RF Micro/Nano Resonators for Signal Processing

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Outline

• FBARs vs. lateral bulk resonators
  - Electrical models
  - Hybrid component vs. integrated arrays

• Electrostatic lateral bulk resonators
  - Materials: poly-SiGe, poly-SiC, poly-Si
  - Damascene blade process

• Improving transduction
  - Internal electrostatic drive/sense
  - The “EBAR”
Thin Film Bulk Acoustic Resonators

- Commercially available from Agilent (FBAR) and TFR Technologies (SMR)
- Agilent’s volume is ~ 2.5 million / month (Rich Ruby, Agilent, Oct. 2003)
- Advantages include:
  - Up to 20 times area reduction
  - Lower parasitics
  - Steeper skirts
  - Lower insertion loss
  - Operation above 10 GHz
  - Power handling
- Filter bandwidth limited by $K^2$ of AlN piezoelectric film

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J. Black and R. M. White
Equivalent Circuit for an SMR


\[ C_o = \frac{A \varepsilon}{d} \approx 1.9 \quad \text{pF} \]

\[ L = \frac{\rho d^3}{8 Ag} \approx 125 \quad \text{nH} \]

\[ C = \frac{8 Ag}{\pi^2 dc} = \frac{8k^2 C_o}{\pi^2} \approx 800 \quad \text{fF} \]

\[ k^2 = \frac{g^2}{c \varepsilon} \]

(assumes \( Q \approx 1000 \))
Transceiver Implementation

- **Carrier Generation**: FBAR Oscillator
  - 1.9 GHz / 300μW @ 1 V / 100 mV 0-peak
  - Start-up time: 1 ms
  - Measured phase noise: -120 dBc/Hz @ 100 kHz offset

- **Power Amplifier**
  - Center frequency: 1.9 GHz
  - $P_{out}$ (50 Ω) = 0 dBm (1 mW)
  - $P_{out}$ (antenna) = -1.5 dBm (700 mW)

- **Energy Scavenging**
  - Solar cell
  - Prototype piezoelectric bender (180 µW @ 100Hz resonance)
A Major Limitation of FBARs

• Frequency is set by the resonator’s thickness (piezoelectric and metal electrode deposition steps)
  - very limited variation is possible on a single chip

• Who needs a range of frequencies?
  - universal transceiver (Ali Niknejad*)
  - analog OFDM transceiver (Jan Rabaey*)
  - statistical communication (Jan Rabaey*, Kannan Ramchandran*, et al)
Lateral Bulk-Mode Resonators

- Frequency is set by *in-plane* dimension, so it’s under the designer’s control
- DARPA MTO Nanomechanical Array Signal Processor program (Dan Radack, PM) 2001-2005
- Challenges:
  - *materials* (Si, poly-Si, poly-diamond,...)
  - *device structures* (disks, rings, ...)
  - *modes* (extensional, Lamé, shear, ...)
  - *transduction* (electrostatic, piezoelectric)

*the biggest issue*: using them in circuits!
Two-Port Resonator Model

$R_x$ is relatively large due to inefficient transduction
$C_o$ can be relatively large
$C_f$ (feedthrough capacitance) shunts the resonator
RBAR Equivalent Circuit

- $Q = 10,000$
- Gap = $g = 50$ nm
- Film thickness $t = 2$ $\mu$m
- Radius = $r_{av} = 50$ $\mu$m
- Static capacitance = $C_o = 10$ fF
- DC Bias = 10 V

- Neglect interconnect capacitance and parasitic capacitance to ground plane

- Find impedance of the device as a one-port (ground sense electrode)
500 MHz RBAR Impedance

Peter Chen, BSAC

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1 GHz RBAR Impedance

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1 GHz RBAR Impedance: 30 nm Gap

Electrode gap reduced from 50 nm to 30 nm → major improvement in phase shift

Peter Chen, BSAC

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Resonator Arrays

- Integrated Microwatt Transceiver Project
  Motivation: low-power transceiver for wireless sensor network

- Each NM* Filter is an array of resonators
- Another example: wake-up receiver that samples the spectrum using a comb of bandpass filters

*NM = NanoMechanical
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VHF Poly-SiGe Resonator Measurements

