From MEMS to Bio-MEMS and Bio-NEMS: Manufacturing Techniques and Applications

Book 3 of The Fundamentals of Microfabrication and Nanotechnology, Third Edition, Three-Volume Set

Chapter 1: Non-Lithography (Traditional) and Lithography (Non-traditional) Based Manufacturing Compared

1:1

List three different methods one can utilize to deposit a thin metal film on a MEMS structure.

Answer:

Physical vapor deposition (PVD), chemical vapor deposition (CVD), and electrochemical deposition can all be used to deposit a thin metal film on a MEMS structure.

1.2:

What do the following acronyms stand for? MEMS, VLSI, DUV, DOF, SEM, NGL, NA, MTF, OAI, OPC, RIE, and CMOS

Answer:

MEMS: micro-electromechanical systems
VLSI: very-large-scale integration
DUV: deep ultraviolet
DOF: depth of field/focus
SEM: scanning electron microscopy
NGL: next-generation lithography
NA: numerical aperture
MTF: modulation transfer function
OAI: off-axis illumination
OPC: optical proximity correction
RIE: reactive ion etching
CMOS: complementary metal oxide semiconductor

1.3:

Compare laser-machining (LM) with e-beam machining (EBM).

Answer:

(1) EBM uses a stream of focused, high-velocity electrons from an electron gun while LM involves ultraviolet laser radiation, which may consist of long, short or ultra-short pulses.
(2) EBM is performed in a vacuum to reduce scattering of electrons by gas molecules while in LM no vacuum is required.
(3) EBM is a well-established method for microfabrication. The most suitable application is for workpieces requiring large number of simple small holes to be drilled or for drilling holes in materials that are hard and difficult to machine with other processes. Lasers are most cost effective for drilling holes between 1.5 and 0.01 mm.

With very small holes, the high-power focusing lenses required to withstand the energies necessary for drilling holes smaller than 0.01 mm become limiting factors.
(4) EBM is generally effective with an aspect ratio of 1:10 in hard-to-machine materials. Aspect ratios of 1:50 are possible, and holes can be drilled in hard-to-reach areas and at difficult angles.
(5) The material removal rate in EBM is much faster than in LM.

1.4:
The following bulleted list includes examples of micromaching tools.
(a) Classify them according to the applied energy appearance (W: wet chemical and electrochemical machining; M: mechanical machining; E: electrothermal machining) at the workpiece.
(b) Classify them according to machining methods (S: subtractive; A: additive; S/A: subtractive and additive)

- Photofabrication
- Laser beam machining
- Diamond milling
- Chemical and electrochemical milling
- Electron beam machining
- Photochemical milling
- Dry etching
- Ultrasonic machining
- Plasma beam machining
- Abrasive jet machining
- Electroplating and electroless plating
- Stereolithography
- Electrodischarge machining

Answer:
(a) Wet chemical and electrochemical machining
• Photofabrication
• Chemical and electrochemical milling
• Photochemical milling
• Electroplating and electroless plating
• Stereolithography
Mechanical Machining
• Diamond milling
• Ultrasonic machining
• Abrasive jet machining
Electrothermal machining
• Laser beam machining
• Electron beam machining
• Dry etching
• Plasma beam machining
• Electrodischarge machining
(b) Subtractive
• Photofabrication
• Diamond milling
• Chemical and electrochemical milling

- Photochemical milling
- Dry etching
- Ultrasonic machining
- Abrasive jet machining
- Electrodischarge machining

Additive

- Electroplating and electroless plating
- Stereolithography

Subtractive and additive

- Laser beam machining
- Electron beam machining
- Plasma beam machining

1.5:

Provide a comparison of the economic and technical aspects in the construction of sensors with thin-film technology, IC fabrication (semiconductor substrates), thick film, and classic construction.

Answer:

Our comparison is summarized in the Table below. It should be mentioned that the sensor fabrication cost consists of 60 to 80% of packaging, an aspect not addressed in this Table.

TABLE Comparison between Different Sensor Technologies: Economic and Technical Aspects

	Classic Construction	Thick Film Technology	Thin Film Technology	IC Technology
Technology substrate	Wires and tubes	Screen printing Al_2O_3, plastic	Evaporation-sputtering Al_2O_3, glass, quartz	IC techniques silicon, GaAs
Initial investment	Very low	Moderate	High	High
Production line cost	>10 k$	>100 k$	>400 k$	>800 k$
Production	Manual production	Mass production	Mass production	Mass production
Units per year	1-1000	1000-1,000,000	10,000-10,000,000	100,000-
Prototype	Cheap	Cheap	Moderate	Expensive
Sensor price	Expensive sensor	Low cost per sensor	Low cost per sensor	Low cost per sensor
Use	Multiple use, in vitro – in vivo	Disposable, in vitro	Disposable, in vivo	Disposable, in vivo
Markets	Research, aerospace	Automotive, industrial	Industrial, medical	Medical, consumer
Dimension	Large	Moderate	Small	Extreme miniaturization
Solidity	Fragile	Robust	Robust	Robust
Reproducibility	Low	Moderate	High	High
Maximum temperature	800°C	800°C	1000°C	150°C (Si)
Interfacing	External discrete devices	Smart sensors, surface mount	Smart sensors, surface mount	Smart sensors, CMOS, bipolar

1.6:

Why use miniaturization technology?

