Micromachined Floating Element Hydrogen Flow Rate Sensor

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Planned Completion = 3/31/2007

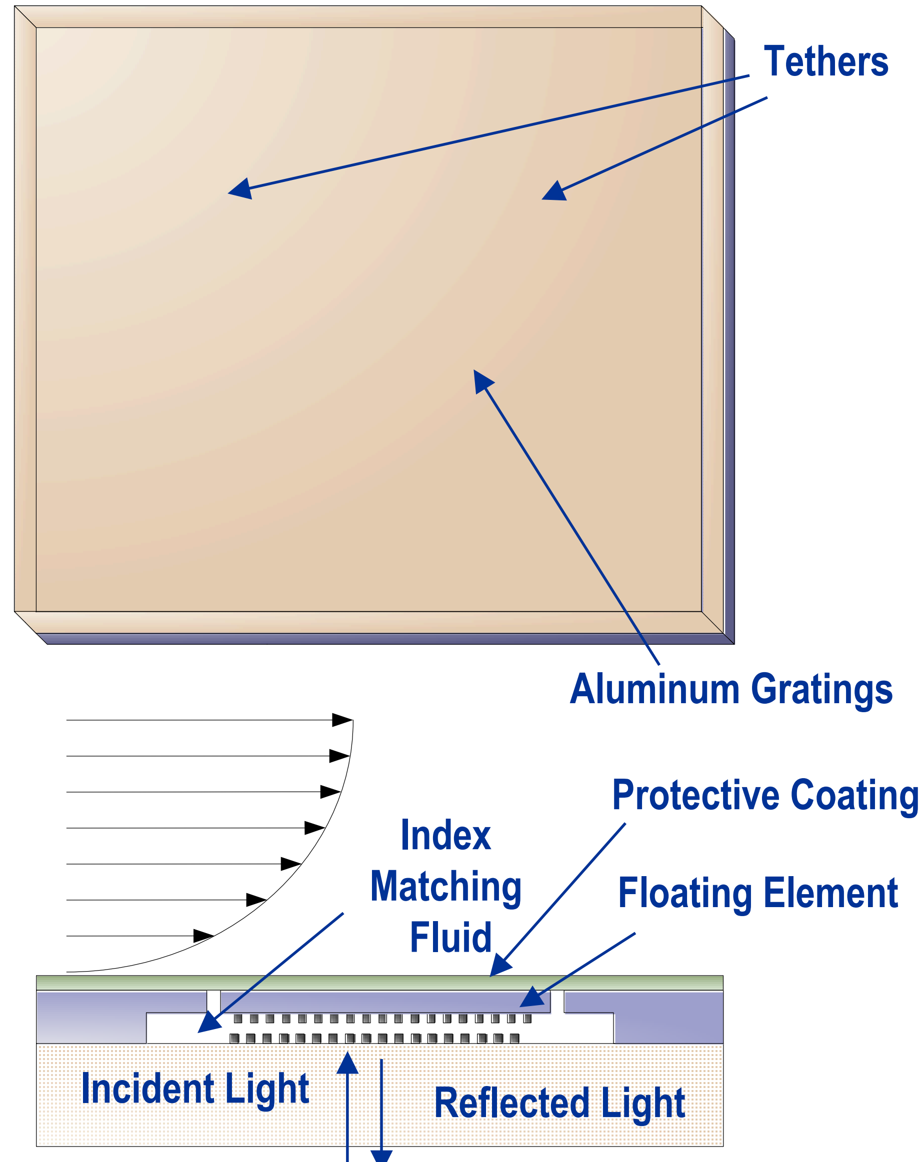
Research Goals and Objectives

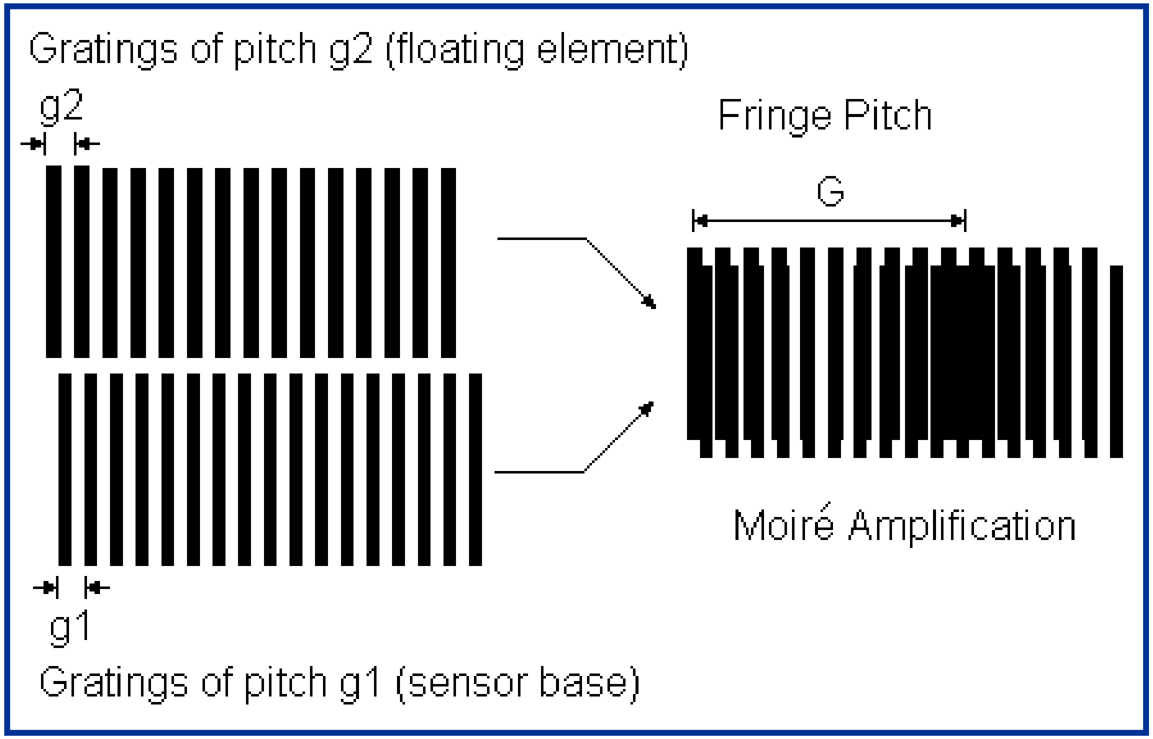
"Develop a robust, miniature, silicon micromachined Moiré optical-based flow rate sensor for hydrogen transport measurement applications"

- Measurement Technique Goals:
  - Light weight, no pressure head losses, non-intrusive, compact, etc.
  - Standard instrumentation falls short
    - Thermal sensors
      - Volumetric flow rate related to heat transfer rate
      - Intrusive by nature and must transfer heat to the flow
    - Differential pressure
      - Flow rate inferred to an induced pressure drop (i.e., orifice, Venturi, nozzle, etc.)
    - Momentum based
      - Flow rate induced from momentum measurement (i.e., turbine, propeller, cup anemometer, etc.) resulting in head loss
- Flow Rate Measurement via Shear Stress
  - Wall shear stress can be theoretically related to flow rate in many cases and can be experimentally fit in most others
    - Need a reliable, direct measurement of wall shear stress

Device Concept

- Floating-Element Sensor
  - Transduction
    - Optical Moiré fringe shifting
  - Benefits
    - Direct measurement of shear stress, flow rate inferred
    - Immune to EMI and optical intensity fluctuations
    - No thermal/electrical energy to flow
  - Construction
    - Silicon floating element
    - Four silicon tethers
    - Pyrex base
    - Two sets of aluminum gratings with slightly differing pitch
    - Protective polymer coating





- Two overlapping gratings of almost identical period
- Resulting Moiré fringe pitch related by

$$\frac{1}{g_1} - \frac{1}{g_2} = \frac{1}{G}$$

- Motion of one grating w.r.t. another leads to amplified motion of Moiré pattern

$$\Delta = \delta\left(\frac{G}{g_2}\right)$$

$\Delta \rightarrow$ displacement of Moire′ pattern

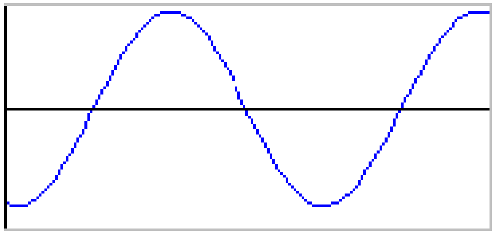
$\delta \rightarrow$ displacement of physical grating

Device Concept

- Floating-Element Sensor

Flow Direction
(Applied Shear Stress)

- Moiré Intensity Pattern



Relevance to Current State-of-the-Art

- The floating element sensor minimizes pressure head-loss due to flow disturbances
- The transducer does not transfer thermal or electrical energy to the hydrogen medium (safety benefit?)

