Talk outline

- Introduction to Cavendish Kinetics
  - NanoMech™ technology
- MEMS cantilever memory switch
- The cavity
- Harsh environment rocker memory design
  - Harsh memory temperature performance
- Harsh memory radiation performance
- Other applications
- Conclusion
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Mission: Enable our Customer to Deliver Breakthrough Products

- *How:* Enable integration of devices and sensors with CMOS
- *Results:* Lower cost, lower power and smaller size
- *Means:* Standard semiconductor processing technology

NanoMech™ Technology Platform – 3rd Generation MEMS

- Fully integrated into the back end process flow
- No unique equipment or materials or packaging
- Capability of delivering *multiple applications* on the same IC

NanoMech™ Memory

- Volatile and Non-Volatile Switch Technology
- Demonstrated Extreme Harsh Operation
Evolution of MEMS Technology

3 Generations of Evolution

Gen1: Build / Assemble
- Large, Very Expensive

Gen2: Package in Package
- Large, Expensive

Gen3: Fully Integrated
- No Package
- Small, Integrated, Low Cost, Scale-able

Gen3 Enables MEMS Performance, But Delivers CMOS Size and Costs
Core Technology: 3rd Gen MEMS

- CMOS Compatible, Packaging Free MEMS platform
- Uses only Standard CMOS interconnect Process Technology
- Mechanical Platform (MEMS) is capable of producing a wide variety of applications

MEMS Technology
- Metal Based MEMS
- Cantilever
- NZRF Cantilever
- Many Operate as One

Cavity
- Package Free MEMS
- Non Contaminating
- CMOS Processes
- Planarized Interconnect
- Controlled Release Design
- Electrically Active Roof
- Roof: Metal or Dielectric
- Via Electrical Connections

Integrates into Standard Flow

Both Integrated together into Standard CMOS
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Anatomy of a CK Switch
Utilize Stiction

Design Attributes
Nonvolatile: $F_o < F_a, F_v$  Volatile: $F_a < F_o < F_v$  Sensor: $F_a = F_o < F_v$

**Key features**
- Can tune the restoring force without a process change
- Can tune for volatile or non-volatile behavior
- Digital sensing (contact either open or closed)
- Native or higher voltage programming as required
- High Endurance contact cycles demonstrated
- Fast response time in the sub 100 nanosecond range
- Environmental Superiority: Operates -150°C to 300°C and Radiation Hard
- Natural frequencies in the 75Mhz range

Simple Concept, Broad Applications
Traditional Style Cantilever

Technology has Ability to Utilize Roof as Electrode

Contact Electrode

Control Voltage

Contact Electrode

Pull In Electrode
Cantilever uses adhesion to make NVM

Cantilever in Cavity “0” State

Programmed “1”
Adhesion Forces Hold in Place once Voltage Removed

Programmed “0”
Material System Fatigue
Completed on Traditional Cantilever

100 Billion Cycle Testing

No Demonstration of Fatigue in Material System
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NanoMech Technology
Each Device is in Own Cavity

Each component is sealed in a cavity

Sealed cavities used individually or built into arrays
Can combine multiple devices in single cavity

• Characteristics:
  • High isolation & high density
  • Standard fab materials and processes
  • Sealing during production lowers cost
  • Variable cavity and array sizes to fit applications
  • Connections through Lower Metals, and Metal Roof
  • Demonstrated WLR Performance of Cavity and Device
    • Temp Cycle, High Temp Storage, Thermal Shock, Unbiased Autoclave

- Robust Cavity and Robust Architecture
# Wafer Level Reliability

**Performance of Cavity & Structure**

<table>
<thead>
<tr>
<th>Test</th>
<th>Conditions</th>
<th>Release</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-alloy (7A)</td>
<td>Cycle from 25°C to 400°C to 25°C, N2 purge, 50 min. dwell</td>
<td>7 cycles</td>
<td>Only minor parametric drifts over cycles</td>
</tr>
<tr>
<td>Thermal Cycling (TC)</td>
<td>Air-air Cycling, -65°C to 150°C</td>
<td>100 cycles</td>
<td>Only minor parametric drifts over cycles</td>
</tr>
<tr>
<td>High Temperature Storage (HTS)</td>
<td>T=250°C, N2 purge, storage, interim tests every 150 hours</td>
<td>1000 hours</td>
<td>Only minor parametric drifts over time</td>
</tr>
<tr>
<td>Thermal Shock (TSK)</td>
<td>Liquid-liquid Shock, -55°C to 150°C, wafer sample</td>
<td>100 cycles</td>
<td>Only minor parametric drifts over cycles</td>
</tr>
<tr>
<td>Unbiased Autoclave (UA)</td>
<td>T=125°C, 100% RH, 2 atm pressure</td>
<td>96 hours</td>
<td>Only minor parametric drifts over time</td>
</tr>
</tbody>
</table>

- Wafer Level Tests of Integrated MEMS Technology
- Minor < 5% Shift (7Alloy), Typically < 2% all Others

