MEMS 2003 and Beyond

A DARPA Vision of the Future of MEMS

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What Are MEMS?

- A way of making things
  - **Leverage on existing infrastructure of IC fabrication tools**
  - **Prototype on mass-production fabrication tools**
- Co-location of sense, compute, actuate, control, communicate, power
  - **Increase performance and decrease cost**
  - **Integrate an increased number of fabrication technologies**
- Closed-loop, microscale control of electrical, thermal, fluid, magnetic, optical, and mass flux
  - **MEMS is a surface technology**
  - **Control phenomena on the microscale**
  - **Cause large effects both on macroscale and microscale**

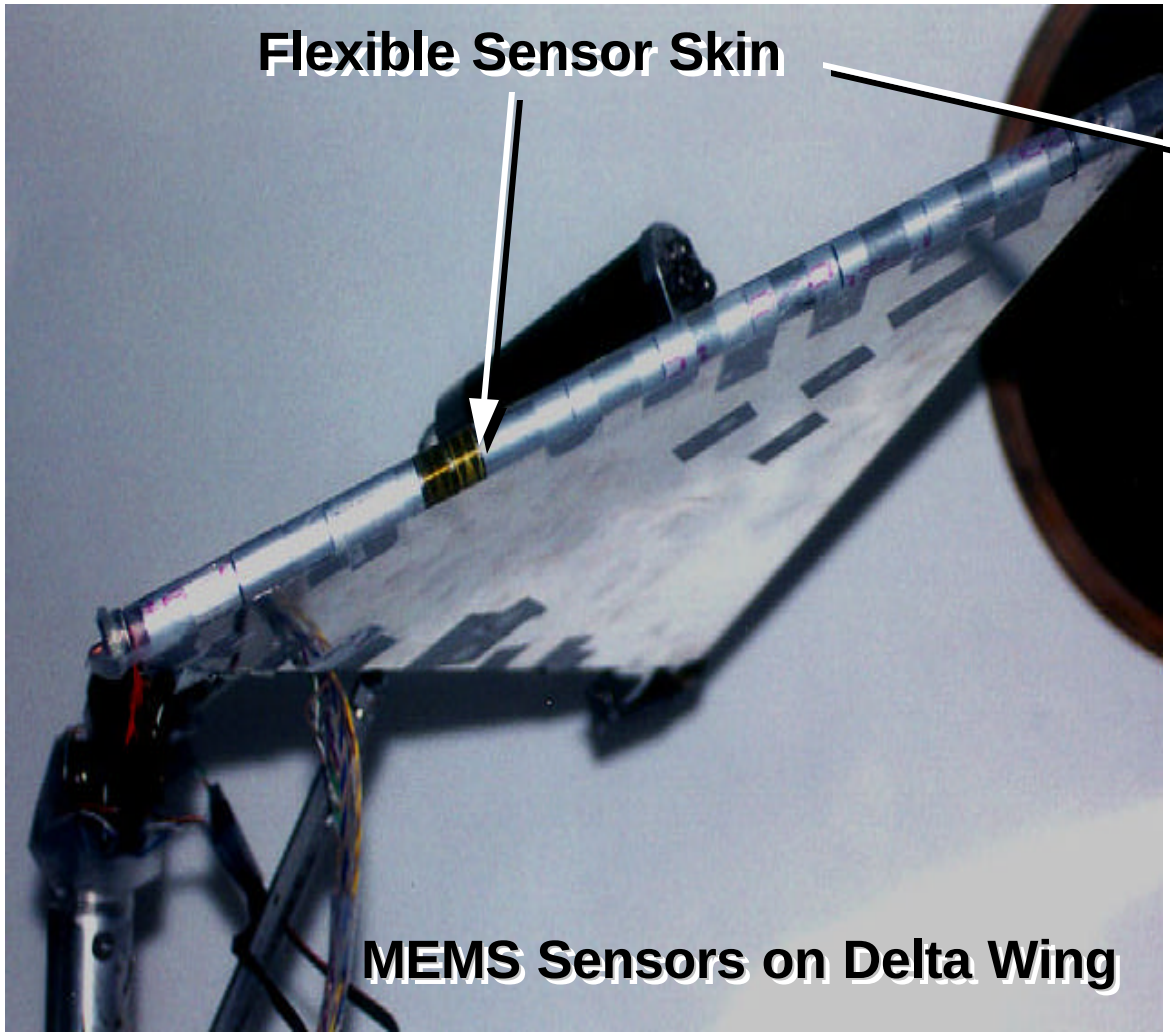
What Are MEMS?

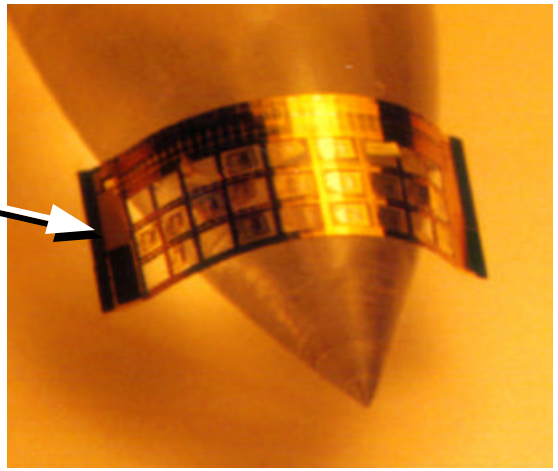
MTO MEMS

- High spatial resolution and high temporal bandwidth
  - **Integrated solutions offer greater physical density**
  - **Miniaturized components offer faster response**
- MEMS at both microscale and macroscale
  - **Large array of MEMS on a chip**
  - **Large array of MEMS “islands” on a macro platform**
  - **Dual-scale interconnect problem (integration required)**
- The relevant size metric is the minimum feature size
  - **Overall device or system size is irrelevant**
  - **Minimum feature size determines the required technology**
- MEMS as Analog of Transistors
  - **Direct and/or control power from macro and other sources**

MEMS Actuators as "Transistors"

MTO MEMS





MEMS actuators make small changes in the air flow which are amplified by the flow itself to cause large macro effects

UCLA and Aerovironment

MEMS Actuators for Aero Control

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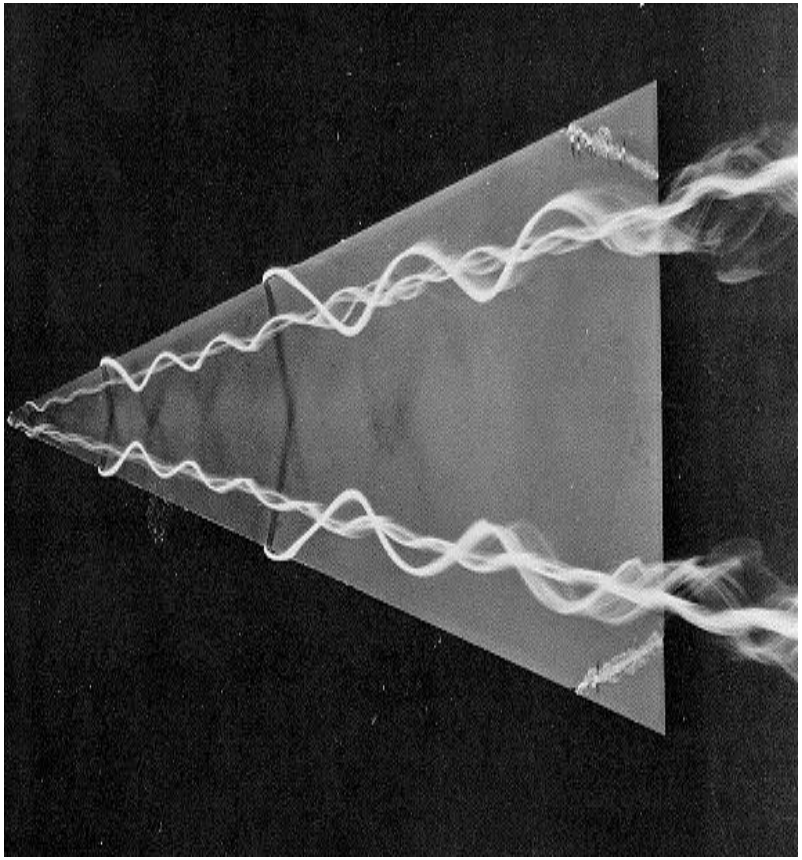

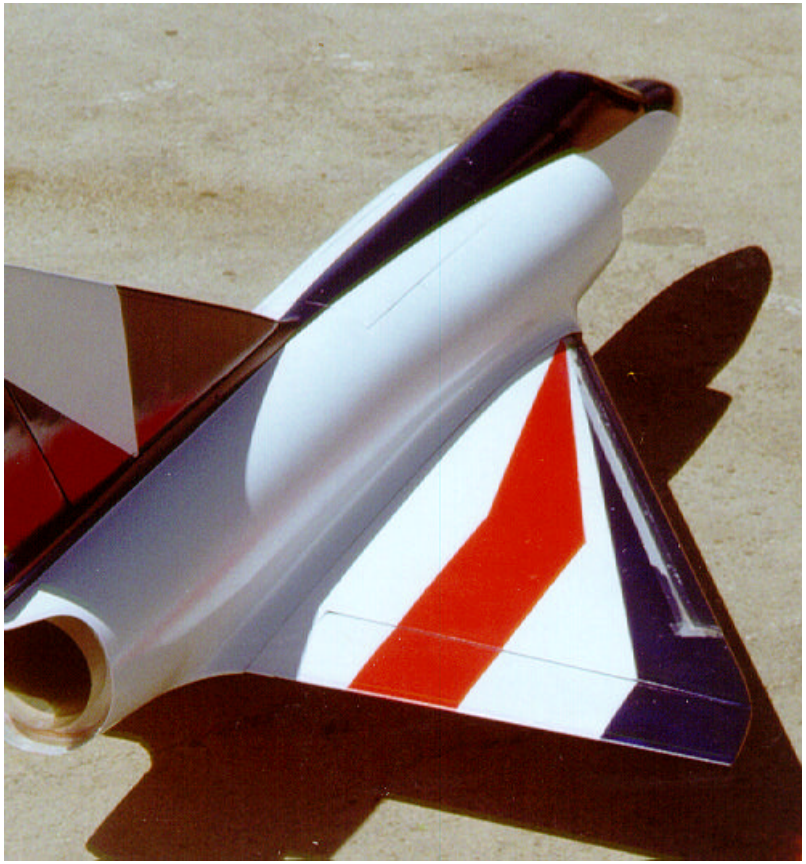

MEMS Actuator Array on the Leading Edge of Wing of 1/7 Scale Mirage III Fighter

UCLA and Aerovironment

Microelectromechanical Systems

MTO MEMS

- Sense locally, compute locally, actuate locally, but cause large effects globally
- MEMS uniquely enables:
  - **Complete system control on the microscale**

    MEMS allows the flux control loop to be closed locally on the microscale.
  - **Contingency tolerance**

    MEMS allows greater tolerance of macroscopic systems to unexpected events (sense & compute).
  - **Performance enhancement**

    MEMS allows adjustment in flux and/or structure for better performance of macroscopic systems (compute & actuate).

