CMOS MEMS Technologies for the Next Big Things - *IoT*

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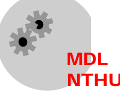
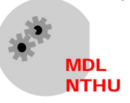
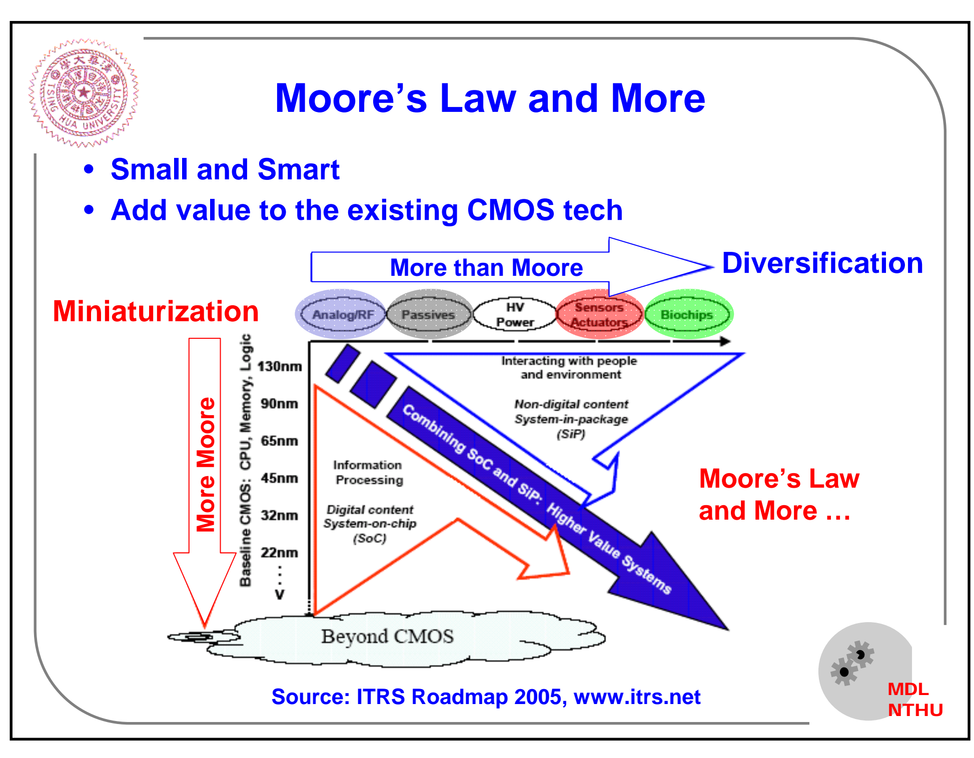


Outline

- Introduction
- CMOS MEMS Motion Hub
- CMOS MEMS Environment Hub
- CMOS MEMS Resonators Hub
- CMOS MEMS Acoustic/Optical Hubs
- Outlook and Concluding Remarks





Moore's Law and More
Small and Smart
Add value to the existing CMOS tech
More than Moore
Diversification
Miniaturization
Analog/RF
Passives
HV Power
Sensors Actuators
Biochips
More Moore
Baseline CMOS: CPU, Memory, Logic
130nm
90nm
65nm
45nm
32nm
22nm
Interacting with people and environment
Non-digital content System-in-package (SiP)
Information Processing
Digital content System-on-chip (SoC)
Combining SoC and SiP: Higher Value Systems
Moore's Law and More …
Beyond CMOS
Source: ITRS Roadmap 2005, www.itrs.net
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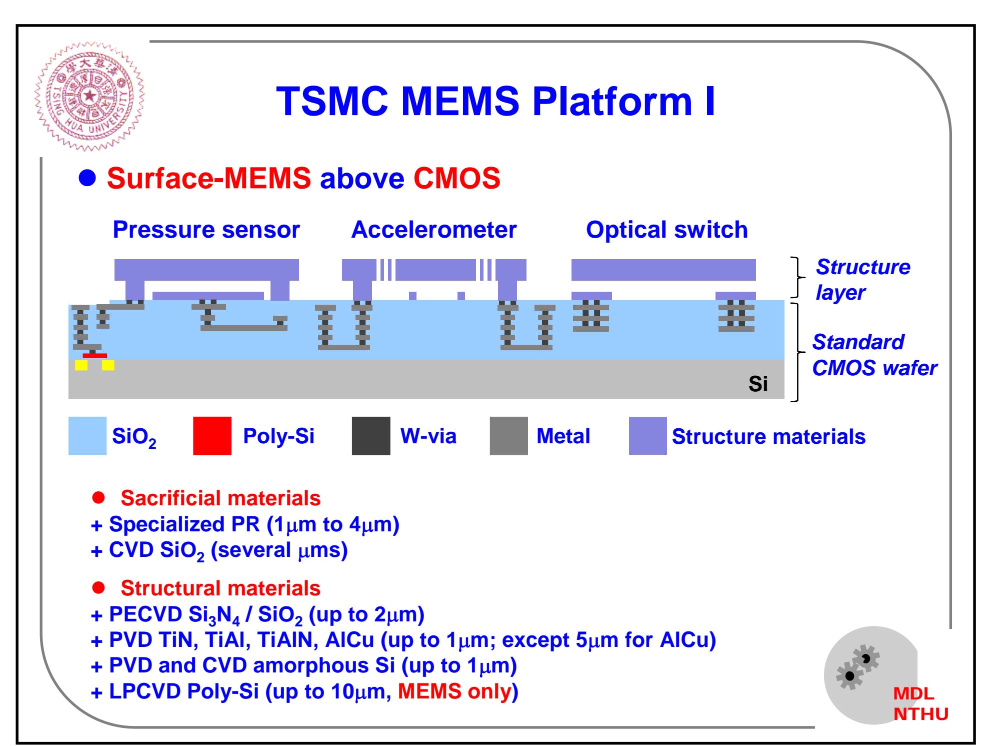
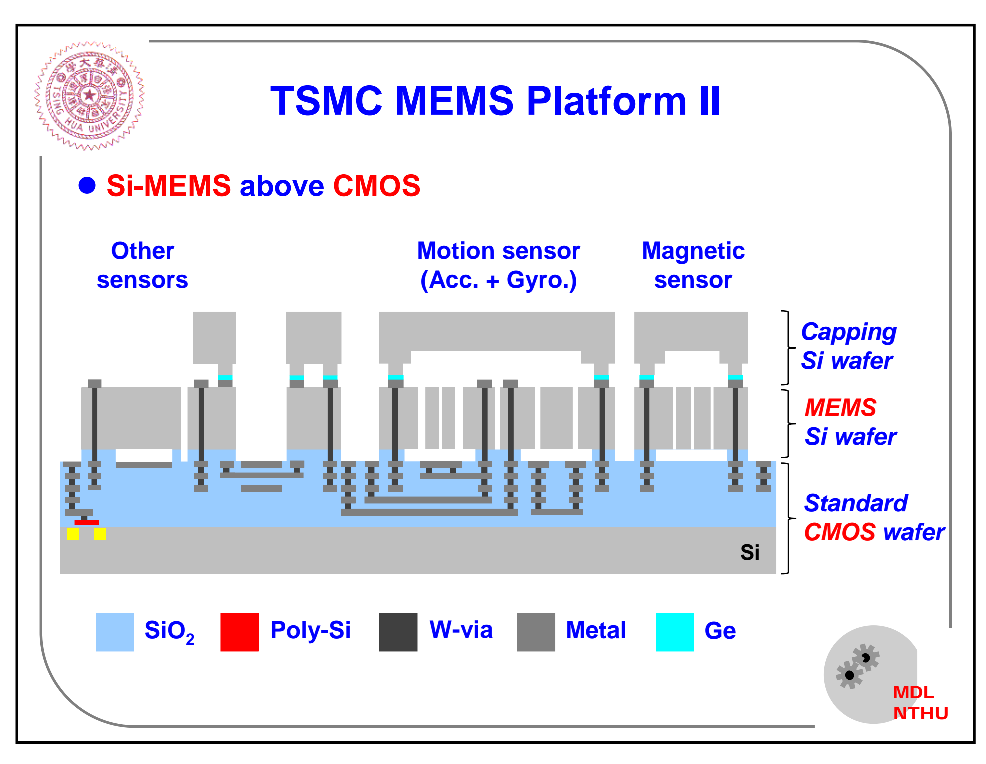
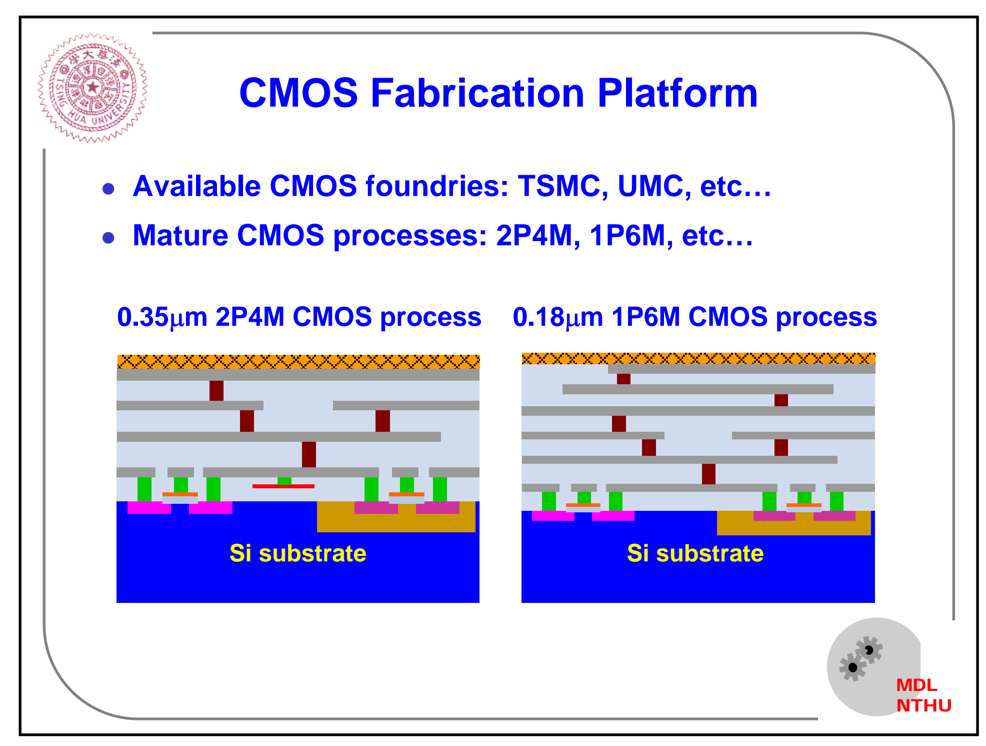
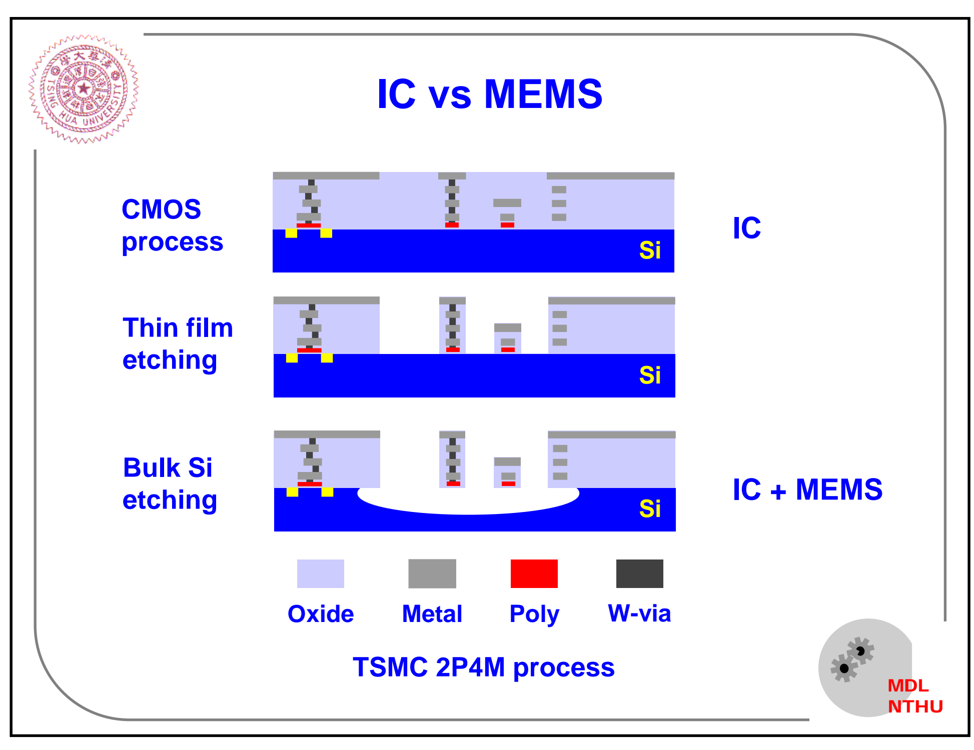


TSMC MEMS Platform I
Surface-MEMS above CMOS
Pressure sensor
Accelerometer
Optical switch
Structure layer
Standard CMOS wafer
Si
SiO2
Poly-Si
W-via
Metal
Structure materials
Sacrificial materials
+ Specialized PR (1µm to 4µm)
+ CVD SiO2 (several µms)
Structural materials
+ PECVD Si3N4 / SiO2 (up to 2µm)
+ PVD TiN, TiAl, TiAlN, AlCu (up to 1µm; except 5µm for AlCu)
+ PVD and CVD amorphous Si (up to 1µm)
+ LPCVD Poly-Si (up to 10µm, MEMS only)
MDL NTHU


TSMC MEMS Platform II
Si-MEMS above CMOS
Other sensors
Motion sensor (Acc. + Gyro.)
Magnetic sensor
Capping Si wafer
MEMS Si wafer
Standard CMOS wafer
Si
SiO2
Poly-Si
W-via
Metal
Ge
MDL NTHU


CMOS Fabrication Platform
Available CMOS foundries: TSMC, UMC, etc…
Mature CMOS processes: 2P4M, 1P6M, etc…
0.35μm 2P4M CMOS process
0.18μm 1P6M CMOS process
Si substrate
Si substrate
MDL NTHU