Relevance to NASA

- Accurate determination of fluidic (gas and liquid phase) flow rates is critical in all fluid transport systems
- Flow rate sensor is key component to enable the future hydrogen economy is the development of "advanced technologies to ensure its [hydrogen] safety in production, transport, and storage"

Budget, Schedule and Deliverables

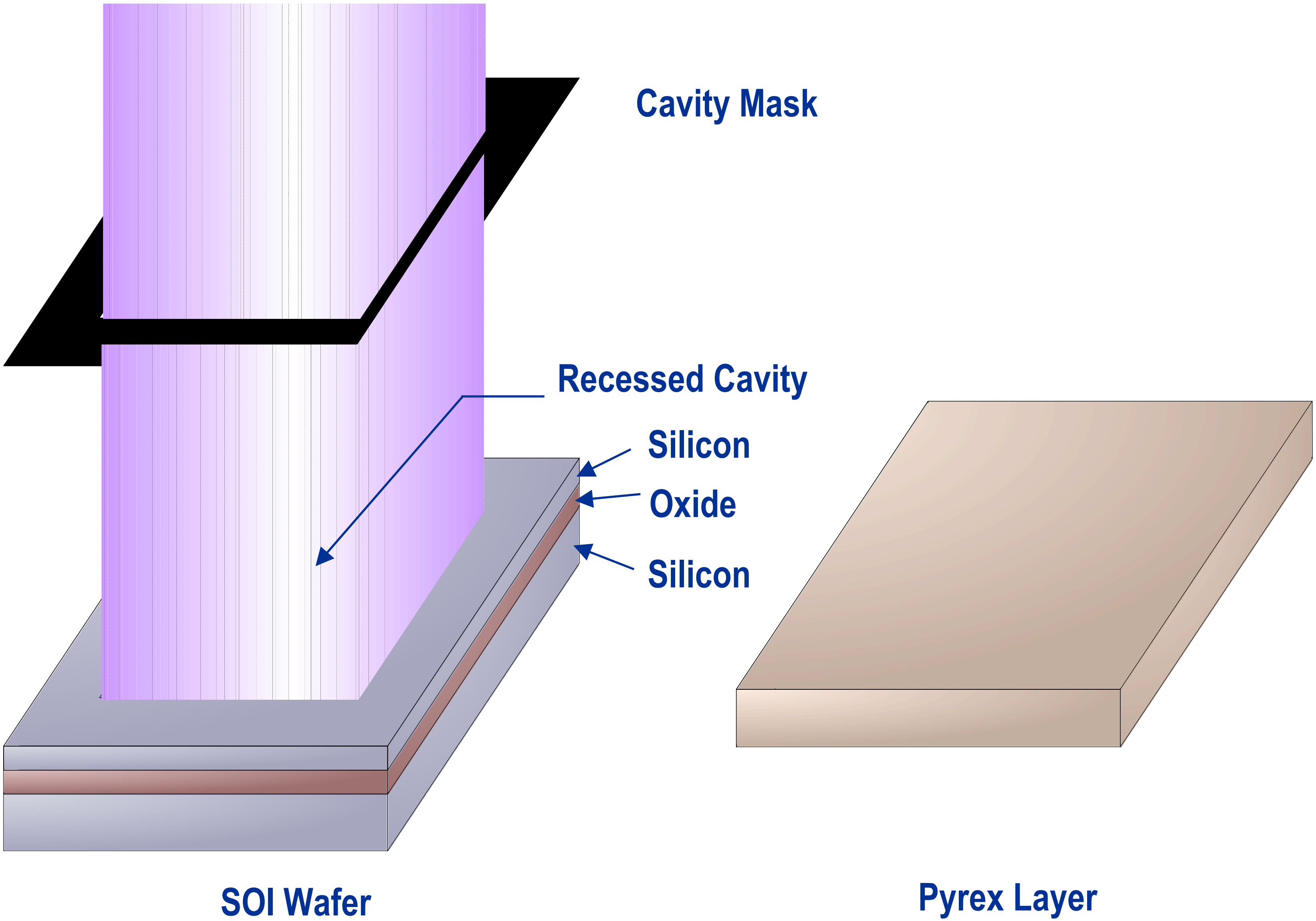
- 1st Grant
  - Budget: 70k$ / 12 months
  - Deliverable: 1st generation, proof of concept sensor
- 2nd Grant
  - Budget: 60k$ / 18 months
  - Schedule and Deliverables:
    - 1st Qtr: Optimally designed new sensor
    - 2nd Qtr: Improved microfabrication process flow and mask set
    - 3rd Qtr: New package design
    - 4th Qtr: Functioning sensor ready for characterization
    - 5th Qtr: Gas/water flow-cell test-bed
    - 6th Qtr: Characterized sensor ready to transition to hydrogen flow

