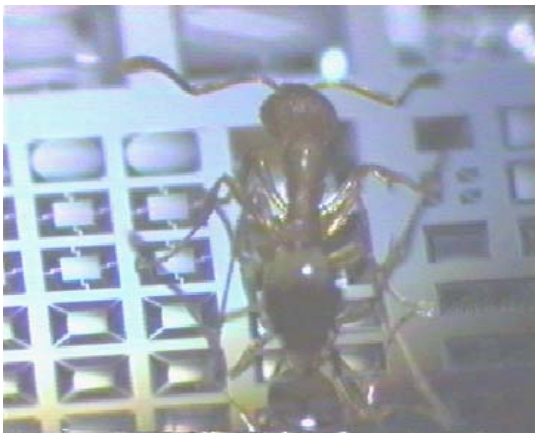
微機電系統簡介

方維倫 講座教授
國立清華大學 動機系/奈微所

fang@pme.nthu.edu.tw
http://mdl.pme.nthu.edu.tw

前言

About MEMS

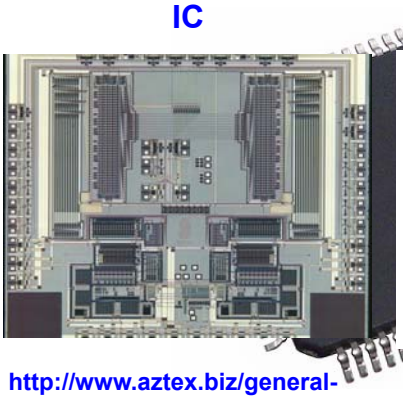


MDL
NTHU

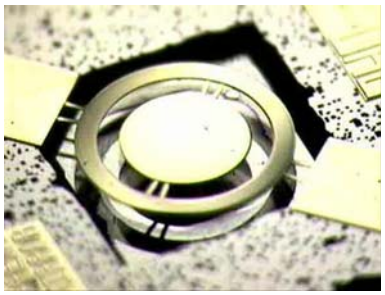
MDL
NTHU

What's MEMS

IC



MEMS



http://www.aztex.biz/general-computer/integrated-circuit-work/

Texas Instruments Inc.

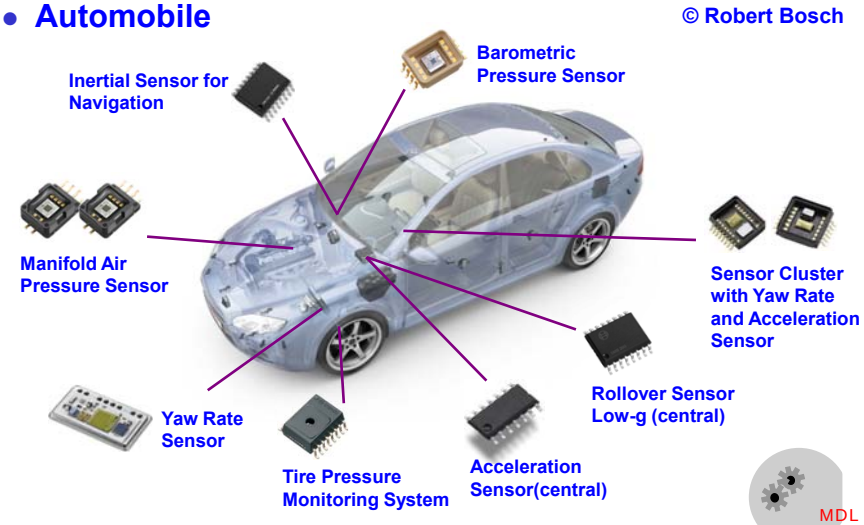
MDL

MDL
NTHU

Where's MEMS

- **Automobile**

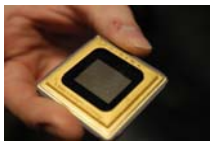
© Robert Bosch

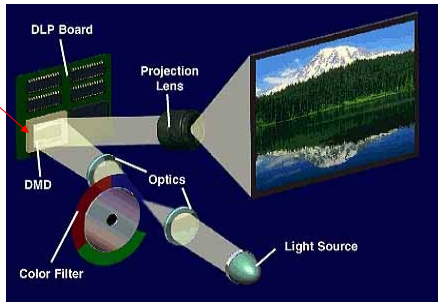


MDL
NTHU

Where's MEMS

- **Before 2000 – inkjet printer, projector**





Texas Instruments Inc.

MDL
NTHU

Where's MEMS

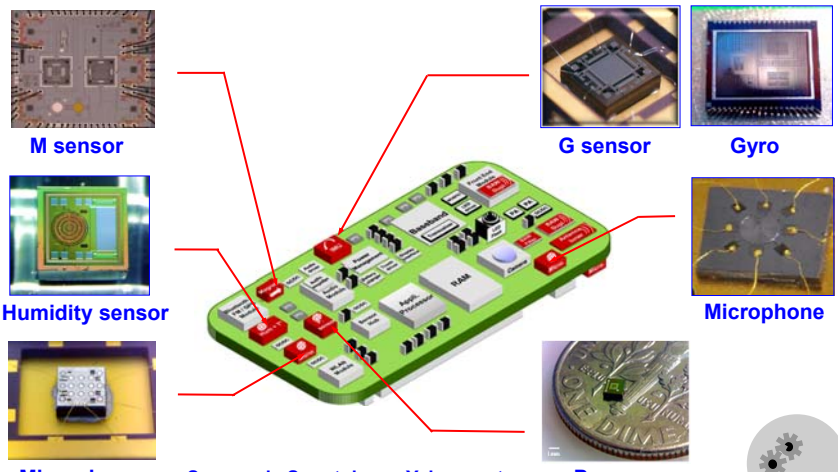
- **2006~2013 – consumer electronics**

Wii | Smart phone | Wearable

MDL
NTHU

Where's MEMS

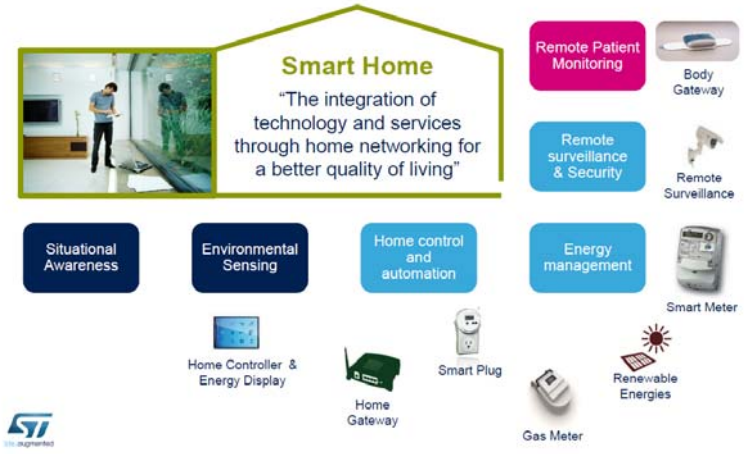
- **MEMS Devices in volume in 2013 (from Yole)**



MDL NTHU

Where's MEMS

- **Internet of Things (IoT)**



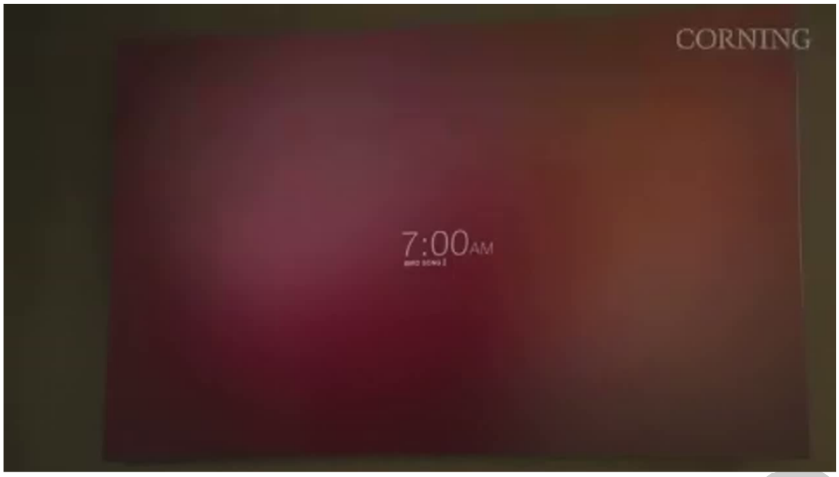
MDL NTHU

Corning - A Day Made of Glass

http://www.corning.com/index.aspx

MDL
NTHU

Corning - A Day Made of Glass



http://www.corning.com/index.aspx

MDL
NTHU

Drone

http://www.parrot.com/

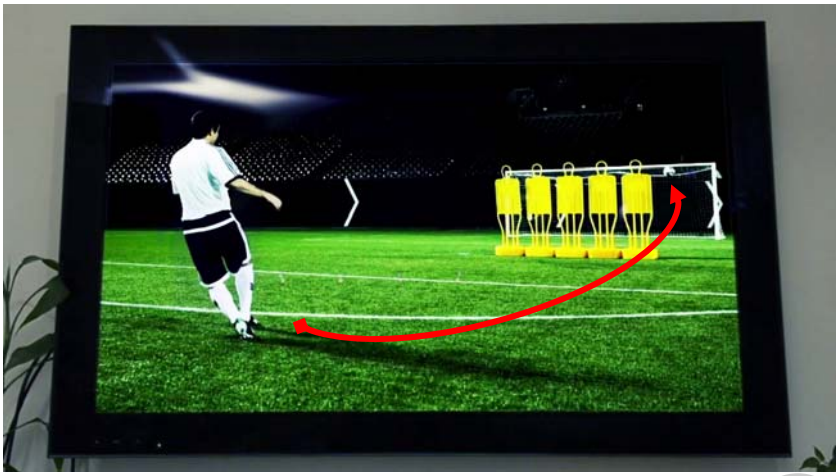
MDL
NTHU

Drone

http://www.parrot.com/

MDL
NTHU

Smart Ball



http://micoach.adidas.com/

MDL
NTHU

Smart Ball

http://micoach.adidas.com/

MDL
NTHU

Smart Earphone

http://www.bragi.com/

MDL
NTHU

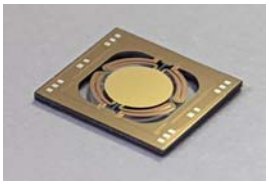
Smart Earphone

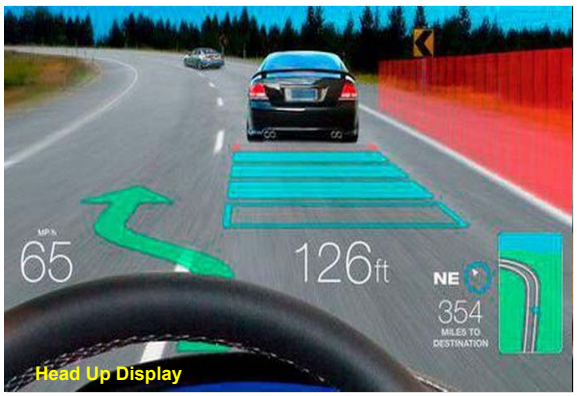
http://www.bragi.com/

MDL
NTHU

MEMS Scanning Mirror

- AR HUD, also for AR Glasses of Metaverse





Cheng, Liu and Fang, 2022 https://reurl.cc/EzozDv

MDL NTHU

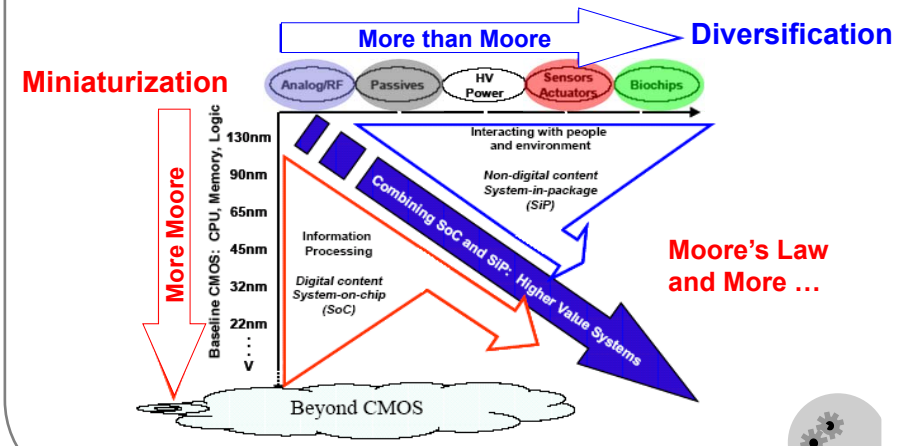
Why MEMS

- Small and Smart

MDL NTHU

Why MEMS

- Small and Smart
- Add value to the existing CMOS tech



Source: ITRS Roadmap 2005, www.itrs.net

MDL NTHU

平面加工技術

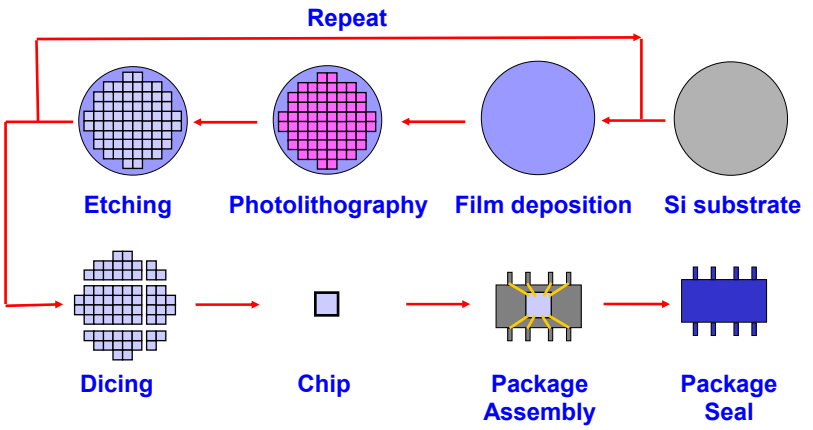
MDL NTHU

Planar Technologies

- IC : TSMC, UMC, Vanguard, ...
- LED/VCSEL/Diode laser : Liteon, Epistar,…
- TFT-LCD : AUO, Chimei-Innolux, ...
- Magnetic recording head : Seagate, WD, ...
- MEMS : TSMC, UMC, APM, ...

