12月8日(水)10:50-11:30

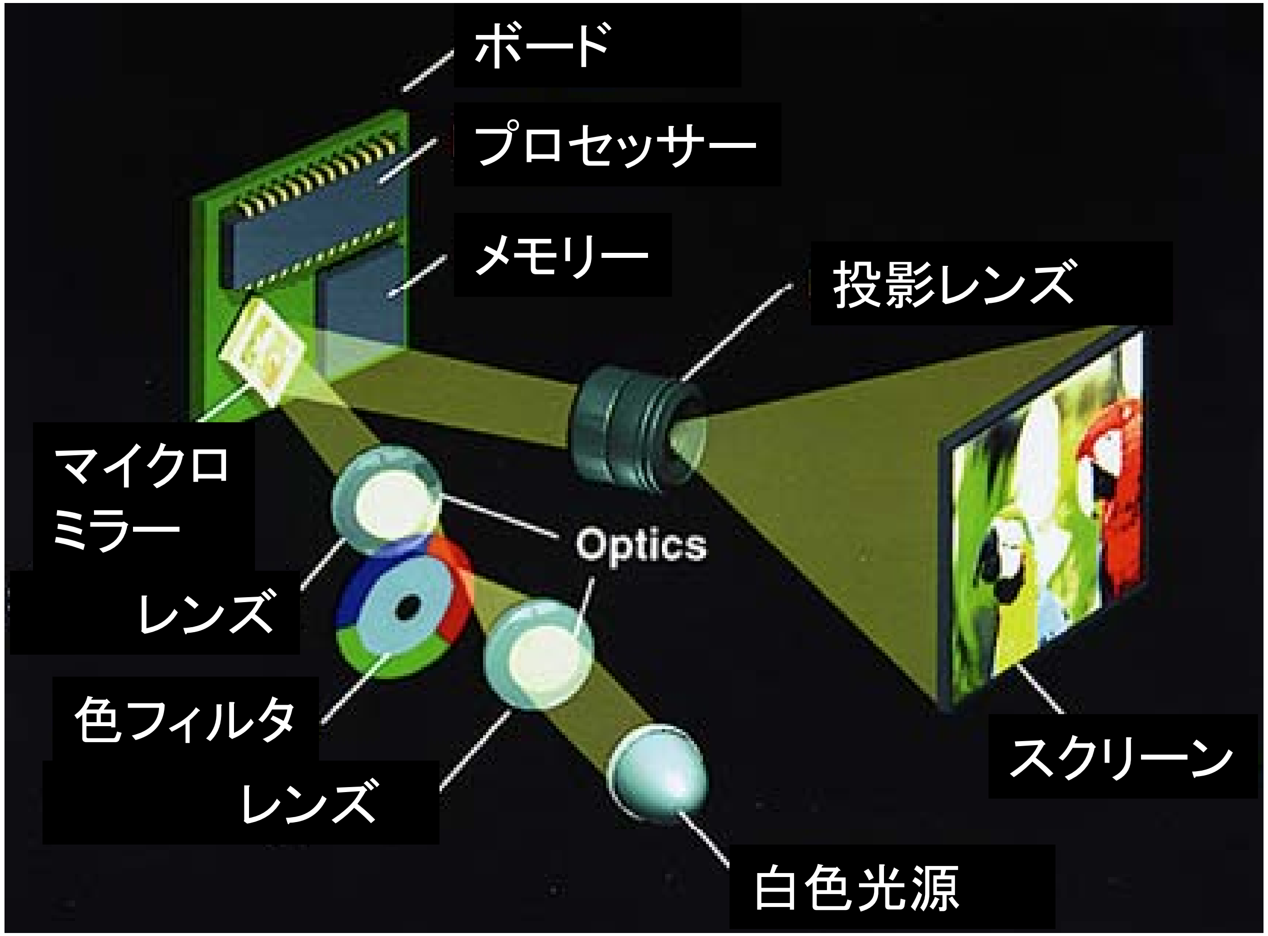
MEMSミラーと集積化

東北大学　工学研究科
羽根　一博

内容

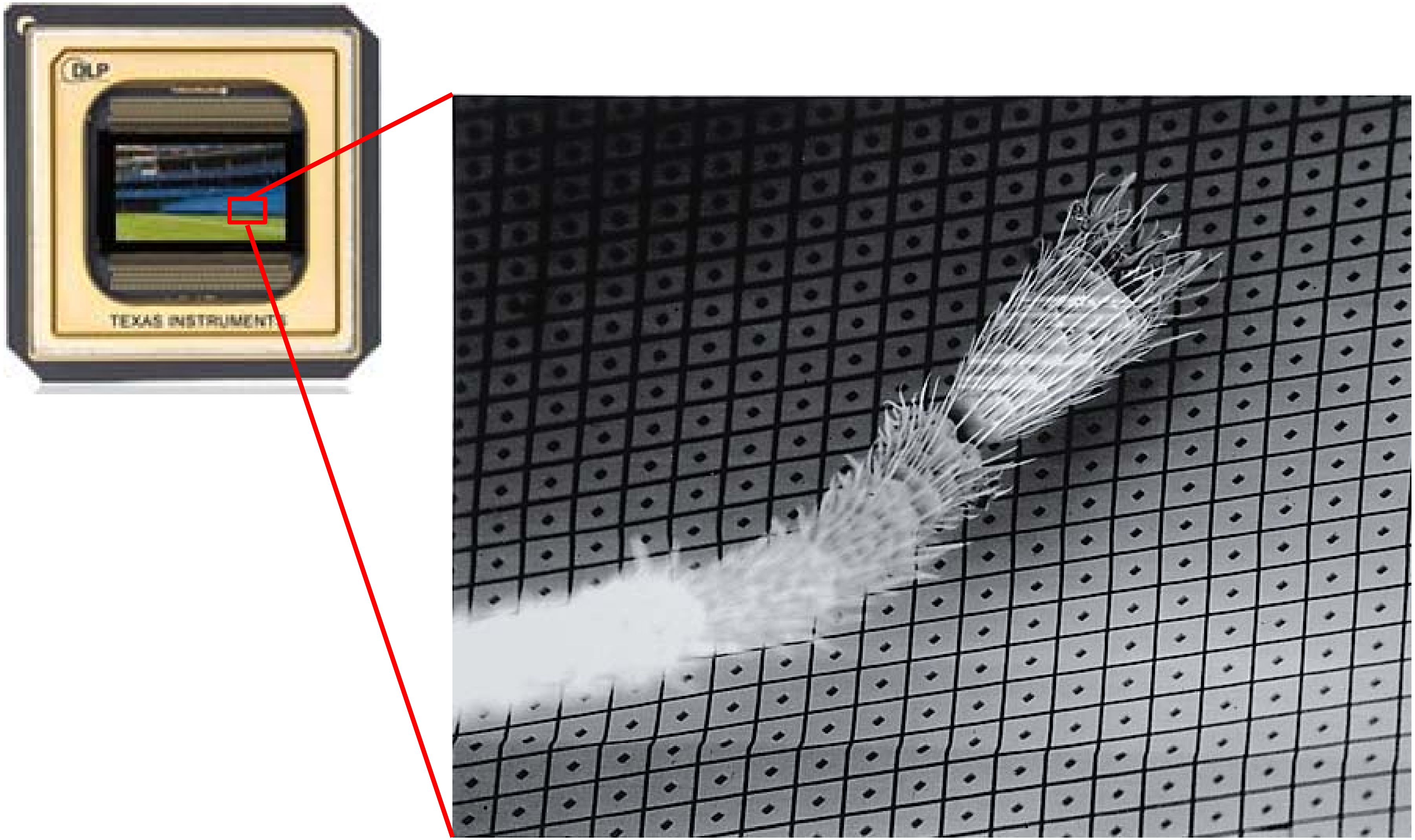
ホームシアター
データプロジェクター

マイクロミラー（DMD）ディスプレイの光学系



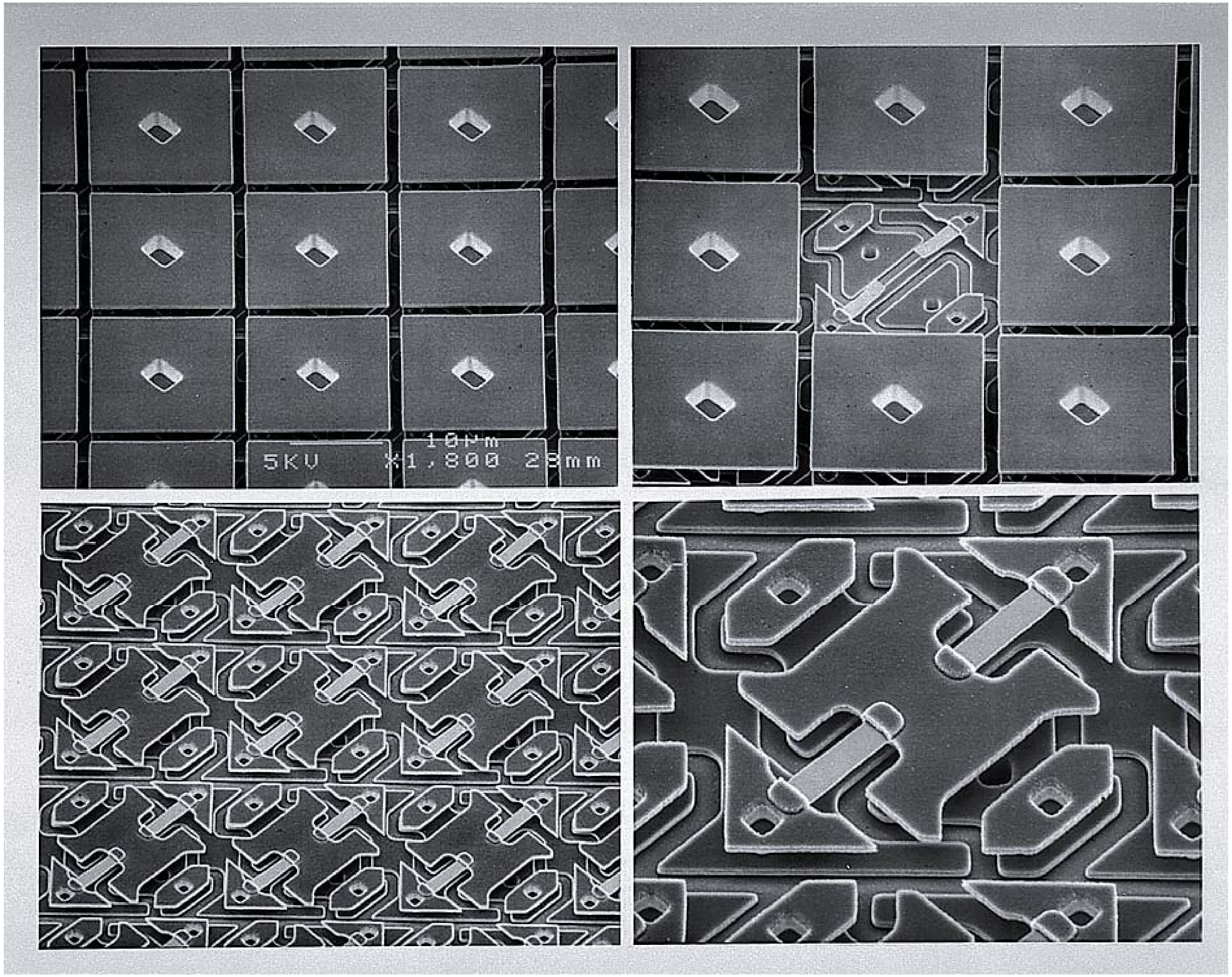
https://youtu.be/qOsibeDX8jM

マイクロミラー（DMD）ディスプレイの構造

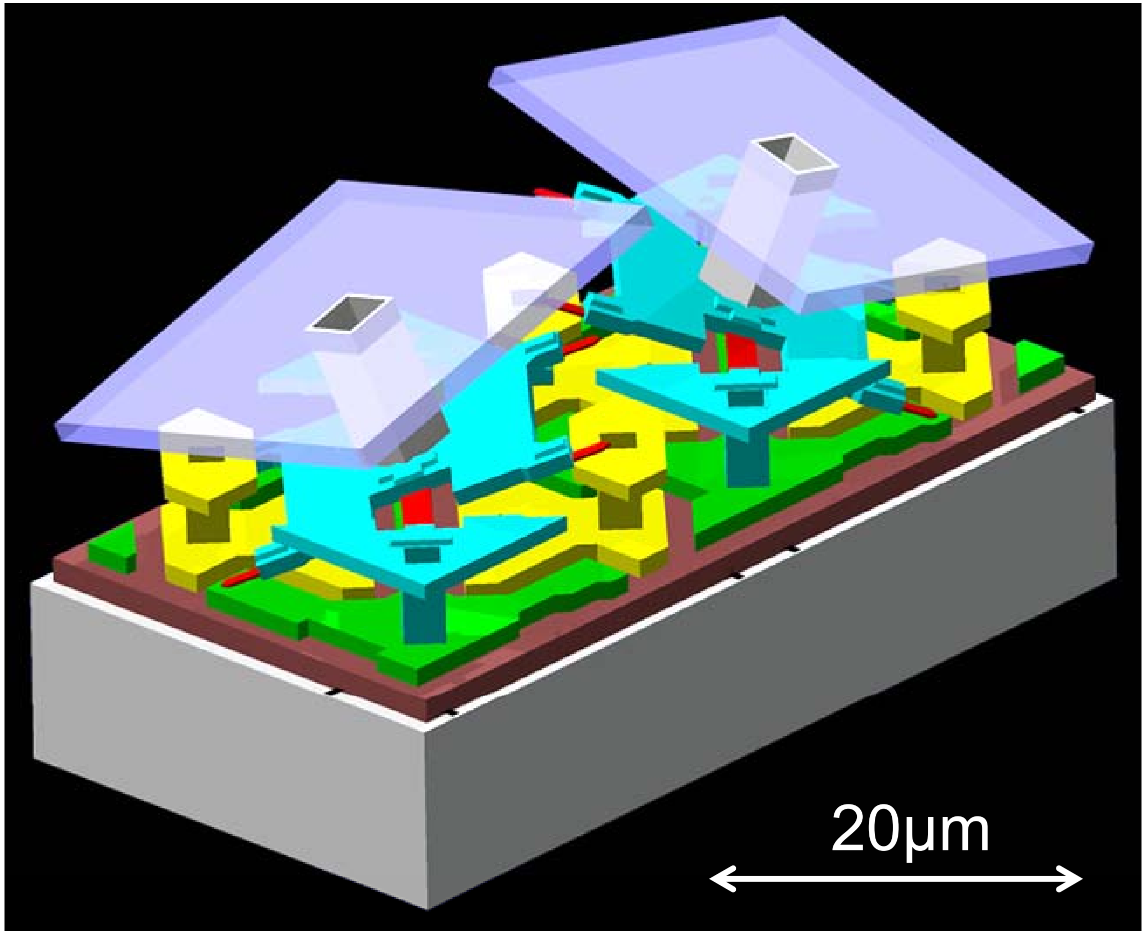


マイクロミラーとありの足

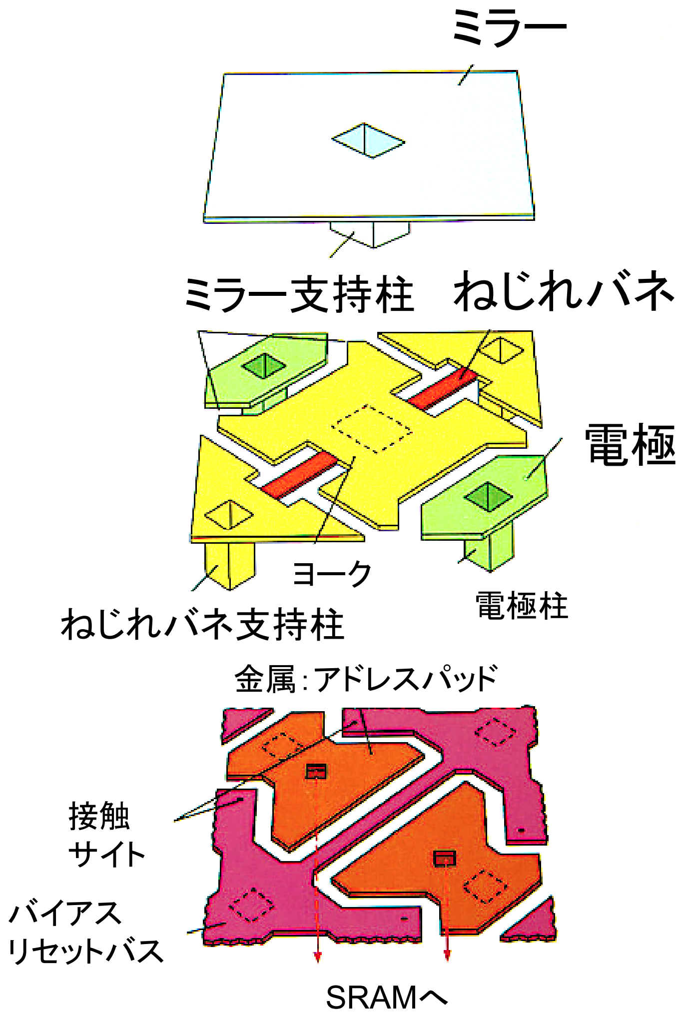
マイクロミラー（DMD）ディスプレイの内部構造



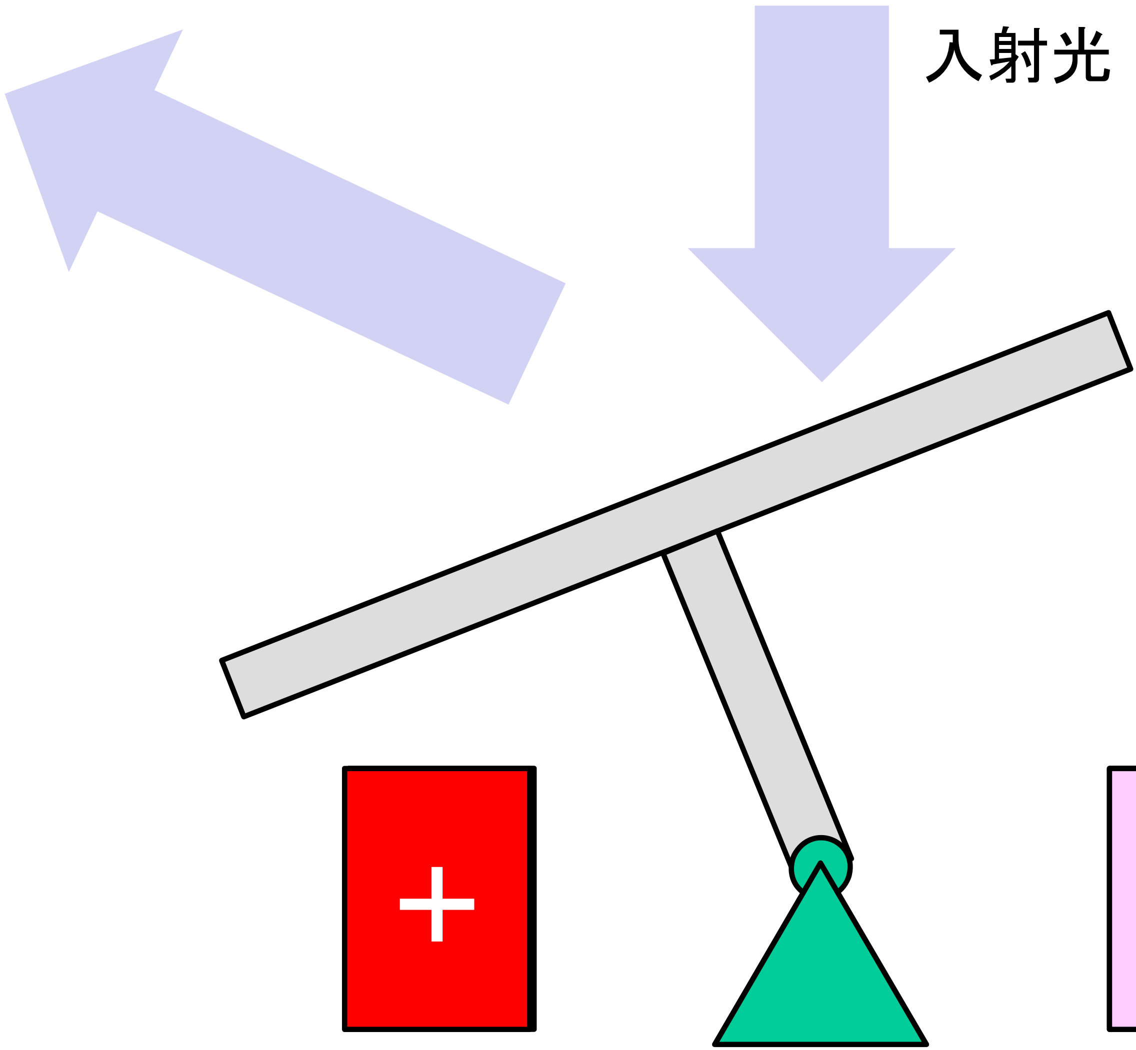
マイクロミラーの構造と動作



マイクロミラーの構造

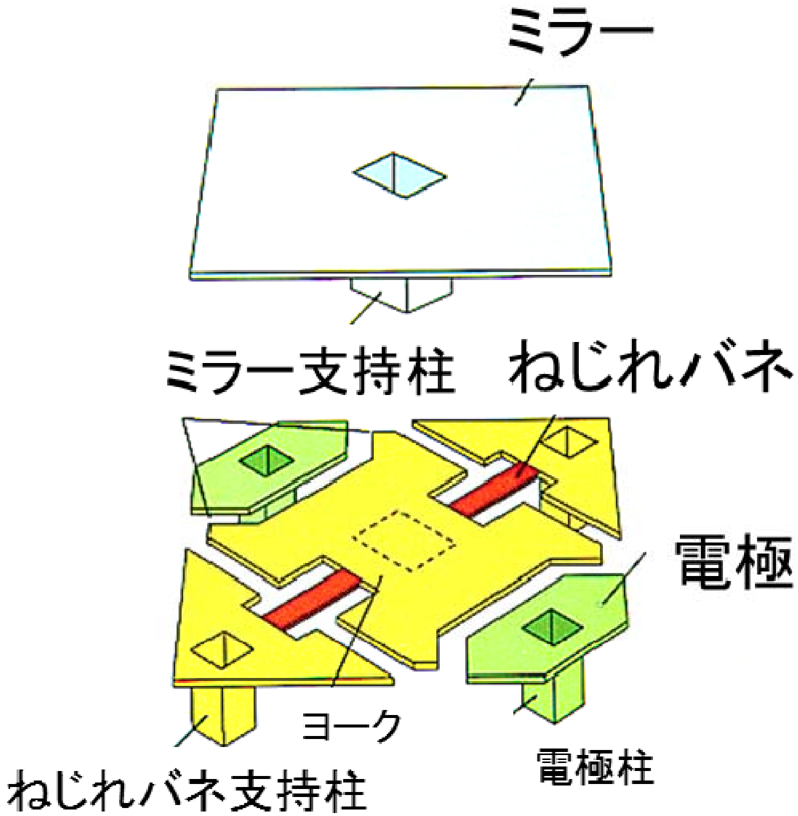


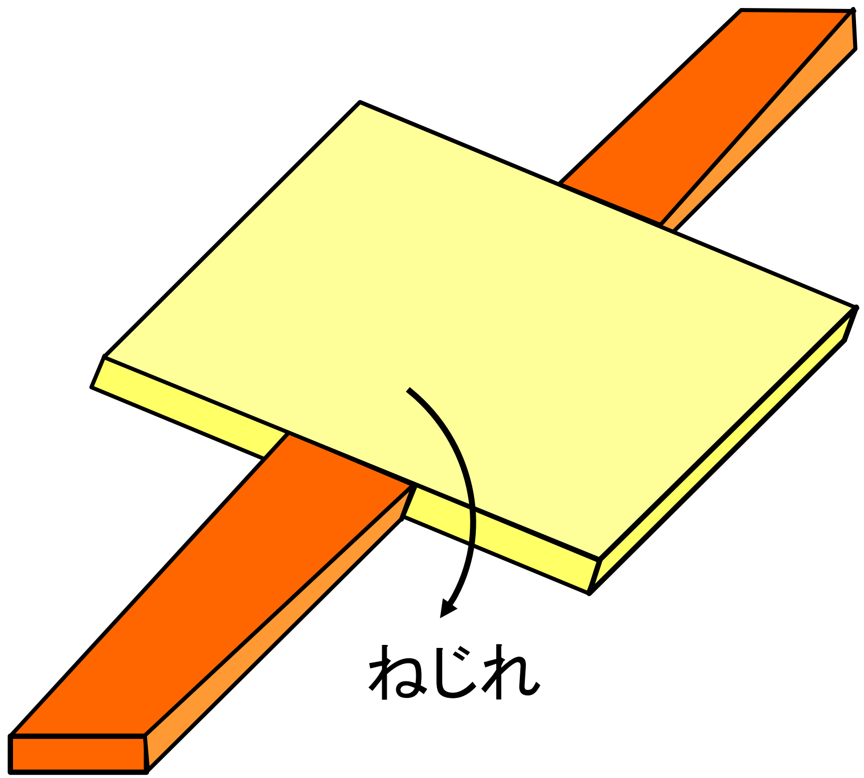
マイクロミラーの動作原理



帯電とクーロン力 $F = K\frac{-q^2}{r^2}$ 力のモーメント: $L = F \cdot r$