MEMS Description/Fabrication

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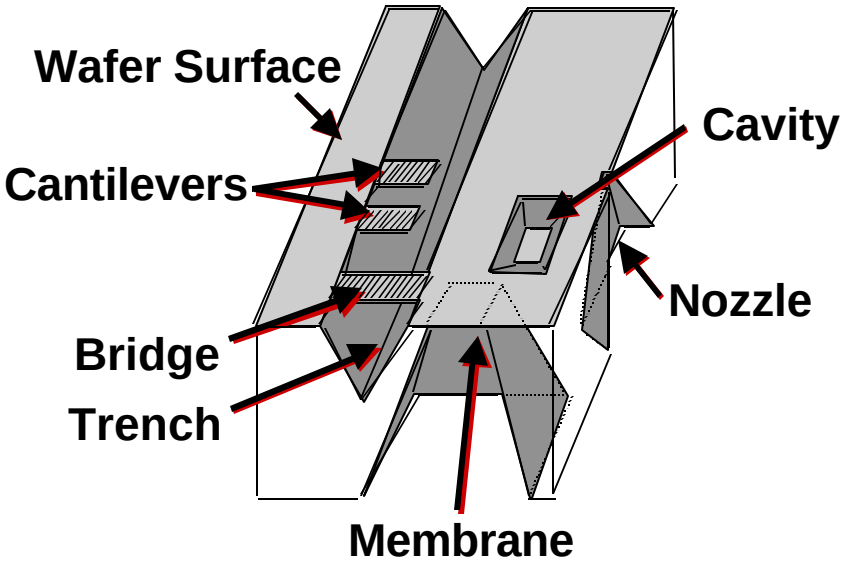
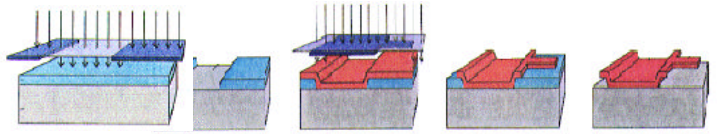
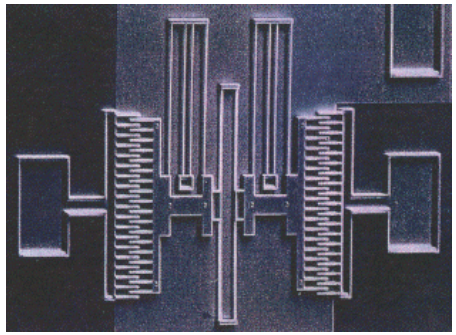
Bulk Micromachining



Surface Micromachining



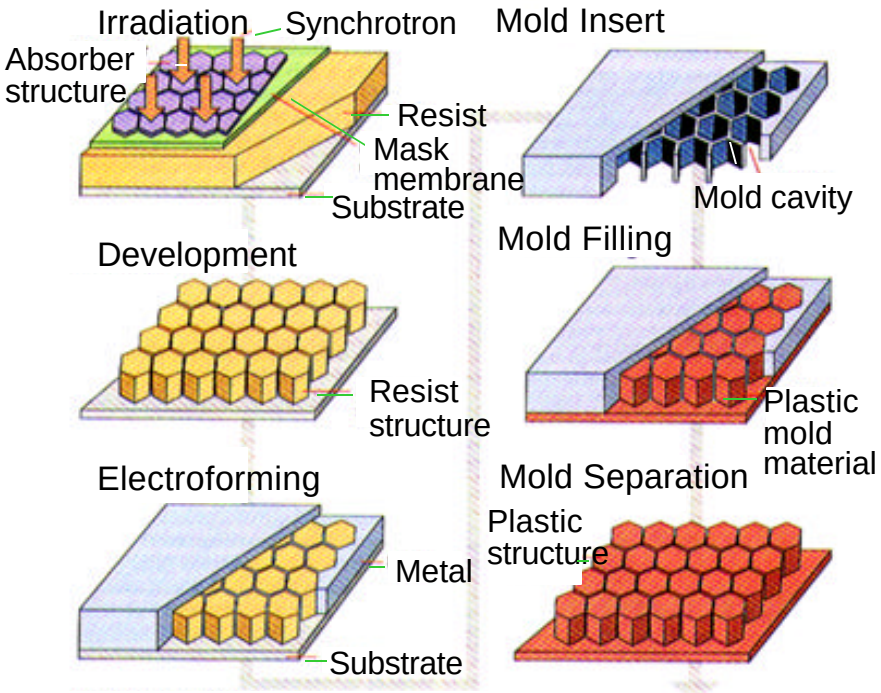


MEMS co-locate sensing, computing, and actuating to change the way we perceive and control the physical world

MEMS Description/Fabrication

MTO MEMS

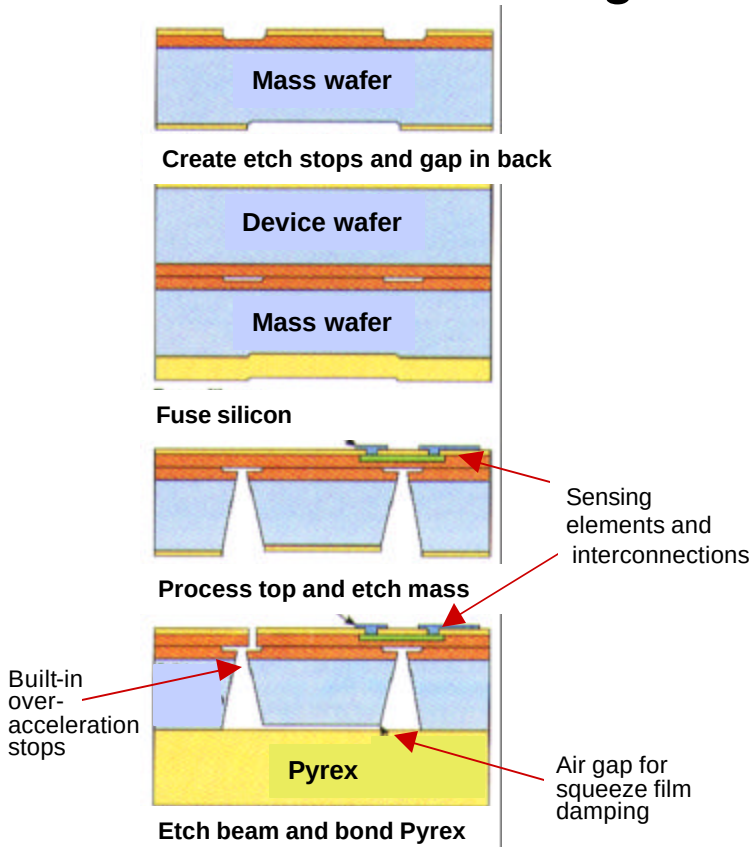
LIGA*, Deep UV



Source: IMM (Mainz Institute for Microtechnology)

*Lithographie, Galvanoformung, Abformung

Wafer-to-Wafer Bonding



MEMS are a new way to make both mechanical and electrical components for microscale flux control

MEMS Go Beyond Standard Microelectronics Manufacturing

DARPA

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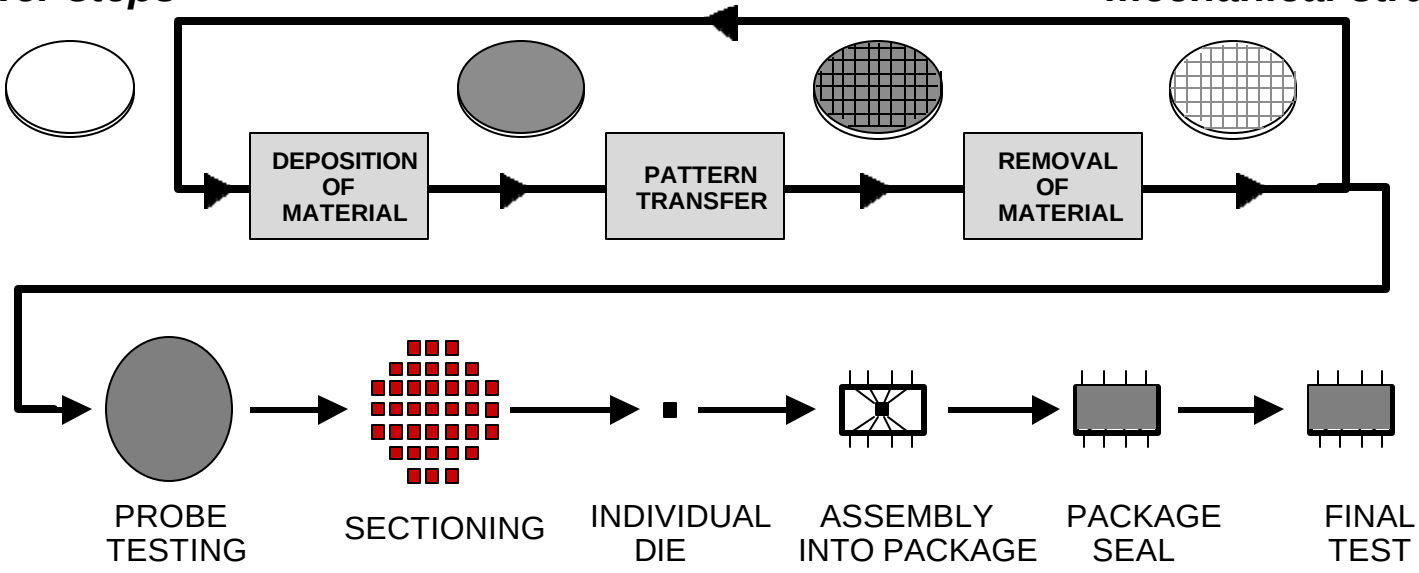
Thicker films deeper etches fewer steps

Multiple Processing Cycles

Removal of underlying materials to release mechanical structures



Special probing, sectioning and handling procedures to protect released parts

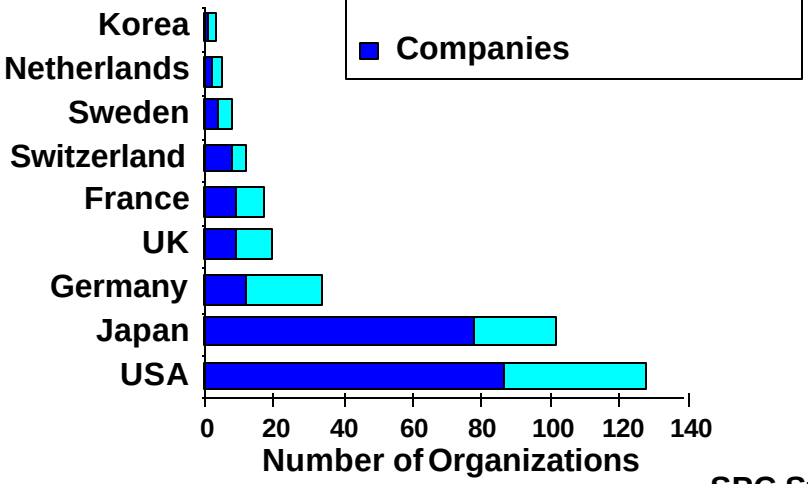
Encapsulate some parts of device but expose others

