We Make Your MEMS Work

IMT Open MEM Foundry Services & Experience of Micro-fluid MEMS

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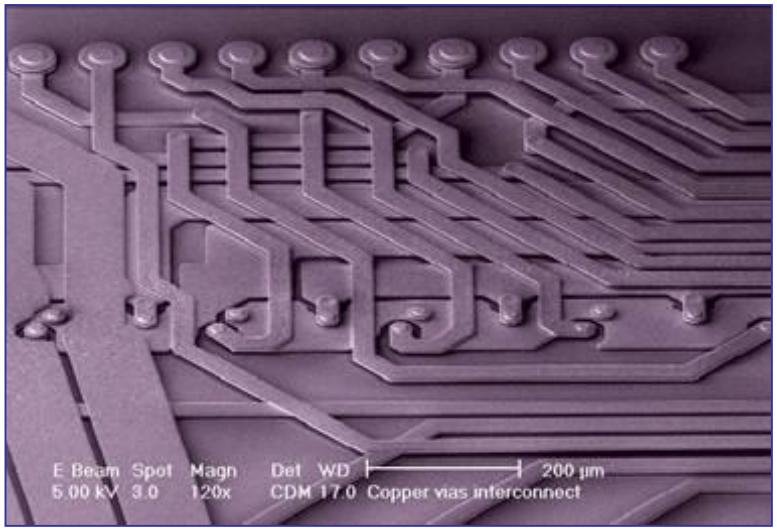
Company Introduction

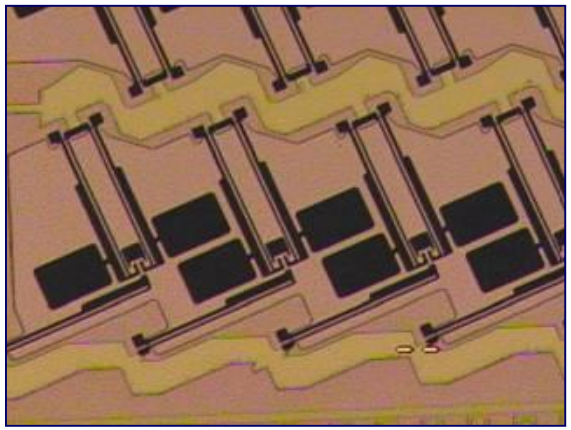
- Largest pure-play MEMS foundry in US
- Founded in 2000
- MEMS Services:
  - Process Development
  - Volume manufacturing
- > 350 MEMS processes developed
- 13,000 m², Manufacturing Facility, Santa Barbara, CA
  - 3,000 m², class 100 clean room
  - 6" wafers prodution line
- 8" Fab in development
- Broad MEMS intellectual property portfolio:
  - patents, trade secrets and know-how
- Staff of ~110, ~15% PhD's

IMT Foundry Services

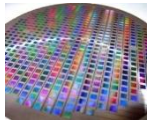
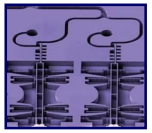
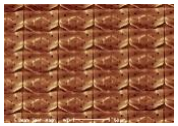
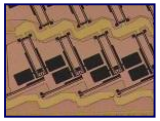
Turn-key MEMS Design and Manufacturing Services

- Photolithography
- Deposition
- Wet chemical etch/electroplating
- Reactive Ion Etching
- Ion milling
- CMP planarization and wafer grinding/polishing
- Wafer bonding
- Cleaning
- Die slice
- Assembly/packaging
- Testing
- Metrology/analysis
- Design/Modeling



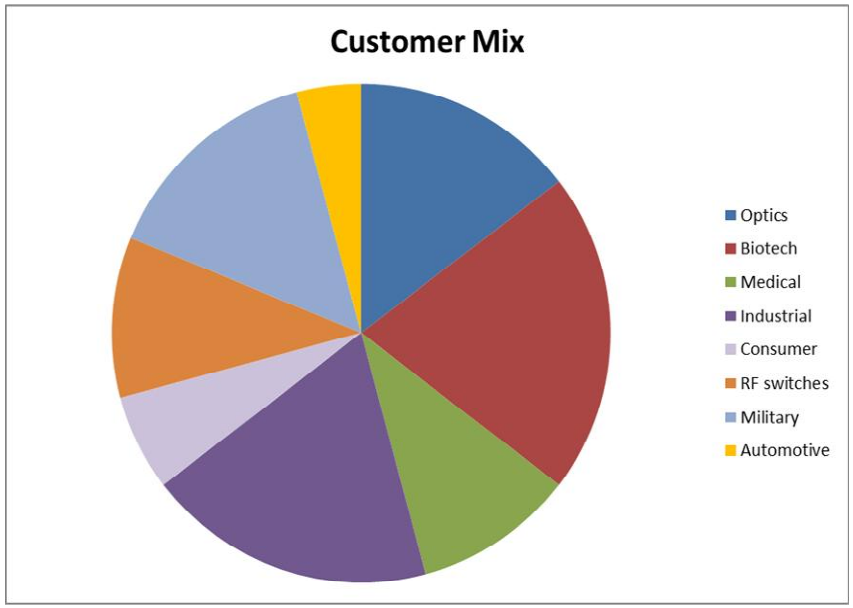


IMT Focus Technologies

Technology		Growth Driver
Optical Comm	 Sub-Wavelength Anti-Reflective Structures (SWARS)™	Data centers, 4G cellular, FTTH, & visual media
Magnetics	 Electromagnetic Actuators	Pervasive in Automotive, Handsets, & Biotech fluidics
InfraRed	 Focal Plane Array (Wavelength Shifter)	Security: smaller size & weight, lower cost Automotive & Handsets: night-vision cameras
Switches	 Latching Switches	Small size, lower cost & power Replace Reed Relays and GaAs
Microfluidics	 3D Microfluidics	Better medical diagnostics & care

3D Packaging (WLP and TSVs)

Diverse Customer Base



Business Segment	Description
Automotive	Accelerometers, pressure sensor, IR sensor
Biotech	Cell filter, microfluidics, DNA detection, gene testing, protein detection, mass sensor, immunohematology, liquid chromatograph, gene sequencing
Consumer	DLP projector, motion sensor, battery
Industrial	Accelerometers, seismic sensors, particle metrology/detection, gas sensors, magnetic sensors, EUV lithography, probe cards, inverters
Medical	Cell sorter, cardiac implant sensor, diagnostics, ear infection diagnosis, IV drug safety
Military	Wafer-level packaging, microfluidics, IR imager, navigation grade gyro, TSV interposers
Optics	Non-blocking optical switch, router and switch transceiver module, active optical cables, LED mirrors, embedded computer networking
RF switching	RF switches, phase array antenna, capacitors

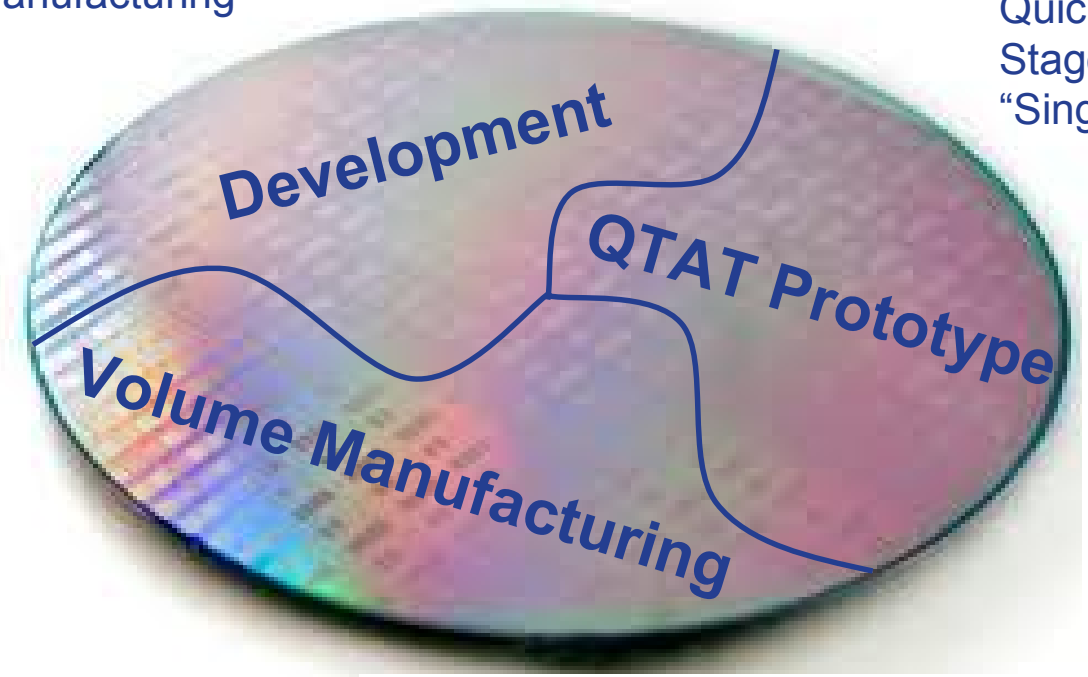
Rapid MEMS Development and Manufacturing

Technology Development

MEMS Process Customization
Design Implementation
Design for Manufacturing

Prototype and Proof of Concept

Quick Wafer Cycle Time
Staged Wafers
"Single Roof" Co-Location
with engineering

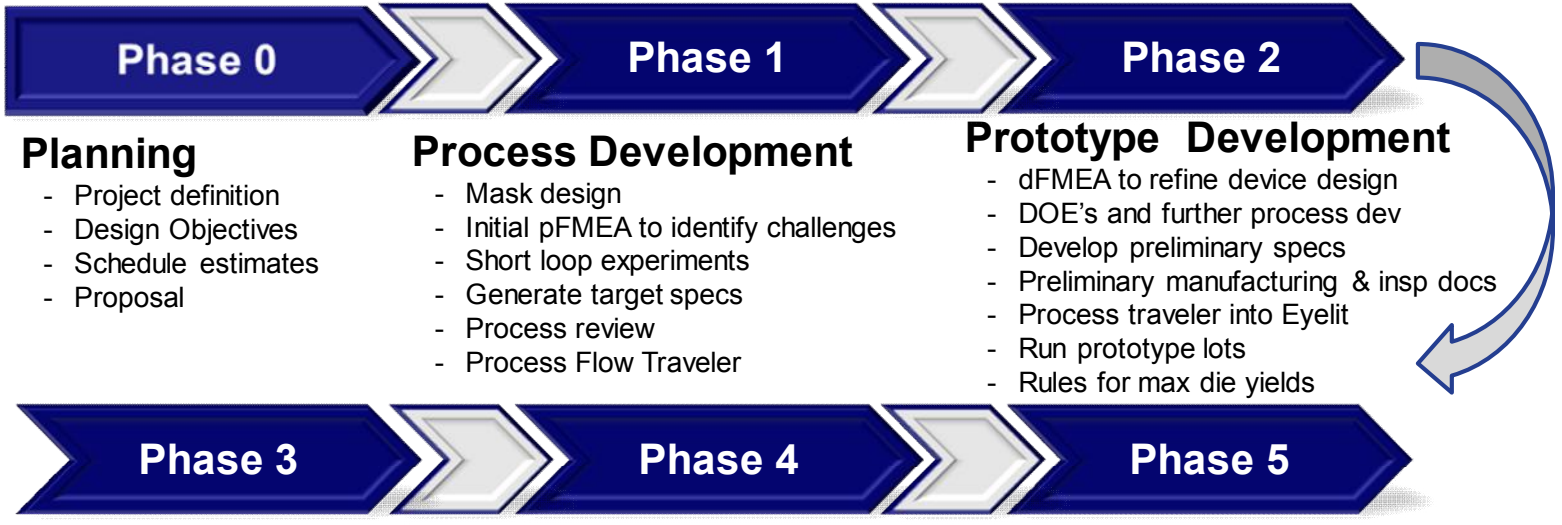


High Volume Manufacturing

Smooth Transition from Development to Production
Scalable Manufacturing Capacity and Small Lot Flexibility
Manufacturing Control Systems

