TACOM

Lethality, Survivability, Mobility and Sustainment for America's Army

13-16 May 2002

NDIA Joint Services Small Arms Conference

Atlantic City, NJ

Development and Demonstration of a MEMS-based Safety and Arming Device for the 20-mm OICW Fuze

US Army TACOM ARDEC Fuze Div.
AMSTA-AR-CCF-A
Adelphi, Maryland
301-394-0754

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Outline

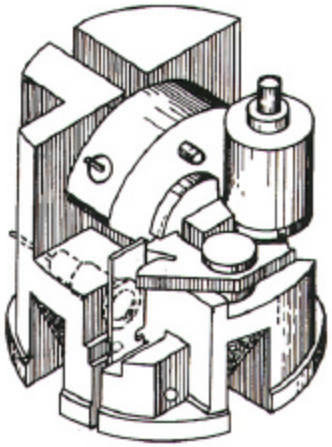
- **Review**
- **MEMS Fabrication**
- **Assembly**
- **Testing**
- **Results**
- **Conclusions**

Micro-Electro-Mechanical Systems Based S&A

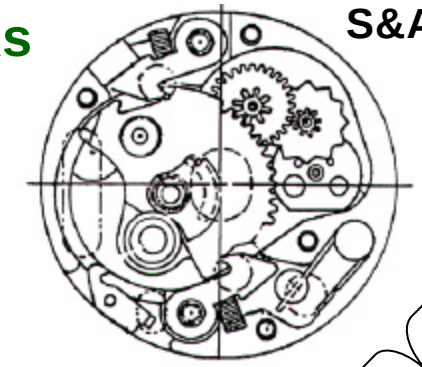
- **Goal - Develop, demonstrate, and evaluate:**
  - → MEMS mechanical S&A device for 20-mm OICW weapon system, and
  - → Compatible micro-scale firetrain (MSF)
- **Approach**
  - → MEMS "inertial mechanical logic" maps S&A functions to planar domain
  - → New methods of assembly
  - → New approach to out-of-line energetics – micro-scale firetrain (MSF)
  - → Demonstrate in laboratory and ballistic tests (5,000 to 80,000 Gs)
- **Why OICW?**
  - → Reduce *cost*, weight, volume of S&A (lethality and affordability)
  - → Cost (including firetrain): several $$ in production quantities of millions
- **Why MEMS? (micro-electro-mechanical systems)**
  - → Economies of high-volume production via semiconductor industry
  - → MEMS die readily integrated with fuze electronics board---sandwich with MEMS chip
  - → Similar architecture for many weapon systems

MEMS Technology Reinvents the Mechanical S&A

Conventional Mechanical S&As

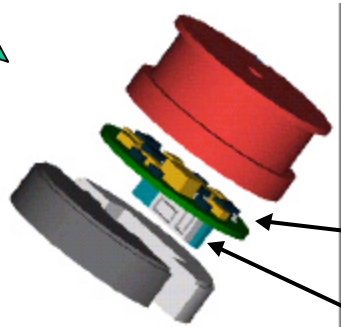


Missile S&A



Artillery S&A

Incorporate the functions of a conventional mechanical S&A in a single S&A die integrated with a fuze circuit.



Concept Fuze for OICW

Fuze Circuit

MEMS S&A die

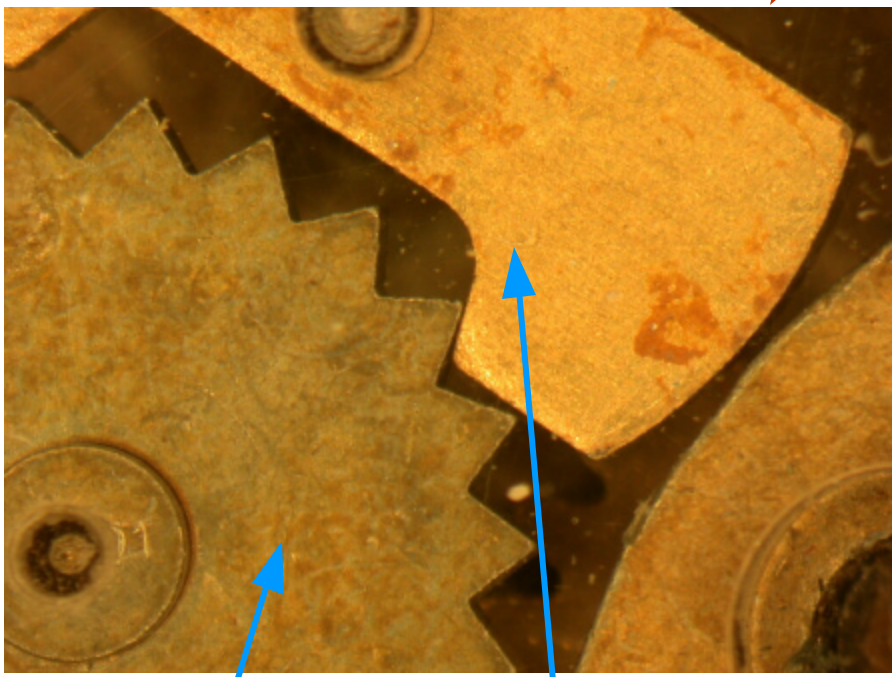
A MEMS mechanical S&A is not a “sensor” per se. Rather, its components intrinsically combine both sense and actuate functions in a single unpowered chip.

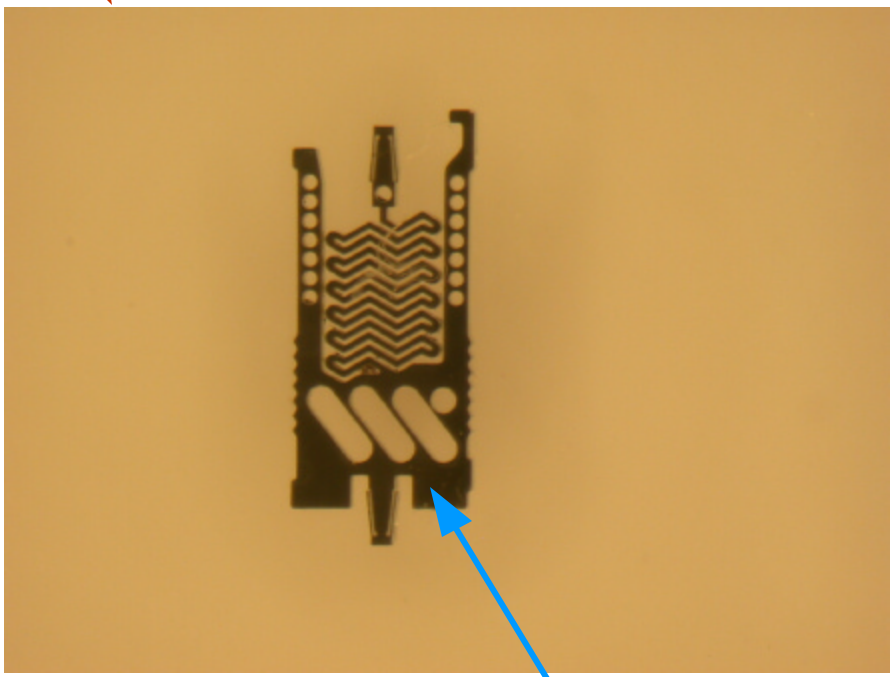
MEMS – “In a Nutshell”