Test more than just electrical functions

MEMS Market and Industry Studies

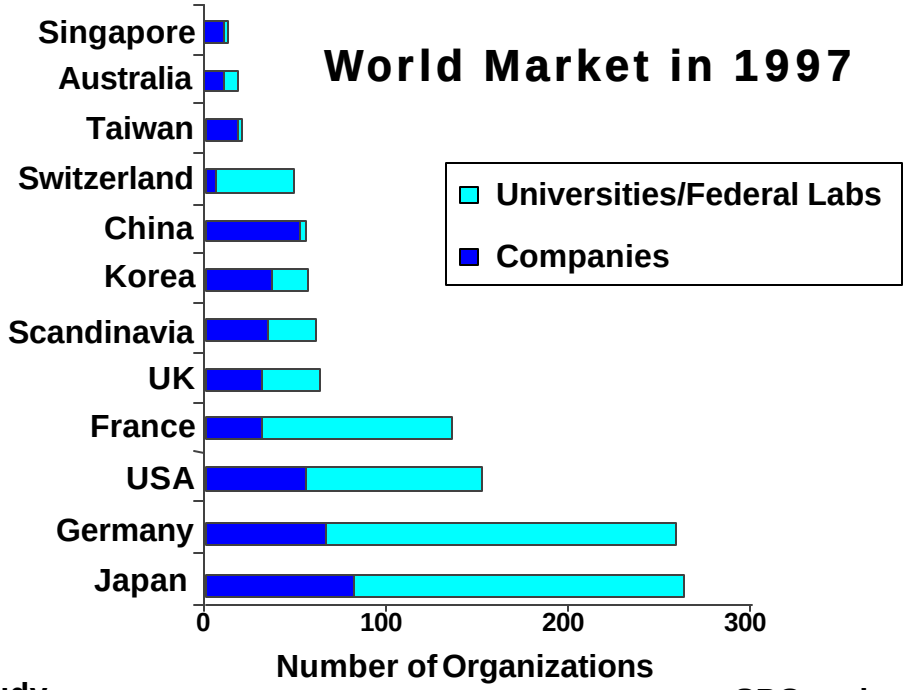
MTO MEMS

World Market in 1994



SPC Study

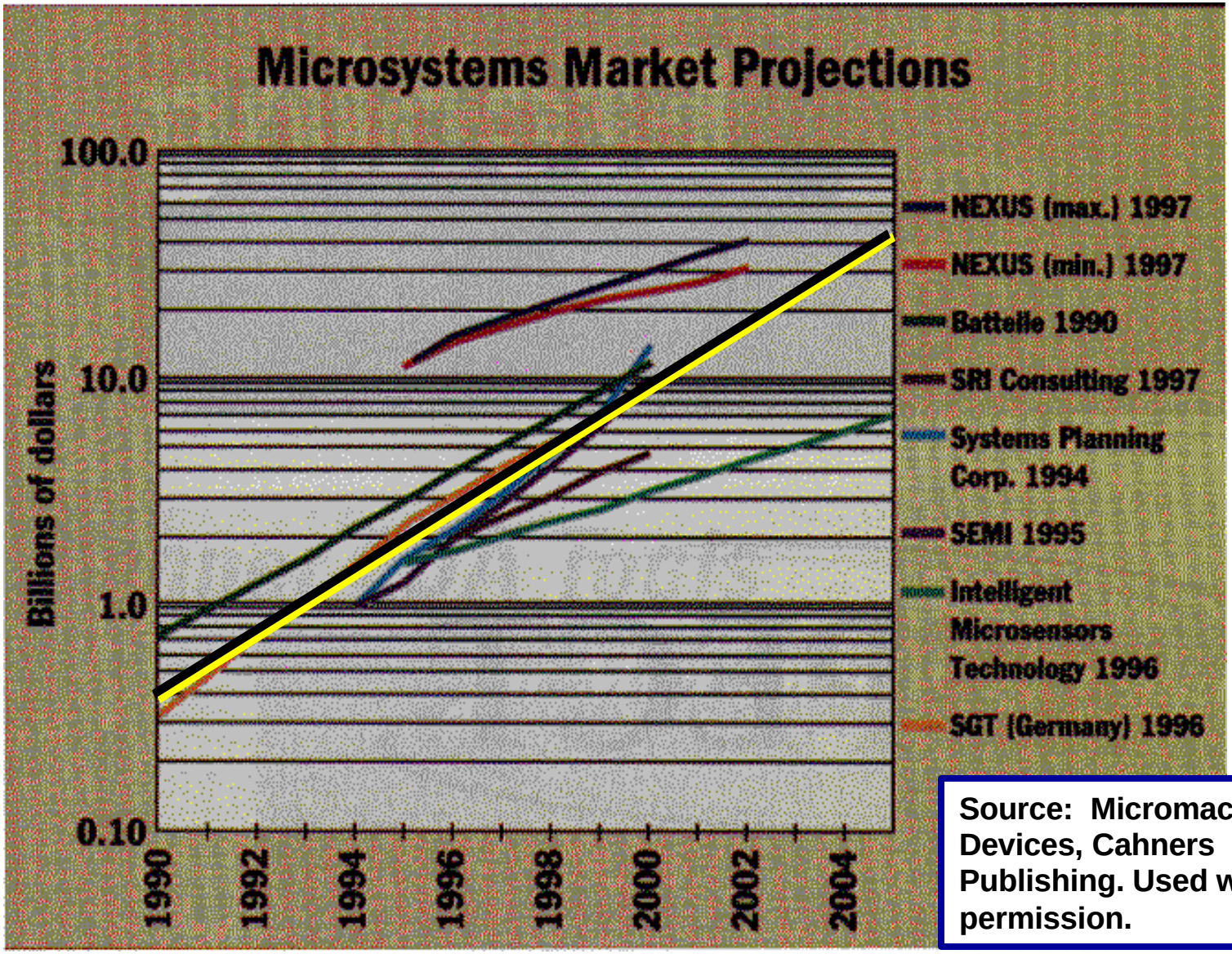
World Market in 1997



SPC and ATIP Studies

- Not dominated by traditional defense contractors
- In FY97 there were 95 U.S. companies active in MEMS
- In FY97 15 U.S. companies represented 90% of the market
- In FY98 U.S. MEMS program supported 50 small businesses

MEMS Market and Industry Studies



Source: Micromachine Devices, Cahners Publishing. Used with permission.

MEMS Market and Industry Studies

MTO MEMS

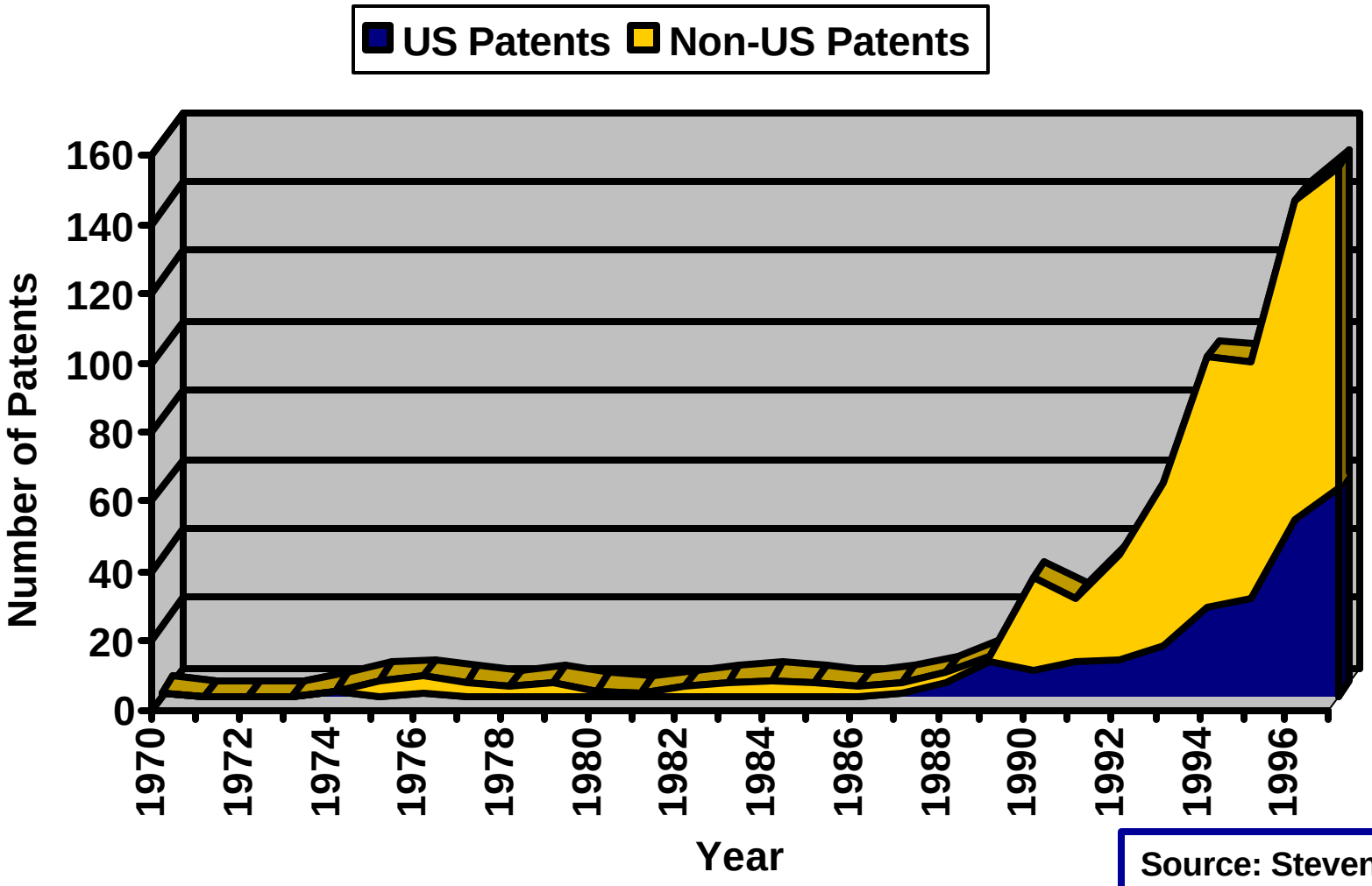
Technology Area	Typical Devices/ Applications	Companies	Market Baseline ($Millions)	Market 2003 (Est.) ($Millions)
Inertial Measurement	Accelerometers, Rate Sensors, Vibration Sensors	TI, Sarcos, Boeing, ADI, EG&G IC Sensors, AMMi, Motorola, Delco, Breed, Systron Donner	$350-$540	$700-$1400
Microfluidics and Chemical Testing/ Processing	Gene Chip, Lab on Chip, Chemical Sensors, Flow Controllers, Micronozzles, Microvalves	Battelle, Sarnoff, Microcosm, ISSYS, Berkeley MicroInstruments, Redwood, TiNi Alloy, Affymetrix, EG&G IC Sensors, Motorola, Hewlett Packard, TI, Xerox, Canon, Epson	$400-$550	$3000-$4450
Optical MEMS (MOEMS)	Displays, Optical Switches, Adaptive Optics	Tanner, SDL, GE, Sarnoff, Northrop-Grumman, Westinghouse, Interscience, SRI, CoreTek, Lucent, Iridigm, Silicon Light Machines, TI, MEMS Optical, Honeywell	$25-$40	$450-$950
Pressure Measurement	Pressure Sensors for Automotive, Medical, and Industrial Applications	Goodyear, Delco, Motorola, Ford, EG&G IC Sensors, Lucas NovaSensor, Siemens, TI	$390-$760	$1100-$2150
RF Technology	RF switches, Filters, Capacitors, Inductors, Antennas, Phase Shifters, Scanned Apertures	Rockwell, Hughes, ADI, Raytheon, TI, Aether	(Essentially $0 as of 1998)	$40-$120
Other	Actuators, Microrelays, Humidity Sensors, Data Storage, Strain Sensors, Microsatellite Components	Boeing, Exponent, HP, Sarcos, Xerox, Aerospace, SRI, Hughes, AMMI, Lucas Novasensor, Sarnoff, ADI, EG&G IC Sensors, CP Clare, Siemens, ISSYS, Honeywell, Northrop Grumman, IBM, Kionix, TRW	$510-$1050	$1230-$2470

Companies currently under contract. Companies with past contracts.

Worldwide Patent Activity in MEMS

DARPA MTO MEMS

MEMS Patents Per Annum



Source: Steven Walker, Dave Nagel, NRL

Defense Applications of MEMS

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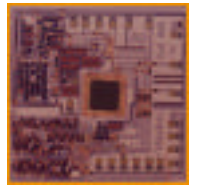
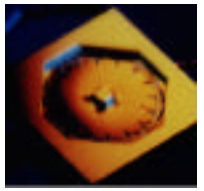
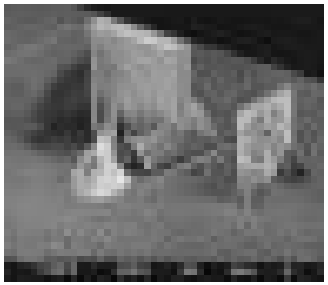
- **Inertial navigation** units on a chip for munitions guidance and personal navigation
- **Electromechanical signal processing** for ultra-small, ultra low-power wireless communication
- **Distributed unattended sensors** for asset tracking, environmental monitoring, security surveillance
- **Integrated fluidic systems** for miniature analytical instruments, propellant and combustion control
- **Weapons safing, arming and fuzing**
- **Embedded sensors** and actuators for condition-based maintenance
- **Mass data storage** devices for high density, low power
- **Integrated micro-optomechanical components** for identify-friend-or-foe systems, displays and fiber-optic switches
- **Active, conformable surfaces** for distributed aerodynamic control of aircraft and adaptive optics







What is the Future of MEMS?