Fast Time-to-Market & Fast Time-to-Volume

Design for Manufacturability: Phase-Gate Development

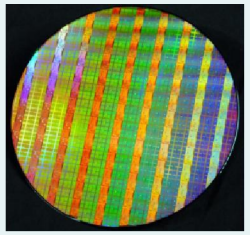
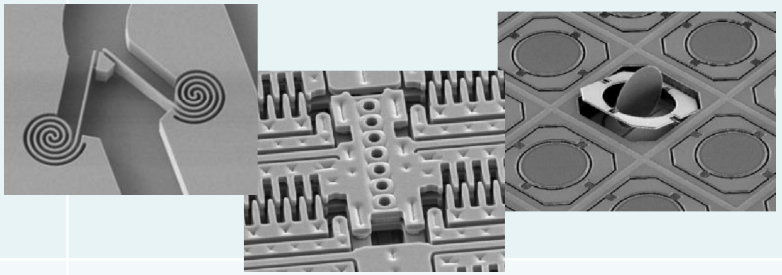
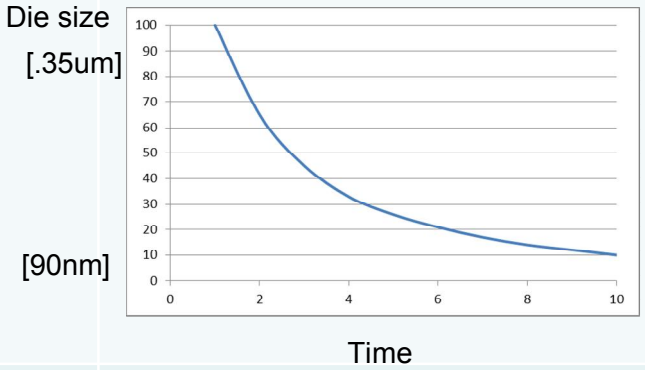


Volume Production Systems

– basic: ISO 9000, SPC

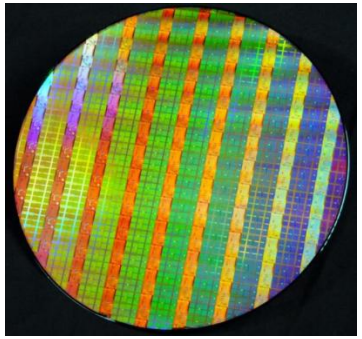
– advanced: ISO 16949 for Automotive & Handsets, ISO 13485 for Medical

Parallel Paths for CMOS and MEMS

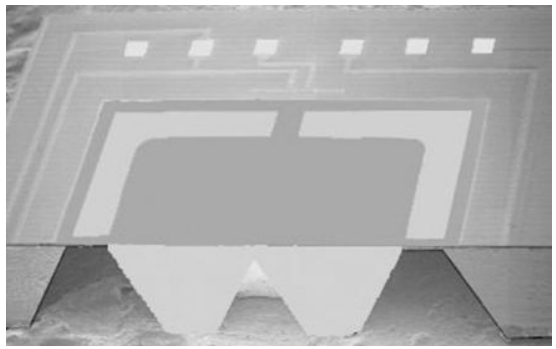
	CMOS	MEMS
Basic Structure	Transistor 	Valves, actuators, springs, mirrors, diaphragms, etc. 
Trend	Smaller transistors 	New chemistries & materials New structures
Key Capabilities	Photolithography, Ion Implantation	DRIE, lift-off processes, plating, wafer bonding

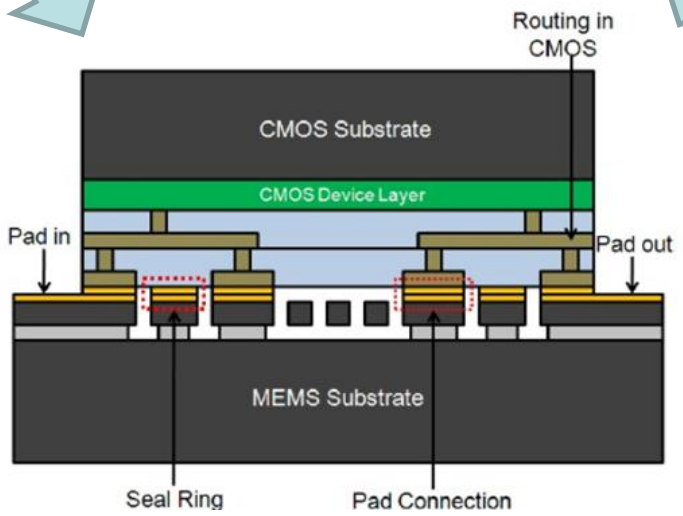
CMOS & MEMS Integration – 1

CMOS



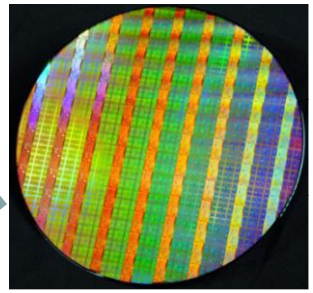
MEMS



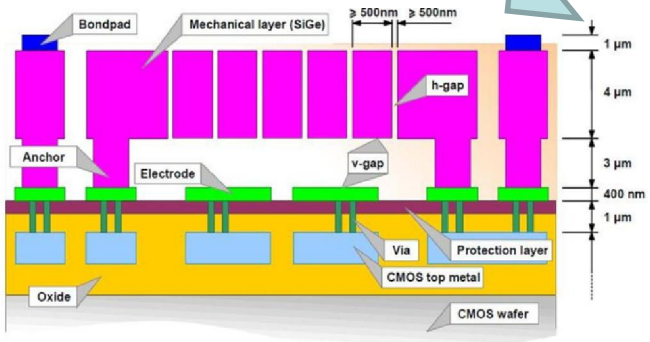


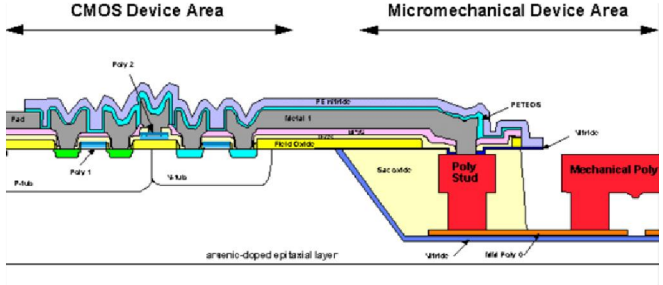
CMOS & MEMS Integration - 2

CMOS

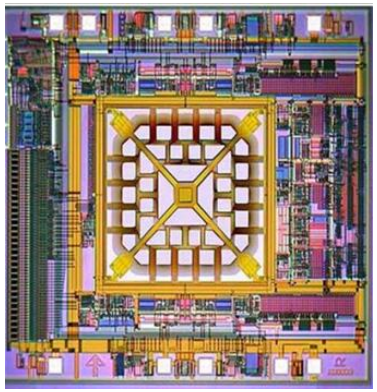


MEMS device is built on CMOS wafers





MEMS on Top



MEMS on the same plane

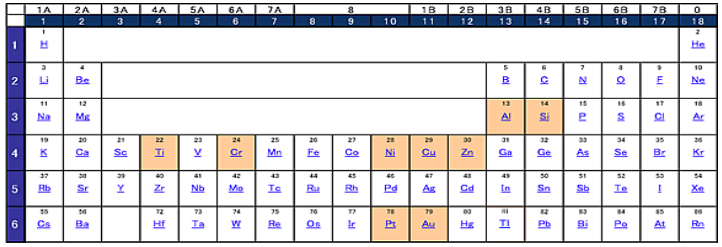
Talent Composition

- CMOS foundries:
  - Electrical Engineering
  - Device Physics
- MEMS foundries
  - Chemistry
  - Mechanical Engineering
  - Material Science
  - Metallurgy
  - Electrical Engineering
  - Physics
  - Optics
  - Magnetics
  - Biology

Broad Offering of Elements, Alloys and Gasses for MEMS Function & Performance

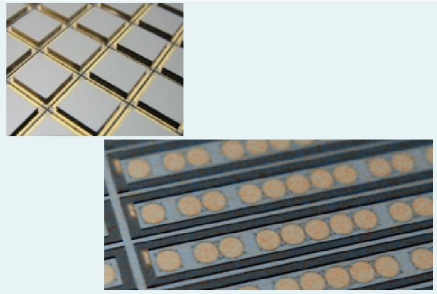
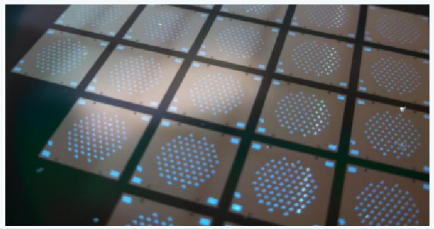
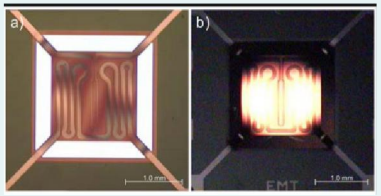
hydrogen 1 H 1.0079																	helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122											boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305											aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]

Competing Foundry Material Support

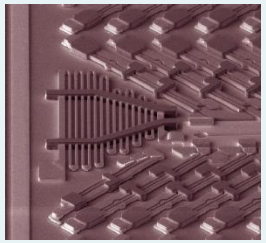
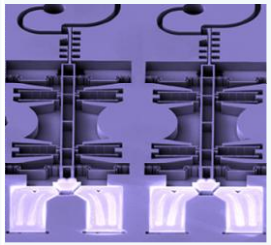
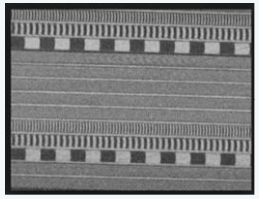