Environmental stress tests confirmed **no issues** for: (1) Sealed Cavity; (2) MEMS membrane and anchor; (3) metallization and vias
NanoMech™ vs. Existing MEMS Technology

Traditional Approach vs. NanoMech Technology

Integrated into metal stack of any IC using standard equipment and materials

Integrated into metal stack of any IC using standard equipment and materials

Surface Micro Machined

Bulk Micro Machined
Cavity Embedded in CMOS
Array of Cavities with Switches on 4LM CMOS

FIB of Switches in Cavities integrated with CMOS

NanoMech Switch Fully Integrated into Interconnect
Device Integrated into Chip

Graphical Schematic

IMD

Metal_X+2

Metal_X+1

Metal_X

Integrates into Standard Flow

Integrated into Standard CMOS, No Unique Packaging

Lateral TEM

Cross TEM

2000Å
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Elements of Non Volatile Switch
Harsh Environment Operation

- **Pristine Cavities**
  Minimize Reliability Issues

- **Differential Cell**
  Simplified Sensing

- **Proprietary Mechanical Design**
  Near Zero Restoring Force

- **Refractory Metal**
  Wide Temp. Range Operation

- **Mechanical Storage Element**
  No Charge Storage

- **Equa-Potential**
  No Charge Induced Issues

Diagram:
- Contact Electrode
- V_{program-0} = V_{program-1}
Extended Life Operation
Harsh Design

Contact Resistance (Ohm)

Non Volatile Switching Cycles

$R_{\text{off}}$

$R_{\text{on}}$

Memory Window:
Greater than
> 5 Orders of Magnitude Delta
Temperature Performance
Harsh Design

Core Technology – Robust and Very Stable
Data retention and memory window (168hr Bake Retention)

Adhesion grows at 350°C and Greater

No change in Memory Window And No loss of Data
The only failure mode observed is increase in stiction between the cantilever and contact interface, primarily at higher operating temperature.

This implies that the bit may fail as:
- failure to erase or
- failure to re-program, but
- never any loss of data
Test data showed, once cycled after temperature, adhesion force was as original 25°C value.
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Test Details:
- 4 Mrad TID (Si)
- Cobalt 60
- 389 Minutes
- 5.5 cm Spacing

Radiation has no impact on Harsh Environment Design
But does Impact Traditional cantilever
Radiation Hardness
Harsh Design Performance

Testing Condition
4 Mrad (Si) TID

No impact on Resistance due to Radiation
## NanoMech™ Specs For Non Volatile Memory

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Voltage</td>
<td>Native voltage (eg. 1.8V to 5 V)</td>
</tr>
<tr>
<td>Write Current</td>
<td>Electrostatic device; baseline CMOS current</td>
</tr>
<tr>
<td>Standby Power</td>
<td>Non-volatile memory; baseline CMOS power</td>
</tr>
<tr>
<td>Write Time</td>
<td>&lt; 200 ns</td>
</tr>
<tr>
<td>Read Time (NDRO)</td>
<td>&lt; 20 ns</td>
</tr>
<tr>
<td>( R_{on} ) versus ( R_{off} ) Range</td>
<td>Five orders of magnitude</td>
</tr>
<tr>
<td>Endurance</td>
<td>&gt;1 Million Cycles</td>
</tr>
<tr>
<td>Retention</td>
<td>&gt;10 years (power off)</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>-150°C to + 300°C</td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>-200°C to + 350°C</td>
</tr>
<tr>
<td>Shock Survival</td>
<td>&gt;&gt; 50,000 G</td>
</tr>
<tr>
<td>Total Dose Hardness</td>
<td>&gt; 4 x 10^6 rad (Si)</td>
</tr>
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NanoMech Applications

Electrical Components

- Non-Volatile Switches
- Integrated RF Components
  - Programmable Variable Capacitors
  - Low Impedance Switches
  - Programmable Filters
  - Integrated Resonators
  - Phase Shifters
- Metal Logic
- I/V Switch in Interconnect
  - Signal routing
  - Power switching

Other Applications of Technology

- Display
  - Pico Projector, Light Modulator
- Focal Plane Array
- CMUT
  - Ultrasonic sensors
- Inertial Measurement Sensors
  - Drop sensor
  - Accelerometer
- MEMS needing 3rd Gen Packaging

Wide Range of Applications that Can be Enabled
Conclusions

- Cavendish Kinetics has developed a robust, low voltage, non-volatile memory using standard CMOS interconnect processing.

- ROCKER tested for 1 million switches, cantilever tested to 100 billion switches
  - No sign of performance degradation

- Could also be embedded in the back end of other material systems such as Bipolar, GaAs, GaN, SiC etc.

- Reliability was demonstrated from -150 °C to +300 °C
  - Extendable based upon MEM Design

- Non-volatile memory reliability was also demonstrated under radiation doses of 4Mrad (TID (Si))