Answer:

Some of the most obvious reasons to apply miniaturization techniques are summarized in the table below. Usually, not all those reasons apply at once. For example, the small dimensions of micromachines might be crucial in medical and space applications but often lack importance in the automotive industry where cost is the more important driver.

TABLE Why Use Miniaturization Technologies?

- Minimizing of energy and materials consumption during manufacturing
- Possibility for redundancy and arrays
- Integration with electronics, simplifying systems (e.g., single point vs. multipoint measurement)
- Reduction of power budget
- Taking advantage of scaling when scaling is working for us in the micro domain, (e.g., faster devices, improved thermal management, etc.)
- Increased selectivity and sensitivity
- Minimally invasive
- Wider dynamic range
- Exploitation of new effects through the breakdown of continuum theory in the micro domain
- Cost/performance advantages
- Improved reproducibility
- Improved accuracy and reliability
- Self-assembly and biomimetics with nanochemistry
- More intelligent materials with structures at the nanoscale

1.7:

Get calibrated: What is a mil or a thou? How many microns in a mil? How many thousandths of an inch (thou or mil) are there in an mm? Approximately how thick is a human hair? Approximately how big is a virus? A bacterium? A red blood cell? How thick is a standard sheet of paper?

Answer:

A "mil" is a unit of thickness equal to one thousandth of an inch. To convert mil to inches take mil and divide by 1000. Thus, a 2 mil bag would be .002 inches thick.
One mil is exactly 25.4 microns, just as one inch is exactly 25.4 millimeters.
1 mm = 39.4 mils
Thickness of human hair = 80–100 μm
Size of a virus = 100 nm
Size of a bacterium = 1 μm
Size of a red blood cell = 10 μm
Thickness of a standard sheet of paper = 130 μm

1.8:

How small is small? There are many manufacturing processes other than silicon micromachining for making small parts. Do some research to find specifications for various manufacturing processes, small devices, and tools. Search the Web, call companies, use the Yellow Pages, use a Thomas's Register, ask a machinist, ask your instructor, etc. We're looking for the lower limits on traditional machining or tools that are currently commercially available at a local job shop or a tool distributor. The objective is to get a feel for the boundary between MEMS and traditional machining.

Answer:
Lathe: *Smallest holes that can be drilled: 30 microns*; **Company: Kern Micro- und Feinwerktechnik GmbH & Co.KG** http://www.kern-microtechnic.com/kern-short-eng02.pdf
Milling machine: *Cutter diameter of smallest end mill: 1 mil*; **Company: Performance Micro Tool (PMT);** http://www.pmtnow.com/ *Diameter of smallest drill bit: 2 mils*; **Company: Drill Technology** P.O. Box 456, Ada, MI 49301 USA; Phone: 616-676-1792; Fax: 1-616-676-1287; Email: sales@drilltechnology.com http://www.drilltechnology.com/drilltec.html
Disco saw: *Smallest cut that can be made: 1.5 mils*; **Company: Thermocarbon, Inc**.; West Coast Sales Office: 2672 Bayshore Parkway Suite 1020, Mountain View, CA 94043 USA; Phone: 650-968-0570; http://www.thermocarbon.thomasregister.com/olc/thermocarbon/
Stamping: *Smallest thickness: 0.5 mil*; **Company: Micro Precision Technology** 333 Litchfield Road, New Milford, CT 06776 USA; Phone: 860-355-3198; Fax: 860-210-0138
Punching: *Smallest punch diameter: 1.8 mils*; **Company: Schneider & Marquard, Inc.** P.O. Box 39, 112 Phil Hardin Road, Newton, NJ 07860 USA; Phone: 973-383-2200; Fax: 973-383-6529; http://www.schneidermarquard.com/
Chemically etched parts: *Material thickness: 0.5 mils*; **Company: Powers Manufacturing** Ontario, California; Phone: 909-947-0253; Fax: 909-947-3693; Email: powers@powersmfg.com; http://www.powersmfg.com/
Waterjet cutting: *Smallest hole: 1.5 mils; Smallest kerf: 7 mils*; **Company: Waterjet-Tech Inc** 3402 'C' St. NE, Suite 214, Auburn, WA 98002 USA; Phone: 253-833-3800; http://www.waterjet-tech.com/
Diamond turning: *Resolution: 0.01 microns; Surface finish: 20 nm*; **Company: Optical Electro Forming, Inc.** 13100 56th Court North, Suite 704, Clearwater, FL 33760 USA; Phone: 727-572-8142; Fax: 727-572-7668; http://www.opticalelectroforming.com/
EDM: *Smallest hole: 0.8 mil*; **Company: Aurora Micro Machine, Inc.** 14000 Sunfish Lake Blvd., Suite L, Ramsey, MN 55303 USA; Phone: 763-433-8318; Fax: 763-433-8319; http://www.auroramicromachine.com/machineshop.htm
Laser machining: *Smallest hole: 2 microns*; **Company: Potomac Photonics, Inc.** 4445 Nicole Drive, Lanham, MD 20706 USA; Phone: 301-459-3031; Fax: 301-459-3034; Cell: 301-908-8558; http://www.potomac-laser.com/
Printed Circuit Board: *Smallest trace widths and air gap: 3 mils; Drill hole sizes: 3 mils*; **Company: Cirexx Corporation** 3391 Keller Street, Santa Clara, CA 95054 USA; Phone: 408-988-3980; Voice: 408-988-4534; Fax 800-444-6817; Email: cirexx@cirexx.com; http://www.cirexx.com/
Electroplating: *Thickness of deposition: 0.02 mils*; **Company: Cal-Aurum Industries** 15632 Container Lane, Huntington Beach, CA 92649 USA; Phone: 714-898-0996/800-303-0996; Fax: 714-895-4681; http://www.electroplating.com/
Injection molding: *Minimum structure size approx. 1 micron*; **Company: Protron Microtechnik** Protron Mikrotechnik GmbH Universitätsallee 5 D - 28359 Bremen / Germany; Phone +49-421 / 22348-18 (-19); Fax +49-421 / 22348-20; E-mail info@protron-mikrotechnik.de; http://www.protron-mikrotechnik.de/

