St Petersburg Electrotechnical University "LETI"
Department of Micro- and Nanoelectronics
Professor Victor Luchinin
IEEE MOS-AK GSA Workshop, Sept. 16, 2011, Helsinki
Saint Petersburg Electrotechnical University
St. Petersburg Electrotechnical University "LETI"

- Founded in 1886
- Alexander III Imperial Electrotechnical Institute
- First specialised electrical engineering higher education institution in Europe

Prof. Alexander Popov, the 1st elected Director, Radio pioneer

Academician G. I. Alferov, Nobel Price Winner in Physics 2000, LETI graduate
Experimental research and modeling of bulk SiC crystal growing
Growth model of SiC politypes in the matrix replication process under the non-equilibrium conditions
Experimental research and modeling of the structure formation of SiC and AlN layers on heterogeneous substrates
Modeling of graphene layers on SiC surface formation
Experimental research and modeling SiC power devices
MATERIALS: Si, SiC, AlN

- **Electrical strength, MV/cm:**
  - AlN: 6.2
  - SiC: 3.02
  - Si: 1.12

- **Energy gap, eV:**
  - AlN: 6.2
  - SiC: 3.02
  - Si: 1.12

- **Modulus of elongation, 10^11 N/m^2:**
  - AlN: 950
  - SiC: 1430
  - Si: 1430

- **Piezoelectric modulus, 10^{-12} KI/Nt:**
  - AlN: 5.8
  - SiC: 4.0
  - Si: 4.0

- **Debye temperature, K:**
  - AlN: 4.9
  - SiC: 3.2
  - Si: 1.5

- **Lattice constant, nm:**
  - AlN: 0.3112
  - SiC: 0.3076
  - Si: 0.543

- **Thermal conductivity, Wt/(cm*K):**
  - AlN: 1.7
  - SiC: 4.68
  - Si: 5.2

- **Thermal extinction coefficient, 10^{-6} 1/K:**
  - AlN: 0.25
  - SiC: 0.25
  - Si: 0.25
BULK SiC CRYSTAL GROWTH

1955 Method
“Lely”

1976 Method
“LETI” (ETU)
Reactions of the charge dissociation

\[ \text{SiC}(s) \rightarrow \frac{1}{2}\text{Si}_2\text{C}(v) + \frac{1}{2}\text{C}(s) \]

\[ \text{SiC}(s) \rightarrow \frac{1}{2}\text{SiC}_2(v) + \frac{1}{2}\text{Si}(v) \]

Reactions on the crucible surface

\[ \text{C}(s) + 2\text{Si}(v) \rightarrow \text{Si}_2\text{C}(v) \]

\[ 2\text{C}(s) + \text{Si}(v) \rightarrow \text{SiC}_2(v) \]
Crucible (a) and Temperature distribution (b)

\[
\frac{\Delta}{\Delta} \approx \frac{K}{sm}
\]

\(T > 2000 \, ^\circ C\)
Temperature distribution

Simulation tool – “Softimpact”
SiC Boules and wafers (ETU)
SiC WAFERS
SIC POLYTYPICISM

Diagram showing various crystal structures labeled 2H, 3C, 4H, 6H, 8H, 10H, and 15R.
SiC CRYSTAL LATTICE ENERGETICS
Fundamental research expertise
SiC polytypism: 2H, 4H, 6H, 21R, 3C-SiC
TIME CRITERIA OF THE STRUCTURE FORMATION

\[ \frac{\lambda_i \cdot V_\tau}{\delta \cdot D} \]

\[ A \cdot \Phi_0 \]

\[ \frac{k \cdot T}{\kappa} \]

\[ \tau < \]

- reproduction

\[ \tau > \]

- transformation

\[ \frac{\lambda_i^2 \cdot kTV_\tau}{A \Phi_0 D \delta} \]
Fundamental research expertise
SiC polytypicism: 2H, 4H, 6H, 21R, 3C-SiC
NON-EQUILIBRIUM THERMODYNAMIC APPROACH OF THE STRUCTURE FORMATION PROCESS

\[ S_{\text{мат}_j} = S_{\text{ед}_j} + \Delta M_{\text{изб}_j} \]

\[ \frac{dS}{dt} = \frac{d_i S}{dt} + \frac{d_e S}{dt} \]

\[ \frac{dS}{dt} = \Delta \frac{1}{\tau_{\text{ун}_n}} \]

\[ \tau_{\text{ун}_n} = \sum \tau_{\text{рел}_l} \]

\[ \tau_{\text{ун}_n} = \tau_j \cdot \nu^{-1} \left( \exp \left( \frac{E_{\text{акт}}}{RT} \right) \right) \]

\[ 1 - \exp \left( - \frac{\tau_{\text{мат}_j}}{RT} \right) \]

Matrix Imperfection increase

CRystallisation Medium

Delay of the ordering process

Crystal matrix
CONTROL OF SiC STRUCTURE

Method of control

- Kinetic growing structural phase transition (self structuring in the open system)
- Matrix coping (replication)
- Evolutional selection.