Same Scale

OLD WAY

MEMS WAY

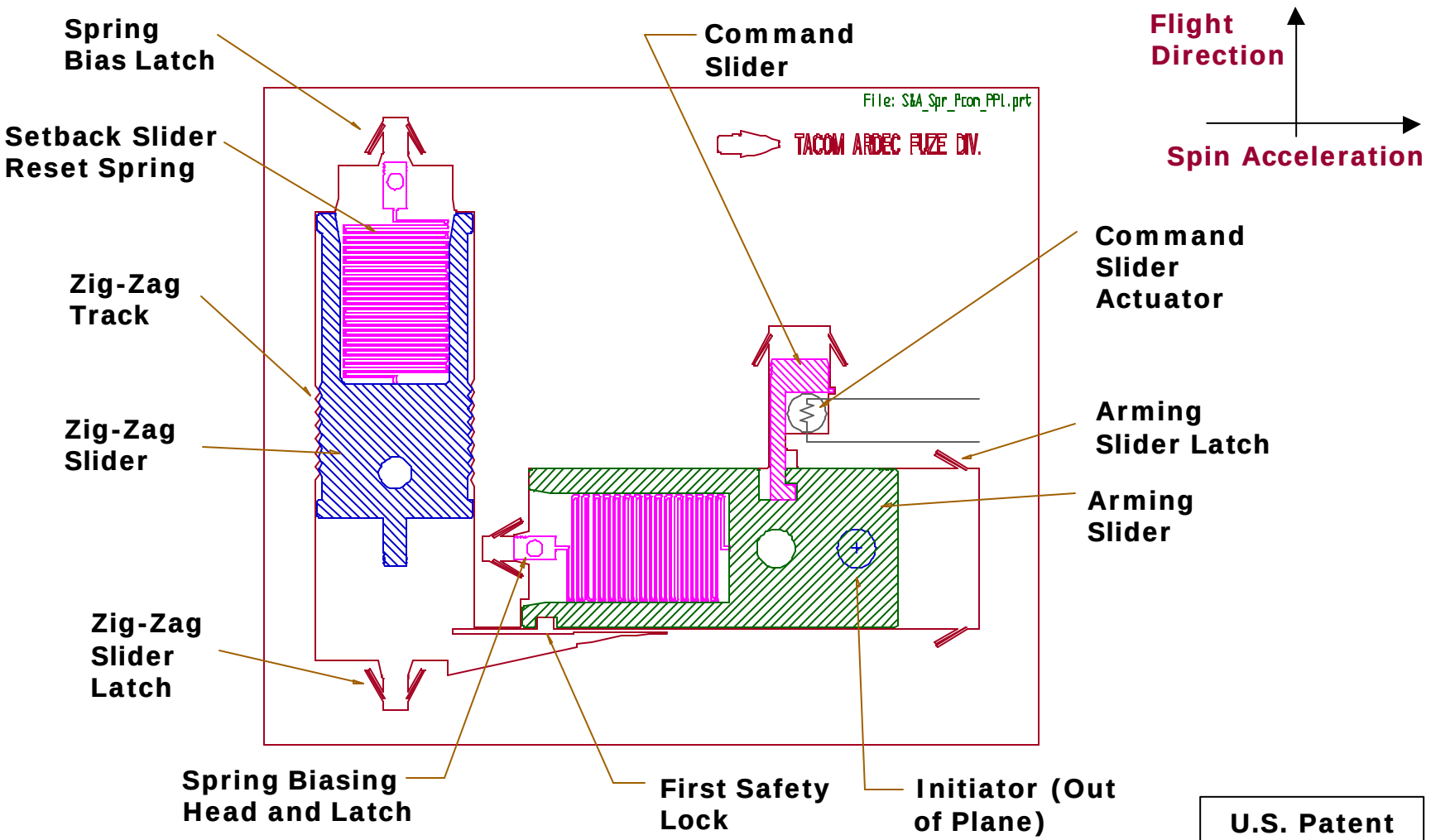




Gear Drive and Pallet

Zig-Zag Slider

Ultra-Miniature Monolithic Mechanical S&A

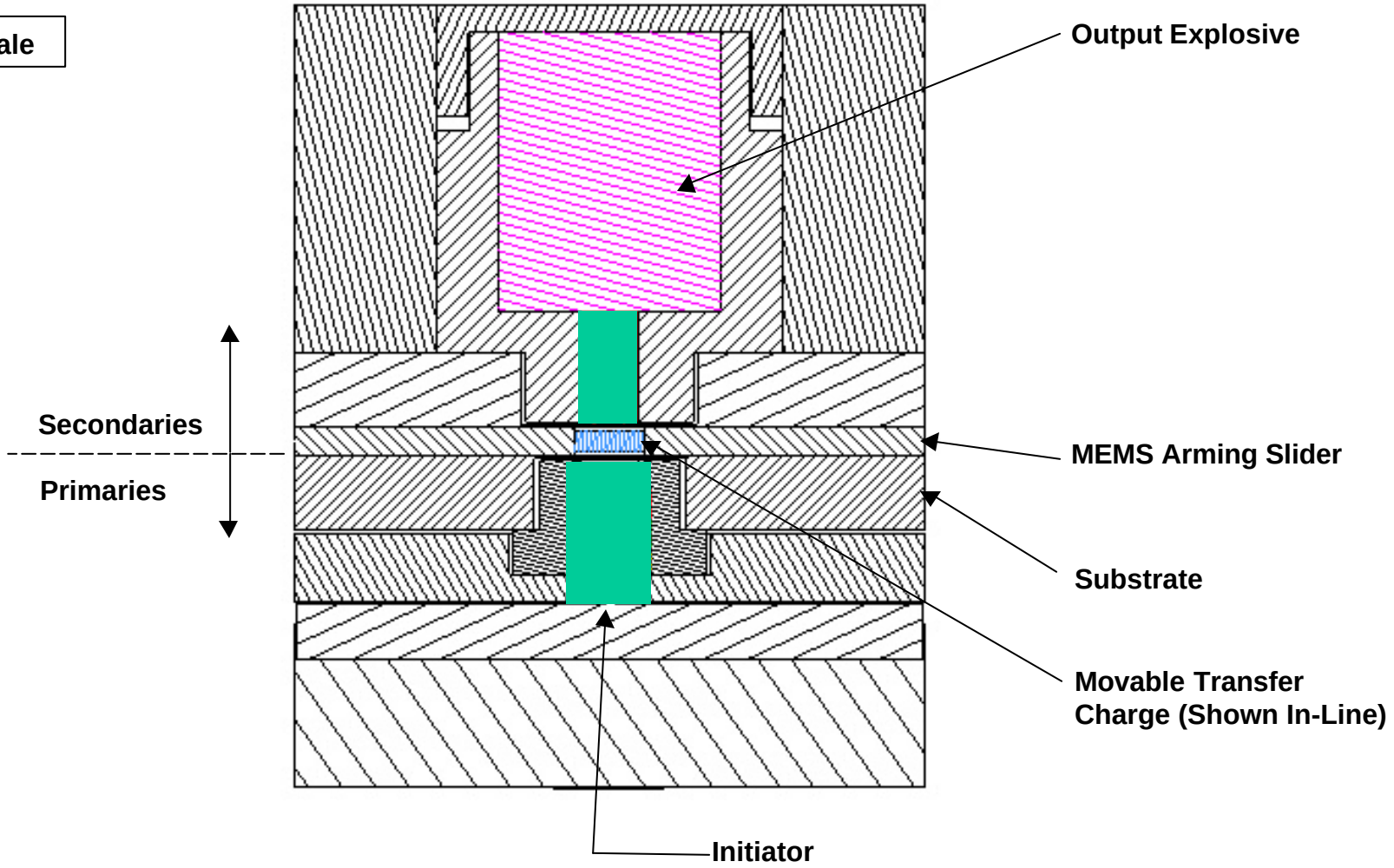


U.S. Patent 6,167,809

Committed To Excellence

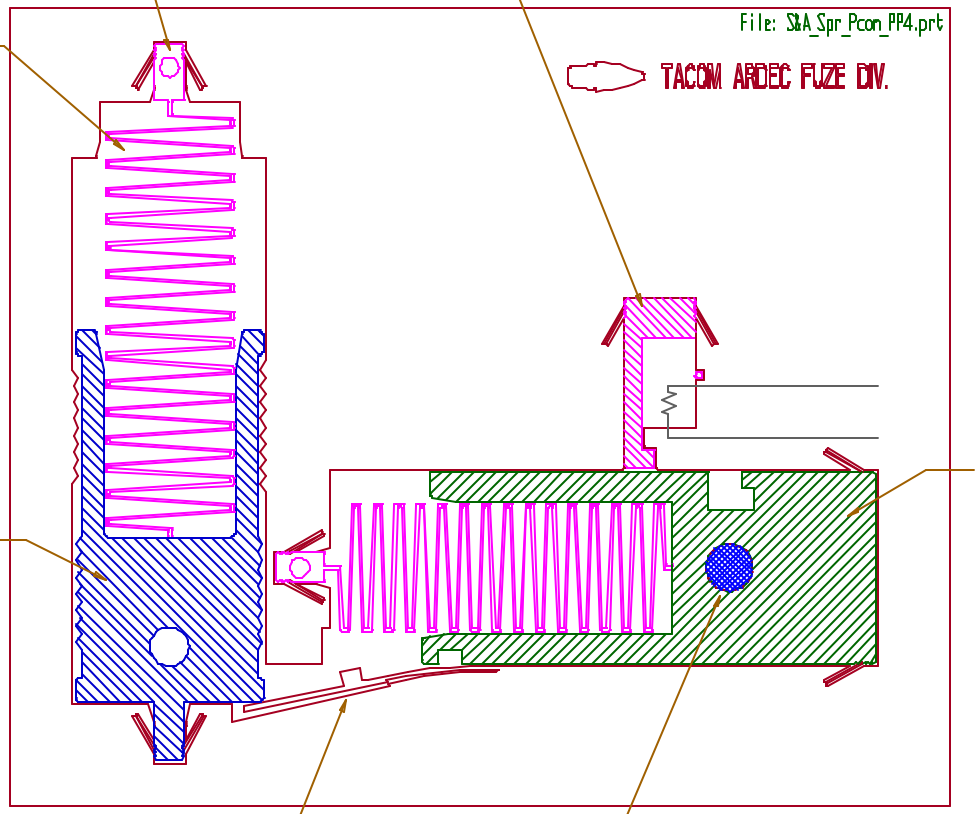
MEMS-Enabled Firetrain per MIL-STD-1316

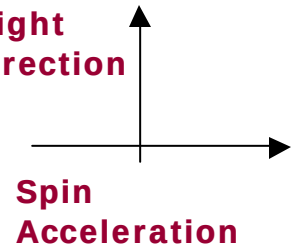
Not to Scale



Committed To Excellence

Components in Armed Position

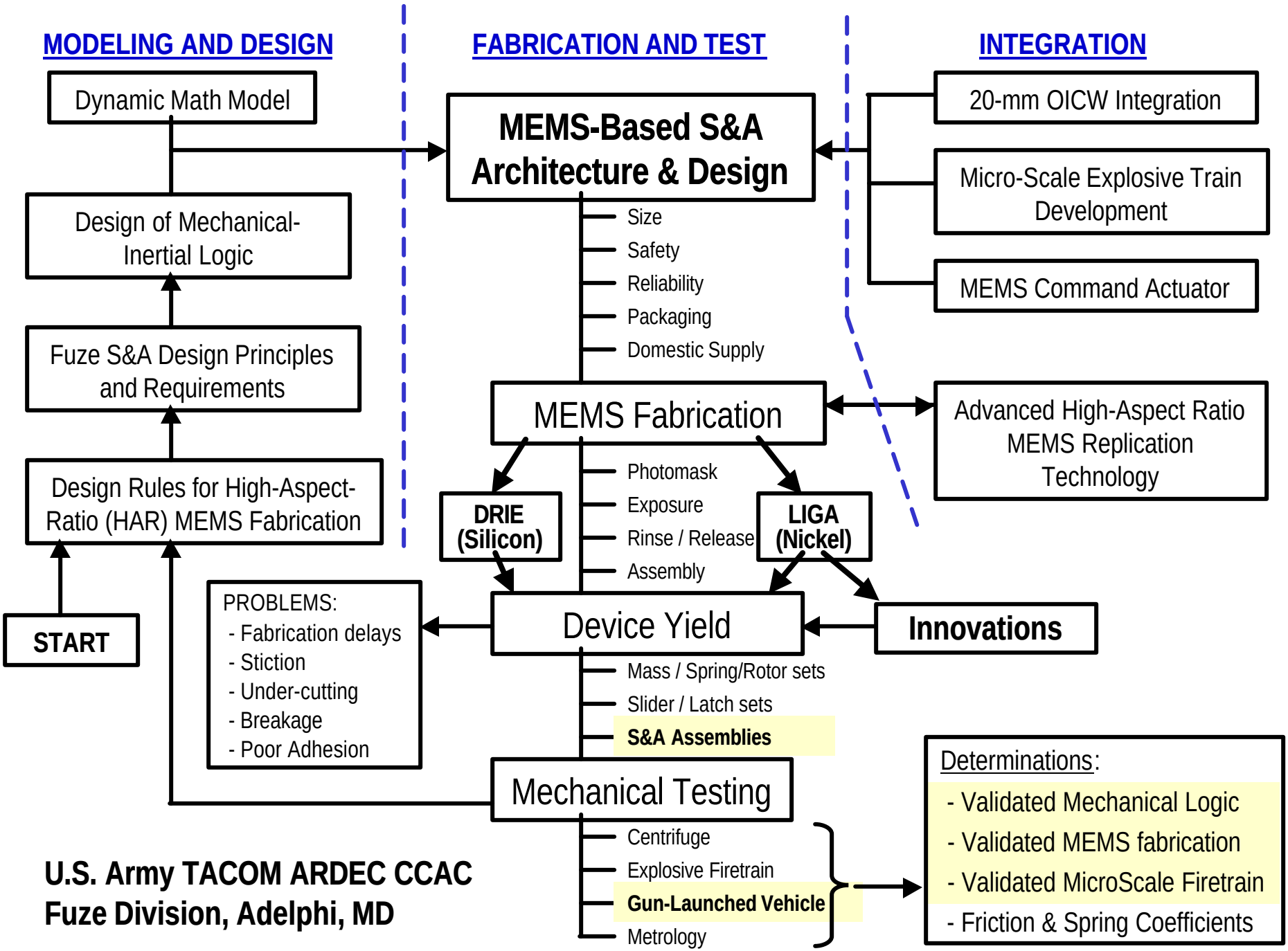




U.S. Patent
6,167,809

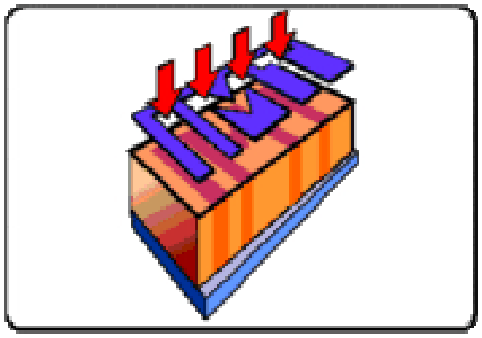
Technical Teamwork

- **Program Coordination:**
  - → Technical Lead, TACOM ARDEC CCAC Fuze Division
  - → Program Sponsor, JSSAP (OICW System Enhancements STO)
- **MEMS S&A Device**
  - → Concept, Analysis, and Design: TACOM ARDEC CCAC Fuze Division
  - → MEMS Fabrication, CNRI MEMS Exchange, Reston, VA
- **Micro-scale Firetrain**
  - → Firetrain development, NAWC-China Lake
  - → Firetrain producibility, TACOM ARDEC WECAC
- **Flight Test Support**
  - → 40-mm Grenade (MK19 LMG platform): ARL Blossom Point Test Facility
  - → 20-mm OICW Projectile (Mann barrel): Alliant Techsystems

