Lecture 16
RF MEMS (4)

Agenda:

- MEMS Switches
  - Capacitive Shunt Switches
  - DC-Contact Shunt Switches
  - DC-Contact Series Switches

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

Capacitive MEMS Shunt Switches

- Robust Switch (Raytheon)
- Low-Voltage Switch (U-Michigan)
- Low-Gap-Height Switch (U-Michigan)
- High Capacitance Ratio (LG, Korea)
- Many Others
Raytheon Capacitive Switch

- Chuck Goldsmith et al, demonstrated in 1995
- Bridge membrane: 0.5μm-thick Al
- Sacrificial layer: Polyimide
- Capacitance ratio: 80-120
- Most mature MEMS shunt switch available to date

Fabrication

(a) Tungsten sputtering (0.4μm); PECVD nitride (0.1μm); Thick Al evaporation (4-6μm) for bridge anchors and t-line
(b) Spin-on polyimide, followed by planarization
(c) Al sputtering
(d) O2 plasma etching of polyimide
### U-Mich Capacitive Switch (1)

**Low-voltage Switch**

- Meander spring beams for low spring constant
- Gap height: 4-5 µm
- Pull-down voltage: 6-12V
- Switch time: 20-40 µs
- Separate actuation and capacitive electrodes
- Sensitive to mechanical forces
- Small restoring force

![U-Mich Capacitive Switch diagram](image)

Pacheco, Peroulis, and Katehi
U-Mich Capacitive Switch (2)

- Low Gap-Height Ti/Au Switch
  - Inline CPW (the bridge is part of t-line)
  - Gap height: 1.5-2.2 µm
  - Pull-down voltage: 12-24 V
  - High spring constant
  - Switch time: 6-15 µs

U-Mich Capacitive Switch (2) (cont'd)

- Low Gap-Height Ti/Au Switch
  - 0.3µm gold layer selectively covered by nitride
  - 1.5-2.3µm-thick PECVD oxide layer
  - 0.8µm sputtering gold layer, followed by gold electroplating (2-3µm) on anchors
  - Oxide removal using BHF and critical point dry etching

Rebeiz's Group
Univ. of Michigan
LG Capacitive Shunt Switch

- High Capacitance-Ratio Shunt Switch

  - High dielectric-constant material: Strontium-titanate-oxide (SrTiO3), $\varepsilon_r=30-120$
  - Gap height: 2.5-3.5 $\mu$m
  - Pull-down voltage: 8-15 V
  - Switch time: N/A
  - High capacitance ratio: >600

  Park et al., LG, Korea

DC-Contact MEMS Shunt Switches

- Low-Voltage Switch (UIUC)
- Inline Shunt Switch (U-Michigan)
- Curled-Beam Switch (National Taiwan Univ.)
- Many Others
  - Northrop Grumman
  - Daimler Chrysler Research Center
  - NASA – Lewis
  - UC-Santa Barbara
  - UC-Berkeley
  - etc.
UIUC DC-Contact Shunt Switch

- **Low-Voltage Shunt Switch**
  - Separate actuation electrodes for pull-down and pull-up
  - Narrow support beams for low spring constant
  - Sacrificial layer: polyimide
  - Gap height: 4 µm
  - Contact metal: gold
  - Pull-down voltage: 9-16 V
  - Loss: -0.1 dB (0.1-40 GHz)

Shen and Feng, UIUC

U-Mich DC-Contact Shunt Switch

- **Inline Metal-to-Metal Shunt Switch**
  - Separate actuation electrodes for pull-down
  - The bridge is part of t-line
  - Two metal layers underneath the bridge: one ground metal layer and one bias electrode layer
  - Ground metal layer has openings to allow static fields from bias electrode
  - Sacrificial layer: polyimide
  - Gap height: 1.7 µm; Pull-down voltage: 35 V

Muldavin and Rebeiz, Univ. of Michigan
NTU DC-Contact Shunt Switch

- Curled-beam DC-Contact Shunt Switch

  - Pull-down voltage: 26-30 V
  - Insertion loss: -0.2 dB at 10 GHz

Chang et al, National Taiwan Univ.