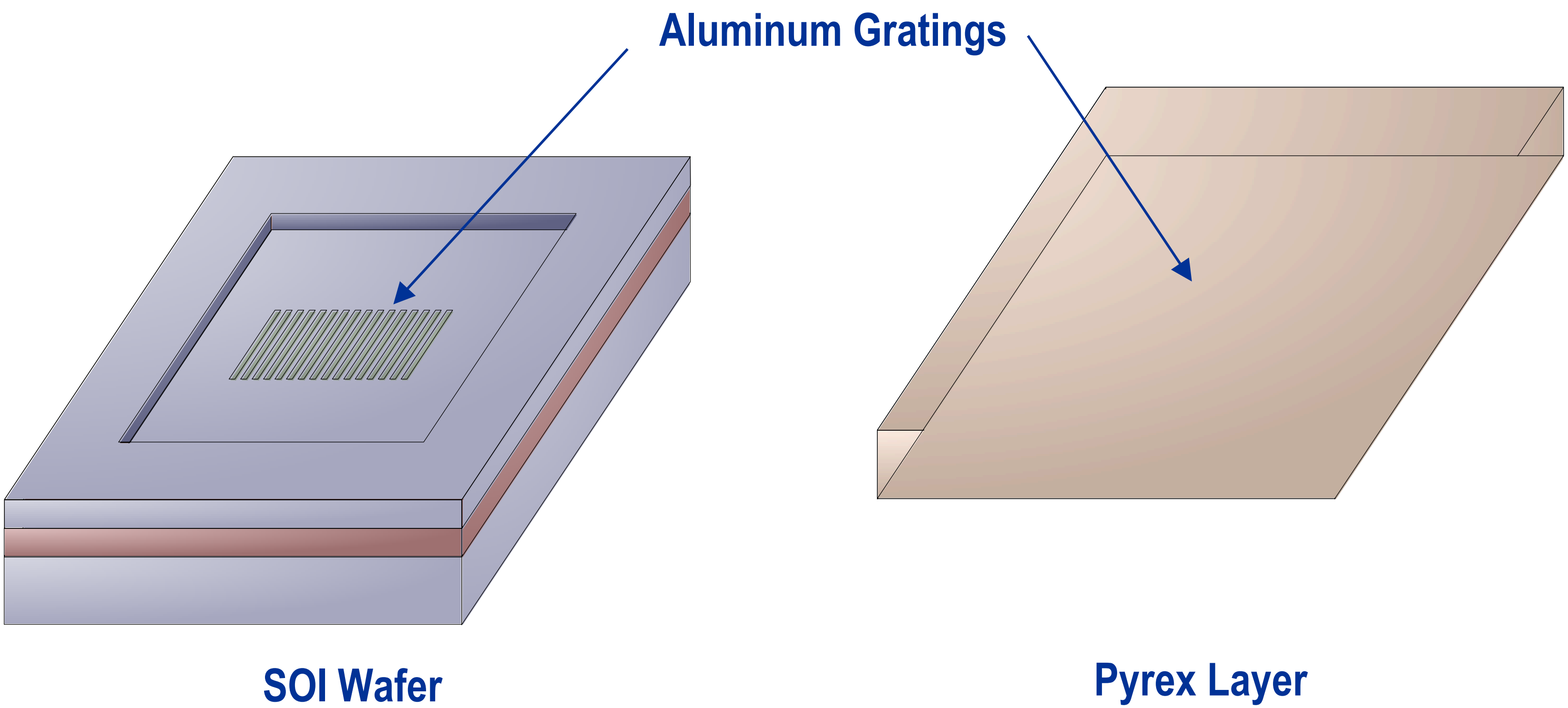
Anticipated Technology End Use

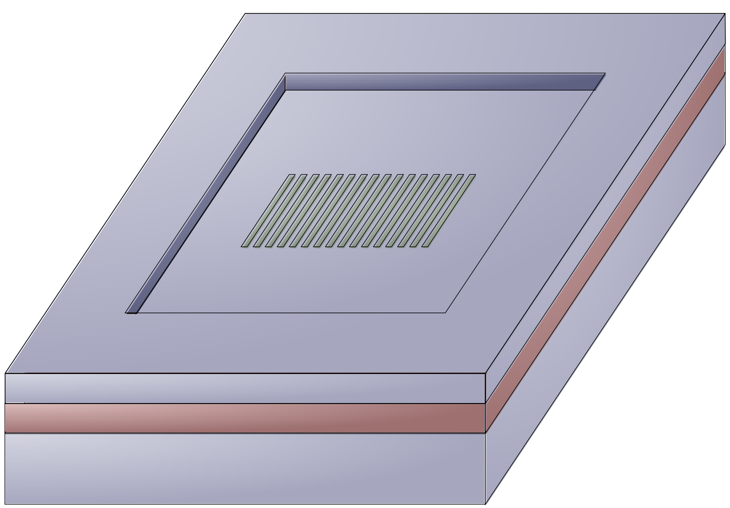
- NASA:
  - Sensor for the measurement of flow rates in hydrogen transport systems
- Dual Use:
  - General flow rate sensor
    - Industrial process control
  - Shear stress (skin friction) sensor:
    - Turbulence measurements
    - Flow control
    - Biological fluid mechanics

Accomplishments and Results

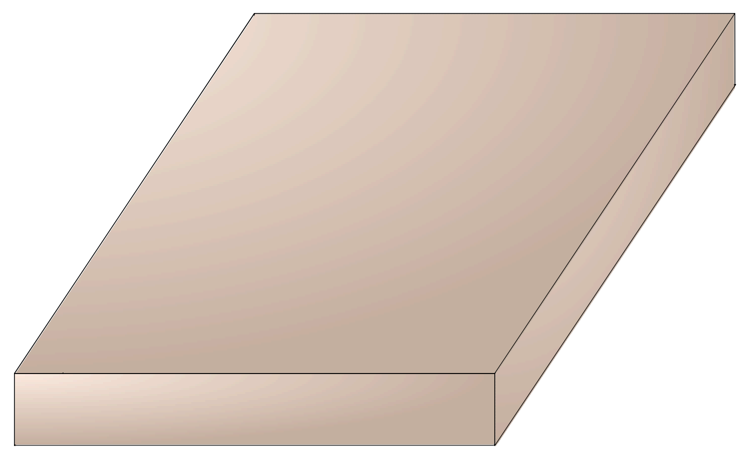
- Proof of Concept Device Demonstrated
  - Non-optimized device design
  - Wafer-bond/thin-back fabrication
  - Moiré optical transduction scheme realized
    - Static calibrations in an air-based flow cell
    - Optical package consisted of microscope


