Diamond Power Transistors Enabled by Phosphorus Doped Diamond

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Project Objectives

- Diamond p-i-n Diodes
  - Fully Depleted or Bipolar operation
  - Current density $\geq 100$A/cm$^2$
  - Reverse blocking field of 200V/µm of i-layer.
  - Blocking voltage 1000, 2500, 5000V;

- Diamond p-n-i-p BJTs
  - Current density $\geq 100$A/cm$^2$
  - Tested to 250C
  - Blocking voltage 600V, 1200V, Simulated to 5,000V
  - Sp. on-resistance 150 mΩ-cm$^2$
  - Gain 10, 25, 50

![Diamond p-i-n Diodes](image1)

![Diamond p-n-i-p BJTs](image2)
Project Impact

(1) Cooling system free, ultra downsizing
- In wheel
- In motor

(2) High current density
- Small, high output

(3) High voltage, high current density
Example: High voltage SBD for train
- Wind power generation, etc.
- Downsizing distribution system

(4) Others
- High-temperature operation
- Radiation resistance

- Space development
- Nuclear power plant

Development of diamond power electronics devices, S. Shikata, and H. Umezawa, Synthesiology, 6 (2013) pp. 152-161
Project Impact

(1) Cooling system free, ultra downsizing

(2) High current density

Outside range of diamond

Inside range of diamond

Low output market

Medium output market

High output market

(3) High voltage, high current density

Example: High voltage SBD for train
Wind power generation, etc.
Downsizing distribution system

(4) Others
High-temperature operation
Radiation resistance

- Space development
- Nuclear power plant

Development of diamond power electronics devices, S.Shikata, and H.Umezawa, Synthesiology, 6 (2013) pp.152-161
Single Crystal CVD Diamond Substrates

**Fabrication**
- Plasma CVD growth -10mm
- Diamond Plates by HPHT -10mm (NDT)
- Heteroepitaxial CVD 10mm (Shin-Etsu and AIST)

**Scaling**
- Lift off new mosaic crystal
- 50 x 50 mm²
- 12 - 25 mm dia

**Dislocations**
- $10^4$-$10^5$ cm⁻²
- $10^2$-$10^3$ cm⁻²
- $10^7$-$10^8$ cm⁻²

**Suppliers**
- MWE element 6 EDP
- Sumitomo NDT TISNCM
- Namiki Shin-Etsu Augsburg U

**Others**
- 75-100 mm dia (Schreck et al)
Diamond Power Transistors

- Epitaxial growth on (100) and (111) with controlled n-type doping ($N_d = 7 \times 10^{19} \text{ cm}^{-3}$).
- Epitaxial growth on (100) and (111) with controlled p-type doping ($N_d = 1 \times 10^{20} \text{ cm}^{-3}$).
- Epitaxial growth of high purity intrinsic diamond layers.
- Schottky pin diodes with early turn-on and $>100\text{A/cm}^2$ at 4 V with $>1000\text{V}$ blocking and bipolar characteristics.
- Device processing with re-growth approach for BJT fabrication.
- Device simulations for diamond BJTs at high temperatures and high frequency.
- Beachhead strategy for technology development based on common pin devices.
Growth advances (Base layer)

- Phosphorus and Boron Doped diamond (100) and (111) layers for n and p-type conductivity.

- 3rd Year Accomplishments

- Step-flow growth mode on (111) for P doping concentration approaching $10^{20} \text{cm}^{-3}$.

- Boron doping using Trimethylboron in an iPlas reactor.
Growth advances (Intrinsic layer)

- Epitaxial, high purity intrinsic diamond (100) and (111) layers

**Impurity levels:**
- $[H] \approx 2 \times 10^{17}$ cm$^{-3}$
- $[N] \approx 2 \times 10^{16}$ cm$^{-3}$
- $[O] \approx 4 \times 10^{16}$ cm$^{-3}$
- $[P] \approx 2 \times 10^{14}$ cm$^{-3}$
- $[B] \approx 2 \times 10^{14}$ cm$^{-3}$

From similar film

**Pyrometric interferometry:**

In situ monitoring and controls for film thickness.
Growth advances (Base layer)

Device structure to accurately determine growth parameters of the base layer. Temperature controlled n-layer growth with slowly increasing temperature (p). Growth termination at a temperature maximum.
PIN – Diode: CVD Ila substrate
- p-layer with \(~10\mu m\) thickness
- Forward J \(~55\ A/cm^2\) at 20 V
- Breakdown: \(~1040\ V\) at \(10^{-3}\ A/cm^2\)
- Width of depletion region \(~8.5\ \mu m\)
- Breakdown field \(~1.2\ MV/cm\)

PIN – Diode: HPHT Iib substrate
- i-layer: Reduced growth temperature \(<750^\circ C\) for 29 hrs under \(\text{CH}_4\) increase for smooth epitaxial film.
- Forward J \(~0.4\ A/cm^2\) at 20 V
- Breakdown: \(>1.1k\ V\) at \(10^{-1}\ A/cm^2\)
- Width of depletion region \(~5\ \mu m\)
- Soft breakdown voltage (CV) of 1226V
Diodes Simulation

3rd Year Accomplishments

- Diamond n-i-p and Schottky n-i-p junction diodes:
  - Early turn-on voltage (~1V).
  - Close to 1.0 ideality factor.
  - High forward current density >100 A/cm² at 4V.
  - High reverse breakdown voltage.
  - Unipolar transport (holes).