Stereolithography: *Smallest feature size: 5 mils*; **Company: ProtoCAM** 3848 Cherryville Road, Northampton, PA 18067 USA; Phone: 610-261-9010; Fax: 610-261-9350; http://www.protocam.com/
Smallest screw: *Screw diameter: 40 mils*; **Company: sadev-decolletage** http://www.sadev-decolletage.com/index_en.html
Smallest DC motor: *1.91 mm in diameter, 9.58 mm in length; Stall torque: 1.06e-6 oz-in no-load speed for rated voltage: 100,000 rpm*; **Company: MicroMo Electronics, Inc.** 14881 Evergreen Ave., Clearwater, FL 33762-3008 USA; Phone: 800-807-9166; Phone: 727-572-0131; Fax: 727-573-5918; Email: info@micromo.com; http://www.micromo.com/
Best resolution of a pair of calipers *Best resolution on a pair of calipers: 1 micron*; **Company: Mitutoyo** http://www.mitutoyo.com/
Best resolution of a micrometer *Best resolution with a micrometer: 0.1 micron*; **Company: Mitutoyo** http://www.mitutoyo.com/

1.9:
Reconstruct the decision tree to reach an optimized micromanufacturing option for a given miniaturization problem.

Answer:
To become a proficient MEMS/NEMS engineer one needs to first understand the application and market for the product very well. These aspects should be apparent from a very detailed specification list. Once, based on the specifications, an appropriate sensor/actuator principle for the MEMS/NEMS has been chosen through brainstorming sessions and by making preliminary designs, one needs to develop a clear understanding on how this sensor/actuator principle scales into the microdomain. Then one must choose the optimum manufacturing approach and the optimized materials, including substrate material, for the most cost-effective practical implementation. These choices are tested through a new design phase and evaluation of critical process steps. A major challenge in this regard often concerns partitioning; i.e., how far to push the integration of electronics with the sensing function (hybrid vs. monolithic)? If the MEMS product compromises both a disposable and a fixed instrument the question becomes: what to include with the MEMS disposable and what to include into the fixed instrument? With partitioning decisions made, a CAD design is followed by research prototyping, engineering prototyping, and finally α and β products for the user/client to test. With a satisfied customer, manufacturing of a new MEMS product may begin.

In the Table below we introduce a checklist to help make the decision of optimized manufacturing option and substrate material easier. For the checklist, which serves as a control gate, we start from the assumption that the market and specifications list are well understood and that the detailed specifications list, scaling appreciation, and market understanding agree best with one particular sensor/actuator approach.

TABLE Checklist to Determine Substrate and Machining Approach for a New Micromachining Application

1. What will the package of the sensor or system be, and how does it interface with the real world? The package and the interface with the environment determine size and cost of the total product and the nature of the micro device inside, as well as the answers to most of the following questions.