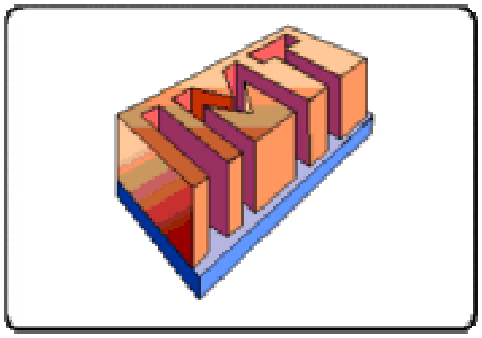

MODELING AND DESIGN
FABRICATION AND TEST
INTEGRATION
Dynamic Math Model
MEMS-Based S&A Architecture & Design
20-mm OICW Integration
Micro-Scale Explosive Train Development
MEMS Command Actuator
Design of Mechanical-Inertial Logic
Size
Safety
Reliability
Packaging
Domestic Supply
Fuze S&A Design Principles and Requirements
MEMS Fabrication
Advanced High-Aspect Ratio MEMS Replication Technology
Design Rules for High-Aspect-Ratio (HAR) MEMS Fabrication
Photomask
Exposure
Rinse / Release
Assembly
DRIE (Silicon)
LIGA (Nickel)
START
PROBLEMS:
- Fabrication delays
- Stiction
- Under-cutting
- Breakage
- Poor Adhesion
Device Yield
Innovations
Mass / Spring/Rotor sets
Slider / Latch sets
S&A Assemblies
Mechanical Testing
Centrifuge
Explosive Firetrain
Gun-Launched Vehicle
Metrology
Determinations:
- Validated Mechanical Logic
- Validated MEMS fabrication
- Validated MicroScale Firetrain
- Friction & Spring Coefficients
U.S. Army TACOM ARDEC CCAC
Fuze Division, Adelphi, MD

Materials and Micromachining for MEMS

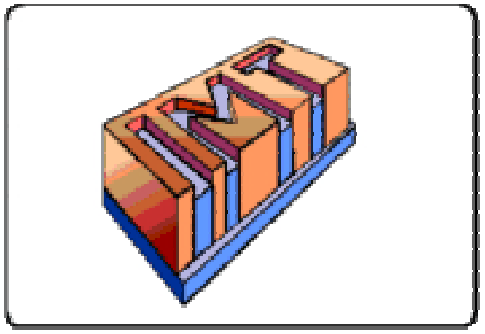
Lithograph (LIGA) Process



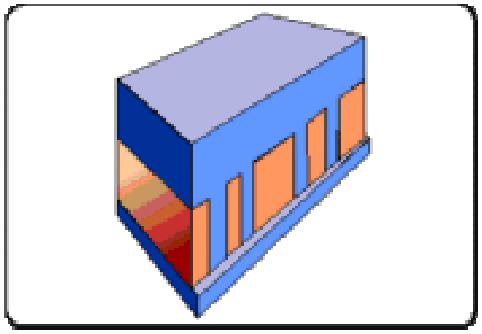
1 Exposure



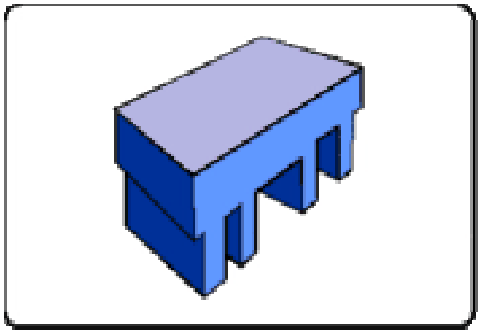
2 Development



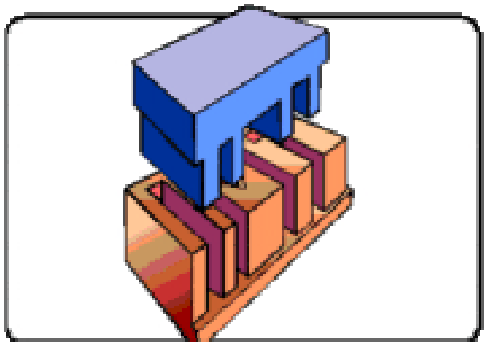
3 Electroforming



4 Fabrication of molding tool



5 Molding tool



6 Molding

“MEMS” Technology – Define Terms!

MEMS ≠ MEMS

PROCESSES

LIGA
RIE and DRIE
SU-8
Bulk Etching
iMEMS
Wafer bonding
HAR and LAR
Surface Etching

Sensors
Actuators

Active
Passive

MATERIALS

Silicon
Nickel
SiC
Ceramic
Poly-silicon
Piezoelectric Film
Shape-memory alloy

PHYSICAL PRINCIPLES

Inertial
Thermal
Electromagnetic
Piezoelectric
Fluidic
Chemical
Electrostatic
Optical

SIGNATURES

Acceleration
Force
Rate
Flow
Chemical
Pressure

Status/Issues One Year Ago (April 2001)

One Year Ago (May 2001)

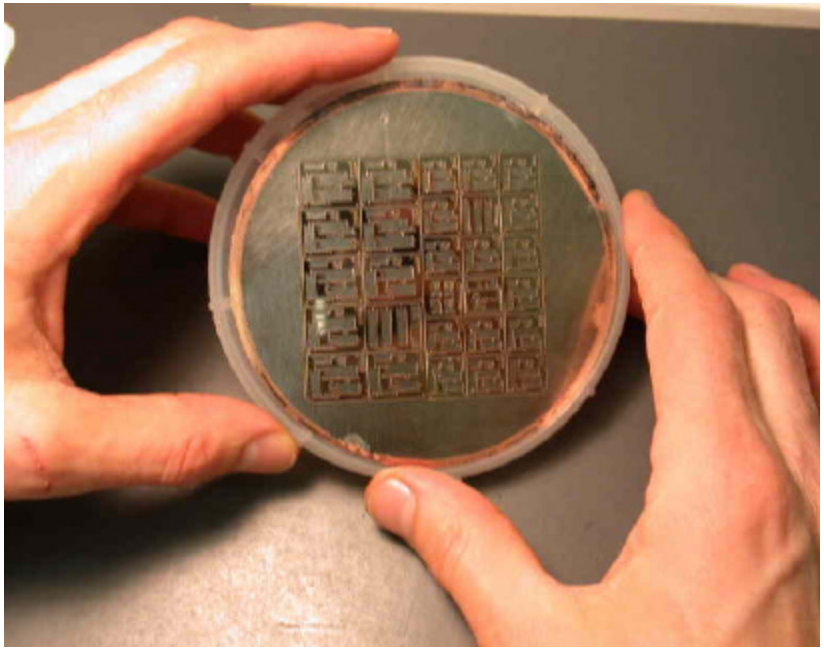
- **Demonstrated components/assemblies for 3-slider mechanical logic**
  - → springs, sliders, masses, locks, latches
- **Dearth of MEMS parts**
  - → Fabrication cycle times were 6 to 12 months
  - → Silicon process "yield" was low, approximately 20%
  - → Moving from silicon to nickel technology
- **Testing:**
  - → Lacked hardware to do scheduled gun launch demonstration
- **Parallel development of micro-scale firetrain in laboratory:** Proceeding well

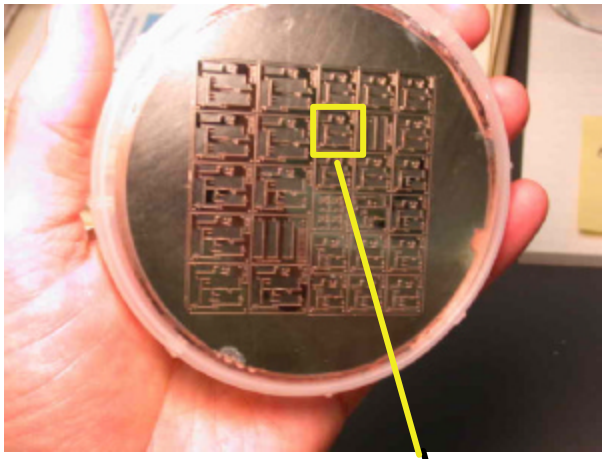
This Year (May 2002)

- **Lots of parts**
- **Flight test results**
- **Firetrain development is keeping pace**

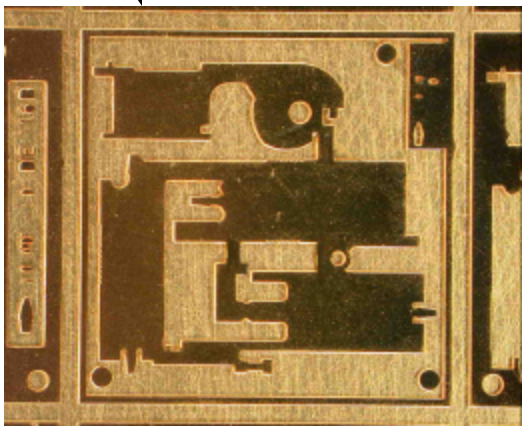
Fabrication –MEMS Substrates

- **LIGA high-aspect-ratio MEMS fab**
- **10 x 10-mm substrate dies**
- **About 36 dies fit on a 4” wafer**



