SUB-MICRON FBAR MODELING INCLUDING FEM SIMULATIONS

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Outline

- Motivation
- Introduction
- FBAR Fabrication Using Bulk Micromachining
- Analytical Modeling
- FEM modeling
- Conclusions

Motivation

Applications:

- wireless communication systems as mobile phones, wireless local area networks (WLAN)
- navigation
- various applications involving data transmission.

Introduction

- **Electricity : electrical displacement**

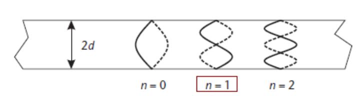
$$\mathbf{D} = \varepsilon_T \mathbf{E}$$

- **Solid mechanics : Hooke's law**

$$\mathbf{S} = s_E \mathbf{T}$$

- **Piezoelectric material** : **both laws are coupled!**

$$\mathbf{S} = s_E \mathbf{T} + d^T \mathbf{E}$$
$$\mathbf{D} = d\mathbf{T} + \varepsilon_T \mathbf{E}$$

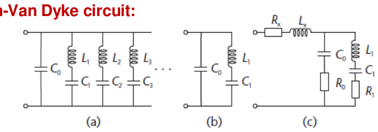


Mechanical resonances in a plate of thickness *2d*

(**RF Bulk Acoustic Wave Filters for Communications,** Ken-ya Hashimoto *Editor, ARTECH HOUSE, 2009)*

Introduction

Butterworth-Van Dyke circuit:



(a) Multiresonant BVD circuit (b) Single resonant circuit
(c) Circuit taking into account losses

(RF Bulk Acoustic Wave Filters for Communications,
Ken-ya Hashimoto *Editor, ARTECH HOUSE, 2009)*

$$Z(\omega)=\frac{V}{I}=\frac{1}{j\omega C_0}\left[1-K_t^2-\sum_n\frac{\omega^2k_n^2}{\omega_{a,n}^2-\omega^2}\right],\quad k_n^2=\frac{8K_t^2}{[(2n+1)\pi]^2}$$

(b)

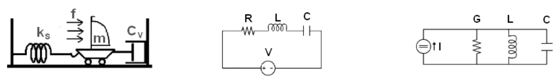
$$Z(\omega)=\frac{j(\omega L_1-1/\omega C_1)}{1-\omega^2C_0L_1+C_0/C_1},$$

$$\omega_r=\frac{1}{\sqrt{L_1C_1}}\quad \omega_a=\omega_r\cdot\sqrt{1+\frac{C_1}{C_0}}$$

(c) $$Z(\omega)=j\omega L_x+R_x+\left[\frac{1}{R_0+1/j\omega C_0}+\frac{1}{R_1+j(\omega L_1-1/\omega C_1)}\right]^{-1}$$

Introduction

Correspondences between mechanical and electric quantities:

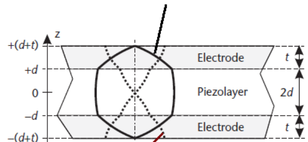


Mechanical	Electric (series)	Electric (parallel)
$f=m\frac{d\dot{u}}{dt}+c_v\dot{u}+k_s\int\dot{u}dt$	$V=L\frac{di}{dt}+Ri+\frac{1}{C}\int idt$	$I=C\frac{dv}{dt}+Gv+\frac{1}{L}\int vdt$
f, exerting force (N)	V, voltage generator (V)	I, current generator (A)
m, mass (kg)	L, inductance (H)	C capacitance (F)
c_v viscous coeff. (Nm/s)	R resistance (Ω)	G conductance (S)
$\dot{u}$ velocity (m/s)	C capacitance (F)	L, inductance (H)
$(k_s)^{-1}$ elastic compliance (m/N)	i current (A)	v, voltage (V)
f, force (N)	v, voltage (V)	i current (A)
$1/2M\dot{u}^2$, kinetic energy (kgm²/s²)	$1/2Li^2$, magnetic energy (HA²)	$1/2Cv^2$, electrostatic energy (FV²)
$1/2k_su^2$, elastic energy (kgm²/s²)	$1/2Cv^2$, electrostatic energy (FV²)	$1/2Li^2$, magnetic energy (HA²)
$f\cdot\dot{u}$, power (W=Nm/s)	$v\cdot i$, power (W=VA)	$i\cdot v$, power (W=AV)
$F\cdot\dot{U}$, complex power (W=Nm/s)	$V\cdot I$, complex power (W=VA)	$I\cdot V$, complex power (W=AV)
$F/\dot{U}$, impedance (W=Nm/s)	V/I, impedance (Ω =V/A)	I/V, admittance (S =A/V)

(***Modeling and characterization of piezoelectric transducers by means of scattering parameters, Part I: Theory*,**
Rudi P. Paganelli, A. Romani, A. Golfarelli, M. Magi, E. Sangiorgi, M. Tartagni, *Sensors and Actuators A: Physical, 2010)*

