Gallium Nitride Surface Acoustic Wave Resonators for Harsh Space Environments

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• Modeled and micro-fabricated GaN-on-Sapphire surface acoustic wave resonators

• Modeling and preliminary results for the space resonators subjected to space-like temperature excursions

• Characterized fabricated resonators under gamma radiation for space environments
Resonator Concept

**Harsh Environment Conditions in Space**

**Mission to Venus**
- Extreme high temperatures up to 460-470°C
- Total ion dose (TID) radiation exposure
- Vibrations, shock, high pressure

**Mission to Mars**
- Extreme low temperatures ~ -180 °C to -200 °C
- Total ion dose (TID) radiation exposure
- Large number of thermal cycles
- Vibrations, shock, high pressure

Current Technology - Quartz Resonators

😊 Cheap, industrial dominance ~50 years
😊 Low temperature coefficient of frequency (TCF) at operating temperatures between -40°C to +85°C
Current Technology - Quartz Resonators

😊Cheap, industrial dominance ~50 years
😊Low temperature coefficient of frequency (TCF) at operating temperatures between -40°C to +85°C
😊Quartz cannot be reliably operated at extreme high temperatures
  • Quartz changes phase at 573°C
😊Quartz has integration problems with CMOS
😊Packaging needed to protect it from harsh space environments
  • Additional packaging ~$25,000/kg

Proposed Design

• Gallium nitride thin film (on a sapphire substrate) with Au/Cr Interdigital electrodes (IDTs) used to generate surface acoustic wave.
• Generated surface acoustic wave has wavelength of 20 μm.
• Silicon dioxide used as a temperature compensation layer.

New Materials - Gallium Nitride

- GaN is a radiation-hardened wide bandgap III–V material.
- Rad-hard temperature-compensated timing solution using AlGaN/GaN resonator that can be monolithically integrated with ICs and sensors.

<table>
<thead>
<tr>
<th>Property</th>
<th>GaN</th>
<th>AlN</th>
<th>Quartz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting Point ($^\circ$C)</td>
<td>2500</td>
<td>2470</td>
<td>1700</td>
</tr>
<tr>
<td>Energy Gap (eV)</td>
<td>3.4</td>
<td>6.2</td>
<td>8.9</td>
</tr>
<tr>
<td>Atom Displacement Energy (eV)</td>
<td>23</td>
<td>24</td>
<td>5.4</td>
</tr>
<tr>
<td>Young’s Modulus (GPa)</td>
<td>390</td>
<td>340</td>
<td>1035</td>
</tr>
<tr>
<td>Acoustic Velocity ($x10^3$ m/s)</td>
<td>8.0</td>
<td>11.4</td>
<td>5.75</td>
</tr>
<tr>
<td>Curie Temperature ($^\circ$C )</td>
<td>-</td>
<td>-</td>
<td>573(phase change)</td>
</tr>
<tr>
<td>Monolithic Integration</td>
<td>Yes</td>
<td>CMOS Compatible</td>
<td>No</td>
</tr>
</tbody>
</table>
Fabrication Process

1) 5 μm Gallium Nitride on Sapphire

2) Spin SPR3612 photoresist

3) Pattern photoresist with IDT + reflector pattern

4) Evaporate metal and perform lift-off

5) Deposit and Pattern CVD Oxide to obtain compensated device
Modeling Results

Relative frequency change (ppm/°C)

\( h_{\text{GaN}} / \lambda = 0.1 \)
\( h_{\text{GaN}} / \lambda = 0.2 \)
\( h_{\text{GaN}} / \lambda = 0.25 \)
\( h_{\text{GaN}} / \lambda = 0.3 \)

SiO\(_2\) thickness \( (h_{\text{SiO}_2} / \lambda) \)
Test Setup for Temperature Excursions

• A network analyzer was used to record the frequency response at different temperatures.

• An infrared spot heater was used to heat the sample from room temperature up to 100°C.

• Liquid nitrogen was used to cool the die down to -180°C.
Preliminary Temperature Compensation Results

Measured relative change in frequency versus temperature for GaN-on-sapphire SAW resonator with and without a 9-μm-thick SiO₂ layer.

- 9 μm thick plasma enhanced chemical vapor deposition (PECVD) silicon dioxide was deposited and patterned for temperature compensation.
- The oxide improved the relative change in frequency from -38 ppm/°C to -11.7 ppm/°C.
- Porous PECVD silicon dioxide could have contributed to sub-optimal improvement in temperature compensation.

Cryogenic Temperature Response

Cryogenic response of the uncompensated GaN-on-sapphire SAW resonator showing self-compensation at temperatures between –180°C and –150°C.

- At cryogenic temperatures (between −180°C and −150°C), the GaN-on-sapphire resonator shows a constant relative frequency change.
- Such characteristics need to be studied for NASA’s Mars and Europa missions.

Experimental Setup - Radiation Tests

Radiation Test Specifications

<table>
<thead>
<tr>
<th>Source</th>
<th>Cs-137</th>
</tr>
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<tbody>
<tr>
<td>Dose Rate</td>
<td>1.2 rad/s</td>
</tr>
<tr>
<td>Total Ion Dose</td>
<td>1 Mrad</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>0.66 MeV</td>
</tr>
</tbody>
</table>
Radiation Test Results

- $S_{11}$ peak height decreases by ~30% over 850 krads which demonstrates lower piezoelectric coupling coefficient.
- Resonant frequency changes by $1.2 \times 10^{-3}$ ppm/rad.
- Device shows recovery/healing after annealing.

Measured $S_{11}$ response of unirradiated, irradiated (up to 850 krad), and thermally annealed GaN/sapphire SAW devices.

Future Work

• Perform additional radiation experiments using neutrons and protons
• Perform material characterization for radiated samples through advanced techniques like TEM, AFM and XRD maps.
• Improve the TCF of GaN-on-Sapphire SAW resonators with LPCVD and sputtered oxide
• Monolithically integrate the resonator with GaN/AlGaN high electron mobility transistors (HEMTs).
Conclusions

• Finite element analysis was used to model GaN-based SAW resonators and predict SiO\textsubscript{2} thickness for temperature compensation.

• One port surface acoustic wave resonators using Gallium Nitride as a piezoelectric substrate were fabricated and characterized within space-like environments.

• Radiation tests show decreasing $S_{11}$ peak intensity with increasing dosage of radiation with minimal frequency drift.

• Temperature compensation techniques have been shown to improve the temperature-induced frequency drift in the resonator.