IC vs MEMS
CMOS process
Thin film etching
Bulk Si etching
Si
IC
IC + MEMS
Oxide
Metal
Poly
W-via
TSMC 2P4M process
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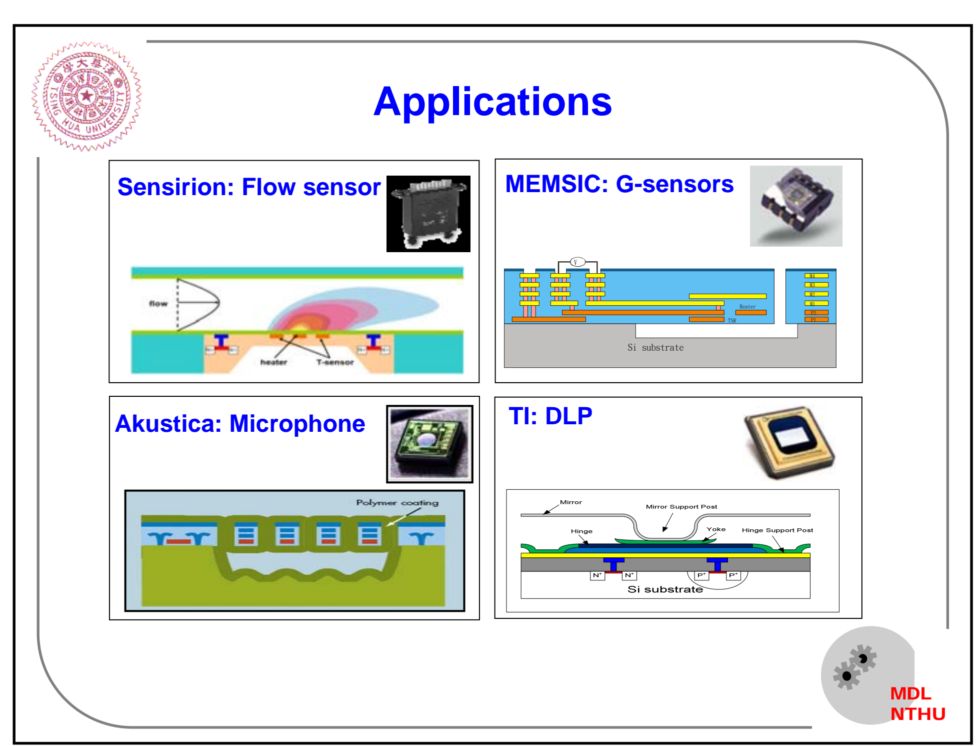
Applications
Sensirion: Flow sensor
MEMSIC: G-sensors
Akustica: Microphone
TI: DLP
Si substrate
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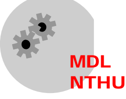
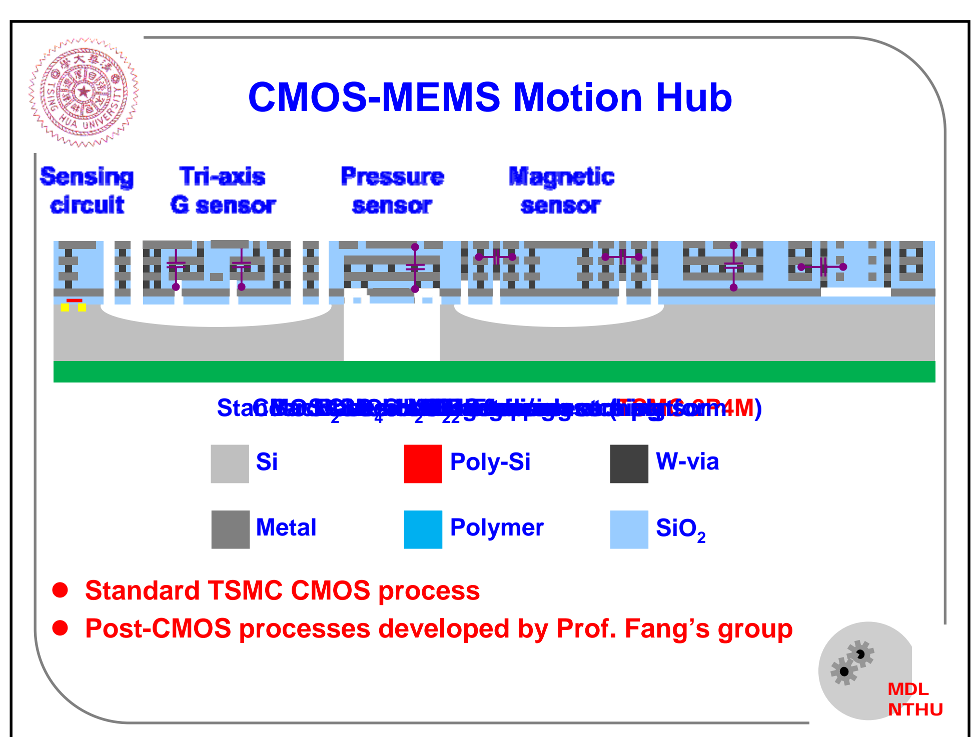


CMOS-MEMS Motion Hub



- Standard TSMC CMOS process
- Post-CMOS processes developed by Prof. Fang's group

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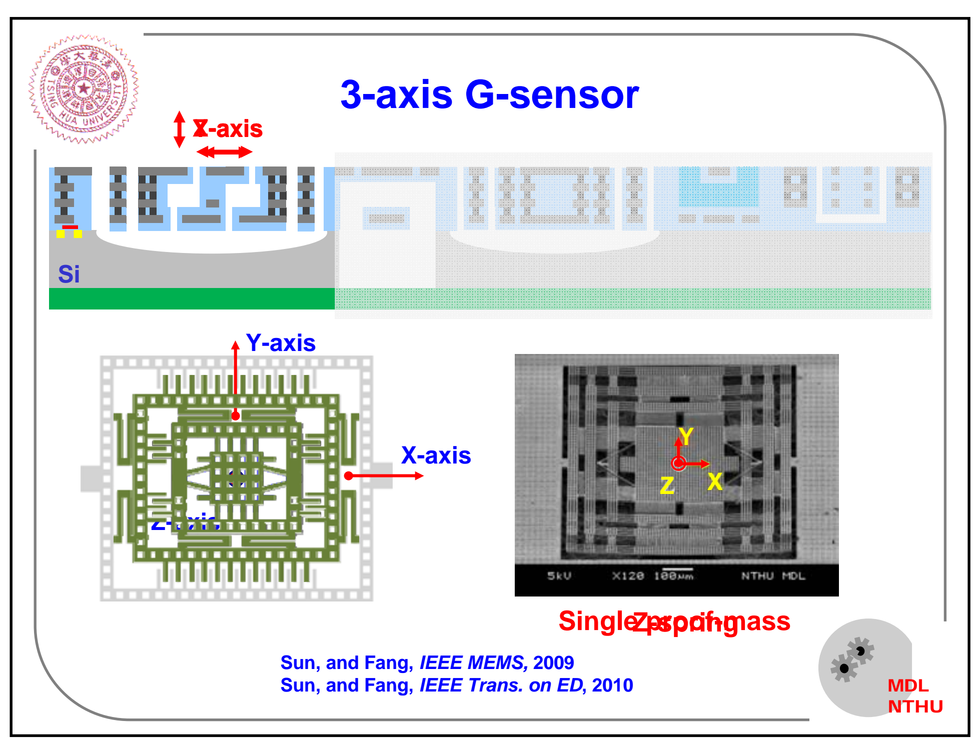
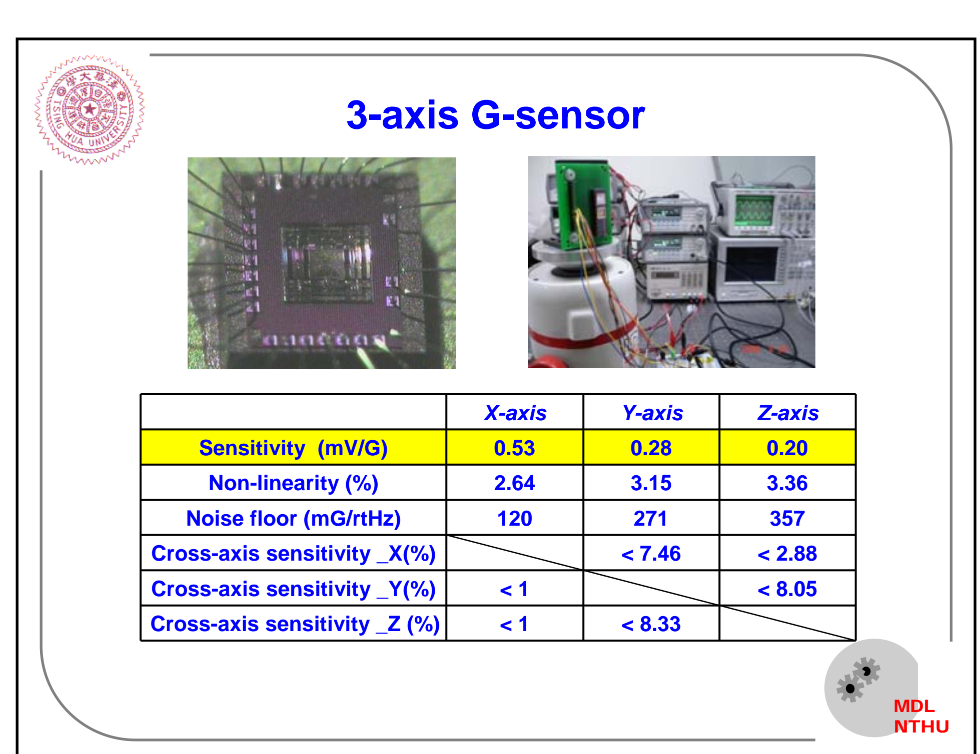
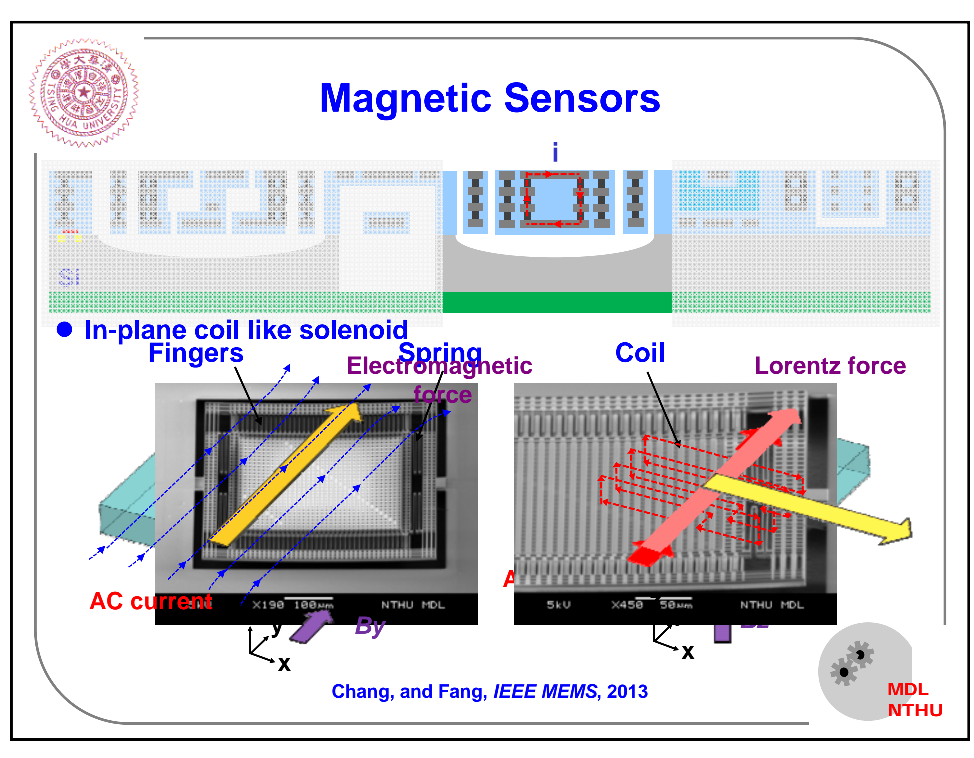
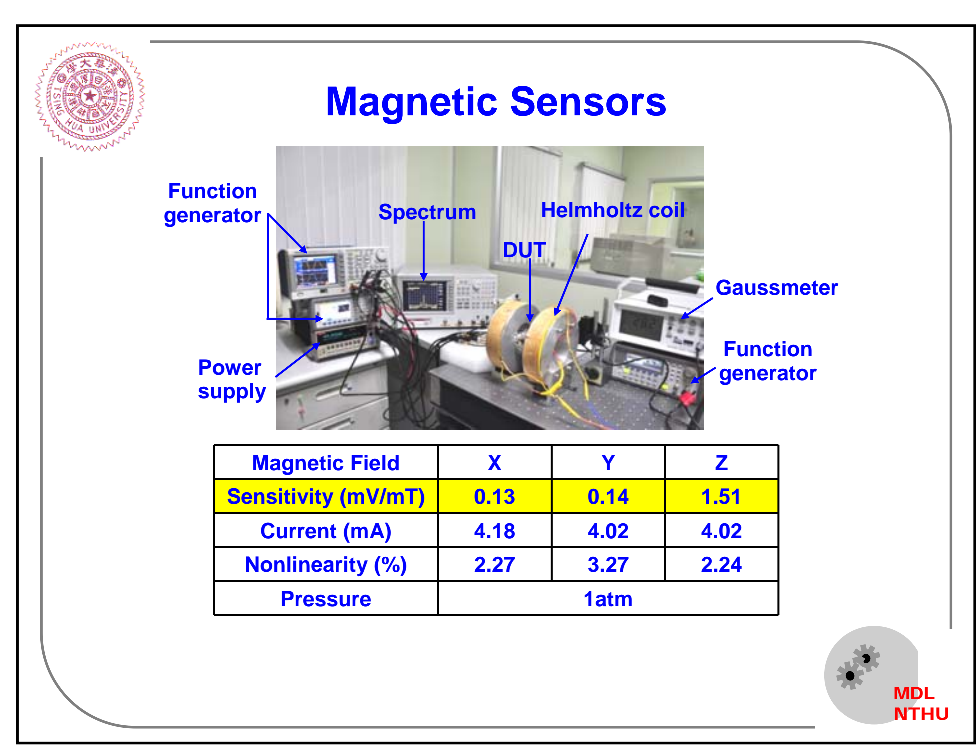


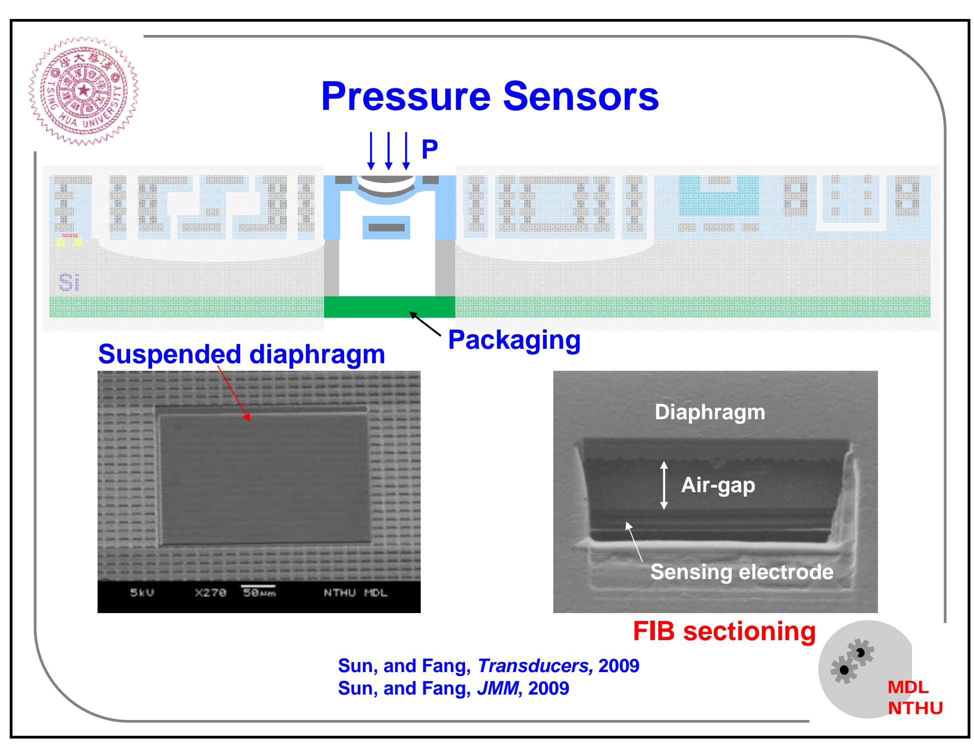


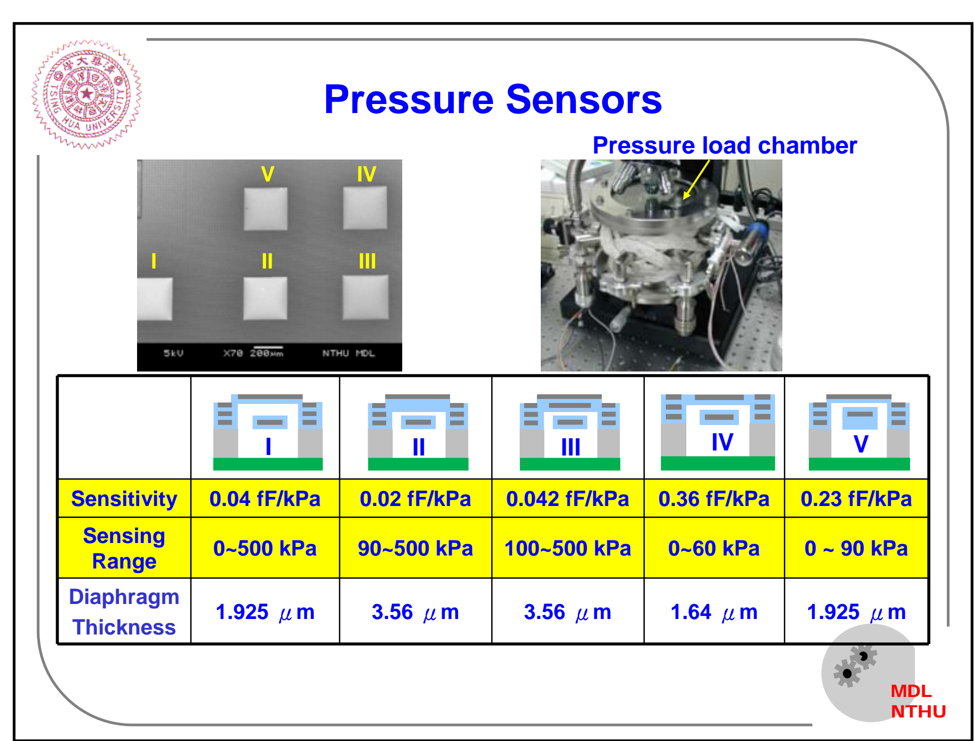
	X-axis	*Y-axis*	*Z-axis*
Sensitivity (mV/G)	0.53	0.28	0.20
Non-linearity (%)	2.64	3.15	3.36
Noise floor (mG/rtHz)	120	271	357
Cross-axis sensitivity _X(%)		< 7.46	< 2.88
Cross-axis sensitivity _Y(%)	< 1		< 8.05
Cross-axis sensitivity _Z (%)	< 1	< 8.33	



