Environmentally Benign Deposition of Photoresist and Low-k Dielectrics

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Outline

- Motivation
- Objective
- Approach
- FEM Analysis of the micro-machined ejector
- Previous 6-month research
  - Experimental setup
  - Ejection
- Problems
- New fabrication process
- Conclusions
- Future Research
Motivation: Current Best Technology

• Current best coverage technology:
  Photoresist or Low-\(k\) dielectric wafer coverage by spinning

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Motivation: Waste

- Inefficient use of Expensive Chemicals
- Cost of disposal of Hazardous Waste
- Environmental Pollution
- Spinning Technology
- Resist on the wafer 5%
- Over 95% of the spinned resist
Motivation: Cost

- DUV resist costs $5000 /gal
- Throughput per year for a four inch wafer track
  (60 wafers/hr) (360 days/year)(0.90 track utilization) = 466,560 wafers/year

- Spinning Technology $2.6 Million
- Inefficient use of chemicals $2.5 Million
- Resist on the wafer $0.1 Million
- Hazardous Waste Disposal Costs
Objective

- Since a large amount of photoresist, low-\(k\) and high-\(k\) dielectrics is wasted during spin coating, our aim is to reduce the waste.
  - Develop a fluid ejection system capable of depositing fluids with a minimum of waste.
  - Develop a system capable of drop on demand and continuous ejection.
  - Develop a coating system to demonstrate waste reduction with full coverage of wafers.
  - Demonstrate photoresist and low-\(k\) and high-\(k\) dielectric coating of 20 cm and 30 cm silicon wafers.
Approach: Full Device

Micromachined Ejector Array

Ejected Resist

Shift & Eject
Approach: Design Requirements

• Use flex-tensional ejectors for deposition
  – Design and implement micro-machined ejector arrays with either single or multiple piezoelectric drivers

• Ejector requirements
  – Able to deposit low and high viscosity fluids
  – No damage caused to the ejected fluids
  – High flow rate
  – Compatible with most chemicals
  – Can be made using IC process technology
**Approach: A Unit Cell of the Device**

- Flex-tensional ejectors for deposition
  - Design and implement micro-machined ejector arrays with either single or multiple piezoelectric drivers
Large Scale Single Ejector

Membrane: brass, steel
Diameter: 9 mm
Membrane thickness: 25 µm
Orifice size: 50-200 µm
Operating frequencies: 9.5 kHz, 16.4 kHz, 19.0 kHz

- Photoresist covered deep trench
- Deposited Photoresist Thickness: 3.5 µm ± 0.15 µm
- Direct write with resist: 350 µm-wide lines
Micromachined Device Configuration

- **Piezoelectric Transducer**
- **Liquid**
- **Silicon Substrate**
- **Membranes**
- **Controllable vertical distance**
Finite Element Modeling of Ejector

FEM modeling of a Silicon membrane that is 1 μm thick and 100 μm in diameter. Membrane and cavity resonance govern operation at resonance for ejection.
### FEM: Membrane Diameter vs. Frequency

<table>
<thead>
<tr>
<th>Resonance Number</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Membrane diameter</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500 µm</td>
<td>382 kHz</td>
<td>1.49 MHz</td>
<td>3.34 MHz</td>
<td>5.91 MHz</td>
<td></td>
</tr>
<tr>
<td>200 µm</td>
<td>78 kHz</td>
<td>480 kHz</td>
<td>1.33 MHz</td>
<td>2.72 MHz</td>
<td></td>
</tr>
<tr>
<td>500 µm</td>
<td>61.26 kHz</td>
<td>238.3 kHz</td>
<td>533.5 kHz</td>
<td>946.9 kHz</td>
<td>1.479 MHz</td>
</tr>
<tr>
<td>200 µm</td>
<td>11.4 kHz</td>
<td>66.4 kHz</td>
<td>187.6 kHz</td>
<td>388.1 kHz</td>
<td>677.1 kHz</td>
</tr>
</tbody>
</table>

Vacuum

Water
2D Micro-machined Ejector Array

- 2D array of ejectors
- Membrane actuation by a transducer through the fluid reservoir
- Thin single crystal silicon uniform membrane
- Deep reactive ion etched reservoir
- High frequency operation for high flow rate (MHz)
- Drop-on-demand and continuous modes of operation
2D Micro-machined Array: Dimensions

Device Properties
- Membrane material: Single crystal silicon, Si₃N₄
- Membrane Diameter: 100 µm, 200 µm, 300 µm, 500 µm, 1 mm
- Membrane thickness: 1 µm for Si, 2.1 µm for Si₃N₄
- Orifice diameter: 4 µm, 10 µm, 14 µm
- Operating frequencies: 470 kHz, 1.24 MHz, 2.26 MHz for Si₃N₄
Experimental Setup

- Oscilloscope
- Function Generator
- Power Amplifier
- Transducer
- Reservoir
- 2D Array Ejector
- LEDs
- Camera
- LED
- TV Screen
- Camera

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Experimental Setup: Ejecting Device

- Ejection is difficult to see due to very small droplets
1. 24 MHz Droplet Ejection

Water Ejection at 1.24 MHz
(5 μm in diameter droplets)
## Ejection Summary

<table>
<thead>
<tr>
<th></th>
<th>470 KHz</th>
<th>1.24 MHz</th>
<th>2.26 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Droplet Diameter</strong></td>
<td>6.5 um</td>
<td>5 um</td>
<td>3.5 um</td>
</tr>
<tr>
<td><strong>Center to Center Distance</strong></td>
<td>14.8 um</td>
<td>14.1 um</td>
<td>9.2 um</td>
</tr>
<tr>
<td><strong>Droplet Speed</strong></td>
<td>6.9 m/sec</td>
<td>17.5 m/sec</td>
<td>20.8 m/sec</td>
</tr>
</tbody>
</table>
Two Membrane Ejection at 1.24 MHz