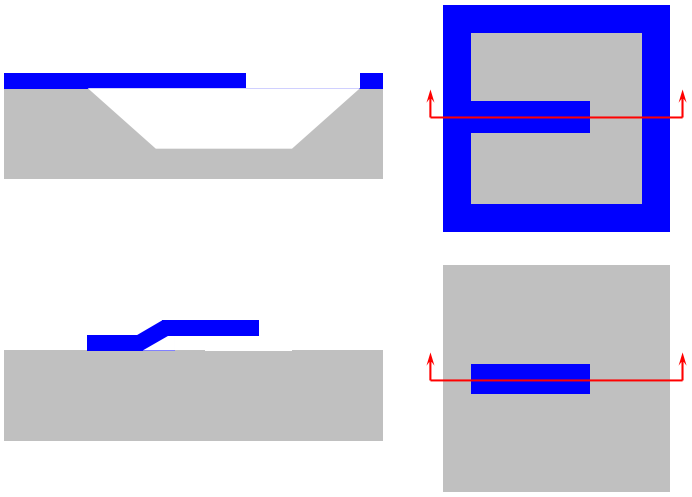
MDL
NTHU

Semiconductor processes



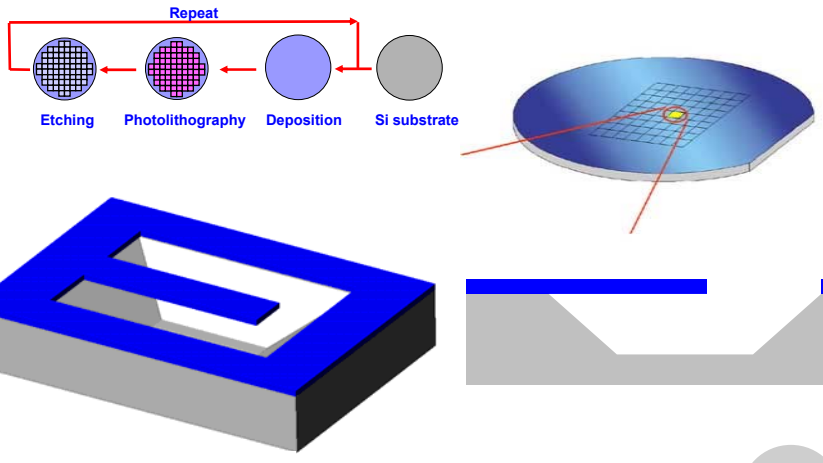
MDL
NTHU

Suspended MEMS Structures



MDL
NTHU

Bulk Micromachining



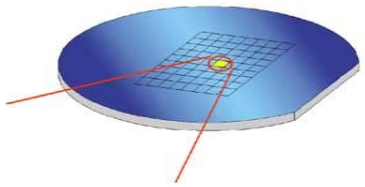
MDL
NTHU

Thin film deposition

Photolithography

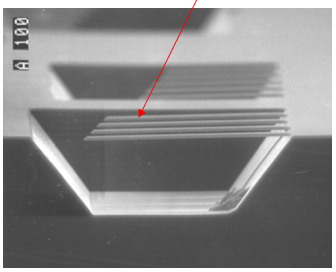
Thin film etching

Bulk Si etching

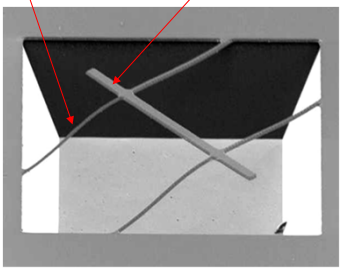


MDL
NTHU

- **Bulk Micromachined Beams**



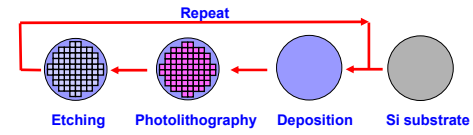
W. Fang, 1994

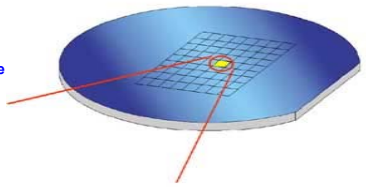


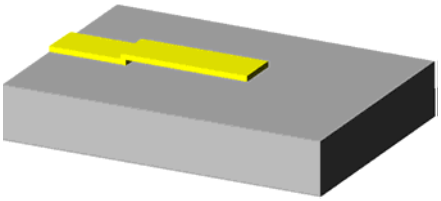
Yu and Fang, *JMM*, 2005

MDL
NTHU

Surface Micromachining







Lith[illegible]hing

MDL
NTHU

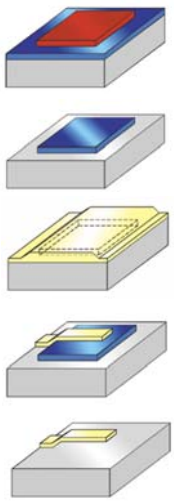
Photolithography

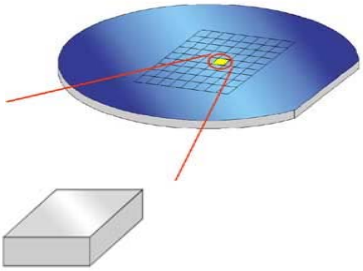
1st film etching

2nd film deposition

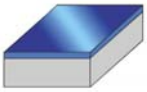
Photolithography &
2nd film etching

1st film removing



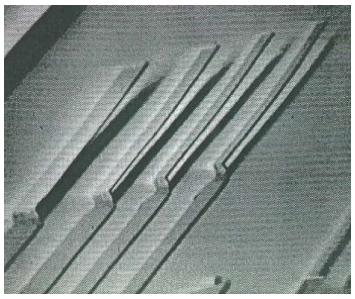


1st film deposition

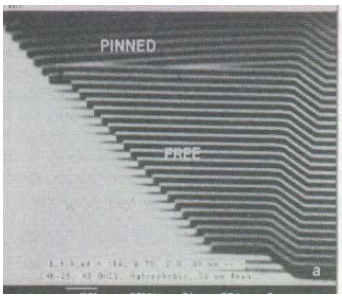


MDL
NTHU

- **Surface Micromachined Beams**



Howe and Muller, 1983



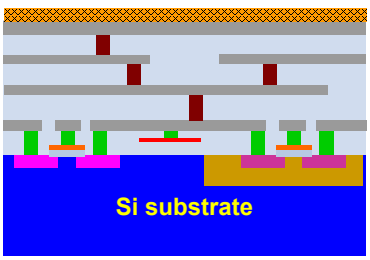
Mastrangelo and Hsu, 1993

MDL
NTHU

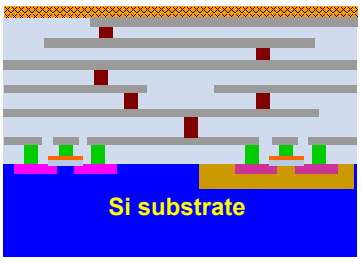
Semiconductor Devices

- **Examples: by CMOS processes at TSMC, UMC, etc…**

0.35μm 2P4M CMOS process

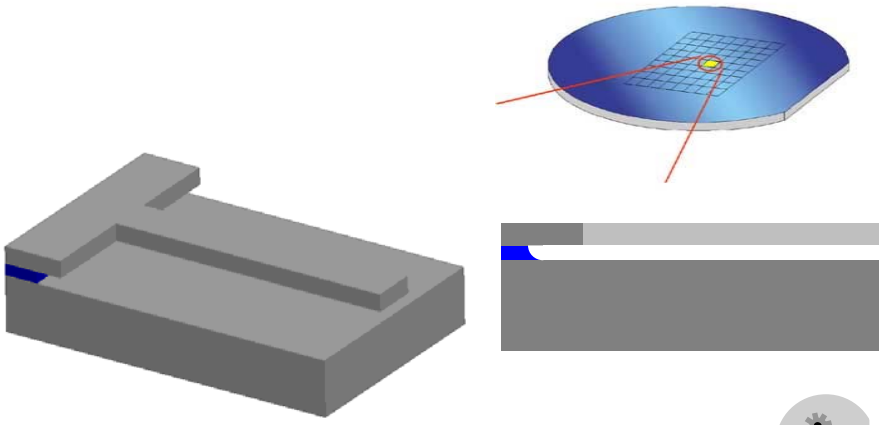


0.18μm 1P6M CMOS process



MDL
NTHU

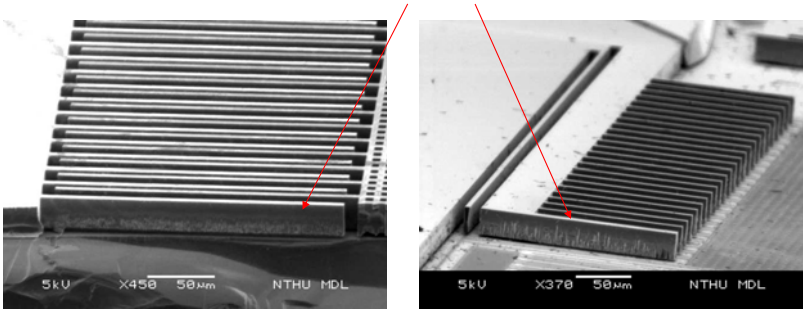
SOI Micromachining



MDL
NTHU

• SOI Micromachined Beams

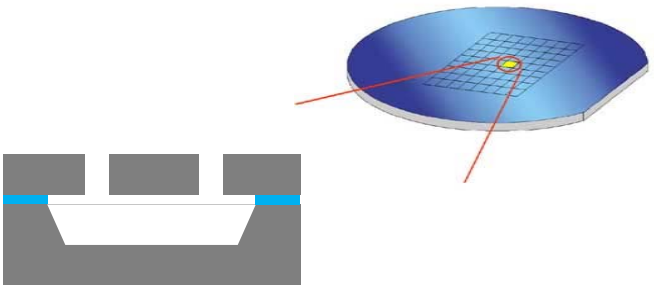
30μm thick beam



MDL

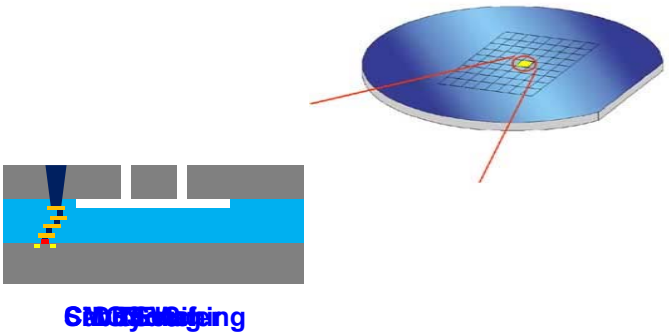
MDL
NTHU

Cavity SOI Micromachining

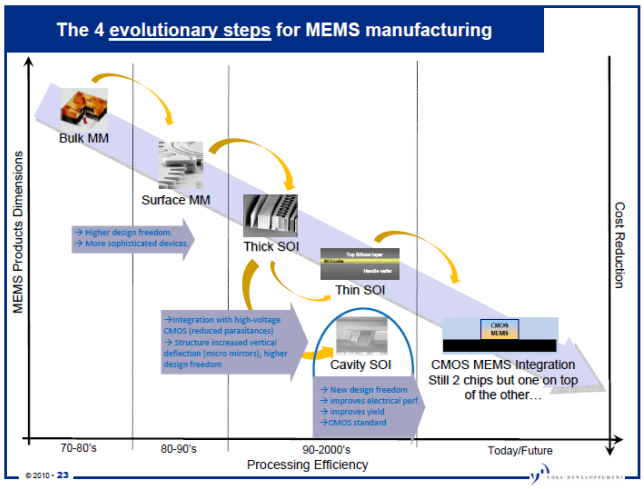


MDL
NTHU

CMOS SOI Micromachining



MDL
NTHU



Yole's report, 2010

MDL
NTHU

關鍵元件

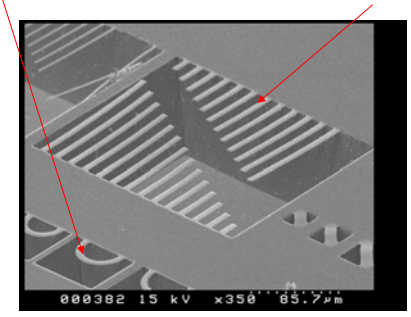
MDL
NTHU

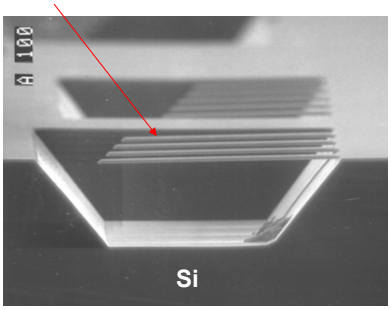
Passive component

- Cantilever, suspension - springs

Semi-circular suspension

Cantilever





T. Tzou and W. Fang, 1999

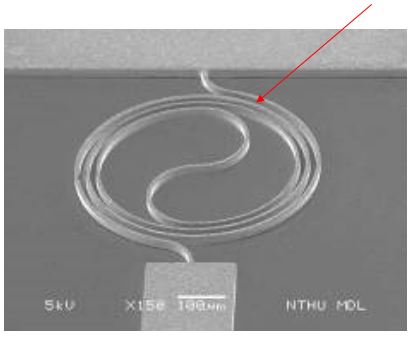