Cavity Mask
Recessed Cavity
Silicon
Oxide
Silicon
SOI Wafer
Pyrex Layer

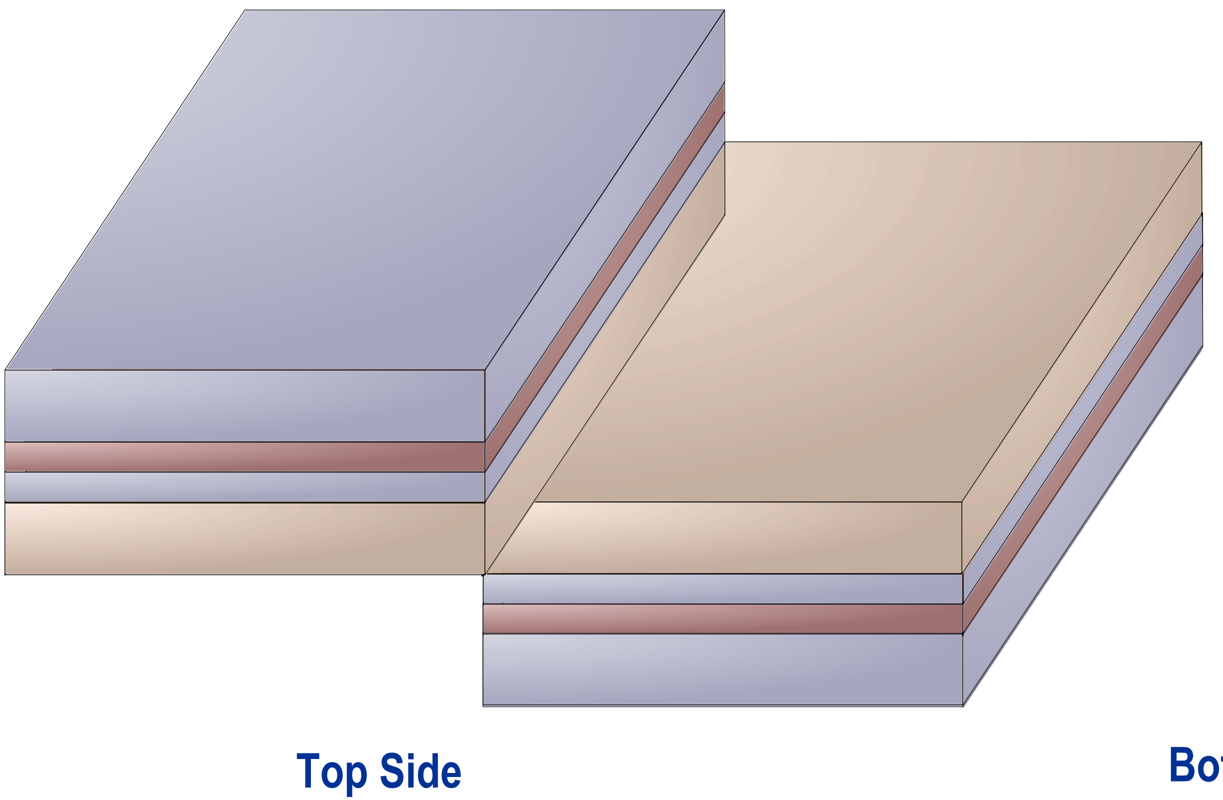

Aluminum Gratings
SOI Wafer
Pyrex Layer

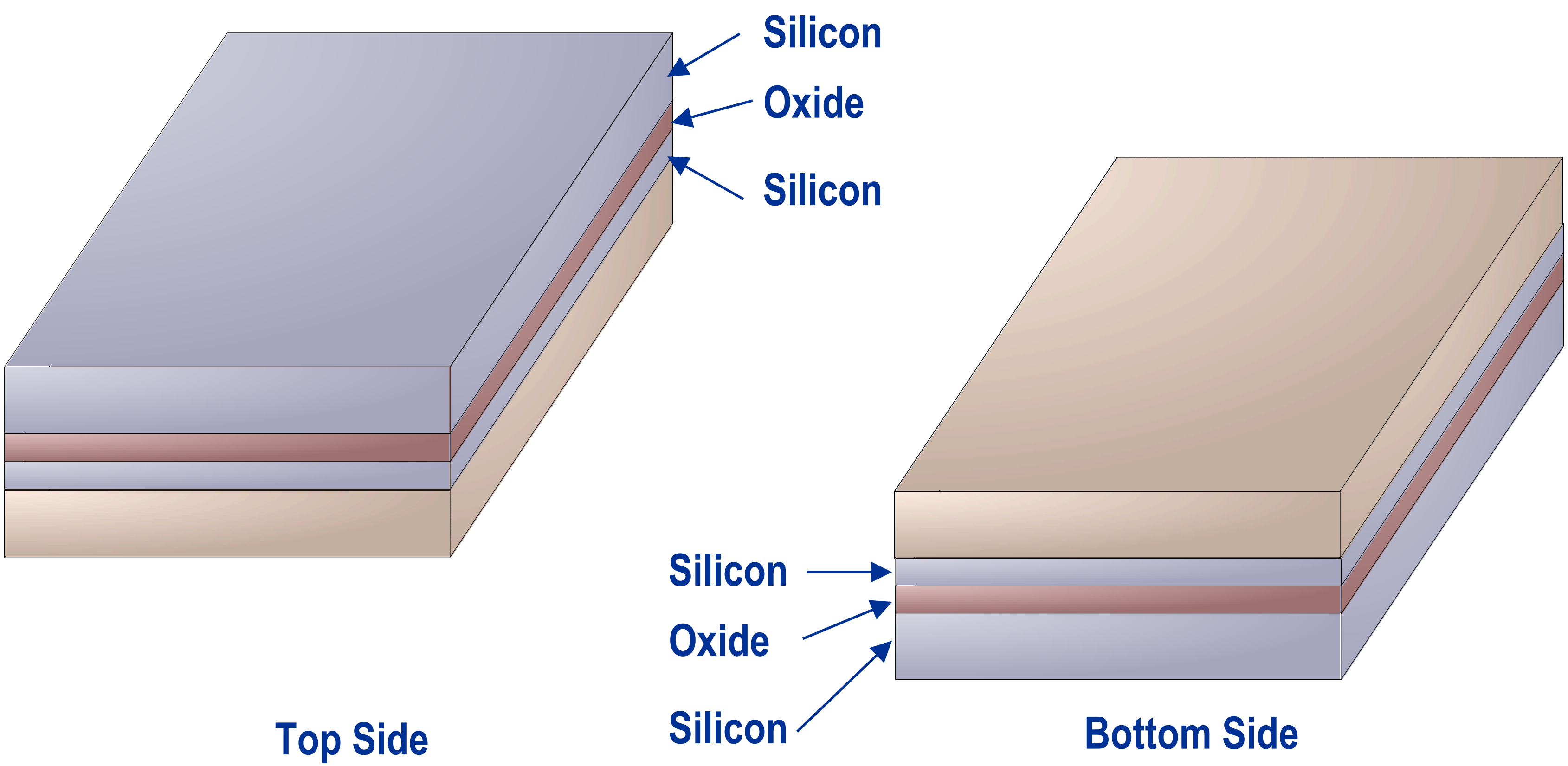


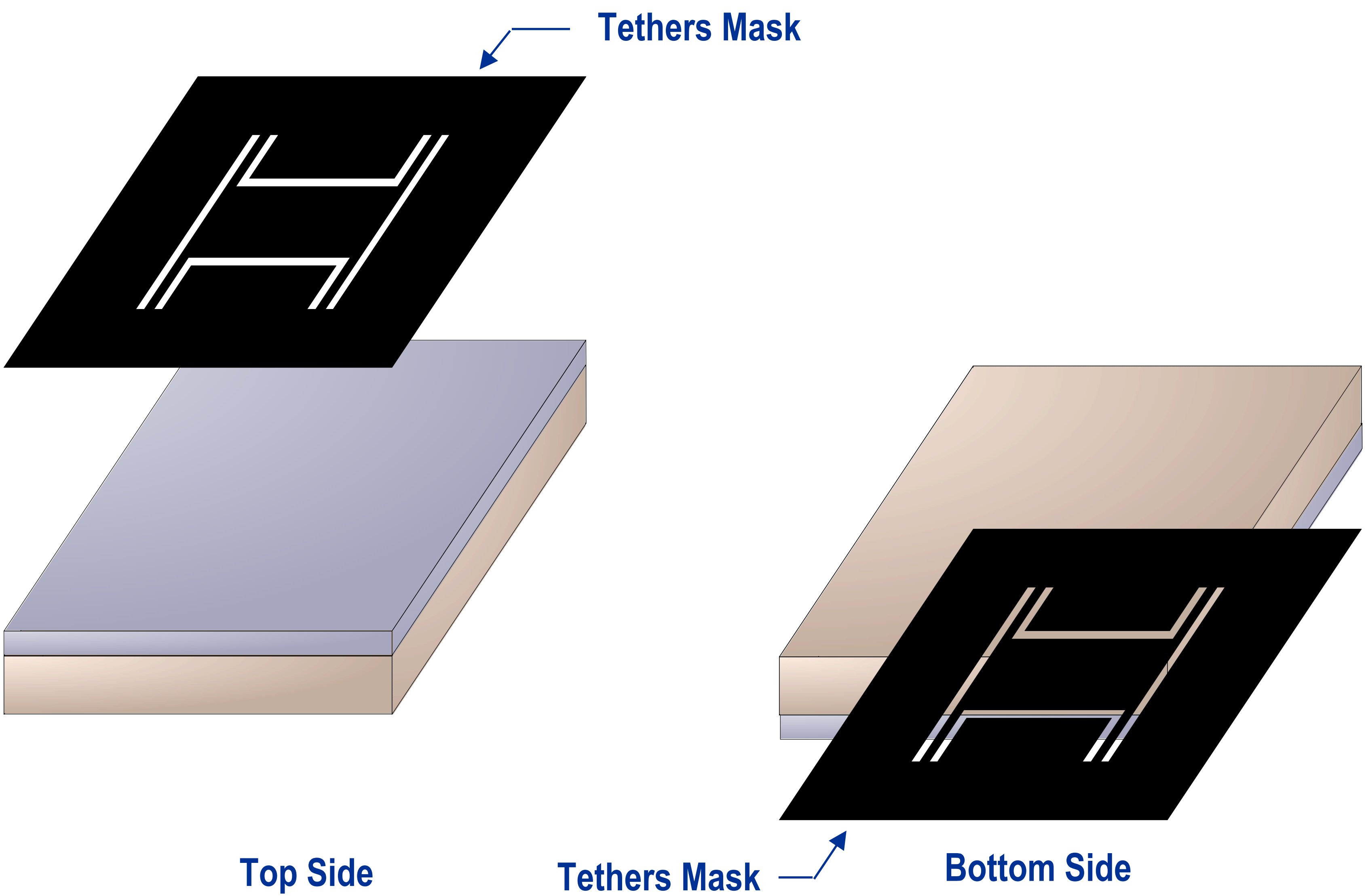
SOI Wafer

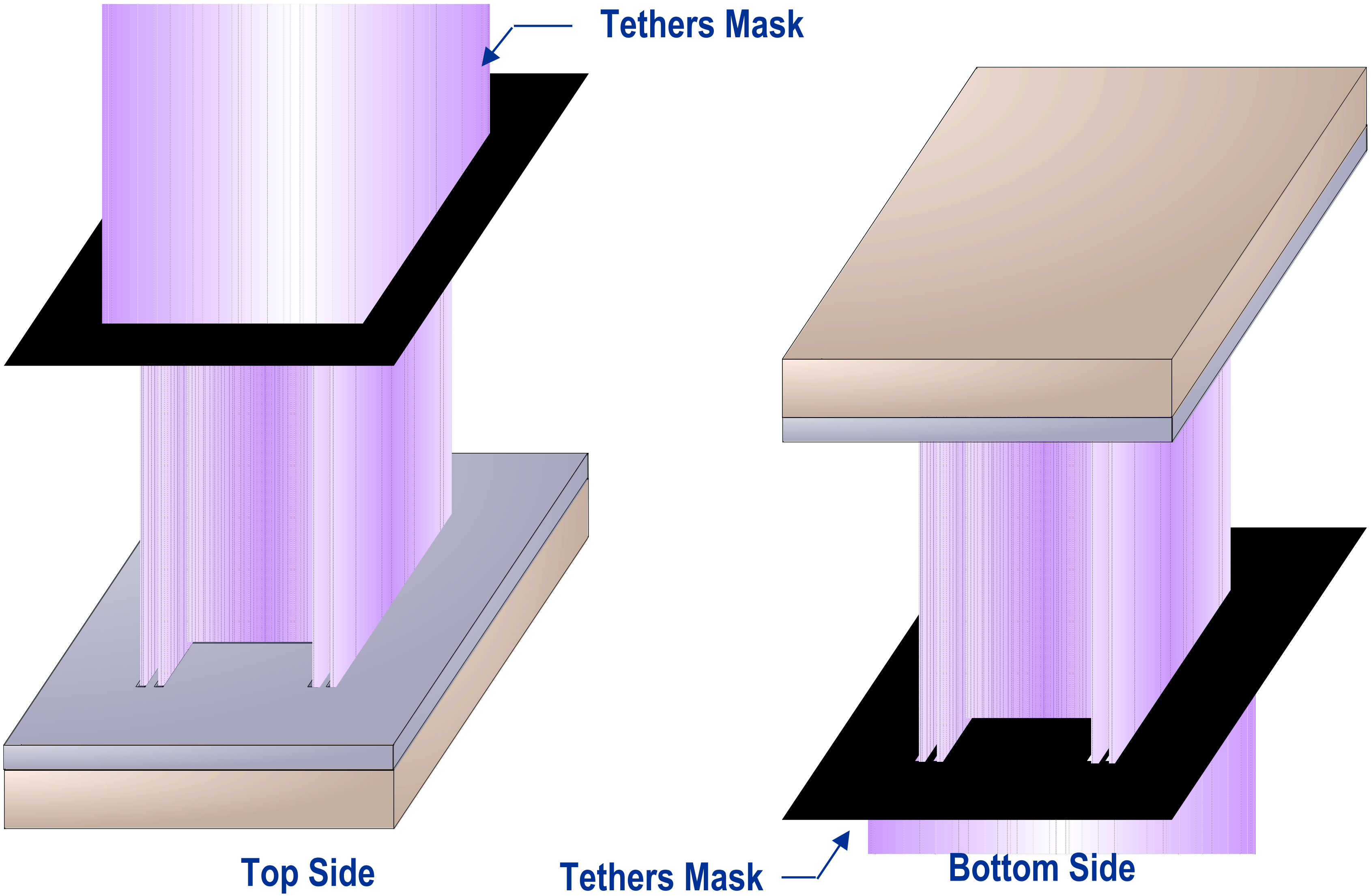