マイクロミラーの機械構造



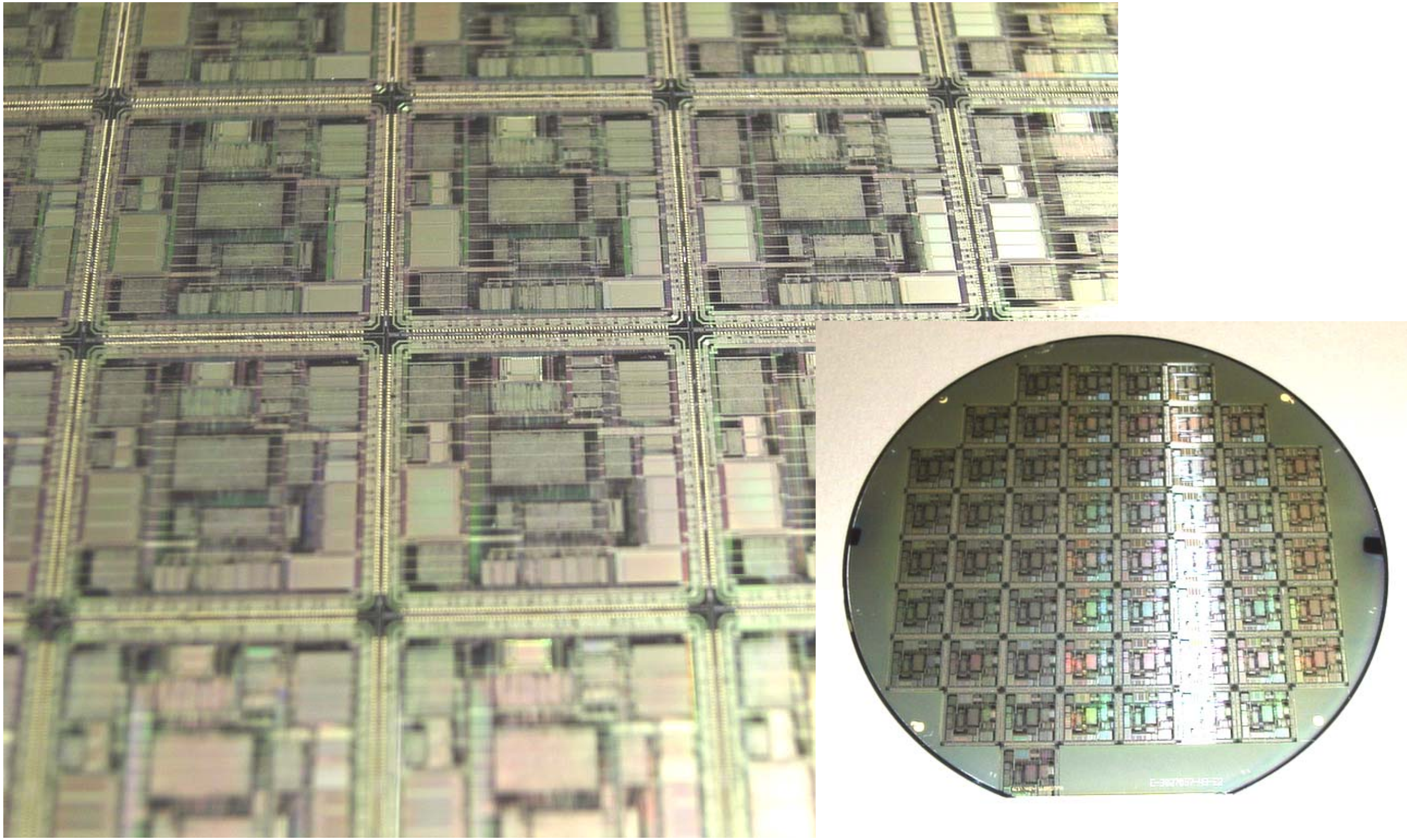


フックの法則 $F = k\,x$

ねじれのフックの法則 $L = k_\theta\,\theta$

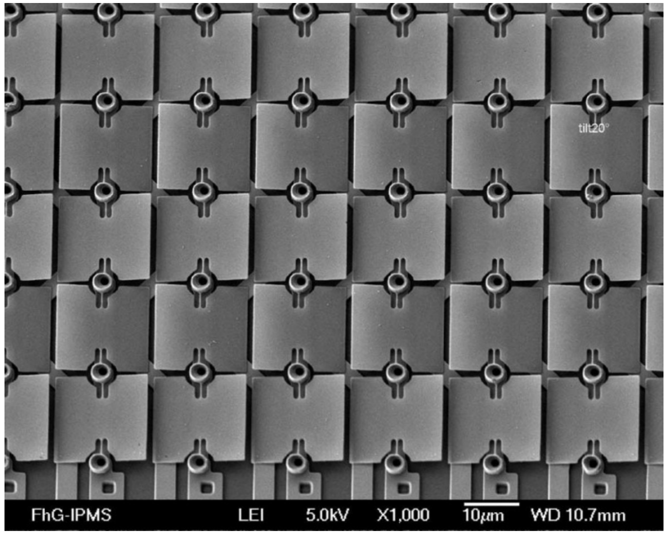
（L:力のモーメント　θ: 回転角）

集積回路の微細加工技術



One-Megapixel Monocrystalline-Silicon Micromirror Array on CMOS Driving Electronics Manufactured With Very Large-Scale Heterogeneous Integration

F. Zimmer, M. Lapisa, T. Bakke, M. Bring, J. MEMS 20(3)(2011)564-572 Fraunhofer Institute



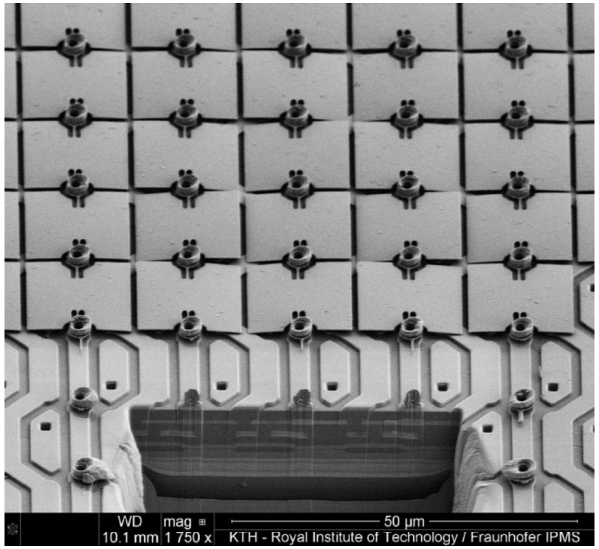
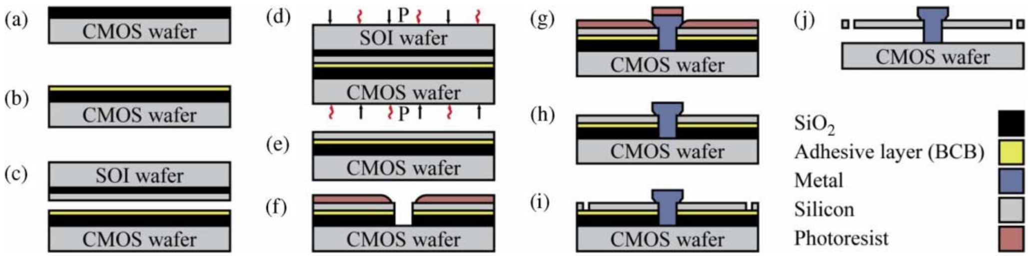
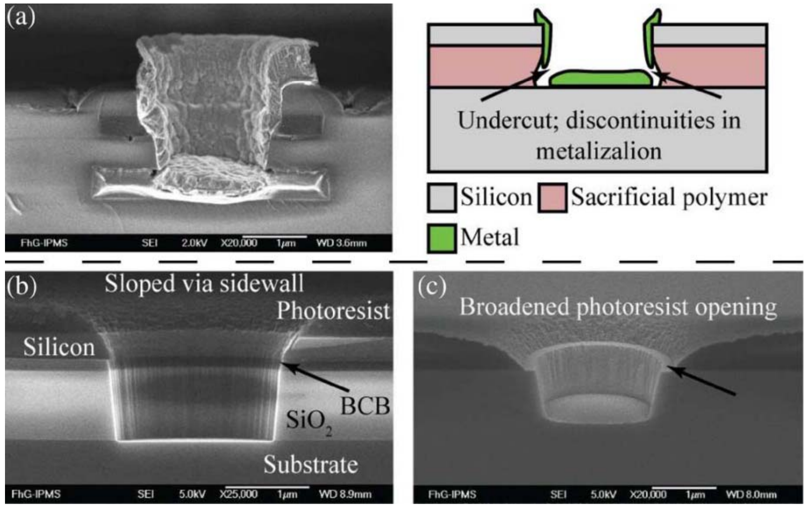
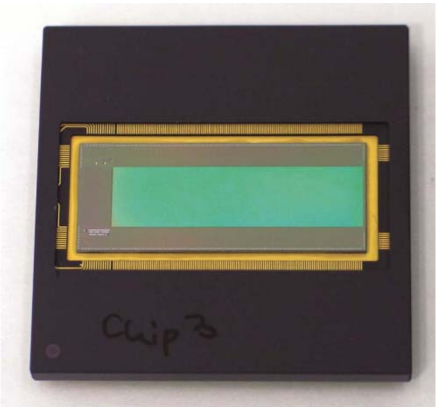