W. Fang, 1994

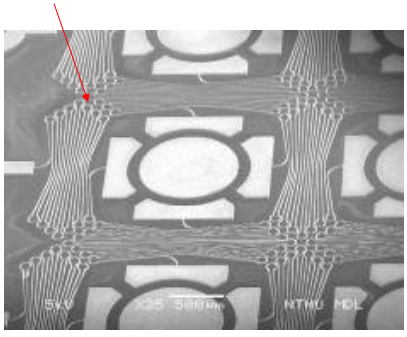
MDL
NTHU

Passive component

- Curved beam - spring

Curved beam



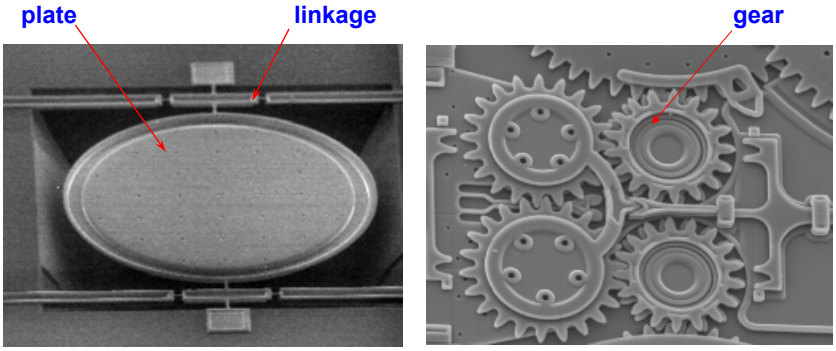


W.-L. Sung and W. Fang, 2014

MDL
NTHU

Passive component

- Plate, linkage, gear



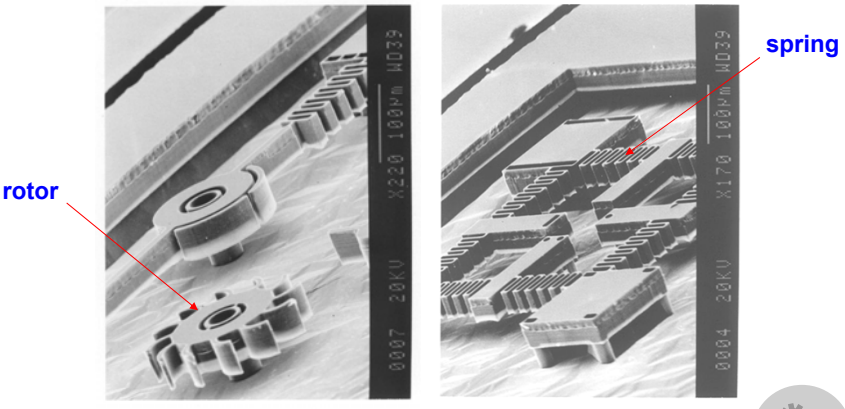
H.-Y. Lin and W. Fang, 2000

Sandia National Lab

MDL
NTHU

Passive component

- Gear, rotor, linkage

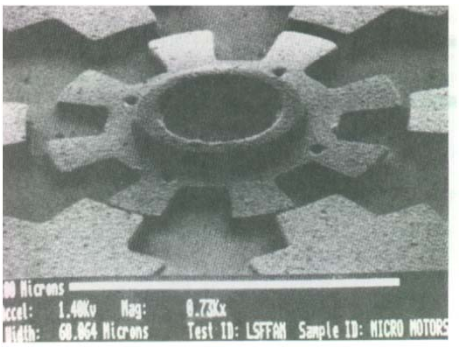


J. Hsieh and W. Fang, 2000

MDL
NTHU

Active component

- Angular electrostatic actuator - motor

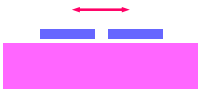


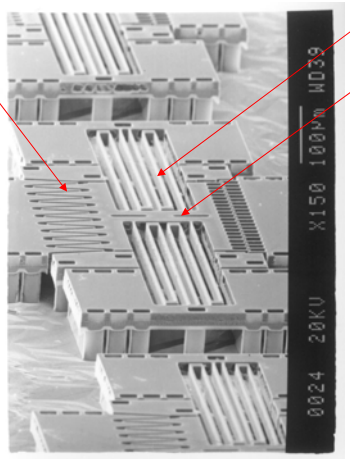
L.-S. Fan, et.al., Int. Electron Devices meeting, 1988

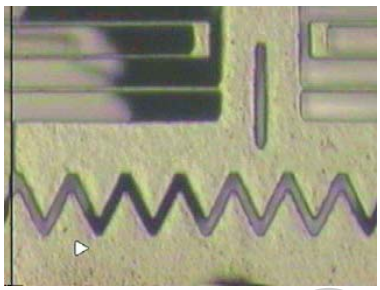
MDL
NTHU

Active component

- Linear electrostatic actuator





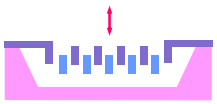


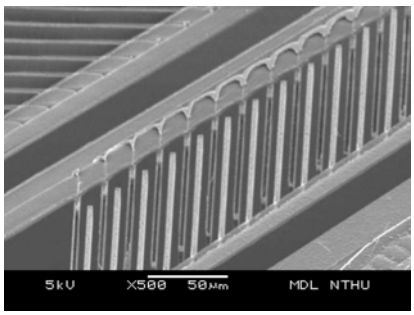
J. Hsieh and W. Fang, 2000

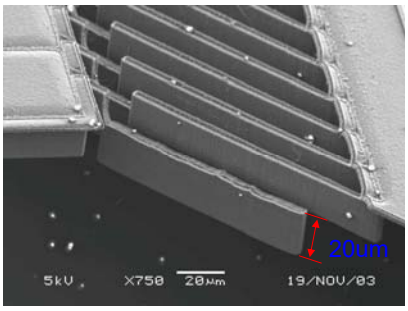
MDL
NTHU

Active component

- Linear electrostatic actuator







M. Wu and W. Fang, 2005

MDL
NTHU

Active component

- Angular electrostatic actuator

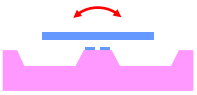
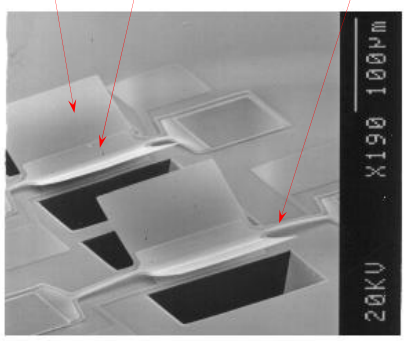
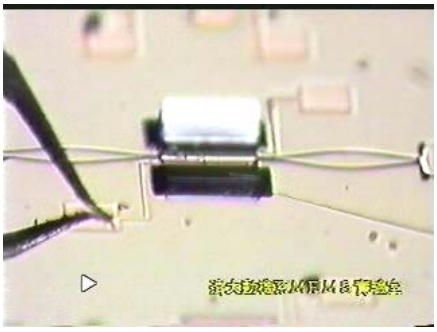


Plate Electrode Spring



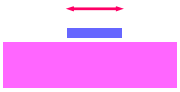


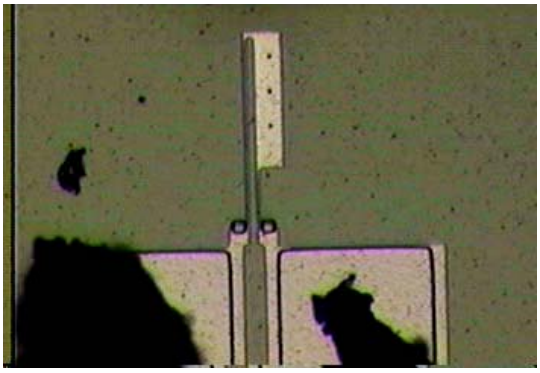
J. Hsieh and W. Fang, *Sensors and Actuators A*, 2000

MDL
NTHU

Active component

- Linear thermal actuator

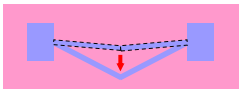




MDL
NTHU

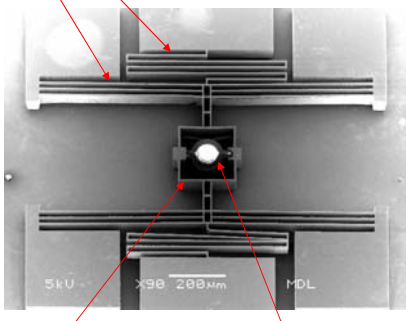
Active component

- Linear thermal actuator



Spring (passive)

V-beam actuator (active)



Supporting frame (passive)

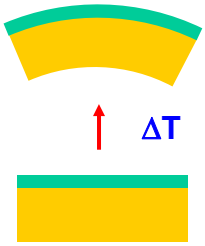
Lens (passive)

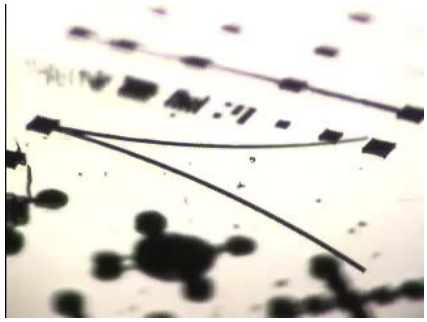
C. Lai, J. Hsieh, and W. Fang, *IEEE Optical MEMS'04*, 2004

MDL
NTHU

Active component

- Linear thermal actuator



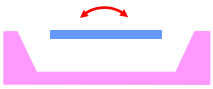


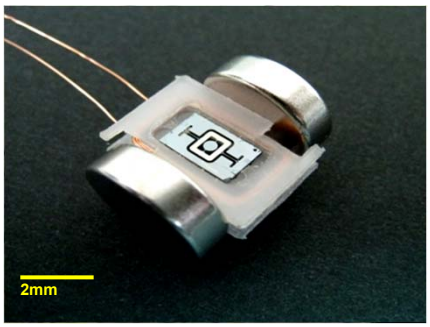
W.-K. Hsu, and W. Fang, *Nanotech*, 2008

