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Silicon and III-V Compounds for Detectors – Technology and Characterisation at ITME

R. Kozlowski, Z. Luczynski and E. Nossarzewska-Orlowska

Institute of Electronic Materials Technology, Warsaw, Poland
www.itme.edu.pl
Plan of presentation

- short characteristic of ITME
- materials for detectors:
  - silicon (bulk and epitaxial)
  - III-V compounds (SI GaAs, SI InP and MOCVD III-V including GaN layers)
- materials characterisation methods
The Institute consists of the following divisions:

- Department of Silicon Technology
- Silicon Epitaxy Laboratory
- Department of Semiconductor Compounds Technology
- III-V Materials Epitaxy Laboratory
- Department of III-V Materials Applications
- Department of Oxide Single Crystals Technology
- Department of Ceramics and Seals Technology
- Laser Laboratory
- Glass Laboratory
- Department of Thick Films Technology
- Department of Piezoelectronics
- Laboratory of Characterization of High Purity Materials
- Department of Microstructural Analyses
Czochralski silicon crystals

Orientations <111>, <100> and <110>
Carbon content: max. 0.5 ppm
Oxygen content: controlled level in the range of 24-38 ppm
Silicon wafers
-as cut, lapped, etched and polished

• Diameter: 76 mm, 100 mm, 125 mm, 150 mm (6”),
• Orientation: <111>, <100> and <110>,
• One-side or double-side polished,
• Thin double-side polished wafers (down to 50 µm)

Available resources:
• Thermal donors annealing furnace,
• Silicon oxidation furnace (quartz tube up to 8”)

Float Zone silicon crystals

- diameter: 2”
- orientation: <111> or <100>
- doping:
  - p-type: boron
  - n-type: phosphorus
- resistivity range:
  - boron: 20 - 300 $\Omega$cm
  - phosphorus: 6 - 200 $\Omega$cm

FZ silicon doped with different impurities for research purposes (Sn, O).
Magnetic CZ puller*

- Better homogeneity of the dope in axial and radial direction
- Minimum available oxygen concentration: \( \sim 3 \times 10^{17} \) at/cm\(^3\).

Magnet - 5000 Gauss
Charge capacity of the above: 30 kg
Diameter of pulling crystals: 100 mm
Cable pulling system:
Max pulling stroke: 1350 mm
Seed pulling speed: 0.2 - 6.0 mm/min
The full automatic crystal growing control system.

* pulling will start in the beginning of 2003
Si:Ga crystals (1)

A new generation of crystalline silicon solar cells

Parameters of Ga doped silicon crystal:

Diameter – 3”
Type – p
Resistivity – (0.5 – 2.0) $\Omega$ cm
$[\text{Ga}]$ – (4x$10^{16}$ – 7x$10^{15}$) cm$^{-3}$
$[\text{O}]$ – 6.5x$10^{17}$ cm$^{-3}$
$[\text{C}]$ < 5x$10^{15}$ cm$^{-3}$
The life time of minority carriers - 25÷30 $\mu$s.
The absorption spectrum (FTIR) of Si:Ga related to the transition from the ground state to the exited states of gallium.

Silicon epitaxial layers (1)

Epi-layer on substrates of diameter:
   2”, 3”, 4”, 5”, 6” (CEMAT-Silicon)
Type n - phosphorus doped
Type p - boron doped
Thickness range: 1÷ 200 µm
Resistivity range: 0.01 ÷ 1000 Ωcm
Single layers and multi-layers structures

Characterization:
thickness by IR reflectance spectrometry
resistivity by: C-V method with Hg probe; spreading resistance
(resistivity profile on a bevel), 4-points probe
Silicon epitaxial layers (2)

Epitaxial layer thickness map measured on BIO-RAD spectrometer
Silicon epitaxial layers (3)

4$\pi$ epitaxial Si detectors array for in-beam spectroscopy experiments

Resistivity profile measured by SR method for high-resistivity silicon epitaxial layer

Schematic view of silicon ball detector
Silicon epitaxial layers (4)
Perspective material for thin silicon detectors

