Optical MEMS

Outline

• Imaging and displays
  – Infrared radiation imager
  – Projection display with the digital micro-mirror device
  – Grating light valve display
• Fiber-optic communication devices
  – Digital $M \times N$ optical switch
  – Beam-steering micro-mirror
• Free-space micro optical bench
Infrared Radiation Imager

- Honeywell (U.S. Patent 6621083 B2)
- Achieves high sensitivity to radiation by providing extreme thermal isolation for a temperature-sensitive resistive element
- Incident infrared radiation heats a suspended sense resistor, producing a change in its resistance that is directly proportional to the radiation intensity

Principle
Design

- **Two-level structure**
- An upper silicon nitride plate suspended over a substrate, provides a high degree of **thermal isolation**
- The thin resistive element rests on the silicon nitride and has a large temperature coefficient of resistance (TCR)
- The **fill factor** – the area covered by the sensitive element as a fraction of the overall pixel area – must approach **unity**
- The silicon nitride plate and a thin reflecting metal directly underneath it form a **quarter-wave resonant cavity** to increase infrared absorption

Fabrication

- **Surface micromachining**
  - Incorporates an organic layer, such as polyimide, as the **sacrificial material**
  - Occurs **after** the fabrication of standard CMOS electronic circuits on the silicon substrate
  - The last step in the CMOS process ensures that the surface is **planar**
Projection Display with the Digital Micro-Mirror Device

- The operation of each mirror is digital - in other words, the pixel is either bright or dark
- The system is capable of achieving gray shades by adjusting the dwell time of each pixel - the duration it is bright or dark

Principle

![Diagram showing the principle of a Digital Micro-Mirror Device](image-url)
Principle

![Diagram of micromirror principle](image1)

Fabrication

1. Pattern spacer 1 layer
2. Deposit hinge metal; deposit and pattern oxide hinge mask
3. Deposit yoke and pattern yoke oxide mask
4. Etch yoke and strip oxide
5. Deposit spacer 2 and mirror
6. Pattern mirror and etch sacrificial spacers
Fabrication

• **Surface micromachining**
  – On wafers incorporating CMOS electronic address and control circuitry
  – Occurs at temperatures below 400°C, sufficiently low to ensure the integrity of the underlying electronic circuits

Fabrication

• **Reliability** is the key of the commercial success of DMD technology
• The designs are the result of extensive efforts at TI aimed at understanding the long-term operation of the pixels as well as their failure modes
• The DMD micro-mirrors are sufficiently robust to withstand normal environmental and handling conditions, including 1,500G mechanical shocks, because the weight of the micro-mirrors is insignificant
• The major failure and malfunction mechanisms are surface contamination and hinge memory (the result of metal creep in the hinge material that causes the mirror to exhibit a residual tilt in the absence of actuation voltages)
Grating Light Valve Display

- Silicon Light Machines of Cypress Semiconductor
- Relies on closely spaced parallel rows of reflective ribbons suspended over a substrate
- A phase grating, diffracting the incident light into higher orders
- The angle of **diffraction** depends on the **wavelength** and the pitch - or **periodicity** - of the ribbons

Principle

Unactuated - reflective state
- Aluminum (50 nm)
- $Si_3N_4$ (100 nm)
- Air gap (130 nm)
- Tungsten (100 nm)
- Oxide (500 nm)

Actuated - diffractive state
- Silicon
Digital $M \times N$ optical switch

- An optical switch redirects an incoming light signal into one of many output fibers.
- Arrays of optical switches allow the rapid reconfiguration of optical networks in data communications by altering the light path in a system of intersecting fibers.
- $M \times N$ switches are two-dimensional arrays with $M$ input and $N$ output fibers.
Design

• The basic cell for a $2 \times 2$ switch element consists of an electrostatic comb actuator controlling the position of a vertical mirror plate at the intersection of two perpendicular slots.

• Applying approximately 70V to the actuator combs causes the mirror to retract, letting the light pass through unobstructed.