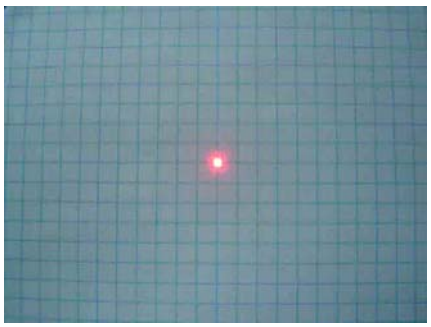
MDL
NTHU

Active component

- Angular magnetic actuator







Yang, and Fang, *JMEMS*, 2007

MDL
NTHU

組裝與整合

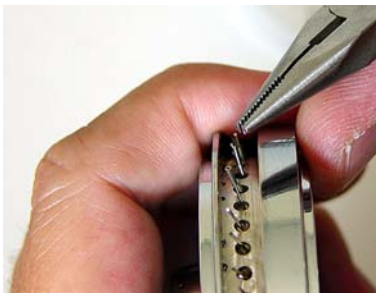
MDL
NTHU

Parts Assembly

amazon.com

MDL
NTHU

Assembly



www.precisionscalereplicas.com

www.kukausa.com

MDL
NTHU

Assembly

- Toyota and Foxconn assembly lines

www.youngertoyota.com

www.zaeke.com

MDL
NTHU

Assembly

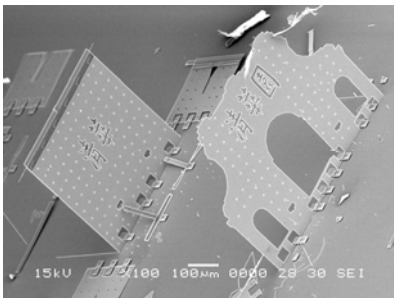
- Boeing 777 assembly lines

www.ainonline.com

www.flightglobal.com

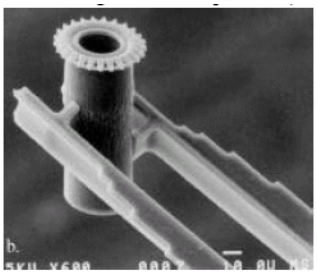
MDL
NTHU

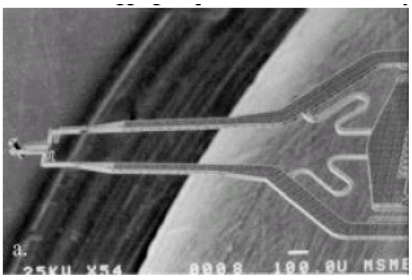
- Manually assembled by probe



MDL
NTHU

- **Manually assembled by micro gripper**

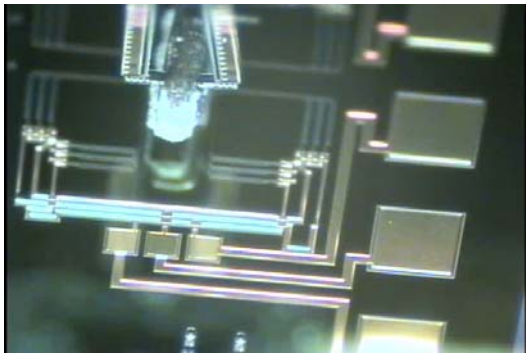




Keller, UC Berkeley, 1998

MDL
NTHU

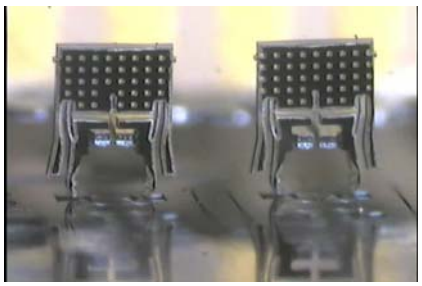
- **Automatically assembled by precision machine**



Zyvex Inc.

MDL
NTHU

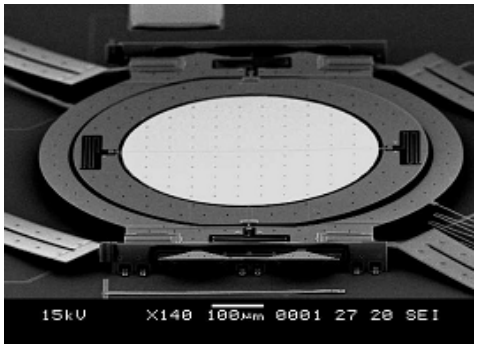
- **Automatically assembled by precision machine**

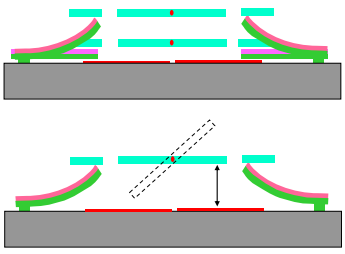


Zyvex Inc.

MDL
NTHU

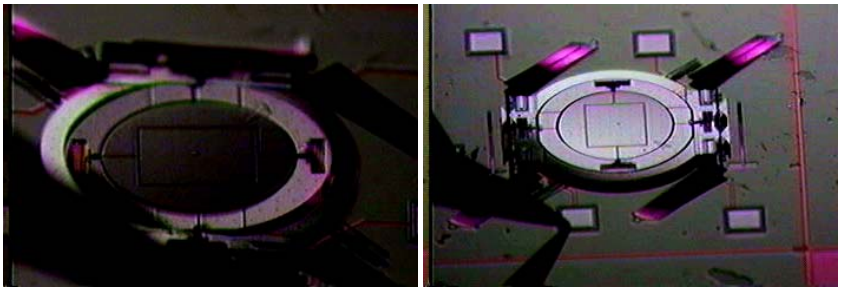
- **Self assembly by residual stress deformed beam**





Y.-P. Ho, M. Wu, H. Lin, and W. Fang, *IEEE Optical MEMS '02*, 2002

MDL
NTHU



Y.-P. Ho, M. Wu, H. Lin, and W. Fang, *IEEE Optical MEMS '02*, 2002

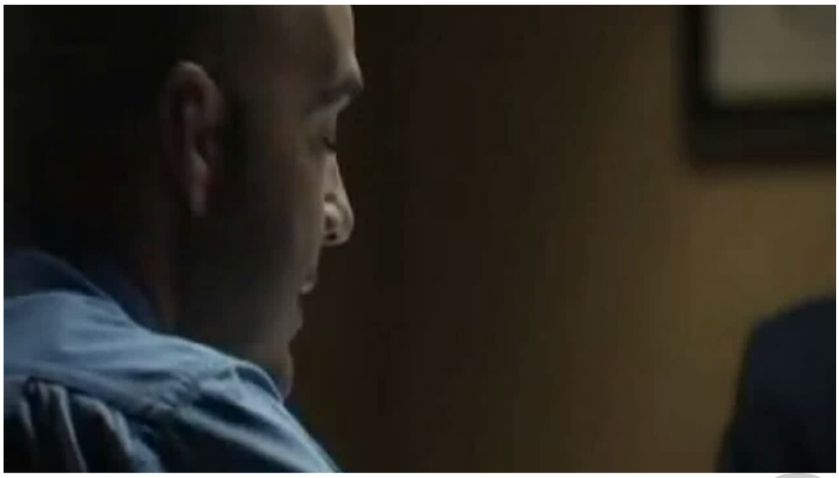
MDL
NTHU

About Mechanical Device

https://www.patek.com/

MDL
NTHU

About Mechanical Device



https://www.patek.com/

MDL
NTHU

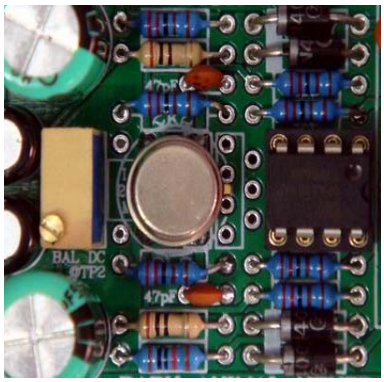
https://today.line.me/tw

https://magazine.ncfta.gov.tw/

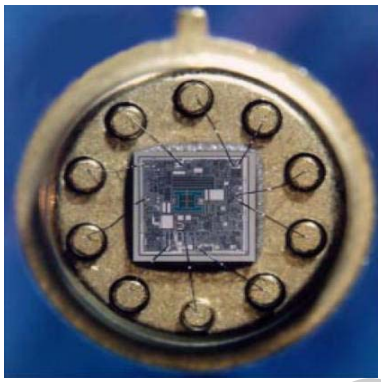
MDL
NTHU

Process Integration

- Discrete vs Integrated electronics components



ATM Elektro, Czech Republic



ADI, USA

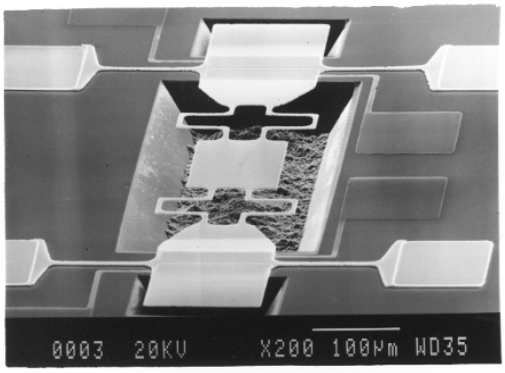
MDL
NTHU

- Assembly by process integration (一體成形)

Brigham Young Univ., USA

MDL
NTHU

- **Assembly by process integration**



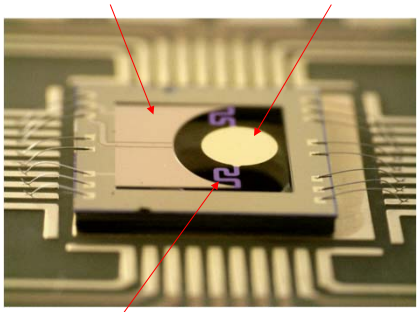
J. Hsieh and W. Fang, *Transducer'99*, 1999

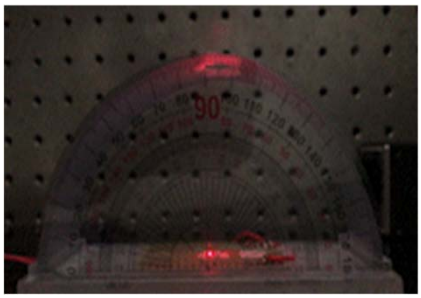
MDL
NTHU

- **Assembly by process integration**

Actuator

Mirror



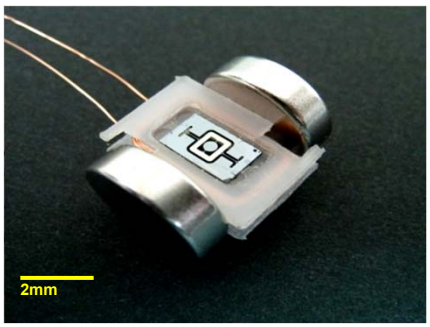


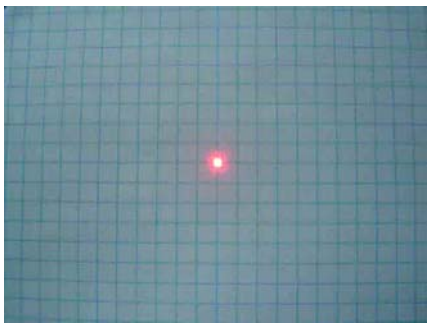
Spring

H. Lin, and W. Fang, *Transducers'23*, Kyoto, Japan, 2023

MDL
NTHU

• Scanning images

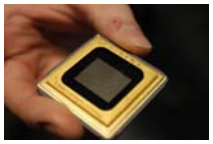


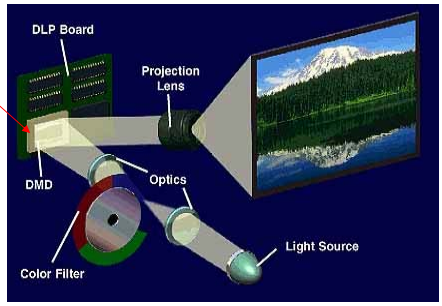


Yang, and Fang, *JMEMS*, 2007

MDL
NTHU

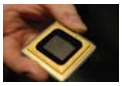
Example - DLP Projector, TI

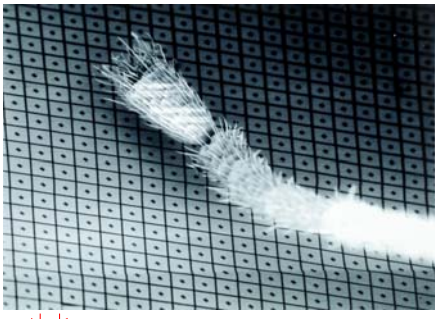




Texas Instruments Inc.