Resistivity profile of 50 µm, 50 Ωcm epitaxial layer

Idea: the depletion voltage might stay constant up to very large fluences!
Silicon epitaxial layers (5)

Epitaxial structure of integrated telescope $E + \Delta E$ for identification of light charged particles and heavy ions in nuclear and heavy ions physics
III-V compounds (1)

Ingots

GaAs
- grown by Czochralski (LEC) method (low and high-pressure)
- diameter 2", 3" and 4", orientation <100> or <111>
- n-type : Te, Sn or Si \( (n=10^{17}....10^{19} \text{ cm}^{-3}) \)
- p-type : Zn \( (n=10^{17}....10^{19} \text{ cm}^{-3}) \)
- **Semi-Insulating** : undoped \( (\mu > 6\times10^3 \text{ cm}^2/\text{Vs}, \rho > 10^7 \text{ }\Omega\text{cm}) \).

InP
- grown by Czochralski (LEC) method
- diameter 2", orientation <100> or <111>
- n-type : undoped \( (n=5\times10^{15}..1\times10^{16} \text{ cm}^{-3}) \)
- n-type : S, Sn \( (n=2\times10^{17}..1\times10^{19} \text{ cm}^{-3}) \)
- p-type : Zn \( (p=5\times10^{17}..1\times10^{19} \text{ cm}^{-3}) \)
- **Semi-Insulating** : Fe \( (\mu > 2 \times 10^3 \text{ cm}^2/\text{Vs}, \rho > 10^7 \text{ }\Omega\text{cm}) \)
III-V compounds (2)

The $\alpha$ particle detector

SI GaAs crystal parameters:
$\mu > 6000 \text{ cm}^2/\text{Vs}$, $N_D < 10^{15} \text{ cm}^{-3}$, $\text{EPD} < 5 \times 10^4 \text{ cm}^{-2}$, homogeneity

Simplified structure of $\alpha$ particle detector based on SI GaAs or SI InP substrate
III-V compounds (3)
The $\alpha$ particle detector

Spectra of $\alpha$ ($^{228}$Th) particle detected by Si GaAs detector. (a) structure illuminated from Schottky barrier side, (b) structure illuminated from ohmic contact side
III-V compounds (4)

The $\alpha$ particle detector

Charge collection efficiency for $\alpha$- 5.48 MeV as a function of bias voltage for SI GaAs detector
The growth of structures applying binary, ternary and quaternary compounds related to GaAs, InP and GaN

**EPITAXIAL LAYER THICKNESS:**

* from 1ML to 15µm;
* radial thickness variation on the wafer: in the range of 1ML.

The following methods are used for the characterisation of layers:

- X-ray;
- Photoluminescence;
- Hall method;
- C-V profile with electrochemical etching;
- Atomic Force Microscopy.
LP MOVPE - Low Pressure Metalorganic Vapor Phase Epitaxy

AXT 200 system

P = 20 ÷ 100 mbar
T = 650-700 °C

Epitaxial layers: InP, GaAs and related materials

as III group elements:
TMGa - trimethylgallium,
TMIn - trimethylindium,
TMAI - trimethylalumininum

as V group elements:
AsH₃ - arsine
PH₃ - phosphine

as dopant:
DMZn - dimethylzink
SiH₄ - silane

Quantum well laser structure
LP MOVPE - Low Pressure Metalorganic Vapor Phase Epitaxy

AXT 200/4 RF-S system
P = 100 ÷ 300 mbar
T = 1200 °C

as III group elements:
TMGa - trimethylgallium,
TMIn - trimethylindium,
TMAI - trimethylalumininum

as V group elements:
NH₃ - ammonia

as dopant:
Cp₂Mg
SiH₄

Epitaxial layers: GaN, AlN, AlGaN, InGaN
Applications: LEDs, HEMTs, lasers, photodetectors
Substrates: sapphire, NGO, Si, SiC and GaN (homoepitaxy)
MIXED PEROVSKITE – (La, Sr) (Al, Ta) O₃ – LSAT
- Crystal system: regular (mixed perovskite)
- Lattice constant: \( a = 7.735 \text{ Å} \)
- Lattice mismatch: \( \Delta < 1\% \)