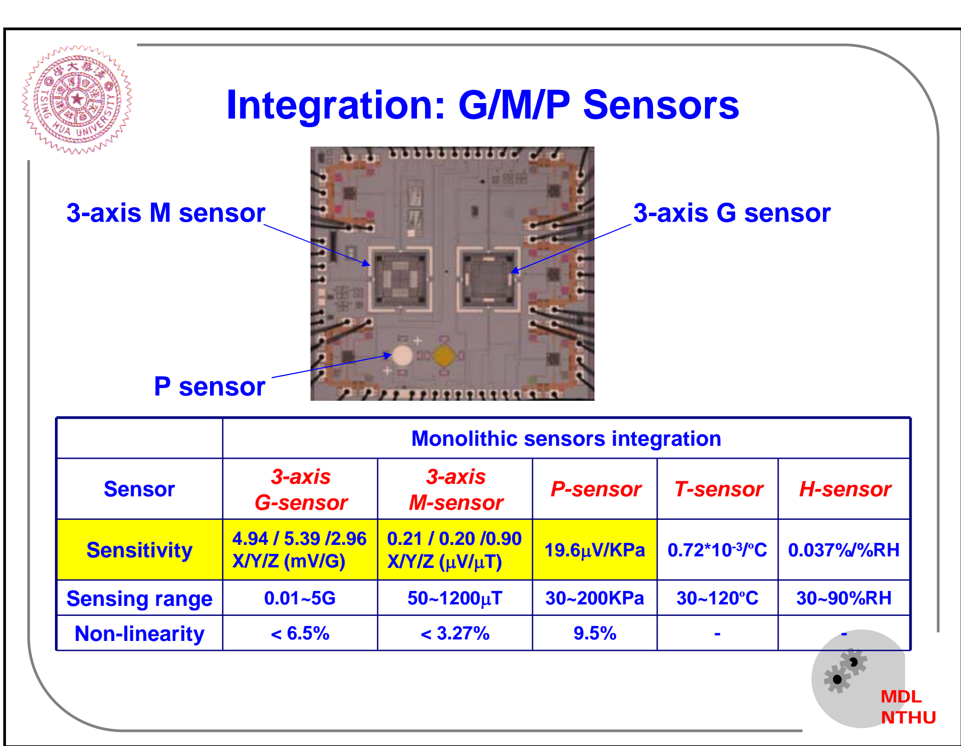


Magnetic Field	X	Y	Z
Sensitivity (mV/mT)	0.13	0.14	1.51
Current (mA)	4.18	4.02	4.02
Nonlinearity (%)	2.27	3.27	2.24
Pressure	1atm		





	I	II	III	IV	V
Sensitivity	0.04 fF/kPa	0.02 fF/kPa	0.042 fF/kPa	0.36 fF/kPa	0.23 fF/kPa
Sensing Range	0~500 kPa	90~500 kPa	100~500 kPa	0~60 kPa	0 ~ 90 kPa
Diaphragm Thickness	1.925 μm	3.56 μm	3.56 μm	1.64 μm	1.925 μm



	Monolithic sensors integration				
Sensor	*3-axis G-sensor*	*3-axis M-sensor*	*P-sensor*	*T-sensor*	*H-sensor*
Sensitivity	4.94 / 5.39 /2.96 X/Y/Z (mV/G)	0.21 / 0.20 /0.90 X/Y/Z (μV/μT)	19.6μV/KPa	$0.72*10^{-3}$/°C	0.037%/%RH
Sensing range	0.01~5G	50~1200μT	30~200KPa	30~120°C	30~90%RH
Non-linearity	< 6.5%	< 3.27%	9.5%	-	-

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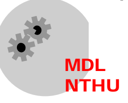

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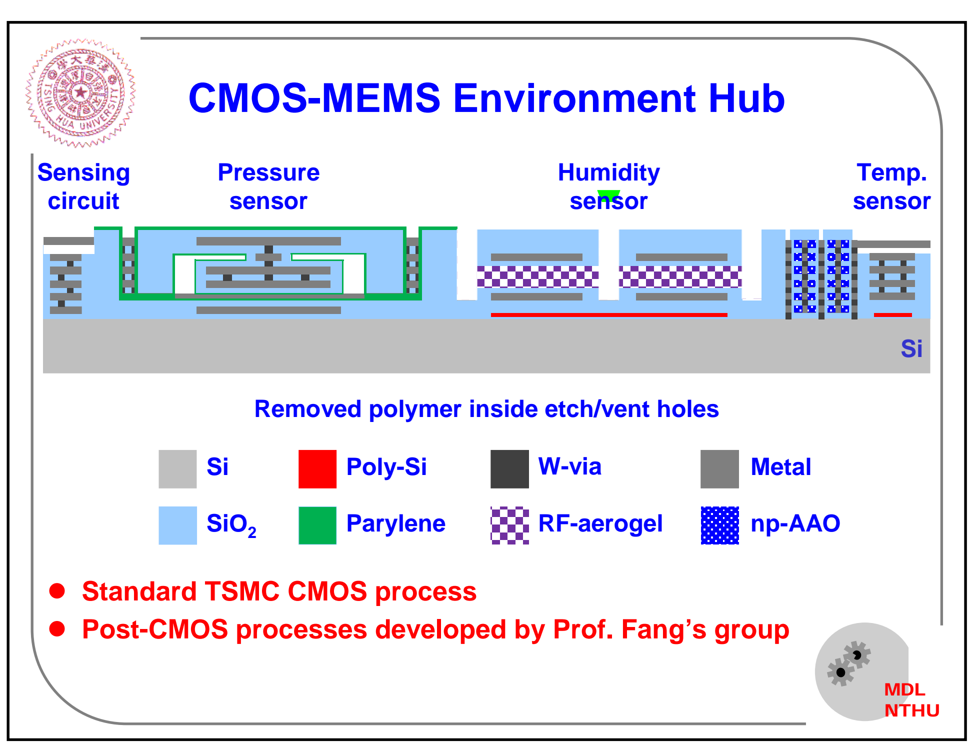
CMOS-MEMS Environment Hub
Sensing circuit
Pressure sensor
Humidity sensor
Temp. sensor
Si
Removed polymer inside etch/vent holes
Si
Poly-Si
W-via
Metal
SiO2
Parylene
RF-aerogel
np-AAO
Standard TSMC CMOS process
Post-CMOS processes developed by Prof. Fang's group
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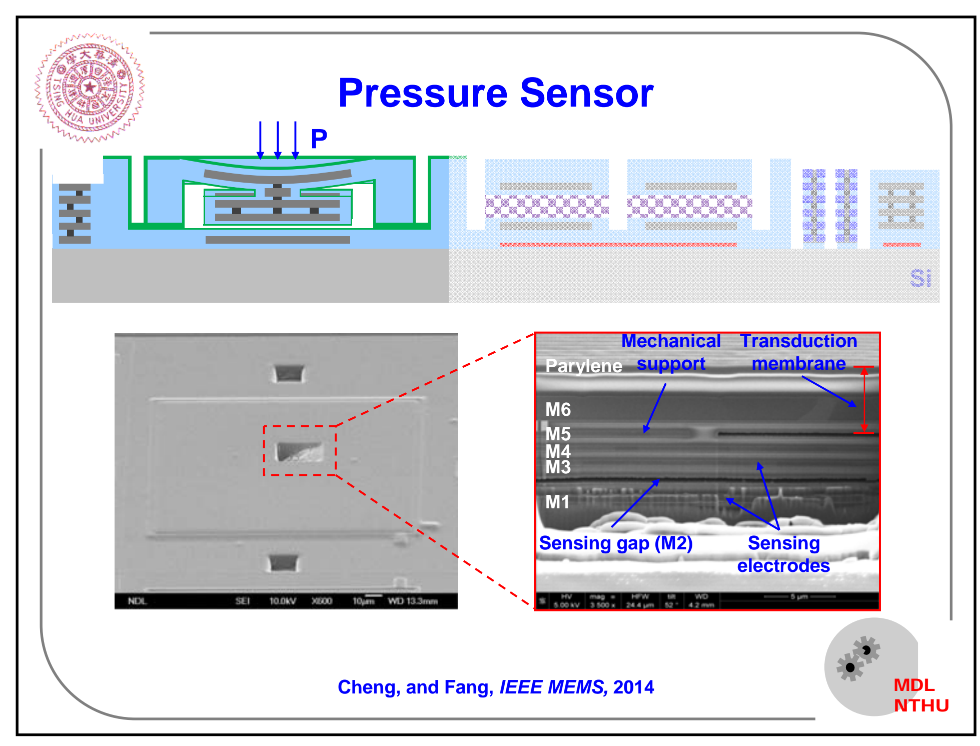
Pressure Sensor
P
Si
Mechanical support
Transduction membrane
Parylene
M6
M5
M4
M3
M1
Sensing gap (M2)
Sensing electrodes
Cheng, and Fang, IEEE MEMS, 2014
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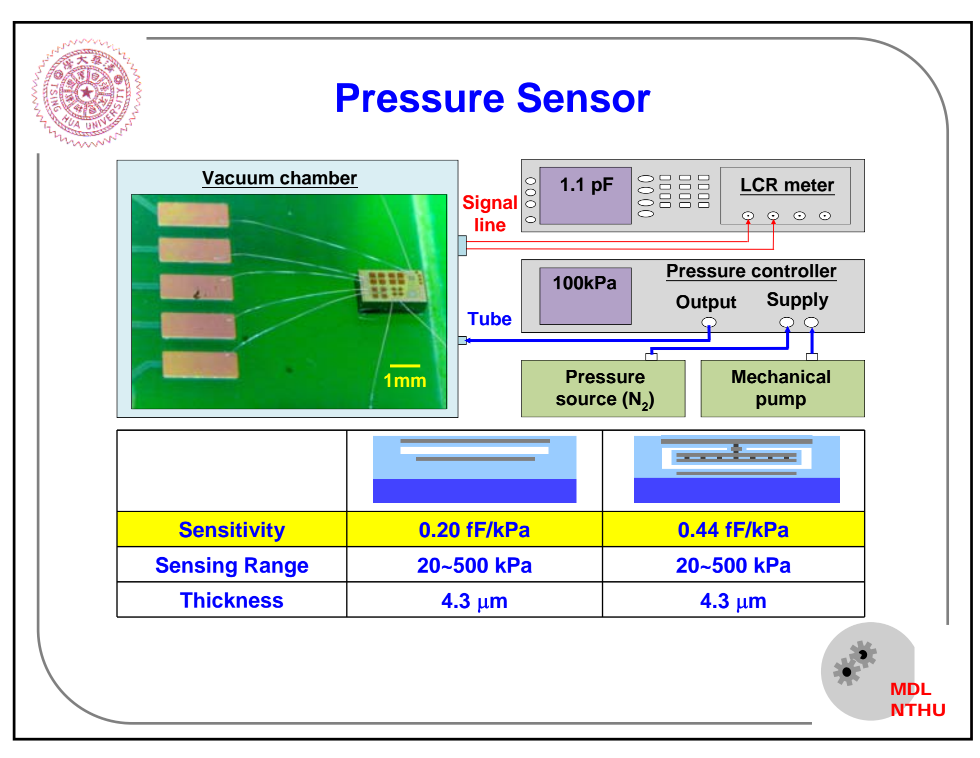
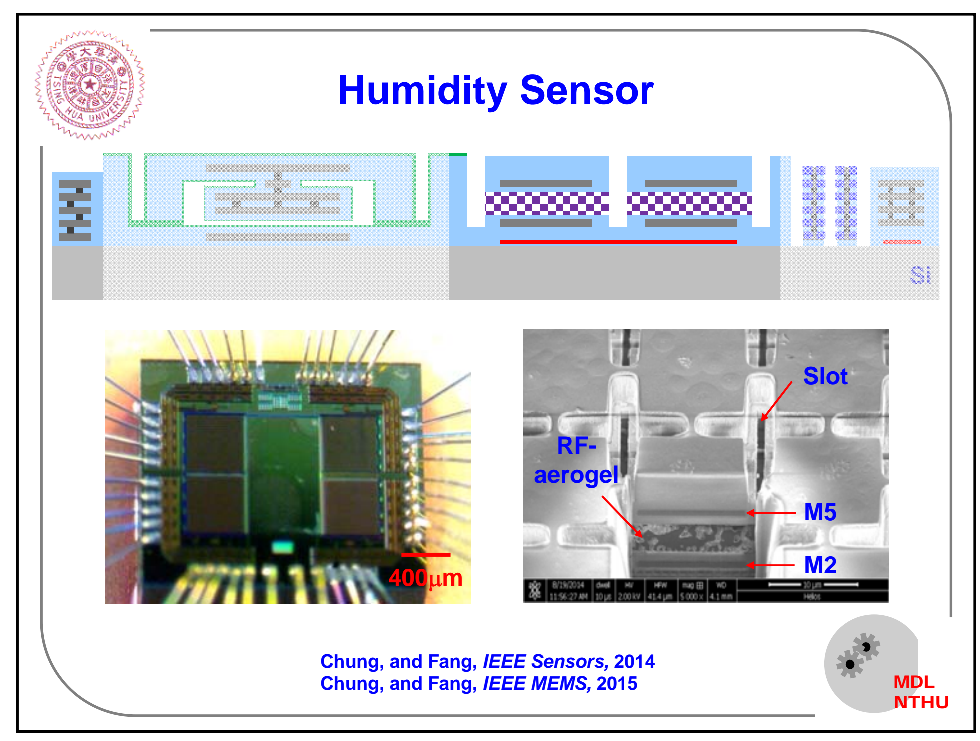
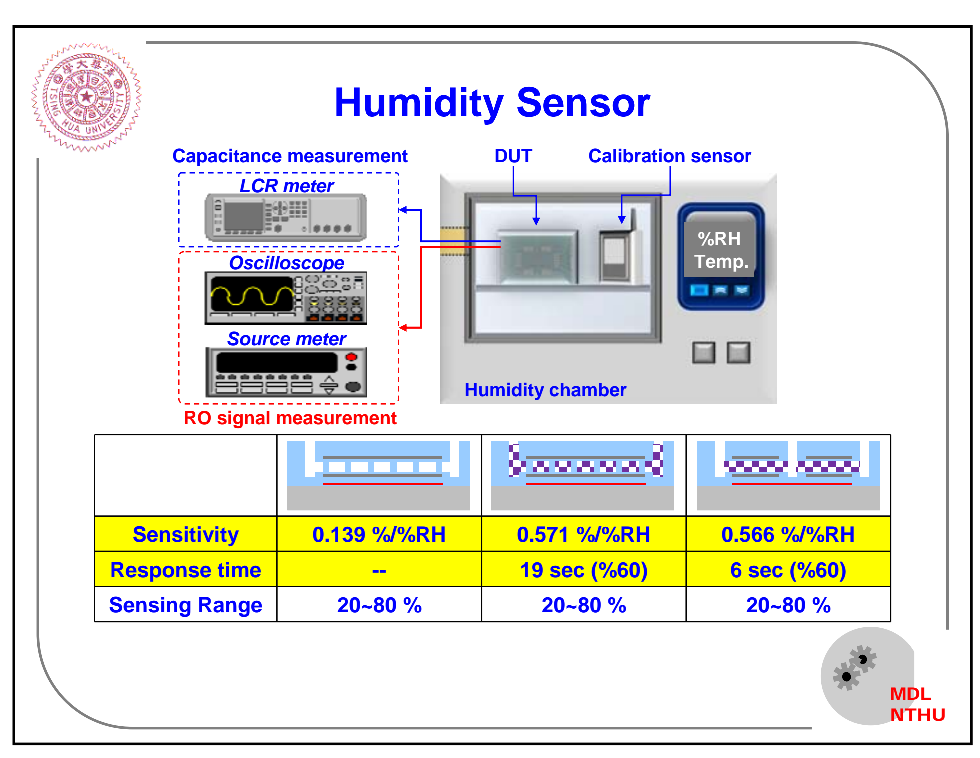
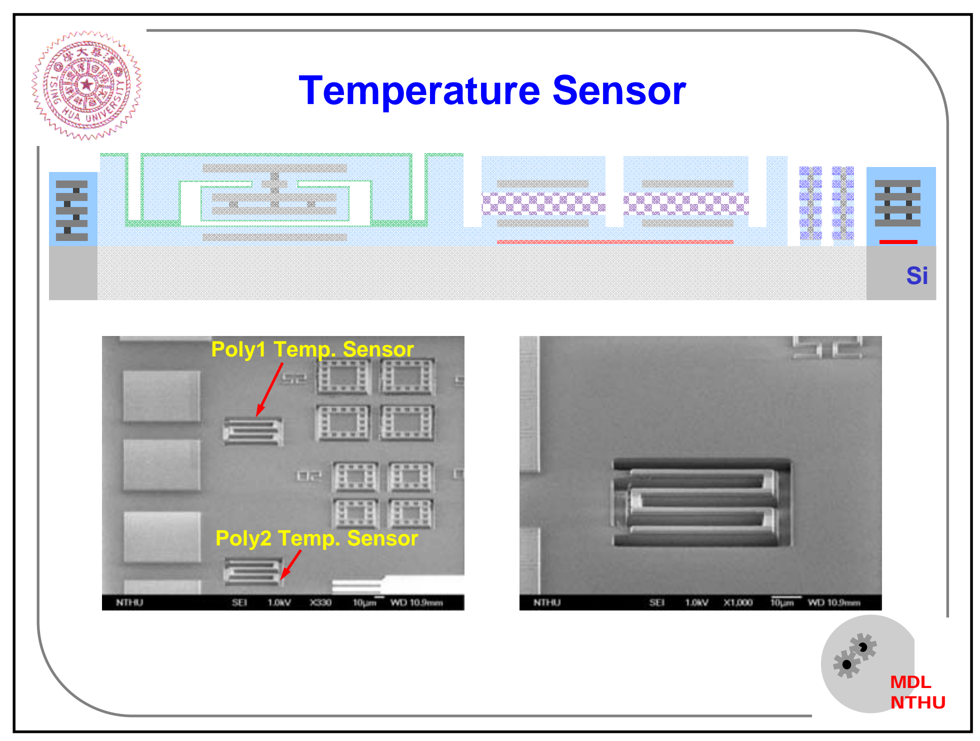