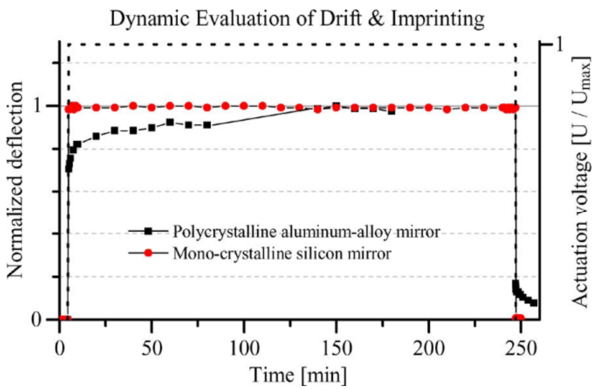
TABLE I
CHARACTERISTICS OF THE MONOCRYSTALLINE-SILICON SLM

Property	Nominal value
SLM architecture	Tilting micro-mirrors with reflective surface and hinges in same plane (1-level)
Array size	1 megapixel (2048x512 px)
Mirror material	Mono-crystalline silicon
Crystal type (c-Si)	Diamond-cubic (100)
Plastic deformation (c-Si)	None (brittle material)
Young`s modulus	160 GPa
Hinge material	Mono-crystalline silicon
Hinge type	Torsional
Hinge dimensions (LxWxH)	2.6 μm x 0.6 μm x 340 nm
C-Si roughness (RMS)	<1 nm (for area of 1 μm^2) (measured)
Mirror size	16x16 μm^2
Smallest dimension of micro-mirror features	600 nm
Mirror-membrane thickness	340 nm
Mirror air gap to electrode	700 nm
CMOS operating voltage	~ 25 V
Max. edge deflection (tilt)	~ 160 nm









PACKAGING OF 11 MPIXEL CMOS-INTEGRATED SIGE MICRO-MIRROR ARRAYS

A Witvrouw et.al. IMEC, Philips Applied Technologies, ASML

MEMS 2009 136-139

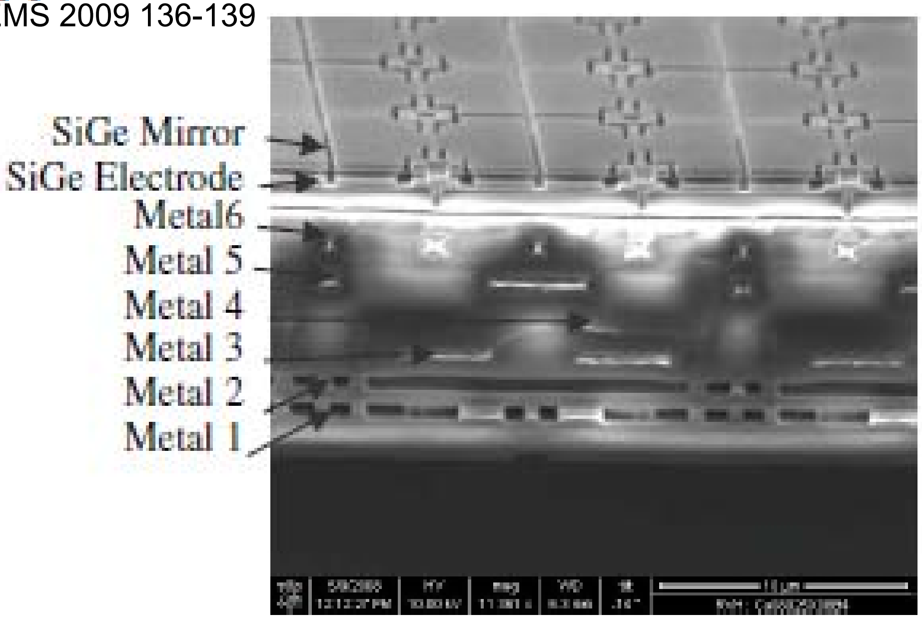


Figure 1: Cross-sectional view of the integrated micro-mirror array, showing the mirrors on top of the 6 layers of Al interconnec

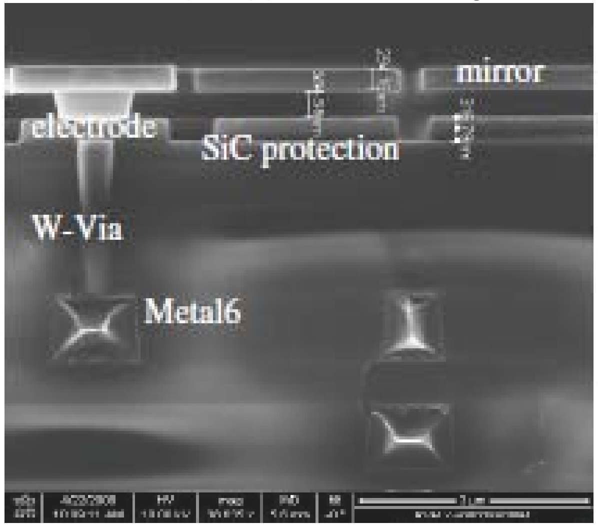


Figure 3: Cross-section of mirror showing W-via, SiC protection layer, SiGe electrodes, SiGe mirror layer.

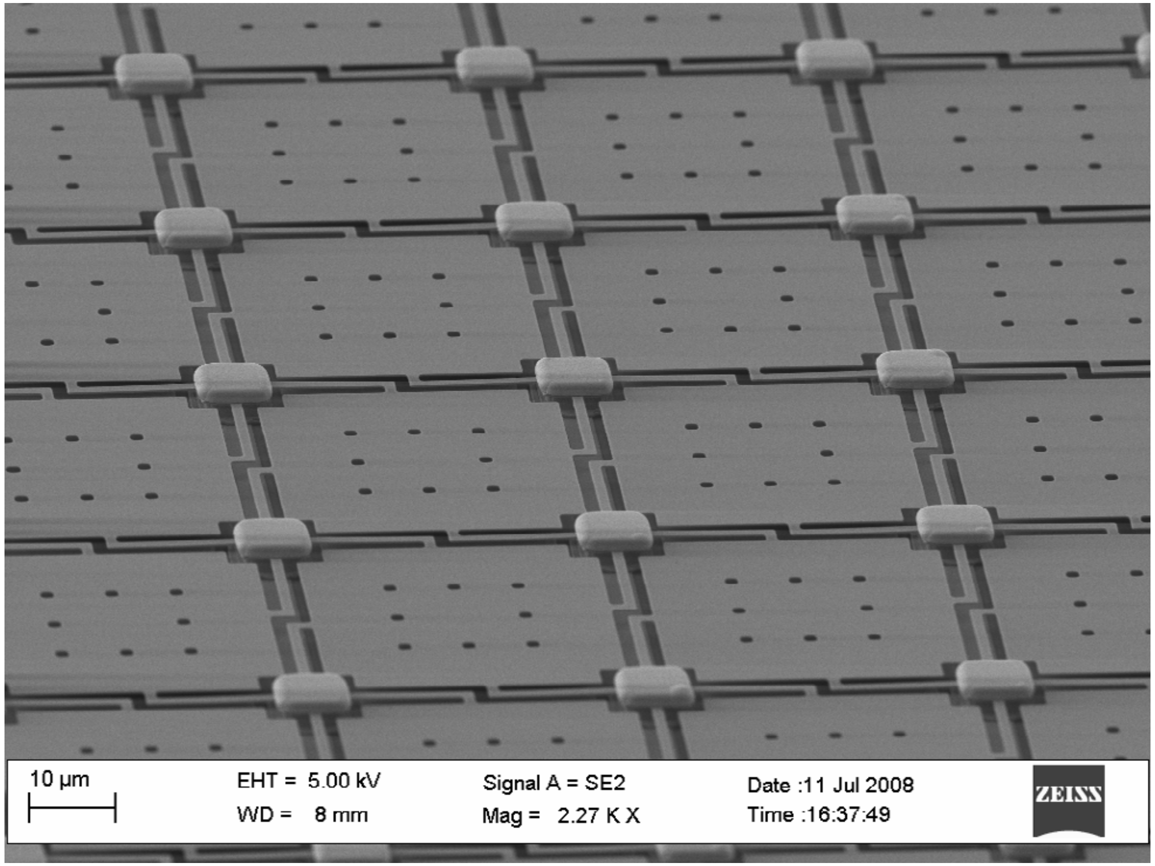
Figure 11: Fully packaged and wire-bonded SLM assembly.

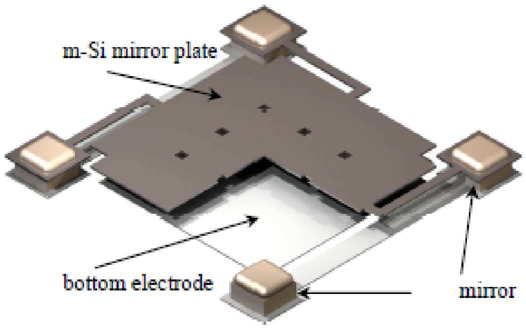
Table 1: Schematic process flow of micromirror module.

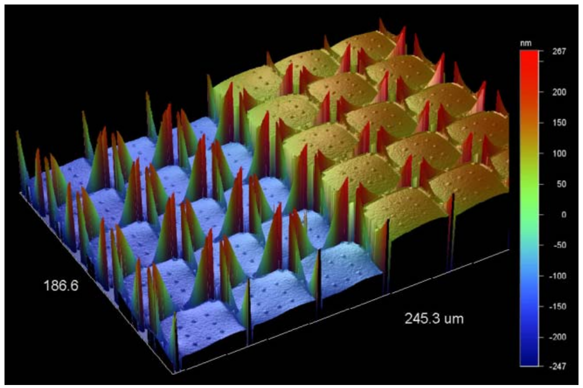
Start: CMOS base wafer (from NXP)
Top level metal planarisation + passivation
SiC protection layer
W-vias
SiGe electrode + planarisation
Sacrificial oxide deposition
Mirror hinge formation
SiGe mirror layer deposition + CMP
Phasestep etch (optional)
Al coating (optional)
Mirror etch
Oxide protection + Al bondpads
Release etch mirrors

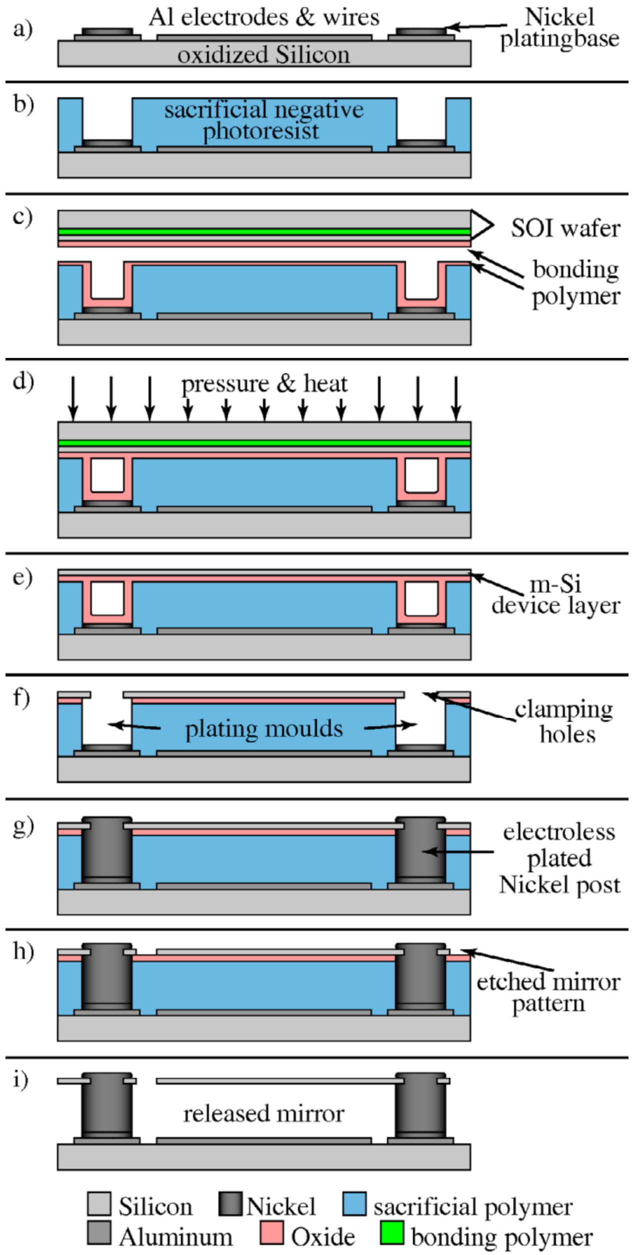
CMOS-INTEGRABLE PISTON-TYPE MICRO-MIRROR ARRAY FOR ADAPTIVE OPTICS MADE OF MONO-CRYSTALLINE SILICON USING 3-D INTEGRATION

M Lapisa, F Zimmer, F Niklaus, A Gehner, G Stemme Royal Institute of Technology, Fraunhofer Institut MEMS (2009) 1007-1010









32×32 OPTICAL PHASED ARRAY WITH ULTRA-LIGHTWEIGHT HIGH-CONTRAST-GRATING MIRRORS

Transducers 13 pp. 2505-2508

B. W. Yoo[1], M. Megens[1,2], T. K. Chan[2], T. Sun[1], W. Yang[1], D. A. Horsley[2], C. J. Chang-Hasnain[1], and M. C. Wu[1]*

[1]University of California, Berkeley, CA, USA

[2]University of California, Davis, CA, USA

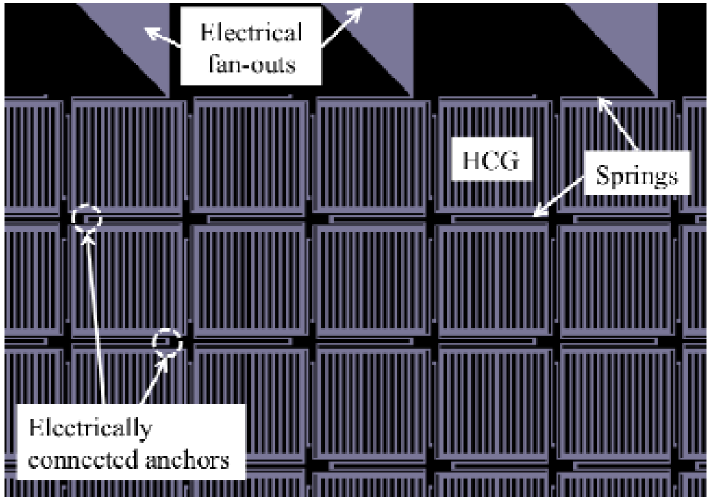


Figure 1: Layout of the MEMS optical phased array. Anchors of HCG mirrors electrically connect adjacent mirrors in the same row, increasing fill-factor.

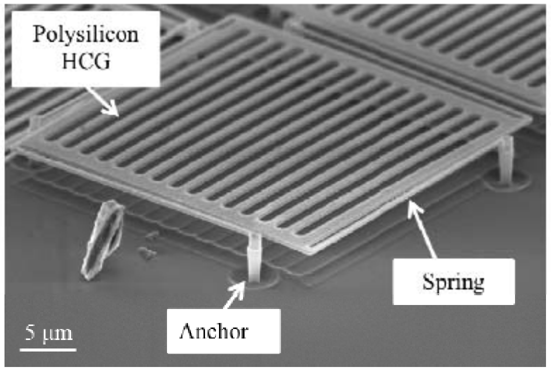


Figure 2: Scanning electron microscope (SEM) image of a polysilicon high contrast sub-wavelength grating (HCG). The pixel surface is extremely flat due to the low stress 400

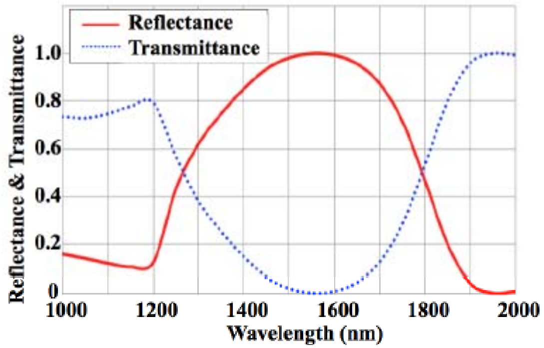


Figure 4: Theoretical Reflectance and transmittance spectra of the HCG mirror.

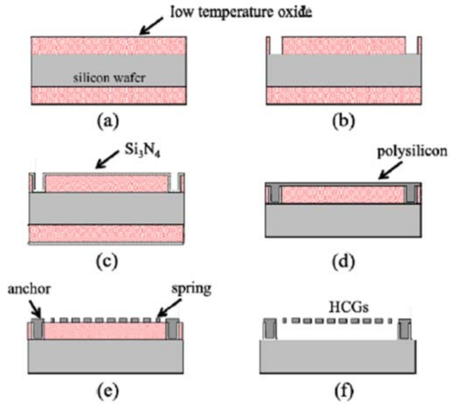
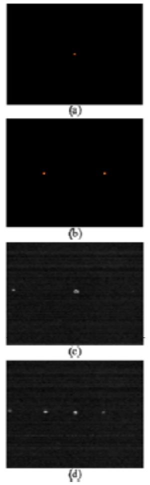


Figure 5: Fabrication process.



