Silicon on Insulator CMOS and Microelectromechanical Systems: Mechanical Devices, Sensing Techniques and System Electronics

Dissertation Defense
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Bulk, SOI and SOS CMOS

- **Bulk CMOS**
  - Semiconductor device layer results in coupling

- **SOI CMOS**
  - Thin isolated device layer
  - Semiconductor handle wafer

- **SOS CMOS**
  - Thin isolated device layer
  - Isolating handle wafer
Peregrine Semiconductor SOS CMOS

- 0.5 micron feature size
- 3 metal, 1 poly
- 100nm active silicon layer
- 6 types of MOSFETs
- Sapphire substrate

J. Jamieson et. al. Infrared Physics and Engineering
Microelectromechanical Systems (MEMS)

- What are MEMS?

- MEMS fabrication technologies are based on integrated circuit fabrication

- Integration of MEMS and their supporting electronics is achieved in several ways
MEMS and CMOS integration can generally be divided into 4 categories:

- MEMS packaged to CMOS
- MEMS before CMOS
- MEMS after CMOS
- MEMS with CMOS

- This work is the first demonstration of MEMS with CMOS in a silicon on sapphire process and in a 3D SOI CMOS process.
Research Flow

1. Hypothesize about Unknowns
   - Electronics
     - Design Test Structures Based on Current Knowledge
       - Circuit Architecture Definition
         - Hand Calculations
           - Implement Circuit Design with Cadence, LEdit: Schematic, Simulation, Layout
             - Create Electronic System Model
       - Complete System Modeling with Simulink
         - Fabricate Test Structures
           - Characterize Structures and Extract Information
             - Build Test Setup
               - Collect Data using MATLAB, LabView, Test Instruments
                 - Analyze Data - MATLAB
               - Build Test Setup
                 - Collect Data using MATLAB, LabView, Test Instruments
                   - Analyze Data - MATLAB
   - Mechanics
     - Mechanical Structure Definition
       - Hand Calculations
         - Layout Design
           - Perform Finite Element Analysis with ANSYS, FEMLAB: Modal, Stress
             - Create Mechanical System Model

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Building CMOS MEMS in SOS

- Build CMOS MEMS structures using stacked metal and oxide layers

- Release steps
  - Step 1 vertical etch down to sapphire substrate
  - Step 2 lateral sacrificial release layer etch to free MEMS
Oxide Etch Issues

- Metal mask erosion
- Metal mask undercutting
Oxide Etch Issues

- Reactive ion etch (RIE) grass
  - Grass formation due to micro masking of oxide by un-etchable material
- Energy dispersive spectroscopy (EDS) used to determine grass composition
Cutting the Grass

- Upon careful inspection of the RIE etch chamber, several aluminum parts were identified.
- Replacing the parts eliminated the RIE grass.
Extraction of Material Properties

- Examining the resonant frequency of cantilever beams allows for the calculation of Young’s Modulus

- A beam deflection setup is used to gather resonant frequency data

$$E = \frac{\omega_n^2 \rho WTL^4}{\left(\frac{\kappa_n}{2\pi}\right)I}$$
Material Properties Continued

- Residual stress present in the mechanical layers causes curling
- Determining the radius of curvature allows for the calculation of the residual stress

\[
\sigma = \frac{1}{2} \left( \frac{EH}{\rho_x} \right)
\]
We need confirmation that the surface micromachining steps have little or no effect on the characteristics of the CMOS electronics.

A change in current output can be seen after the RIE step.
SOS MEMS Switch

- Uses residual stress to curl up for open state
- Pull down is achieved using comb fingers that run along the length of the beam
SOS MEMS Electrostatic Beam

- Data taken by driving beam with a 1V sine wave

- A change in mass will result in a change resonant frequency
SOS MEMS Issues

- Residual stress causes problems with many MEMS devices
  - Causes deviations from the ideal mechanical behavior
  - Can be added to ANSYS models
Sensing MEMS Motion

- The industry standard for sensing MEMS motion is the measurement of capacitance change.