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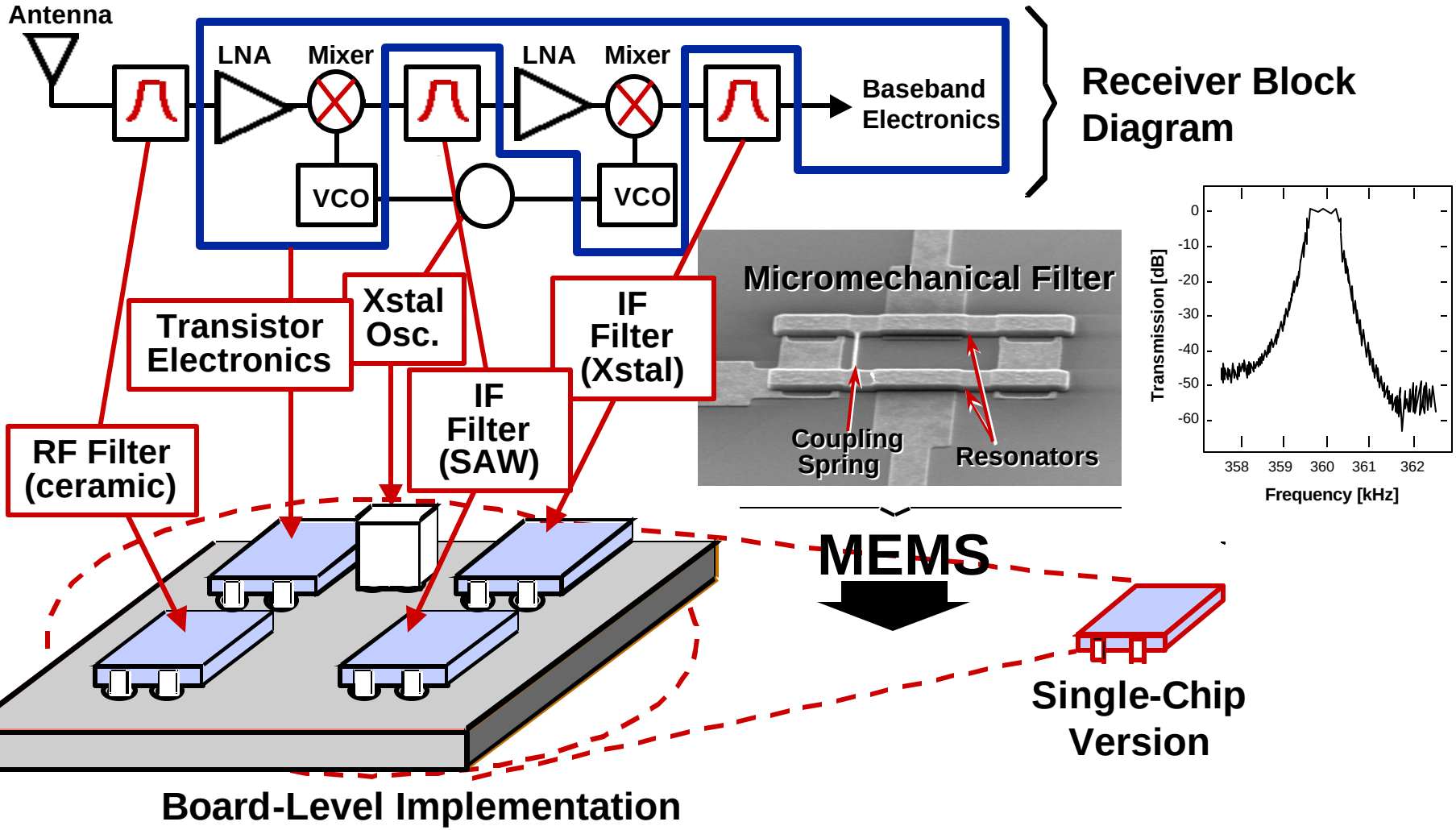
- MEMS is an enabling technology that will be part of both macro and micro systems.
  - **Wrist Communicator**
  - **Indestructible Jet Engine**
  - **Stand-Off Chemical Sensing**
  - **Micro Airborne Sensor/Communicator**
  - **Micro Thermal-Chemical Power Systems**

Wrist Communicator

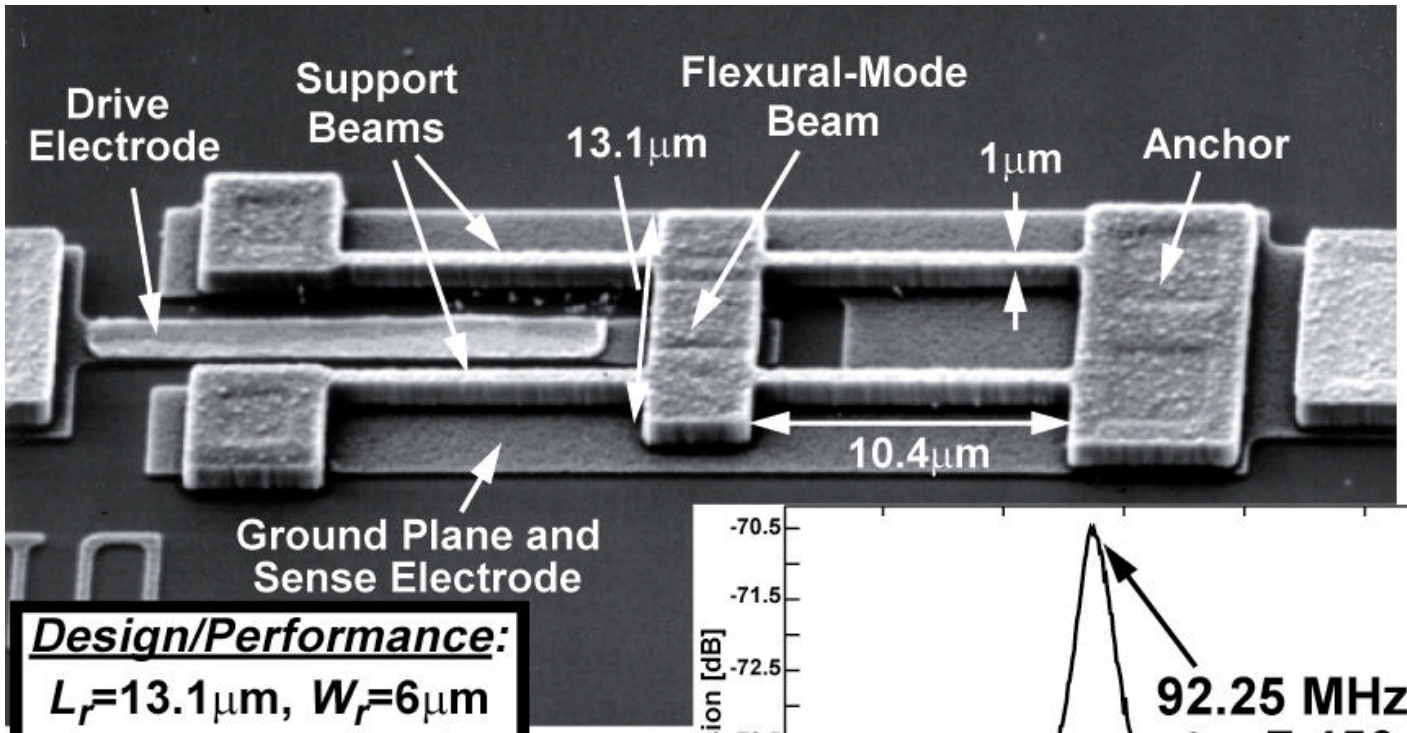
MTO MEMS



- Off-chip high-Q mechanical components present bottlenecks to miniaturization → replace them with mmechanical versions

University of Michigan
MEMS for Signal Processing

Wrist Communicator



Design/Performance:

L_r=13.1μm, W_r=6μm

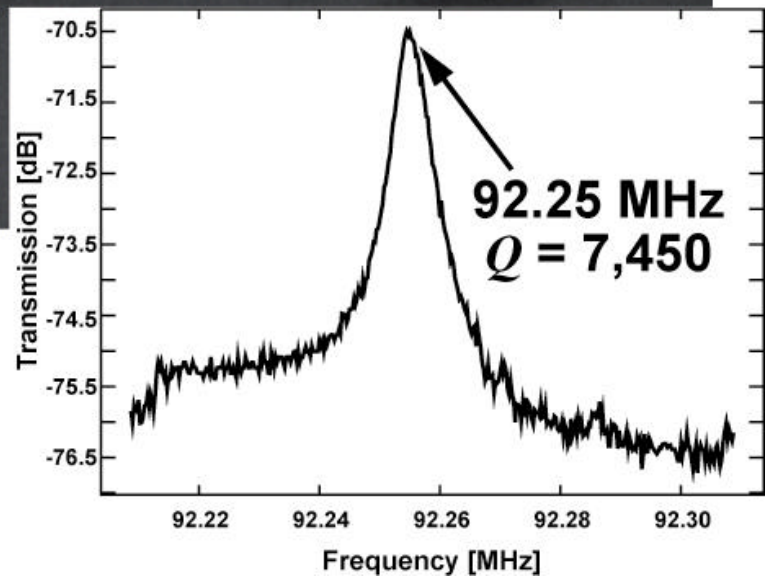
h=2μm, d=1000Å

V_P=76V, W_e=2.8μm

f_o~92.25MHz

Q~7,450 @ 10mTorr

[Wang, Yu, Nguyen 1998]

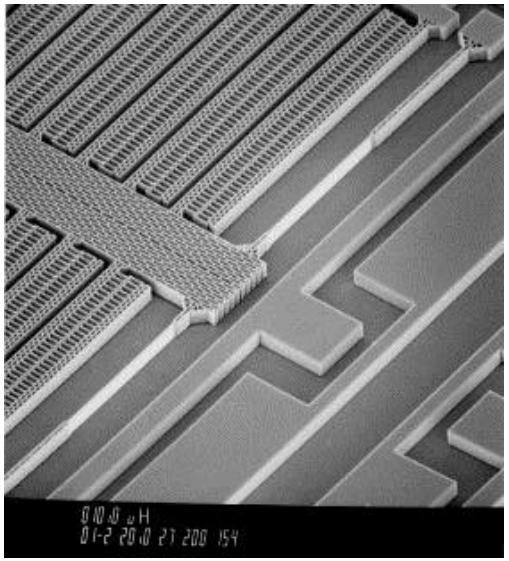


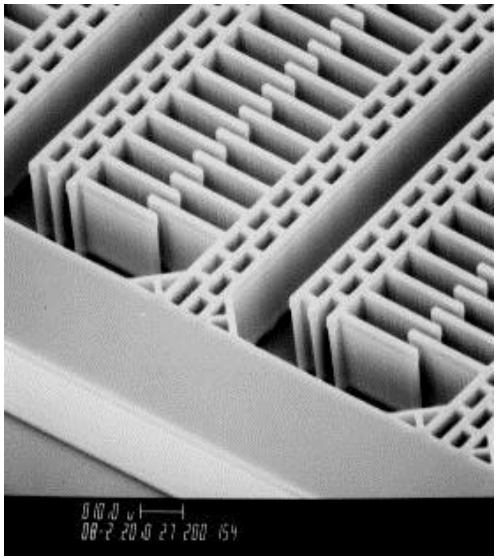
Wrist Communicator

- Technical challenges
  - **Antenna, Frequency Band**
  - **Size, Weight, Power**
- MEMS solution
  - **Replace all discrete components (switch, varactor, inductor)**
  - **Replace electrical circuits with electromechanical signal processing (filters, oscillators, modulators, de-modulators)**

Highlights of the Rockwell MEMS Tunable Capacitor

- Single Crystal Silicon
- Superior Mechanical Properties
- High Aspect Ratio (20 to 1)
- Higher Linearity
- Large Tuning Ratio (> 6.5 to 1)

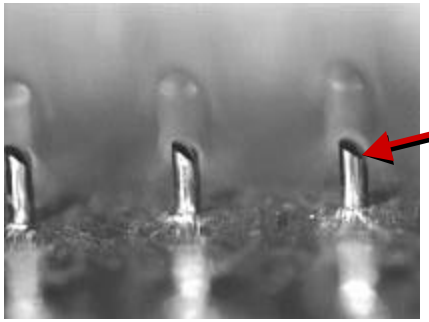




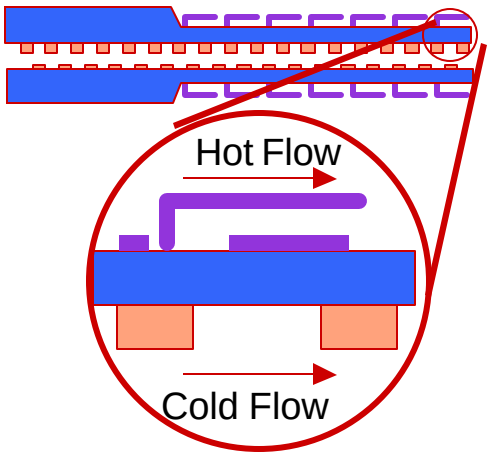
SEM micrograph showing the high aspect ratio feature of the MEM tunable cap.

