Development of next generation
Far- and Mid- infrared detectors

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

Takehiko Wada (ISAS/JAXA),
Kensuke Wada (TITECH), Toyoaki Suzuki (NAOJ),
Hidehiro Kaneda (Nagoya univ.), Kentaroh Watanabe (ISAS/JAXA),
and
Kazuyuki Hirose (ISAS/JAXA)
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
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

- 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

Petroff et al.
US patent 4568960 (1986)
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

  - Chemical Vapor Deposition (CVD) growth of blocking layer on high doped wafer

  - 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
H₂(2), O(16), OH(17), H₂O(18), N₂/CO(28), NO/C₂H₆(30), CO₂(44)
What is contamination source? Vacuum?

Quadrupole Mass Spectrometer (QMASS) analysis results:
- H₂(2), O₁₆(16), OH₁₇(17), H₂O₁₈(18), N₂/O₁₈(28), NO/C₂H₆(30), CO₂(44)

QMASS predicts 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.

Carrier concentration profile from Spread Resistance Analysis (SRA)
What is contamination source? Vacuum?

- Quadrupole Mass Spectrometer (QMASS) analysis results:
  - H2(2), O(16), OH(17), H2O(18), N2/CO(28), NO/C2H6(30), CO2(44)

- 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)
### BIB structure fabrication with MBE

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>Description</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocking layer</td>
<td>High pure Ge layer by MBE</td>
<td>1 \text{um}</td>
</tr>
<tr>
<td>IR active layer</td>
<td>High dope Ge:Sb layer by MBE</td>
<td>10 \text{um}</td>
</tr>
<tr>
<td>Common contact</td>
<td>Ohmic contact</td>
<td>&lt;\text{nm}</td>
</tr>
<tr>
<td>Transparent wafer</td>
<td></td>
<td>500 \text{um}</td>
</tr>
</tbody>
</table>

Silicon wafer (transparent >20 \text{um})
200X: Ge BIB detector on Silicon Wafer

flip detector wafer and bump it with Silicon ROIC

IR photons reach IR active layer without absorption

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