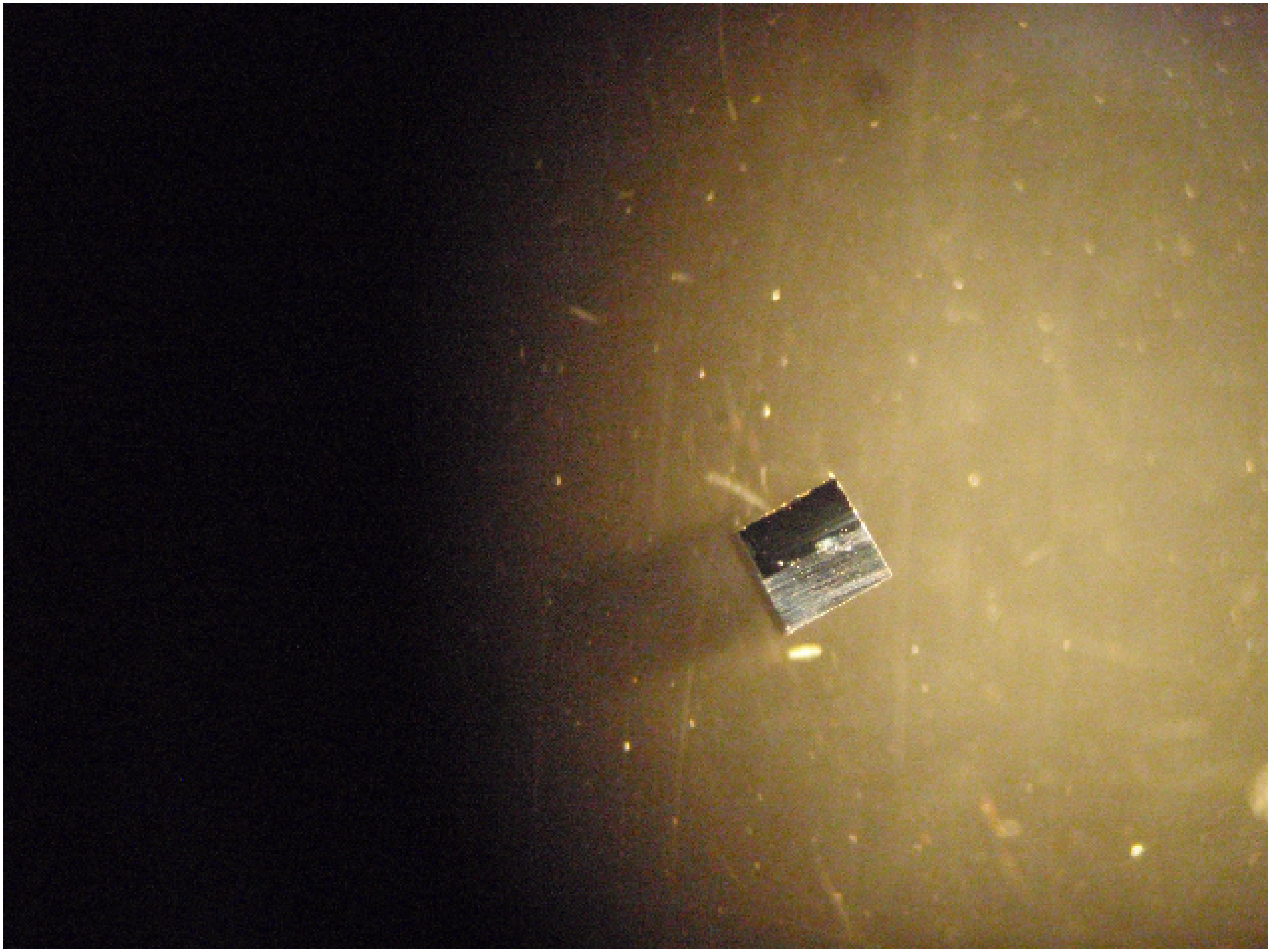


IR photons goes to directory to the active layer (no phonon absorbtion!)

no special separation bewteen elment is needed.

free from thermal expansion mismatch between detector wafer and ROIC

other technique... Wafer bonding technique



Summary

- BIB detector enables low dark current and high sensitivity
- MBE technique is suitable for fabrication of blocking layer of BIB structure
- development of Ge material has been finished
- MBE facility is now ready in ISAS/JAXA
- epitaxial growth on Ge:Ga has been achieved with clear density profile of Ga
- carrier concentration in the epitaxial layer is still large
- we will search for optimal crystal growth condition
- we will also try new technique: wafer bonding