Source: Competitor Website

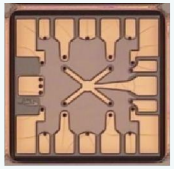
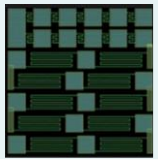
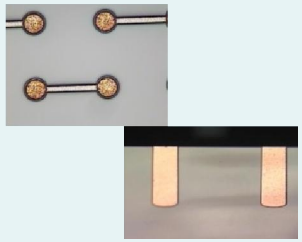
Noble Metals

Materials		Applications	Function	Benefits
Gold		RF Switches Optical Comm Devices	Bondline for wafer level packaging Mirrors Circuit traces	Corrosion resistant High IR reflectivity Electrical & thermal conductivity
Silver		LED lighting reflectors	Mirrors Heat dissipation	Highest reflectivity in visual spectrum Highest electrical & thermal conductivity
Platinum		Sensors BioMEMS	Heaters Electrodes Diffusion Barrier	Corrosion resistant Very good barrier Indestructible
Rhodium		RF Switches Test Probe Tips	Contact surfaces	Wear resistant

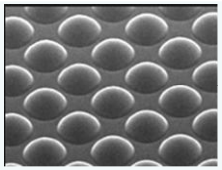
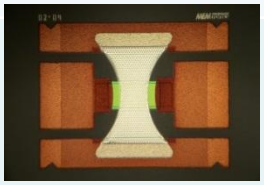
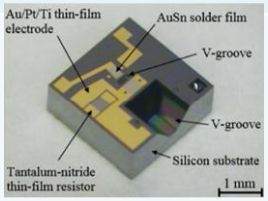
Magnetic Materials

Materials		Applications	Function	Benefits
Nickel		Thermistor Devices Switches	Barrier Layer for Wirebond Pads Thermal Actuators Electrodes	Corrosion resistant Can be electroplated
Nickel-Iron		Microfluidics pumps & valves Magnetic sensors	Magnetic Flux Guides Magnetic Actuators	Simple processing High permeability Zero magnetostriction Can be electroplated
NiCr		Sensors BioMEMS	Heaters Electrodes	High Resistivity Oxidation resistant
CoPtCr		Gene Sequencing Mag Read Sensors	Permanent Magnets	Very high coercivity

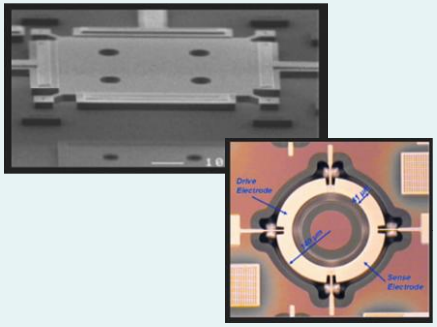
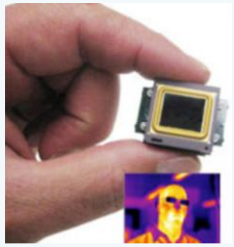
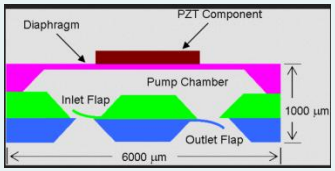
Other Metals

Materials		Applications	Function	Benefits
Molybdenum		Accelerometers Gyroscopes	High Temperature Diffusion Barrier Layer for Electrodes And Circuits	High temperature operation Sacrificial layer (easily etched)
Ruthenium		RF switches	RF And DC Switch Contacts	Long Life
Tantalum		Sensors	Resistors	Can be reactively sputtered
Ni Alloys		Sensors BioMEMS Springs	Heaters Electrodes	Corrosion resistant Very good barrier Indestructible
Copper		RF Switches Si interposer	TSVs Interconnects	Low resistance Can be electroplated and CMP'ed

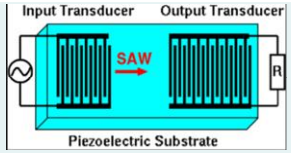
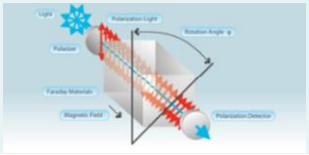
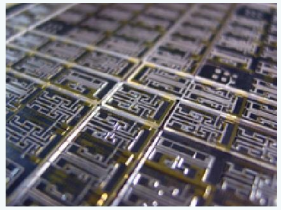
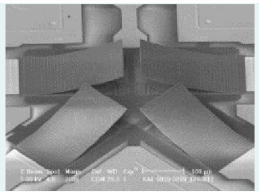
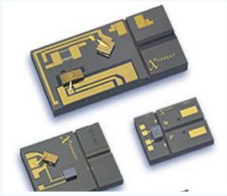
Sputtered Dielectrics

Materials		Applications	Function	Benefits
Alumina Al_2O_3		Magnetic sensor LED lighting	Optical Coating Hard Masking Passivation	Broad optical spectrum
Titania TiO_2		Microlens Mirrors	Optical coating	Catalytic
Tantalum Oxide		RF switches	Resistor	Can be reactively sputtered
Tantalum Nitride		RF switches	Resistor Diffusion barrier	Can be reactively sputtered
Diamond-like Carbon		AFM probes	Hard Coating For MEMS Wearing Structures	Low temperature deposition

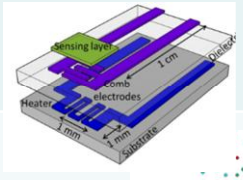
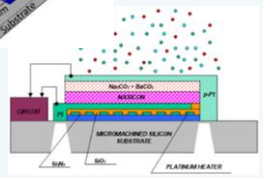
Piezoelectrics

Materials		Applications	Function	Benefits
Aluminum Nitride AlN		RF Filters Strain gauges Chemical sensors Energy harvesting	FBAR Resonators Mechanical Actuators	Good alternative to PZT Very high thermal conductivity
Zinc Oxide ZnO		IR microbolometer	Optical coating	High Resistivity Change As A Function Of Temperature
Lead Zircronium Titanate PZT		Inkjet print heads	MEMS Micro-Actuators Nozzles	Very High Force Generation

Substrates

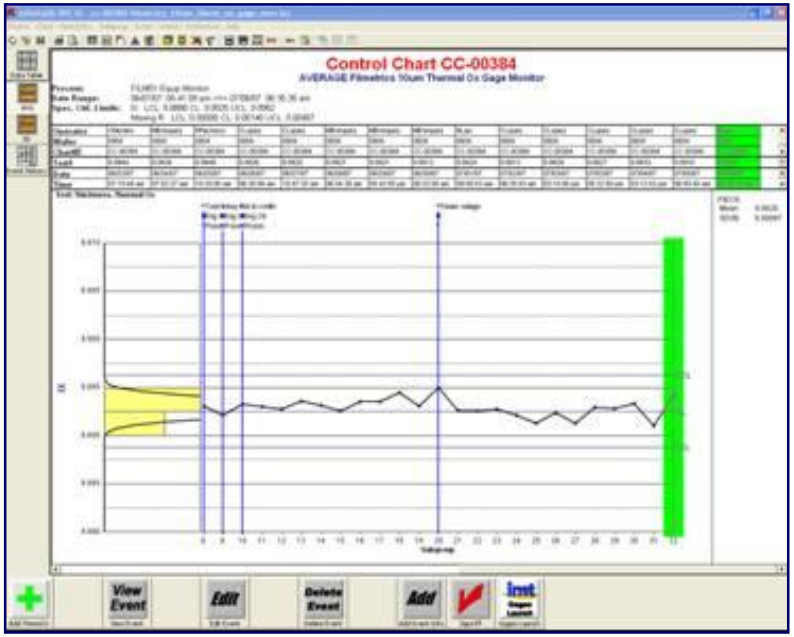
Materials		Applications	Function	Benefits
Quartz	 	RF filter Optical re-polarizer	Surface Acoustic Wave Resonators Optical Half Wave Plates	Can be processed like glass
BoroFloat Glass		Microfluidics devices Optical communications devices	Transparent lid for wafer-level packaging	CTE matched to Silicon
Float Zone Si		RF Switches	Base substrate wafer	High resistivity Very low loss in RF application
MCZ Si		FTTx	Base substrate wafer	Similar Characteristics as Float Zone

Gas Sensors & Chemical Sensors

Materials		Applications	Function	Benefits
Pyrolytic Carbon		Chemically inert sensor electrodes	Sensing electrode	Simple Process Photo-Definable
Metal Oxide TiO2 ZnO SnO		Chemical Sensors	Sensing electrode	Simple Process

Statistical Quality and Process Control

- ISO 9001: 2000 certified
- Comprehensive process control plans
  - Electronic control charts with automated notification of out of control conditions
- Industry-best SQC methodology:
  - Each process characterized for variability and statistical sampling applied
  - Critical processes optimized using design of experiments (DOE)
  - Processes controlled using statistical process control (SPC) and reaction plans
  - Each gage assessed for capability (measurement error) and controlled using SPC and reaction plans
- Rigorous operator qualification



Manufacturing Quality Systems

- Eyelit paperless Manufacturing Execution System (MES)
- Infinity relational database software, electronically linked to Eyelit
  - Data input auto-loaded directly into > 300 control charts (product, process, equipment, gages)
    - Tracks all lots and wafers through the process real time
    - Tracks and controls all reworks
    - Tracks equipment status and provides reports
    - Schedules all daily equipment start up testing
    - Schedules all equipment preventative maintenance
    - Tracks daily and weekly wafer moves by device type
    - Tracks cycle time by device type
    - Tracks wafer yield by device type
    - Collects wafer data and transmits to control chart system
    - Provides detailed process instructions to wafer operators
    - Ensure operators are tracking wafers into qualified equipment
    - Prevents operators that are unqualified from performing certain operations
    - Places future holds on wafers and lots as required

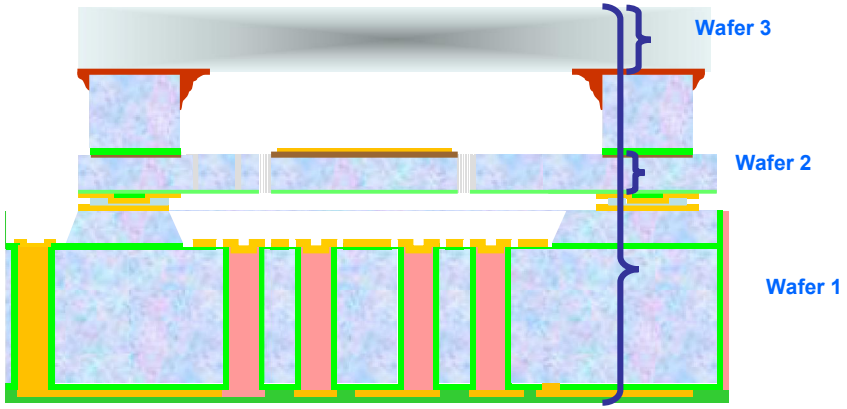
Manufacturing Quality Systems

- Full documentation of process and procedures includes:
  - Customer and process specs (visual & parametric)
  - Product acceptance criteria
  - Incoming material acceptance
  - Equipment and manufacturing procedures
  - Document and Change control
  - Training and operator/tech certification procedures
- Transfer from paper travelers to Eyelit/Infinity system
- Implementation of process/product audits, validations, process reviews
- Establishment of weekly program-specific operations meetings
- Implementation of SPC
  - Control charts, reaction plans, process capability, gage capability