Bulk Longitudinal Resonator

RF/LO Technique

74 MHz Fundamental Mode
- $F_{m}=74.4\text{MHz}$
- $Q=2863$
- $V_{p}=40\text{V}$
- $P_{RF}=10\text{dBm}$
- $V_{LO}=10\text{Vp-p at 10MHz}$
- Output Gain Stage = 20dB

205 MHz Third Harmonic
- $F_{m}=205.35\text{MHz}$
- $Q=3540$
- $V_{p}=40\text{V}$
- $P_{RF}=25\text{dBm}$
- $V_{LO}=10\text{Vp-p at 10MHz}$
- Output Gain Stage = 20dB

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Emmanuel Quévy and Sunil Bhave,
Hilton Head 2004
Radial Bulk Annular Resonator (RBAR)


\[ r_{av} = \frac{r_o + r_i}{2} \]

\[ W_r = r_o - r_i \]
Corner-Coupled Poly-Si Lamé Mode Resonator Array

Electrode gaps will be cut by focused ion beam (FIB) etching

Di Gao, Sunil Bhave, Roya Maboudian, and Roger Howe
1.14 GHz 3rd Harmonic Polysilicon Disk Resonator

Self Aligned Stem—[Poly3] Electrodes

Ground Plane [Poly1] Interconnect

(d’) Final device after HF release

Heroic signal processing needed to detect motional current

J. Wang and Clark Nguyen, (Univ. of Michigan) 
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Electrostatic Transduction: How Can We Increase its Efficiency?

- Energy density is proportional to the dielectric constant $\varepsilon_g$ of the gap
- Why not fill the gap with a dielectric material?
- Indeed, why not?

* demonstrated with Si$_3$N$_4$ by Siebe Bouwstra at Twente in 1989 ... not very interesting for a cantilever beam
Internal Electrostatic Transduction

\[ R_x = \frac{\sqrt{K \cdot M}}{Q \cdot \left( \frac{V_p^2 \cdot \varepsilon_r^2 \cdot g}{A} \right)} \]

Replace Air \((\varepsilon_r = 1)\) with a high-k dielectric like TiO\(_2\) \((\varepsilon_r \sim 80)\) or HfO\(_2\) \((\varepsilon_r \sim 30)\)

Design Issues:

- Internal electric fields couple to bulk modes
- Electrodes are part of the resonator
- Dielectric layers at locations of maximum strain, minimum displacement (acoustic energy)
Lateral Bulk Resonator Using Internal Electrostatic Transduction

> Single crystal silicon resonator with high-k dielectric (TiO$_2$, HfO$_2$) \(\rightarrow\) paper designs look feasible to UWB frequencies

\[ Y = \text{Young's modulus} \]
\[ A = \text{Cross-section area} \]
\[ Q = \text{Quality factor} \]
\[ \omega = \text{Resonant frequency} \]
\[ L = \text{Half wavelength} \]
\[ g = \text{Length of transducer element} \]
\[ V_{dc} = \text{Bias Voltage} \]
Quick Verification: The “EBAR”

Electrostatic transduction of Agilent’s FBAR

- Dielectric: AlN ($\varepsilon_r \sim 9$)
- Use half-frequency drive to ensure linear piezoelectric excitation is not an issue
- Verify square-law dependence

\[ V_{dc}, V_{ac} \rightarrow \text{AlN} \rightarrow I_{out} \rightarrow \text{Spectrum Analyser} \]
Experimental Results I

- Sweep frequency on RF synthesizer near $\omega_0/2$
- Add a 1 GHz low-pass filter to remove harmonics and DC bias to provide bias for output current
- Set Spectrum Analyser to MAX_HOLD to construct the transfer function
- Resonant peak at 1.922 GHz, with measured $Q \sim 1400$
Experimental Results II

- Linear sweep of input RF power shows that output power has a square-law dependence, as expected.
- Note that the FBAR was *not* designed to optimize the electrostatic transfer function and is a very poor EBAR!
Conclusions

• Lateral-mode integrated RF resonators are required for ultra-low power wireless communications

• A variety of resonator designs have been proposed and some demonstrated

• Promising new direction using internal electrostatic transduction to achieve high-efficiency (low $R_x$) resonators
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