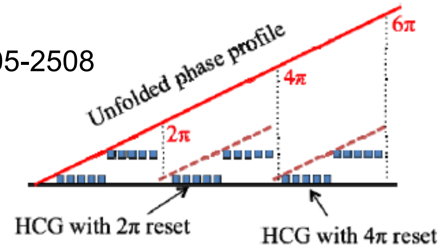


Figure 8: Modulo 2π phase shifting using HCGs to create beamsteering at maximum angle. Light is in the form of a sine wave. Thus, 2nπ (n=0,1,2…), from a phase point of view, are all the same so that a stair-step ramp approach can be used to steer light.

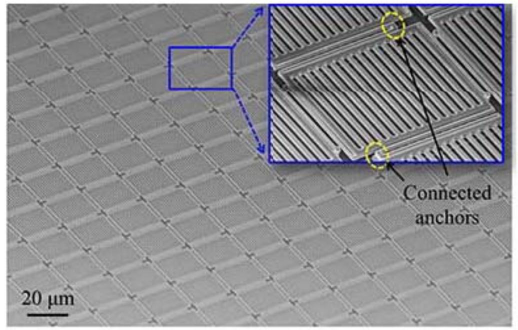


Figure 6: SEM image of the fabricated HCG phase shifter array. Inset shows that anchors in the same column are linked to adjacent HCGs via mechanical springs for one-dimensional beamsteering. This can be extended to two-dimension beamforming by adding multi-layer interconnects underneath the HCG mirrors.

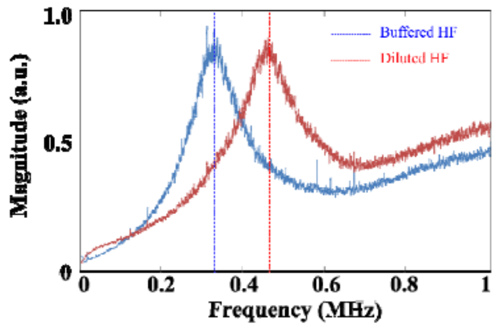
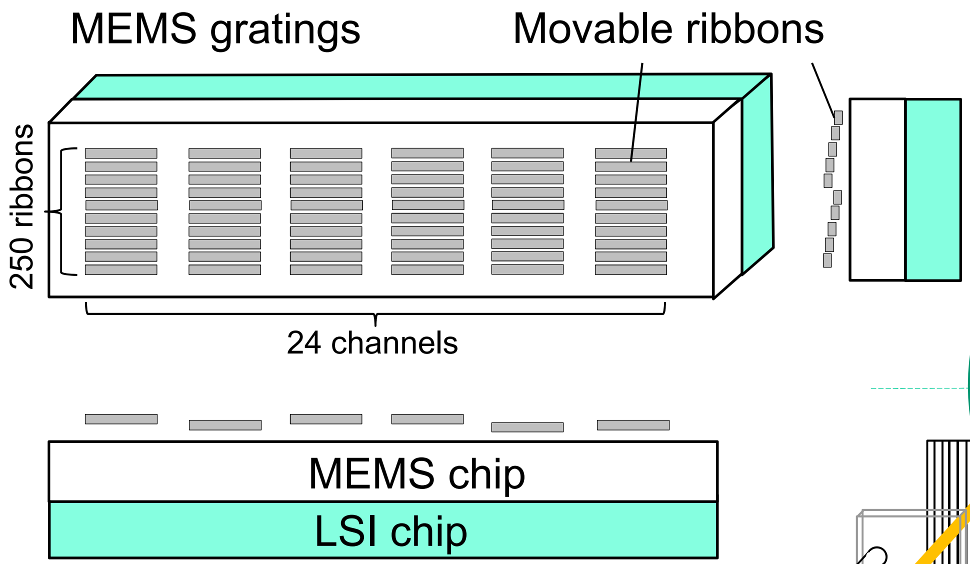


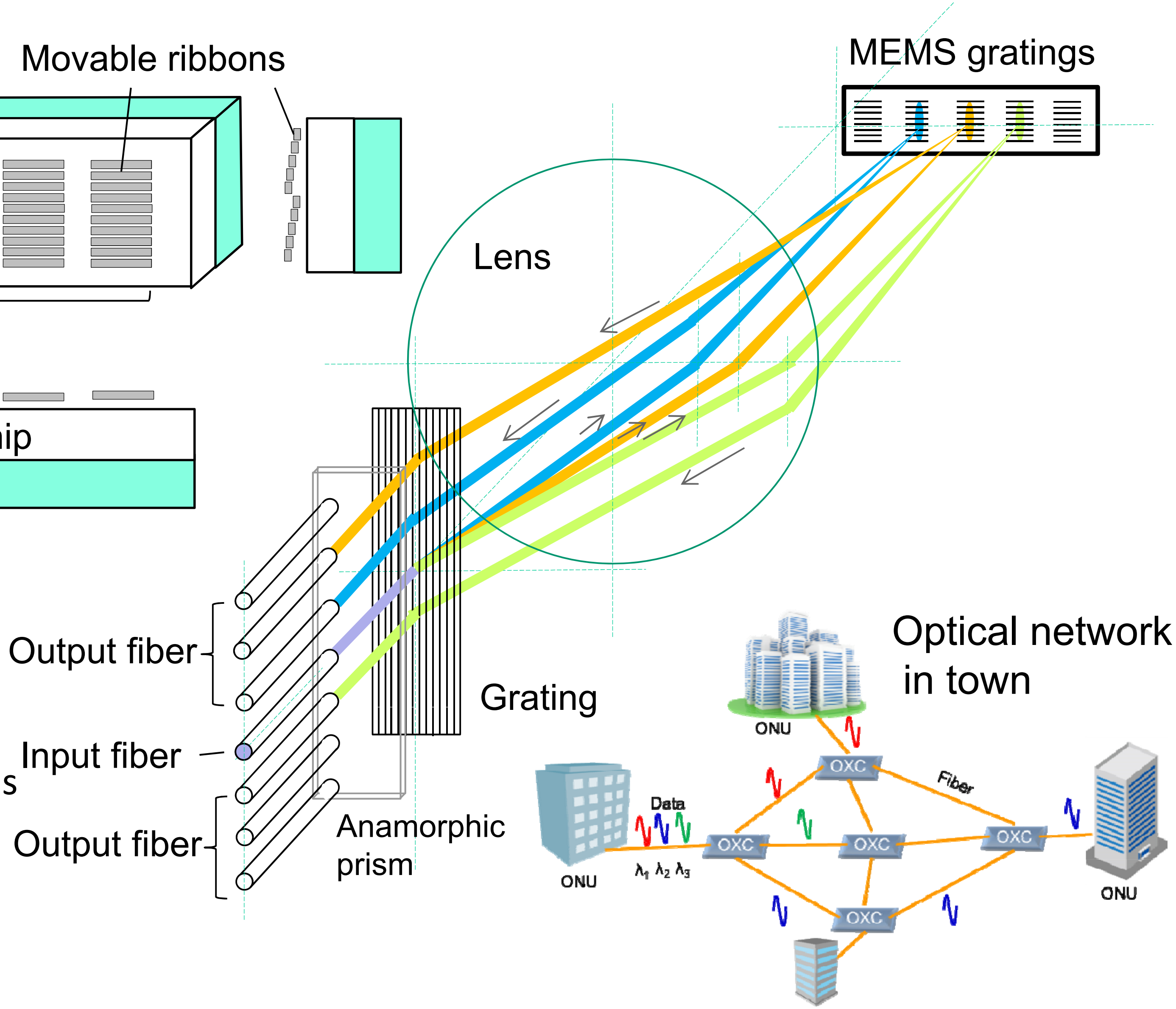
Figure 7: Experimental resonant frequencies of an HCG using a laser Doppler vibrometer (LDV) system. A HCG released in diluted HF depicts the measured resonant frequency is 0.46 MHz, which agrees well with the theory.

波長選択スイッチ（MEMSグレーティング）

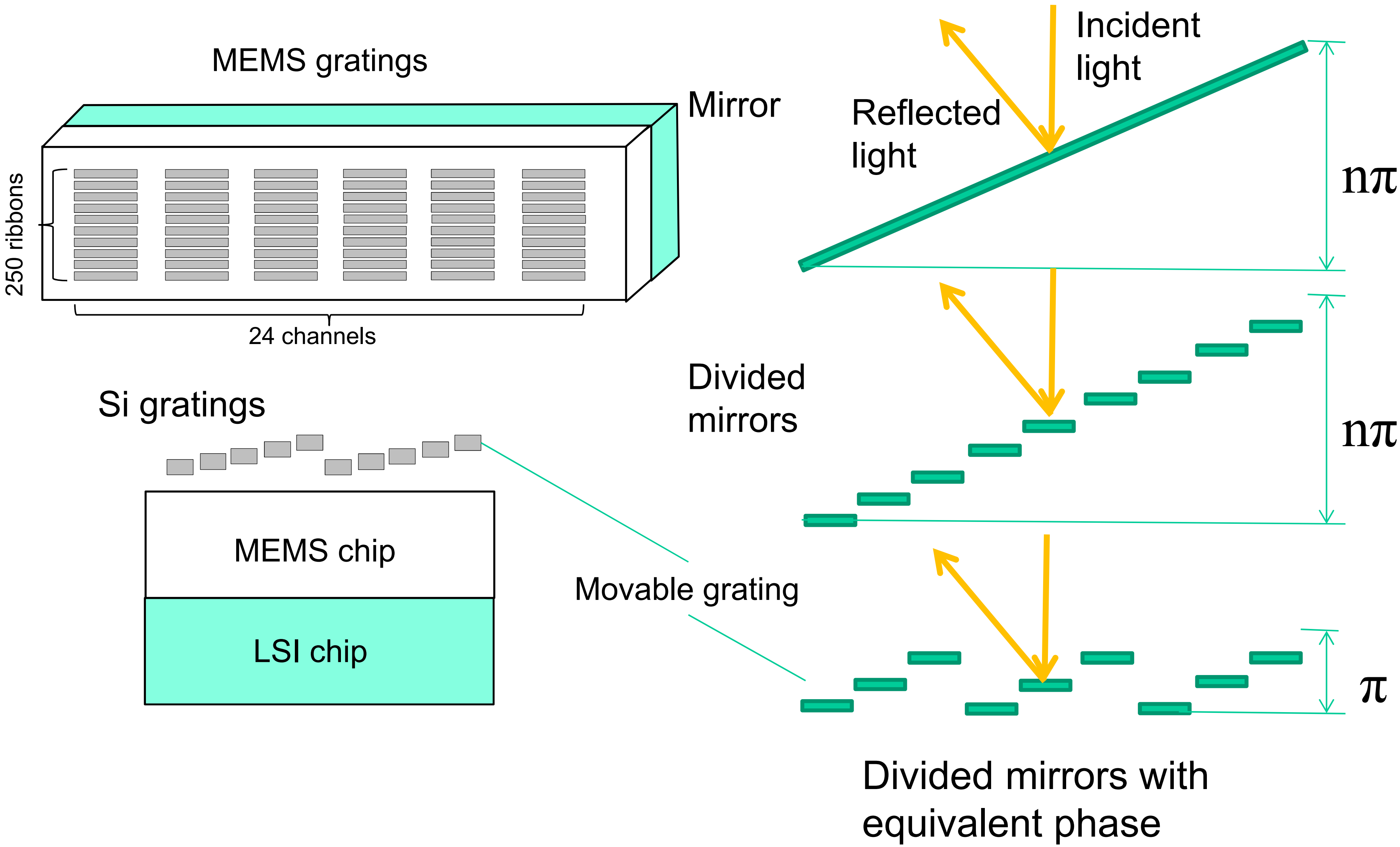


Ribbon MEMS

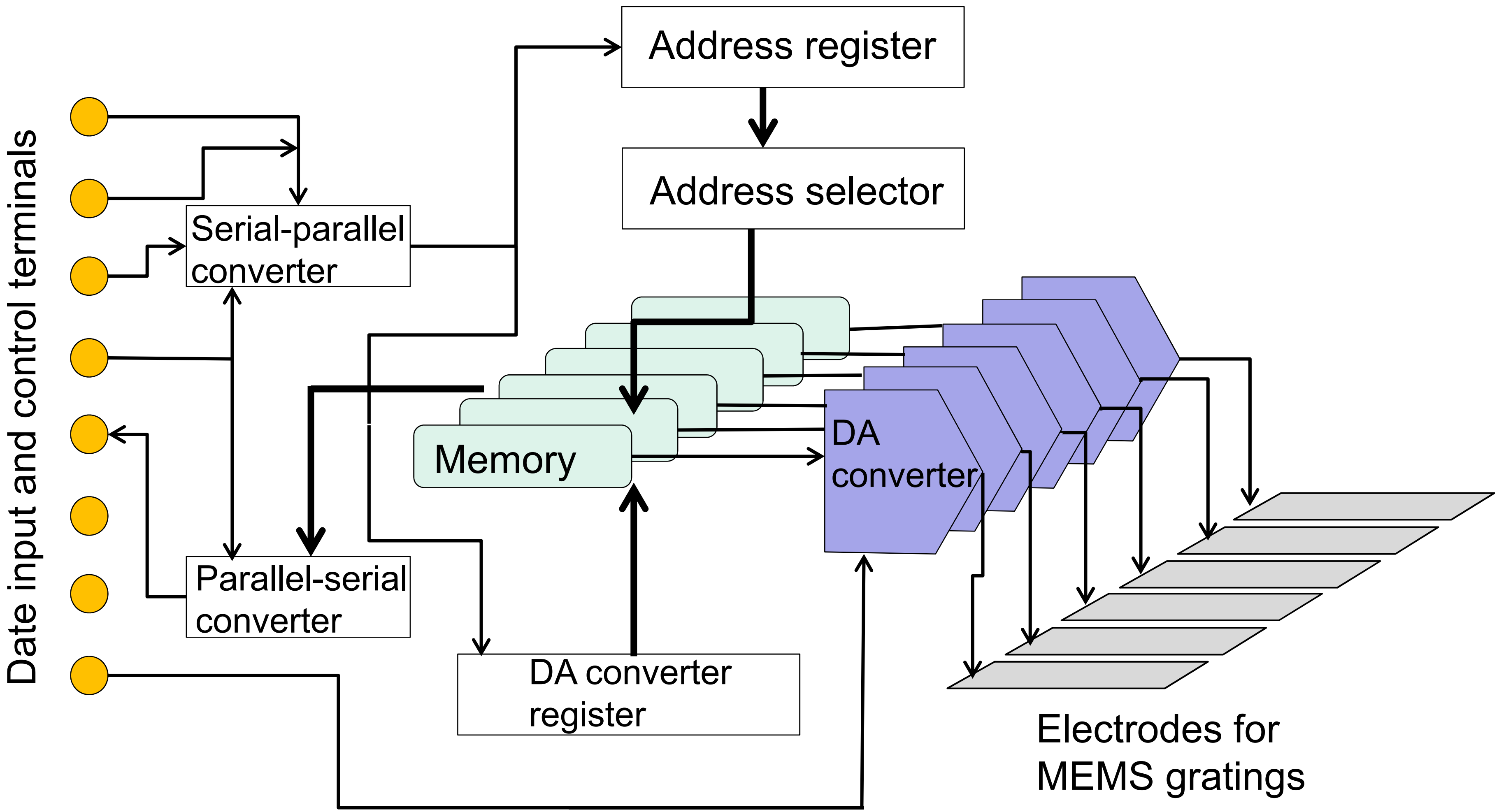
MEMS grating:
9µm wide, 1µm space
400µm long, 250 ribbons
1µm-3µm gap