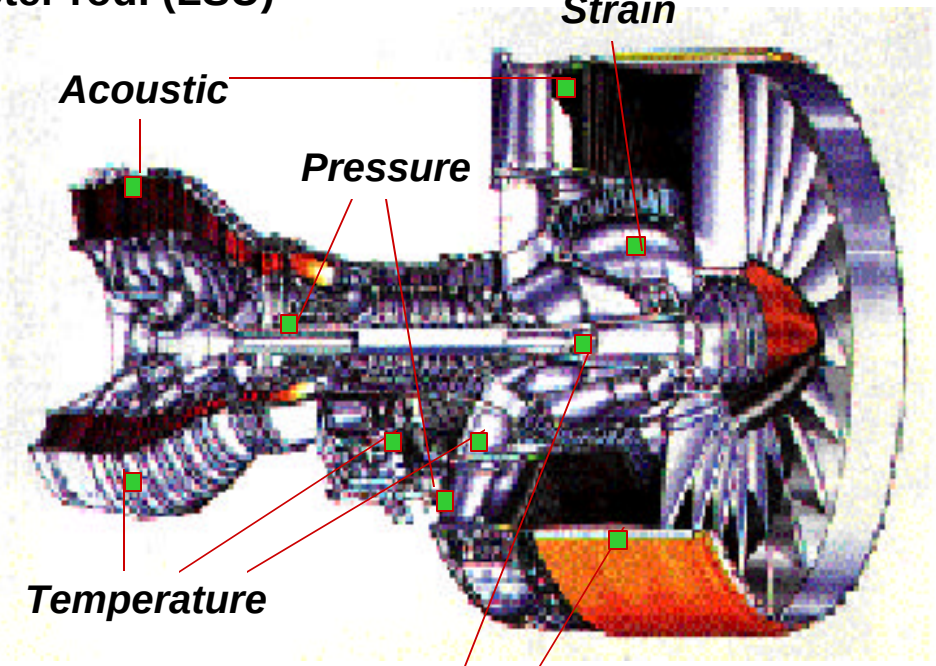
Indestructible Jet Engine

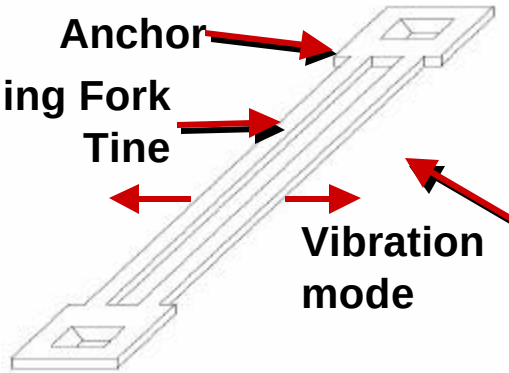
MTO MEMS



Micro heat fins of nickel rods with posts 150 μm diameter, 500 μm tall, spaced on 1.0 mm centers on a 1.7 cm diameter rod. (LSU)



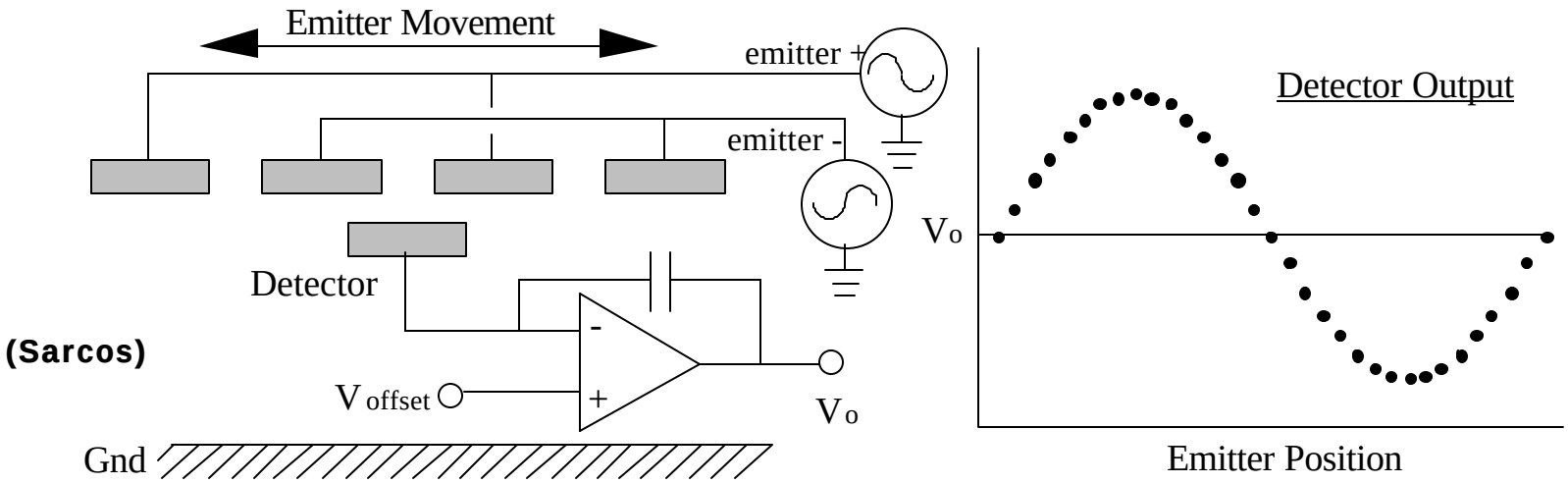




Micro resonant strain gage with over 10,000x sensitivity of metal foil strain gages. Nominal sensitivity 600Hz/μstrain. (UCB)

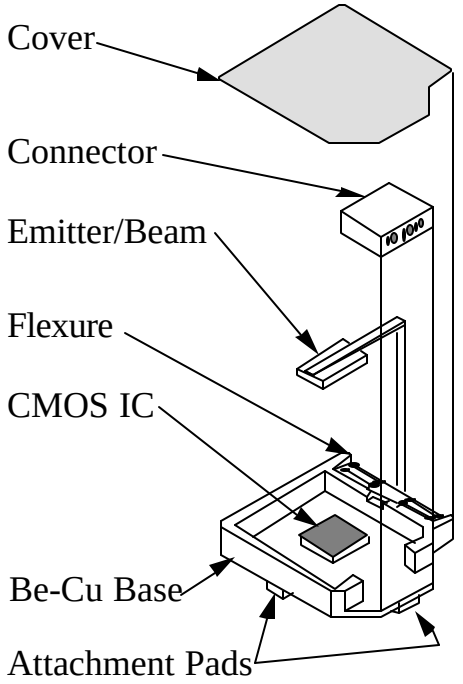
Indestructible Jet Engine

MTO MEMS



SENSOR SPECIFICATIONS:

- **Detector Array:** CMOS; 64 Elements on 55.8 µm centers
- **Emitter Type:** Bipolar, Interdigitated on 57.6 µm centers
- **Gage Length:** 10 mm (nominal)
- **Resolution & Sample Rate:** 0.35 µ-strain @ 150 Hz (15 bits)
  (dynamically configurable for 2.8 µ-strain @ 1000 Hz (12 bits)
  10, 11, 12, 13, 14, or 15 bits) 11.4 µ-strain @ 2500 Hz (10 bits)
- **Dynamic Range:** ±5760 µ-strain
- **Sensor Output:** 15 data bits+1 parity bit, digitally multiplexed
- **Sensor Package Size:** 12.0 mm x 13.6 mm x 2.5 mm
- **Sensor Weight & Power:** 1.5 grams; <150 mW
- **Sensor Network:** up to 128 Sensors per String (2.5 Mbits/sec)
- **Network:** token passing w/ differential data lines; 6-conductors



Indestructible Jet Engine

UAST Demo on 1/2-Scale F/A-18 Tail

Indestructible Jet Engine

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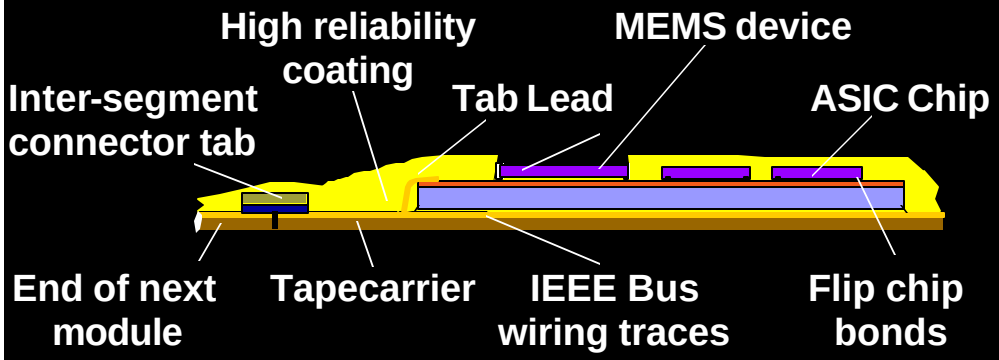
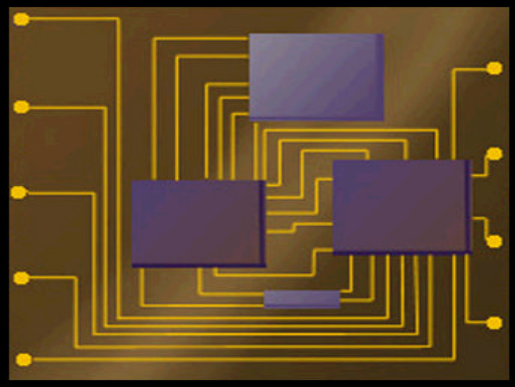
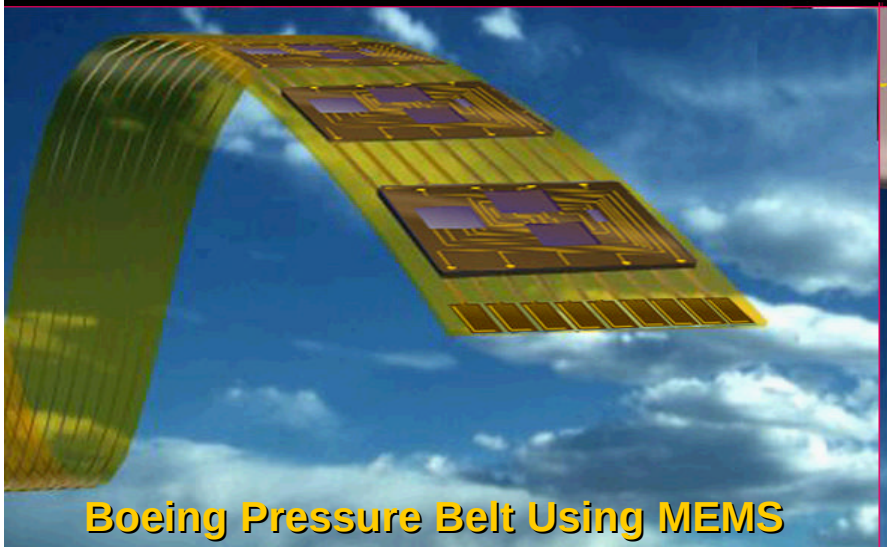
Pressure Belt Cross Section



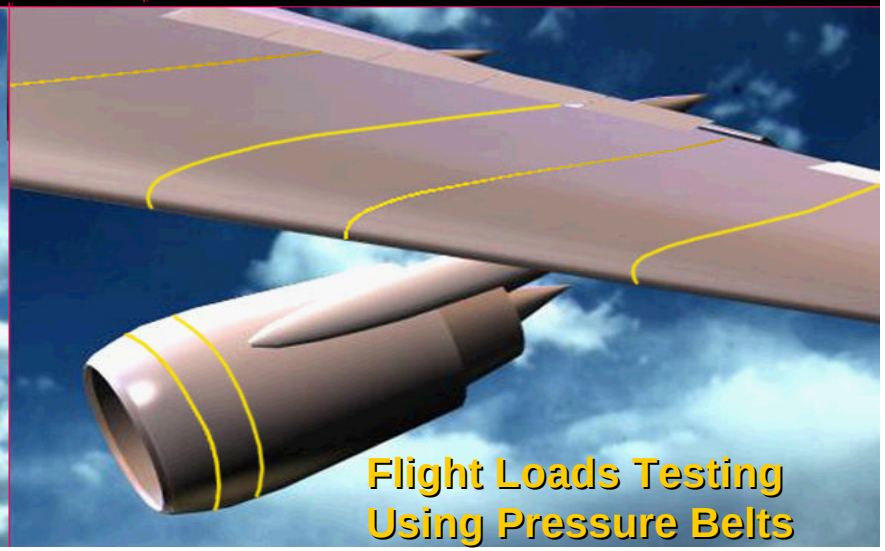
(Vertical scale enlarged for illustration only)

