Micro-machined High Density Embedded Capacitor Technologies for Energy Storage Applications

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MEMS Super Capacitors: Application

• Substrate embeddable to provide current to circuits during power anomaly (i.e. Interposer)

• Requires low inductance path for rapid current discharge

• Requires etched cavities to increase surface area of capacitor
Interposer Provides Power Source Directly to Chips
Approach and Concepts

• Fabricate Planar Structure with SiO$_2$ (relative permittivity $\sim$ 3.8)

• Fabricate Planar Structure with Atomic Level Deposition (ALD) HfO$_2$ (large relative permittivity $\sim$ 25) from multiple vendors

• Fabricate Planar Structure with ALD HfO$_2$ and DRIE etched features

• Characterize Discharge Characteristics

• Summary
MEMS Super Capacitors: Fabrication

- n-type <100> silicon wafers
- Oxidized in steam/dry O$_2$ @ 1050° C for 1-4 hours, 0.15μm < $t_{ox}$ < 0.8μm
- Top side selectively DRIE etched (increase surface area) and selectively doped
- Atomic Level Deposition performed
- Metalized with 100nm Ti /0.4μm of Cu
Basic Atomic Level Deposition Process
Interposer Capacitor 100 mm Silicon Test Wafers

Thermal SiO₂  ALD HfO₂  ALD HfO₂

GIT Cam. Nano.

All Samples Initially Charged to 2V and then Discharged

800nm  3nm & 10nm  30nm
MEMS Super Capacitors: Micromachining Pattern

Layout of Wafer

Layout of Individual Chip
Cylinder and Triangle Pattern Utilized
SEM & Photo Micrographs of DRIE Etched Features
Thermal SiO$_2$ E-beam TiCu

800 nm Thermal SiO$_2$ ebeam TiCu
Ion gun 9nH ESL
ALD HfO$_2$ GIT E-beam TiCu

![Graph showing current vs time for ALD HfO$_2$ GIT E-beam TiCu with three curves for 3 nm and 10 nm thicknesses with and without an ion gun.](image-url)
ALD HfO$_2$ Cam. Nano. E-beam TiCu

30 nm HfO$_2$ Cam. Nano. Trench Etch ebeam TiCu Ion gun 9nH ESL
Half Wafer HfO$_2$ Capacitor

Sample Charged to 12.5V and then Discharged

\[ C = \left( \varepsilon_R \varepsilon_0 \text{Area} \right) / t_0 \]

\[ C \sim 30,000 \text{nF} \]
Test Circuit for Half Wafer HfO$_2$ Capacitor: 9nH ESL
Ringdown in Time Domain

- 30nm thick hafnium oxide 30,000nF 12.5V discharge with an ESL = 9nH
  ESR = 0.25Ω
FFT of Ringdown

- 30nm thick hafnium oxide 30,000nF 12.5V discharge with an ESL = 9nH
  ESR = 0.25Ω

\[ f_r = \frac{1}{2\pi}(LC)^{1/2} \]
MEMS Super Capacitors: SPICE Modeling

- High speed ringdown tests for a variety of configurations performed to determine capacitor performance under rapid discharge conditions

- Empirical data compared graphically to theoretical voltage discharge profiles

- Current discharge calculated from $C(dV/dt)$

- Results plotted and compared
MEMS Super Capacitors: Photos
• 30nm thick hafnium oxide capacitor  $C = 734\text{nF}$, 19.5V discharge voltage with an ESL = 25pH  ESR = 14mΩ
Ringdown in Time Domain

- 30nm thick hafnium oxide capacitor $C = 734\text{nF}$, 19.5V discharge voltage with an ESL $= 25\text{pH}$  ESR $= 14\text{m}\Omega$
Summary

- Possible to fabricate high value capacitors for interposer

- Rises time dependent upon load

- HfO$_2$ has high dielectric constant (~25)

- SiO$_2$ is more readily available from silicon foundries