MEMS technology based on CVD-diamond

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Diamond – a short introduction

- First mentioning in India used as royal jewel
- Used by Romans to engrave sapphires
- Used as dies to draw thin wires for cross bows
- Chemically identified in 1796
- Semiconducting properties identified in 1952
- First synthesized in 1953
- First CVD diamond deposition reported in 1968
Some properties of wide gap semiconductors

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>(6h)SiC</th>
<th>(3c)SiC</th>
<th>(h)GaN</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electronics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band Gap (eV)</td>
<td>1.12</td>
<td>2.9</td>
<td>2.2</td>
<td>3.45</td>
<td>5.45</td>
</tr>
<tr>
<td>Breakdown Field (10^6 V/cm)</td>
<td>0.5</td>
<td>4-6</td>
<td>3</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Mobility (cm²/Vs)</td>
<td>1500</td>
<td>500</td>
<td>~1000</td>
<td>1800</td>
<td>3800 (h)</td>
</tr>
<tr>
<td>Sat. Velocity (10^7 cm/s)</td>
<td>1.0</td>
<td>2.0</td>
<td><strong>2.2</strong></td>
<td>~1.5</td>
<td>1.1 (h)</td>
</tr>
<tr>
<td><strong>Micro-systems</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Youngs Modulus (GPa)</td>
<td>170</td>
<td>-</td>
<td>450</td>
<td>390</td>
<td>1050</td>
</tr>
<tr>
<td>Fracture Strength (GPa)</td>
<td>1.37</td>
<td>?</td>
<td>?</td>
<td>~2.5</td>
<td>10.3</td>
</tr>
<tr>
<td>Thermal Conductivity (W/cmK)</td>
<td>1.47</td>
<td>4.9</td>
<td>4.9</td>
<td>1.3</td>
<td>22</td>
</tr>
<tr>
<td>Thermal stability (°C)</td>
<td>500</td>
<td>1240</td>
<td>873</td>
<td>650</td>
<td>2200</td>
</tr>
</tbody>
</table>
Doping in diamond

- Nitrogen donor: $E_{DN} = 1.7 \text{ eV}$
- Phosphorus donor: $E_{DP} = 0.62 \text{ eV}$
- Boron acceptor: $E_{AB} = 0.37 \text{ eV}$
Boron doping activation

Data points after Borst et al, 1996
Diamond FET concepts

Boron doped $\delta$-channel FET
- Mono-layer precision
- Complex device technology

Surface-channel FET
- With H-termination:
  - 2DHG-like ($\delta_p$-type)
  - Sub-surface channel
  - $N_s \sim 10^{13} \text{ cm}^{-2}$
  - MOS-like charge control

Expectations:
- High power devices $P = 40 \text{ W/mm}$
- High current switches $I_{\text{max}} = 2 \text{ A/mm}$
- High Temp. operation $T = 1000 \degree \text{C}$
Films available for diamond technology

**MPCVD HOD film (on 2" Si)**
- 2" diam.
- 3 µm
- Single crystal
  - ideal properties
  - no large area substrate
  - used for electronics, heat sinks, windows

**MPCVD textured MCD film on SiO₂**
- 25 mm
- HOD and textured diamond
  - good crystal quality on surface, thick layers possible
  - high surface roughness and built-in stress
  - used for heat-sinks, optical windows, radiation detectors etc.
Nanocrystalline diamond (NCD)

- high mechanical strength,
  smooth surface,
  stress controlled,
  large substrates
  well suited for MEMS

- but considerable percentage of
  grain boundaries (effecting
  thermal conductivity)
Controlling stress in NCD-films

Built-in stress can be adjusted from virtually stress free ($\sigma < 5$ MPa) to highly strained ($\sigma > 500$ MPa)
Mechanical properties of NCD-films

Bending of 4 mm long cantilever
- measure force vs. distance
- record fracture point

Youngs Modulus
1020 GPa

Fracture stress
4.1 GPa

Stress (Pa)

0 1x10^9 2x10^9 3x10^9 4x10^9 5x10^9

0.000 0.001 0.002 0.003 0.004 0.005

Strain
Nano-diamond surface channel MESFET

DC – output characteristics

Performance similar to TFTs
mobility approx. 0.1 cm²/Vs

RF performance (L_g = 0.3 µm)

MO S-A K 2004
R. Müller, 09/04
♦ Diamond electronics is still a challenge but the opportunities are there.