MDL
NTHU





~15 μm

www.theatlantic.com

DLP Chip, TI

MDL
NTHU

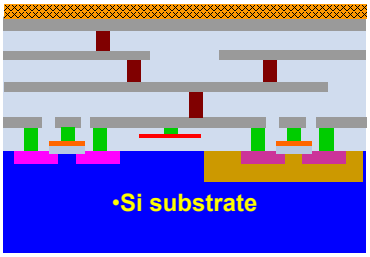
製程平台 – 標準製程

MDL
NTHU

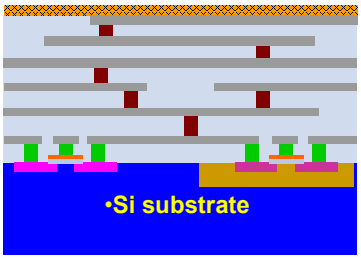
Standard CMOS Processes

- Available in CMOS foundries: TSMC, UMC, etc…

0.35μm 2P4M CMOS process



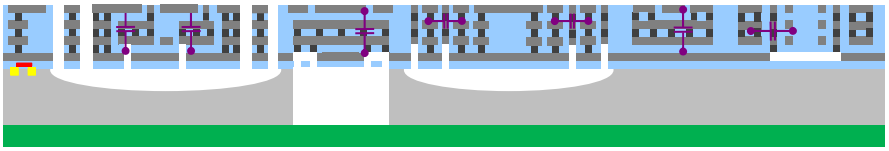
0.18μm 1P6M CMOS process



MDL
NTHU

CMOS-MEMS Platform

Sensing circuit | Tri-axis G sensor | Pressure sensor | Magnetic sensor | Tactile sensor | RF resonator



Sta[illegible] TSMC 0.35μm 2P4M)

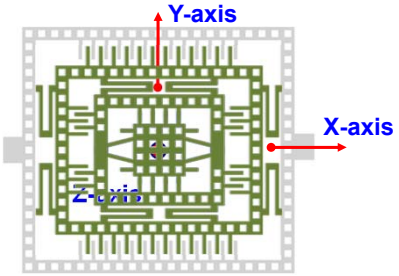
Si | Poly-Si | W-via

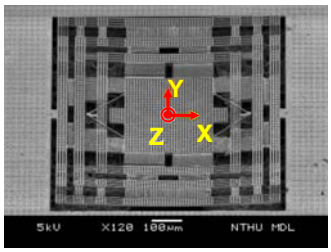
Metal | Polymer | SiO_2

- Standard TSMC 0.35μm 2P4M CMOS process
- Post-CMOS processes developed by Prof. Fang's group

MDL
NTHU

3-axis G-sensor



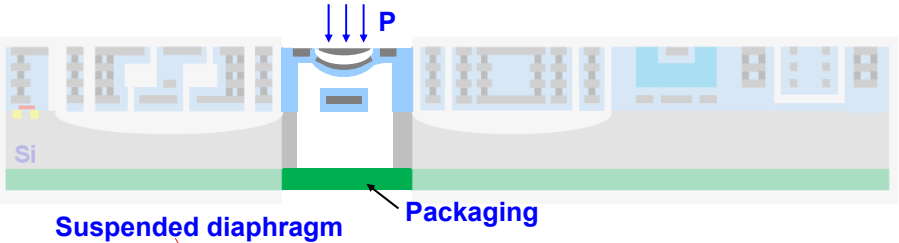


Single proof mass

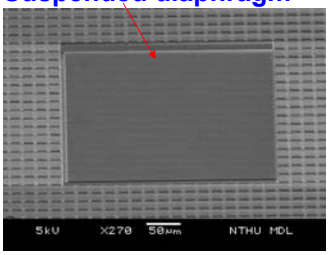
Sun, and Fang, *IEEE MEMS*, 2009
Sun, and Fang, *IEEE Trans. on ED*, 2010

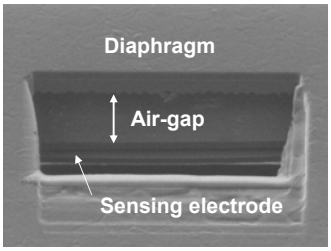
MDL
NTHU

Pressure Sensors



Suspended diaphragm

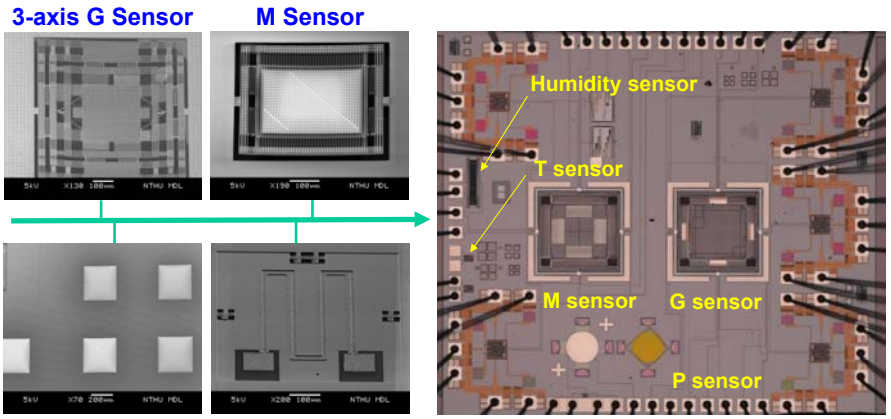




FIB sectioning

Sun, and Fang, *Transducers*, 2009
Sun, and Fang, *JMM*, 2009

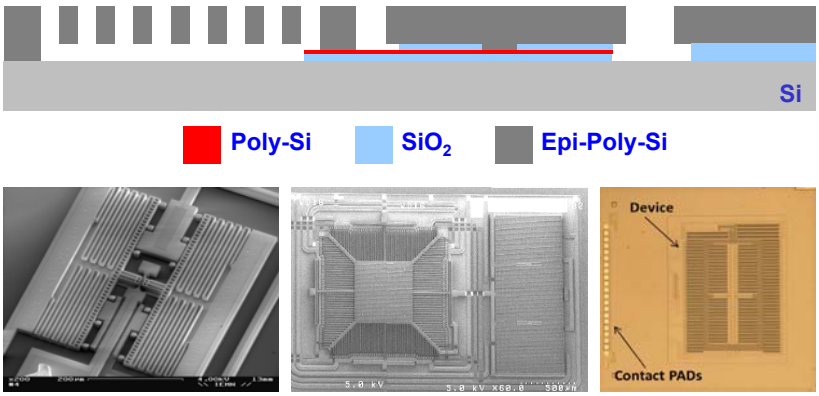
MDL
NTHU



MDL
NTHU

STM THELMA Platform

- Thick Epi-poly Layer for Microactuators and Accelerometers

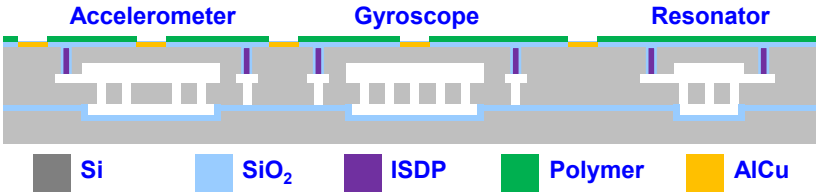


http://www.st.com/
G. Langfelder et al., *IEEE Trans. on IE*, 2012

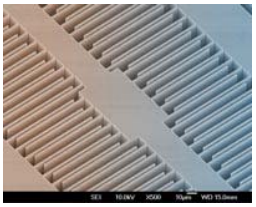
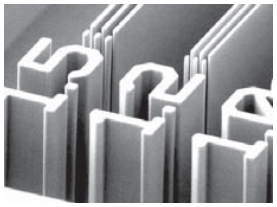
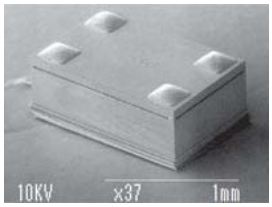
MDL
NTHU

Teledyne DALSA MIDIS Platform

- MEMS Integrated Design for Inertial Sensors



Si SiO_2 ISDP Polymer AlCu

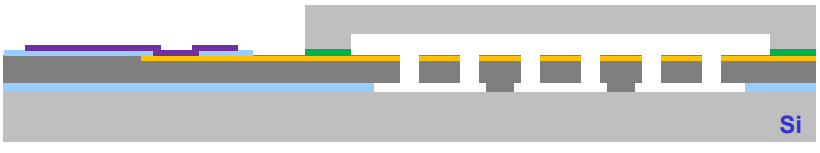




http://www.teledynedalsa.com/

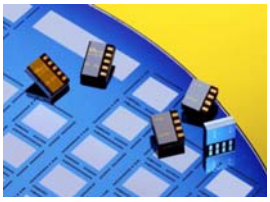
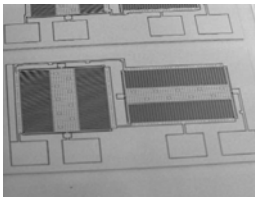
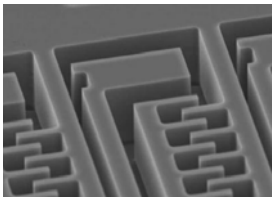
MDL NTHU

Tronics Platform

- Epi-SOI technology



Epi-Si SiO_2 Implant Metal Polymer

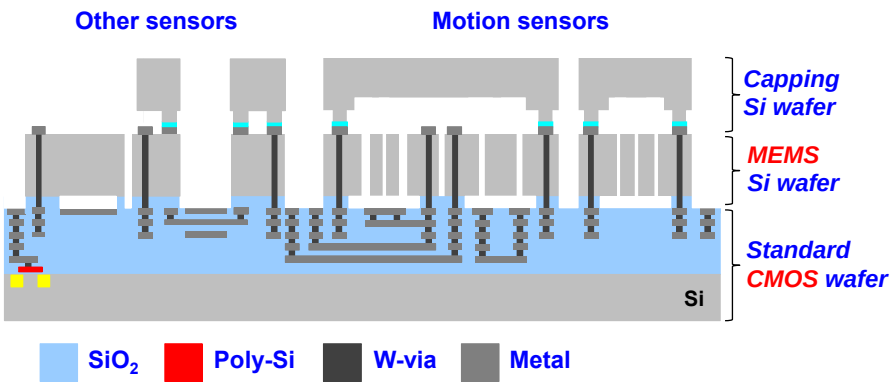
http://www.tronicsgroup.com/

S. Renard, *JMM*, 2000

MDL NTHU

TSMC MEMS Platform

- Si-MEMS above CMOS



Source：TSMC

MDL NTHU

台灣現況簡介

MDL NTHU

About Taiwan

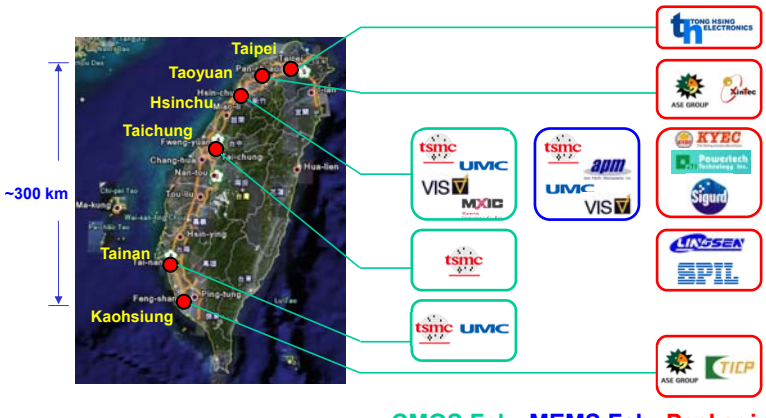
Taiwan
Area: ~36,000 km²
Population: ~23.4 M

The Netherlands
Area: ~41,500 km²
Population: ~16.5 M

Belgium
Area: ~30,500 km²
Population: ~11.2 M

MDL
NTHU

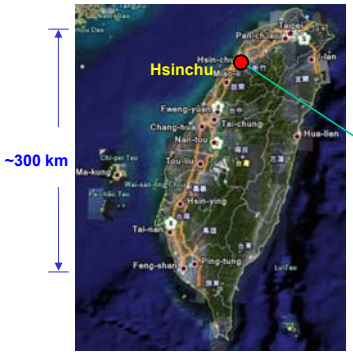
MEMS Eco-system at Taiwan



CMOS Fab MEMS Fab Packaging House

MDL
NTHU

MEMS Eco-system at Taiwan



sensortek
MEMS Coretronic
POI
STARMEMS
RICHTEK
egis
ORISYSTECH
ZILLTEK
Prolific
MERRY
Solid State System

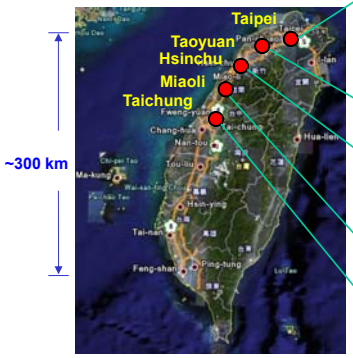
MEDIATEK
NOVATEK
Himax
Raydium
REALTEK
SiliconMotion
PHISON
ESMT
fitipower
Sitronix

MEMS design

IC design

MDL
NTHU

MEMS Eco-system at Taiwan



LITEON
COMPAL
PEGATRON
Inventec
wistron
ASUS
DELTA
PRIMAX

Unimicron
MeiLoon
Quanta Computer

AUO
Coretronic
OPTOTECH

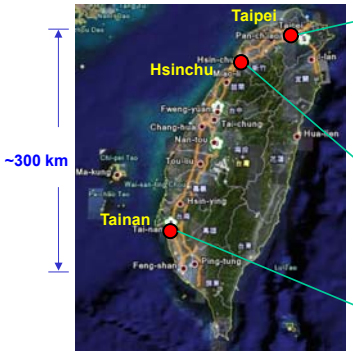
INNOLUX

HIWIN

System and application

MDL
NTHU

MEMS Eco-system at Taiwan



TSRI: Taiwan Semiconductor Research Inst.