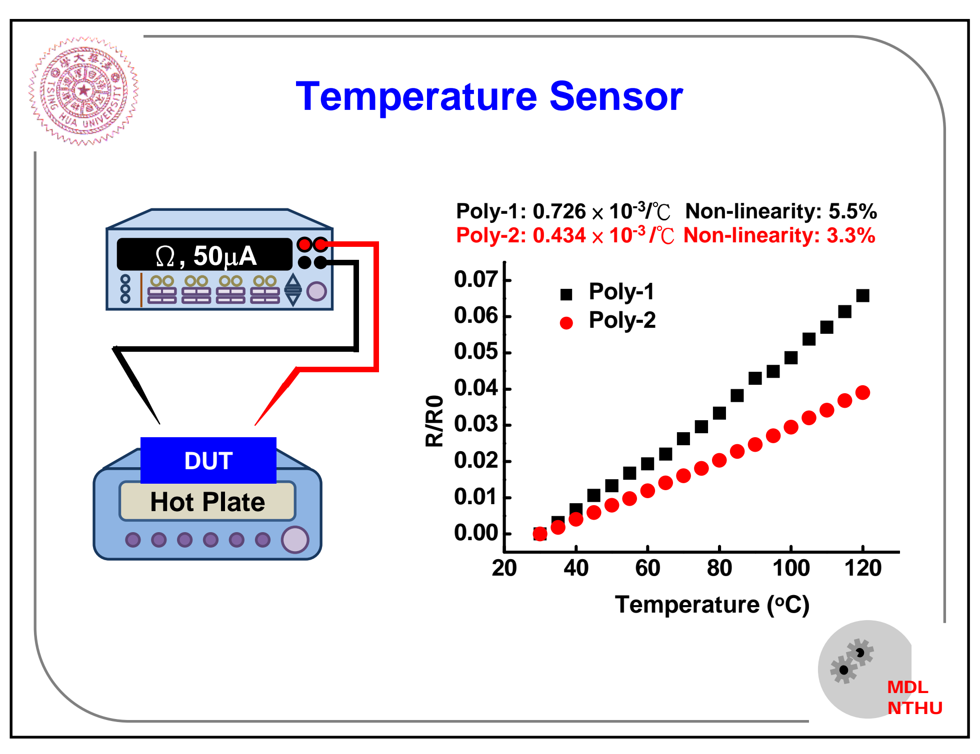
Sensitivity	0.20 fF/kPa	0.44 fF/kPa
Sensing Range	20~500 kPa	20~500 kPa
Thickness	4.3 μm	4.3 μm

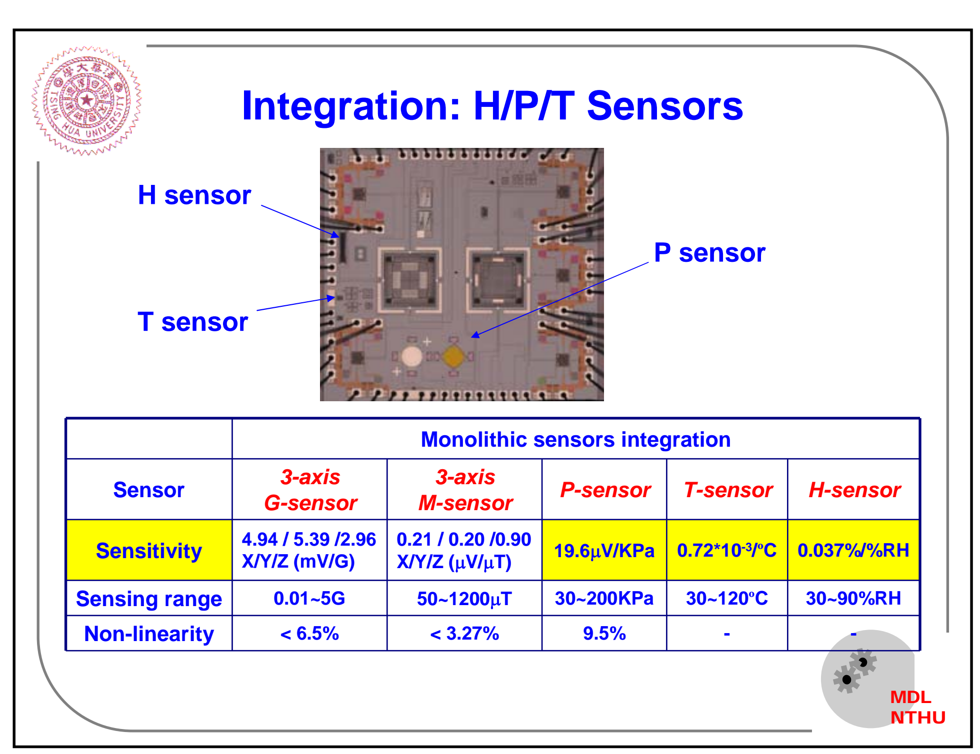




Sensitivity	0.139 %/%RH	0.571 %/%RH	0.566 %/%RH
Response time	--	19 sec (%60)	6 sec (%60)
Sensing Range	20~80 %	20~80 %	20~80 %







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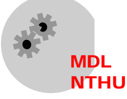

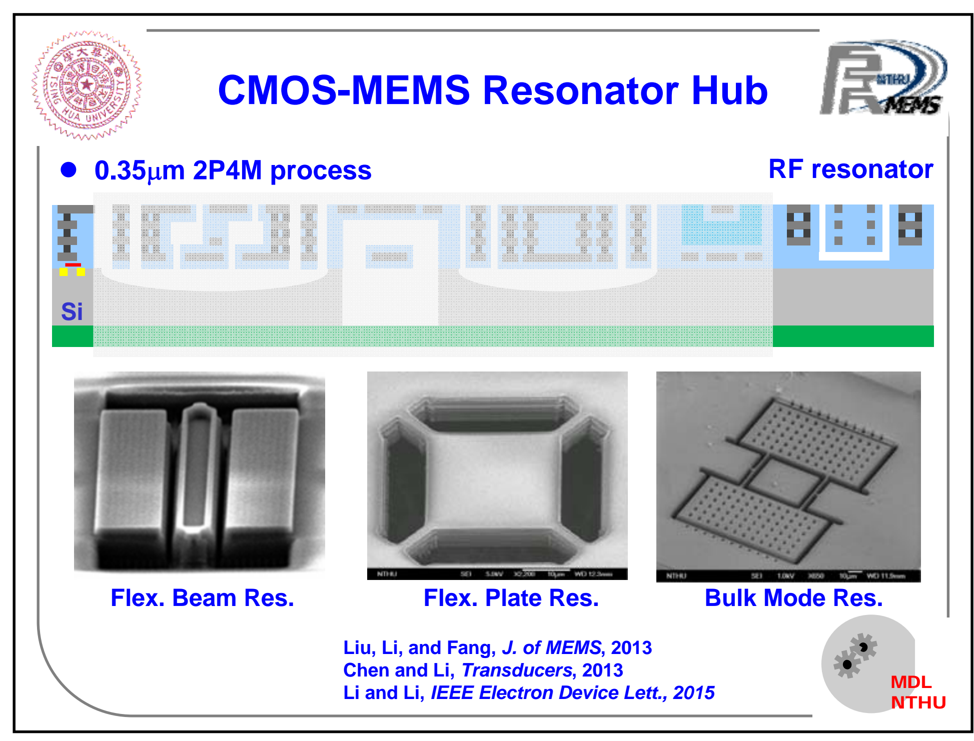

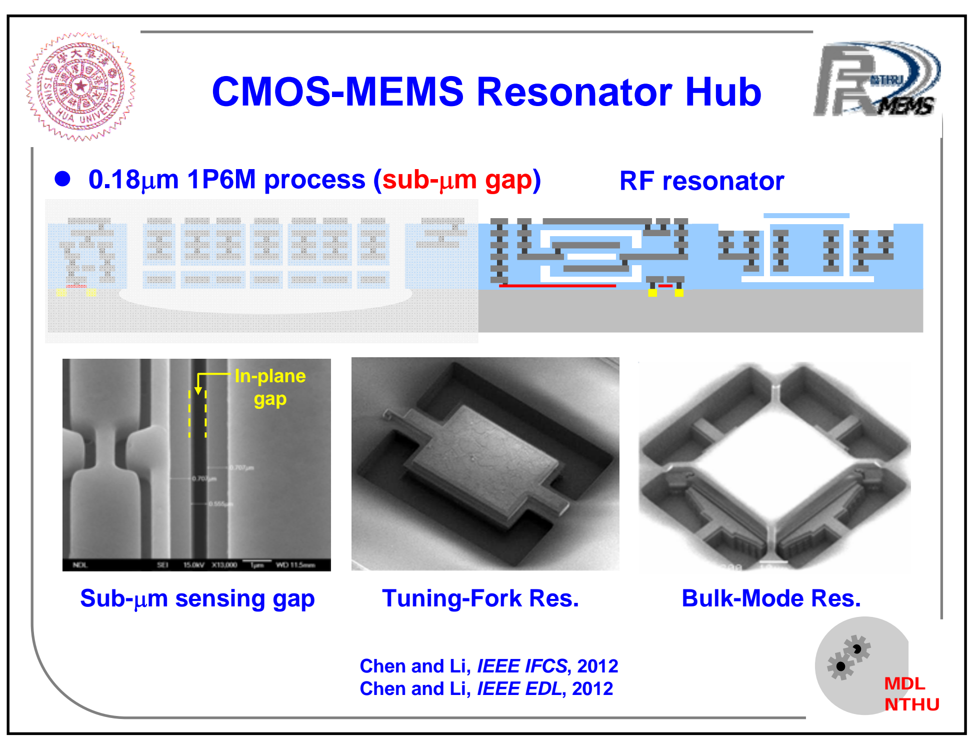
CMOS-MEMS Resonator Hub
0.18μm 1P6M process (sub-μm gap)
RF resonator
In-plane
gap
Sub-μm sensing gap
Tuning-Fork Res.
Bulk-Mode Res.
Chen and Li, IEEE IFCS, 2012
Chen and Li, IEEE EDL, 2012
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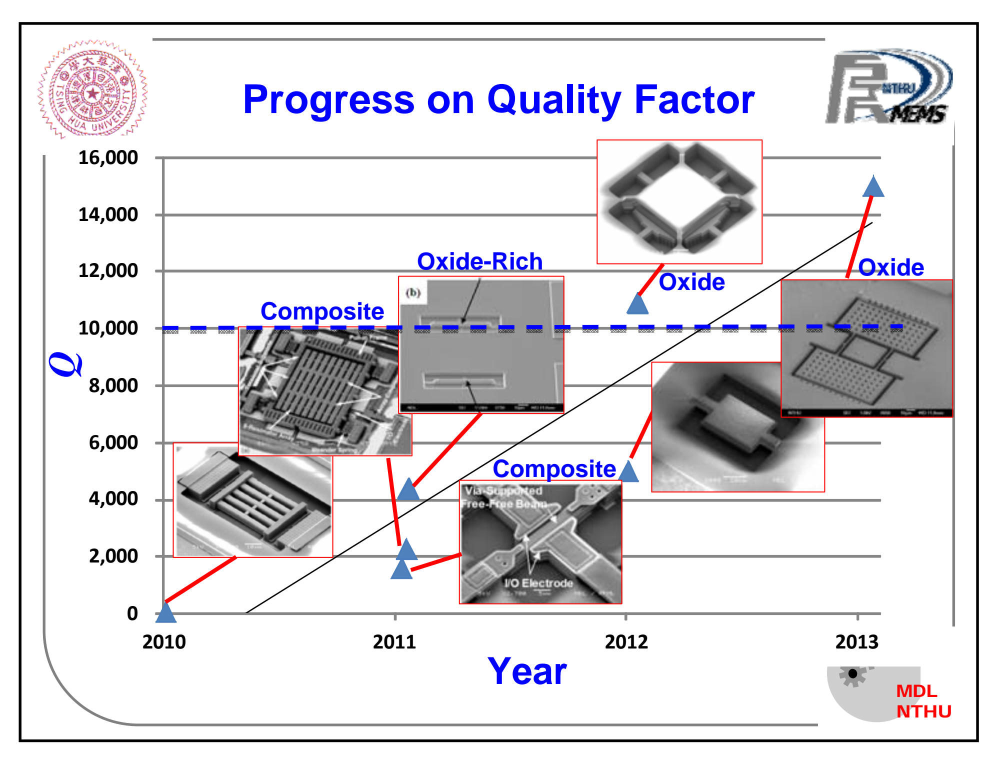
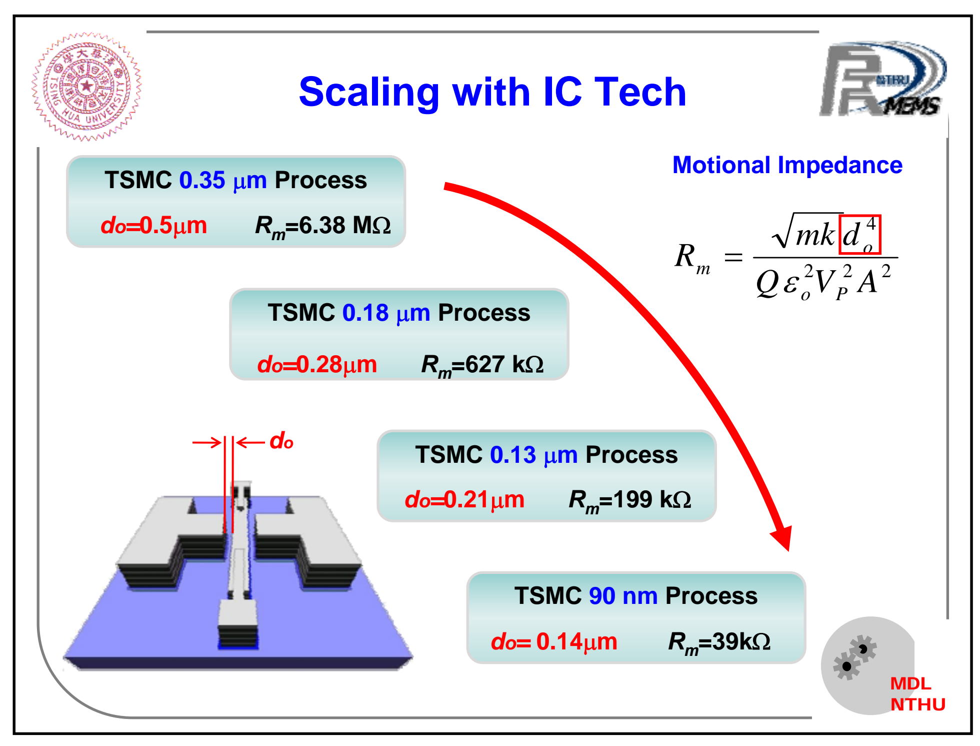

