Recent developments in microwave filters based on GaN/Si SAW resonators, operating at frequencies above 5 GHz

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Outline

- Introduction
- Design of SAW-BPF
- Fabrication and characterization
- Thermal stability analysis
- Conclusions & Future developments
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- Introduction
  - Design of SAW-BPF
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  - Conclusions & Future developments
• “Microwave filters based on GaN/Si SAW resonators, operating at frequencies above 5 GHz” (ESA project No. 40000115202/15/NL/CBi)

• **Main project objectives**: design, fabrication and characterization of monolithic integrated band pass filters processed on GaN/Si, operating at >5 GHz
  – IDTs with digit/interdigit widths below 200 nm
  – use of multiple SAW-Rs integrated monolithically with printed inductors (connected in series or in parallel)
Surface Acoustic Wave (SAW) resonator

Reflectors

IDT

Reflectors

220 digits; L=150 µm; w=s=200 nm

Custom grown wafer specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>NTT-AT Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si Wafer resistivity</td>
<td>&gt;6000 Ohm·cm</td>
</tr>
<tr>
<td>Si Wafer thickness</td>
<td>500 ± 25 µm</td>
</tr>
<tr>
<td>Si orientation</td>
<td>(111) ± 0.1°</td>
</tr>
<tr>
<td>Si wafer diameter</td>
<td>3” (76.2 mm)</td>
</tr>
<tr>
<td>Wafer bow</td>
<td>&lt;30 µm</td>
</tr>
<tr>
<td>Buffer thickness</td>
<td>300 nm</td>
</tr>
<tr>
<td>Buffer content</td>
<td>AlN</td>
</tr>
<tr>
<td>GaN thickness</td>
<td>1 µm</td>
</tr>
</tbody>
</table>
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SAW Bandpass Filters:

a) Delay line type filters: high propagation losses
b) Longitudinally-Coupled Resonator filter: difficult to implement in CoPlanar Waveguide topology
c) Impedance Element Filters (ladder filters): performances limited by the SAW resonators parameters
Impedance Element Filter in PI topology

Selected filter configuration using Impedance Element Filter approach:

The SAW-R components were selected for a resonance frequency around 5.5 GHz, corresponding to digit/interdigit widths of 200 nm.

\[
\begin{align*}
    f_{s, SAW_H} &= f_0 = f_{p, SAW_V} \\
    f_{p, SAW_H} &= f_{c2} > f_0 \\
    f_{s, SAW_V} &= f_{c1} < f_0
\end{align*}
\]
Design procedure – Analytic design

Effect of a series inductor $L_s << L_m$: same $f_p$, but:

$$\omega^4 + \left( \frac{1}{L_s C_0} - \omega_p^2 \right) \omega^2 - \frac{\omega_p^2}{L_{ser} C_0} = 0$$

$$(\omega_s')^2 \approx \frac{\left( \omega_p^2 - \frac{1}{L_s C_0} \right) \pm \sqrt{\left( \frac{1}{L_s C_0} - \omega_p^2 \right)^2 + 4 \frac{\omega_p^2}{L_s C_0}}}{2}$$

Effect of a parallel inductor $L_p << L_m$: same $f_s$ but:

$$\omega^4 - \omega_p^2 \omega^2 (1 - \eta) + \eta \omega_s^2 \omega_p^2 = 0$$

$$\eta = \frac{L_m}{L_p \left( 1 + L_m C_0 \omega_s^2 \right)}$$

$$(\omega_p')^2 \approx \frac{1}{2} \omega_p^2 \left[ (1 - \eta) \pm \sqrt{(1 - \eta)^2 - 4 \eta \frac{\omega_s^2}{\omega_p^2}} \right]$$

(© 2018 IEEE. D. Neculoiu et al., IEEE ACCESS, Vol. 6, DOI: 10.1109/ACCESS.2018.2867456)
Band Pass Filter in PI configuration

- very compact of only 3x0.8 mm$^2$
- the series printed inductors have a width of 20 µm
- input/output CPW lines have the gap-signal-gap widths of 50-100-50 µm, for a characteristic impedance of ~50Ω
Co-simulation approach for filter design

3D EM Model

Block level schematic

PORT Z=Zo Ohm
PORT Z=Zo Ohm

Schematic used for filter design

SAW-R mBVD equivalent circuit

S-Parameters [Magnitude in dB]

Frequency / GHz

P=1 Rs
Cm Rm Lm

P=2 Co Ro
Band Pass Filter in PI configuration

Equivalent circuit parameters for the vertical (V) and the horizontal (H) SAW-R

<table>
<thead>
<tr>
<th></th>
<th>Co [pF]</th>
<th>Cm [fF]</th>
<th>Lm [nH]</th>
<th>Rm [Ω]</th>
<th>Ro [Ω]</th>
<th>Rs [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAW-R-V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAW-R-H</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Layout parameters for the vertical (V) and the horizontal (H) SAW-R