NEODYMIUM GALLATE – NdGaO₃
- Crystal system: orthorombic
- Lattice constants: \( a = 5.4276 \text{ Å} \)
  \( b = 5.4979\text{Å} \)
  \( c = 7.7078\text{Å} \)
- Lattice mismatch: \( \Delta \sim 0.7\% \) (101)

SAPPHIRE – Al₂O₃
- Crystal system: trigonal
- Lattice constants: \( a = b = 4.7589 \text{ Å} \)
  \( c = 12.991 \text{ Å} \)
- Lattice mismatch: \( \Delta \sim 14\% \)
Technological line consists of:
- deep UV optical lithography (0.5µm smallest feature size),
- reactive ion etching (RIE) technique (and ICP type of RIE),
- plasma enhancement chemical vapour deposition reactor (PECVD),
- RF/DC sputtering unit,
- Rapid Thermal Annealing (RTA),
- Ion Implantation.

Deposition of:
- dielectrics (Si₃N₄, SiO₂, Al₂O₃, Y₂O₃),
- semiconductors (AlN, GaN),
- multilayer metal sandwiches.

Chromium masks on up to 7” substrates (smallest line width of 0.5µm)

Devices with sub micrometer geometry approaching quantum regime of operation (using e-beam writer).
Electron-Beam Lithography

Main fields of applications:

• fabrication of master masks and reticles for contact, proximity and projection lithography, especially for large area structures, like nuclear radiation detectors or SAW filters and resonators.

• direct exposure of semiconductor wafers, especially to be used in the sub-0.5-micrometer range (e.g. monolithic microwave integrated circuits, diffractive optical elements).
Processing department and mask laboratory (3)

Electron-Beam lithography

- high resolution and quality

Split gate 0.07 μm
Lift-off metallization Au/Cr 0.1 μm

Submicron strip structure
Lift-off metallization, line width 0.8 μm

- special 3D structures

The 0.2 μm footprint T-shaped gate
Lift-off metallization Au/Cr 0.4 μm

Central part of the 8-phase-level Fresnel microlens
Sensor of ultraviolet radiation on Gallium Nitride

- Absorption edge - 365 nm.
- Detector exhibits high sensitivity only in the UV range without applying expensive optical filters.
- Sensitivity is 3 orders of magnitude lower for visible light.

- active surface 0.8 mm
- current sensitivity > 0.07 A/W
- detectivity D > 10^9 cm Hz^{1/2}/W
- dynamic resistivity (U = 0) 10 GΩ
- UV/visible light rejection ratio > 10^3
Materials characterisation methods at ITME:

- C-V and S-R,
- FTIR spectrometer,
- photoluminescence,
- SIMS (Cameca IMS 6F)
- electron micro-probe analysis (Cameca SX100),
- HRPITS and C-DLTS,
- ESR
SIMS profile of O-concentration for silicon sample, O-diffusion: 16 hrs at 1150 °C
(Measurement on bevelled sample)
ESR spectra of Mn$^{2+}$ in GaN crystal

In GaN crystals Mn$^{2+}$ have 3d$^5$ electron configuration with $S=5/2$. Therefore in EPR spectra we observe 5 fine structure lines. Each of them is splitted on six components. This splitting is caused by hiperfine interaction between electron spin and magnetic nucleus $^{55}$Mn with nuclear spin $I=5/2$. 
The local vibration modes of $V_nO_n$ defects in:

a) neutron irradiated with dose $6 \times 10^{16} \text{n/cm}^2$;

b) non-irradiated silicon after annealing at $600 \, ^\circ\text{C}$.
Summary

- ITME activities in silicon technology were exemplified through the wide range of parameters of silicon ingots, wafers and epitaxial layers.
- Research and development works in the field of III-V compounds comprise the growth of bulk crystals (in particular SI GaAs and SI InP) and deposition of multilayered structures.
- ITME recent activities in technology of wide-bandgap materials are related both with the preparation of substrates and MOCVD epitaxial growth of GaN structures.
- The ITME facilities for fabrication of semiconductor devices and materials characterisation were also outlined.