Progress on Quality Factor
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Q
2010
2011
2012
2013
Year
Composite
Oxide-Rich
Oxide
Oxide
Composite
Via-Supported
Free-Free Beam
I/O Electrode
MDL
NTHU


Scaling with IC Tech
TSMC 0.35 μm Process
do=0.5μm Rm=6.38 MΩ
TSMC 0.18 μm Process
do=0.28μm Rm=627 kΩ
TSMC 0.13 μm Process
do=0.21μm Rm=199 kΩ
TSMC 90 nm Process
do= 0.14μm Rm=39kΩ
do
Motional Impedance
$R_m = \frac{\sqrt{mk}\, d_o^4}{Q \varepsilon_o^2 V_P^2 A^2}$
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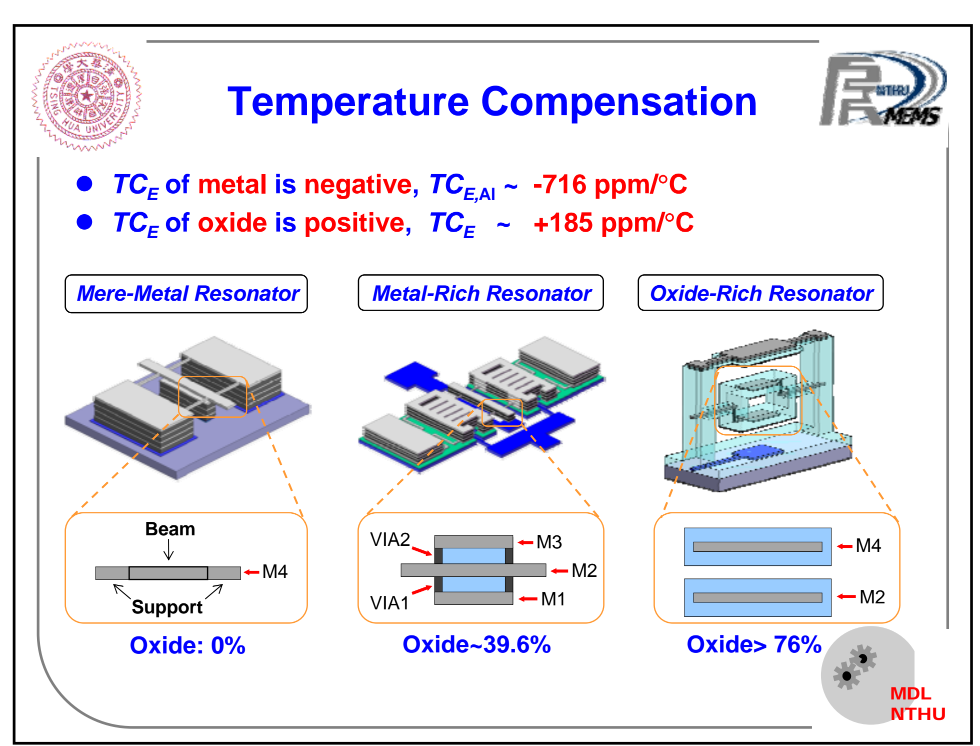
NTHU


Temperature Compensation
TCE of metal is negative, TCE,Al ~ -716 ppm/°C
TCE of oxide is positive, TCE ~ +185 ppm/°C
Mere-Metal Resonator
Metal-Rich Resonator
Oxide-Rich Resonator
Beam
Support
M4
VIA2
VIA1
M3
M2
M1
M4
M2
Oxide: 0%
Oxide~39.6%
Oxide> 76%
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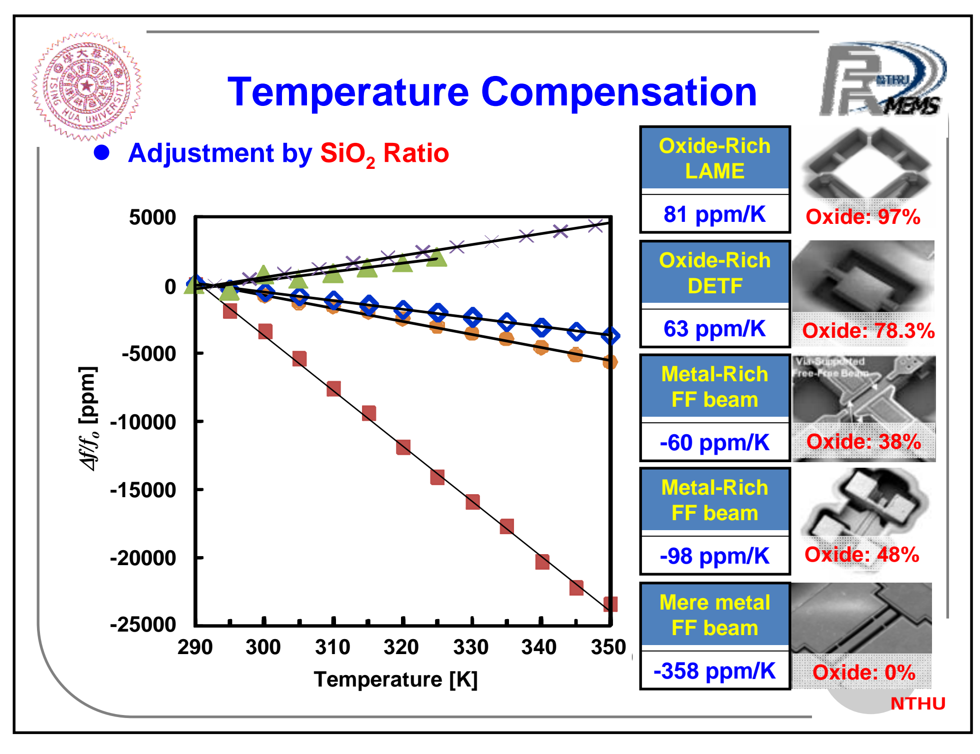
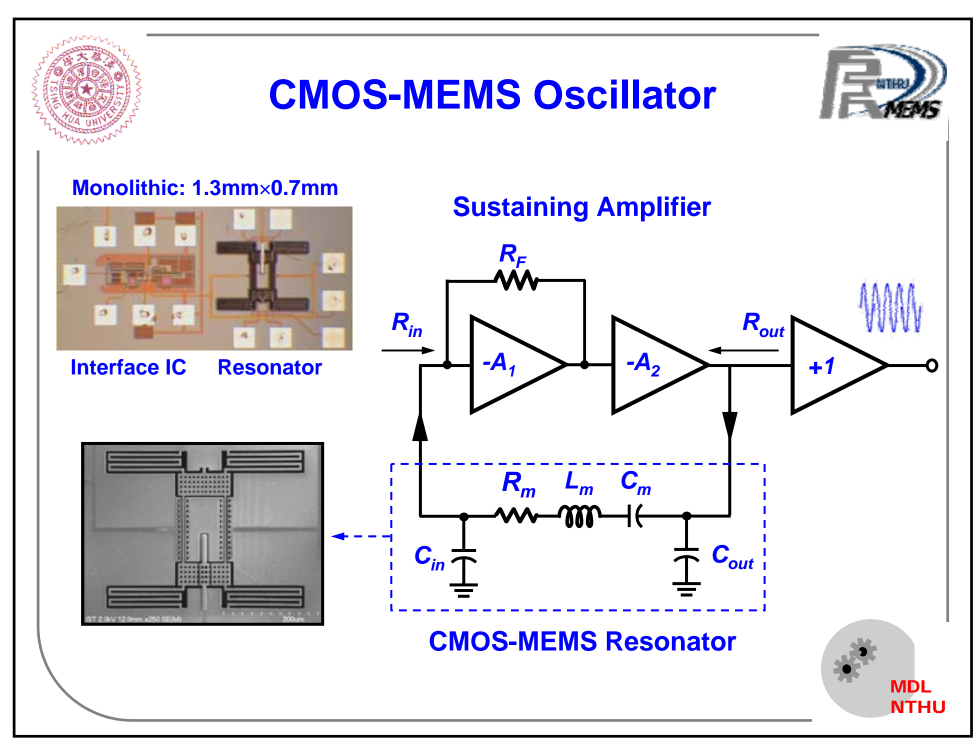
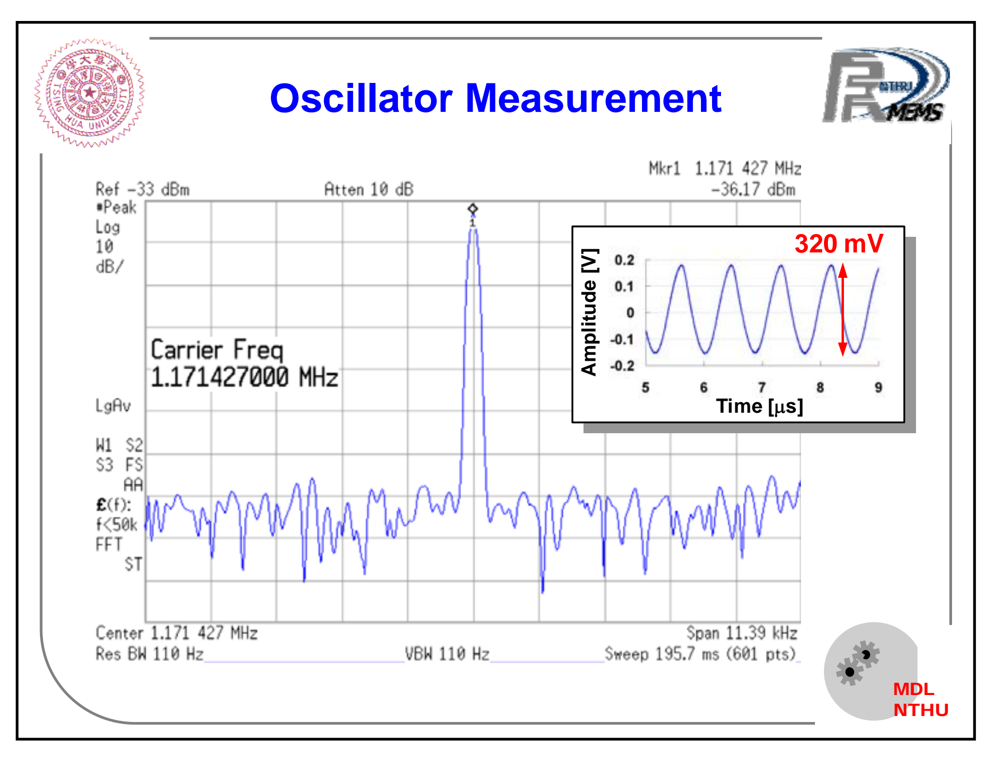

Temperature Compensation
Adjustment by SiO2 Ratio
5000
0
-5000
-10000
-15000
-20000
-25000
Δf/fo [ppm]
290
300
310
320
330
340
350
Temperature [K]
Oxide-Rich LAME
81 ppm/K
Oxide: 97%
Oxide-Rich DETF
63 ppm/K
Oxide: 78.3%
Metal-Rich FF beam
-60 ppm/K
Oxide: 38%
Metal-Rich FF beam
-98 ppm/K
Oxide: 48%
Mere metal FF beam
-358 ppm/K
Oxide: 0%
NTHU


CMOS-MEMS Oscillator
Monolithic: 1.3mm×0.7mm
Interface IC
Resonator
Sustaining Amplifier
RF
Rin
-A1
-A2
Rout
+1
Rm
Lm
Cm
Cin
Cout
CMOS-MEMS Resonator
MDL
NTHU


Oscillator Measurement
Mkr1 1.171 427 MHz
-36.17 dBm
Ref -33 dBm
Atten 10 dB
Carrier Freq
1.171427000 MHz
320 mV
Amplitude [V]
Time [μs]
Center 1.171 427 MHz
Span 11.39 kHz
Res BW 110 Hz
VBW 110 Hz
Sweep 195.7 ms (601 pts)
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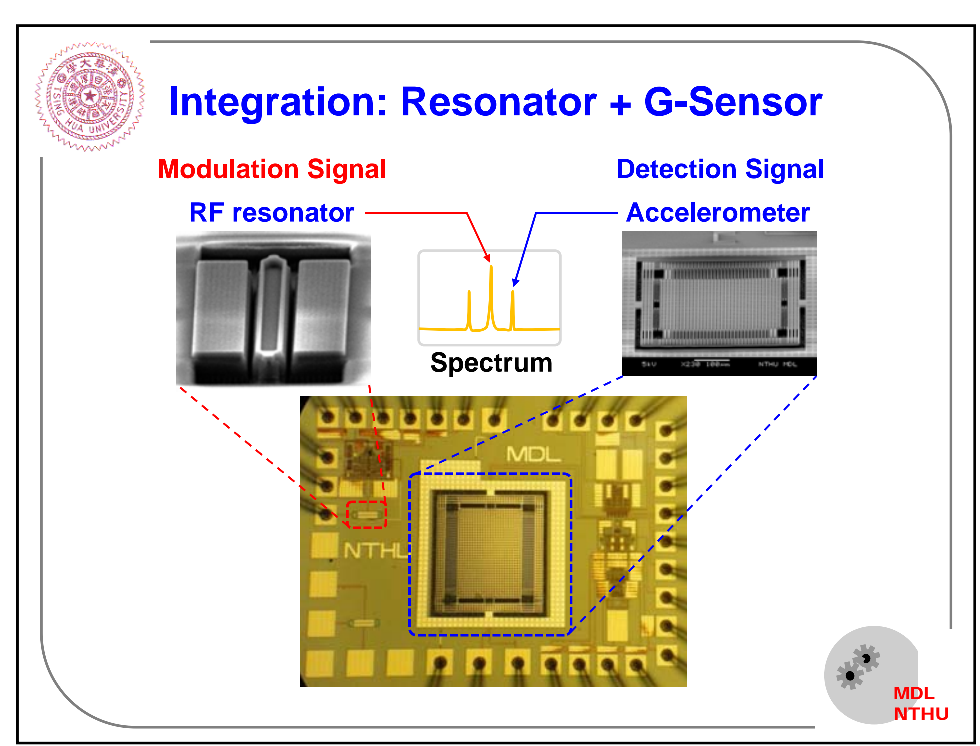
Integration: Resonator + G-Sensor
Modulation Signal
Detection Signal
RF resonator
Accelerometer
Spectrum
MDL
NTHU