光ビーム走査の原理

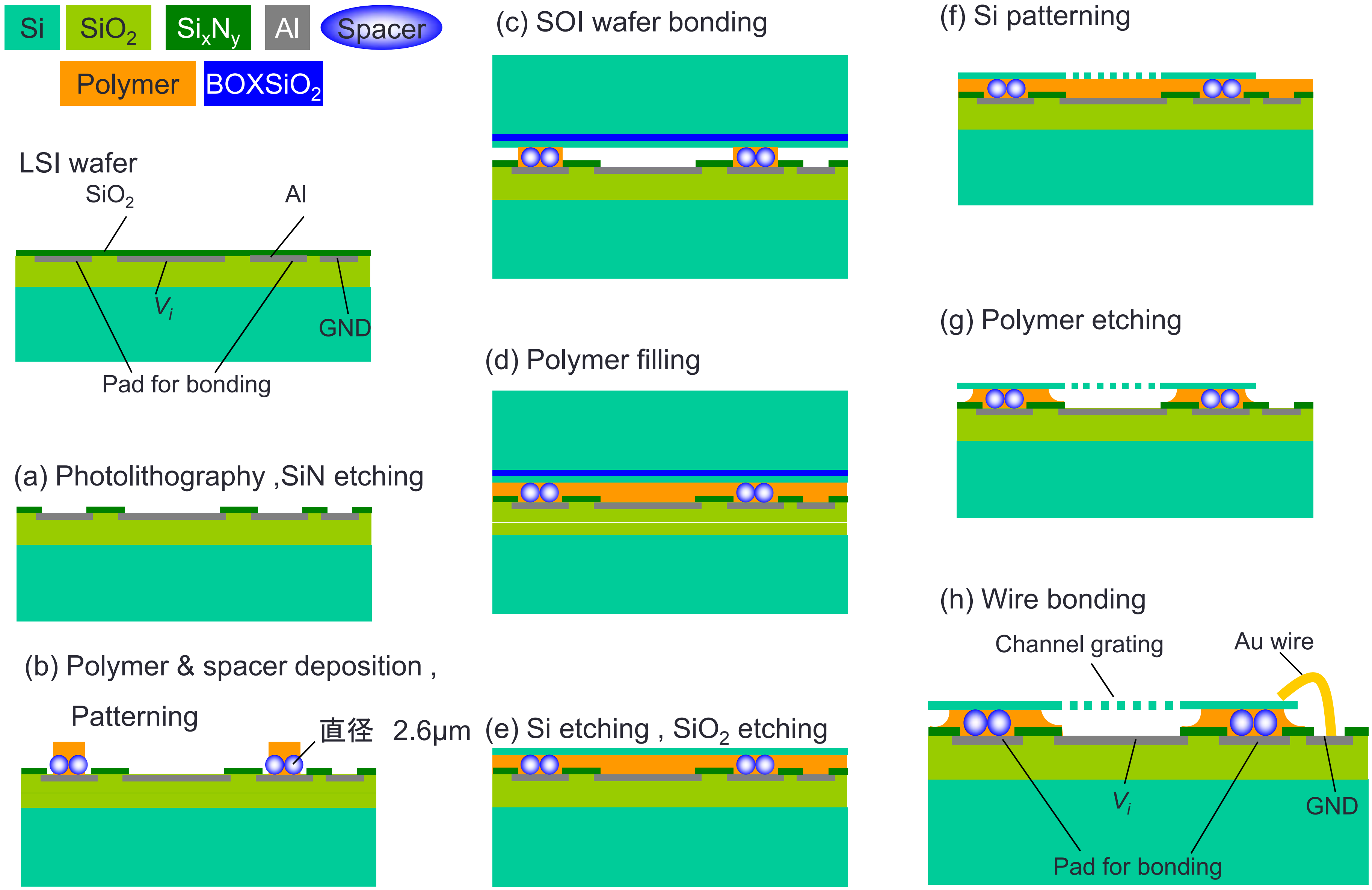

MEMS gratings
Mirror
250 ribbons
24 channels
Si gratings
MEMS chip
LSI chip
Movable grating
Incident light
Reflected light
Divided mirrors
nπ
nπ
π
Divided mirrors with equivalent phase

制御用LSIの設計



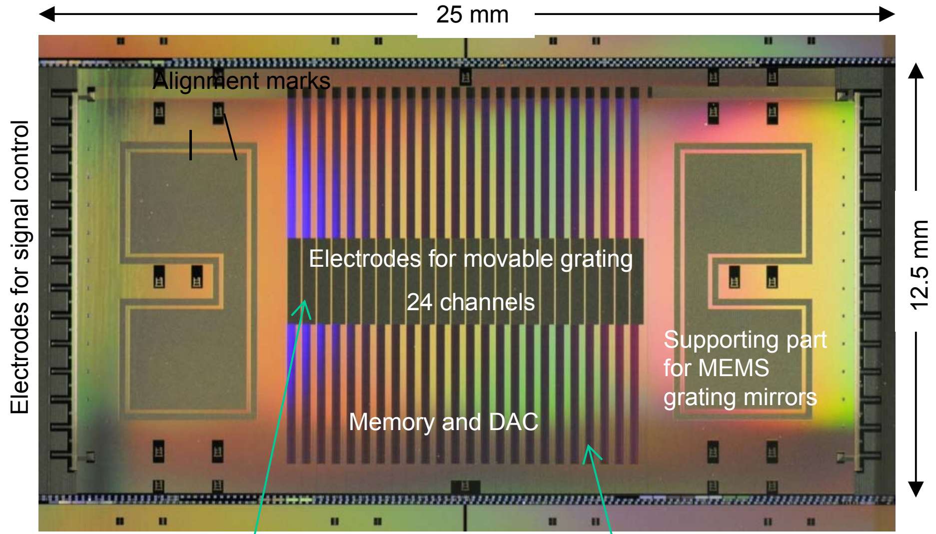
Date input and control terminals
Address register
Address selector
Serial-parallel converter
Memory
DA converter
Parallel-serial converter
DA converter register
Electrodes for MEMS gratings

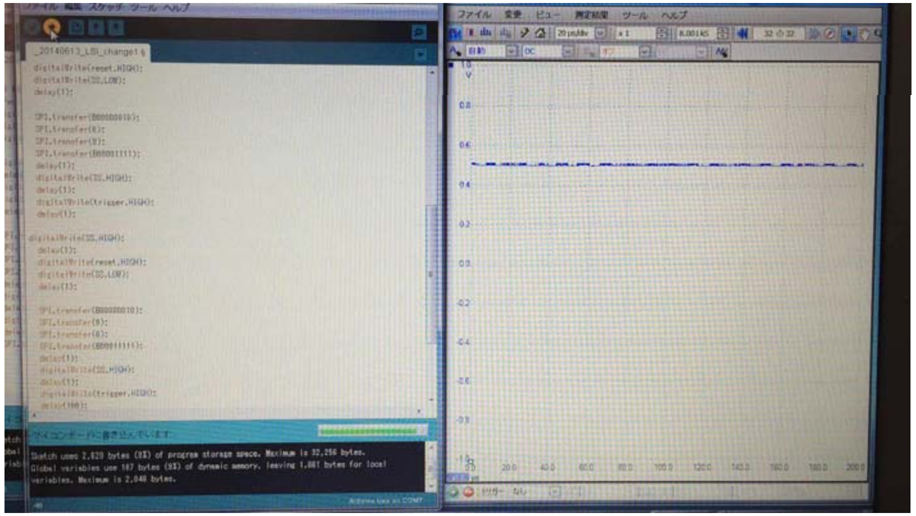
製作プロセス



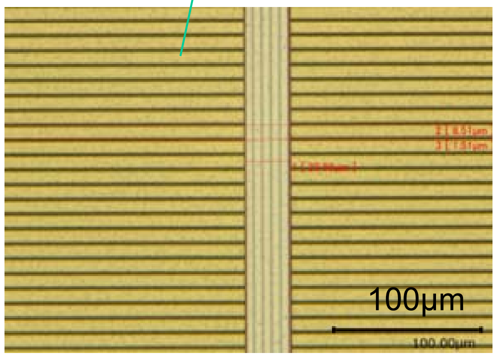
Si
SiO2
SixNy
Al
Spacer
Polymer
BOXSiO2
LSI wafer
SiO2
Al
Vi
GND
Pad for bonding
(a) Photolithography ,SiN etching
(b) Polymer & spacer deposition ,
Patterning
直径 2.6μm
(c) SOI wafer bonding
(d) Polymer filling
(e) Si etching , SiO2 etching
(f) Si patterning
(g) Polymer etching
(h) Wire bonding
Channel grating
Au wire
Vi
GND
Pad for bonding