Introduction

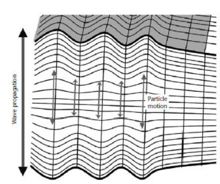
stress field



displacement

Geometry of a resonator with electrodes in the case when Zp >Ze

(RF Bulk Acoustic Wave Filters for Communications,
Ken-ya Hashimoto *Editor, ARTECH HOUSE, 2009)*



Bulk—longitudinal waves:
the bulk particles oscillate or vibrate in the same axis of the wave propagation

(Introduction to Acoustic Wave Resonators,
H. Campanella, *ARTECH HOUSE, 2010)*

The displacement:

$$u(z)=\begin{cases} a\sin(k_pz) & -d\le z\le d \\ b\sin(k_ez+\gamma) & z>d\end{cases}$$

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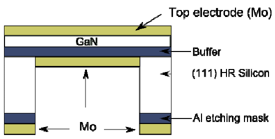
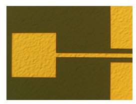
FBAR Fabrication Using Bulk Micromachining



GaN membrane FBAR structures



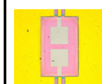
- Mo deposition and **lift-off** techniques to define the FBAR structures on the top.
- Second mask used to cover Mo with a gold layer (500nm)
- **Backside lapping** of the wafer to a thickness of about 150µm.
- Al deposition on the bottom (as mask during RIE of silicon)
- **Backside patterning** for the membrane formation.
- Backside RIE of silicon down to the 2.2µm thin GaN layer using SF_6 plasma.
- Sputtering of thin Mo layer for backside floating electrode formation

FBAR Fabrication Using Bulk Micromachining

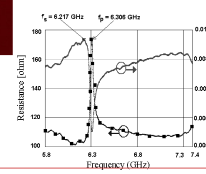
6.3 GHz resonance on a GaN FBAR obtained by micromachining of GaN/Si

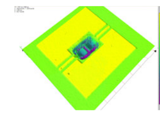
-540nm (340 nm (GaN) +200nm (buffer)) thin membrane supported FBAR structure based on GaN micromachining

-50nm thin **Mo metallization** *GaN/Si wafers from NTT AT Japan*



Top view with top and bottom illumination





White Light Interferometer

f_r=6.3 GHz

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

IEEE Electron Devices Letters , vol 30, no 8, August 2009, pp 799-801

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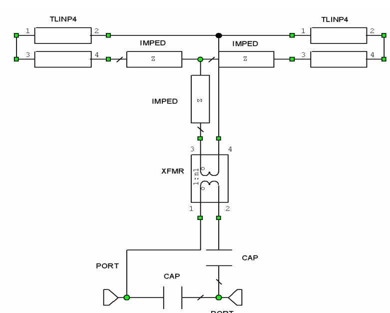
Analytical Modeling

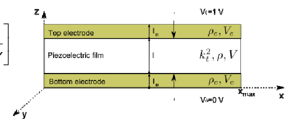
Mason's circuit



Analytical Modeling

Mason's model

Simulated FBAR geometry



$$Z_{in} = \frac{1}{j\omega C_0}\cdot\left[1-\frac{k_t^2}{\gamma}\frac{(z_1+z_2)\sin\gamma+2j(1-\cos\gamma)}{(z_1+z_2)\cos\gamma+j(1+z_1z_2)\sin\gamma}\right]$$

$C_0 = \varepsilon_{33} S / l$ Static capacitance

$\gamma = \omega l / V$ phase delay of the longitudinal acoustic wave

$V = \sqrt{\frac{E}{\rho}}$ velocity in the piezoelectric layer

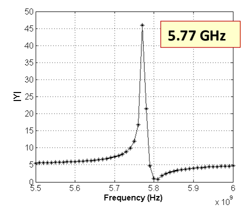
z_1, z_2 acoustic load impedances on both sides of the GaN layer normalized to $Z_0 = S\rho V$

$k_t^2 = \frac{\frac{e_{33}^2}{\varepsilon C_{33}}}{1+\frac{e_{33}^2}{\varepsilon C_{33}}}$ electromechanical coupling coefficient of the piezoelectric layer

Analytical Modeling

The parameters of the composite FBAR structure used in simulations

	Electrodes (Mo)	Piezoelectric film (GaN)
ρ [kg/m³]	10220	6150
V [m/s]	67	5844
l [μm]	0.06	0.5
ε_T	-	9
e_{31} [Cm⁻²]	-	-0.36
e_{33} [Cm⁻²]	-	1
e_{15} [Cm⁻²]	-	-0.3
C_{33} [GPa]	330	398



Simulated input admittance of FBAR versus frequency (MATLAB)