♦ Large area case restricted to nano-diamond only useful for TFT applications.

♦ Nano-diamond new basis for MEMS:
  - electro-mechanical
  - electro-thermal
  - electro-chemical (bio-chemical)
Application examples

- MEMS - Switch
  - RF circuits (T/R Modules, filters ...)
- Inkjet for bio-chemistry
  - Liquid environment
Switch principle

Nearly all parts can be made of diamond depending on the design, we expect:

- high temperature operation
- high power switching
- no sticking if contacts are diamond
- good electrical insulation
- fast switching
Actuation principles

Signal contacts (Diamond)

Cantilever
Anchor
Base layer

Metalization

Substrate (Silicon)

Electrostatic drive

Thermal drive

Piezoelectric drive
Actuation principles

Electrostatic drive
Electrostatic drive

**Electrostatic operation:**

**Advantages:**
- High temperature / high power
- Dynamic switching loss only

**Disadvantages:**
- High driving voltages needed
Simulation of dynamic performance
(comparison with Si)

Identical geometry for diamond and silicon switch (d = 3 µm, L = 1100 µm)

- Switch closing comparable for both materials, depending on bias
- Diamond allows faster opening (higher deformation energy density released)
High temperature application

Mechanically actuated up to 850°C

Operation at 650 °C

RF switch

Threshold Voltage vs. Temperature

Youngs modulus constant

Operation in vacuum

Threshold voltage $V_{th}$ [V] vs. Temperature [°C]

$I$ vs. $V_{Driving}$

$V_{Th}$
Switching after overload

After overload:
- No contact sticking - switch opened!
- Diamond cantilever partly oxidized, but device still operational!

Switching characteristics after overload
RF switch characteristics

- Insertion loss
- Isolation
- OFF-state
- ON-state
- Attenuation (dB)
- Frequency (GHz)
- mechanically operated
- 1mm
Actuation principles

Signal contacts (Diamond)

Metallization

Cantilever

Anchor

Base layer

Diamond

Substrate (Silicon)

Electrostatic drive

Thermal drive

Piezoelectric drive
Actuation principles

Thermal drive
Thermal drive

- large bi-metal effect
- no heat storage (slow switching, interference with neighboring device)
- low driving voltage

<table>
<thead>
<tr>
<th>Material</th>
<th>therm. exp. coeff. [1/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>0.8 – 1.1 x 10^{-6}</td>
</tr>
<tr>
<td>Ni</td>
<td>12.0 x 10^{-6}</td>
</tr>
<tr>
<td>Cu</td>
<td>16.5 x 10^{-6}</td>
</tr>
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<table>
<thead>
<tr>
<th>Material</th>
<th>therm. conductivity [W/mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>&lt; 1000</td>
</tr>
<tr>
<td>Si</td>
<td>&lt; 150</td>
</tr>
<tr>
<td>Ni</td>
<td>91</td>
</tr>
<tr>
<td>Cu</td>
<td>384</td>
</tr>
</tbody>
</table>

Thermal drive

- but temperature sensitive
Thermally actuated cantilever switch

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Ni electroplated at 80 °C → pre-stressed cantilevers bends upwards

- all fingers un-heated
- Middle finger heated

- High driving force, low driving voltage
- Static power loss

Ni bi-metal

Joule heating by current flow

\[ \Delta y \sim \text{Temp.} \]
Bi-stable beam layout

Disadvantage: static power loss
→ Can be avoided by a bi-stable beam layout

Beam buckles under lateral compression → 2 stable positions
Bi-stable switch operation

4 Volt
90 µs
→ 70 µJ

3.3 Volt
70 µs
→ 40 µJ

No static power dissipation
Application examples

Applications

MEMS - Switch
- RF circuits
  (T/R Modules, filters ...)

Inkjet for bio-chemistry
- Liquid environment
Spotting of bio molecules

- pipette array
- inkjet array
- substrate
- spots
- DNA
- fluorescence marker
- marker
- DNA
- chip
- injector
Challenges in ink-jet technology

Limitation in
- lifetime
- temperature range
- aggressive fluids, solvents
- size (adjustment)

Stack of materials
- adhesion
- thermal stress

Nozzle plate bonding
- alignment
- gluing
“All-diamond” ink-jet

- Diamond
- Cu
- Si
- heater
- liquid
- V

University of Ulm
Visualization of drop ejection characteristics

- Slow motion using pseudo cinematography
- probe needle
- ejection chamber
- heater size: 50 µm x 50 µm
- nozzle size: Ø 20 µm
- drop frequency: 500 Hz
- liquid: purified water
- t_{heat} = 4.8 µs
NCD enables µm-size nozzles

existing system

20 µm diameter: 4 pl/drop

1 µm ball shaped droplet: ~ atto-liter/drop?