National Lab Research Inst Univ. Lab

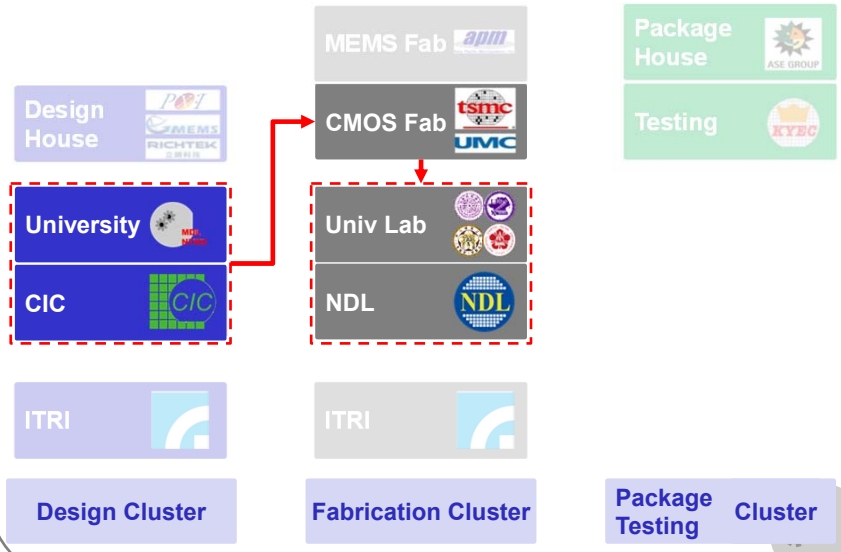
MDL
NTHU

MEMS Networks at Taiwan

	MEMS Fab	Package House
Design House	CMOS Fab	Testing
University	Univ Lab	
CIC	NDL	
ITRI	ITRI	
Design Cluster	Fabrication Cluster	Package Testing Cluster

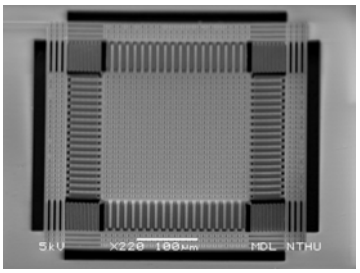
MDL
NTHU

MEMS Networks at Taiwan

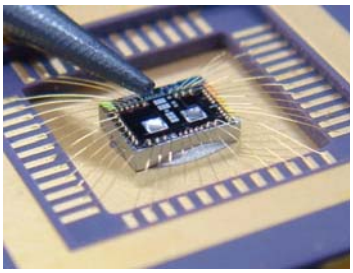


MDL NTHU

0.18um 1P6M TSMC CMOS Process



3-axis accelerometer

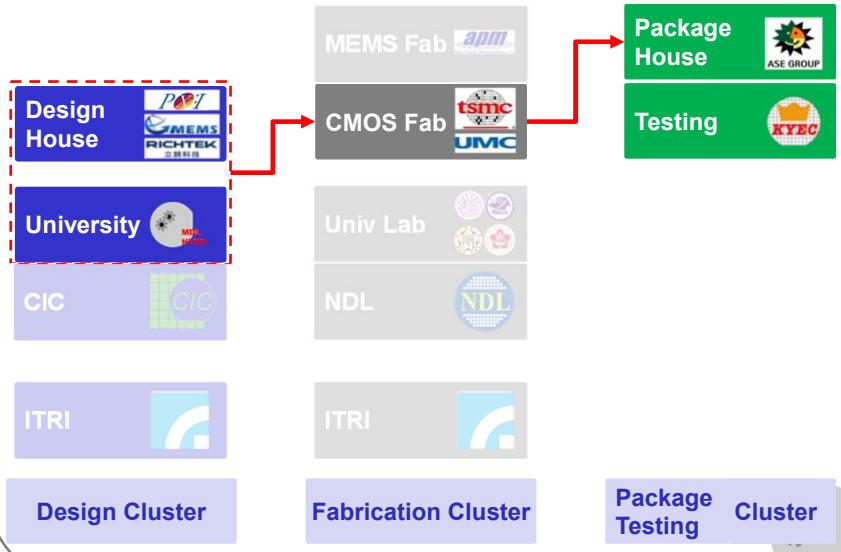


Sensor after bonding

Sensing-axis	*X-axis*	*Y-axis*	*Z-axis*
Measurement Range (G)	0.01~1	0.01~1	0.01~1
Sensitivity (mV/G)	14.2	14.6	8.0
Non-linearity (%)	3.0%	1.5%	1.8%
Noise (mG/sqrtHz)	1.9	2.9	3.4

MDL NTHU

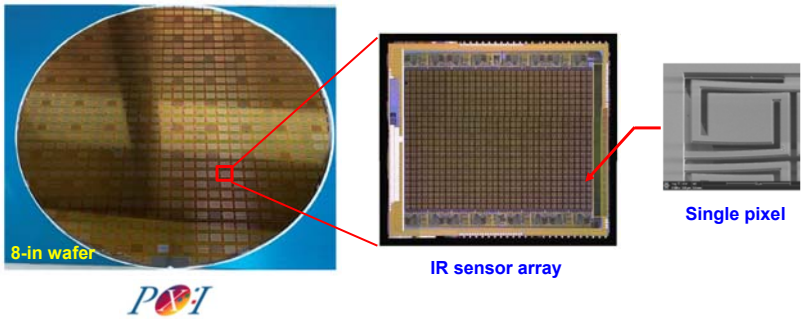
MEMS Networks at Taiwan



MDL NTHU

IR Sensor – Design Houses

- UMC CMOS MEMS processes: 8-inch 0.18um 1P6M



MDL NTHU

IR Sensor – Design Houses

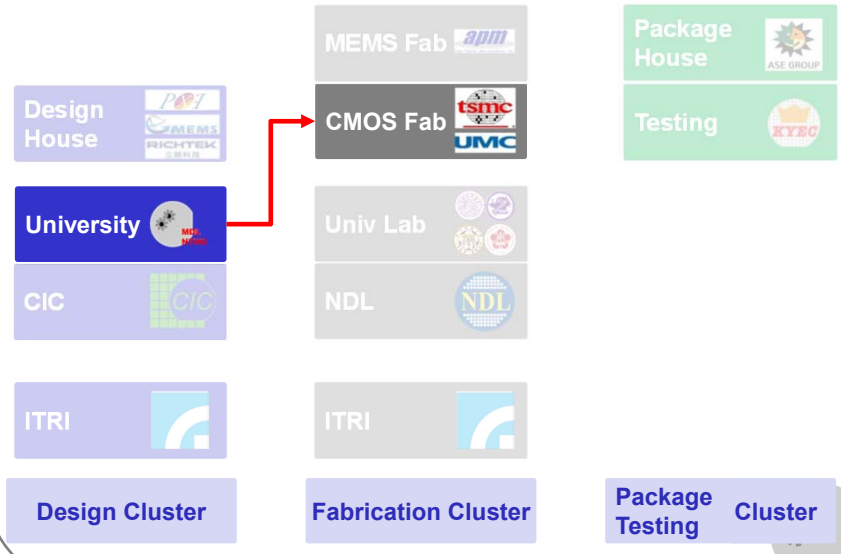
- System level integration for data mining/fusion: image + IR sensors

Voice: normal body temp. Voice: wear mask!

https://www.eetimes.com/smart-thermal-sensing-creates-machine-intelligent/

MDL NTHU

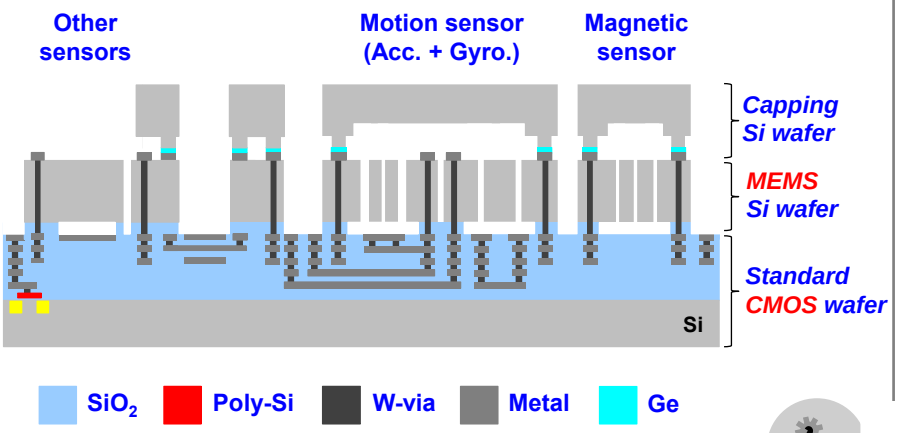
MEMS Networks at Taiwan



MDL NTHU

TSMC MEMS Platform

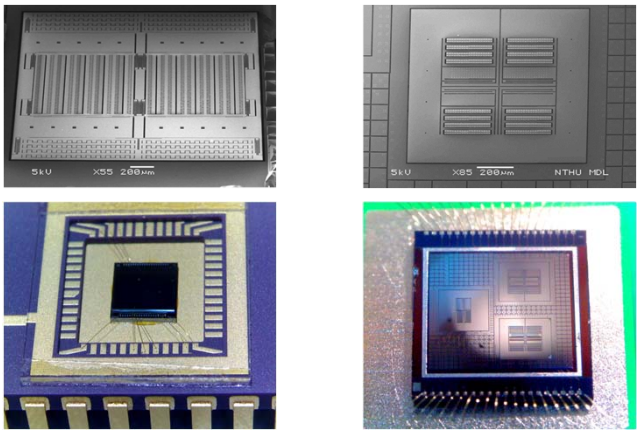
- Si-MEMS above CMOS



MDL NTHU

TSMC MEMS Platform

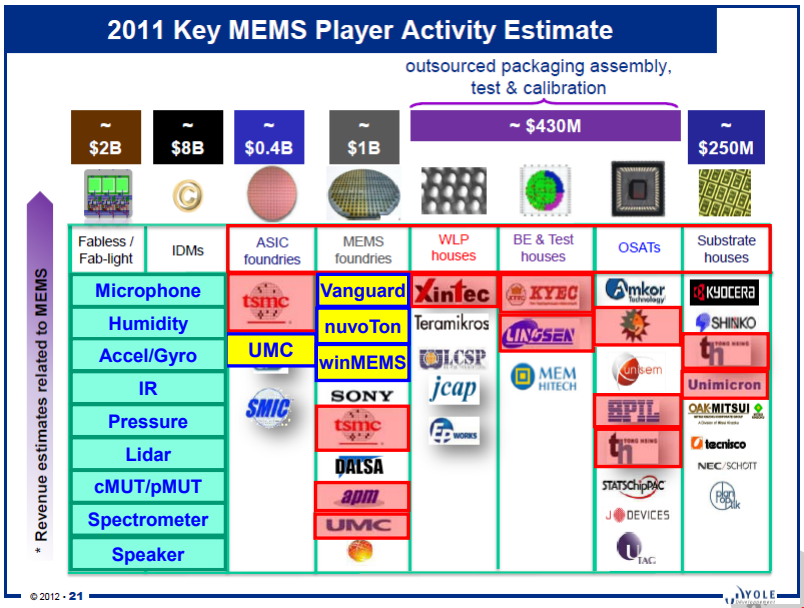
- Gyroscope and Magnetic Sensor



Lee and Fang, *IEEE MEMS*, 2016

Sung and Fang, *IEEE MEMS*, 2016

MDL NTHU



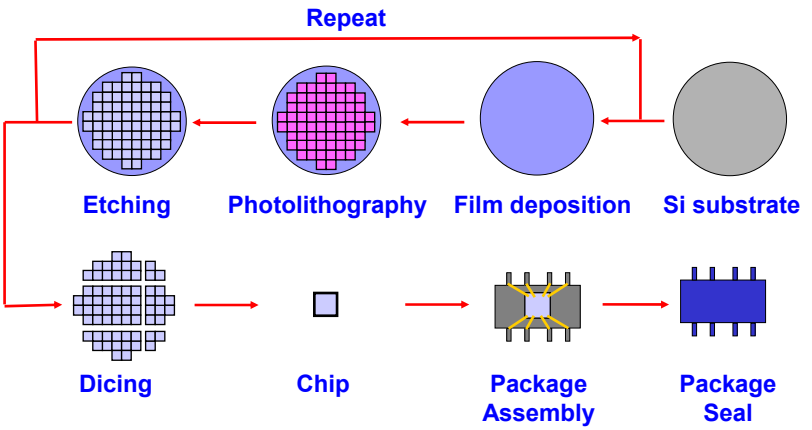
Yole report, SEMICON Taiwan 2012

MDL NTHU

結論

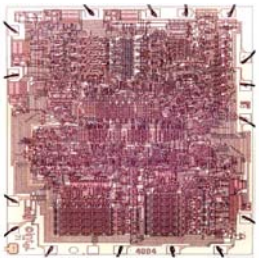
MDL NTHU

Semiconductor processes



MDL NTHU

Microprocessor



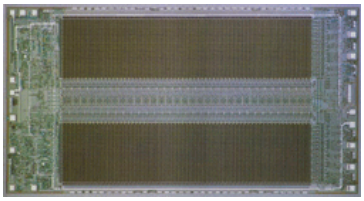
The 4004 – 2.3k transistors, 1971

8088/8086 - 29k transistors, 1978

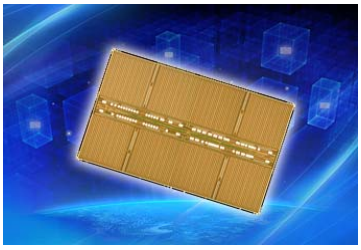
Pentium IV – 42M transistors, 2000

MDL NTHU

Memory



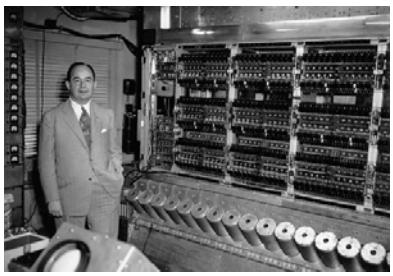
The 16kb DRAM, 1976



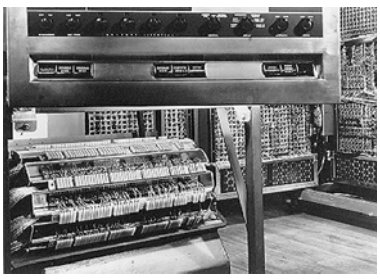
The 2Gb DRAM, 2011

MDL
NTHU

Computer



von Neumann and his "computer", 1952

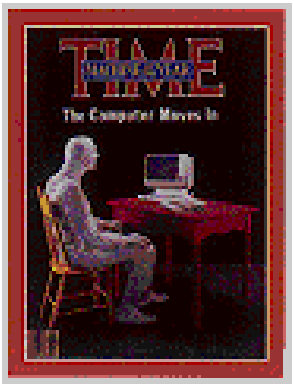


IBM 650, 1954

MDL
NTHU

Computer

Jobs & Wozniak with Apple II - 1976



IBM PC – 1981/2

MDL
NTHU

Computer

ENIAC (Vacuum tube)