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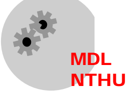
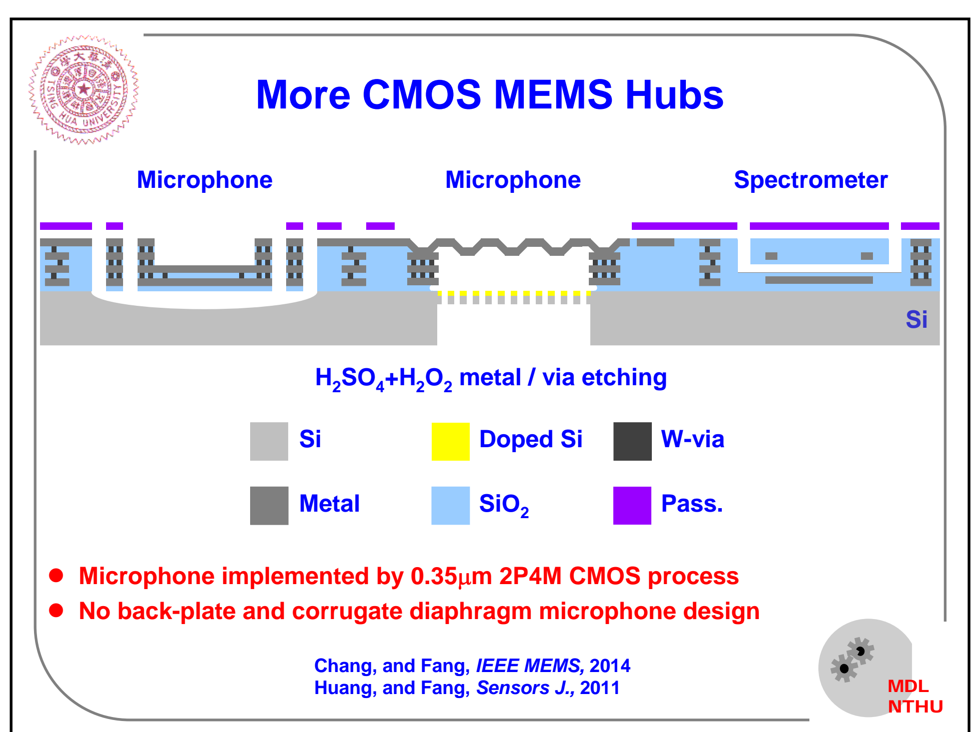


More CMOS MEMS Hubs



- Microphone implemented by 0.35μm 2P4M CMOS process
- No back-plate and corrugate diaphragm microphone design

Chang, and Fang, *IEEE MEMS*, 2014
Huang, and Fang, *Sensors J.*, 2011

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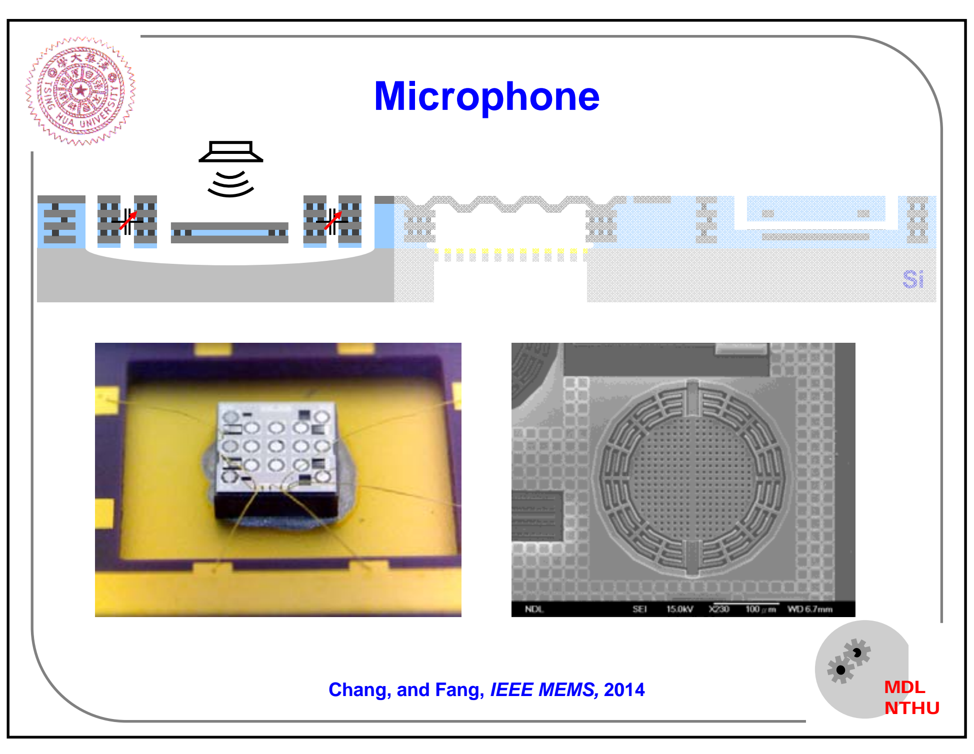
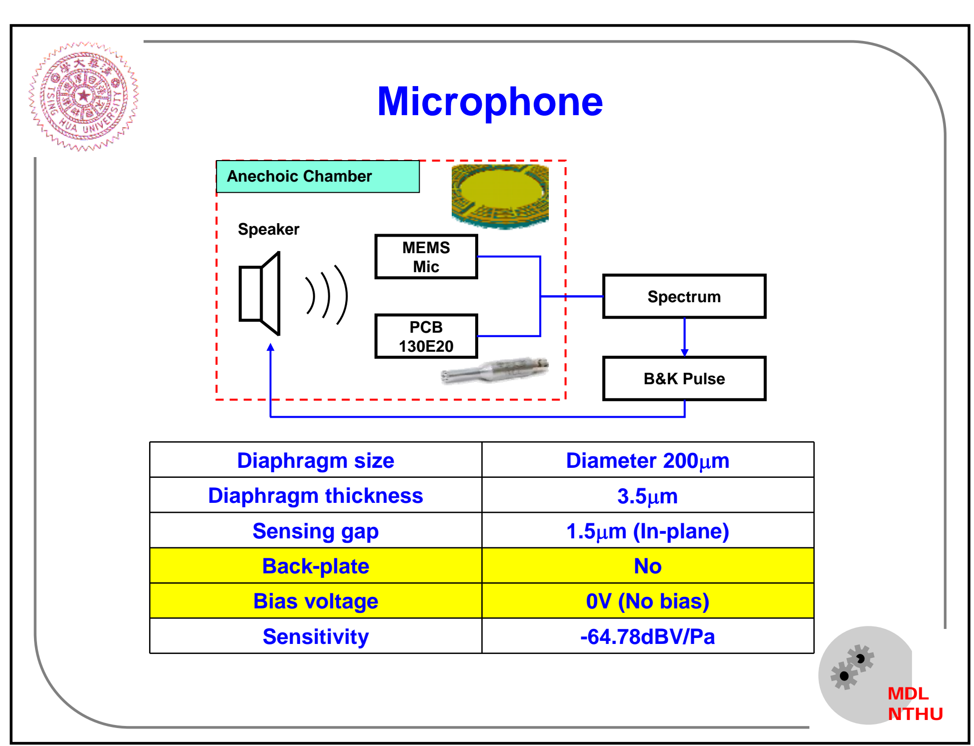
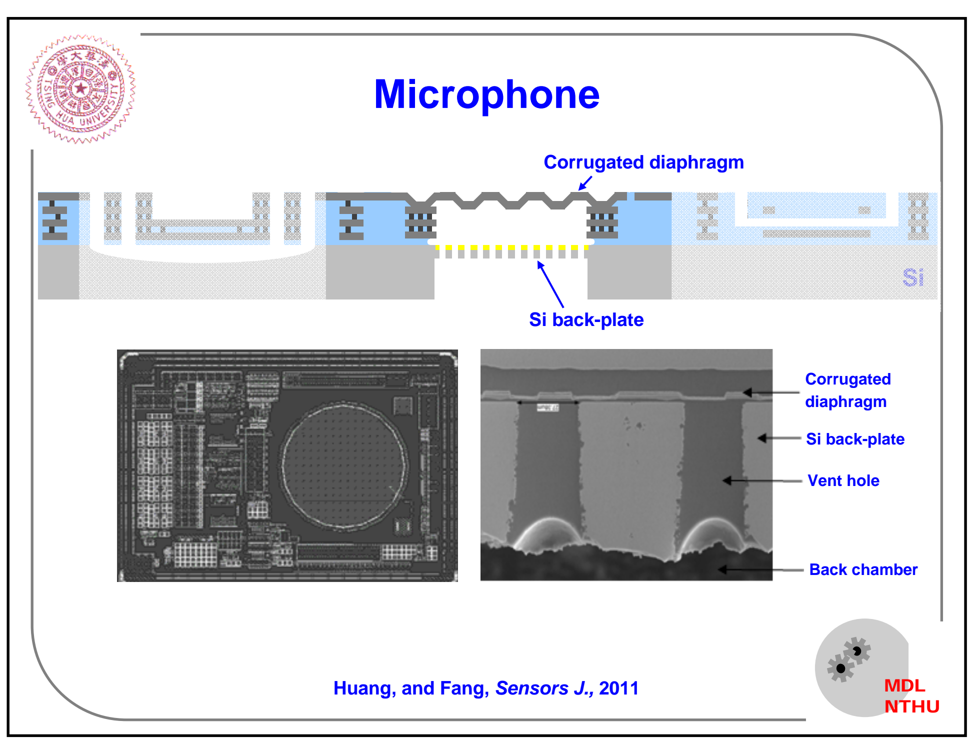
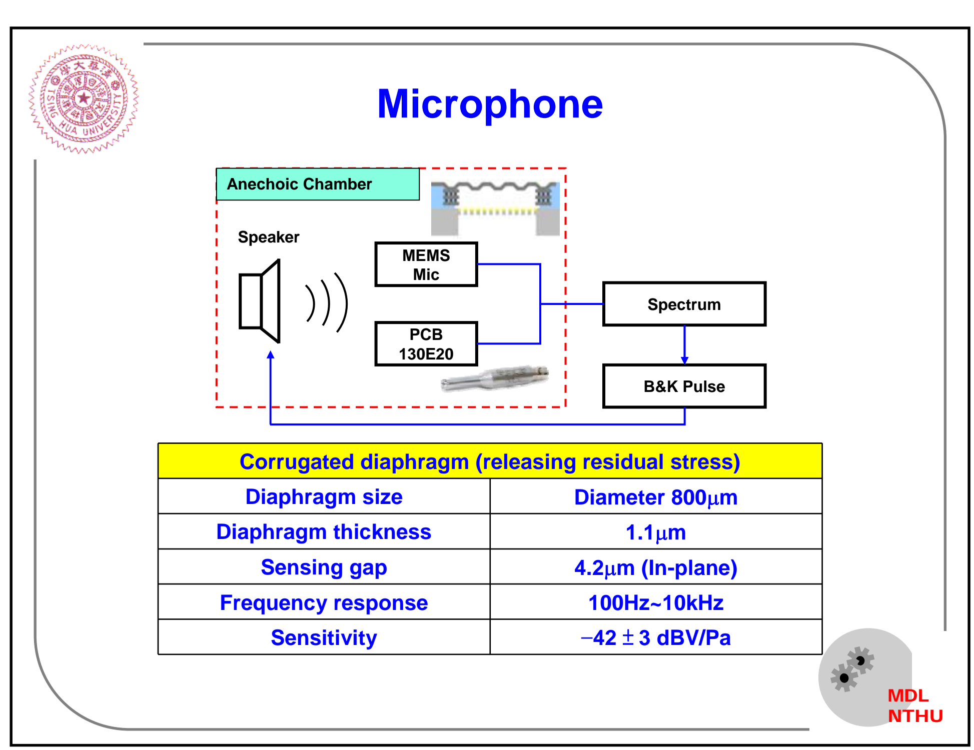


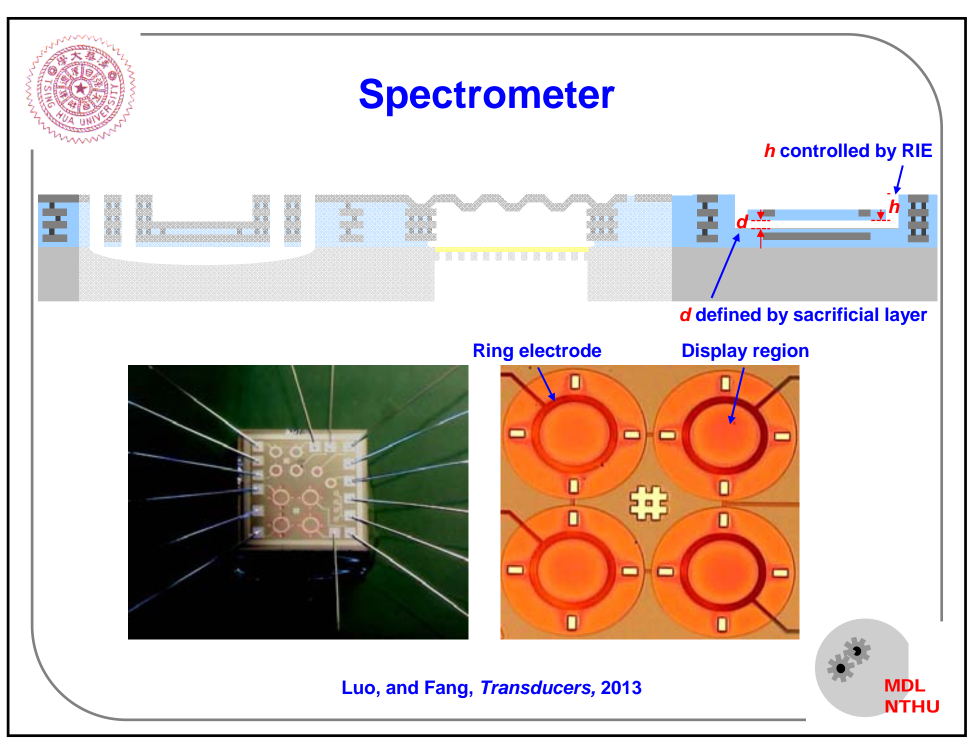


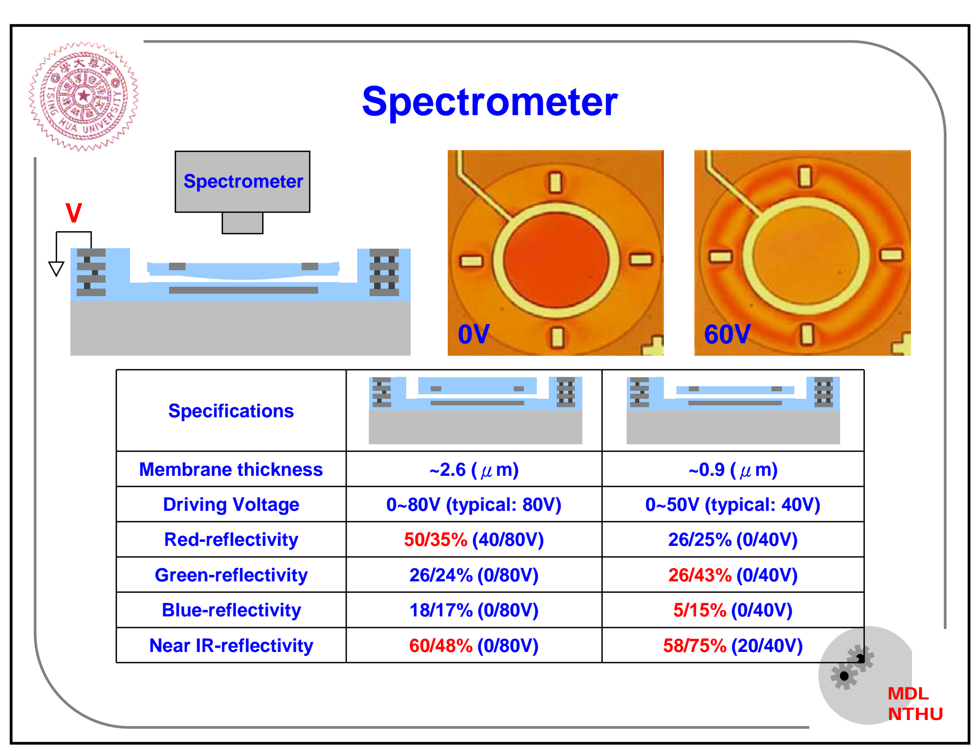
Diaphragm size	Diameter 200μm
Diaphragm thickness	3.5μm
Sensing gap	1.5μm (In-plane)
Back-plate	No
Bias voltage	0V (No bias)
Sensitivity	-64.78dBV/Pa





