Th2C

3.7GHz, Low Loss, 100MHz Bandwidth, Single Crystal, Aluminum Nitride on Silicon Carbide Substrate (AlN-on-SiC) BAW Filter

Presented by Rama Vetury

Akoustis Technologies, Inc.
Outline of this Presentation

• Motivation:
  – Acoustic Filter Market Dynamics
  – Evolving Requirements on Filter Technology
  – Limitations of Current Filter Technologies

• Approach
  – Single Crystal Piezoelectric Materials
  – Materials Characterization

• Results
  – BAW Resonator
  – RF Filter

• Conclusions
$10.5B Total Acoustic RF Filter Market

- Current $10.5B TAM for Acoustic RF filters
- Mobile communications is dominant market segment
- Developing opportunities for wireless infrastructure, WiFi, military (radar and communications), and emerging IoT applications

Source: Mobile Experts 2016, Acoustis Dedalus Consulting 2015
Mobile RF Filter Market

- Mobile RF Filter Market anticipated to grow to ~ $12.4B by 2021
- BAW segment fastest growing RF Filter opportunity ($5B market by 2021)

Source: Mobile Experts 2016

SAW Filters (Low Band)
Multiple Suppliers (Commodity)

BAW Filters (High Band)
2 Dominant Suppliers

2016 2021
High Frequency, Bandwidth Drivers

- 4G/LTE Mobile wireless RF filter market: 6B+ band shipments (26% of total)
- Wide Bandwidth RF filters: require high $k_{eff}^2$ resonators
- High Frequency RF filters: resonator center frequency is >2.5GHz
Wi-Fi RF Filter Drivers

New tri-band routers require high rejection coexistent filters at 5GHz. Shift to Multi-user 4x4 (& 8x8) MIMO to increase the number ofTx & Rx Filters.

Steep skirt & good OOB rejection to improve tri-band performance. High Q, small form factor filters are necessary. Reduce size to enable integration of multiple Tx/Rx.
Wireless Infrastructure RF Filter Drivers

Small Cell MIMO & Active Antenna Systems (or FD-MIMO) driving increased number of filters in same size system

LTE-Advanced Pro Carrier Aggregation driving increased bands at higher frequencies

Femto  Pico  Micro

Reduce size and handle 1-4W avg. to enable integration of multiple Tx/Rx

High Q, small form factor power capable filters are necessary

High frequency, high bandwidth technology to support LTE-U

LTE Licensed

3.5GHz

LTE-U/LAA

Unlicensed

5GHz

Th2C
BAW Filter Technologies

- **Poly Crystal Solidly Mounted Resonator (SMR)**
- **Poly Crystal Film Bulk Acoustic Resonator (FBAR)**
- **Single Crystal Bulk Acoustic Resonator (BulkONE®)**

- **SMR**: 1 air interface, 1 reflector, poly-crystal AlN
- **FBAR**: 2 air interfaces, poly-crystal AlN
- **BulkONE®**: 2 air interfaces, **Single Crystal AlN**
ALN in Today’s Acoustic Filters

Hexagonal wurtzite crystal structure of AlN\(^1\).

- Current acoustic filters use AlN films deposited via Physical Vapor Deposition (PVD)
- c-axis, [0001] direction preferred orientation in hexagonal wurtzite AlN
- Optimizing deposition conditions $\rightarrow$ Improvements in PVD material quality
  - Metal surfaces with hexagonal symmetry enhance c-axis orientation

Polycrystal AlN: High Frequency Challenges

- Frequencies > 3 GHz require thinner piezoelectric films.
- Previous work* on PVD AlN shows that crystal quality & piezoelectric parameters degrade in thinner films.

Single Crystal & Poly Crystal AlN: XRD

- MOCVD: Epitaxial growth on SiC: High temperature nucleation
- PVD: Deposition on AlN/Mo seed layer (Commercially sourced)
- Both Diffraction peaks centered at Bragg angle for AlN

**Single Crystal**

- AlN/Mo/AlN: 1 μm AlN
- FWHM: (002) = 4539.6 arcsec [1.261°]

**Poly Crystal**

- Single Crystal AlN
  - (002) = 101 arcsec [0.028°]

Commercially sourced PVD AlN

- AlN/Mo/AlN: 1 μm AlN
- FWHM: (002) = 4539.6 arcsec [1.261°]
Elastic & Piezoelectric Parameters - Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single Crystal AlN</th>
<th>PVD Thin Film AlN¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{ac}$ (km/sec)</td>
<td>10.73</td>
<td>~ 10.4</td>
</tr>
<tr>
<td>$C_{13}$ (GPa)</td>
<td>108.6</td>
<td>100</td>
</tr>
<tr>
<td>$C_{33}^D$ (GPa)</td>
<td>375.1</td>
<td>419 +/- 4</td>
</tr>
<tr>
<td>$C_{33}^E$ (GPa)</td>
<td>343.2</td>
<td>382 +/- 12</td>
</tr>
<tr>
<td>$d_{33}$ (pm/V)</td>
<td>4.85</td>
<td>3.9</td>
</tr>
<tr>
<td>$e_{33}$ (C/m²)</td>
<td>1.67</td>
<td>1.505</td>
</tr>
<tr>
<td>$k_t^2$ (%)</td>
<td>8.48</td>
<td>6.5 – 7.0</td>
</tr>
</tbody>
</table>

