Micromachining and nanoprocessing of GaN/Si for GHz acoustic resonators and UV photodetecting applications

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The most common **WBG materials** are **SiC, GaN and AlN**.

WBG materials exhibit unique physical properties like:

- high breakdown field
- high electron saturation velocity
- high sound velocity
- strong piezoelectric effects
- high power capabilities
- high temperature environment

**GaN and AlN** present pronounced **piezoelectric properties**.

All these properties make them very attractive for **microwave** and **millimeter wave applications** and also for creating a **new generation of sensing devices** capable of working in harsh environments at temperatures higher than 600 °C.
Surface Acoustic Wave (SAW) and Film Bulk Acoustic Resonators (FBAR) have a major interest in the fabrication of radio frequency (RF) filters for mobile and satellite communication systems, various forms of data transmission (WLAN).

- Most SAW resonators used in the actual mobile communication systems are manufactured on quartz, lithium tantalite or lithium niobate.
- Classical technologies for FBAR resonators are based on ZnO sputtered layers.

It becomes very difficult to achieve low-loss and sharp-cut off filters working at frequencies higher then 2 GHz using the classical SAW and FBAR technologies.
Because

► The cellular phone is evolving from a third generation (3G) system to a fourth generation (4G) system. The radio frequency of 4G systems is expected to be within the high-frequency range from 3 to 6 GHz.

► Using MEMS micromachining techniques and nanolithography, applied to WGB materials it is possible to obtain devices with low losses, and high operating frequency.

► Also is important the possibility of monolithic or hybrid integration with other circuit elements (e.g. HEMT transistors), because these materials (GaN, AlN) can be grown or deposed on semiconductor wafers (high resistivity GaAs or silicon).

Sensors based on SAW and FBAR structures have the sensitivity $\sim f^2$. 
1. The **sub-micron** thickness of the GaN or AlN membrane in FBAR devices can increase their operating frequency.

2. The use of **nanolithography** *(fingers and interdigits 100–300 nm wide)*, to fabricate the interdigitated transducer (IDT) of the SAW structures will result in an increasing of operating frequency.

3. Micromachining for GaN/Si and the use of **nanolithography** for the MSM interdigitated structure can improve **UV photodetector** performances and permits back-side illumination.
<table>
<thead>
<tr>
<th>AIN/Si</th>
<th>GaN/Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition by magnetron sputtering</td>
<td>Deposition by MBE and MOCVD</td>
</tr>
<tr>
<td>Sound velocity 9000 m/s □</td>
<td>Sound velocity 7000 m/s □</td>
</tr>
<tr>
<td>Coupling coefficient 6% □</td>
<td>Coupling coefficient 2% □</td>
</tr>
<tr>
<td>Band gap 6.3 eV</td>
<td>Nanolithography a big challenge □ □</td>
</tr>
<tr>
<td></td>
<td>Monolithic integration with HEMT transistors is possible □</td>
</tr>
<tr>
<td></td>
<td>Band gap 3.4 eV □ for UV photodetection</td>
</tr>
</tbody>
</table>
FBAR-Film Bulk Acoustic Resonator  
Surface Acoustic Wave Resonator

**FBAR**

- Electrodes
- Piezoelectric
- Substrate (Si, GaAs)

**SAW**

- IDT
- Reflective gratings

\[
\begin{align*}
\text{d} &= \lambda/2 = v_s/2f_r \text{ (resonance)} \\
\text{f}_r &= v_s/2d \\
2w &= \lambda/2 = v_s/2f_r \\
f_r &= v_s/4w; \\
\text{v}_s &\sim \text{km/s; } d, w \sim \text{nm, } f_r \sim \text{GHz}
\end{align*}
\]
We develop for the first time a **FBAR** structure on a **thin membrane**! increasing drastically the resonance frequency!

**GaN membrane supported series connection of two FBAR structures (test structures)**

**IMT- Bucharest-FORTH Heraklion –TU Darmstadt 2006**

The GaN on silicon structure grown by MOCVD (Azzuro Ltd. Magdeburg)

2.2 μm thin membrane

\[ f_r = 1.3 \text{ GHz} \]

6.3 GHz resonance on a GaN FBAR obtained by micromachining of GaN/Si (1)

-540nm \{340 nm (GaN) +200nm (buffer)\} thin membrane supported FBAR structure based on GaN micromachining

-50nm thin Mo metallization

GaN/Si wafers from NTT AT Japan

Top view with top and bottom illumination

Cross section

Maximum deflection 2.7μm

IMT and FORTH
July 2008

XRD

White Light Interferometer
6.3 GHz resonance on a GaN FBAR obtained by micromachining of GaN/Si (2)