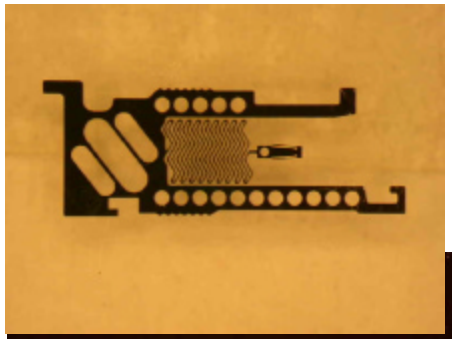


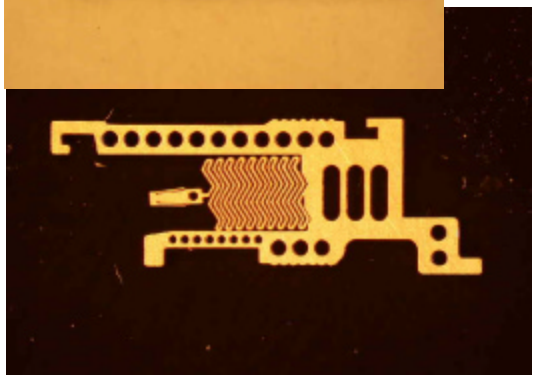
‘Frame’ die

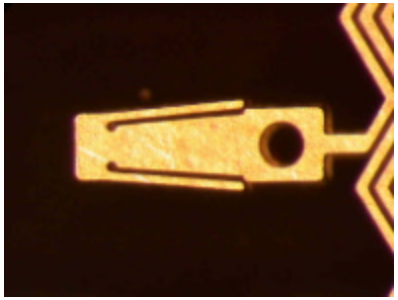


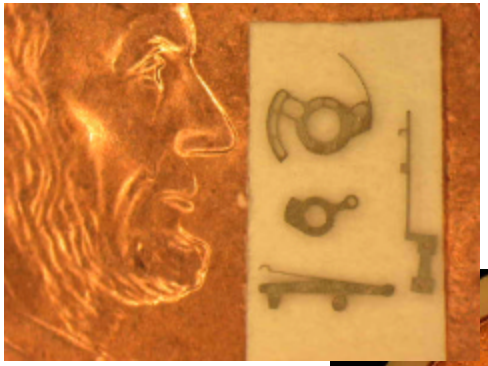
LIGA (nickel) micro-parts are micro-assembled into LIGA-formed “frames”