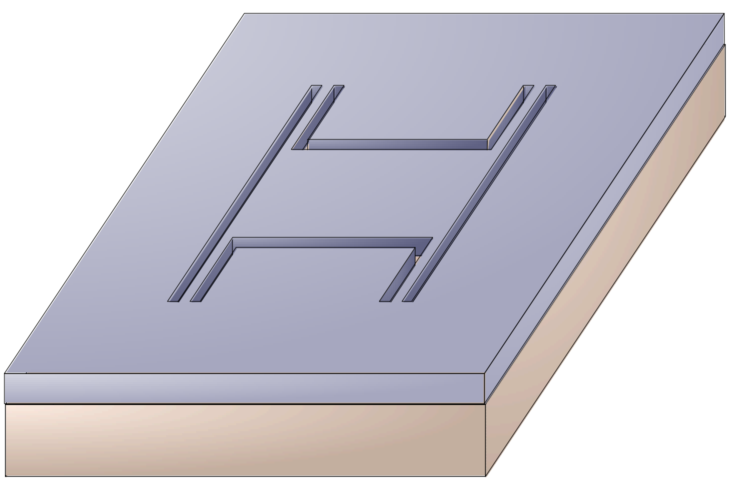
Pyrex Layer


Top Side
Bottom Side

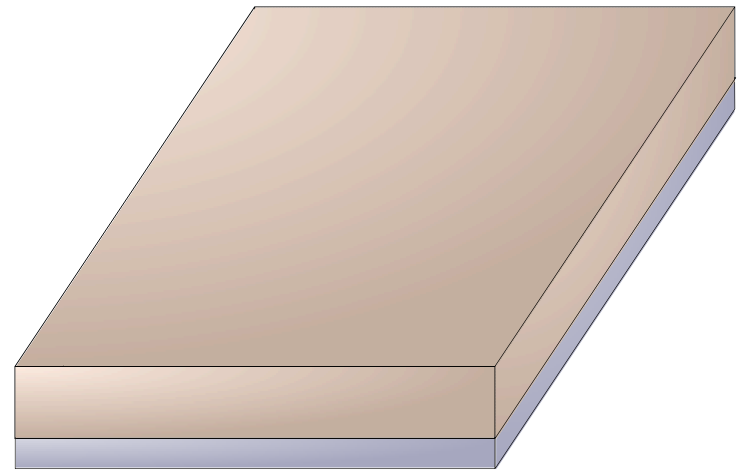

Silicon
Oxide
Silicon
Silicon
Oxide
Silicon
Top Side
Bottom Side


Tethers Mask
Top Side
Tethers Mask
Bottom Side

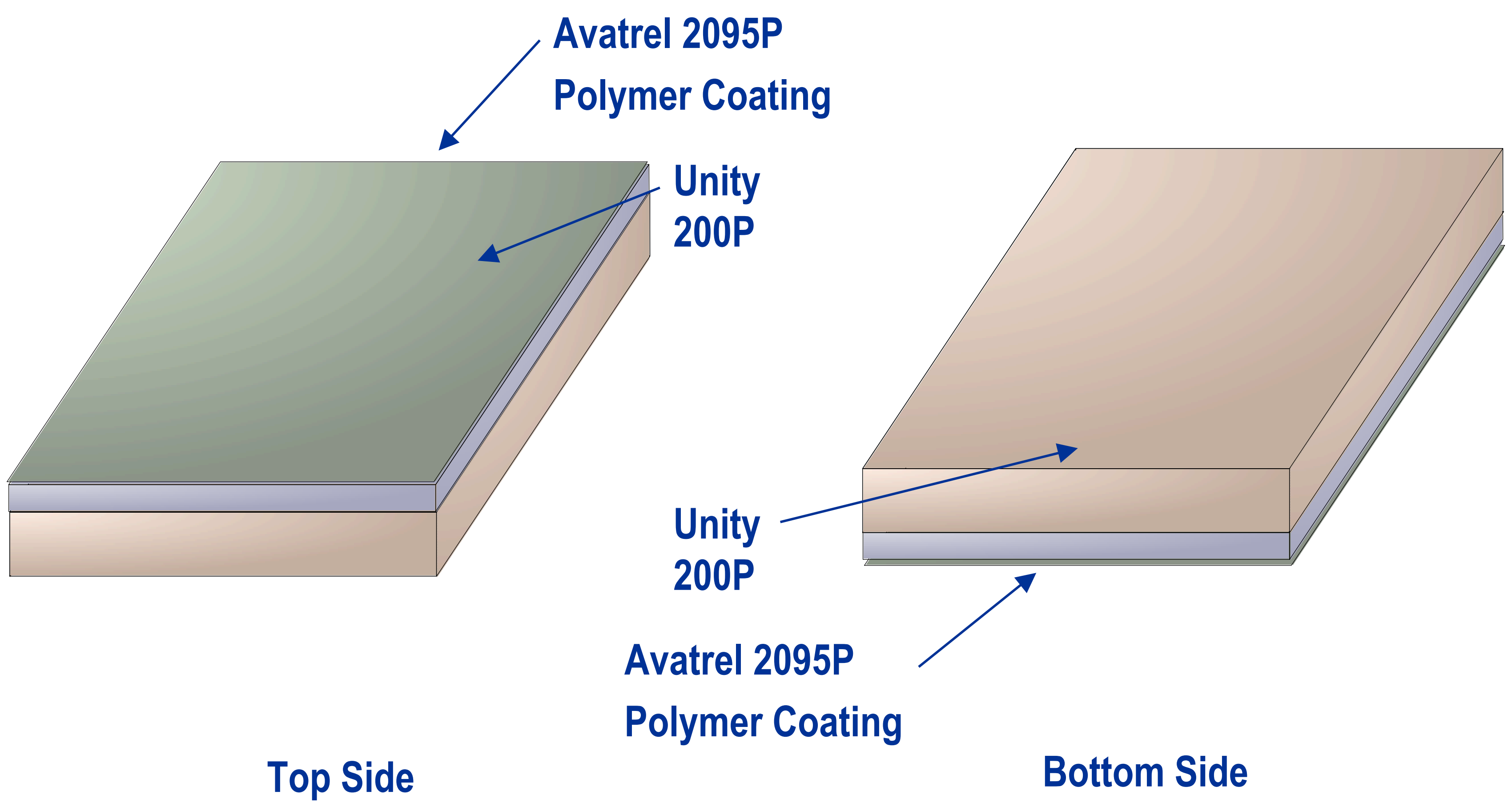