Scaling requires:
• Uniform material of small grain size
• High mechanical stability during ejection
• High resistance against corrosion
• Small thermal stresses for reliable operation
Diamond micro devices – the rest of the family

Diamond **DUV (220nm) Detector**

Diamond **pressure / acceleration sensor**

Diamond **micro pump & capillary**

0.2 µm gate length **FET**
- $f_{\text{max}} = 81$ GHz

Schottky **diode**
- $T = 1000$ °C

Diamond **electrochemical probe**
The end

Thank you for your attention
Diamond deposition techniques (CVD)

Microwave PECVD

Gas: H₂ with 1.5% CH₄
Temperature: 650°C
Pressure: 30 Torr
Frequency: 2.45 GHz
Power: 700 W

Hot Filament CVD

Gas: H₂ with 0.3% CH₄
Temperature: 700°C
Pressure: 15 Torr
T (Filaments): 2200°C
Power: 6 kW
What is nanocrystalline diamond?

- **HOD, textured diamond**
- **nanocrystalline diamond**
- **2D NCD**
- **3D NCD**
- **HOD (nanocrystalline)**
- **UNCD (ultrananocrystalline)**
- **amorphous α-diamond**

Size scales: 1μm, 100nm, 10nm, 1nm, 0.1nm
Surface roughness of 2D NCD

SEM Micrograph

2D-Nanocrystalline Diamond

- Film thickness: 9.2µm
- Surface roughness: 96.21nm (RMS)

AFM Micrograph

- Film thickness: 2µm
- Peak to peak: 73nm
- Surface roughness: 17.24nm (RMS)

400nm
Surface roughness of 3D NCD

3D-Nanocrystalline Diamond

Film thickness: 8.4 µm
Surface roughness: 54.96 nm (RMS)

SEM Micrograph

AFM Micrograph

Section Analysis

300 nm
# Mechanical cantilever properties

<table>
<thead>
<tr>
<th>Mechanical parameters</th>
<th>CVD-Diamond on silicon</th>
<th>Single crystal diamond</th>
<th>Single crystal silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [gcm⁻³]</td>
<td>3.5</td>
<td>3.515</td>
<td>2.329</td>
</tr>
<tr>
<td>Young’s Modulus [GPa]</td>
<td>600 - 1150</td>
<td>910 - 1250</td>
<td>98</td>
</tr>
<tr>
<td>Fracture Strength [GPa]</td>
<td>2 - 5</td>
<td>10.5</td>
<td>1.1 - 1.3</td>
</tr>
</tbody>
</table>

## Static:

Hooke’s Law:
\[ \frac{\Delta L}{L_{\text{max}}} = \frac{P_{\text{Fracture}}}{YM} \]

- \[ \frac{\Delta L}{L_{\text{maxSi}}} \sim 10^{-2} \]
- \[ \frac{\Delta L}{L_{\text{maxDia}}} \sim 0.4 \times 10^{-2} \]

## Dynamic:

\[ f_{\text{res.}} \sim \sqrt{YM/\rho} \]

### Graph:
- Nano-diamond measured point
- Diamond
- Silicon

### Axis:
- Resonance Frequency (MHz)
- Cantilever Length (µm)
Diamond NEMS
Diamond ‘Nano Xylophones’

NANOMECHANICAL RESONANT STRUCTURES IN NANOCRYSTALLINE DIAMOND
L. Sekaric, J.M. Parpia, H.G. Craighead, T. Feygelson, B.H. Houston, and J.E. Butler

Resonant Frequency vs. Length

Q’s ~ 3000

640 MHz!

Young’s Modulus > 700 GPa

NRL
Washington DC
Cornell University
Ithaca NY
Robustness test, Aqua-Jet

Operation in water:
Pulse: 200 V at 50 Ω -> 0.8 kW
Length 2.5 µs, Repetition 10 kHz

Heater geometry:
1 mm x 1 mm
thickness: 4 µm

No thermal stresses in diamond-
SiO₂ multi-layer-stacks at heavy
thermal cycling

open system
Lab-on-a chip systems

- Peristaltic pump
- Capillary for electrophoresis
- Micro-mixing device