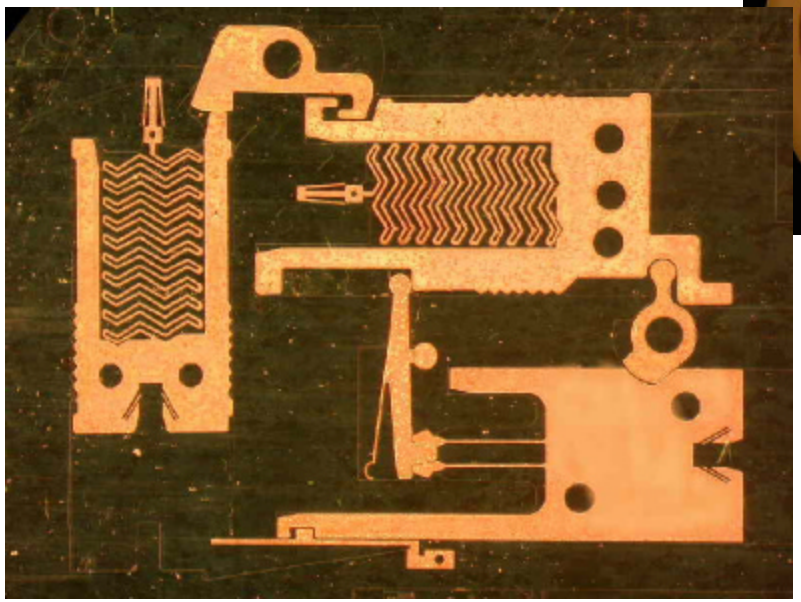
Fabrication – Parts and Assembly











U.S. Patents

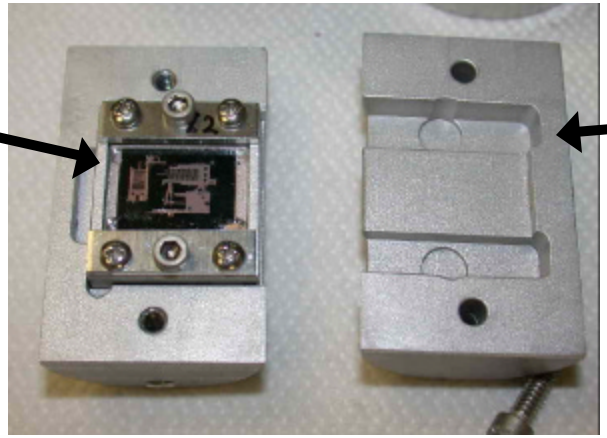
5,705,767

6,167,809

6,321,654

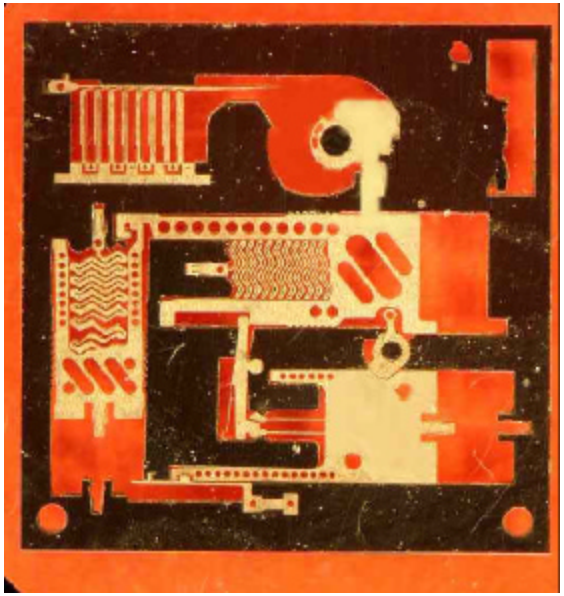
Assembly for Test

Die Carrier



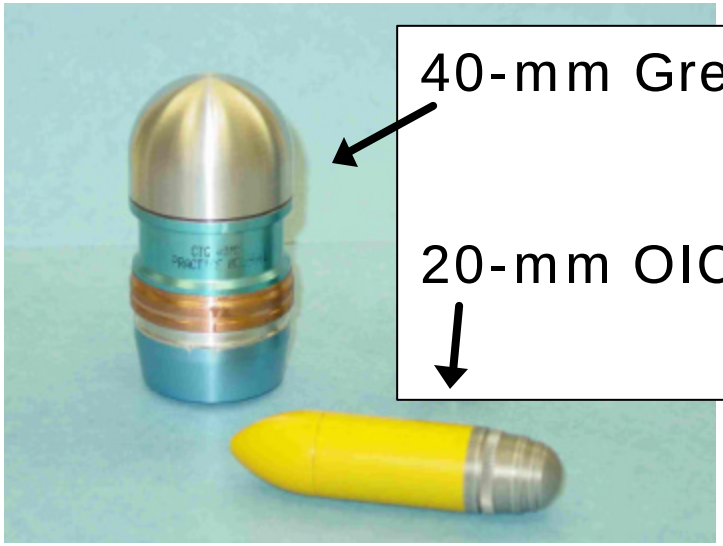
Clamshell Module

S&A Die, 10 x 10 mm



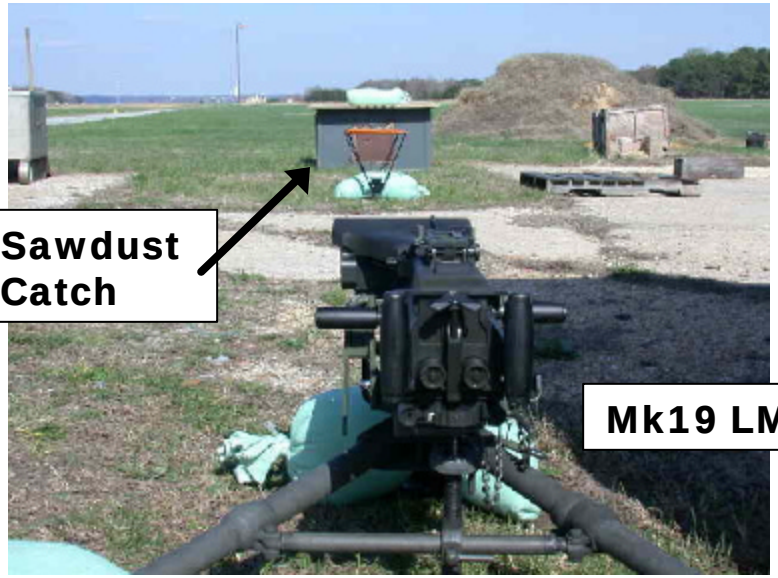
40-mm Grenade

April 2002
Ballistic Test of S&A, 40-mm Grenade



Flight Test, 02 April 2002

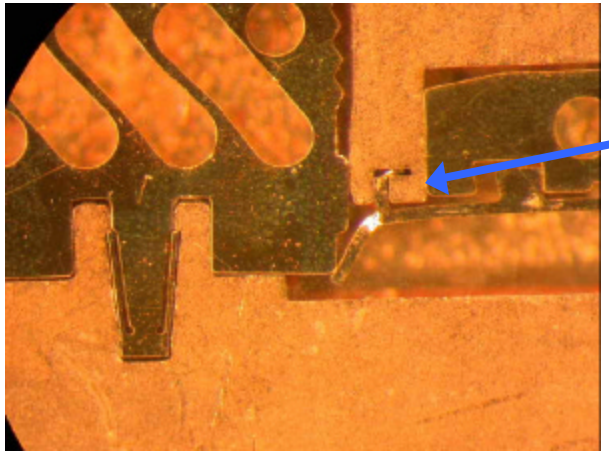
- **ARL Blossom Point Test Range**
- **Mk19 LMG, 40-mm grenade**
  - **42 kGs Setback (peak)**
  - **200 RPS Spin**
- **12 inert S&A Assemblies Fired***
- **Sawdust catch box and recovery**



*** Command actuator not included**

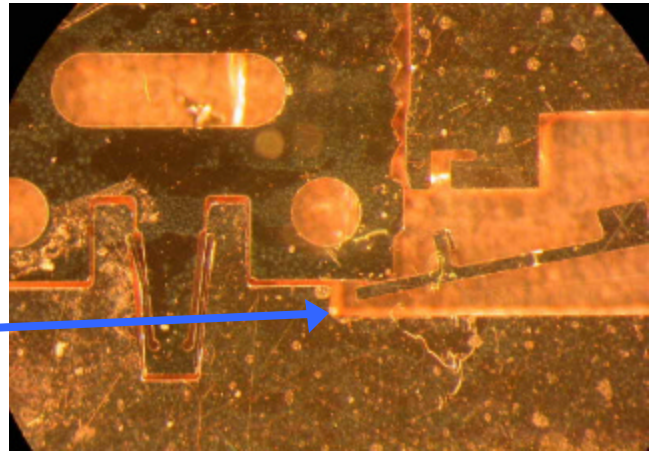
Committed To Excellence

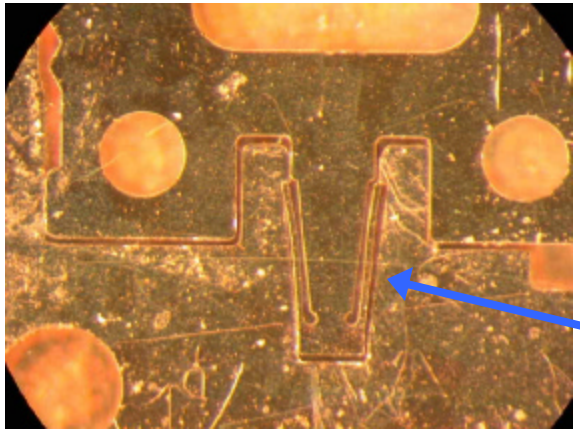
Results continued, Mk19 Flight Test



Failure Analysis: shear tab did not release and lock lever bent.

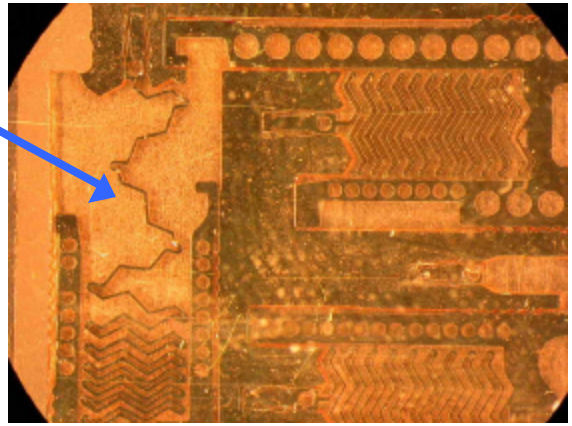
Solution: strengthen lock lever and re-engineer sheer tab





Slider Locks: some did not hold, make design more robust

Setback Slider Spring Deploys OK



Results from Mk19 Test

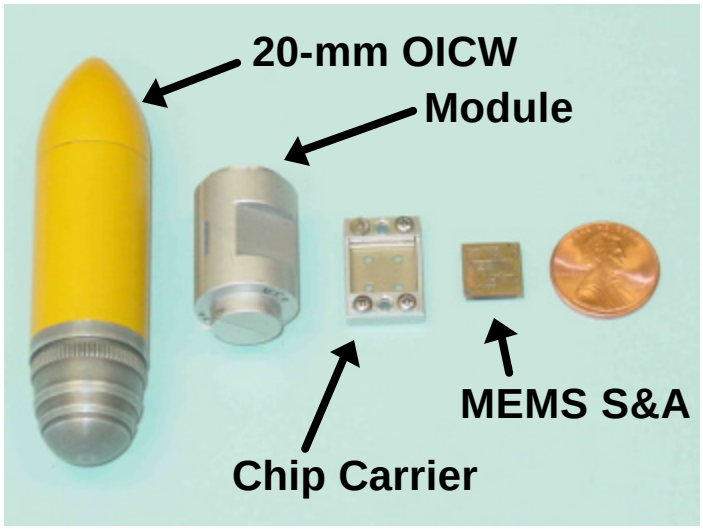
Summary:

- Eight of twelve S&As armed correctly
- Three S&As did not arm because setback lock shear tab was too strong
  - → Lock lever was too weak, failed in bending
  - → Setback slider provided plenty of force!
- One S&A did not arm, reason not yet known

Findings:

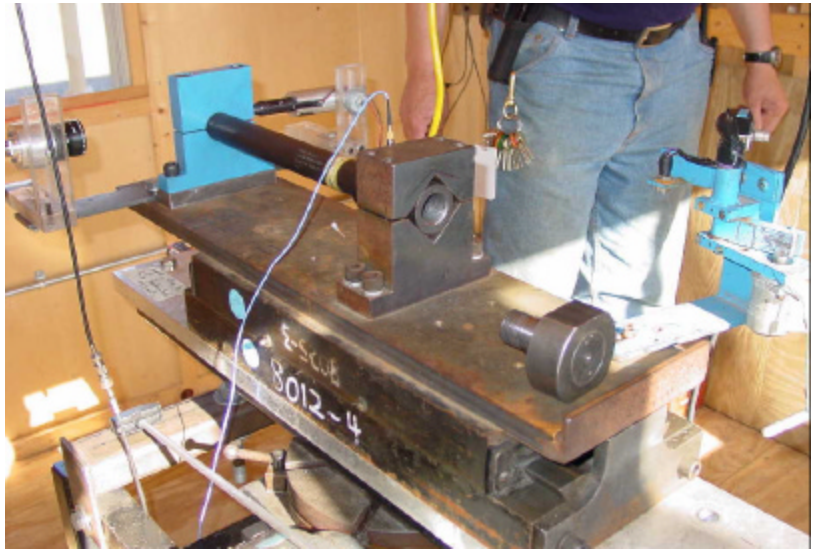
- With correct shear tab and lock lever, S&A will arm
- If first lock not removed, arming slider remains in SAFE position!
- Some spring latches came loose, need to improve design