MEMS Sensor Integrated on an MCM with Embedded Passives

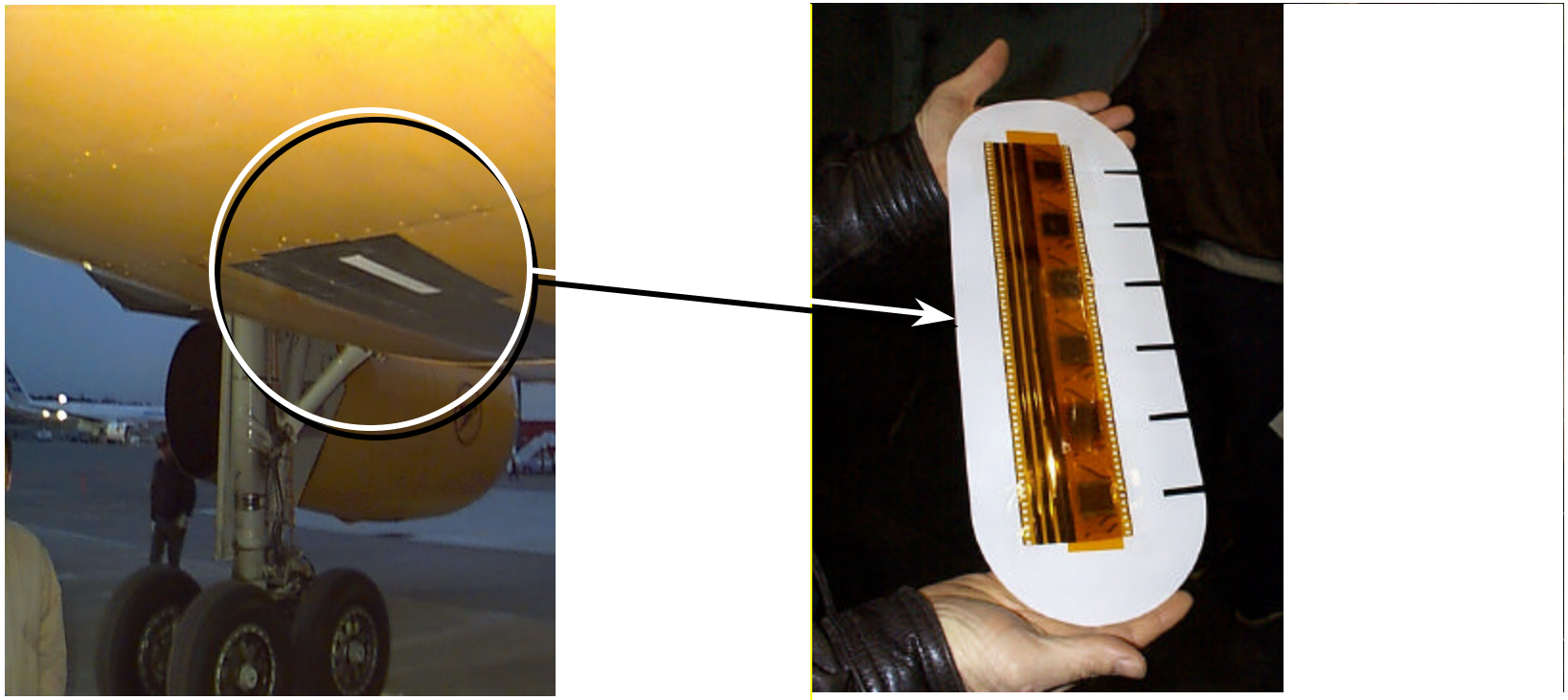




Boeing Pressure Belt Using MEMS



Flight Loads Testing Using Pressure Belts



Boeing MEMS Pressure Belt on Belly Tank of 737

Boeing Information, Space & Defense Systems, Phantom Works

Indestructible Jet Engine

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- Technical challenges
  - **Temperature / Thermal gradients**
  - **Turbine blade flutter / High cycle fatigue**
  - **Blade tip clearance / Flow seals / Compressor Efficiency**
  - **Precision thrust control**
  - **Real-time performance versus lifetime tradeoff**
- MEMS solution
  - **Micro thermal flux control**
  - **Resonant strain measurement (10,000x sensitivity)**
  - **Surface microactuators (anti-ice/de-ice)**
  - **High-bandwidth flow rate sensors**
  - **High-temperature sensors (pressure, temperature, strain)**

Standoff Chemical Sensing

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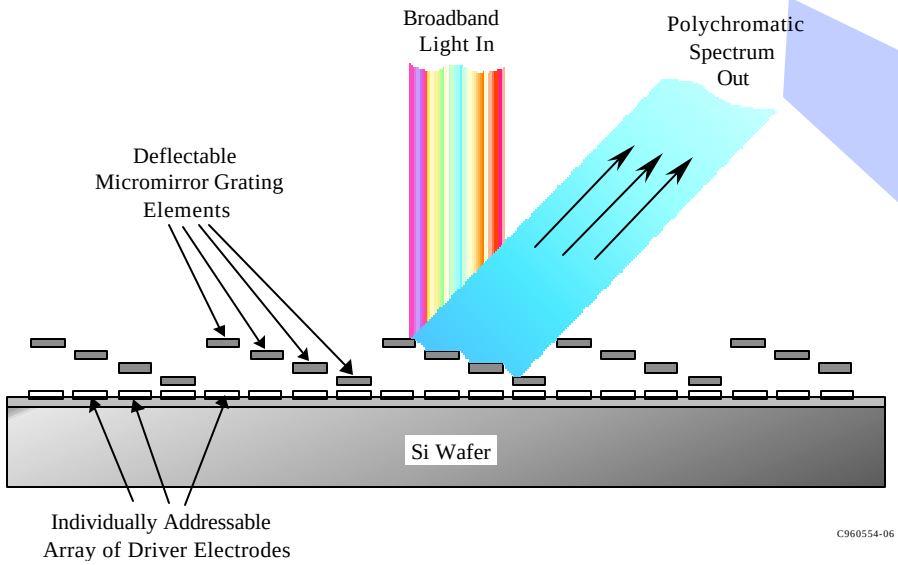
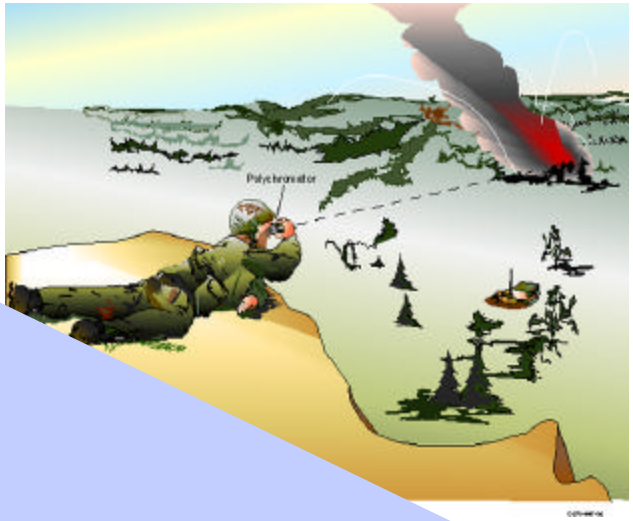
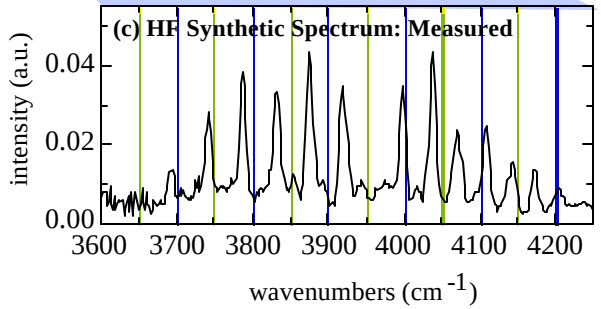
MEMS Polychromator





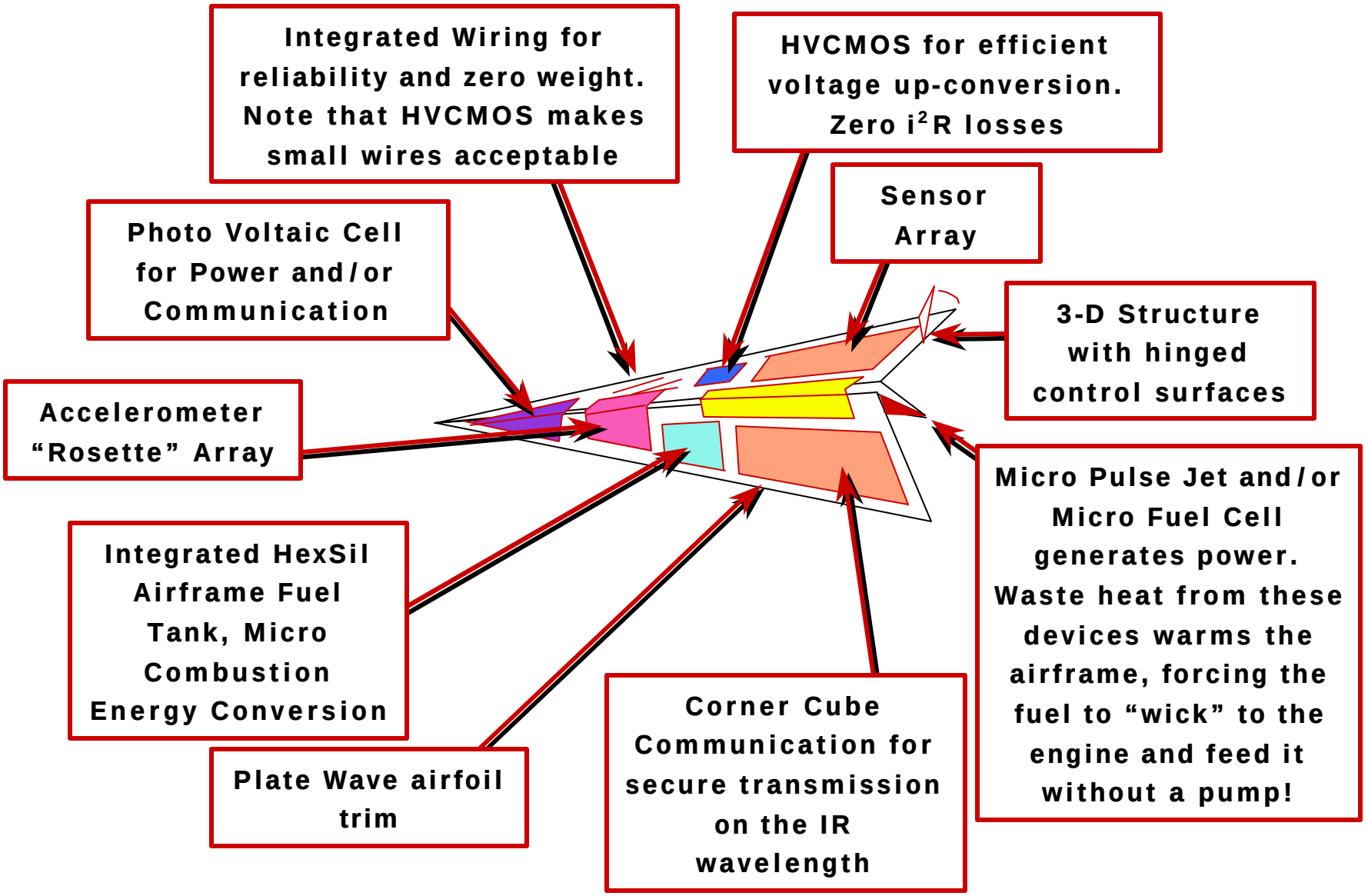


Honeywell Corp.

- **A new concept for an electronically programmable, dark-field correlation spectrometer based on a MEMS diffraction grating.**
- **Leads to development of a miniature, electronically programmable remote chemical detection system for field use.**

Micro Airborne Sensor/Communicator

MTO MEMS



Micro Airborne Sensor/Communicator

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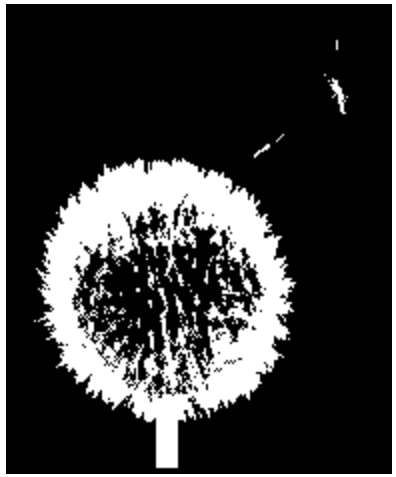