3D Integration

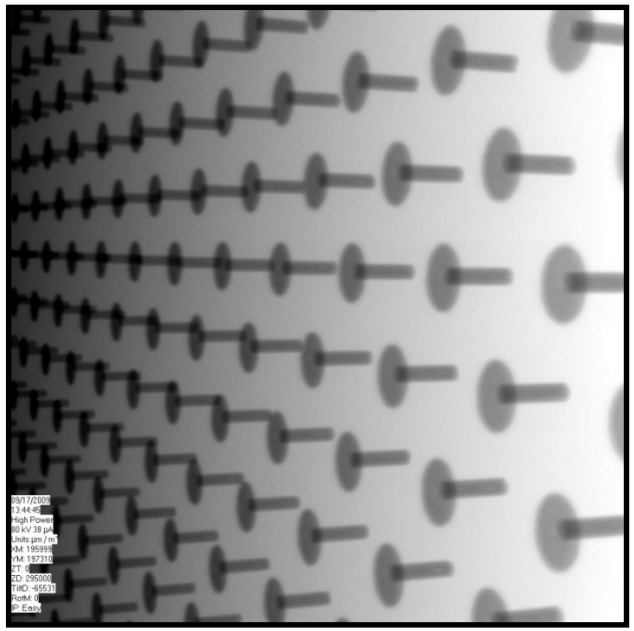
IMT's Portfolio of WLP Bonding Techniques

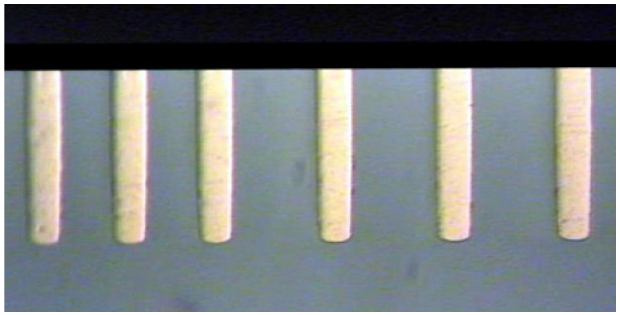
Bonding Technologies	Useful for CMOS+MEMS Bonding	Bonding Temperature	Bond Line Width Requirement	Cost	Benefit
Hermetic					
Fusion	No	1050 °C	10 microns	Low	Manufacture SOI starting materials
Anodic	No	400 °C	50 microns	Low	Only direct Si-glass bonding
Glass Frit	Yes	400 -450°C	400 microns	Low	High strength
Au-Au Thermocompression	Yes	250-350 °C	10 microns	Low	Narrow bondline
Metal Alloy	Yes	< 200 °C	50 microns	Med	Narrow bondline
Non-Hermetic					
Polymer	Yes	< 200 °C	10 microns	Lowest	Lowest cost

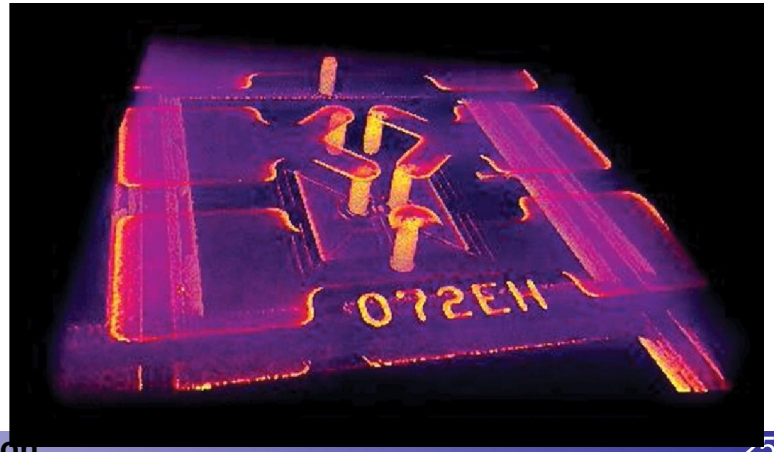


IMT Through-Silicon Vias (TSV)

- **TSV's can be used to provide electrical connectivity from outside to inside of chip**
  - Low-resistance copper vias
  - Polysilicon vias
- **99.96% yield**
- **Copper vias offer extreme performance**
  - DC resistance: < 0.01 ohms per via
  - IL: -0.01dB @ 6Ghz
  - 15μm diameter x 60μm depth via in production





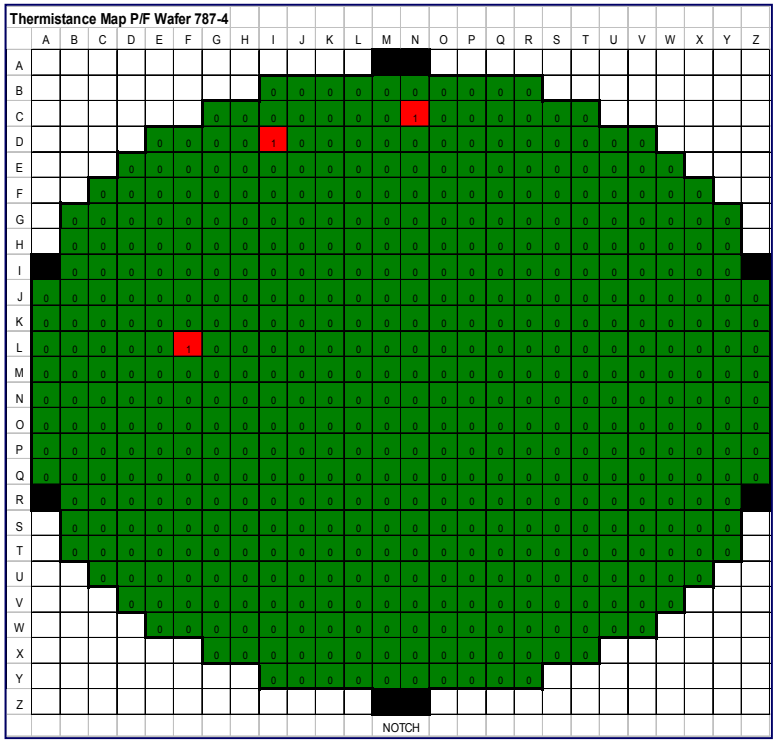


Wafer Bonding

- Bonding Method Selected to Best Suit Customer's:
  - Design/die size
  - Temperature budget
  - Materials requirement
  - Hermeticity requirement
  - Packaging environment
    - Gas/pressure requirement

- Hermeticity in Production
  - >99% yield through wafer bond, slice, assembly, RoHS solder reflow, packaging, shipping
  - Hermeticity verified by probing on-board thermistors
  - Vacuum, atmospheric, or partial pressure with unique gases
  - No detectable leak rate during air bombing at 2 atm for 1,000 hours at 150C (verified by independent lab) – certified for >20 yr life

- <1 mTorr vacuum in production



Wafer map of 1 wafer showing 3 failed dies

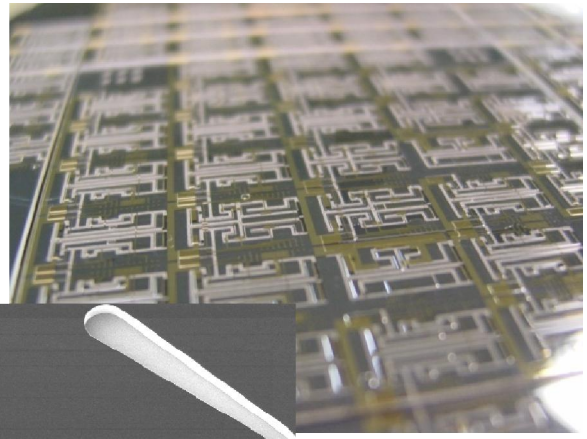
IMT Microfluidics Platforms

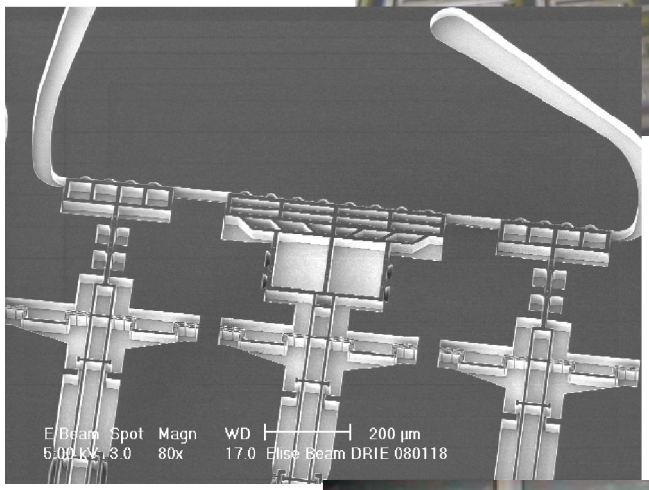
5 Key Technologies Required

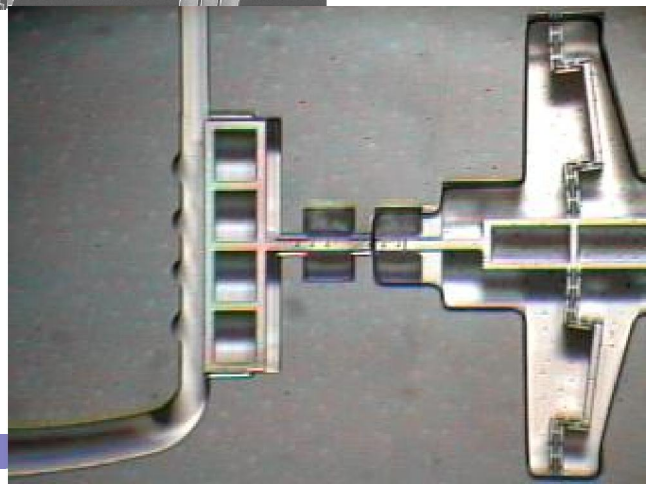
- January 2015

12 Years Manufacturing Microfluidic Devices

- Broad Experience Designing
  - Ultra high speed valves
  - Micro pumps
  - Micro channels
  - Micro channel molds
  - Fluidic sensors
- Silicon and Glass
  - Advanced MEMS processes
  - Wafer Level Bonding
- Fluidics Modeling and Design for Manufacturing
- Medical, Biotech and Industrial Applications