OICW Ballistic Test of MEMS S&A



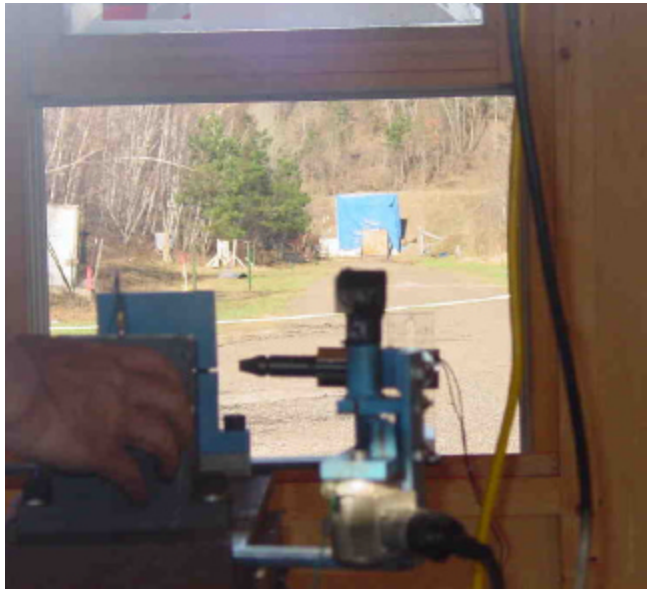
17 April 2002 Flight Test

- **5 rounds* at 65 kGs Setback**
- **5 rounds* at 45 kGs Setback**
- **Mann Barrel Fixture**
- **Performed at ATK Elk River**



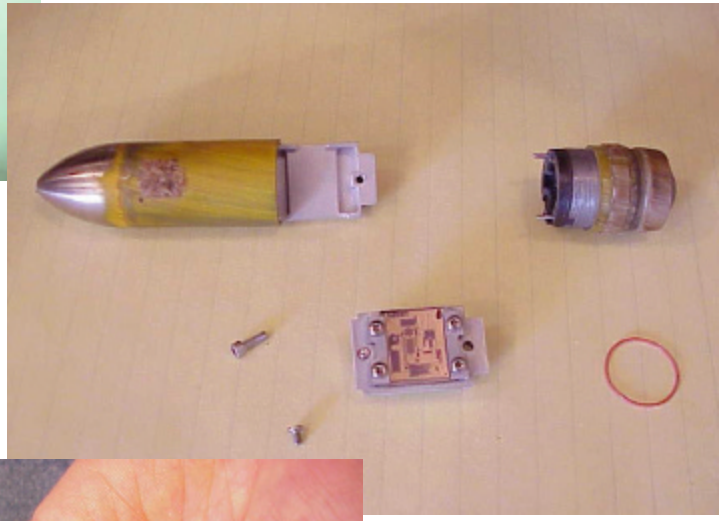
*** Command actuator not included**

OICW Ballistic Test of MEMS Mechanical S&A



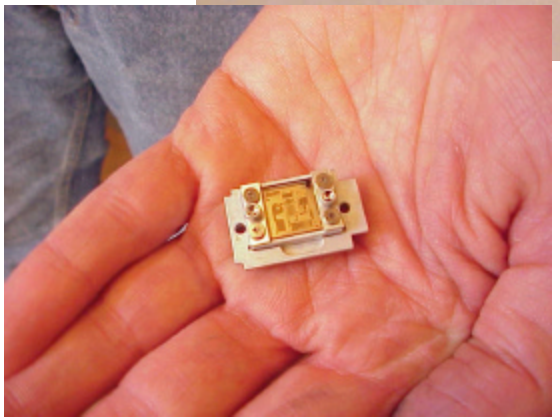
Mann Barrel and Target

Recovered Assembly



17 April 2002 Flight Test

- 300-m range to target
- 490 RPS spin
- Soft Catch (fiberboard)
- Rounds recovered
- Nine of nine S&As armed



Armed S&A!

Results from OICW Flight Test

- **Of 10 shots:**
  - → Nine S&As armed correctly (but command actuator was inactive)
  - → One of the nine missed target, bounced, was recovered fully armed
  - → The one that did not arm was mis-assembled in lab (deemed a no-test)
- **Facts to notice:**
  - → No breakage: MEMS construction robust even in the 40% over-test
  - → Dynamic over-test at 65 kGs produced same results as OICW loads
  - → All latches stayed latched (retained sliders and springs as designed)
  - → Locks in the mis-assembled S&A retained arming slider in safe position

Conclusions

Findings: In OICW, MEMS S&A armed as designed, feasibility partially demonstrated

Fabrication:

- ARDEC's design and selected fabrication technology improved yield from <20% to >75%!
- MEMS foundry turnaround is now less than 6-weeks (vs. 6 months) thru MEMS Exchange
- New materials (nickel) prove robust in OICW dynamic loading

Firetrain:

- Laboratory tests validate micro-scale firetrain (MSF) at OICW sizes
- Working on 'printing' or slurry-loading of explosives in MEMS (WECAC and NAWC-CL)

Future:

- (near) 20-mm flight test of explosively-loaded S&A, ~Aug 02
- (near) Demonstration of MSF and MEMS-compatible loading techniques, ~Aug 02
- (near) Contract: MEMS fabrication solicitation on street in May 02
- (near) Contract: MEMS integration into fuze
- (farther out) Implement MEMS command actuator (1-2 years)
- (farther out) MEMS packaging and volume fabrication (3-5 years?)

END

SEM of Slider, Spring, Zig-Zag Track

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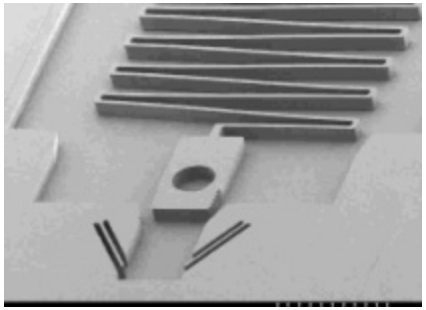
Sprg111a.jpg, 19kB



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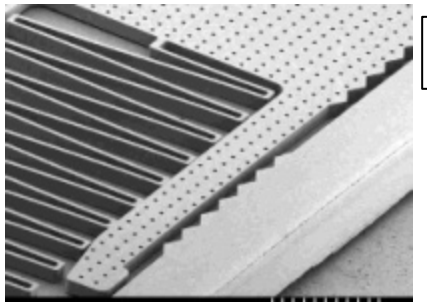

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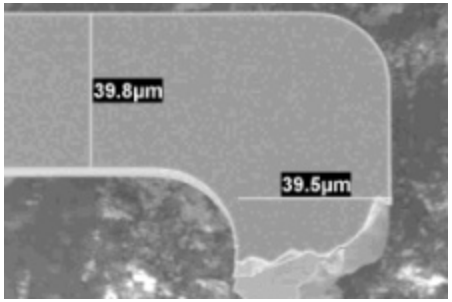

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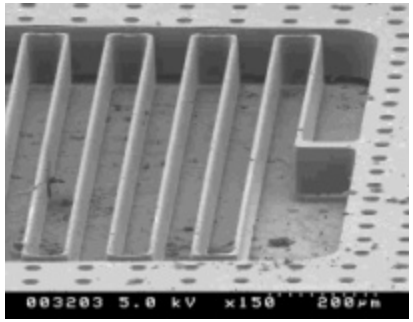

8

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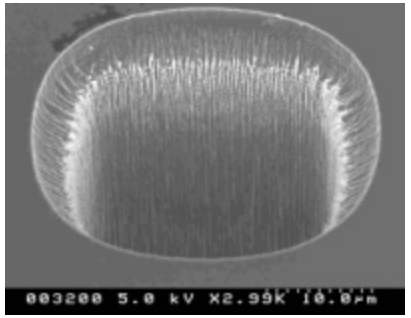