Parametres and criteria of control

\[ \frac{\lambda_j \tau_j}{\tau_S} \]

\[ \frac{\Delta S}{dT} = \frac{\Delta S_{\text{изб}}}{\tau_S} \]
CONTROLLED POLYTYPOICISM
Heteropolitypes structures of NH/3C/NH

- $N = 4, 6, 8$
- $E_C(NH)$, $E_V(NH)$, $3C$, $NH$
- $eFL$, $\varepsilon_0$
- $E_g(3C)$

Energy vs. Distance

- Energy, eV vs. Hexagonality $D$
- Graphs for $1 - \Delta E_C$, $2 - \varepsilon_0$, $3 - \Delta E_V$
- Hexagonality $D$ values: $8H$, $6H$, $4H$, $2H$

Graphical representations of energy levels and transitions within the structures.
3C-SiC epitaxial CVD-growth on Si substrates

Equipment and process parameters

Carrier gas: \( H_2 \), process gases: \( \text{SiH}_4, \text{C}_3\text{H}_8 \)

Substrate temperature: 1100 – 1490 ± 5°C;

\( \text{C}_3\text{H}_8 \) flow: 40 - 150 ml/min;
\( \text{SiH}_4 \) flow: 25 – 400 ml/min;
\( H_2 \) flow: 2 – 16 l/min.

Pressure in chamber during growth: 1 Torr

RF-heating of substrates at 30 kHz
Main steps of 3C-SiC/Si manufacturing

- **Porous silicon formation**
- **1000°C etching**
- **1300°C carbonization**
- **1390°C growth**
Heteroepitaxial structures of 3C-SiC/Si

Lattice mismatch Si and SiC approximately 20%,
Differences of temperature coefficients of linear extension ~8%

Epi-layer 3C-SiC, 0.5 – 3 μm

Buffer layer 3C-SiC, 15 – 20 nm

Nanoporous silicon layer, 50 - 120 nm

Silicon substrates p-, n-type (100)

Characteristics of 3C-SiC-layer
- Hall concentrations: $5 \cdot 10^{17} – 1 \cdot 10^{18}$ cm$^{-3}$;
- Electron mobility: $\mu = 145 – 280$ cm$^2$/Vc;
- Specific resistance: $\rho_v = 10^{-3}$ Ohm·cm
CVD ordered growth of carbon nanotubes on SiC and Si substrates
MAGNETRON SPATTER OF SiC AND ALN

T – 950-1050°C, V – 1μ/hour

SiC/Al₂O₃

AIN/Si
Energy diagram for atom placed on binary compound surface

\[
\bar{P}_{cij} = \frac{C_i^s / A_{ij}}{\sum_k C_k^s D_{lk} / A_{lk}}
\]

\[
A_{ij} = 1 + \frac{v_{ij}}{V_c} \exp \left( -E_{aij} / kT \right)
\]

\[
D_{ij} = 1 + \frac{v_{ij}}{V_c} \exp \left( -E_{dij} / kT \right)
\]

Energy diagram for atom placed on binary compound surface

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<th>E_{aij}</th>
<th>Si</th>
<th>C</th>
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<td>Si</td>
<td>1.1</td>
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<td>C</td>
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<tr>
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<td>2.7</td>
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<td>C</td>
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Atom placed on binary compound surface growth
SIMULATED OF SiC GROWTH TEMPERATURE DEPENDANCE TAKING INTO ACCOUNT GAS REACTION ON DEPOSITION PROCESS

Relative growth rate and component fraction in flux

Atom fraction on growth surface

Characteristic diffusion length

Fraction of coupling in the layer
Experimental and theoretical dependence of layer composition on methane content in gaseous mixture when deposited on cold substrate ($P_\Sigma=4\times10^{-2}$ Па)

1 - $U=520$ В,
2 - $U=620$ В.
Temperature dependence of SiC layer growth rate for different ratio of deposition flux main components:

1 – Si/C=1, 2 – Si/C=0.7, 3 – Si/C=1.2

- Layers with Si excess,
- Layers similar to stoichiometric composition of SiC,
- Layers with C excess.
COMPOSITIONS FOR EXTREME CONDITIONS

SiC

\( \text{Al}_2\text{O}_3 \)

\( \text{AlN} \)
- carbon bridges drift
- evaporation of Si atoms
Blue vectors are the basic cell vectors. The carbon atoms of the graphene coincidence cell are not shown.
4H-SiC Schottky diode

$U_{\text{rev max}} = 800...1200 \text{ V}$

$R_{\text{on}} = 0.5 \text{ Ohm}$
ELECTRIC FIELD DISTRIBUTION IN THE STRUCTURE PROTECTION SYSTEM UNDER 1200 V

Simulation tool – TCAD Silvaco
Current-voltage characteristics of 4H-SiC JBS-diodes

Forward current 1 A
Reverse voltage 300 V

$R_{on} = 2.2 \text{ Ohm}$
1 A - 3 V

$Q_{rr} = 0.9 \text{ nQ}$
Since the temperature control inside the closed cavity is rather complicated, a modeling of the thermal fields and fluxes in the crucible is required. The different crystal structure free energy proximity requires to use the models of non-equilibrium nonlinear thermodynamics with ordering time factor separation. Under highly non-equilibrium conditions of binary compound precipitation the analysis of chemical and structure ordering can be based on molecular kinetics models. For Graphene on the SiC surface system the crystallo-chemical model of the structure formation (can be used) considering for the binding energy.
SiC DIOD HIGH TEMPERATURE STABILITY
up to 376 °C
THANKS FOR YOUR ATTENTION