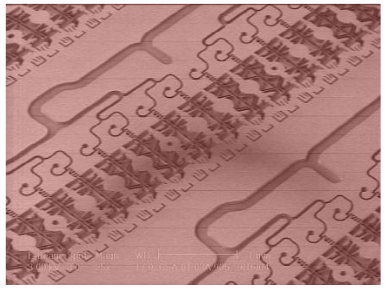




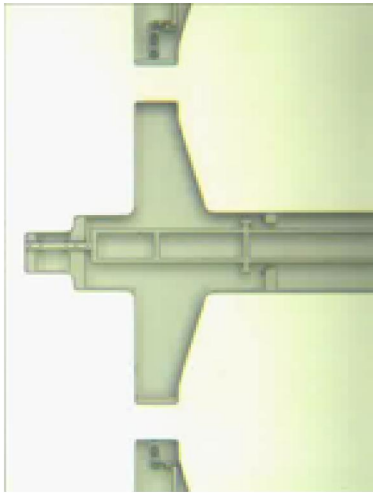
Microfluidic Platforms

5 Key Platforms for Microfluidic MEMS Devices

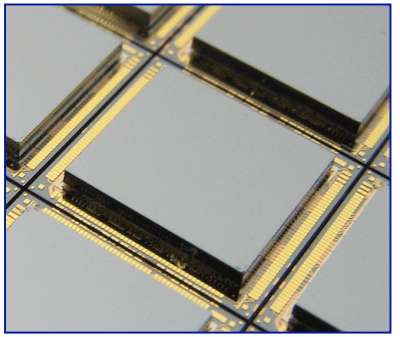
Microfluidic Channels



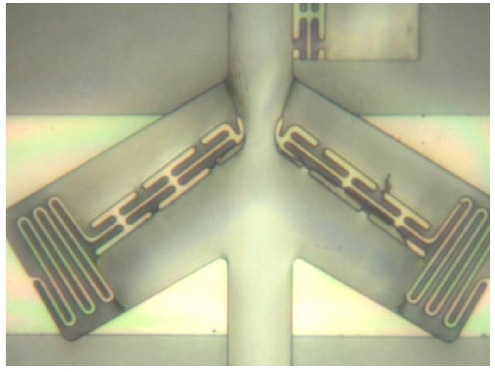
Actuators



Wafer Bonding



Valves

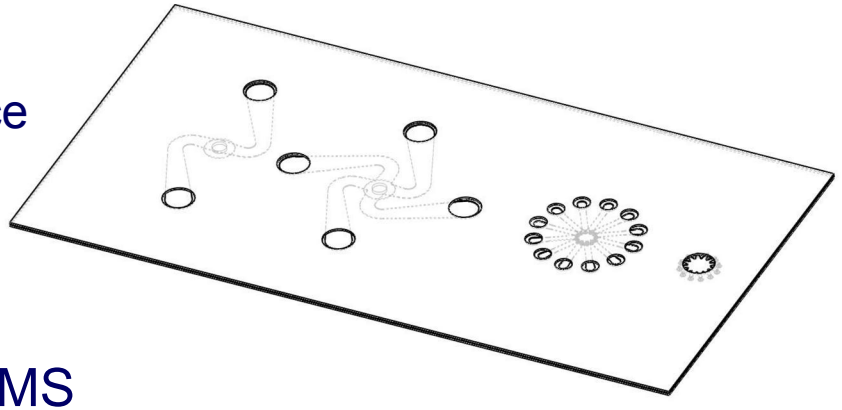


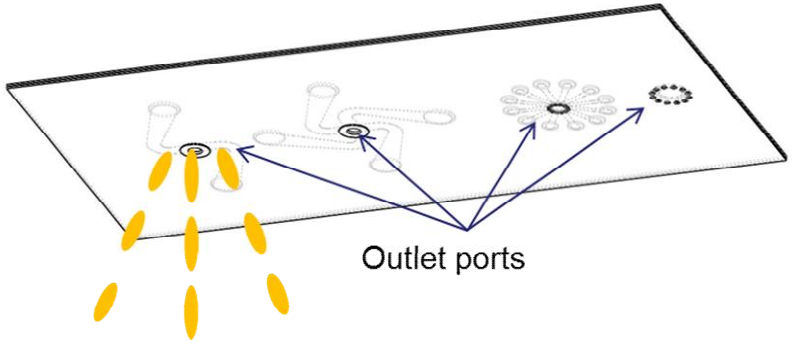
Pumps

Microfluidic Channels

Needed for Fluid Handling

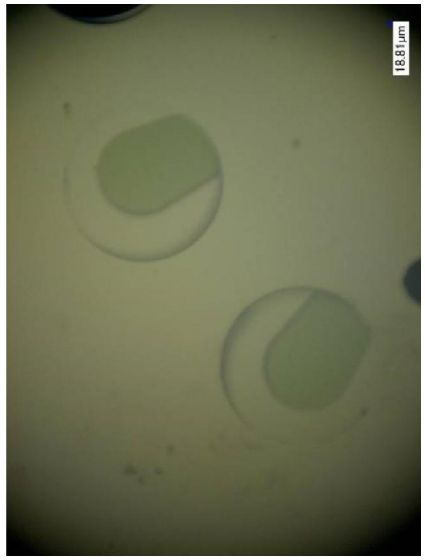
- Holes and Manifolds
  - Connection to Tubes
  - Distribution of fluid within the device
- SOI Starting Wafer
  - Deep Etch using Bosch process (DRIE)
- 3D micro channel manifold using MEMS technology
  - Enclosed channels direct fluid to nozzles
  - Channel widths down to 5 um
  - Nozzle diameters down to 50 um
  - Close clustering of nozzles
  - Mixing capability within channels



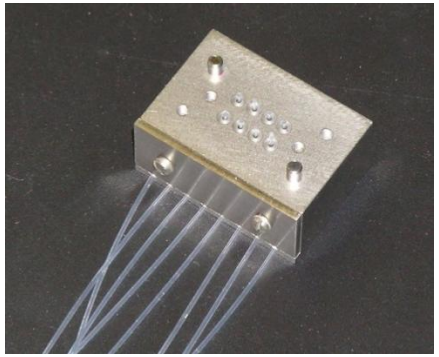


Easy Interface with Your System

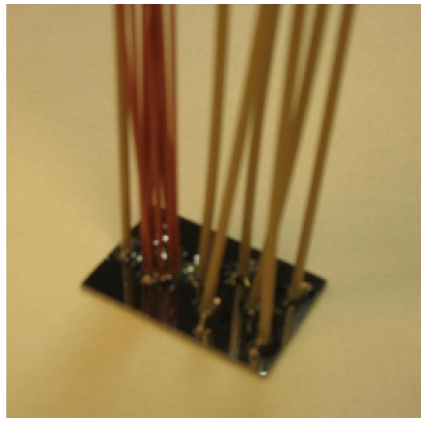
- Numerous options for manifold interface
  - Bonded tubes
    - 1/32 to 1/16 in. diameter standard
    - 160 um tubing
  - Secondary manifold interface
    - Mechanically mounted
    - Quick replacement
    - Compliant gasket



Tube mounting holes



Secondary manifold

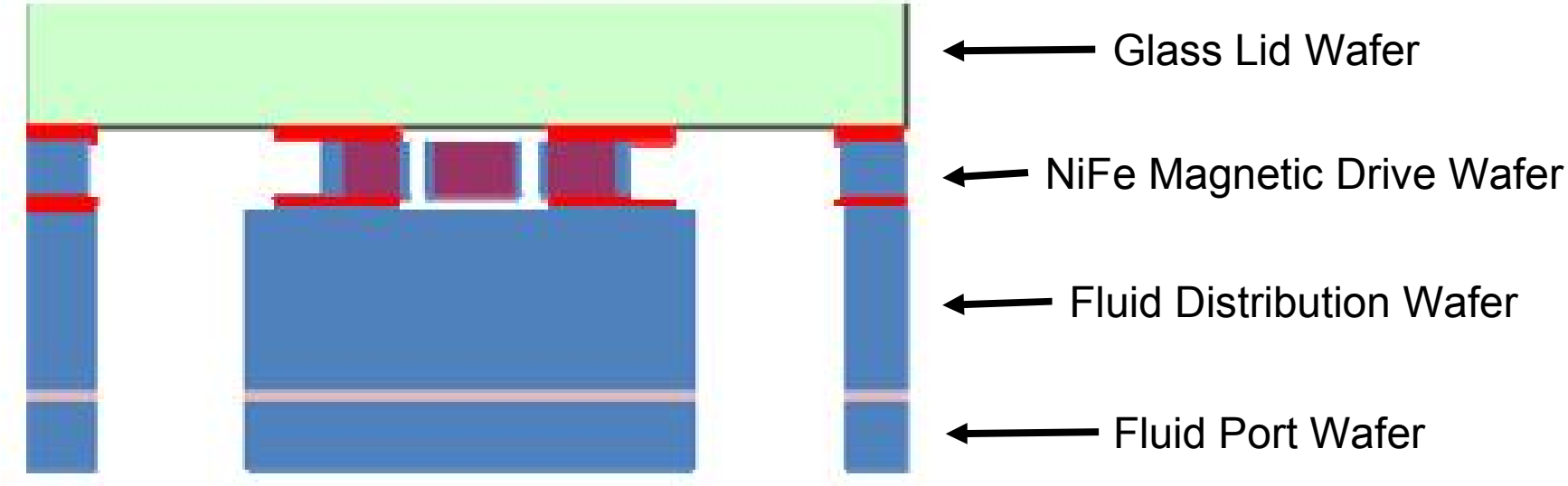


Manifold with Mounted Tubes

Wafer Bonding

Needed For Multi-Level Fluid Distribution

- Various Bonding Techniques:
  - Typically use Polymer, Au Compression and Anodic Bonding
- Microfluidics Devices can use 5 or more wafers in a single device
- Bond Process needs to meet the specific application requirements:
  - Medical Grade, Implantable, Resistant to Chemicals