Tethers Mask
Top Side
Tethers Mask
Bottom Side

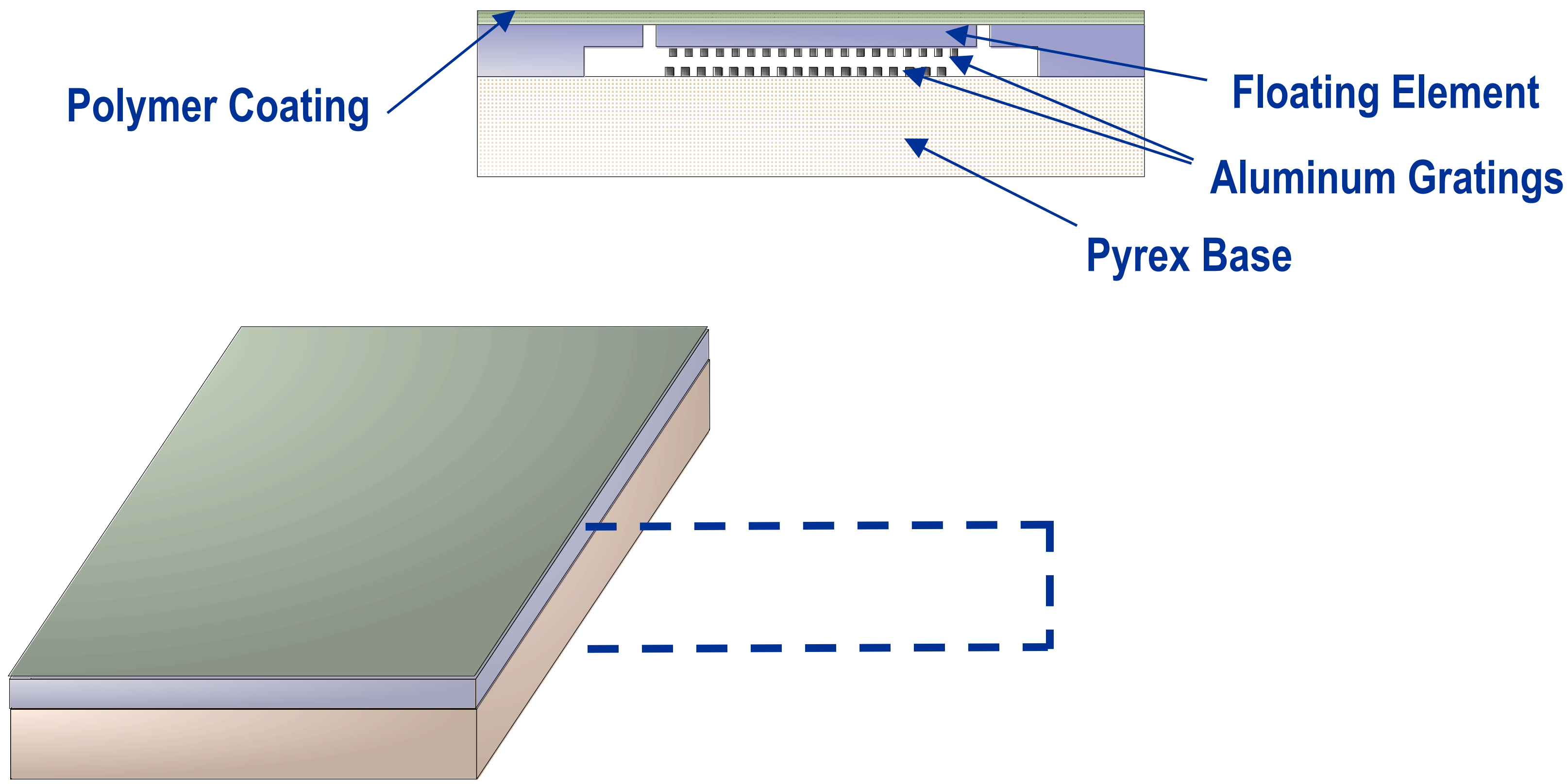


Top Side

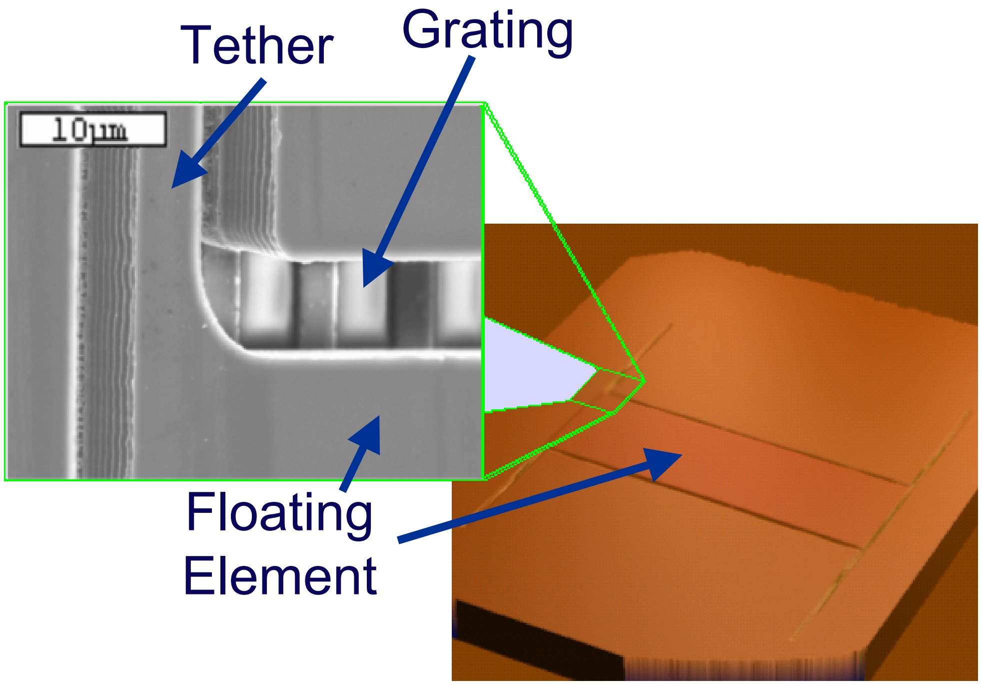


Bottom Side


Avatrel 2095P
Polymer Coating
Unity
200P
Unity
200P
Avatrel 2095P
Polymer Coating
Top Side
Bottom Side