IMT and FORTH
July 2008

A. Müller, D. Neculoiu, G. Konstantinidis et al. “6.3 GHz Film Bulk Acoustic Resonator Structures Based on a Gallium Nitride/Silicon Thin Membrane”

(VNA) Vector Network Analyzer characterization in microwaves

Q_p = 1130
Q_{sp} = f_{sp}/(f_2-f_1), where f_{sp} is the resonance frequency (series or parallel), f_1 and f_2 are the frequencies at which the magnitude of the input impedance is ½ from its resonance (anti-resonance) value

f_r = 6.3 GHz
540 nm thin membrane

f_s = 6.217 GHz
f_p = 6.306 GHz
Last results

- It is under test a run processed in Dec 2009
- **350nm** \{200 nm (GaN) +150nm (buffer)\} thin membrane supported FBAR structure based on GaN micromachining,
- 50nm thin metallization (top) and 120nm bottom

![Graphs showing S parameter and resistance/conductance](image-url)

(Preliminary results)

**f_0** = 9 GHz

350 nm thin membrane
SAW devices for GHz applications with nanolithographic IDTs

Results obtained on AlN (IMT-FORTH-NIMP)


Best previous result obtained before was a SAW on AlN (but on diamond not on silicon) operating at 4.5 GHz [P. Kirsch et al. Appl Phys. Lett. 88, 223504, 2006]
SAW resonators on GaN/Si with fingers and interdigits 250 nm wide (up) and 150 nm wide (down) patterned in IMT on the new “E-Line” equipment from Raith (electron beam lithography)

February 2009
Recent results SAW on GaN/Si -1
(IMT – FORTH 23 Dec 2009)

GaN SAW structures with fingers and interdigits 150 nm wide resonating at a frequency 7 GHz

unpublished

SAW_GAN_150 nm

S21 Parameter [dB]

-41 -40.5 -40 -39.5 -39 -38.5 -38

7.062 GHz

-40.612 dB

5.8 6.3 6.8 7.3 7.4

Frequency (GHz)
Recent results SAW on GaN/Si -1
(IMT – FORTH 23 Dec 2009)

GaN SAW structure with fingers and interdigits 300 nm wide resonating at a frequency close to 4 GHz

unpublished

SAW_300 nm

3.93 GHz -67.49 dB
UV photodetectors have an important commercial and scientific interest for:

- engine control
- astronomy
- lithography aligners
- solar UV monitoring
- space-to-space communications,
- detection of missiles

Most of these applications fit in the optical spectrum range 200–370 nm covered by nitrides, in particular by GaN and AlGaN compounds.

Most used photo detectors devices are based on metal-semiconductor metal (MSM) interdigitated structures due to their simplicity.
The main idea was to manufacture a UV photodetector on a membrane.

Potential advantages:
1. reduction of losses,
2. increased responsivity,
3. possibility of back-side illumination.


Membrane technology + Nanolithography

780 nm (0.28 buffer + 0.5 GaN) thin membrane
500 nm wide finger/interdigit detector structure

SEM photo (left) and detail (right) for the 0.5 µm wide finger/interdigit detector structure manufactured on a 0.78 µm thin GaN membrane

Responsivity vs wavelength for the 0.5 µm wide finger/interdigit for two UV detector structures manufactured on 0.78 µm thin GaN membrane

Higher responsivity!
Very low dark current!


Microelectronics Journal, 40 (2009), pp. 319-321
RECENT results (IMT-FORTH Dec 2009)

characterization in progress

- Excellent yield! for GaN where nano processing is very difficult
- Structures with fingers and interdigits 100nm, 200nm, 500nm successfully achieved due to a very reliable nano-lithographic process (E-Line equipment)

NANOLITHOGRAPHY AT IMT
CONCLUSIONS

• First FBAR structures on GaN/Si have been developed a suspended technology based on very thin (up to 350nm) self sustainable membranes has been developed having a resonance at 6.3 GHz (with Q>1100) and more, has been obtained.

• Nanolithographic process was successfully developed on GaN/Si. IDTs with fingers and interdigits 150nm and 250nm wide have been obtained with an yield of about 70-75%. SAW structures resonating at frequencies in the 5-7 GHz have been obtained for the first time on GaN.

• A new type of UV photodetector structure, based on micromachining and nanoprocessing of GaN/Si has been developed, for the first time. The new structure has low dark current, very high responsivity and offers the possibility of back-side illumination.
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Thank you for your attention!