Plasma Etching for Optical MEMS: Scanning Micromirrors Based on Self-Aligned Vertical Combdrive Actuators

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PLASMA ETCH USERS GROUP MEETING
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Abstract

There is great demand for high-speed, high-resolution micromirrors in a variety of optical applications including optical scanning, optical switching and spectroscopy. For many of these applications, electrostatic combdrives are the preferred actuation mechanism, because combdrives provide high speed and relatively high force, and they can be made using standard materials. We present design, fabrication and characterization of micromirrors that are driven by self-aligned, vertical combdrives based on Deep Reactive Ion Etching (DRIE) of Silicon-On-Insulator (SOI) wafers.

Combdrives produce large deflections at relatively low voltages with continuous stable control over the full range of motion. In vertical combdrives the two sets of comb teeth of a conventional comb drive are staggered in the vertical direction. A voltage applied between the movable top comb array and the static bottom comb array produces a vertical electrostatic force that can be applied to create torsional or piston-like motion of micromirrors.

A critical aspect of combdrive design is the spacing between adjacent comb teeth, because the generated force is inversely proportional to this gap size. Combdrives with small gaps are, however, more susceptible to misalignment between the top and bottom comb arrays. For the actuator to be operational, the misalignment tolerance level between the top and bottom teeth should be an order of magnitude smaller than the gap width.

We have developed a simple fabrication process based on plasma etching that produces self-aligned vertical combdrives. Self-alignment makes it possible to fabricate reliable narrow-gap, high-force actuators with excellent yield. A resonance frequency for 300 mm x 100 mm mirrors around 5.5 kHz has been achieved.

After a first part covering the above described specific application of plasma etching, the needs concerning plasma etching for optical MEMS components will be discussed in a broader context.
Objective
- Vertical combdrives for large force
- Dual-mode Mirrors and Phased Arrays

Fabrication
- STEC process
- Self-aligned process

Characterization
- General Plasma Etching Needs for Optical MEMS

Conclusions

Research support: NSF, DARPA, BSAC
Scanners and Phased Arrays

- Electrostatic Actuators
  - Material Compatibility
- No sliding surfaces
  - Repeatability, stability
- Vertical combdrives
  - Large Force
  - Controllable range of motion
- Suitable for dual-mode operation and phased-arrays
Surface Micromachined Dual-mode Mirrors

Static top comb teeth

Movable comb teeth

Static bottom comb teeth

Optical tilt (degree)

0 0.2 0.4 0.6 0.8 1 1.2 1.4

Potentials applied to opposite drives (volt)

Trace
Retrace

Tilt Right

Potentials applied to two drives (volt)

Vertical displacement

0 0.5 1 1.5 2 2.5 3 3.5 4

Piston Down

Piston Up

0 10 20 30 40 50
MEMS Mirrors in SOI

- DRIE etching of SOI materials
- High quality, flat, and stiff mirrors
- Beam quality!
- High-speed
  - High force => high speed
  - Dual-mode actuators
  - Phased arrays
- Combs are lithographically aligned
  - Reliability
  - Yield
STEC Fabrication

STEC (Staggered Torsional Electrostatic Commdrive)

- Bonding
- Alignment (< 0.1\*G₁ μm)
- Top comb teeth
- Bottom comb teeth
- G₁
- G₂
Self-aligned vertical-comb actuator

Self-alignment

Single mask self-alignment step

More complex fabrication process is required for dual-mode mirrors

Coarse Alignment

<W+2G

< G μm

Self Alignment
Fabricated Micromirrors

Single micromirrors

Arrays of micromirrors

25KV  X79  380 um

25KV  X60  500 um
Current work

- Double sided comb actuators
- Torsional and piston style motion
- Isolated electrodes on SOI wafer
- Array operation
- Gimbals
Vertical comb drives are the preferred actuators for high-speed, high-resolution MEMS scanners

Fabricated and characterized *self-aligned*, vertical, comb-driven single-crystal micromirrors using DRIE and wafer bonding
- High force and large deflection
- Increased stability and yield

Applications
- Optical scanners, Fiber switches, Spectroscopy, Microscopy, Optical coherence tomography, External cavity lasers, Barcode readers, Adaptive optics, Printers, Optical vector scanners, Surveillance, Optical interconnects, Mask-less lithography.....
### Plasma Etching for MOEMS: Current Needs and Challenges

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- **Electrostatic Combdrives**: Electrostatic comb drives are used for actuation in microelectromechanical systems (MEMS) devices, enabling precise control of microstructures.
- **Micromirrors**: Devices used for optical focusing and deflection in microsystems.
- **Refractive Devices**: Components that use the refractive index of materials to control light paths.
- **Diffractive Devices**: Components that use diffraction to control light paths.
- **Waveguides**: Devices that guide light through a waveguide, enabling optical communication in microsystems.
- **LEDs & VCSELs**: Light-emitting diodes and vertically-coupled surface-emitting lasers, used in light sources for various applications.
- **Photonic Crystals**: Structures that manipulate light through photonic band gaps.
- **Organic Devices (OLEDs)**: Organic light-emitting diodes, which are used for displays and lighting.
- **System Integration**: Integration of components into a cohesive system, ensuring functionality and performance of the entire device.