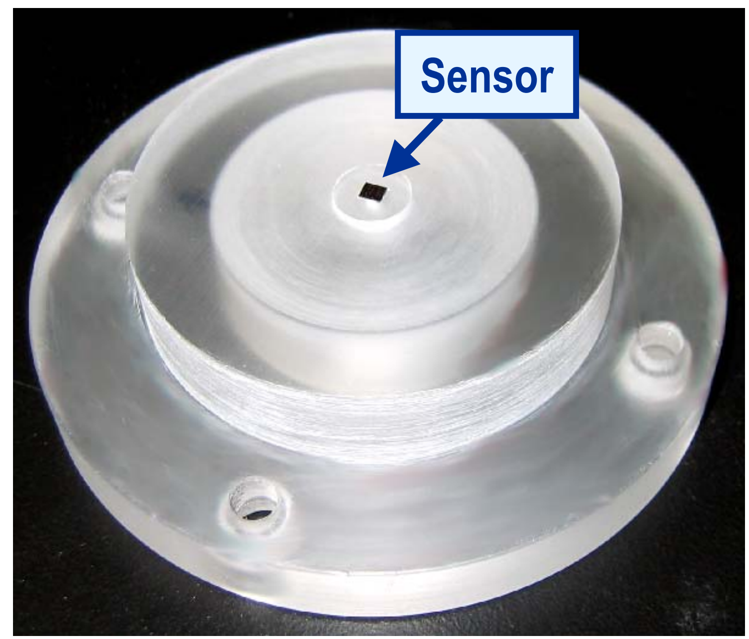

Polymer Coating
Floating Element
Aluminum Gratings
Pyrex Base

SEM and Optical Profilometer Images

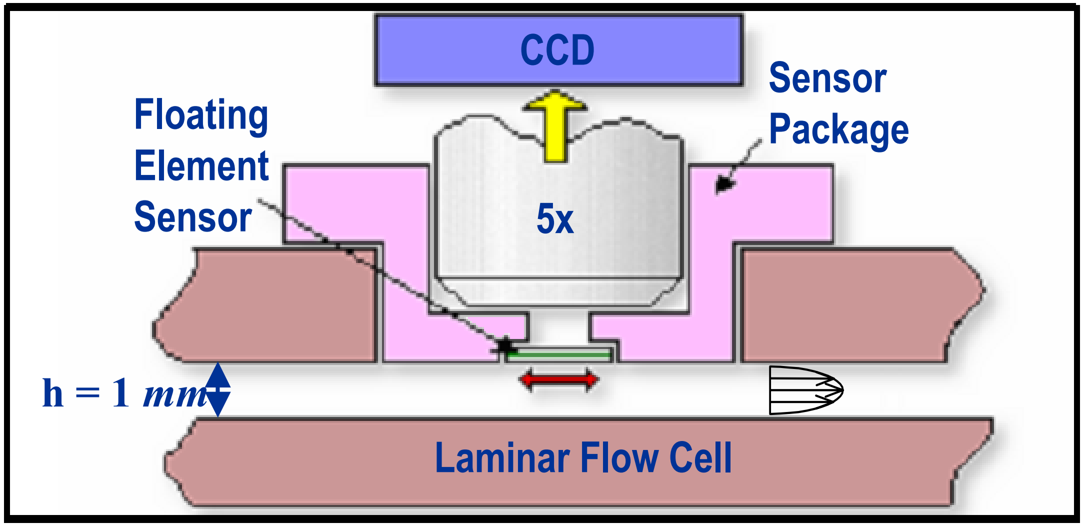


2.7 mm x 3.25 mm
die size

- Lucite Package
  - Fluidic access to floating element
  - Optical access to gratings from backside



Static Calibration Setup



- 2-D laminar flow cell
  - Allows for controlled application of variable mean shear-stress
  - Pressure differential measurement provides calibrated shear-stress values

- Imaging system
  - Optical microscope for image magnification (5x lens)
  - Linescan CCD camera (1024 x 1 pixels, 10 μm pixel size)
    - fringe shift calculated via spatial FFT

Static Calibration Results

- Pixel shift / sensor displacement
  - Extracted from phase of Moiré pattern
  - Sensitivity
    - Pixel