Micro Airborne Sensor/Communicator

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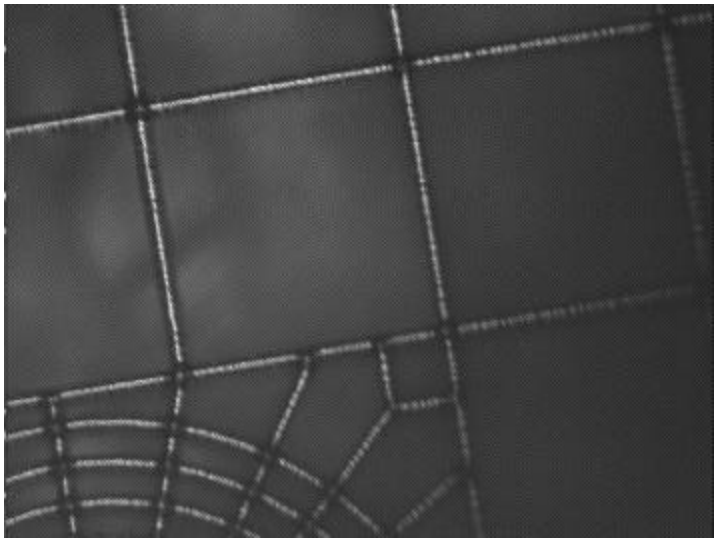
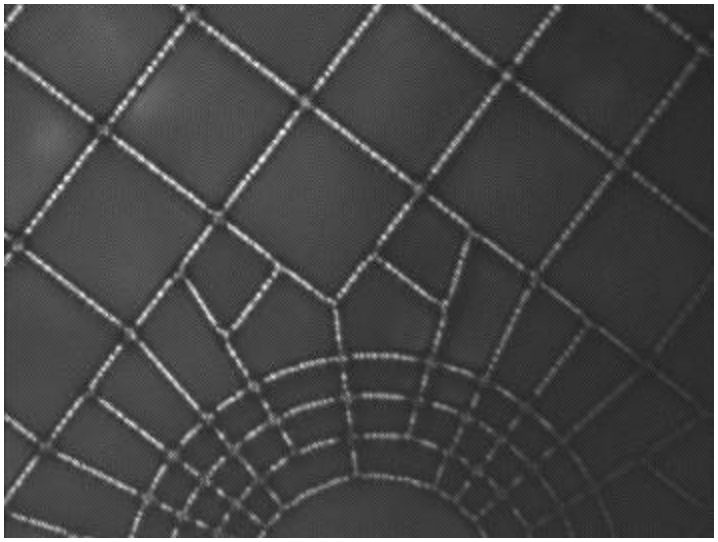
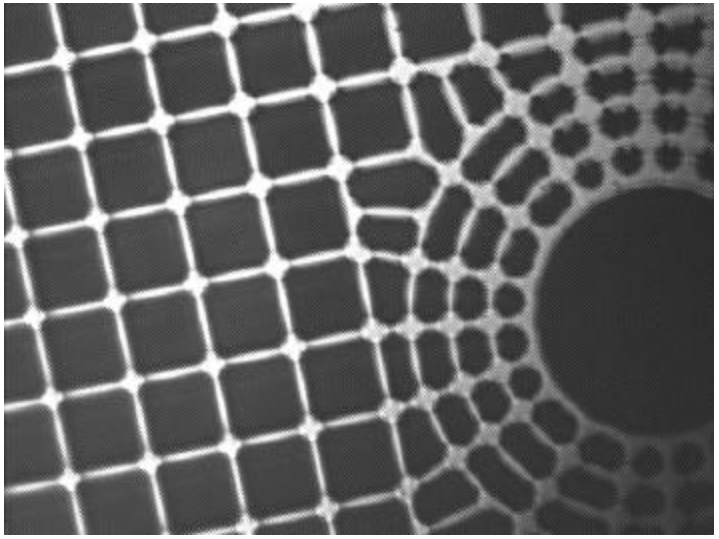


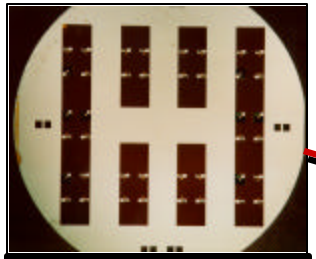




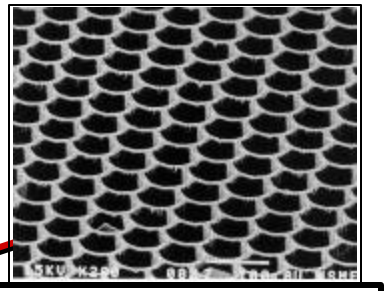
Micro airborne sensor/communicator platform sample with 25, 100 and 50 micron cell sizes. Reinforced hub will support stem.

Micro Airborne Sensor/Communicator

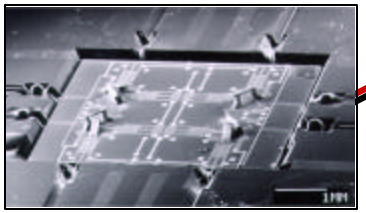
MTO MEMS



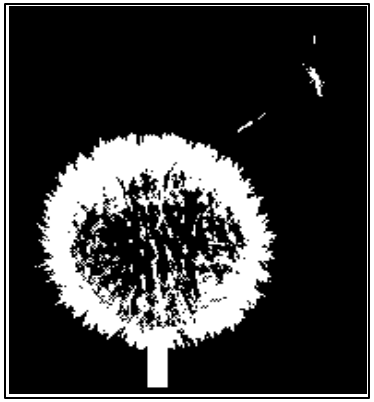
MEMS Microphone



MEMS Structural Material

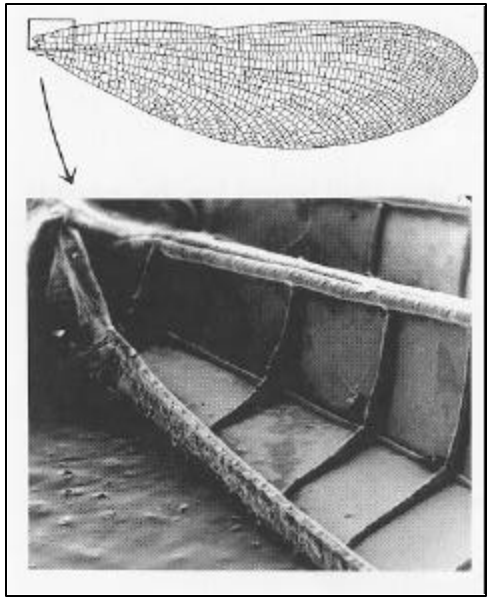


MEMS Optical Communicator



Dandelion Seed Pod

Intel 8086 is only 160 mm square in Pentium-II Fab Process



Damselfly Wing

Micro Airborne Sensor/Communicator

MTO MEMS

- Technical challenges
  - **Size, weight**
  - **Secure communication**
  - **Sensor capability**
  - **Flight control**
  - **Power**
- MEMS solution
  - **HexSil micro honeycomb core material**
  - **Corner cube IR / Wrist communicator**
  - **Micro accelerometer rosette / Micro gyro**
  - **Micro combustor / Micro fuel cell**
  - **HVCMOS/HTCMOS**

Micro Airborne Sensor/Communicator

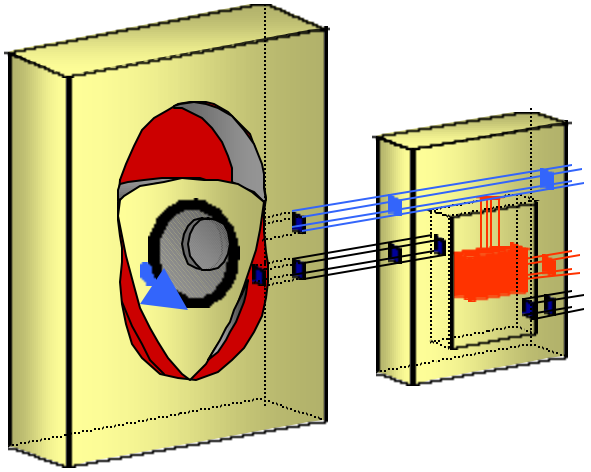
MTO MEMS

- Large area MEMS arrays
- “Zero” interconnect
- “Zero” packaging
- Massively parallel micro assembly
- Insertion of MEMS into fabrication of macro devices
- Distributed sensing, computing, data storing, actuating
- Micro thermo-chemical or chemo-electric power generation
- Integrated structure, fuel reservoir, electronics

Chemical Energy Metrics

MTO MEMS

Compound	W-hr/Kg (Assuming 20% Efficiency)
Methane	3053
Propane	2772
Hexane	2670
n-Octane	2649
n-Decane	2630
Toluene	2347
o-nitrotoluene	1519
p-nitrotoluene	1506
Nitropropane	1245
Dinitrotoluene	1087
TNT	839
Nitromethane	644
Lithium/Organo-Sulfur Polymer	325
Lithium Manganese Dioxide	200
Lithium Polymer	130
Lithium Ion	125

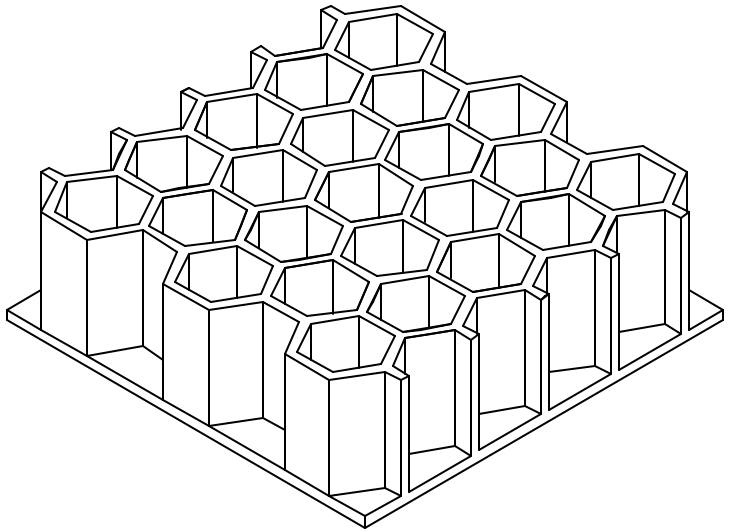


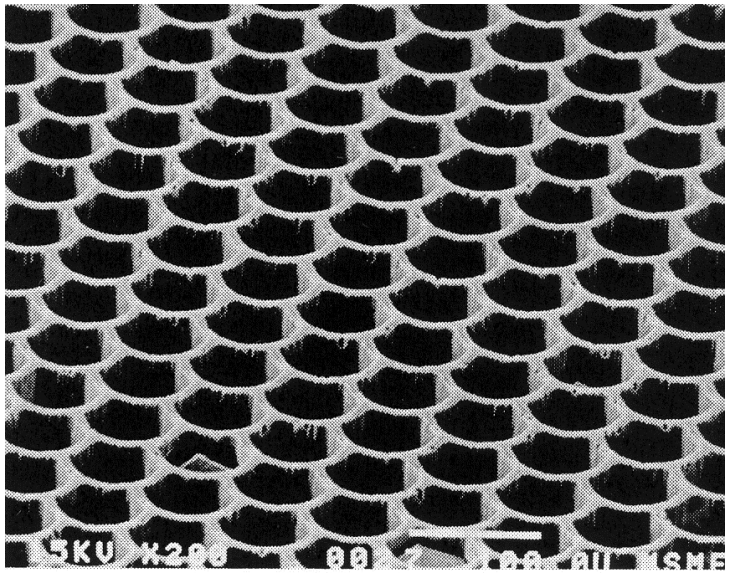
Weight Burden Per Day
for a 9.7 Watt Individual Warfighter System