• Arraying the $2 \times 2$ switch element in both directions creates a generalized $M \times N$ switch matrix.
Electrostatic Scanning Micromirrors

Fabrication Process

<Device wafer>
- Heavily doped device layer
- (a). Pattern devices and backside holes on SOI
- (b). DRIE on both sides
- (c). Release the structure by etching oxides
- (d). Place the lid chip on top of the device chip and apply electrical power for localized heating

<Lid wafer>
- Thermal oxide
- PR
- (1). Pattern pillars and electrodes using oxide and PR masks
- Key-slots
- (2). First DRIE and strip PR mask
- (3). Second DRIE
- (4). Etch oxide and metallization
- (5). Remove the lid chip (flexures are permanently deformed)
Free-Space Micro Optical Bench

- with the micromachining technology, the optical system can be miniaturized and batch fabricated on a silicon substrate
- the optical elements can be integrally fabricated on translation or rotation stages

Diffractive Microlenses

- focal length can be precisely defined by lithography
- microlenses with a wide range of numerical apertures (F/0.3–F/5) can be defined
- microlenses with diameters as small as a few tens of micrometers can be made
- thickness is on the order of an optical wavelength
Refractive Microlenses

- focal length is independent of the optical wavelength (except a weak dependence due to the dispersion of the lens material)
- not suffer from diffraction loss
- easier to make (i) fast refractive microlenses without tight critical dimension control and (ii) high efficiency lenses at low cost

Monolithic Optical-Disk Pickup Head

- Weight reduction, Miniaturization, Low cost, Possible on-chip actuation
Outline

• Passive electrical components
  – Capacitors and inductors
• Microelectromechanical resonators
  – Comb-drive resonators
  – Beam resonators
  – Coupled-resonator band-pass filters
• Microelectromechanical switches
  – Membrane shunt switches
  – Cantilever series switches
Applications

• The largest potential market is in cellular telephone handsets
• Cordless phones for home use, wireless computer networking, radios, and global positioning system (GPS) receivers
• Satellites, missile guidance, military radar, and test equipment

Introduction

• MEMS technology promises to deliver miniature integrated solutions including variable capacitors, inductors, oscillators, filters, and switches to potentially replace conventional discrete components
• In a Nokia 6161 cellular telephone, there are 24 discrete inductors (in addition to even more capacitors and resistors) along with only 15 integrated circuits
Signal Integrity

- Transmitting desired signals with low loss, minimizing reflections, not permitting external signals or noise to join the transmitted signal, and filtering out or not generating undesired signals, such as higher-frequency harmonics
- At high frequencies, these seemingly simple requirements are not readily attained
Passive Electrical Components

• The quality factor $Q$ is a measure of loss in a linear-circuit element and is defined as the maximum energy stored during a cycle divided by the energy lost per cycle.

\[
Q = \frac{1}{2\pi fCR_s}
\]

• The greatest limitation of semiconductor components is their $Q$.

\[
Q = \frac{2\pi fL}{R_s}
\]

Passive Electrical Components

• Micromachining technology is expected to make an impact in the near future with the commercial fabrication of variable capacitors with higher $Q$, the ability to be fabricated on the same chip as semiconductor circuitry for a reduction in part count, the ability to handle large AC input voltages, and potentially wider tuning range.
Surface-Micromachined Variable Capacitors

- Simpler to fabricate
- More readily integrated on the same chip as existing circuitry
- Use less expensive process steps
- Have a nonlinear response to the tuning voltage
- Smaller tuning ranges
Bulk-Micromachined Variable Capacitors

- **Interdigitated-finger (comb-drive) type**
- When a DC voltage is applied, the electrostatic force attracts the movable fingers to increase the length of overlap and thus the capacitance between the fingers
- The capacitance scales linearly with the number of fingers and the finger thickness and is inversely proportional to the gap
Micromachined Inductors

- One approach to improving both quality factor and self-resonance frequency is to reduce the parasitic capacitance and substrate conductive loss by changing to an insulating substrate, which is not possible if circuitry must be integrated on the same chip.

- Alternatively, raising the inductor above the substrate using an air gap or forming a cavity underneath it reduces the parasitic capacitance to the substrate.

Micromachined Inductors

- Minimizing the resistance by using a thick layer (limited by the skin depth) of low-resistivity metal.
Fabrication

1. Deposit Cu ground plane. Deposit and pattern dielectric. Sputter sacrificial metal and Au/MoCr/Au stack with stress gradient in MoCr. Pattern metal with photoresist and etch.

2. Etch sacrificial layer to release MoCr film, which curls slightly. Heat to relax photoresist. Au/MoCr/Au stack curls completely.

3. Strip photoresist. Electroplate Au/MoCr/Au with copper.
Microelectromechanical Resonators

- **Quartz crystals** are presently at the core of every electrical resonant circuit because, historically, integrated electronic oscillators have not been able to achieve the large quality factors necessary for the stable operation of frequency-selective communications systems.