製作したLSI

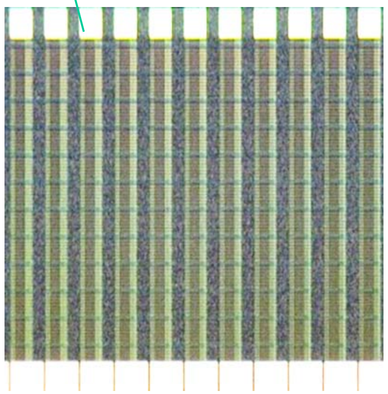




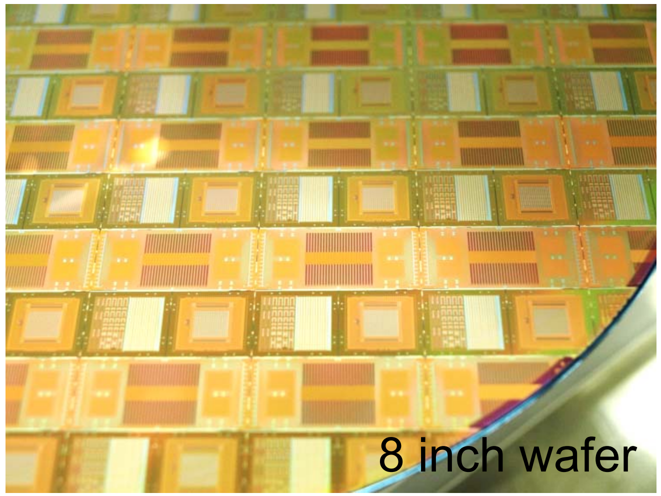
Voltage output by program



Electrodes for grating

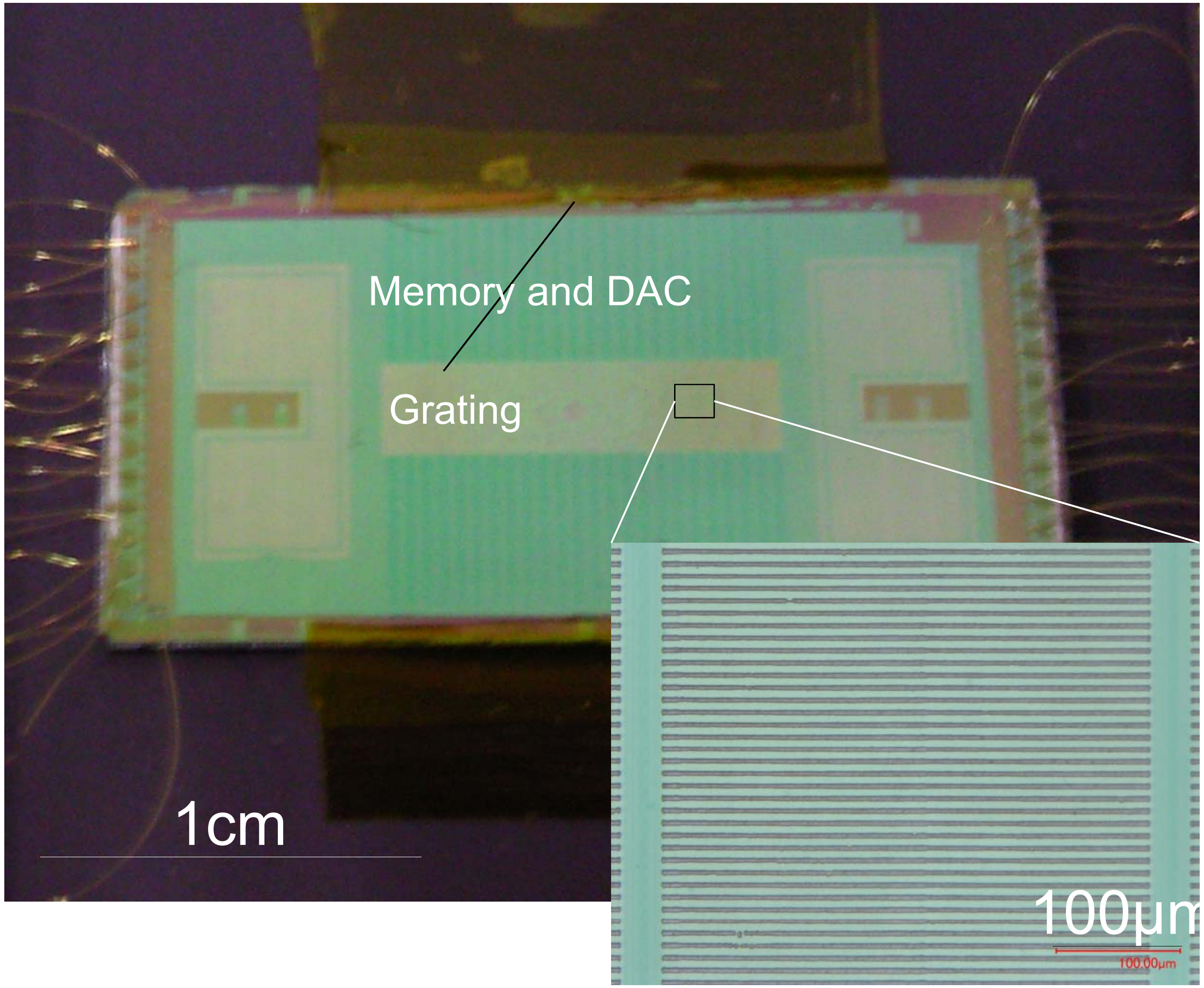


Memory and DAC



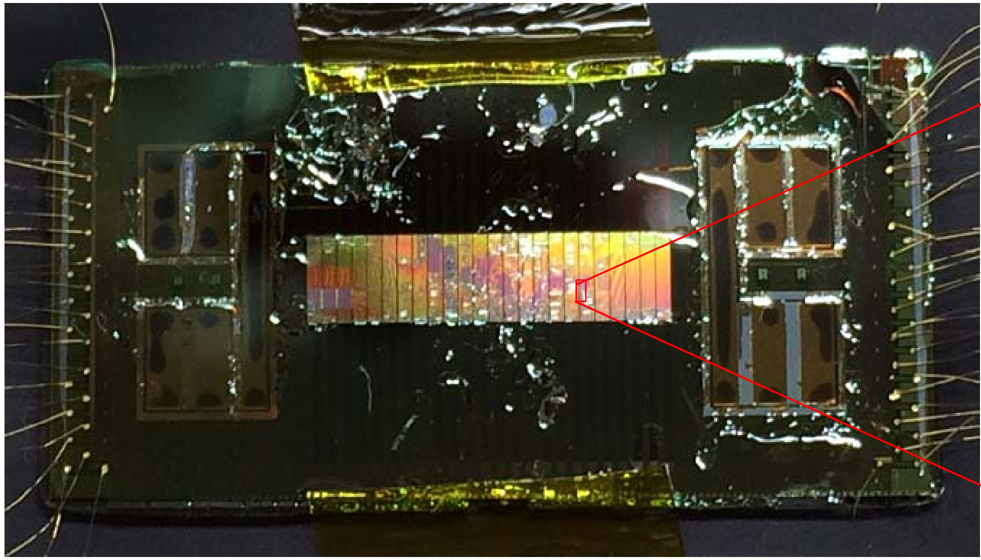
8 inch wafer

LSI上に製作したSiグレーティング

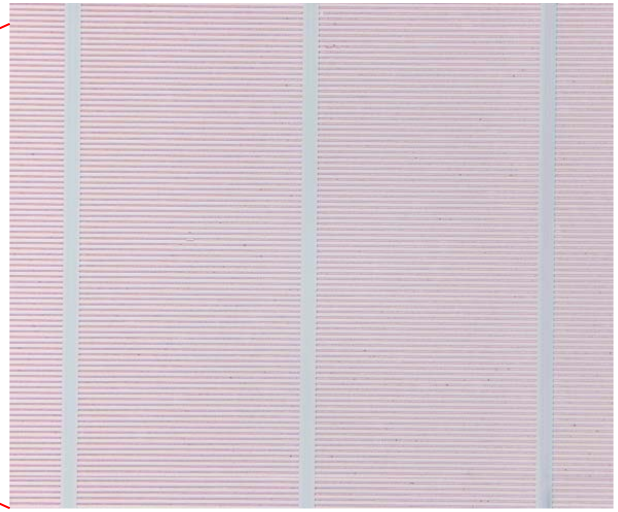


Silicon grating on LSI circuit

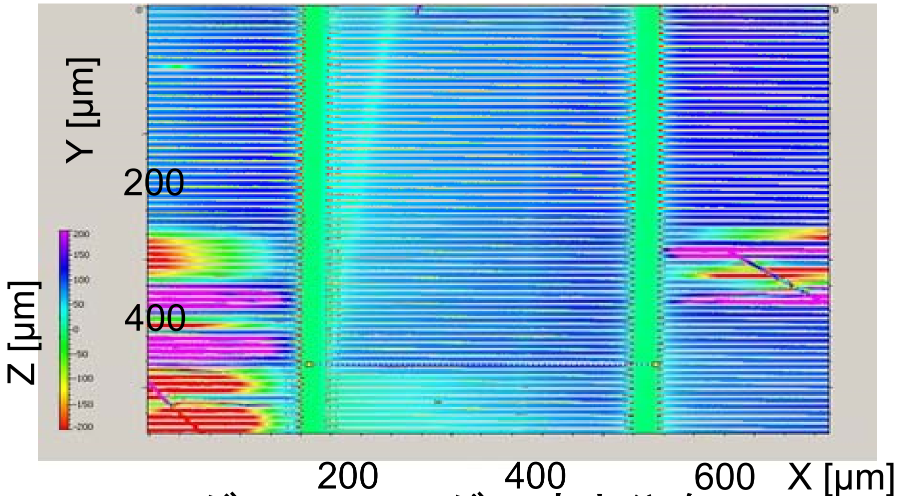
LSI上に製作したMEMSグレーティング



LSI上に集積したグレーティング



グレーティングの光学顕微鏡写真

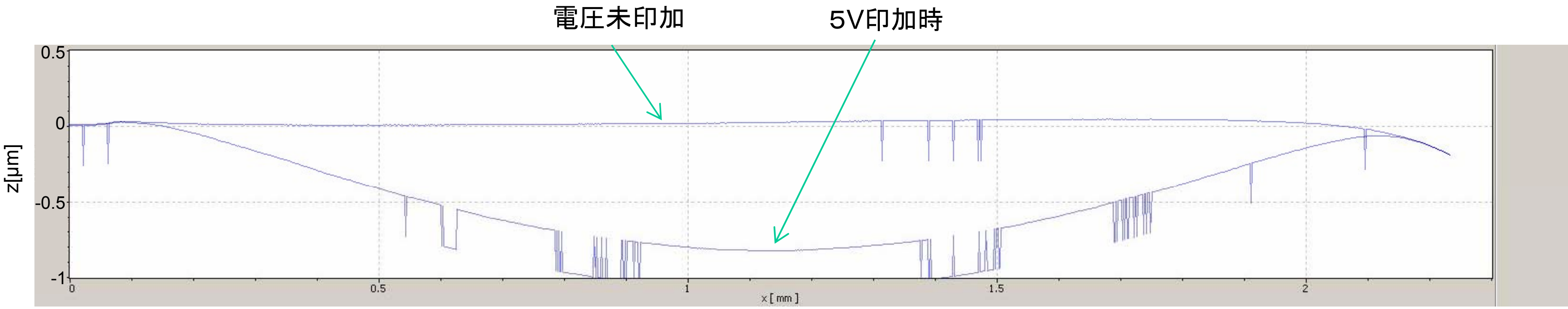


グレーティングの高さ分布

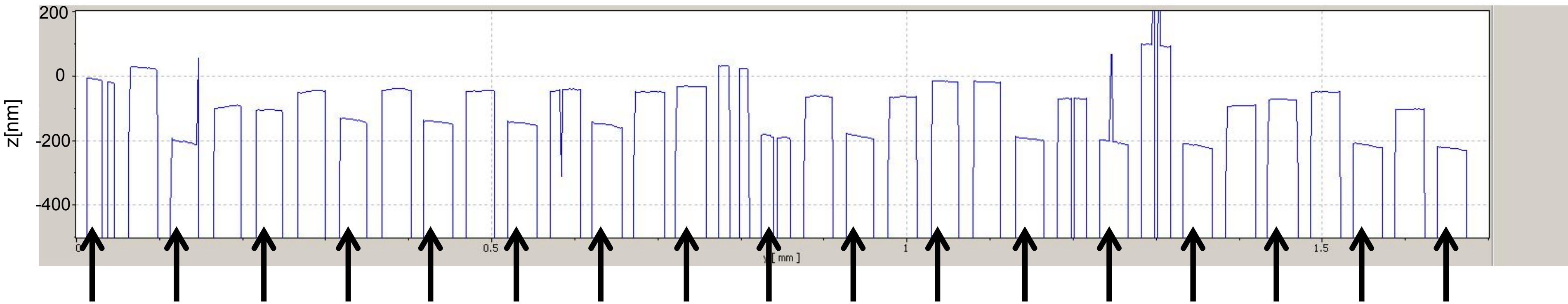
＊一部にポリマー接合が不十分であるが、グレーティングは精度よく製作できた
＊ガラス上に製作したグレーティングで見られた凹凸も解消された

電圧印加時のグレーティング変位測定

グレーティング形状測定:　下部電極に5Vを印加し800nmの変位が得られた



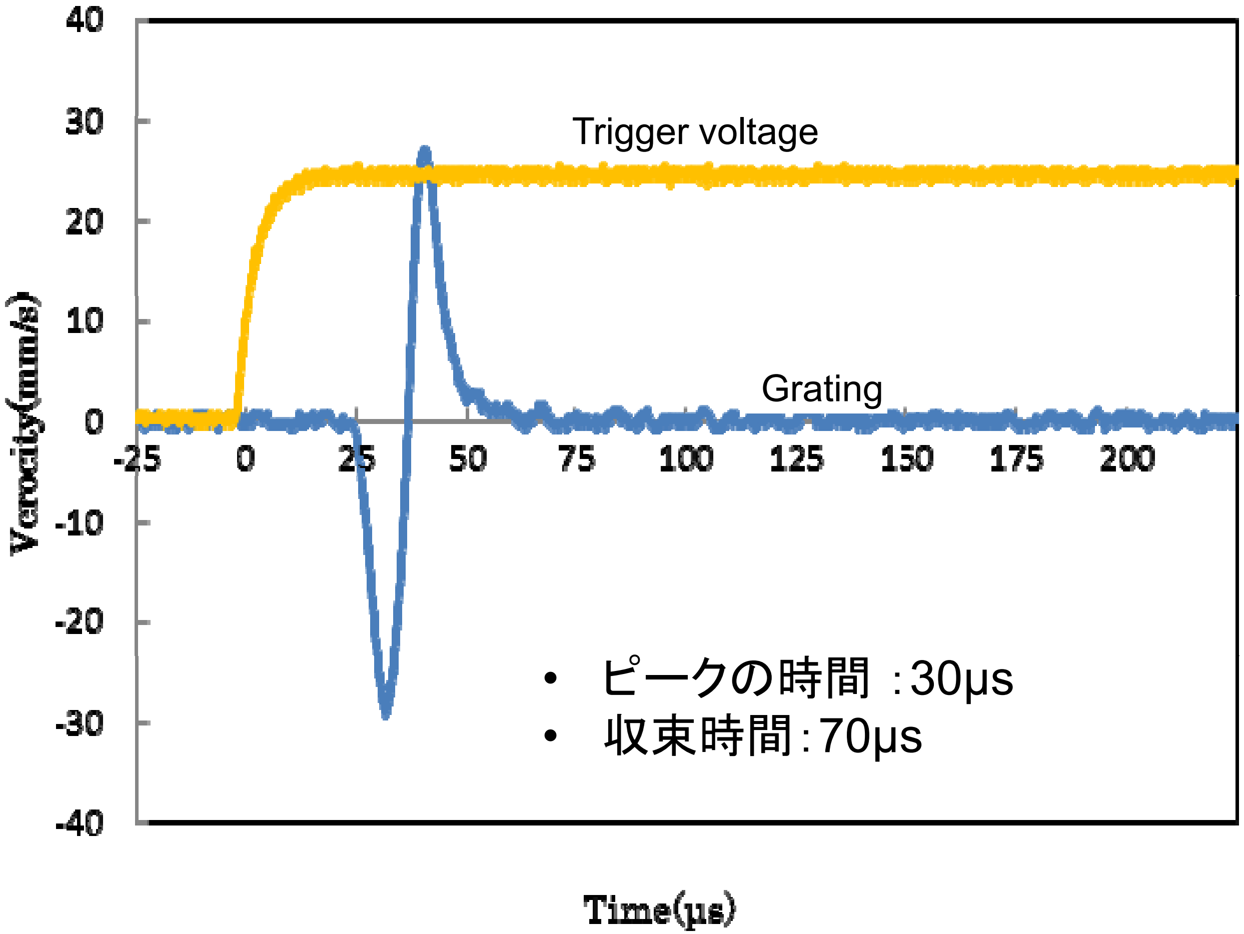
グレーティングを交互の2レベルに動作させた場合の形状測定:　おおよそ目標の断面形状へと変化させることができた



矢印部のグレーティングに5Vの電圧を印加(マイコンの不具合により印加できていない部分がある)

応答速度測定

グレーティングの動的特性をレーザードップラー振動計を用いて測定した



- ピークの時間 :30µs
- 収束時間:70µs

LSIによるSiグレーティングの動作

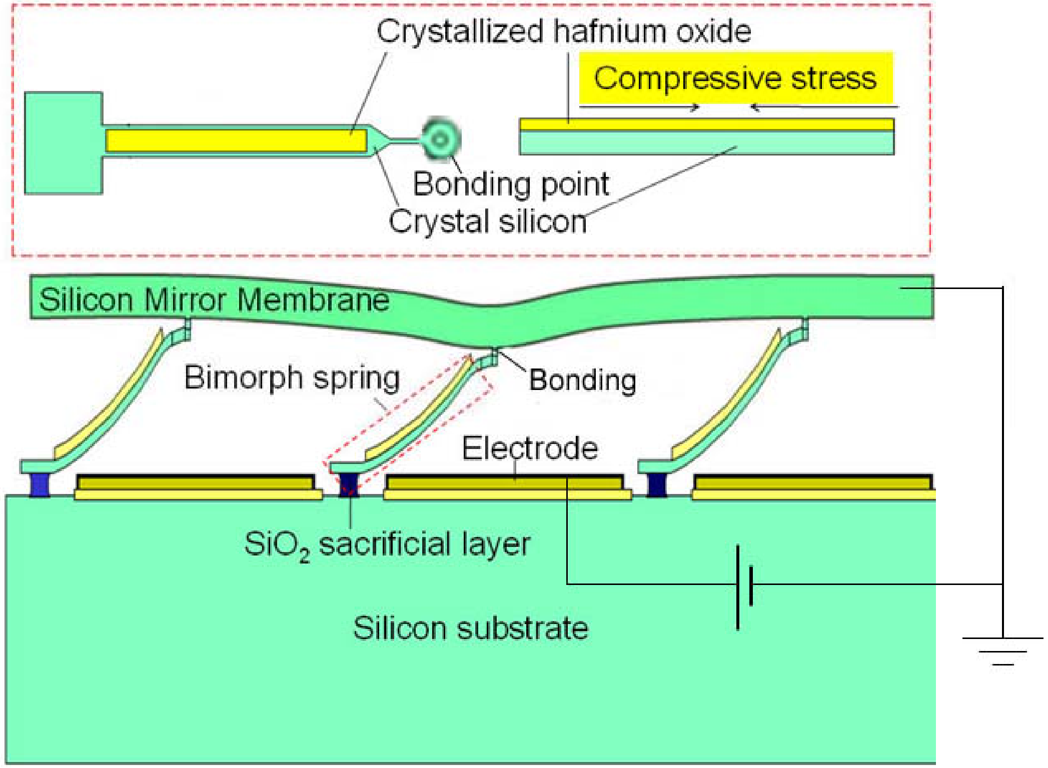
Operation of addressed ribbons of grating

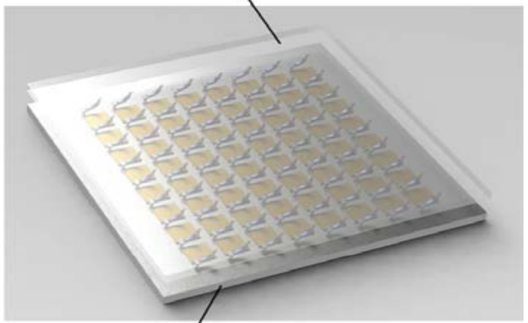
Switching in diffraction pattern

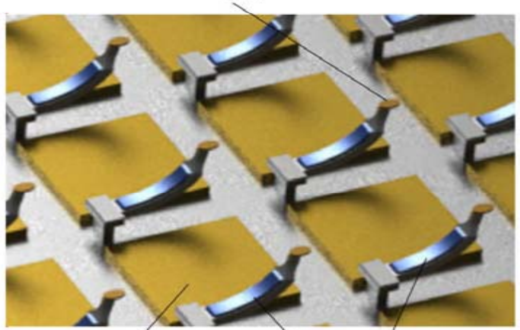
Experimental demonstration by T. Suzuki and T. Sasaki

MEMS-DM – Main design -

We propose a new structure membrane MEMS-DM by combining wafer bonding process and Si/HfO_2 Bimorph spring array







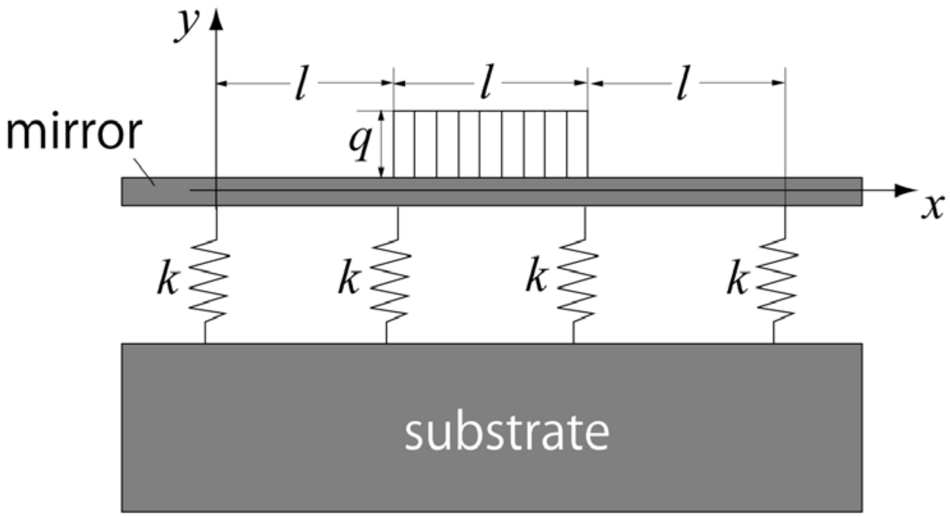
1. HfO_2 crystallization-induced stress is used to introduce large air gap.
2. Relatively soft spring structure (small spring constant) instead of fixed posts is used to increase the stroke.
3. High optical quality mirror surface is guaranteed by single-crystal-silicon membrane.

MEMS-DM – Inter-actuator coupling

It is important to chose the inter-actuator coupling of the mirror actuator at adjacent actuator.

We considered an approximated model for analytic calculation of the influence function. As the inter-actuator coupling is defined as the ratio of the deflection of the pixel adjacent to the actuated pixel to that of the actuated pixel, thus, in the coordinate shown in Fig. 1, the inter-actuator coupling *IC* is given by

$$IC = \frac{y|_{x=l/2}}{y|_{x=3l/2}} = \frac{552EIkl^3 + 1152E^2I^2 - 6k^2l^6}{1260EIkl^3 + 1152E^2I^2 + 13k^2l^6}$$ (EI is the flexure rigidity)

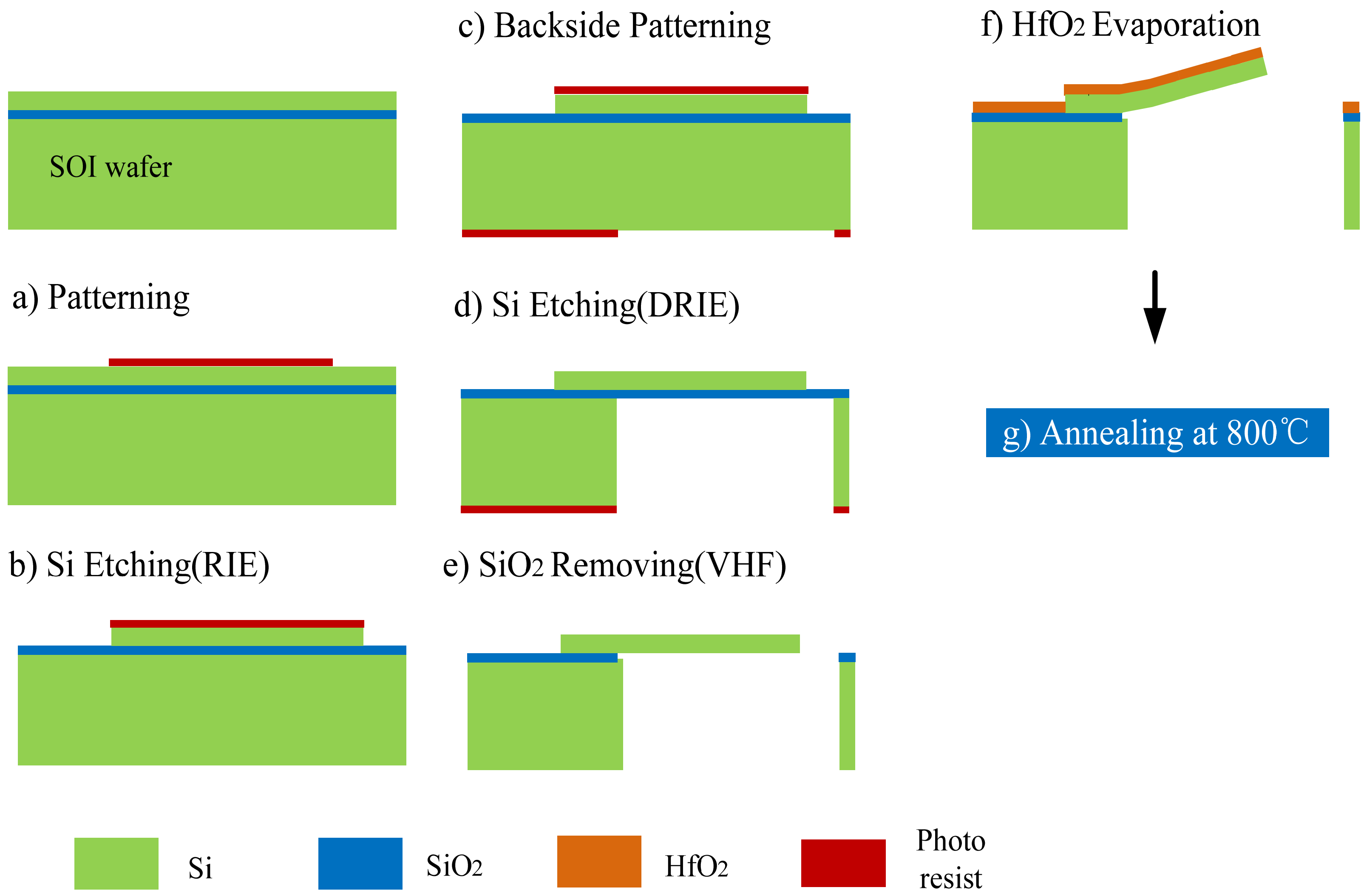


Calculation model of the continuous membrane DM

The calculated inter-actuator coupling for the previous bimorph spring structure: 59%. The measured inter-actuator coupling is 51%.