Corrugated diaphragm (releasing residual stress)	
Diaphragm size	Diameter 800μm
Diaphragm thickness	1.1μm
Sensing gap	4.2μm (In-plane)
Frequency response	100Hz~10kHz
Sensitivity	−42 ± 3 dBV/Pa

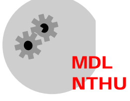




Specifications		
Membrane thickness	~2.6 (μm)	~0.9 (μm)
Driving Voltage	0~80V (typical: 80V)	0~50V (typical: 40V)
Red-reflectivity	50/35% (40/80V)	26/25% (0/40V)
Green-reflectivity	26/24% (0/80V)	26/43% (0/40V)
Blue-reflectivity	18/17% (0/80V)	5/15% (0/40V)
Near IR-reflectivity	60/48% (0/80V)	58/75% (20/40V)

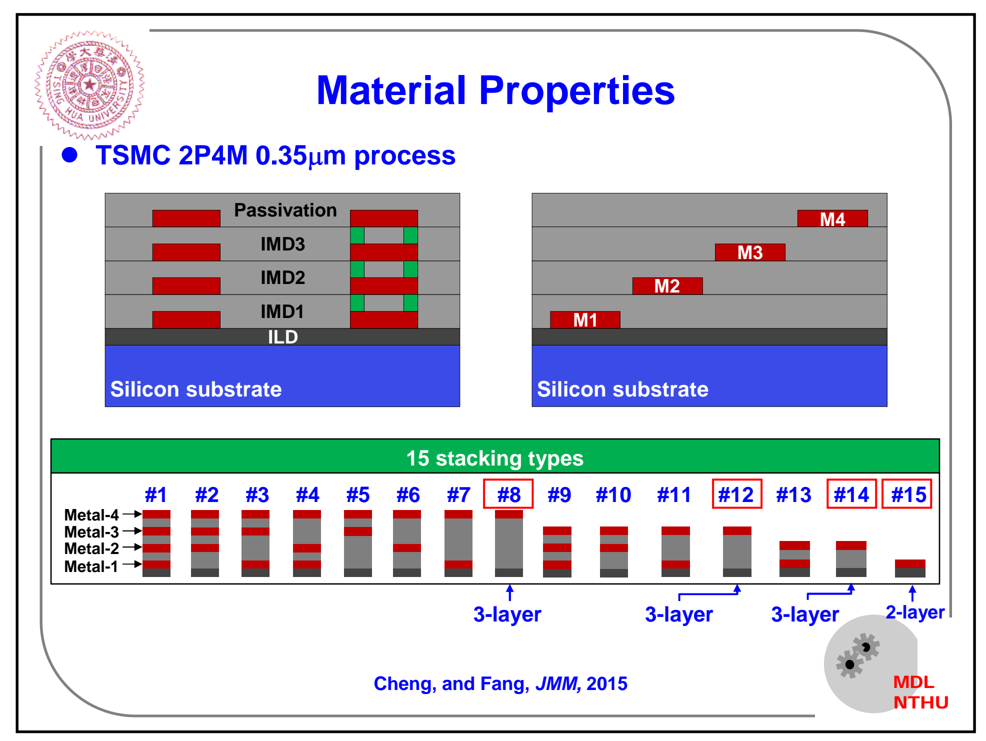
Outline

- Introduction
- CMOS MEMS Motion Hub
- CMOS MEMS Environment Hub
- CMOS MEMS Resonators Hub
- CMOS MEMS Acoustic/Optical Hubs
- Outlook and Concluding Remarks



Material Properties

- TSMC 2P4M 0.35μm process



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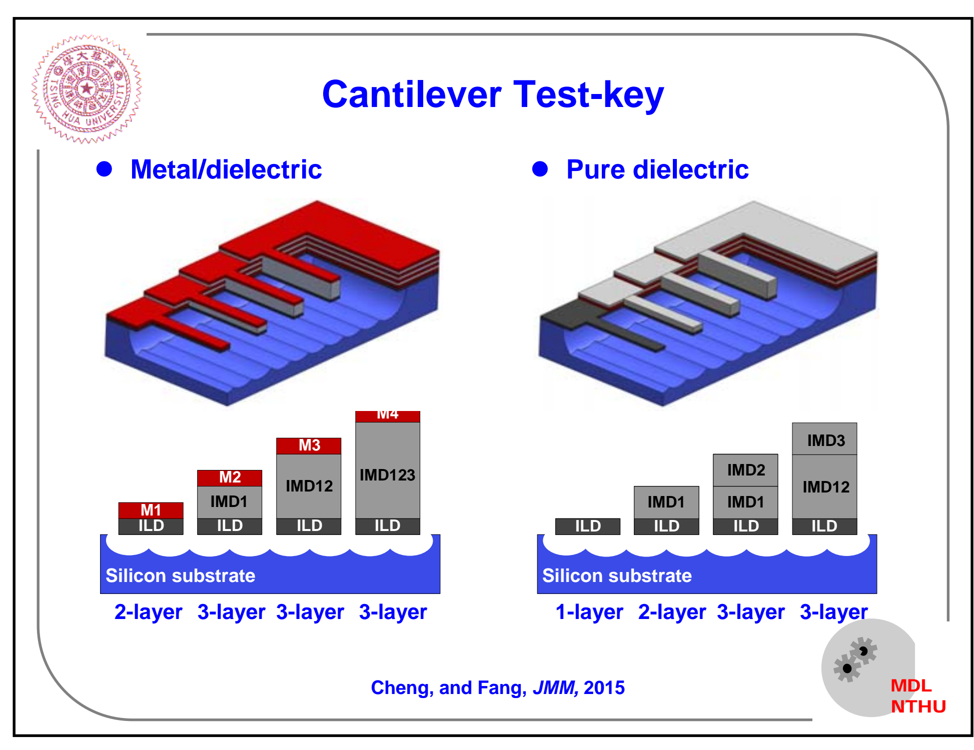
Cantilever Test-key
Metal/dielectric
Pure dielectric
M1
ILD
M2
IMD1
ILD
M3
IMD12
ILD
M4
IMD123
ILD
Silicon substrate
2-layer 3-layer 3-layer 3-layer
ILD
IMD1
ILD
IMD2
IMD1
ILD
IMD3
IMD12
ILD
Silicon substrate
1-layer 2-layer 3-layer 3-layer
Cheng, and Fang, JMM, 2015
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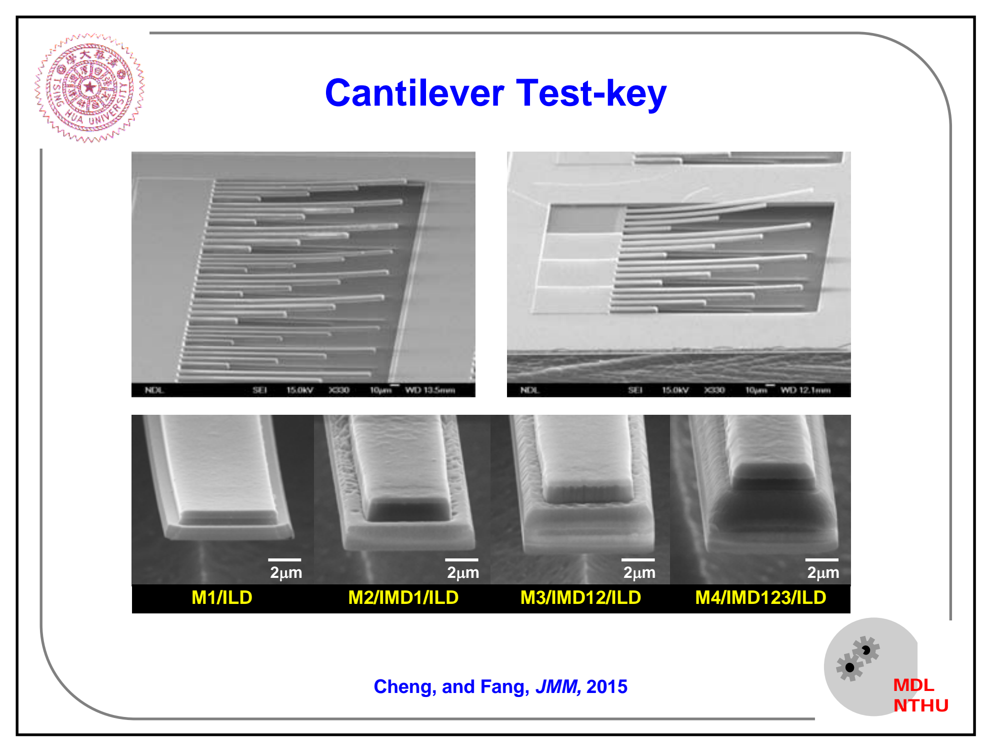
Cantilever Test-key
2μm
2μm
2μm
2μm
M1/ILD
M2/IMD1/ILD
M3/IMD12/ILD
M4/IMD123/ILD
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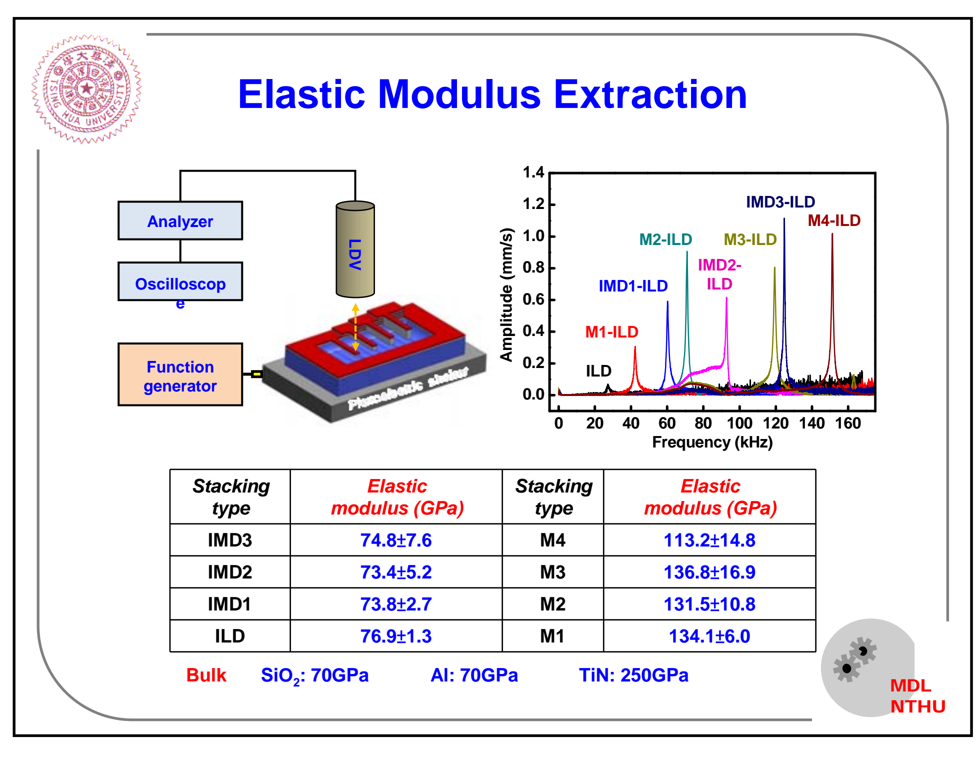
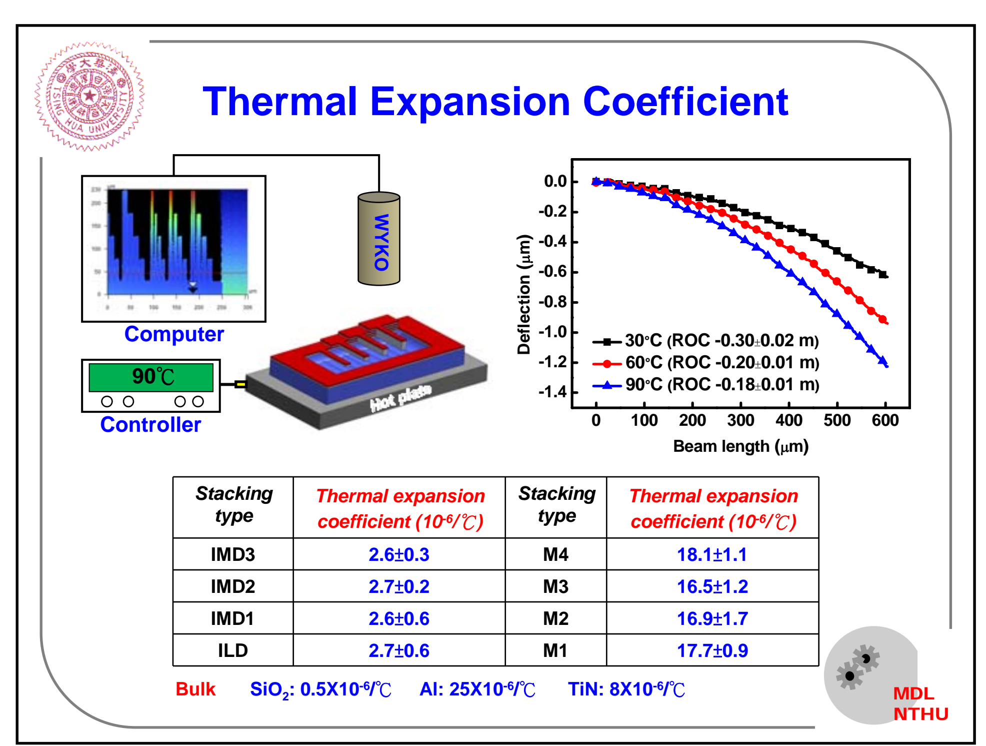


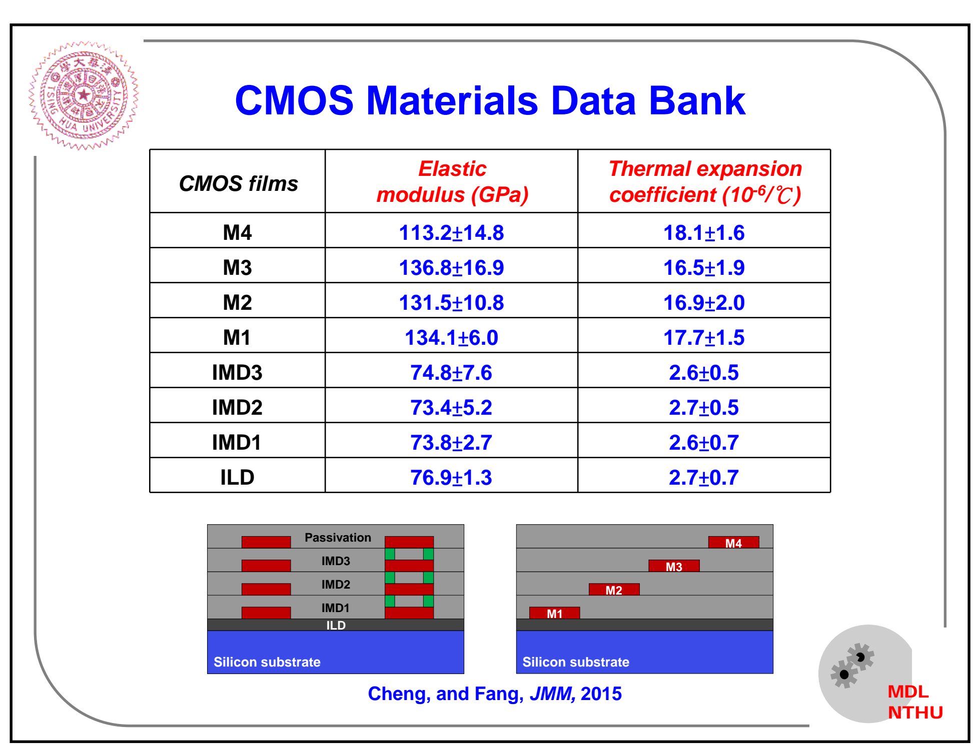
Stacking type	Elastic modulus (GPa)	Stacking type	Elastic modulus (GPa)
IMD3	74.8±7.6	M4	113.2±14.8
IMD2	73.4±5.2	M3	136.8±16.9
IMD1	73.8±2.7	M2	131.5±10.8
ILD	76.9±1.3	M1	134.1±6.0