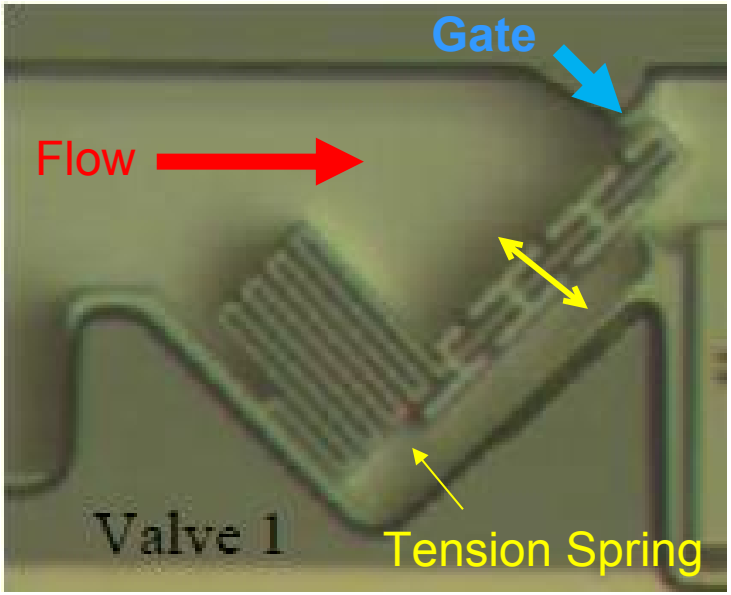


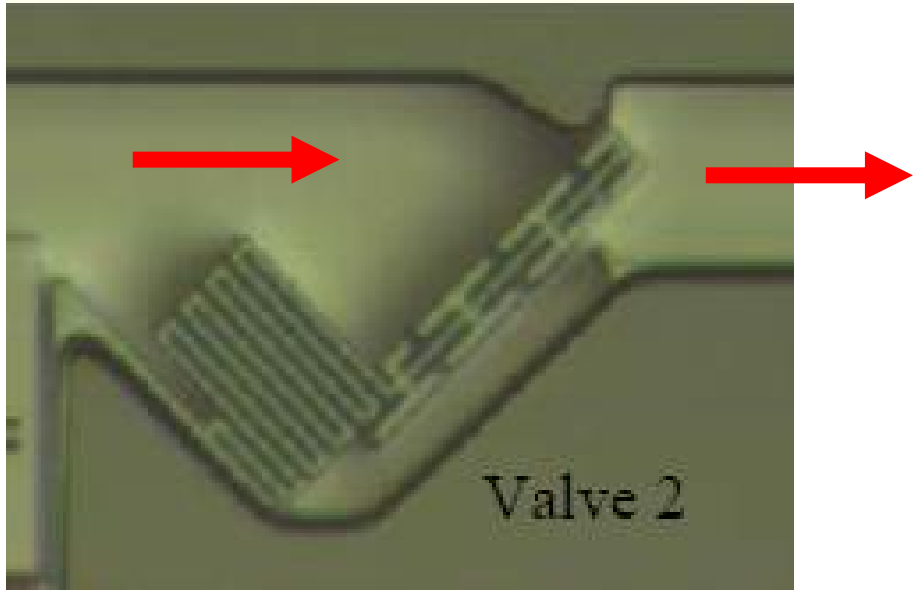
Typical Pump Platform

MEMS Valves

Needed to Control Fluid Flow

- Valves can present a large challenge:
  - Rugged and Flexible is difficult
  - Able to seal well enough to create adequate flow
  - Limited resistance to ensure efficiency of the pump



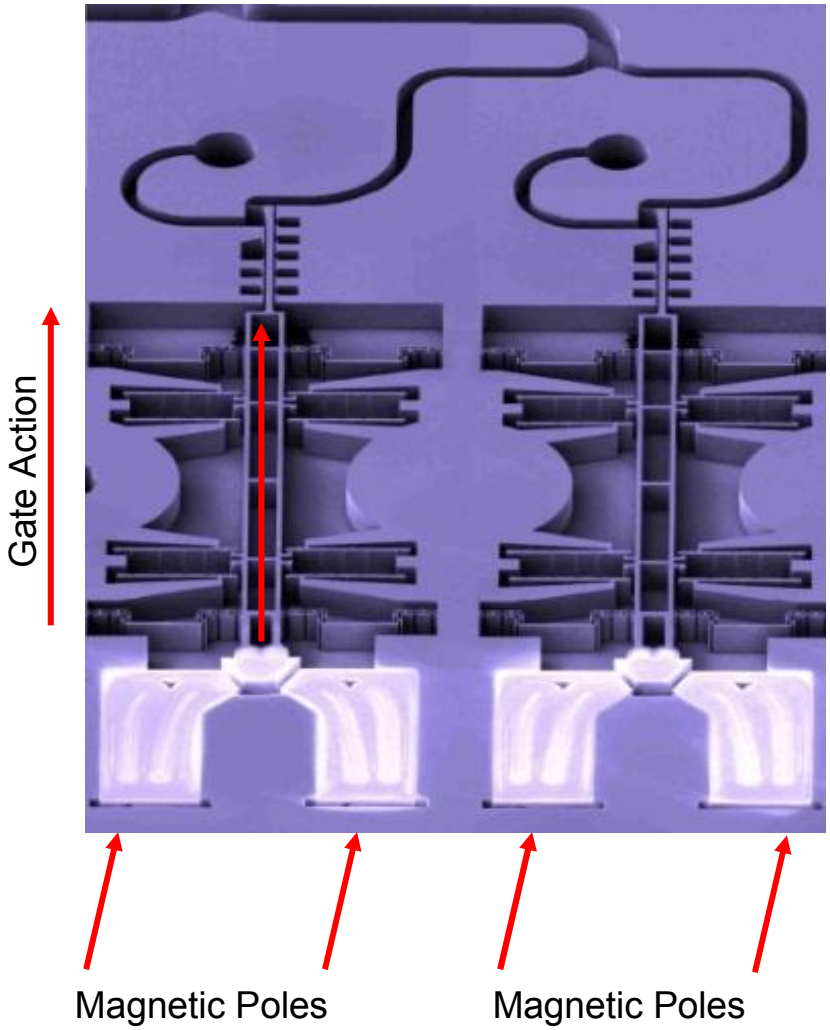


Actuator Techniques

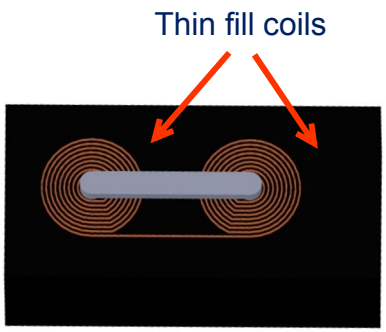
Needed to Create Movement of Pump Membranes and Drive Gates

- IMT uses Magnetic Actuation for most Microfluidic Devices
- Magnetic Motors Are Excellent For:
  - Pump Mechanisms
  - Gate Mechanisms
  - Stirring Mechanism
- Magnetic
  - High Force
  - High Speed
    - 0 to 1.4 m / sec and back to 0…1.4 MS
    - 12000 G acceleration, 22 um stroke
    - Requires external magnetic field

High Speed Gate



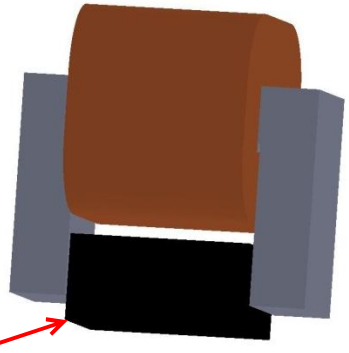
Magnetic Actuation Options

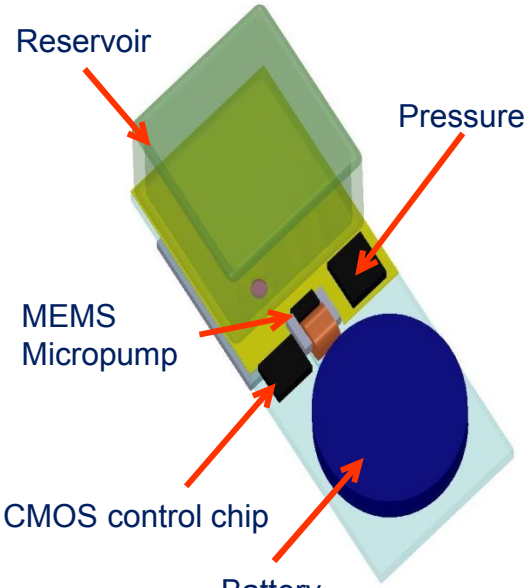


Integrated
MEMS Device

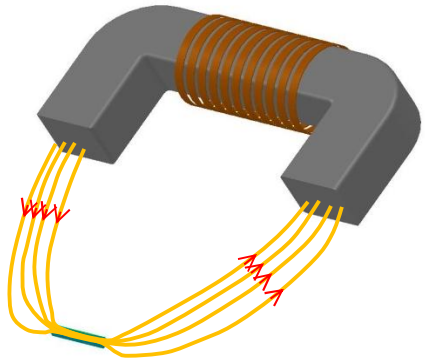
MEMS Coil

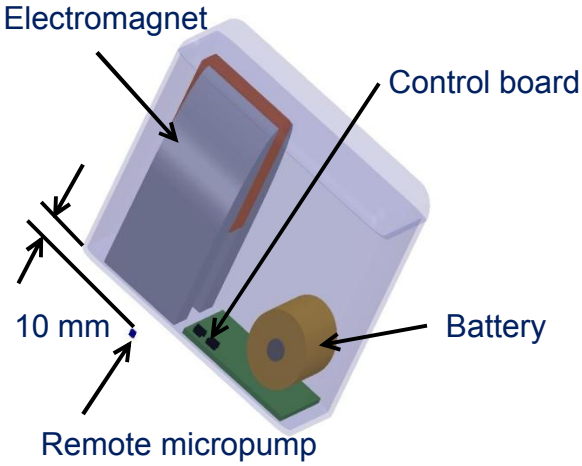
Hybrid attached micro motor





Remote motor

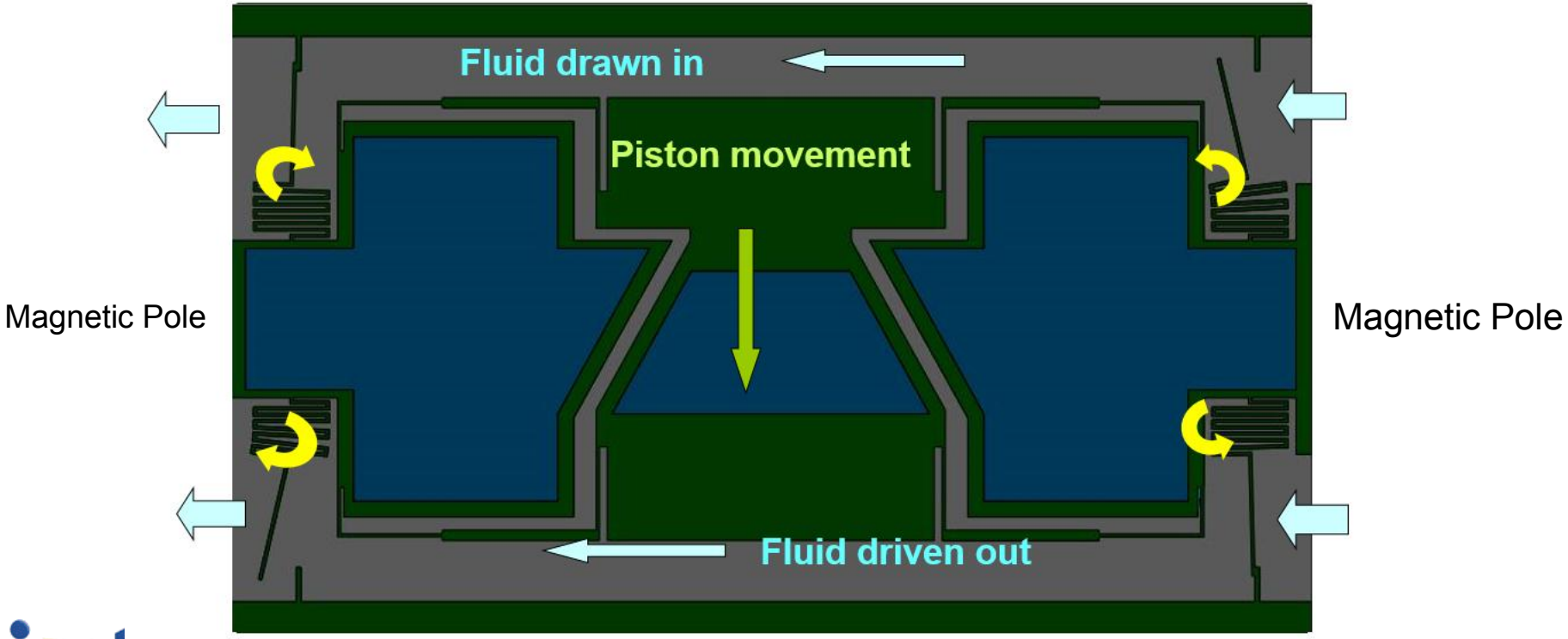




MEMS Pump Platform Technology

Needed to Drive Fluid Movement

Magnetic Drive Dual Chamber Pump
- Planar Construction
- High Fluid Capacity
- Easily Manufactured in Standard MEMS Processes