- If micromechanical resonators can demonstrate high Q over a wide range of tunable frequencies, then integrating them with electronics will consequently lead to system miniaturization.
Comb-Drive Resonators

Beam Resonators

- To build a micromachined structure with higher resonant frequency than that readily achievable with a comb drive, the mass must be further reduced.
Coupled-Resonator Bandpass Filters

- The resonators have a very narrow bandpass characteristic, making them suitable for setting the frequency in an oscillator circuit but not for a more general bandpass filter.
- Bandpass filters pass a range of frequencies, with steep roll-off on both sides.
- Two or more microresonators, of either the comb-drive or clamped beam type, can be linked together by weak springs or flexures to create useful bandpass filters.
Microelectromechanical Switches

- Low insertion loss and return loss in the closed state
- High isolation in the open state
- High linearity
- High power-handling capability during switching
- Low operating voltage
- High reliability
- Small size and low cost
- Tradeoffs among various combinations of these parameters

Membrane Shunt Switches

- Electrostatically driven, 15-V DC
- A 2-μm-thick layer of gold is suspended 2μm above a 0.8-μm-thick gold signal line, which is coated with about 0.15μm of insulating silicon nitride
- The membranes have a span of 300μm and lengths of 20 to 140μm
Cantilever Series Switch

(a) Cap wafer
Thin gold alloy
Thick gold alloy
Glass
Thin gold alloy
Silicon nitride
Base wafer
Polysilicon cantilever
Gold/glass stack forms hermetic seal
Cantilever drive electrode
Ground
Signal
Ground
Three gold lines form coplanar waveguide

(b) Polysilicon cantilever
Silicon nitride insulator
Gold alloy contact
Signal in
Motion
Gold alloy signal line
Signal out

Cantilever Series Switch

(c) Thin gold alloy for seal ring
Polysilicon cantilever 1
Gold alloy contact 1
Cantilever 2
Thick gold/glass for seal ring
Contact area
Input 2
Output

(d) Polysilicon cantilever 2
Gold alloy contact 2
Cantilever 1 drive electrode
Input 1
期末考注意事項

• 範圍
• 題型
• 佔學期成績的百分之三十
• 可攜帶一頁A4 大小的參考資料
• 考試時間
  - 一月三日星期一晚上六點三十分起

範圍

• 期中考前所介紹的各項製程
  + Thick-film lithography
  + Polymer microfabrication
• 製程整合
  + Surface micromachining
  + Bulk micromachining
範圍

- MEMS packaging
- Characterization techniques
- BioMEMS
- Optical MEMS
- RF MEMS

題型

- 問答題
  - 與製程原理及操作相關的基本概念
  - 分析及推論製程結果
  - 比較不同製程
  - 製程整合
- 設計題
  - 簡單的製程設計
**Process Flow**

**Lab 1:**
1. Wafer cleaning
2. Thermal Oxide

**Lab 2-1:**
1. Lithography (PR AZ 5214, mask #1 for bulk etching window)

**Lab 2-2:**
1. Break wafer into A, B
2. BOE wet etching B, RIE dry etch A
3. PR strip, wafer cleaning

**Lab 3:**
1. E-beam evaporate Cr/Ni 0.05/0.15 μm on A
2. TMAH bulk etch B

**Lab 4-1:**
1. Lithography patterning Ni by wet etching (mask #3)

**Lab 4-2**
- AZ4620 lithography
- Plating

**Lab 5:**
1. PR strip and Oxide sacrificial etching (surface micromachining)
Part II (25%)

Process design

1. Surface Micromachining (15%)

Please design a process flow to fabricate the following hinge structure using poly-Si as structural material. How many masks do you need? The starting material is p-type Si wafer.

<table>
<thead>
<tr>
<th>Process description</th>
<th>Cross-sections</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2. Bulk Micromachining (10%)

Please design a process flow to fabricate the following suspended cantilever beam structure. How many masks do you need? The starting material is p-type Si wafer.

<table>
<thead>
<tr>
<th>Process description</th>
<th>Top and side views</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
(a) Bulk micromachining (b) Surface micromachining (c) SOI process

Part II (25%)  
Process design  
1. Surface Micromachining (10%)  
Please design a fabrication process for the following metallic solenoid structure.

<table>
<thead>
<tr>
<th>Process description</th>
<th>Top view</th>
<th>Cross-sectional view</th>
</tr>
</thead>
</table>