Mainframes (LSI)

Notebook

Tablet

1946 1960 1965 1975 1992 2004 2010

First Mainframes
(Transistor)

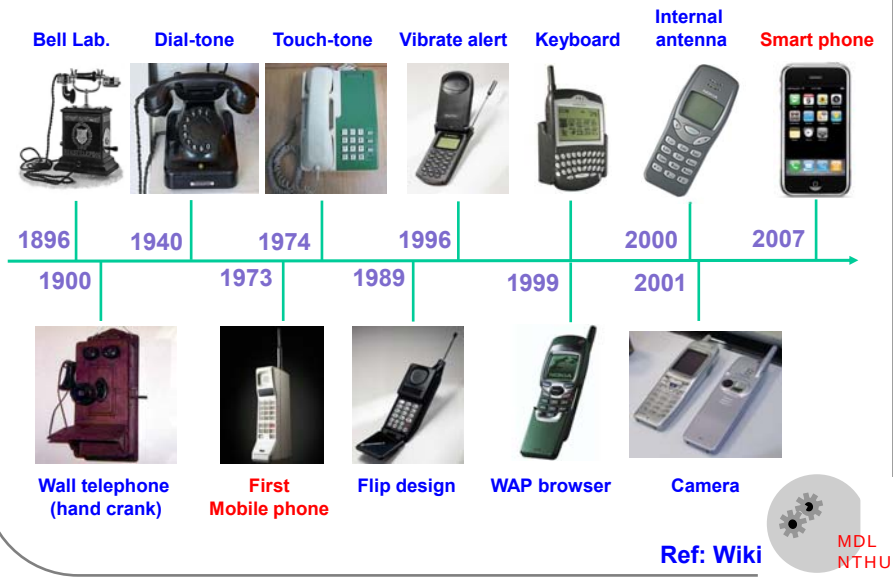
Person computer
(VLSI)

Notebook

Ref: Wiki

MDL
NTHU

Telephone

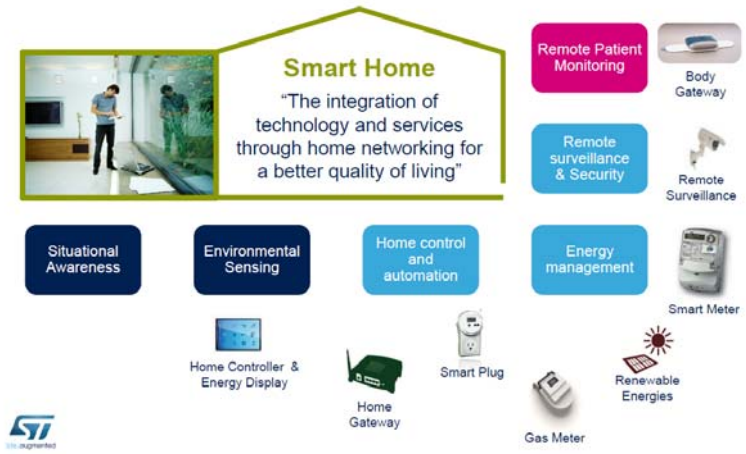


Ref: Wiki

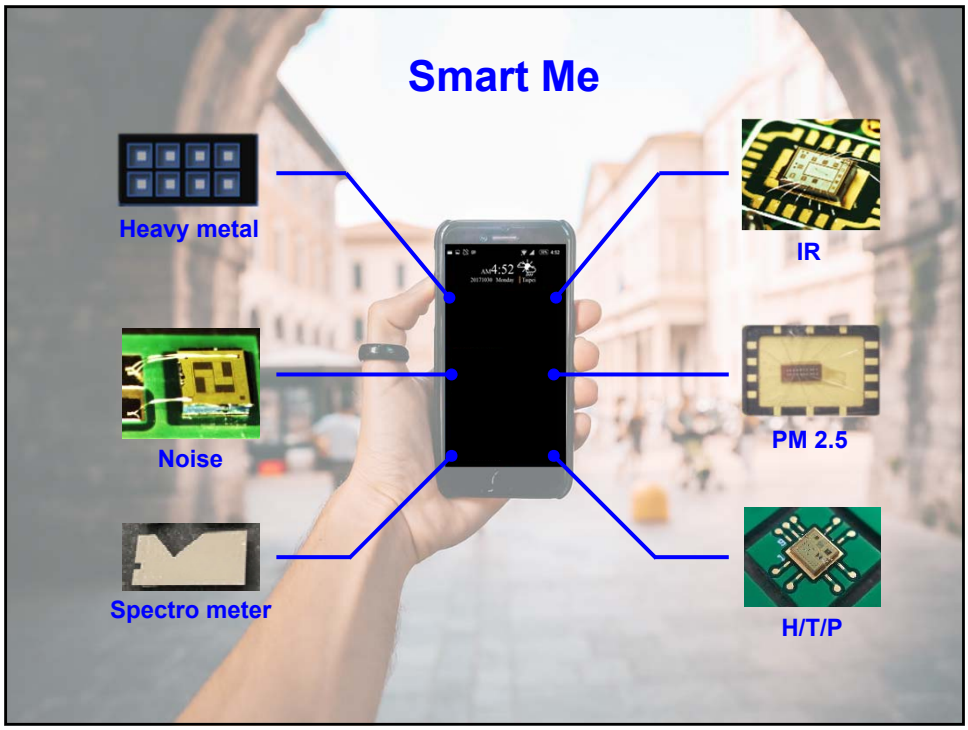
MDL NTHU

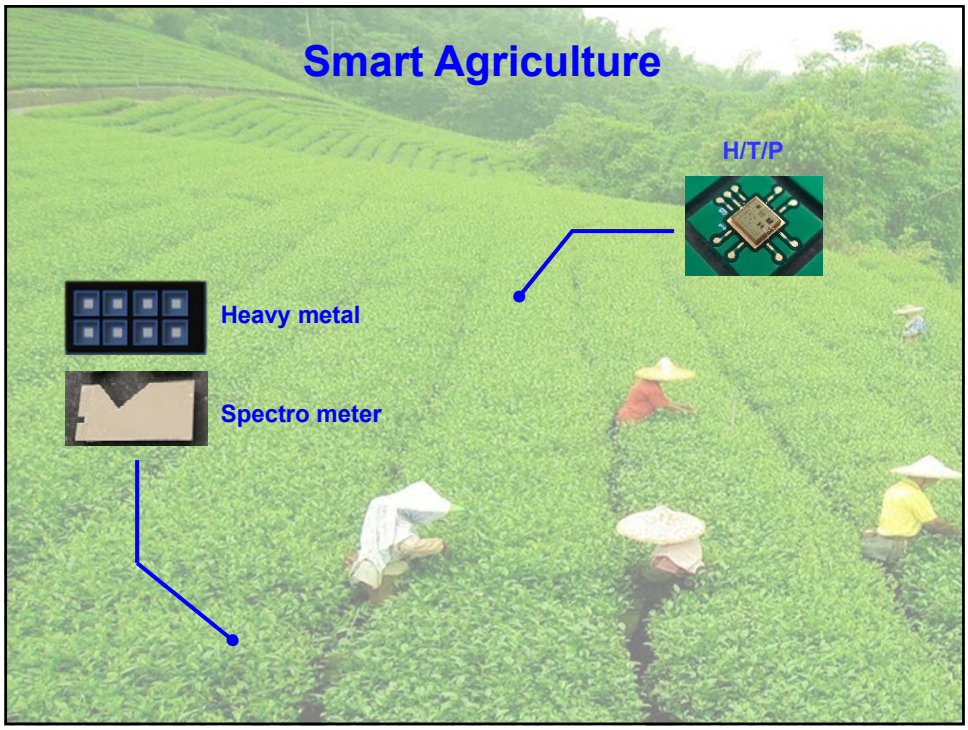
From *IoT* to Smart-X

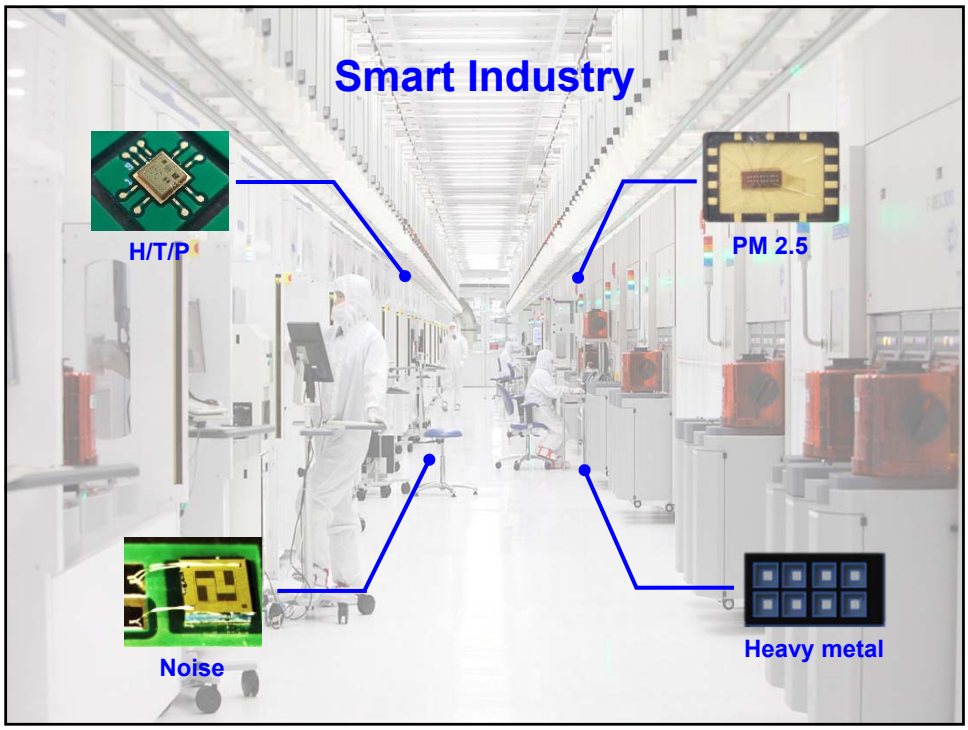
- **Internet of Things (IoT)**

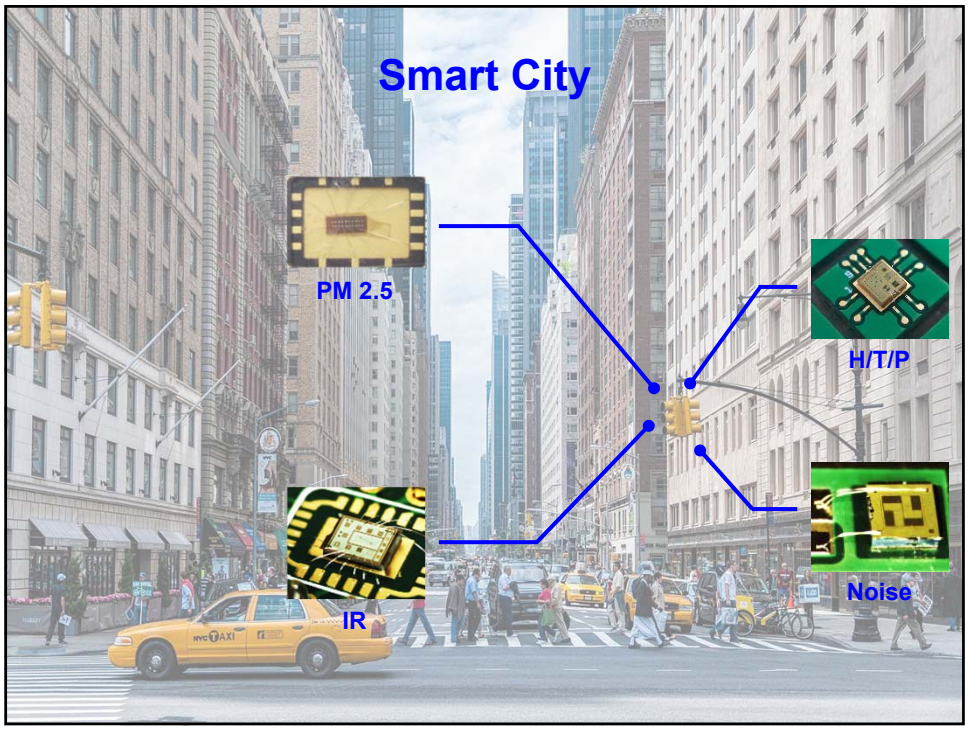


MDL NTHU


Smart Me
Heavy metal
Noise
Spectro meter
IR
PM 2.5
H/T/P


Smart Agriculture
H/T/P
Heavy metal
Spectro meter


Smart Industry
H/T/P
PM 2.5
Noise
Heavy metal


Smart City
PM 2.5
H/T/P
IR
Noise

Ecosystems for IoT

STMicroelectronics

MDL NTHU

IoT – the Next Big Things

- **The next big things**
  - **+ Highlight by Dr. Morris Chang of TSMC in 2014**
  - **+ Major players: Google, Apple, Cisco, Alibaba, Huawei, etc.**
  - **+ Semiconductor remain the key enabling tech.**