- Measurement on 1.1 μm AlN on 150mm SiC substrate
- Compared to polycrystalline AlN:
  - $d_{33}$ increases 24.3%
  - $e_{33}$ improves 10.9%
- **No degradation** in measured sound velocity between 0.5 μm & 1.1 μm thick single crystal AlN
- Explore potential $k_t^2$ benefit

Single Crystal AlN: Conclusions

Advantages of Single Crystal AlN vs. Poly Crystal AlN

➢ Acoustic properties maintained over wide thickness range enabling high frequency applications
  ✓ Consistently low rocking curve FWHM
  ✓ Consistently high sound velocity measured

➢ Epitaxial growth on SiC → superior orientation control for AlN film

➢ Enhanced crystal quality → 40x narrower XRD FWHM
  (0.028° vs. 1.26°)

➢ Single crystal AlN → enhanced piezoelectric properties
  \( (d_{33}, e_{33}) \)
Resonator Metrics

- $k_{eff}^2$
  - Impacts filter bandwidth

- "Q" Quality Factor
  - Measure of energy loss
  - Impacts skirts/roll-off of filter

- FOM = $k_{eff}^2 \times Q$
  - Impacts Insertion Loss of filter
Filter Metrics

Ladder Network [*]

Lattice Network [*]

Generic Filter Response

Loss $\alpha$ 1/FOM, Skirts $\alpha$ Q, Bandwidth $\alpha$ $k^2$

* Hashimoto (ed.) “RF BAW Filters for Wireless Comm.”

Better Materials Characteristics translate to Better Filters

• High Acoustic velocity $\rightarrow$ higher PZ thickness $\rightarrow$ Higher frequency capability
• High Acoustic velocity & Thermal conductivity $\rightarrow$ Higher power handling
• Higher $k^2$ $\rightarrow$ Higher bandwidth
• Higher Q-factor $\rightarrow$ steeper filter skirts, decreased TCF requirement
Resonator Measurement

- De-embedding to plane of intrinsic resonator critical
- 2 approaches
  - Electro-magnetic simulation (EM)
    - Measured on-wafer de-embedding structures
- Calibrating at edge of the Smith Chart critical

3D representation of “manifold” – between intrinsic resonator and probe plane
3.8 GHz Resonator Results

Smith Chart - “Q-circle”

- Wide band resonator characterization
- $F_P = 3.785\, \text{GHz}$
- Good fit between mBVD model fit & de-embedded data
3.8 GHz Resonator Results

Y Parameter

- De-embedding removes manifold elements
- Zero Crossing of \( Y_{11} \) Phase \( \rightarrow \) \( F_s \), \( F_p \) \( \rightarrow \) coupling coefficient \( (k_{\text{eff}}^2) \)
- Good fit between mBVD model and de-embedded data
3.8 GHz Resonator Results

- Good agreement between de-embedded measurement and mBVD model
- mBVD resonator model: $Q_{\text{MAX}} = 1809$, $Q_P = 1575$

**Q-circle**

$$Q(2\pi f) = \frac{d\phi_L}{d\omega} \frac{\text{mag}(S11_L)}{[1-(\text{mag}(S11_L))^2]}$$

- **Model:**
  - $Q_{\text{MAX}} = 1809$
  - $Q_P = 1575$

- **Bode:**
  - $Q_{\text{MAX}} = 1756$
  - $Q_P = 1337$

**Measured (EM de-embedded) modeled**
3.8 GHz Matched Filter Results

- High complexity, 11-element ladder network filter
- Low insertion loss (-2.7dB) at Fc (3.85GHz)
- Excellent out-of-band rejection; No "fly-back" at high frequency
3.8 GHz Filter: Measured vs Model

- Good agreement between measurement and model
- Resonator model based on modified Mason Model (includes loss)
First 5.8 GHz Resonator Results

- Good agreement between de-embedded measurement and mBVD model
- High Q achieved - $Q_P = 609$, $Q_{MAX} = 456$
CW Power Soak Test Details
- Frequency: 3.68GHz (Series Resonance)
- Input Power: 6.6W CW at room temperature

CW Power Sweep Test Details
- Frequency: 3.68GHz (Series Resonance)
- Step Size: 1dB at room temperature, 5 seconds dwell
Single Crystal AlN Filter Technology

<table>
<thead>
<tr>
<th></th>
<th>&lt;2GHz</th>
<th>2.6 GHz</th>
<th>3.8 GHz</th>
<th>5.8 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filters</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Resonators</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Materials</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

✓ Single Crystal AlN Materials enable high bandwidth, high performance filters beyond 5GHz
Conclusions

• Requirements
  – Urgent Need for Small RF Filters in 2-6GHz range
  – Existing acoustic filters challenged to meet high power requirements

• Materials
  – Demonstrated 40x Better Crystal Quality vs Polycrystalline AlN (XRRC FWHM)
  – Demonstrated No Degradation in Acoustic Velocity for 1.1 & 0.5µm thick AlN

• Devices
  – Demonstrated resonators at 2.6GHz, 3.8GHz and 5.8GHz
  – Demonstrated filters at 2.6GHz, 3.8GHz
  – Demonstrated intrinsic resonator/filter power handling >10W at 2.8 & 3.7GHz