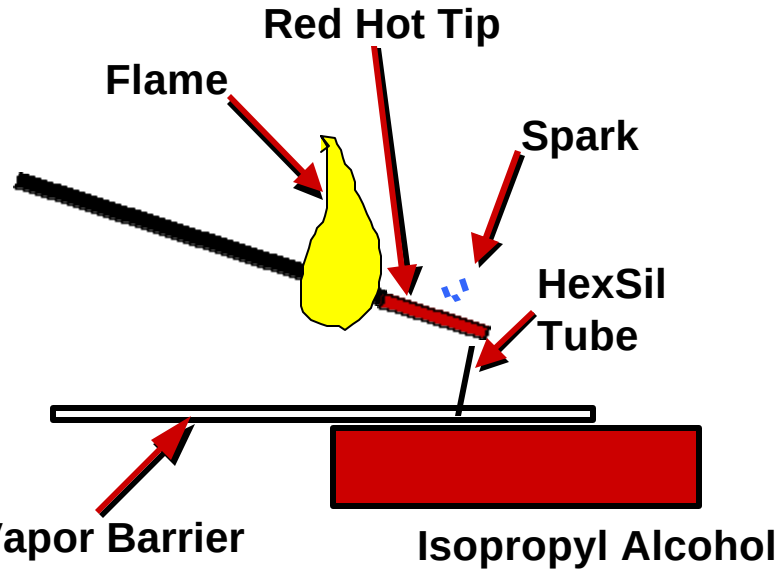
0.58 Kg
0.64 Kg
1.50 Kg
1.69 Kg

Micro Thermal-Chemical Power

MTO MEMS

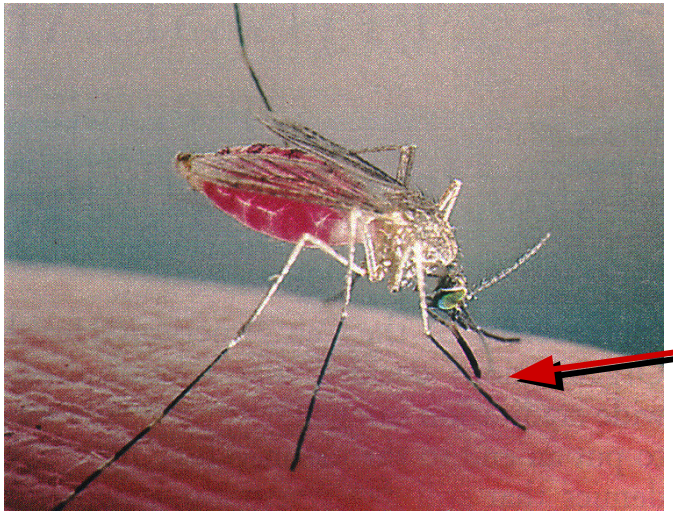


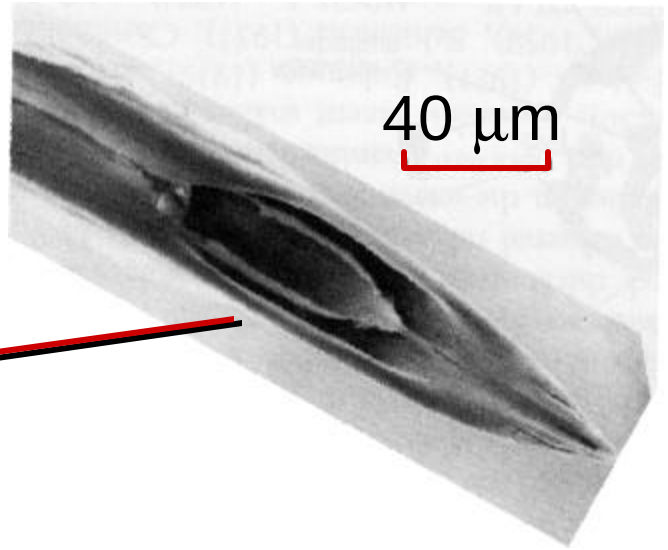


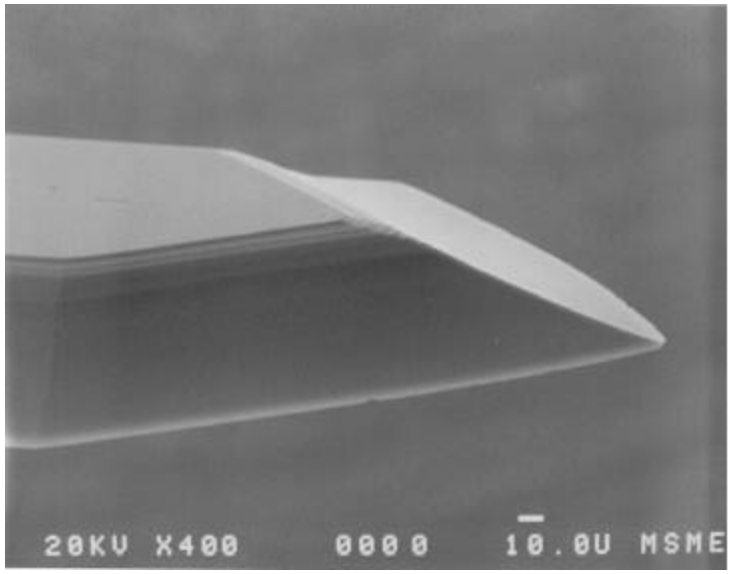


Micro Thermal-Chemical Power

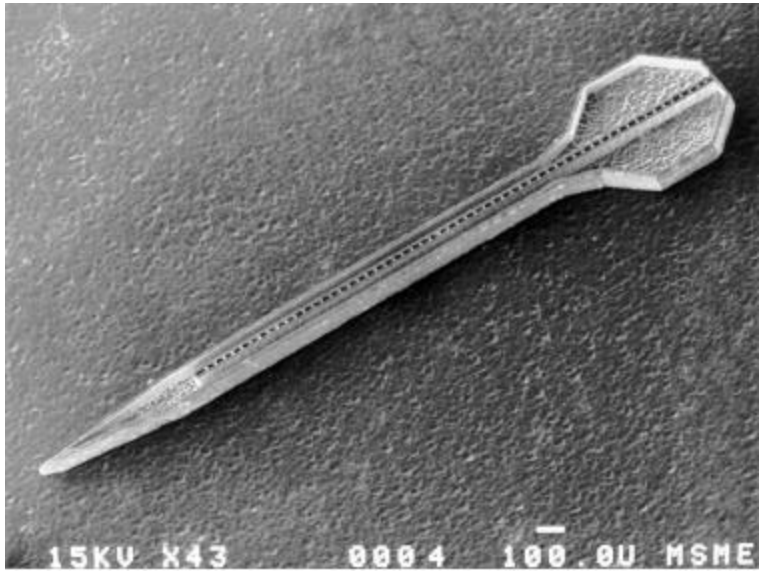
MTO MEMS







Lancet width = 170 mm



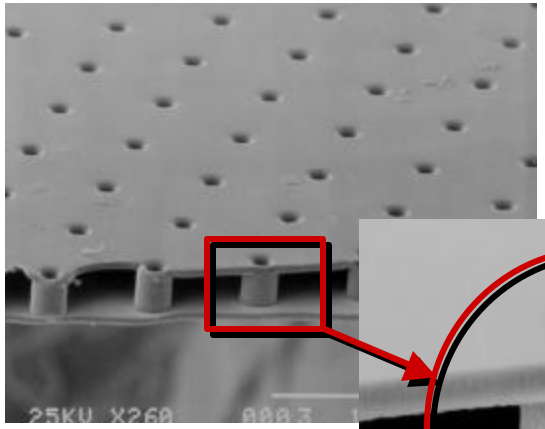
Needle width = 150 mm

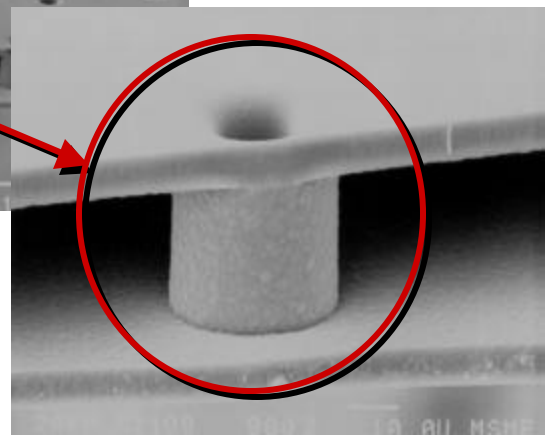
Micro Thermal-Chemical Power

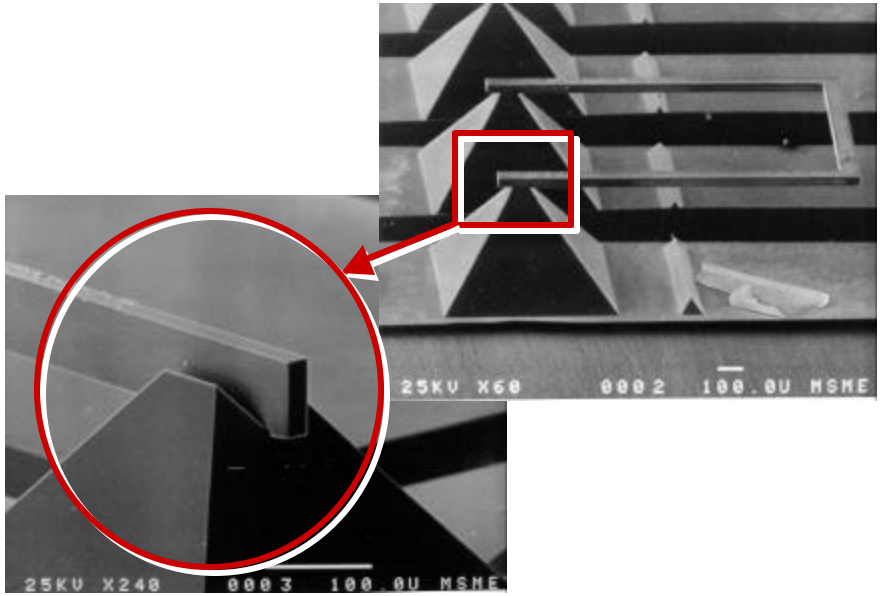
MTO MEMS

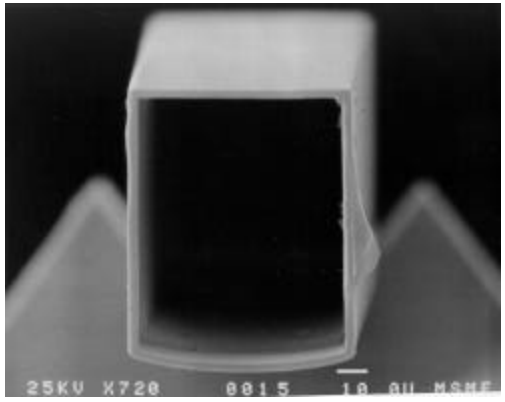
Clockwise from right:

Suspended Microtubes;
Microtube cross section;
Heated Microtube;
Micro Thermal Isolation





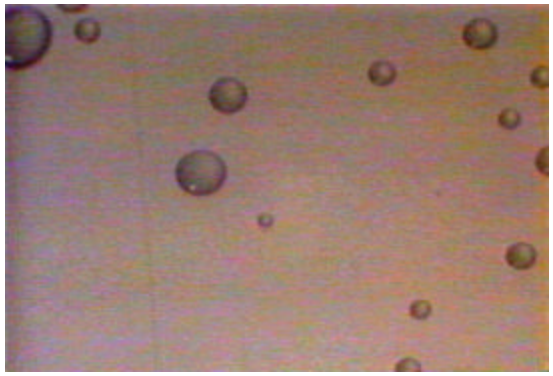




Micro Thermal-Chemical Power

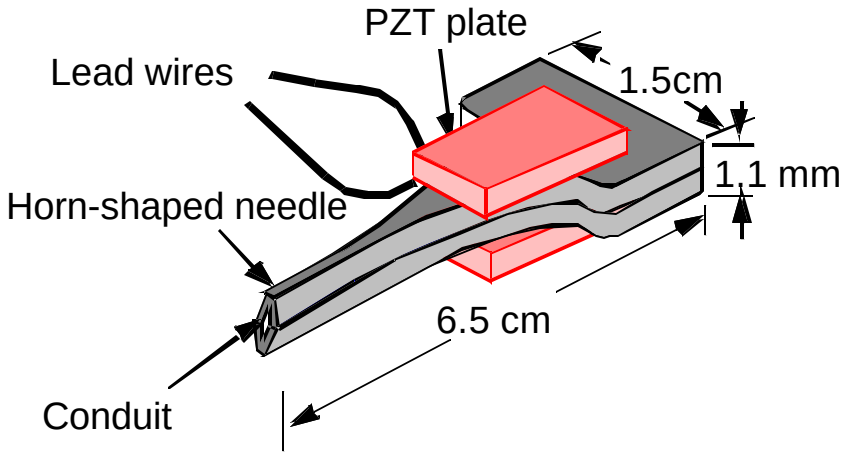
MTO MEMS

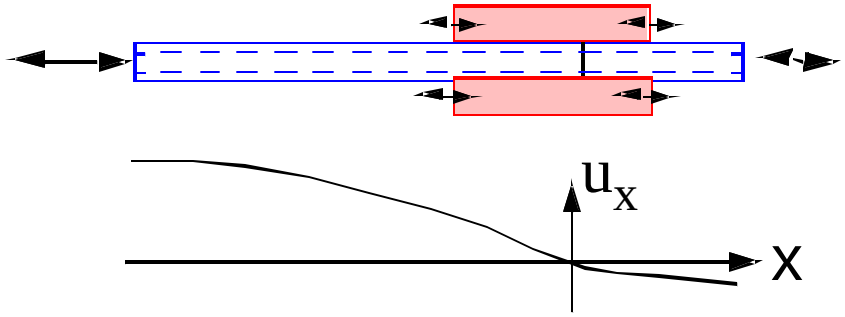
Water Droplets 20-35 μm at 72kHz



Ultrasonic Atomizer

(University of Wisconsin)





Axial Displacement Amplitude

Conclusions

MEMS is an enabling technology that will be part of both macro and micro systems.

- **Extreme miniaturization of low-power communication devices.**
- **Networks of sensors and actuators on macro devices for robustness and performance.**
- **New concepts for stand-off sensing.**
- **Integrated systems for airborne sensing/communication.**
- **Thermal-chemical power on the microscale, for the microscale.**