- **Vertical Sidewalls**: Essential for certain applications, such as waveguides, to achieve high aspect ratio without compromising structural integrity.
- **High Aspect Ratio**: Important for devices requiring high performance, such as high-fidelity optical systems.
- **Low Surface Roughness**: Necessary for critical applications, like photonic crystals, where surface quality affects performance.
- **Small Feature Size**: Required for advanced devices, such as microprocessors, to achieve high density and efficiency.
- **High Etch Rate Uniformity**: Critical for maintaining consistency in device performance across the wafer.
- **Selectivity**: Needed to control etching rates selectively, preventing unwanted material removal.
- **New Materials**: Essential for innovation and adaptation to new technologies.
- **Control of Sidewall Angle**: Important for maintaining structural integrity and functionality in microsystems.
- **Critical Wafer Handling**: Necessary to ensure the integrity and performance of the devices during processing.

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### Notes
- **Plasma Etching**: A critical process in microfabrication, used to etch materials like silicon, glass, and metals, enabling the creation of precise microstructures.
- **MOEMS**: Micro- and nano-technology-based optical and electromechanical systems, which combine optical, electronic, and mechanical components on a single chip.
- **Current Needs**: Reflects the ongoing technological advancements and challenges faced in the field of MOEMS.
- **Challenges**: Highlight areas where improvements are required to advance the technology and meet the demands of modern applications.
Smooth Vertical Surfaces for Optical Switches

- Verticality
- Narrow linewidth (high force)
- Smooth vertical surfaces (\(\lambda/10 - \lambda/50\))

Silicon trenches, 80\(\mu\)m deep
4.5\(\mu\)m space / 2\(\mu\)m line width
Etch rate \(\approx\) 2.2\(\mu\)m/min

2x2 Optical Switch
Vertical Mirror

Surface Technology Systems
http://www.stsystems.com/

University of Neuchatel, Switzerland
http://www-samlab.unine.ch/Activities/Activity.htm
Waveguides

- Etching of up to 30 µm thick (SiO₂) Films
- Smooth surfaces (reduction of losses – 0.01dB/cm)
- Vertical and smooth edges (coupling losses)
- Functionality sensitive towards geometry changes
- New materials (polymers, GaN ...)

Phosphine doped SiO₂ core
SiO₂ cladding

Arrayed Waveguide Grating

AlGaAs Waveguide

www.lightwavemicro.com/PDFs/Lamwhitepaper.pdf

Stanford University, Prof. Harris, Prof. Feyer
Refractive and Diffractive Devices

- Pattern transfer from photoresist to substrate (e.g. glass)
- Smooth surfaces
- Control of etch depth
- Uniformity across wafer
- Gray Scale Lithography (500 levels, 100 nm resolution)
- Tuning of etch rate ratios
Active Optical Devices

- VCSEL: Etch stop at defined depth (uniformity)
- Smooth vertical surface (edge emitting laser diode)
- New materials (organic LEDs)

Kodak, OLED Display

Tunable VCSEL (InAlGaAs)
Cantilever with Top-Mirror, ca. 4 um thick

AlGaAs LED
Mask: Gold, Etch Rate: 1.54 um/min.
Etch Depth: 60 um

Bandwidth9
http://www.bandwidth9.com/content-template.cfm?display=products&sub=products

SAMCO Inc.
http://www.samcointl.com/apps/Optoelectronics.html
Sidewall Angle Control Facilitates System Integration

- Mirror surface at 45° facilitates integration
- Here: Integration of fluidics and optics for fluorescence detection in embryos
- Gray Scale Lithography

Optical Chip with LED/VCSEL and Photodetector
Fluidic Chip with Integrated Lenses and Mirror Surfaces

Fluidic System for automated Fruit Fly Embryo Handling

Fruit Fly Embryo
Actuator
Combdrive Electrodes
Cantilever

Mirror at 45°

Stanford Microphotonics Laboratory
http://www.stanford.edu/group/SML/
Plasma Etching of Small Features
For Photonic Crystals

- Photonic Crystals require sub-wavelength feature size
- Tight fabrication tolerances
- Vertical, smooth sidewalls
- No notching at interfaces (good etch rate uniformity)

www.mrs.org/publications/bulletin
‘MATERIALS SCIENCE ASPECTS OF PHOTONIC CRYSTALS’
http://www.samcointl.com/apps/PC_SOI.html

SAMCO Inc.
New Illumination Methods for Smaller Feature Sizes

- SCALPEL® – E-Beam Projection Lithography
- EUV (Extreme Ultra Violet) Lithography

http://www.bell-labs.com/project/SCALPEL/
-> Dec. 1999 White Paper
SCALPEL® Technology for E-Beam Lithography

SCALPEL®
Scattering with Angular Limitation
Projection Electron Beam Lithography

- SCALPEL combines high resolution e-beam lithography with high throughput of a projection system
- Achievable IC feature size of 50 nm

SCALPEL® Technology for E-Beam Lithography

- Etching of Si-struts (load effect compensation)
- Etching of scattering metal (< 200 nm)
- Handling of wafer with 100 nm thin Si₃N₄ membrane

Trikon Technologies
http://www.trikon.com

Surface Technology Systems
http://www.stsystems.com/latest_news/high_rate.html
Spatial Light Modulators for EUV Lithography

- Light source at 13 nm wavelength (Extrem Ultra Violet)
- Reflective mask necessary
- Micromirror array for maskless lithography
- Pattern on wafer formed by interference
- Plasma etched trenches to avoid cross-talk

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http://www.stanford.edu/group/SML/

Trikon Technologies
http://www.trikon.com
Conclusions

- Electrostatic combdrives suitable for actuation in MOEMS
- Self-aligned etching process
- \[\Rightarrow \text{narrow gaps, higher forces, higher reliability}\]
- Vertical sidewalls
- Higher aspect ratio
- Controllable sidewall angle
- Smooth lateral and vertical surfaces
- Uniformity of etch rate / load effect
- Etching of small features
- Etching processes for new (organic) materials
- Handling of wafer with fragile structures