www.appledaily.com.tw

MDL NTHU

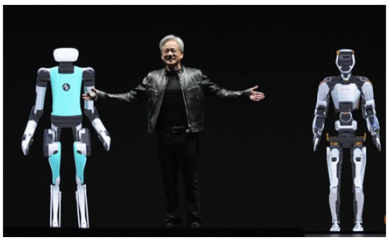
The *PMMP* Era

- **Applications for PMMP** (people-machine-machine-people) **Era**
  - **+ Highlight by Dr. Tien Wu of ASE in 2023**
  - **+ Driven by: big data, AI, Autonomous vehicle, etc.**
  - **+ Future needs: five sense**

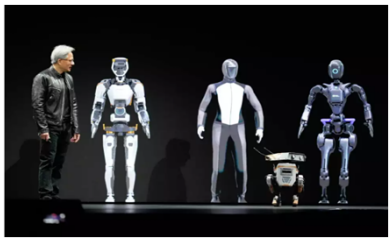
https://udn.com/news/

Humanoid Robots

- **Demonstrated by CEO Jensen Huang of Nvidia in 2024**
- **Once again: " 5 Senses + AI" for future needs**



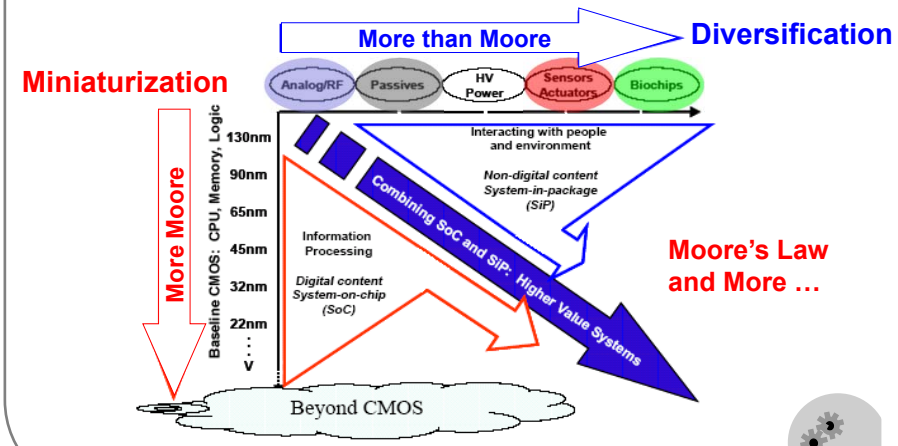
https://tw.nextapple.com/



https://www.sfchronicle.com/

More than Moore

- Moore's Law and More – X on Silicon
- Add value to the existing CMOS tech



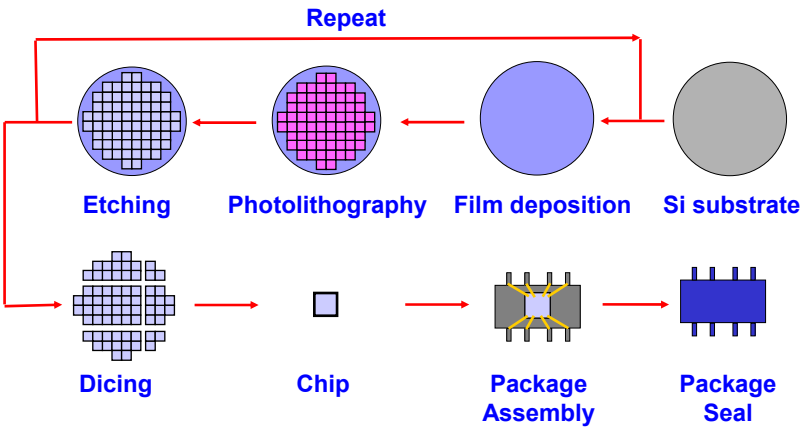
Source: ITRS Roadmap 2005, www.itrs.net

MDL NTHU

課程安排

MDL NTHU

Semiconductor processes

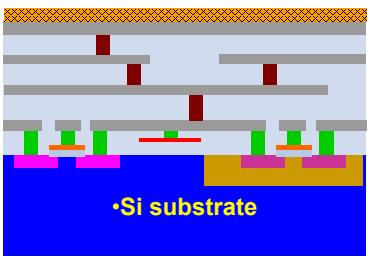


MDL NTHU

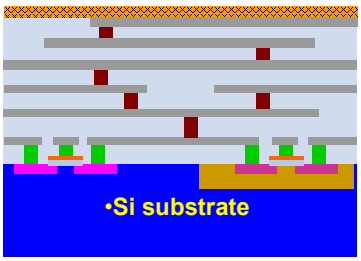
Standard CMOS Processes

- Available in CMOS foundries: TSMC, UMC, etc…

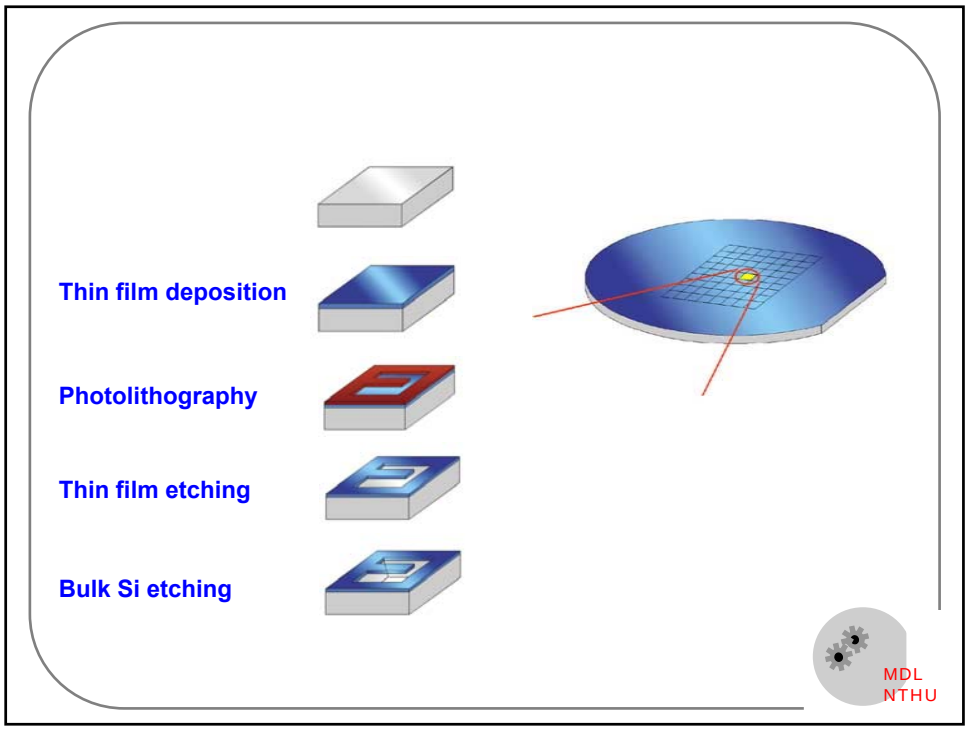
0.35μm 2P4M CMOS process

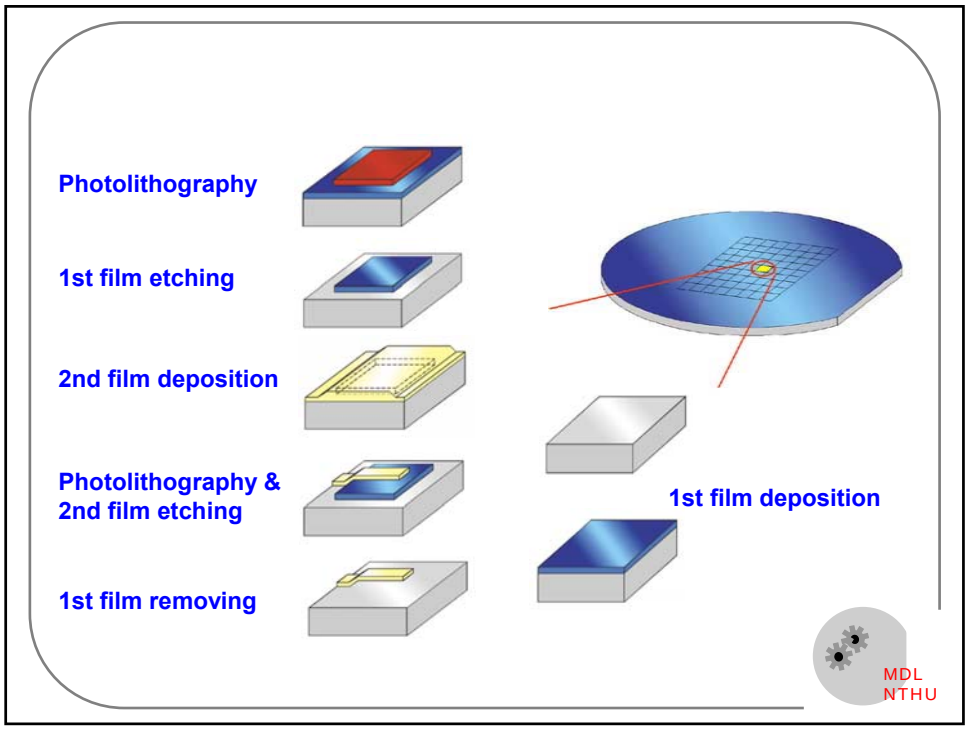


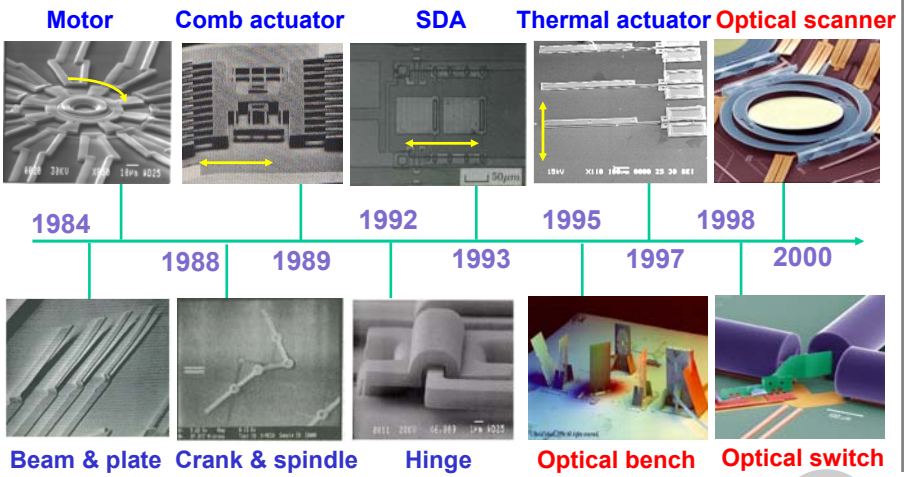
0.18μm 1P6M CMOS process



MDL NTHU


Thin film deposition
Photolithography
Thin film etching
Bulk Si etching
MDL
NTHU


Photolithography
1st film etching
2nd film deposition
Photolithography &
2nd film etching
1st film removing
1st film deposition
MDL
NTHU



BSAC, Sophia U., U. Colorado, UCLA, Agilent

MDL
NTHU