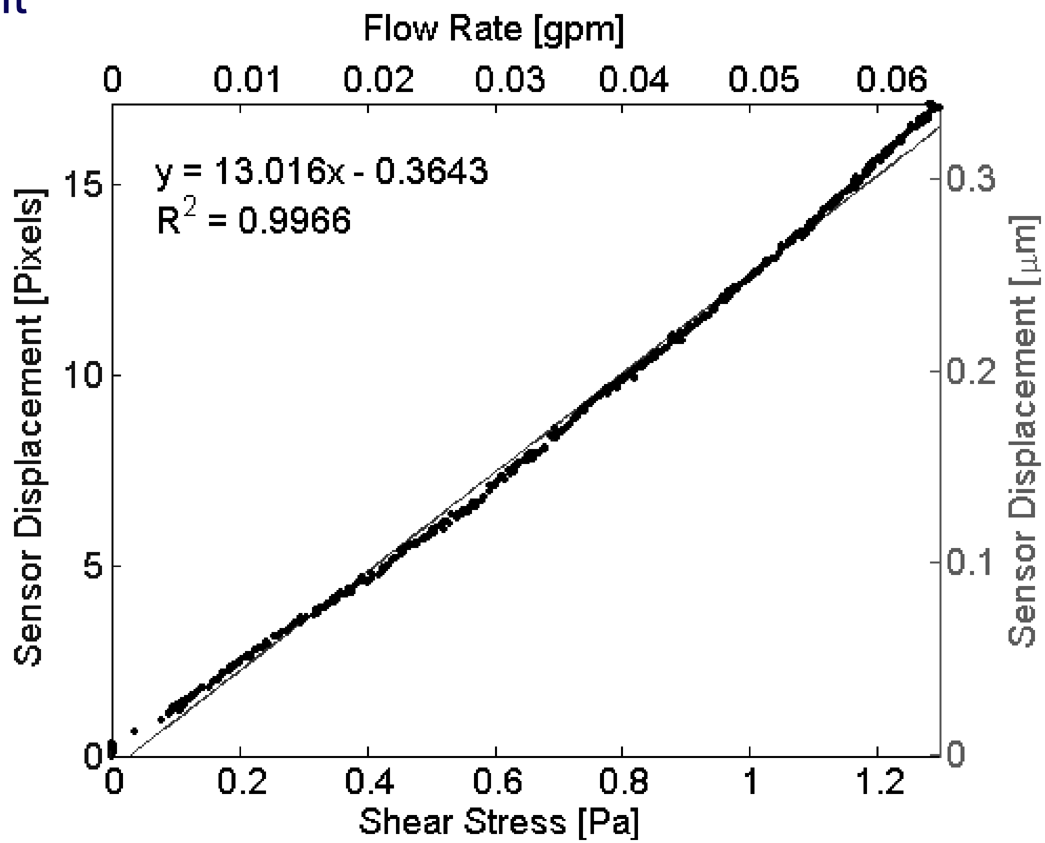
      $13 \ \ Pixels / Pa$

      $260 \ pixels / gpm$
    - Mechanical

      $260 \ \ nm / Pa$

      $0.52 \ \mu m \ \ / gpm$

Note: GPM for 1/8" pipe

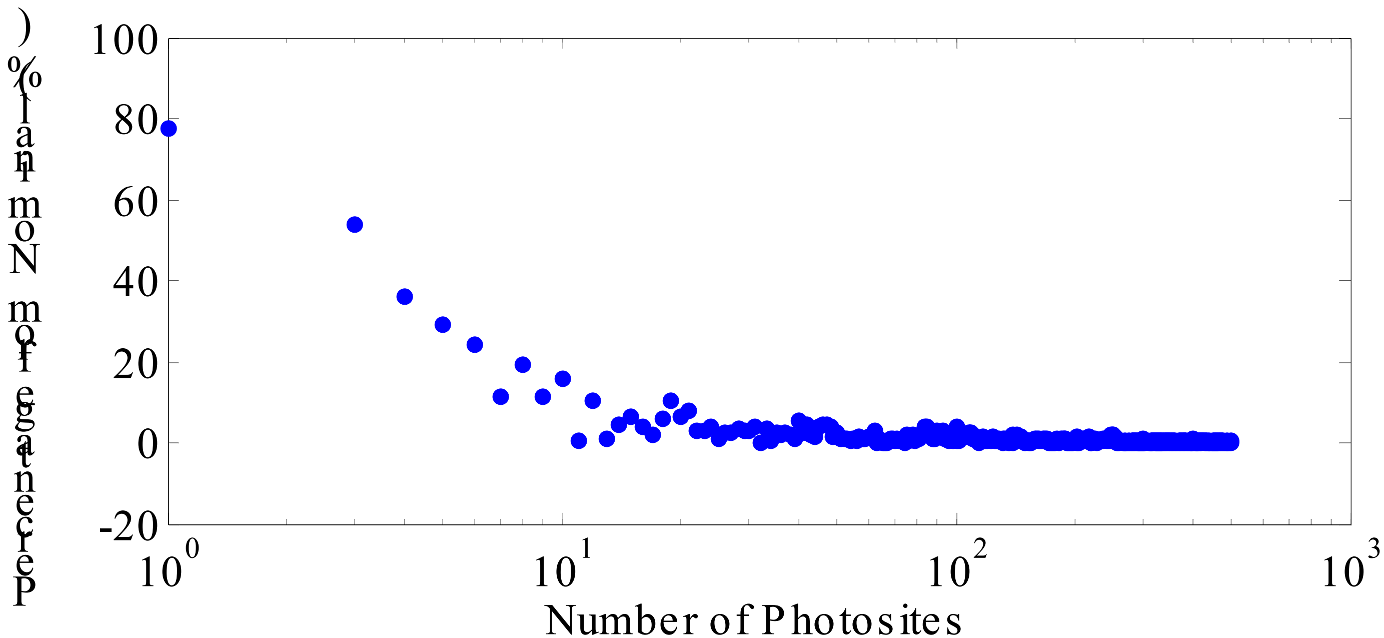


Future Plans

- Complete Optimal Sensor Design
  - Nonlinear mechanical model completed
    - Verified via FEM
  - LEM used to predict dynamic response
  - Design optimization procedure developed
- Complete fabrication process synthesized
  - Address key issues regarding sensor limitations
    - Cover element to protect from debris/environment
- Improve Optical Transduction/Package

Optical Package Improvement

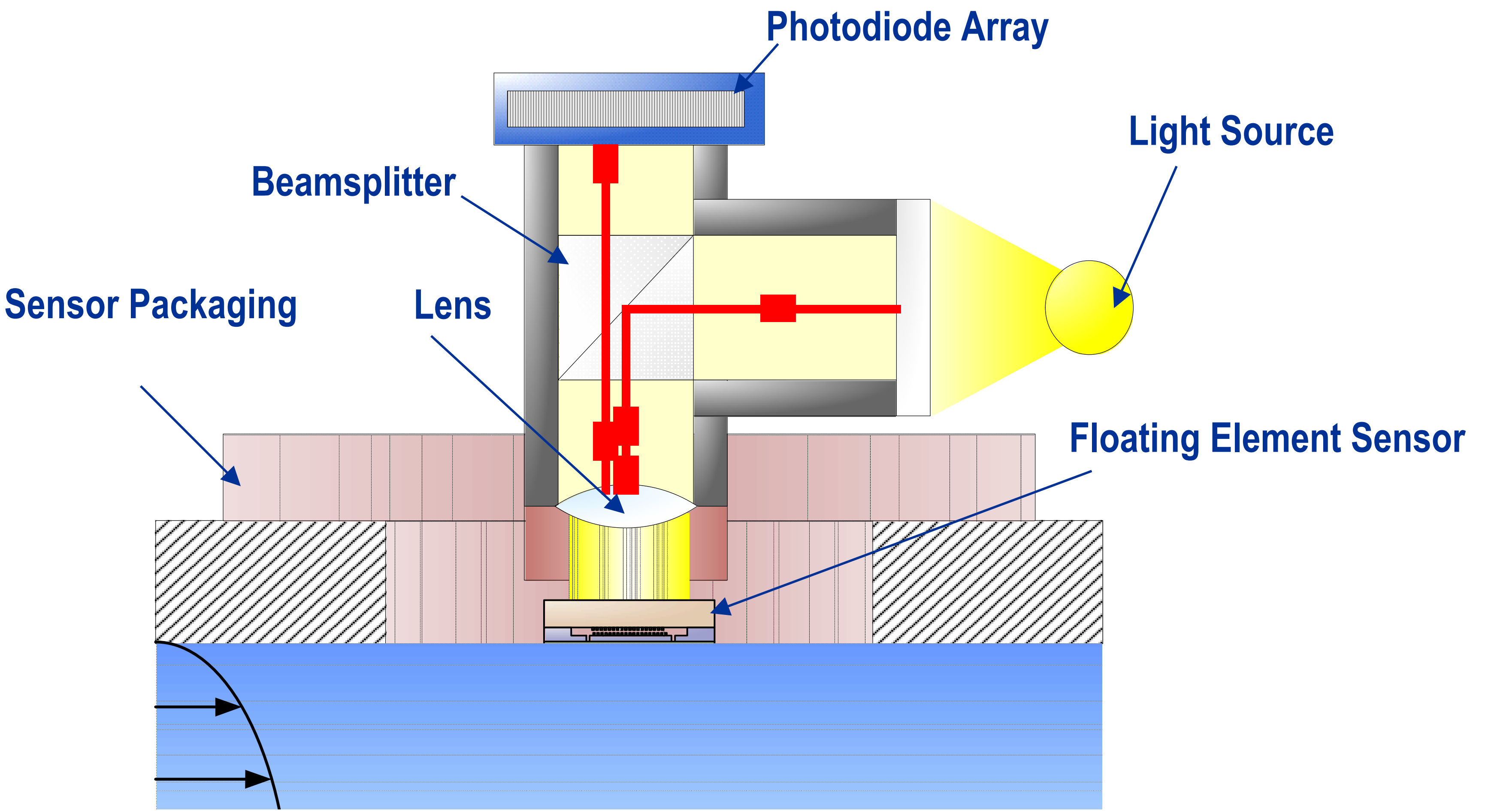
- Old Optics (CCD Array of 1x1024 pixels)
  - Issues- Redundant data
    - Too many channels limit bandwidth
    - 3 dB deviation from nominal value is at 5 pixels



Optics Evaluation

- New Optics
  - Position Sensitive Detectors
    - Simple implementation – single chip, analog voltage output
    - Compressed data – measures position of centroid only
    - Unusable for Moiré – centroid does not shift linearly with Moiré pattern
  - Photodiode Array
    - Moderate implementation – single chip, multiple line output
    - Variable data size - 4, 16, 64, 256 pixel arrays available
    - Ample bandwidth – ~62.5 kHz data acquisition
    - Size constraint – requires compact array or magnifying optics

New Optical Package Concept



Acknowledgements

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