DC-Contact MEMS Series Switches

- Rockwell Scientific
- Motorola
- HRL
- Northeastern Univ./Analog Devices
- Lincoln Lab
- Omron
- Samsung
- Univ. of Michigan
- UC-Berkeley
DC-Contact MEMS Series Switches (1)

- **Rockwell Scientific** (Yao, Chang, Mihailovich, et al.)
  - Dielectric dimples for preventing stiction
  - Separate pull-down electrodes
  - Signal line isolated by oxide
  - Sacrificial layer: polyimide
  - Switch resistance < 2 \( \Omega \)
  - Switch time: 8-10 \( \mu s \)
  - Gap height: 2.5 \( \mu m \)
  - Actuation voltage: 50-60 V
  - Isolation < -56 dB at 2 GHz

(a) 0.25\( \mu m \) gold layer; 2-2.5\( \mu m \) polyimide layer
(b) Contact dimples
(c) 2-2.5\( \mu m \) PECVD oxide layer, followed by evaporating and lifting-off gold (0.2\( \mu m \))
(d) Polyimide removal by O\(_2\) plasma

DC-Contact MEMS Series Switches (2)

- **Motorola**
  - Short SiO\(_2\) cantilever beam: high stiffness
  - Separate pull-down electrodes
  - Signal line isolated by oxide
  - Contact metal: gold; Sacrificial layer: spin-on-glass
  - Switch resistance 1-2 \( \Omega \); Switch time: 2-4 \( \mu s \)
  - Gap height: 2-3 \( \mu m \)
  - Actuation voltage: 50-60 V
  - Isolation < -44 dB at 2-4 GHz

• Short SiO2 cantilever beam: high stiffness
• Separate pull-down electrodes
• Signal line isolated by oxide
• Contact metal: gold; Sacrificial layer: spin-on-glass
• Switch resistance 1-2 \( \Omega \); Switch time: 2-4 \( \mu s \)
• Gap height: 2-3 \( \mu m \)
• Actuation voltage: 50-60 V
• Isolation < -44 dB at 2-4 GHz
DC-Contact MEMS Series Switches (3)

- **HRL (Hughes Research Laboratories)** (Hyman et al.)
  - Double nitride layers for stress compensation
  - Separate pull-down electrodes
  - Signal line isolated by oxide
  - Contact metal: gold
  - Sacrificial layer: silicon oxide
  - Switch resistance 1-1.5 Ω;
  - Switch time: ~30 µs
  - Gap height: 1.5-2 µm
  - Actuation voltage: 50-60 V
  - Isolation: -45dB at 4 GHz

DC-Contact MEMS Series Switches (4)

- **Northeastern Univ./Analog Devices, Inc.** (Zavracky, McGuer)
  - Inline DC-contact series switch
  - Thick electroplated gold (7-9 µm)
  - Very stiff structure: k>100N/m
  - Contact metal: gold
  - Sacrificial layer: copper
  - Switch resistance 1-1.5 Ω;
  - Switch time: 2-3 µs
  - Gap height: 1 µm
  - Actuation voltage: 60-80 V
  - Isolation: -40dB at 4 GHz
  - Maximum current: 1A
Northeastern Univ./Analog Devices, Inc. (Zavracky, Mcgruer)

(a) Gold layer for t-lines and bottom electrode; copper deposition (1-1.2 \( \mu \text{m} \)); partial etch for dimples.
(b) Full etch to form anchors
(c) Sputtering a seed layer and then electroplating gold (7-9 \( \mu \text{m} \))
(d) Wet etching copper for release. No stiction problem since the beam is very stiff

Lincoln Laboratory

- Curling of thin-film plate for up-state position
- Very small up-state capacitance
- Corrugated electrode
- Contact metal: Platinum
- Sacrificial layer: polyimide
- Switch resistance 1-2 \( \Omega \):
- Switch time: <1 \( \mu \text{s} \) (DC-contact switch); 20\( \mu \text{s} \) (Capacitive switch)
(a) High-resistance TaN layer; LPCVD SiO₂; Aluminum deposition; Platinum deposition
(b) Polyimide spun, cured, and patterned to form a “wave-like” surface
(c) Platinum evaporation for dimples; tri-layer membrane deposition: Compressive SiO₂/Al/Tensile SiO₂
(d) Release

Accessory list:
- Omron (Sakata et al., MEMS'99)
- U-Michigan (Muldavin, Tan, Rebeiz, 2001)
- Samsung
**Seesaw Series/Shunt MEMS Switch**

(Milanovic et al., MEMS 2000)

Fabricated in standard CMOS; then transferred to quartz substrate

**Summary**

- **Switch types:**
  - Capacitive Shunt Switches
  - Capacitive Series Switches
  - DC-Contact Shunt Switches
  - DC-Contact Series Switches

- **Sizes:** ~100um by 100um
- **Contact metal:** Gold
- **Isolation:** -20dB ~ -55dB
- **Loss:** 0.05-0.2 dB
- **Power Handling:** <1W
- **Switching time:** 1-50μs
- **Actuation voltage:** 10-80V