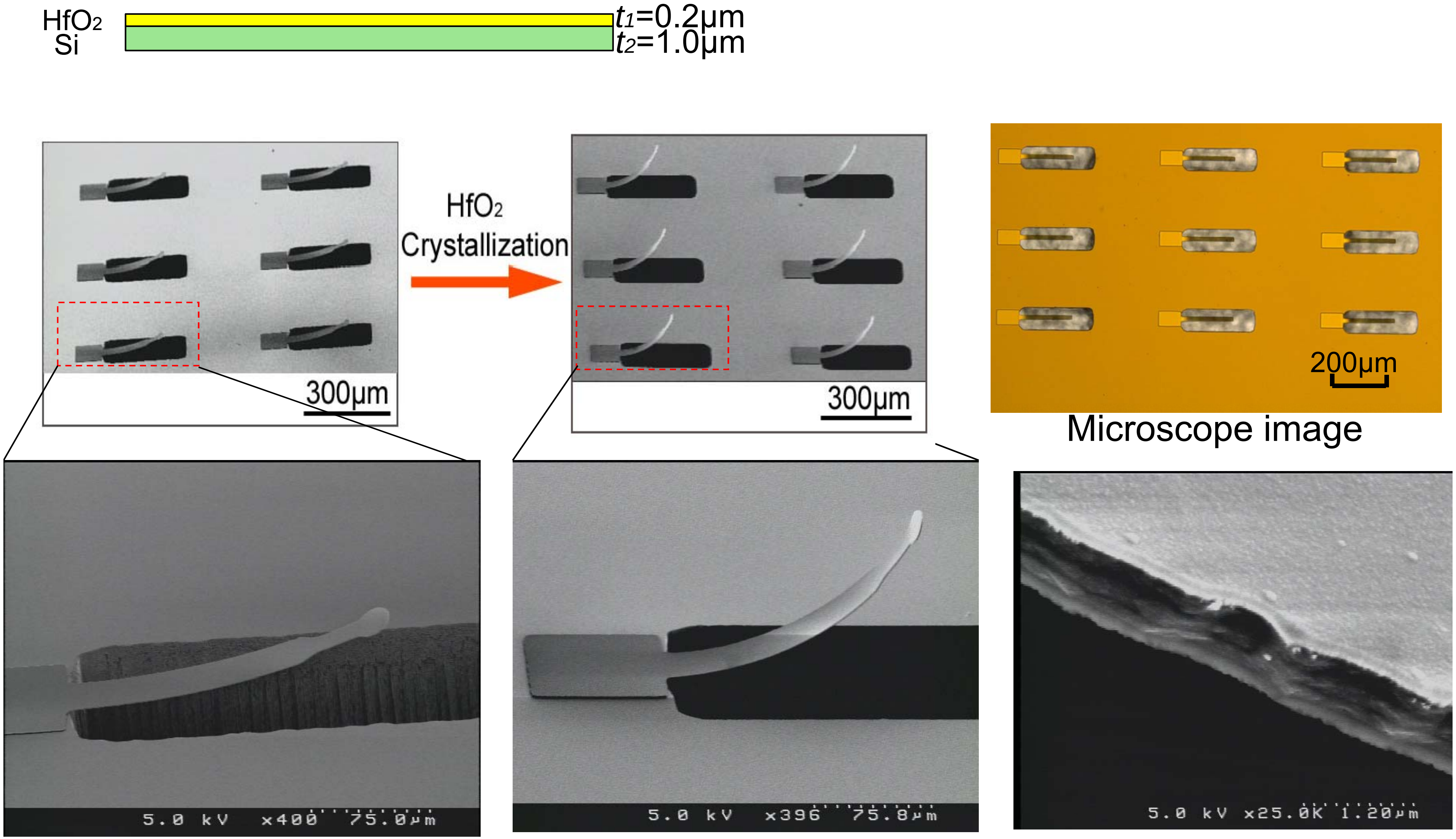
MEMS-DM – Si/HfO_2 Bimorph spring

The out-of-plane deflection needed to be checked to determined the length of the bimorph spring using in DM.



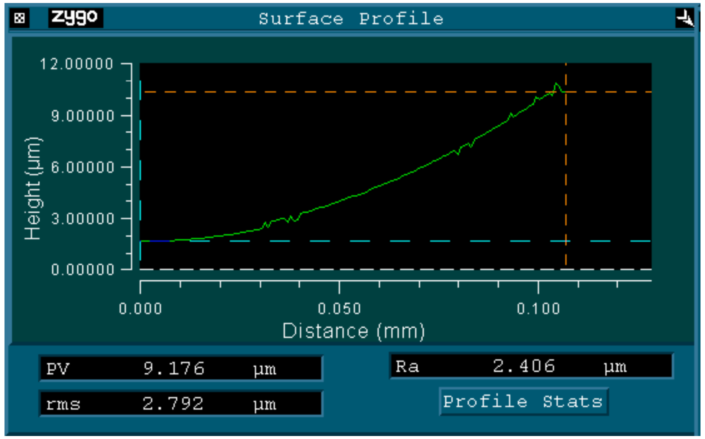
MEMS-DM – Si/HfO2 Bimorph spring

Fabricated bimorph spring



MEMS-DM – Si/HfO2 Bimorph spring: out-of-plane deflection

Before Crystallization



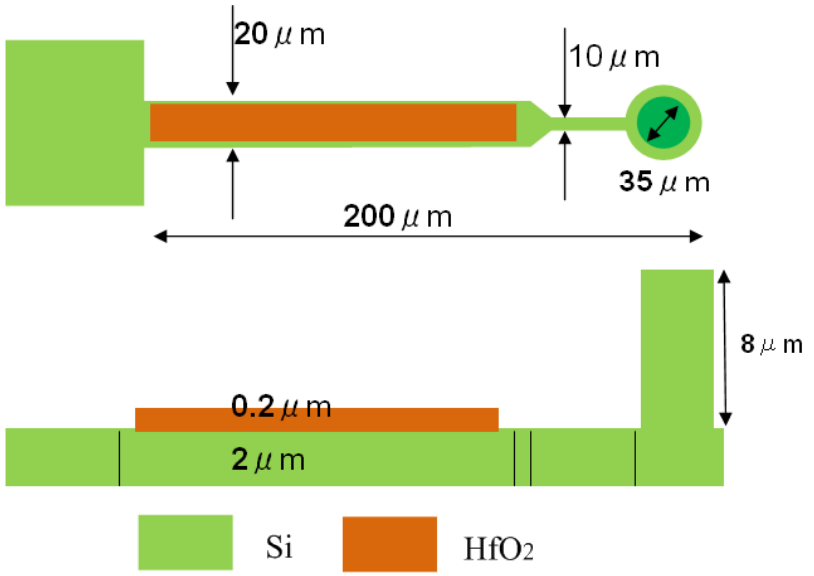
No	Length(μm)	Deflection(μm)	Curvature radius(mm)
1	100	9.29	0.538
2	100	10.06	0.497
3	100	8.65	0.578
4	100	8.78	0.56
		Averange Curvature radius(mm)	0.545

After Crystallization

Measured by Confocal laser scanning microscope

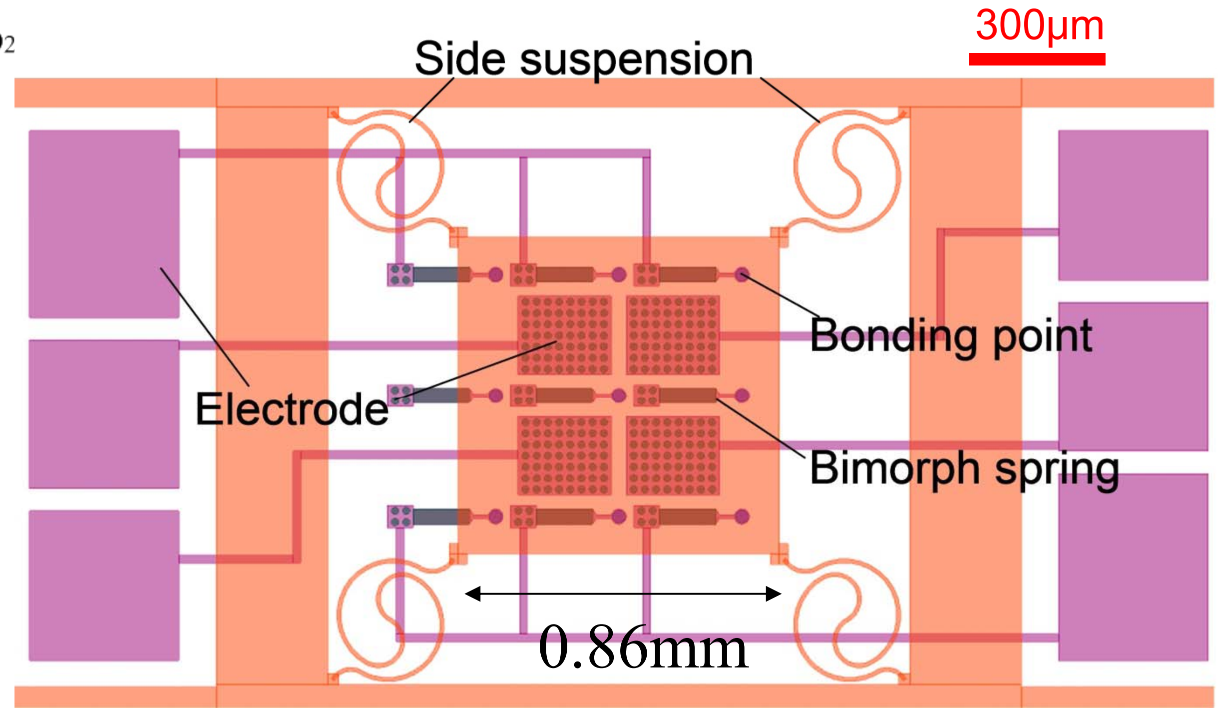
No	Length(μm)	Deflection(μm)	Curvature radius(mm)
1	100	34.44	0.145
2	100	33.13	0.150
3	100	33.70	0.148
4	100	33.59	0.148
5	200	130.46	0.153
6	200	133.80	0.149
7	200	132.64	0.150
8	200	130.54	0.153
		Averange Curvature radius(mm)	0.150

MEMS-DM – Design

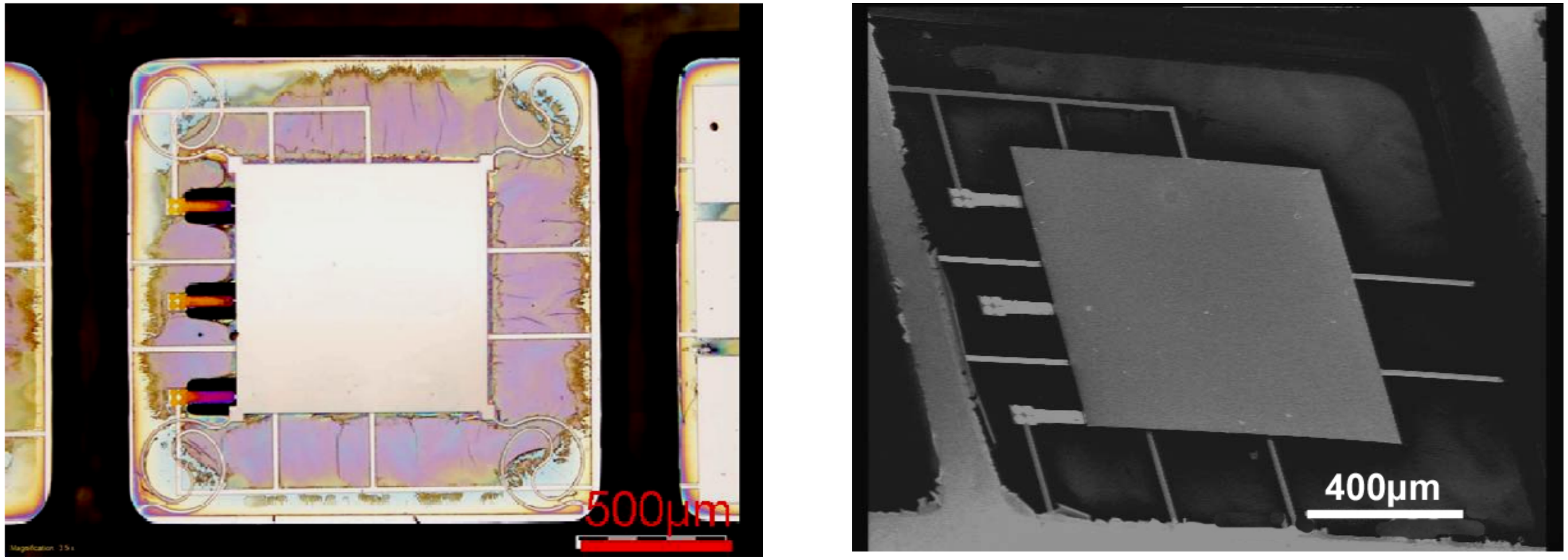


Dimensions of the bimorph spring

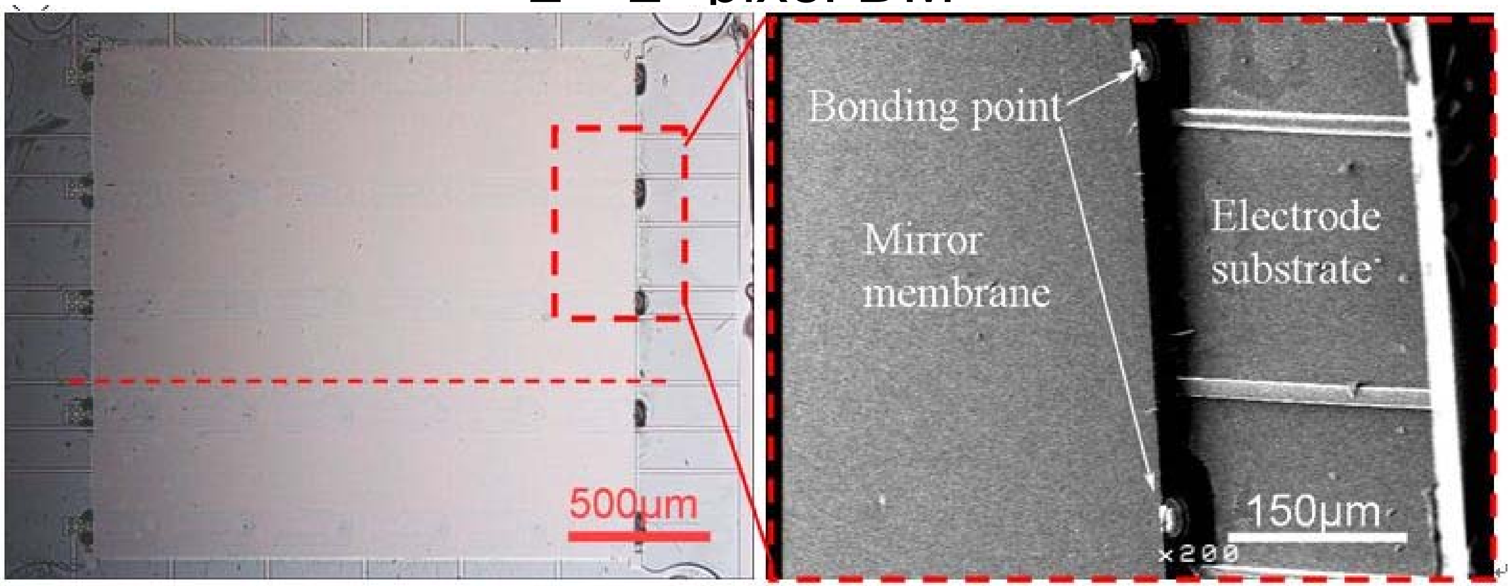
Design of the 2×2 Pixels DM



MEMS-DM – Fabrication results(3)