9

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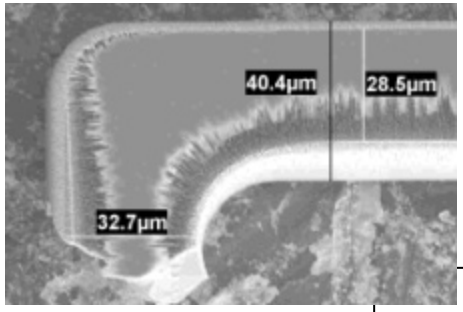

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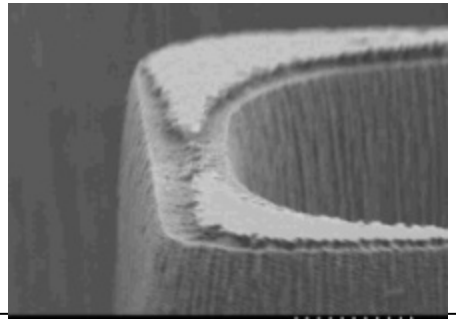

11

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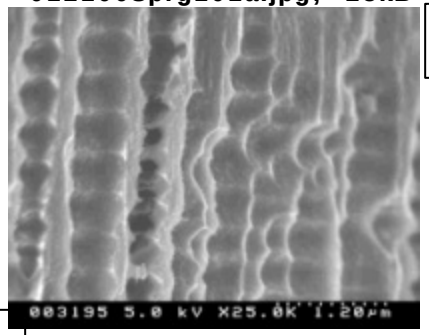
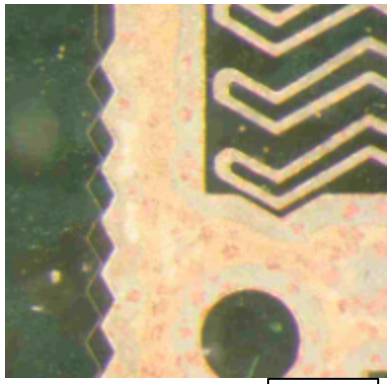


12

SEM of Slider, Spring, Zig-Zag Track

BTZigTrackSetbackCrop.jpg, 19kB



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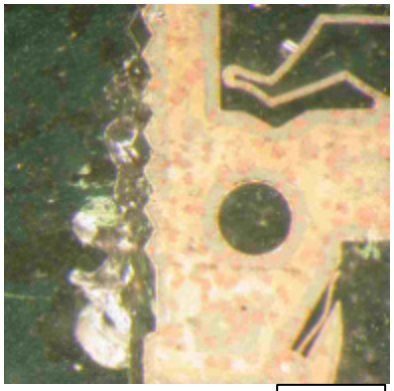
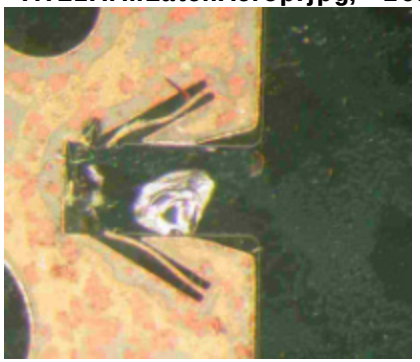
ATL1ZigTrack_SetbackCrop.jpg, 24kB



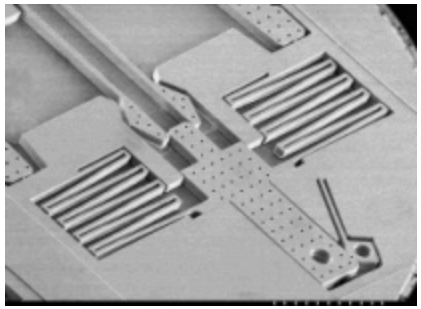
14

ATL1ArmLatchAcrop.jpg, 26kB



15

Sprg201aDarkCrop.jpg 46kB



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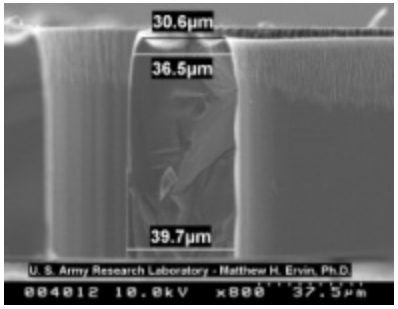
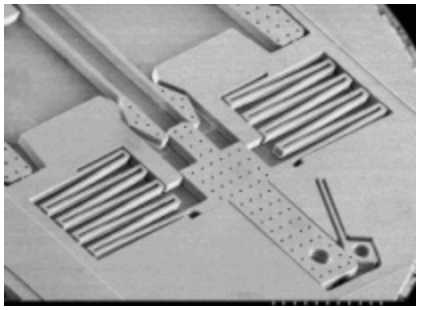


Profiles of nominal 40-µm DRIE spring, showing unintended 25% taper



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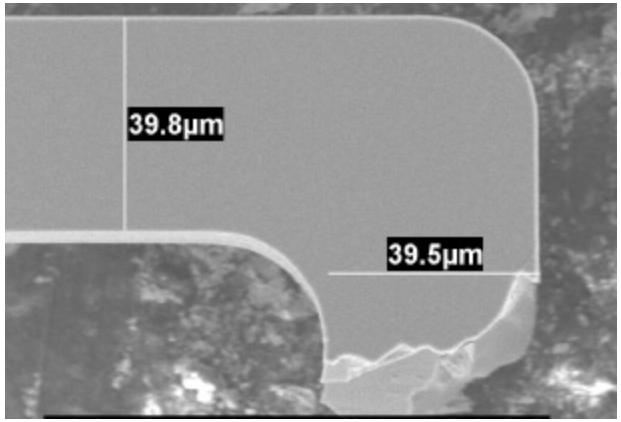
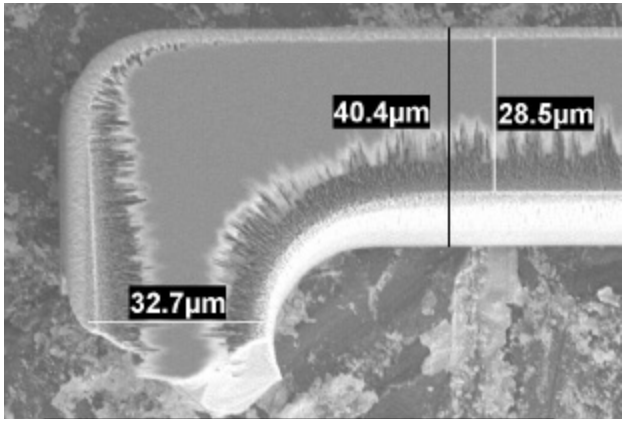
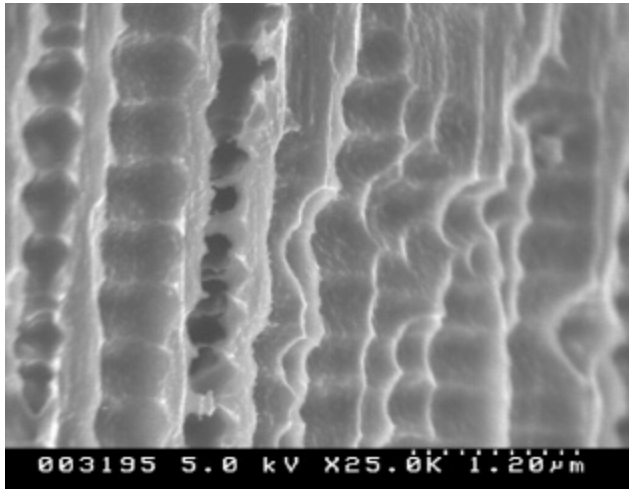
SEM Details From DRIE Fabrication



Width of nominal 40-µm DRIE spring

Details of undercutting of spring (unintended 25% taper)





Texture of DRIE-machined surface

Details of undercutting and release etch for 40-µm spring