<table>
<thead>
<tr>
<th></th>
<th>No. of digits</th>
<th>Digit length [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAW-R-V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAW-R-H</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Simulation results for the PI configuration BPF
Introduction

Design of SAW-BPF

Fabrication and characterization

Thermal stability analysis

Conclusions & Future developments
Fabrication of SAW-Rs operating > 5 GHz

- SAW-R on GaN/Si for frequencies beyond 5 GHz
  - IDTs with digit/interdigit widths below 300 nm
  - nanolithographic patterning of the IDTs
  - writing field limited to a maximum of 100x100 µm² to avoid the negative charging and stitching effects

- e-beam lithography
  - maskless lithography technique; dedicated EBL machine - Raith e-Line; electron resist PMMA 950k A4

- metal layers deposited using a highly directional e-beam evaporation equipment (Temescal FC 2000)
  - favors the lift-off process -> neat lines without side walls

Digit width = 130 nm
Digit width = 150 nm
Digit width = 200 nm
Test structures

![Image of test structures](image)

<table>
<thead>
<tr>
<th>Pitch</th>
<th>DL = 0.2 mm</th>
<th></th>
<th>DL = 0.7 mm</th>
<th></th>
<th>DL = 1.2 mm</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fres @ 20°C [GHz]</td>
<td>TCF [ppm/°C]</td>
<td>fres @ 20°C [GHz]</td>
<td>TCF [ppm/°C]</td>
<td>fres @ 20°C [GHz]</td>
<td>TCF [ppm/°C]</td>
</tr>
<tr>
<td>0.4 μm</td>
<td>5.4485</td>
<td>NA</td>
<td>5.4585</td>
<td>-43.72</td>
<td>5.4565</td>
<td>-43.25</td>
</tr>
<tr>
<td>0.3 μm</td>
<td>7.0285</td>
<td>-41.66</td>
<td>7.0265</td>
<td>-40.47</td>
<td>7.0255</td>
<td>-39.88</td>
</tr>
<tr>
<td>0.26 μm</td>
<td>7.9865</td>
<td>-43.23</td>
<td>7.9895</td>
<td>-42.7</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Thermal stability analysis between 20°C – 150°C

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### Measurement results for the PI-type filter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Re-simulated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion losses</td>
<td>10.5 dB</td>
<td>10.3 dB</td>
</tr>
<tr>
<td>Return loss</td>
<td>8.6 dB</td>
<td>9.2 dB</td>
</tr>
<tr>
<td>Out of band rejection</td>
<td>~22 dB</td>
<td>~20 dB</td>
</tr>
<tr>
<td>-3dB bandwidth</td>
<td>8.3 MHz</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Central frequency</td>
<td>5.506 GHz</td>
<td>5.5 GHz</td>
</tr>
</tbody>
</table>

Measurement vs. simulation

1 μm
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Measurement setup for thermal analysis

In-house developed on-wafer measurement setup used to record S parameter measurements at different temperatures

Anritsu 37397D
- General shape of the frequency response is preserved
- Filter selectivity becomes worse with the temperature increase
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## Results vs. SotA

<table>
<thead>
<tr>
<th>BPF Parameter</th>
<th>Results</th>
<th>SAW-BPF SotA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>[1]</td>
</tr>
<tr>
<td>Insertion losses</td>
<td>10.3 dB</td>
<td>25.5 dB/24.4 dB</td>
</tr>
<tr>
<td>Return loss</td>
<td>9.2 dB</td>
<td>N.A.</td>
</tr>
<tr>
<td>Out of band rejection</td>
<td>20 dB</td>
<td>~35 dB</td>
</tr>
<tr>
<td>-3dB bandwidth</td>
<td>10 MHz</td>
<td>N.A.</td>
</tr>
<tr>
<td>Central frequency</td>
<td>5.5 GHz</td>
<td>237.8 MHz/493.7 MHz</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-55°C…+125°C</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

Obs. Delay lines/Fe-doped GaN on sapphire | Resonator on membrane | GaN/sapphire | Delay line GaN/Si

Reported results are beyond the state of the art for SAW on GaN/Si based band pass filters


• **Compact (3x0.8 mm\(^2\)) monolithic integrated SAW-BPF operating @ 5.5 GHz**
  – 10 dB IL; 20 dB rejection; 10 MHz -3dB BW

• **SAW-BPF on GaN/Si**
  – monolithic integration of active devices (HEMTs) possible
  – can be used in harsh environments and extreme temperature conditions
Thank you for your attention!