Two neighboring membranes ejecting simultaneously

– Observed 20 ejecting membranes out of 400
Fabrication Process: SOI Wafer Bonding

Previous

- Oxide film deposition
- Nitride film deposition
- Silicon bulk etch
- Orifice formation with dry etching
- Oxide etching

New

- Oxide film deposition
- Oxide film patterning
- Silicon bulk etch
- Oxide removal
- SOI wafer bonding
- Wet Oxide etch
- Orifice formation with dry etching

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New Process Flow: Key Step Analysis

A: DRIE of the reservoirs
B: Si-Si Bonding
C: Wet release of SOI Silicon
D: Dry release of SOI Silicon
E: Wet SiO$_2$ release
F: Orifice Formation
A) DRIE of the Reservoirs

**Device**

5x5 STS etched silicon wafer ready to be bonded to a SOI wafer for membrane formation.

**Benefits**

- Uniform 1 μm thick single crystal silicon membrane.
- Membrane radius does not depend on the wet oxide etch rate.
- Uniform membrane radius with Deep Reactive Ion Etching (DRIE).
- Uniform membrane orifice with dry etching.
B) The Bonding Quality Test:
Si to Si Bonding

SOI SiO₂.

Single Crystal Silicon protected under a thin 800 Angstrom thick dry oxide layer. 100 μm
C) Wet Membrane Release: Micro bubble masking

Single Crystal Si Membrane Release with wet-etch is halted before the etch is totally finished.
Very good selectivity for Si vs. SiO$_2$.

- Single Crystal Silicon membranes covered with SOI SiO$_2$ as wet etch stop.
- The ripples on the membranes are due to SiO$_2$ stress.
- SOI wafer silicon is etched to release the single crystal Silicon membranes.
D) Dry Membrane Release: Polymer residue

Single crystal Si membrane release with dry-etch is non-uniform. Due to low selectivity the protective SiO₂ may be etched as well.

- Single Crystal Silicon membranes covered with SOI SiO₂ as a wet etch stop.
- The ripples on the membranes are due to SiO₂ stress.
- Polymer residues remain on the SiO₂. They can be removed.

Single crystal Si membrane release with dry-etch is non-uniform. Due to low selectivity the protective SiO₂ may be etched as well.
E) Wet SiO$_2$ Release

• 1 µm thick uniform Single Crystal Silicon membranes.
• The ripples on the membranes have disappeared.
• Very clean membrane formation.
• No polymers are left on the single crystal silicon.

Single crystal Si membrane release with wet-etch is completed.
F) Orifice Formation

- The orifice should be located in the exact center of the membrane to benefit from maximum membrane displacement.

- The lithography must be very accurate.

- Alignment marks must be well protected during all process steps.

- Orifices are uniform size as a result of good lithography and dry etching.
Various membrane radii and device sizes on a Silicon wafer
2D Micro-machined Array: Actual Device

- 2D array of ejectors (20x20)
- The membrane diameter is 160 µm
- Orifice size is 10 µm
- Thin silicon nitride membrane
- Deep reactive ion etched reservoir
Old Process vs. New Process
Si$_3$N$_4$ vs. Single Crystal Si Arrays

Silicon-nitride membrane

Single Crystal Si membrane

Membrane diameter : 160 $\mu$m
Orifice diameter : 10 $\mu$m

Membrane diameter : 100 $\mu$m
Orifice diameter : 14 $\mu$m
Old Process vs. New Process: 
$\text{Si}_3\text{N}_4 \text{ vs. Single Crystal Membrane}$

**Silicon-nitride membrane:**
- Membrane diameter: 160 $\mu$m
- Orifice diameter: 10 $\mu$m

The black marks are on the camera lens *not* on the membrane surface.

**Single Crystal Si membrane:**
- Membrane diameter: 100 $\mu$m
- Orifice diameter: 14 $\mu$m
Desired Good Ejection by 2D Arrays

- All membranes should be ejecting simultaneously
- Ejection should be perpendicular to the device surface
- Drop on Demand Ejection should be possible
- Droplet size and ejection speed should be controllable
Continuous Wave actuation
All membranes eject simultaneously
The droplets eject perpendicularly to the device surface
Drop on Demand Ejection

- The aim is to be able to eject:
  - a desired number of droplets
  - at a desired time
Conclusions

• A new ejector fabrication process has been developed that provides
  – Uniform membranes
  – More control on material properties
  – Stress free membranes (no membrane buckling)

• Demonstrated **single crystal silicon** membranes in a 2D Array of micromachined ejectors.
Future Work

• Test the fabricated single crystal silicon membranes and compare their operating features with FEM predictions.
• Fabricate single crystal silicon membranes, where the orifice is formed by wet etching.
• Perform FEM simulations to understand cross-talk issues and model the devices.
• Use the new fabrication process to build ejectors capable of better controlled ejection
  – Drop on Demand ejection
  – All array membranes active at a given time
Future Work

- Test silicon nitride membrane devices and single crystal silicon devices for ejection of fluids with higher viscosities than water, i.e. photoresist, low-\(k\) and high-\(k\) dielectrics.
- Upgrade the experimental setup for the new experiments.
- Demonstrate full photoresist coverage of a wafer using micro-machined 2D ejector arrays.