Dual Cycle Platform Specifications and Status

- Implementations targeting lower flow rates and high viscosity fluids
  - Application viscosity: 1,000 cPa.s
  - Flow rate: 0.1 nl/stroke
  - Application frequency: 0.3Hz
  - Tested to 500Hz
  - Tested to 3.0KHz with water
  - 0.4 mm x 1.8 mm total footprint including reservoir
- Derivative design for higher flow rates low viscosity
  - Flow rate: 40 -70 µl/min
  - Viscosity: 1.0 cPa.s
  - Size: 2.5mm x 0.8mm
  - Range of frequency: 1 – 2kHz
  - Backpressure: 0.3 atm

Magnetic Actuator Platform(Exploded View)

Cap

Lid, visual detection, shield, detection slit

Device Layer

Actuator

- Magnetic actuator
- Magnetic valve
- Stirring

Fluidic channels

Electrodes, electrolysis, electro-synthesis

Aqueous expanding material – solgel timing circuits

Support Section

Reservoir

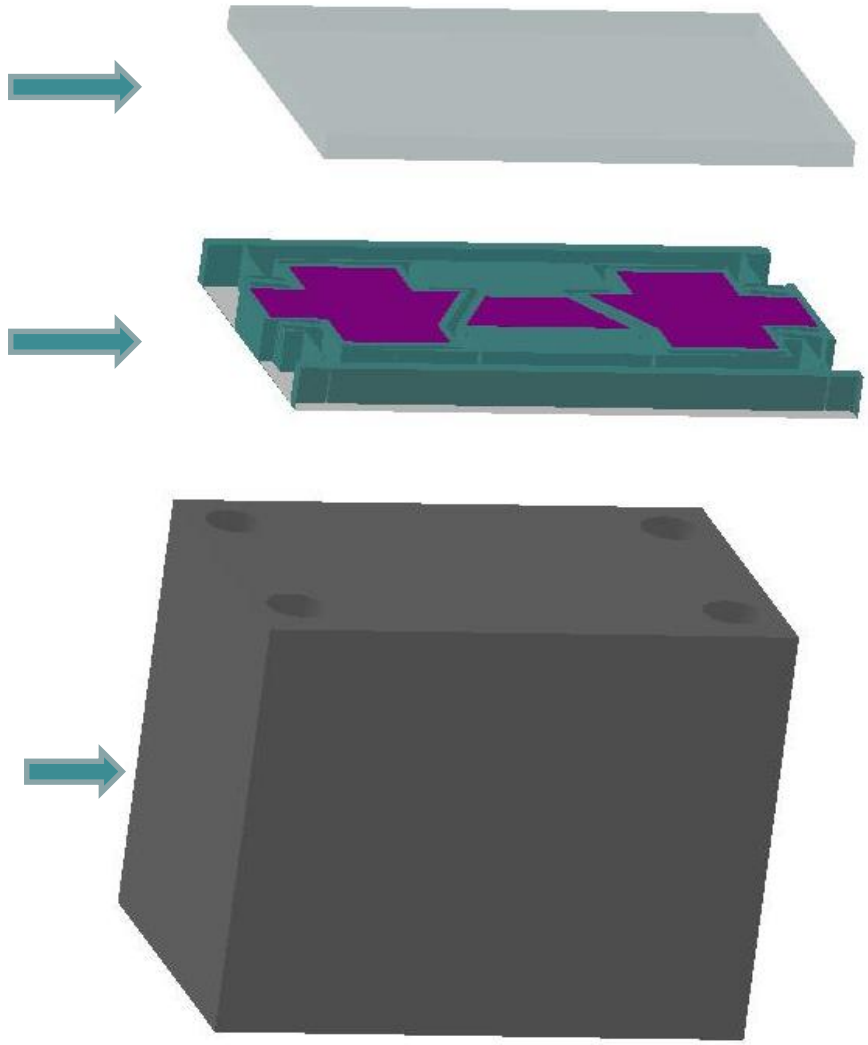
Tubing attachment

Test wells

Fluidic channel

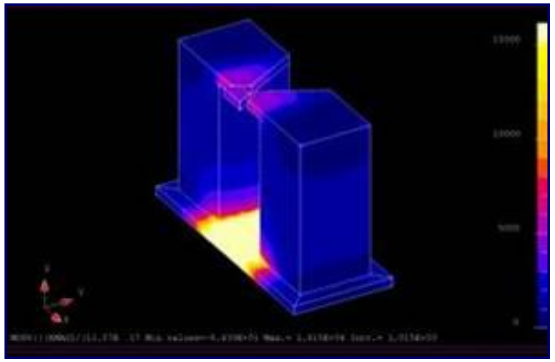
Electrical circuits

Electrodes

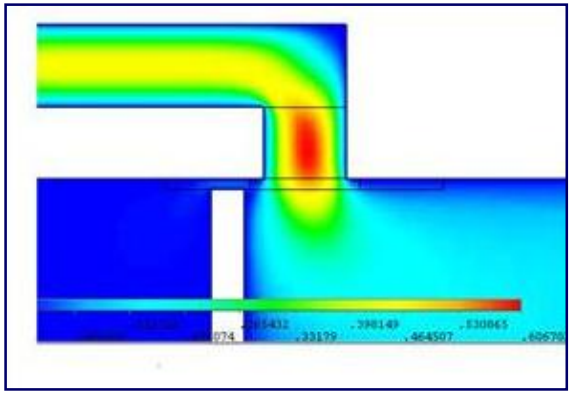


Design for Manufacturability

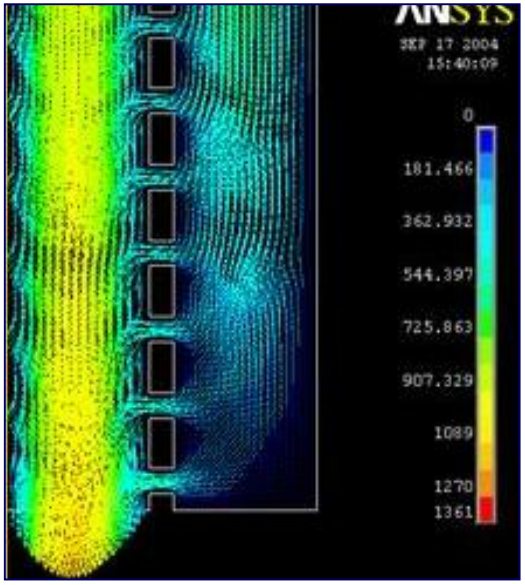
- Design from Customer Specifications
- Design for Manufacturability
- Engineering and Modeling Assistance



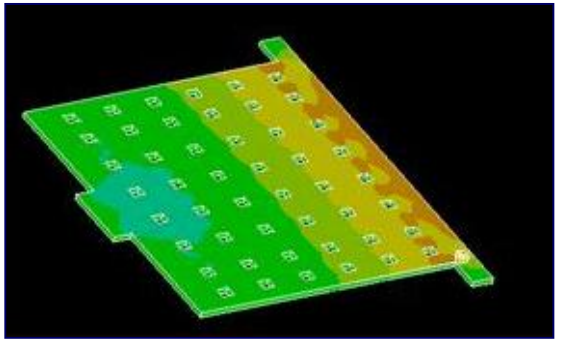
Magnetic Modeling



High-speed microfluidic valves



Computational Fluid Dynamics



Finite Element Analysis

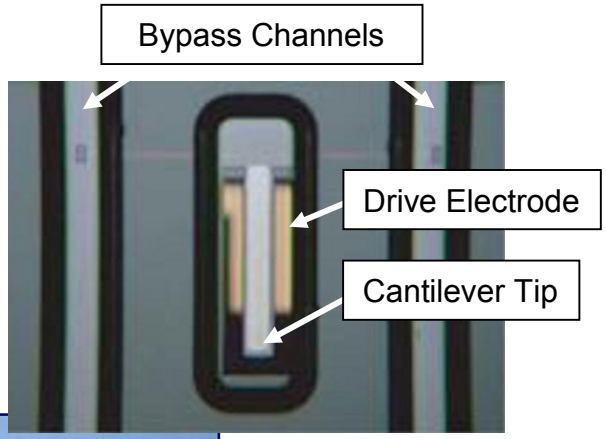
Microfluidics Case Study 1

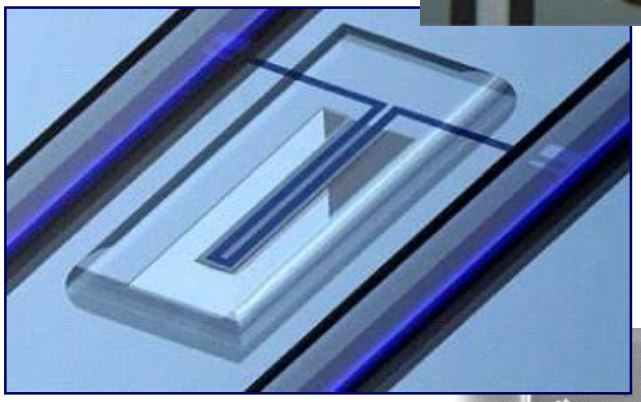
Particle Characterization Device

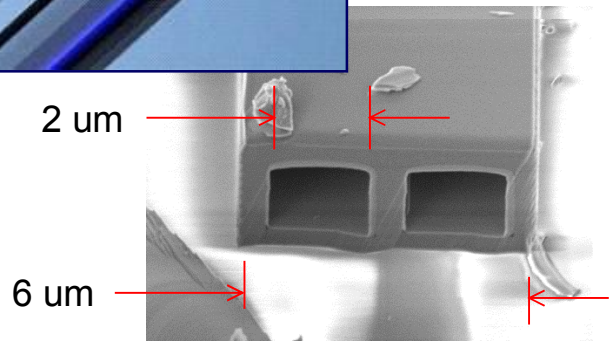
- Weighs single cells or proteins
- Resonance change indicates mass
- Cantilever beam 40um long, 6um wide
- Cavity pressure < 10 mTorr
- Resolution 27 attograms
- Integrated microfluidics
- 10 mask layers

Applications

- Particle metrology
- Diagnostics
- Global Health
- Cytometry
- Proteomics





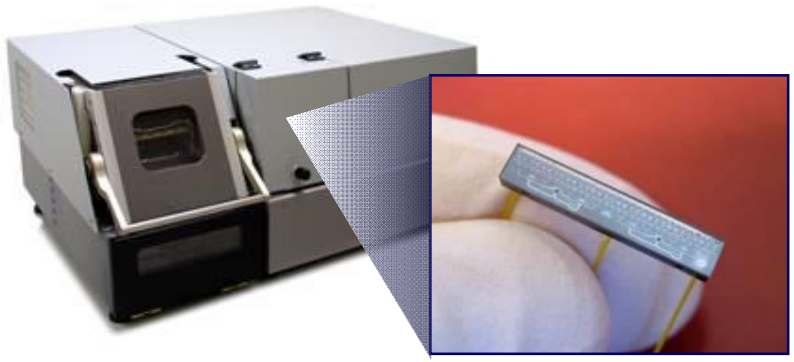


"The ability to measure samples in liquid is essential in many biological applications…they have improved the performance of their system further to achieve a mass resolution of 27 attograms."

