Lecture 18
RF MEMS (6)

- Agenda:
  - MEMS Varactors: Survey
  - MEMS Inductors: Survey

Most figures and data in this lecture, unless cited otherwise, were taken from RF MEMS Theory, Design and Technology by G. Rebeiz.

MEMS Varactors

- Solid-state varactors
  - Si, GaAs, SiGe
  - Q: 30-60
  - Capacitance ratio 4-6

- MEMS Varactors
  - High Q: >100
  - Low cost
  - Small capacitance ratio: 1.2-2.5
  - Small capacitance (not suitable for below 1 GHz)
Varactor Model and Q-Factor

\[ Q = \frac{\text{average energy stored}}{\text{energy loss/second}} \]

\[ Q = \frac{|\text{Im}(Z)|}{\text{Re}(Z)} = \begin{cases} \frac{1}{\omega R C} & \text{For a series model} \\ \frac{1}{\omega R_p C} & \text{For a parallel model} \end{cases} \]

MEMS Varactors

- Electrostatic Parallel-pate Varactors
- Tunable Interdigitated Capacitors
- Thermal Varactors
- Piezoelectric Parallel-pate Varactors
- MEMS Switched Capacitors
- MEMS Varactors with Discrete Values
### MEMS Varactors: Electrostatic

#### Parallel-pate Varactor

- **Anchor**
- **Al plates**
- **1.5μm gap**
- **15% capacitance change at 3V, limited by parasitics**
- **Q = 60 at 1GHz**
- **Low-temperature process**
- **CMOS-compatible**

Young and Boser (UC-Berkeley) Hilton Head 1996

![Parallel-pate Varactor Diagram](image)

#### Three-pate Varactor

- **Fabricated using poly-Si MUMPs**
- **0.75/1.5μm gaps**
- **Tuning range 3.4pF – 6.4pF at 4.5V**
- **Q = 16 at 1GHz**

DeC and Suyama (Columbia University) IEEE Trans. MTT, 2000
MEMS Varactors: Electrostatic

- **MIT Zipper Varactor**
  - Fabricated using poly-Si MUMPs
  - Zipping motion
  - Initial gap: 2µm
  - Tuning range 0.55pF – 1pF at 40V
  - Custom C-V curves
  - Large inductance

Hung and Senturia (MIT)
Transducers’98

- **Tunable Interdigital Capacitor**
  - Large capacitance
  - Large tuning range
  - Single mask
  - 1200 interdigitated fingers (20µm tall, 2µm wide and 2µm spacing)
  - Tuning range: 6pF - 1.3pF at 5V
  - High Q at low freq.

Yao et al (Rockwell Science Center), Hilton Head 1998
MEMS Varactors: Piezoelectric

LG-Electronics Piezoelectric Varactor

Par et al (LG-Electronics)
IEEE MTT-S 2001

- Metal-PZT-metal sandwich
- Bonded to glass substrate
- Thick gold layer
- Air gap: 2.5-3.5 µm
- Capacitance ratio: 3.1 at 6V
- Q = 210 at 1GHz

MEMS Varactors: Thermal

- U-Colorado, Boulder

Feng et al., IEEE MTT-S 1999

- Fabricated using poly-Si MUMPS
- Transferred to alumina substrate (flip-chip)
- Capacitance ratio 2.7:1 at 2.7V

- Carnegie Mellon Univ.

A. Oz, G.K. Fedder, Transducers'03

- Thin-film CMOS-MEMS process
- Tuning range: 42fF → 148fF at 12V
- Q=52 at 1.5GHz
Switched MEMS Capacitors

- Raytheon MEMS Switched Capacitor

Goldsmith et al., In. J. RF Microwave CAE, 1999

- Metal-insulator-metal (MIM) capacitors
- Q: 40-80
- Large capacitance ratio
- But large inductance

\[ C_0 + 4C_u \rightarrow C_0 + 15C_{\text{bit}} \]

MEMS Capacitors w/ Discrete Values

- Two-value MEMS Capacitor
  (Dussopt and Rebeiz, IEEE MTT-S 2002)

- Beam-array MEMS Capacitor
  (Hoivik et al., IEEE MTT-S 2001)

- Center plate can be pulled down after the side electrodes are pulled down
- Different beam widths → Different stiffness → Different pull-down voltages
MEMS Inductors

- Fixed-value inductors
- Tunable high-Q inductors can be synthesized using RF MEMS switches and a set of fixed-value inductors
- Various technologies
  - Thick metal electroplating for low series resistance
  - Substrate etching for low loss
  - 3D solenoid-type inductors for large inductance
- High-Q Inductor Applications
  - Low-phase noise oscillators/amplifiers
  - Low-power consumption
  - Low-loss matching filters/networks

For low to medium frequencies,

\[ Q = \frac{\omega L_s}{R_s} \]

If the metal conductor thickness is greater than twice of skin depth, the lowest series resistance can be obtained and is given by

\[ R_s = \frac{\rho}{\delta_w} \quad \text{Ohm per unit length} \]

where

\[ \delta = \sqrt{\frac{\rho}{\pi \mu f}} \]

At 1 GHz, \( \delta = 2.5\mu m \) for copper.
So at least 5\( \mu m \)-thick copper layer is needed for high Q.
For 10MHz, 50\( \mu m \)-thick copper is needed.
MEMS Inductors

- **Spiral-type**
- **Solenoid-type**
- **Toroidal-meander-type**

### MEMS Inductors – Spiral-type

- Polyimide 15um
- Electroplating copper
- LC filter
- 1.9mm by 2.4mm
- 15–40 nH
- Q: 40–50 @ 0.9–2.5 GHz

Park, Allen, GaTech 1999

- Photoresist mold
- Electroplating copper
- 50um air gap
- 300um by 80um
- 1.4 nH
- Q: 70 @ 6 GHz

Yoon, et al., KAIST, 2002
MEMS Inductors – Spiral-type

• Electroplating copper
• Suspension 60um
• 1.9mm by 2.4mm
• 4.2 nH
• Q: 37 @ 0.05–10 GHz

Wang, et al., Shanghai Jiaotong Univ., 2004

MEMS Inductors – Spiral Type

• Electroplating copper
• Self-assembly by heating solder pads
• 2 nH
• Q: 20 @ 3 GHz

Dahlmann, et al., Imperial College, 2001

• CMOS-MEMS
• Al/Oxide stack
• 4 nH
• Q: 7 @ 5.5 GHz

Zhu, et al., CMU, 2001
MEMS Inductors – Solenoid-type

- Polyimide molds
- 15µm permalloy
- Electroplating copper
- LC filter
- 4mm by 4mm
- 1.5 µH
- Small Q (<5)

Park, Allen, GaTech 2000

Fig. 2. Fabrication procedure for micromachined inductors and transformers: (a) patterning of seed seed layer, (b) depositing of base conductors, (c) generation and patterning of seed seed layer, (d) formation of seed and electroplating of copper, (e) top conductor deposition, (f) pattern for inducer, (g) removal of permalloy and micromachined.

MEMS Inductors – Solenoid-type

- Polyimide molds
- Alternating Permalloy, Cu plating
- 72 laminated layers (Sacrificial Cu)
- 11mm by 6mm
- 2.3 µH
- Q: 9.2 @ 2MHz

Park, Allen, GaTech 2003