Band Diagram

- n-layer
- i-layer
- p⁺-layer

Current Density (A/cm²)

Voltage (V)

Simulations (symbols) vs Experimental Data

Current (A)

Voltage (V)
**Substrate:** HPHT (111) Iib

i-layer growth with increasing methane addition at a final flow rate of 0.5sccm.

Isolation of individual diodes via partial mesa etch and stopping at the i-layer.

Turn on voltage of ~4V indicates bipolar transport with light emission.

CV analysis performed at 30 kHz

Space Charge Density ~6 x 10^{14} / cm³

Width of depletion region ~530 nm

Breakdown field ~3.9 MV/cm
Diamond BJTs

- Epitaxial device preparation (re-growth) on (111) substrates

**BJT selective growth approach:**

- (111) IIb Substrate
  - i-layer deposition
  - n-type layer growth (base)

- Masking (SiO₂)
  - i-layer deposition
  - p-type layer growth (emitter)
Initial BJT Diode Characteristics

Base Collector Diode

- I-layer: ~5 μm
- N-layer: ~200 nm + 50 nm

Base Emitter Diode

- I-layer: ~100-200 nm
- P-layer: ~200 nm

Sample ID 16_86
Initial BJT Characteristics

3rd Year Accomplishments

Gummel Plot

Common Base Characteristics

- Base current (exp)
- Collector current (exp)
- Current gain

$J_c$ vs $V_{BC}$ (Volts)

$J_E = 1.57 \text{A/cm}^2$
$J_E = 4.40 \text{A/cm}^2$
$J_E = 7.23 \text{A/cm}^2$
$J_E = 8.49 \text{A/cm}^2$
Simulation of p-n-p BJT characteristics

Gain > 100 possible with low defects in diamond.

Transition frequencies of several 100 MHz also predicted.
Diamond BJT Simulation

Simulation of a diamond BJT at high temperature and high frequency

- Base thickness simulations for gain >10.
- The cutoff frequency is nearly constant to 850K.
- Breakdown voltage increase due to reduced current crowding.
Thyristors for Higher Voltage

BJT High Power Switch

Low Noise Amplifiers

High-Sensitivity Area Monitors

IGBTs for High Voltage

PIN Emitter Diodes

Medical PIN Radiation Detectors

High Voltage PIN

Real-Time PIN Detector

PIN Diodes

Beachhead Market Strategy

High Voltage & Temperature

Sensitivity
Bipolar Junction Transistors – Cost Model

<table>
<thead>
<tr>
<th>Packaged Device Cost</th>
<th>Plastic Package Values</th>
<th>Hermetic Package Values</th>
<th>Ceramic Package Values</th>
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</thead>
<tbody>
<tr>
<td>assembly cost ($/part)</td>
<td>$0.20</td>
<td>$4.00</td>
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<td>assembly yield (%)</td>
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<td>98%</td>
<td>98%</td>
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<tr>
<td>assembled part cost ($/part)</td>
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<td>class test cost ($/part)</td>
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<td>class test yield (%)</td>
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<td>98%</td>
<td>98%</td>
</tr>
<tr>
<td><strong>Total part cost ($/part)</strong></td>
<td><strong>$2.856</strong></td>
<td><strong>$7.017</strong></td>
<td><strong>$45.136</strong></td>
</tr>
</tbody>
</table>

Cost per Good Tested Die Values
- gross die per wafer (die/waf): 10,699
- die yield (%): 58.5%
- net die per wafer (die/waf): 6,259
- Tested die cost ($/die): $2.790

3” diamond substrate $16,000

Packaged Device Cost
- Plastic Package
- Hermetic Package
- Ceramic Package

Electrical & Destructive Testing

Packaging

Diamond Substrate & Deposition

Base & Emitter Patterning

Base, Emitter & Collector Metallization and Patterning

Dicing
Alternative Fabrication – Minimal Fab

Fabrication using 12.5mm dia wafers in hermetic carriers

Analyses on Cleanroom-Free Performance and Transistor Manufacturing Cycle Time of Minimal Fab, Sommawan Khumpuang, Fumito Imura, and Shiro Hara, IEEE TRANSACTIONS ON SEMICONDUCTOR MANUFACTURING, VOL. 28, NO. 4, NOVEMBER 2015
Conclusions

- Materials engineering advanced for diamond power electronics:
  - n-type (P) and p-type (B)-doped (100) and (111) diamond with low resistance contacts.
- Junction diodes fabricated with >1000V blocking voltage, current density >100A/cm² and light emission.
- Initial BJT fabrication with selective re-growth approach.
- Device simulations accounting for hopping conductivity and realistic materials properties for
  - high breakdown field
  - high gain diamond p-n-i-p power transistors
  - high temperature and high frequency capability
- Technology Transfer Beachhead Strategy