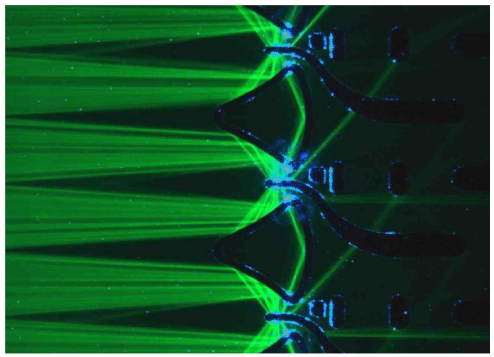
Nature Nanotechnology, July 2010

Microfluidics Case Study 2

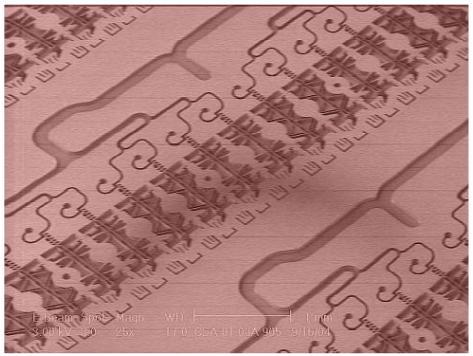
- **Enables High Purity Cell Therapy**
  - High-speed, massively parallel sorting for cancer, autoimmune treatment, and radiation exposure
  - World's fastest MEMS at 0 to 1.4 m/sec back to 0 in 15 microseconds
  - Leverages IMT process modules
    - IMT design and specifications that incorporate microfluidics, actuators and 4 wafers bonded at wafer-level
  - Four wafer bonded stack



World's fastest MEMS (actuator for cell sorting)



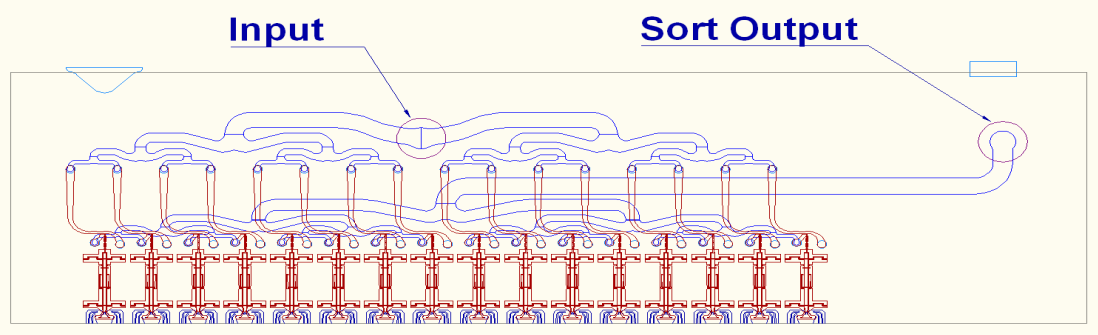
Laser input, reflective and refractive optics on-board

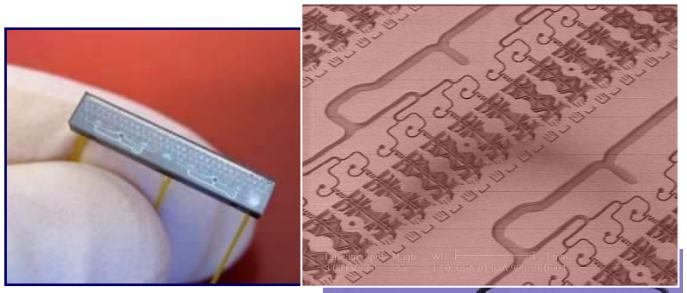


3D Microfluidics enabled by Deep Reactive Ion Etch (DRIE)

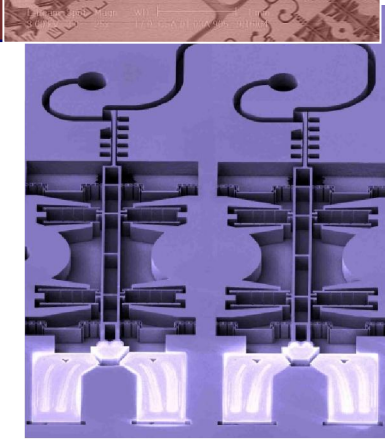
MEMS Cell Sorter Evolution

- On-chip fluidics (manifolds/valves/actuators)

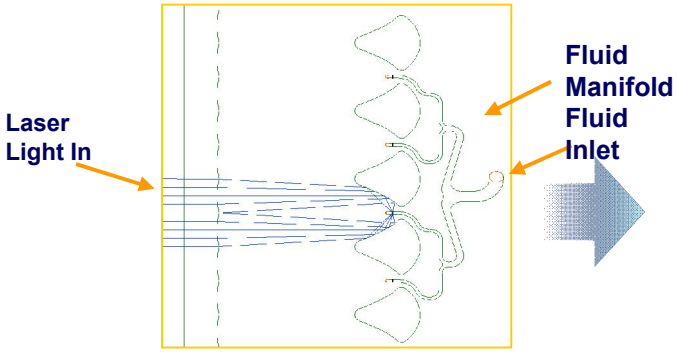


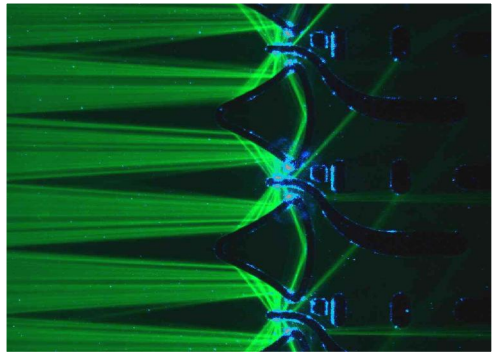


Cell Sorter Device



- On-chip optics – high efficiency illumination/detection
- 3-D structure, 4 wafer bonded stack



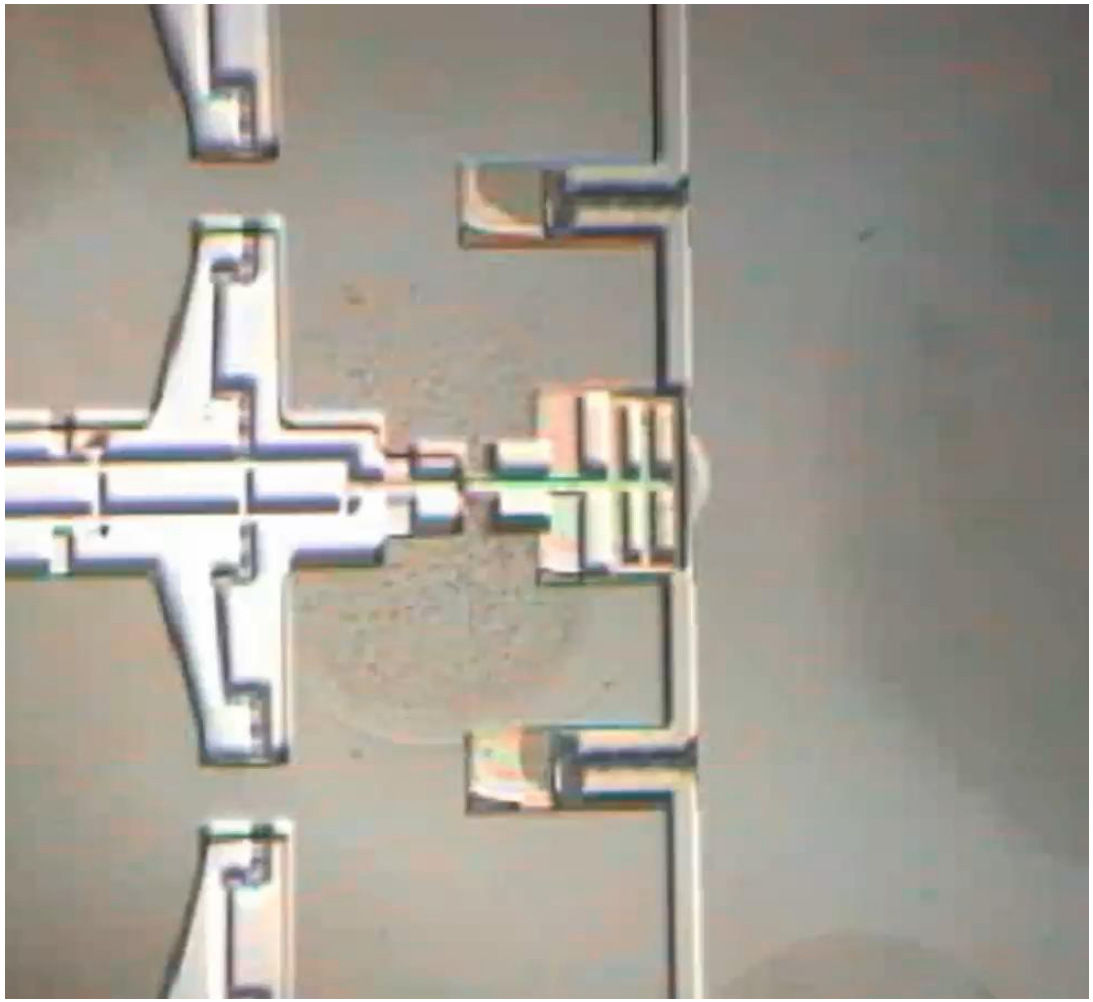


Laser input, reflective and refractive optics on-board

Sorted cells

IMT Single Piston Pump

Double Click on Image to Activate



Summary

- IMT has experience developing more and 50 Microfluidic Devices for Customers
- Key Platforms for Successful Microfluidics Development
  - Channels, Valves, Actuators and Pumps
- Demonstrated up to 5 Bonded Wafers in a Device
- Design Expertise and Modeling has been developed for more than 12 years.