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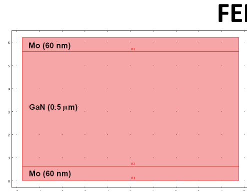
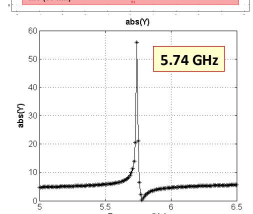
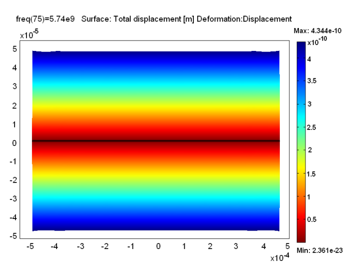
FEM Modeling

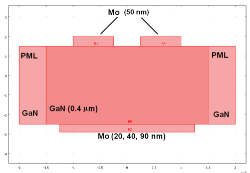


COMSOL model
MEMS module
(Piezo Plane Strain)





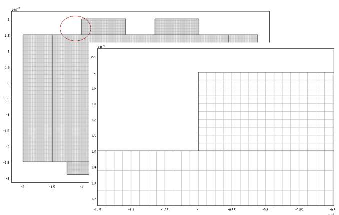
FEM Modeling



COMSOL model - MEMS module
(Piezo Plane Strain + Plane Strain)

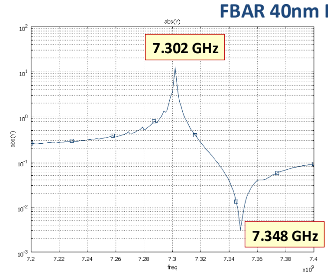
Mesh 13440 elements
153 176 dofs

	Width [m]	Height [m]
Bottom electrode	2.5e-4	40e-9
		20e-9
		90e-9
Top electrode	7.5e-5	50e-9
Piezolayer	3e-4	0.4e-6



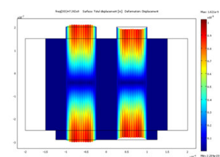
FEM Modeling

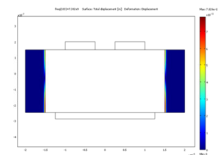
FBAR 40nm Results



Simulated input admittance of FBAR versus frequency

Total displacement

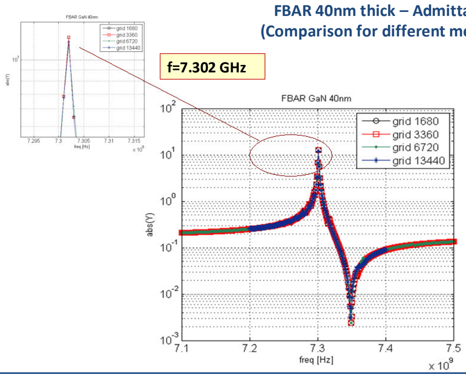




Total displacement on the PML

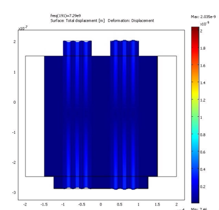
FEM Modeling

FBAR 40nm thick – Admittance
(Comparison for different meshes)



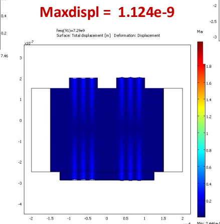
FEM Modeling

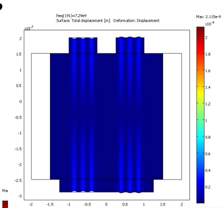
FBAR 40nm Results
Total displacement



Mesh 3360 elem
Maxdispl = 1.02e-9

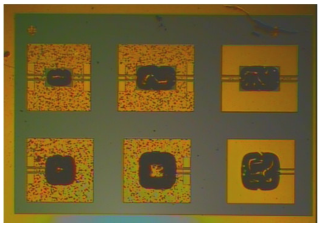
Mesh 6720 elem
Maxdispl = 1.124e-9





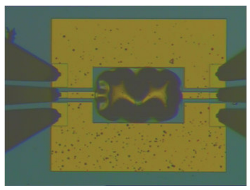
Mesh 13440 elem
Maxdispl = 1.12e-9

FEM Modeling



Fabricated chip with series and parallel connected FBARs

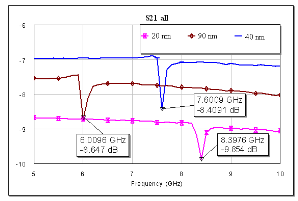
Photo of two FBARs in series configuration



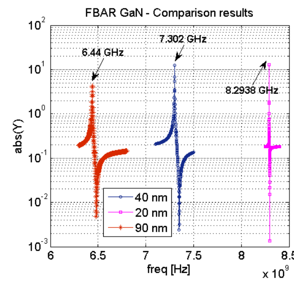
FEM Modeling

FBAR Comparison Results

Measurements



Simulation



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Conclusions

- **Modeling approaches for FBAR structure:**
  - ✓ **Analytical model for film bulk acoustic resonator (physics of the resonator, equivalent circuit model)**
  - ✓ **Finite Element Models based on numerical methods and domain coupling analysis**
- **Good agreement between simulation and experimental data previously reported**
- **Next step: 3D accurate model analysis**

Feedback/Questions

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Thank you for attention!