- Alternative measurement techniques include:
  - Piezoelectric
  - Piezoresistive
  - Tunneling
  - Optical
Using the difference of the output current from multiple detectors the output current due to small deflections is given by:

\[ i \propto I_0 - I_1 \propto IR \sin\left(\frac{4\pi}{\lambda} \Delta x\right) \approx IR \frac{4\pi}{\lambda} \Delta x \]

where \( d_0 \) is the distance between the grating the mirror and \( d_0 = \frac{n\lambda}{8} \), \( n \) odd

Diffraction grating theory is used to determine the desired location and size of the photodetectors.

Degertekin and Hall et. al. 2001
Michelson in Motion
Standing Wave Detector

- The signal in the photodiode is proportional to the intensity of the standing wave contained in the active region and is given by:

\[ I \propto \int_{0}^{t_a} |E_1 + E_2|^2 \, dx \]

\[ = 2E_0^2 \left\{ t_a - \frac{\sin(kn_2 t_a) \cos(2kn_1 l + kn_2 t_a)}{kn_2} \right\} \]

- The optimal thickness for the standing wave detector is given by:

\[ t_a = \frac{\lambda}{4n_2} + m \frac{\lambda}{2n_2} \quad (m = 0, 1, 2, \ldots) \]

Sasaki et. al. 1999
Standing Wave in Motion
Standing Wave Bench Testing

Photodiode standing wave response

Displacement (microns)

Piezo Mount

Mirror

SOS Optical Test Die

Hitachi Laser Diode

Optics

Current Amplifier

Lock-in Amplifier

Function Generator

Data Acquisition Computer

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Die Level Optical Interferometer (DLOI)

- Both schemes utilize
  - Transparent sapphire substrate
  - PIN photodiodes available in the SOS process
  - Vertical cavity surface emitting laser (VCSEL) as source
- Michelson
  - Uses different path lengths of the same laser beam to generate interference pattern
  - Requires diffraction grating between VCSEL and MEMS
- Standing Wave
  - Makes use of 100nm thin photodiode available in the SOS process
  - Incident and reflected beam from VCSEL create a standing wave in the photodiode whose intensity is related to the position of the MEMS
Pictures of Packaged Parts
VCSEL driver circuit is used to modulate and control VCSEL power output

- Off-bias supplies a current to the VCSEL below the lasing threshold

- On bias supplies additional current to bring VCSEL into the lasing regime

- Select is used to modulate the VCSEL
Integrated Electronics: Photodiode Amplifier Circuit

- Uses devices with different thresholds and sizes

- ~40,000x total average gain

![Photodiode Amplifier Response Graph]

Blue: simulated data
Red: experimental data

![Photodiode Amplifier Circuit Diagram]

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Integrated Electronics:
Successive Approximation ADC

- Performs binary search of all possible quantization levels
- Uses monotonic capacitor array, clocked comparator and synthesized control unit
Integrated Interferometer Testing

- Two tests performed
  - Mirror is vibrated at 1kHz while output monitored by spectrum analyzer
  - Mirror is swept across ~5 microns while output monitored by lock-in amplifier
System Drift

- System drift causes output error
- Test performed monitoring a constant magnitude sinusoidal motion
VCSEL Collimation

- The standing wave detector will perform best when the incoming and reflected light intensities are the same
- VCSEL divergence causes significant light loss
Optically Detected Hydrophone

- DLOI packaged with silicon diaphragm and tested as a hydrophone
- System performance is equal to that of a commercial microphone
Optically Detected Magnetometer

- Xylophone bar magnetometer senses magnetic fields via the Lorentz Force
- The first two packaged devices do not function, more being assembled
Combining MEMS and Optical Detection

- Use polymer waveguides underneath SOS die
- Waveguides are currently being tested at APL
Other Future Work

- Combine DLOI platform with Sandia National Labs MEMS devices to produce a navigation grade gyroscope
- Fabricated SOS design for use with optical package
- Implement PID VCSEL driver with modulation capability
- Design and fabricated system electronics for specific systems
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