Bulk SiO_2: 70GPa Al: 70GPa TiN: 250GPa

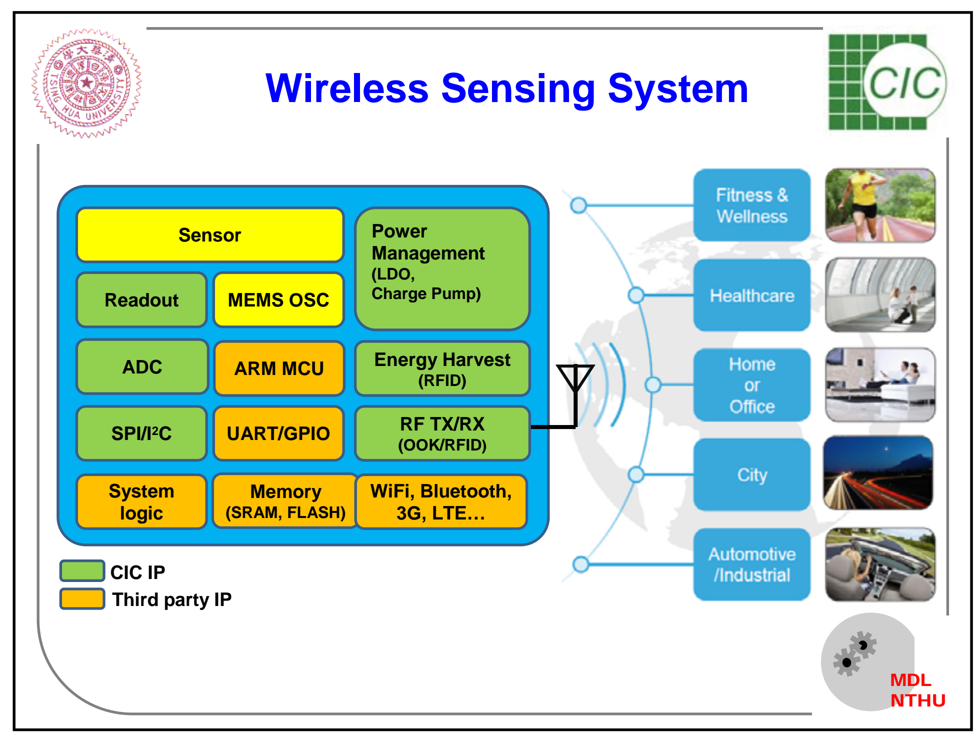


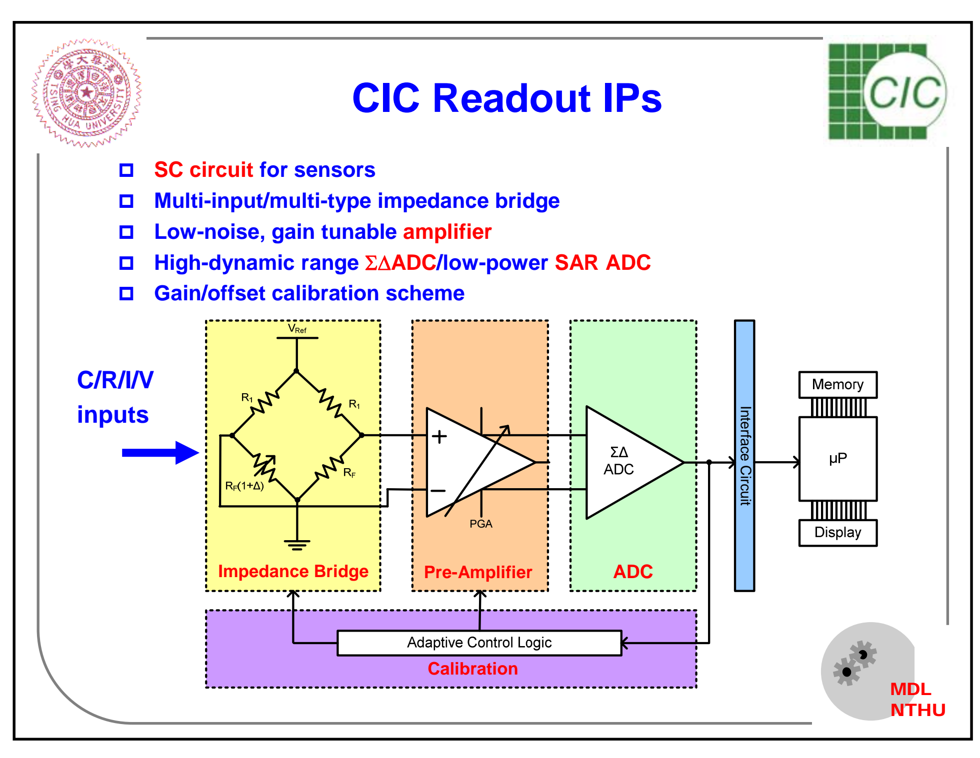
Stacking type	Thermal expansion coefficient (10^{-6}/℃)	Stacking type	Thermal expansion coefficient (10^{-6}/℃)
IMD3	2.6±0.3	M4	18.1±1.1
IMD2	2.7±0.2	M3	16.5±1.2
IMD1	2.6±0.6	M2	16.9±1.7
ILD	2.7±0.6	M1	17.7±0.9

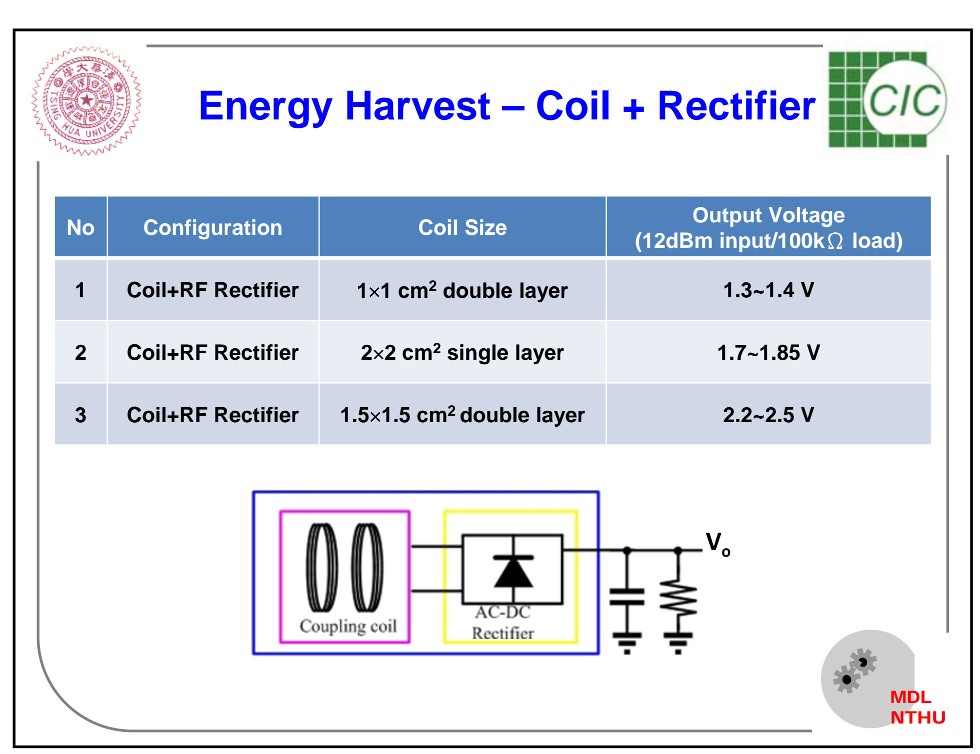
Bulk SiO_2: $0.5X10^{-6}$/℃ Al: $25X10^{-6}$/℃ TiN: $8X10^{-6}$/℃



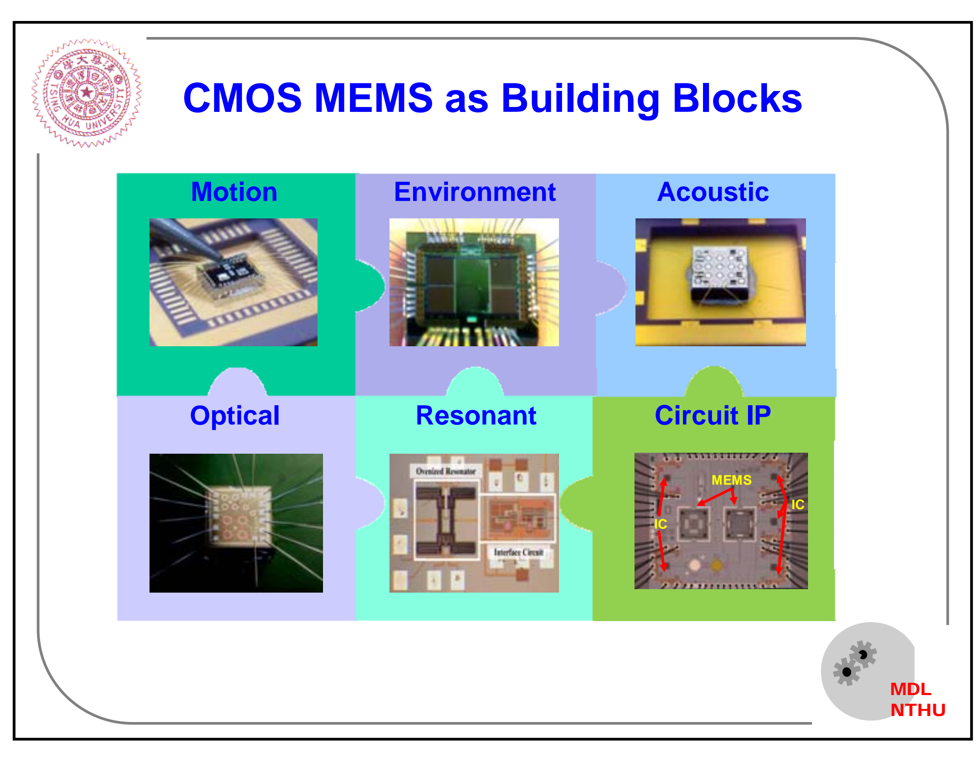
CMOS films	Elastic modulus (GPa)	Thermal expansion coefficient (10^{-6}/℃)
M4	113.2±14.8	18.1±1.6
M3	136.8±16.9	16.5±1.9
M2	131.5±10.8	16.9±2.0
M1	134.1±6.0	17.7±1.5
IMD3	74.8±7.6	2.6±0.5
IMD2	73.4±5.2	2.7±0.5
IMD1	73.8±2.7	2.6±0.7
ILD	76.9±1.3	2.7±0.7

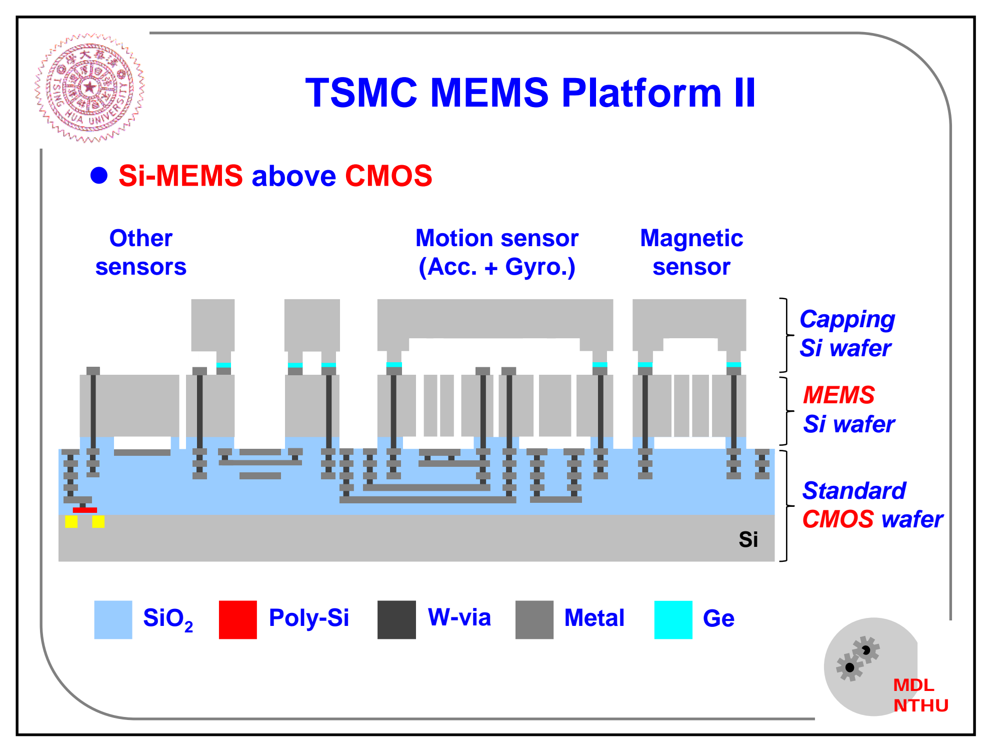






No	Configuration	Coil Size	Output Voltage (12dBm input/100kΩ load)
1	Coil+RF Rectifier	1×1 cm^2 double layer	1.3~1.4 V
2	Coil+RF Rectifier	2×2 cm^2 single layer	1.7~1.85 V
3	Coil+RF Rectifier	1.5×1.5 cm^2 double layer	2.2~2.5 V


CMOS MEMS as Building Blocks
Motion
Environment
Acoustic
Optical
Resonant
Circuit IP
MEMS
IC
IC
MDL
NTHU


TSMC MEMS Platform II
Si-MEMS above CMOS
Other sensors
Motion sensor (Acc. + Gyro.)
Magnetic sensor
Capping Si wafer
MEMS Si wafer
Standard CMOS wafer
Si
SiO2
Poly-Si
W-via
Metal
Ge
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.

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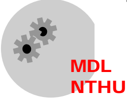

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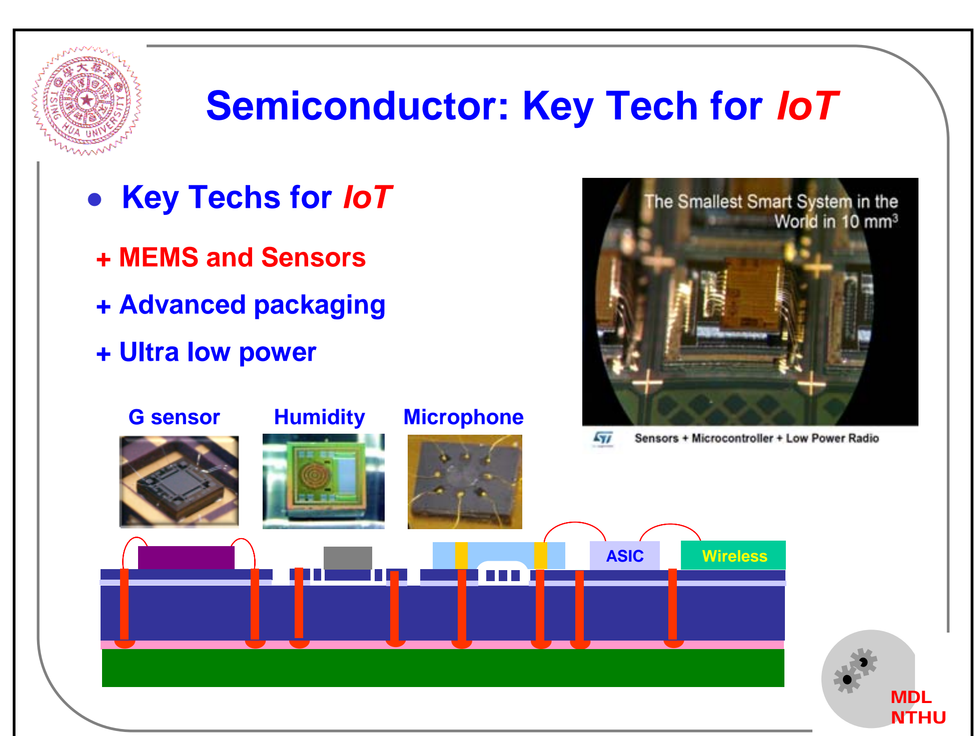

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- Fabrication Common Lab – NTHU, NCTU, NTU
- Prof. S.-S. Li - Resonators related materials
- My graduate students

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