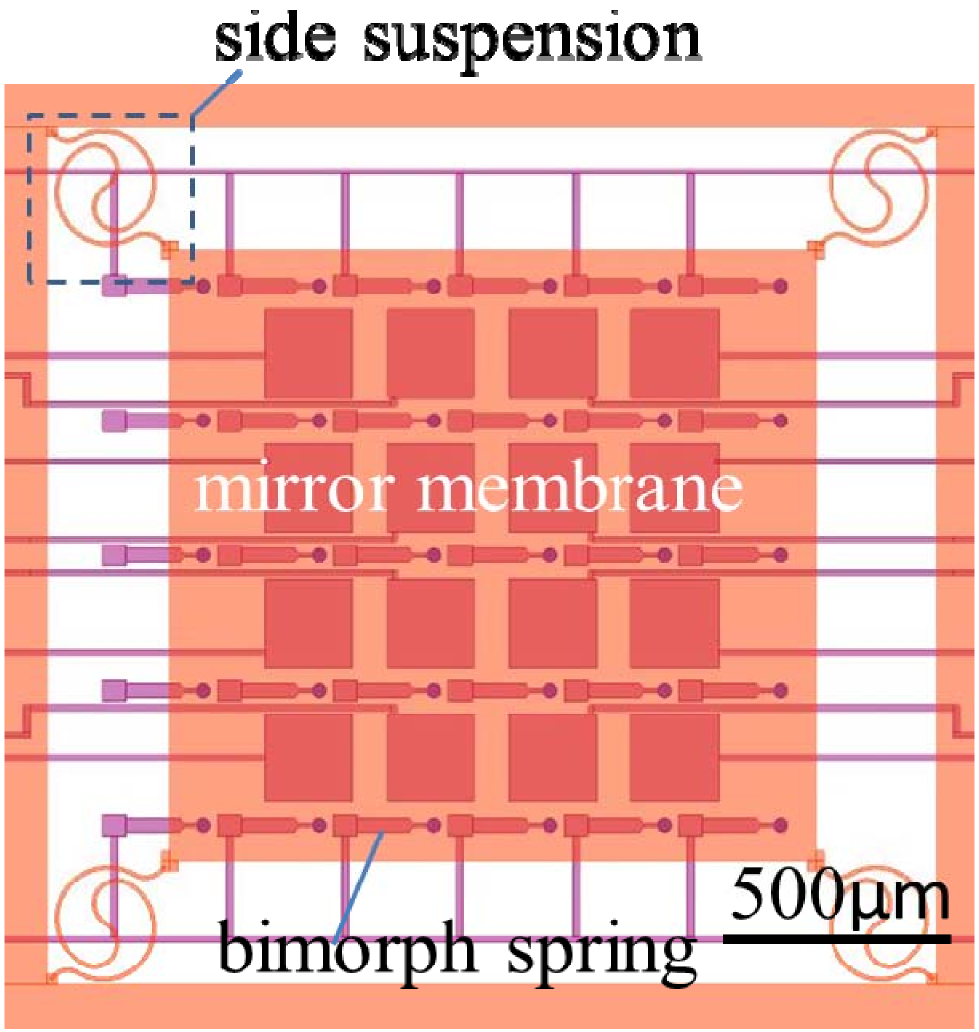


2×2 pixel DM



4×4 pixel DM

MEMS-DM – Design



Design of the 4 × 4 Pixels DM

MEMS-DM –Process flow

(a) Actuator chip

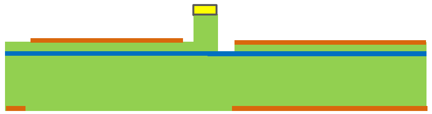
(1) Silicon DRIE(Form bonding point)

(2) Silicon DRIE (Form Electrode)

(3) HfO2 Liftoff

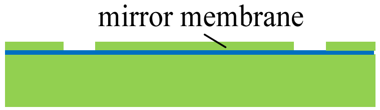
(4) Annealing(HfO2 crystallization)

(5) Au/Cr deposition and patterning



(b) Mirror chip

(1) Silicon DRIE(Form mirror membrane)



(2)HfO2 liftoff

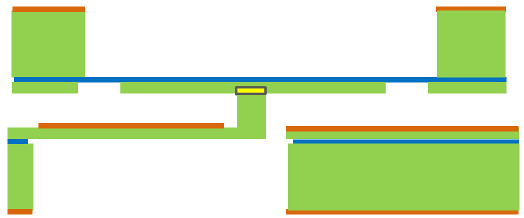
Si SiO_2 HfO_2 Au/Cr

MEMS-DM –Fabrication flow : Bonding and Release

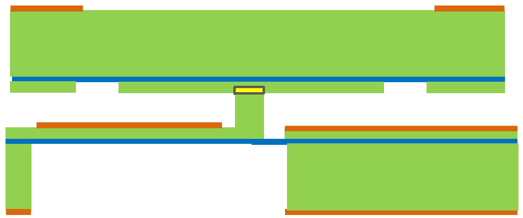
(c) Bonding and release

(1) Au-Si eutectic bonding

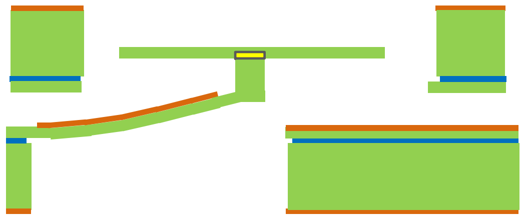
(4) SiO_2 Dry Etching (CHF_3)



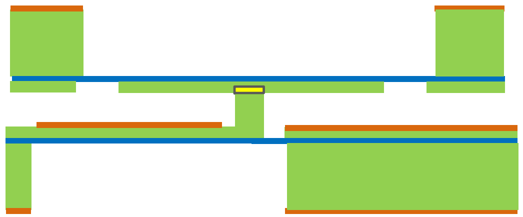
(2) Actuator chip handle layer etching



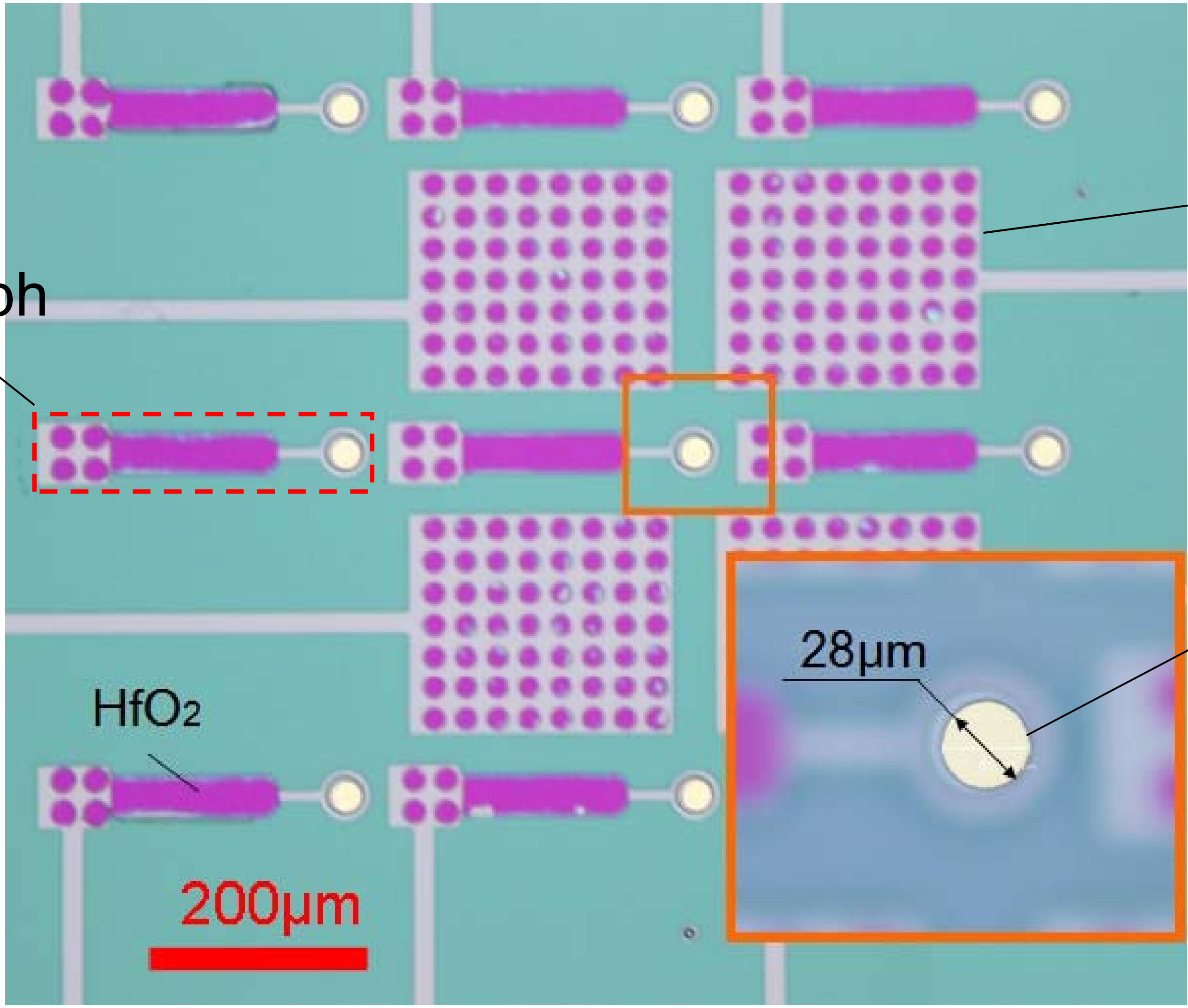
(5) SiO_2 Dry Etching (CHF_3)



(3) Mirror chip handle layer etching



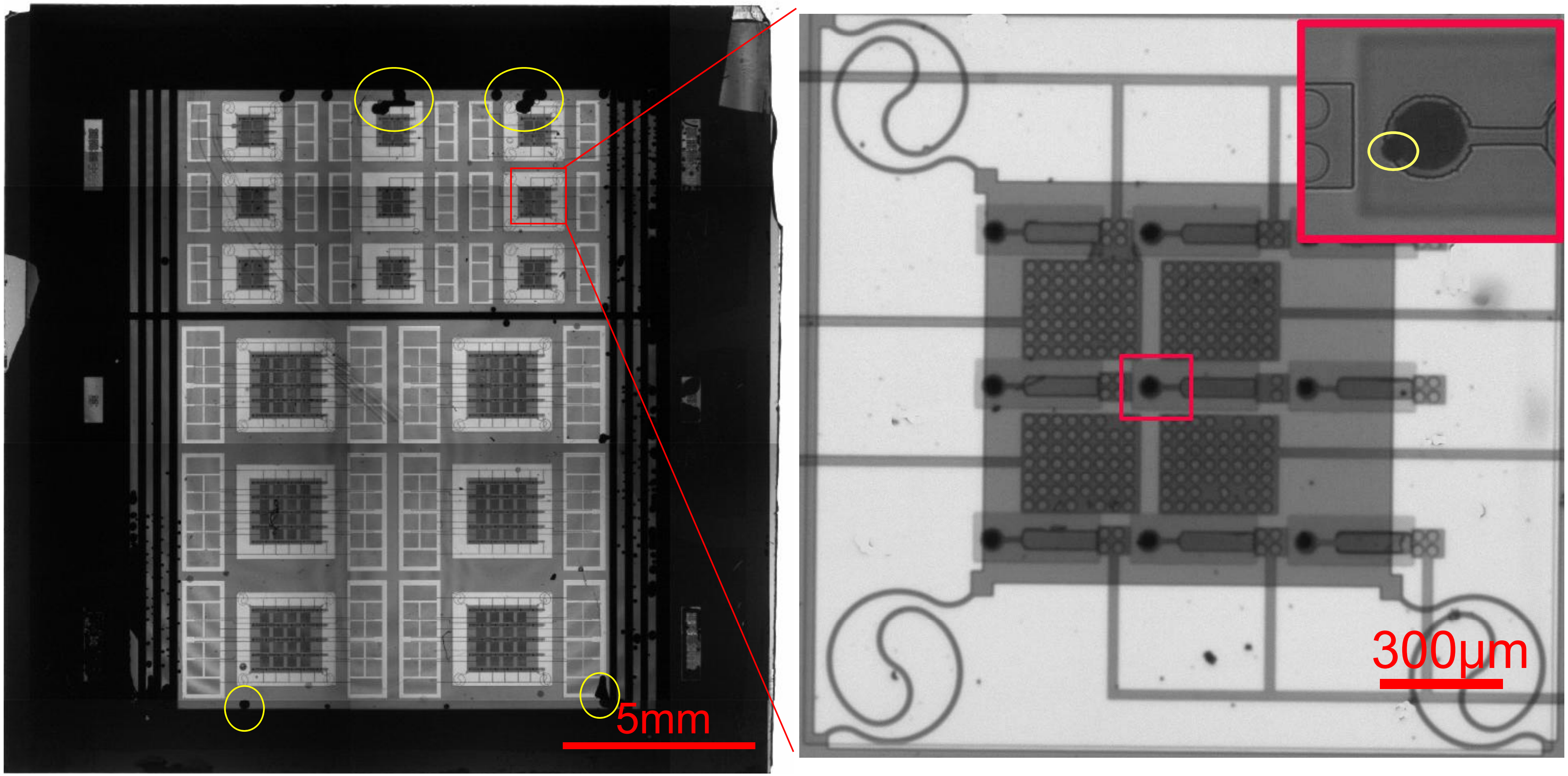
MEMS-DM – Fabrication results(1)



Fabricated actuator chip

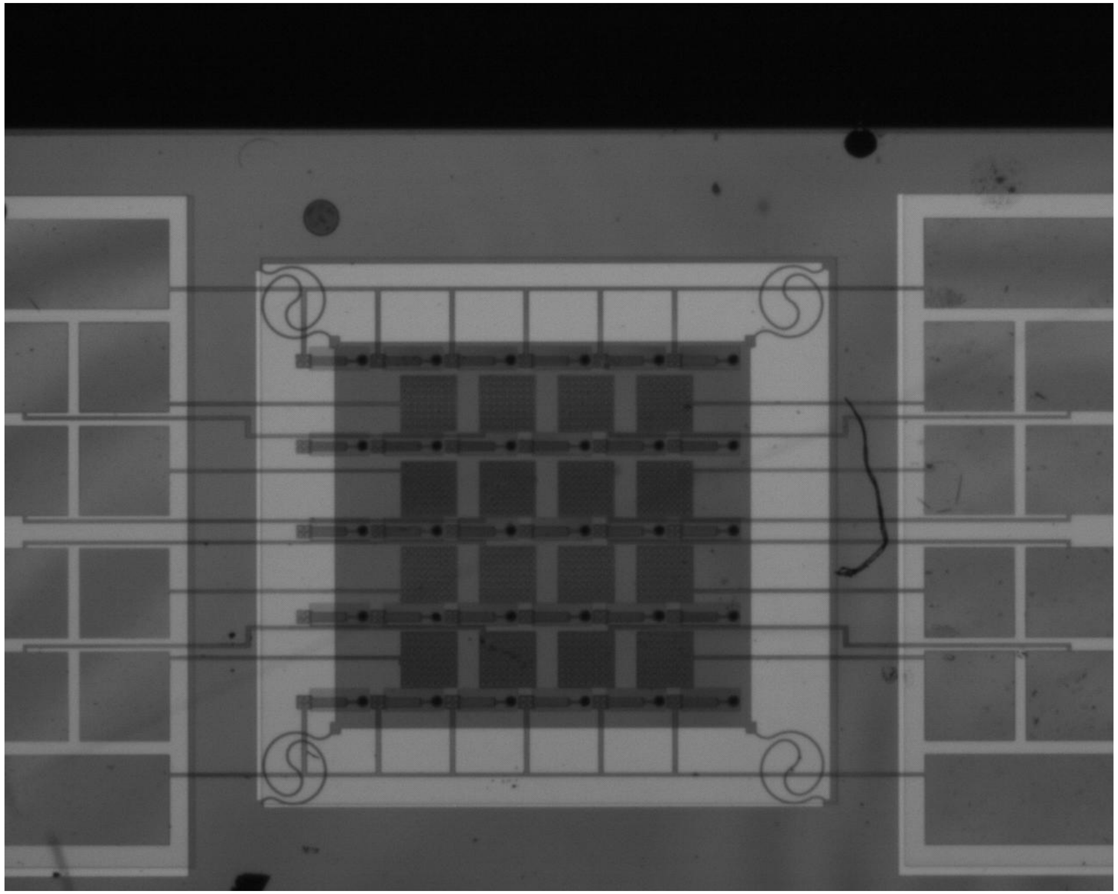
MEMS-DM – Fabrication results(2)

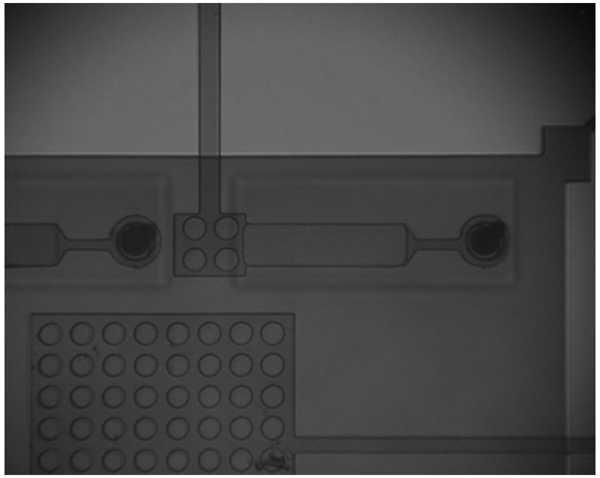
Au-Si eutectic bonding: 400℃, 1.67MPa, 30min, 4.5×10^{-2}Pa



The irregular bonding edge(in yellow line) suggests that Au was melted during bonding.

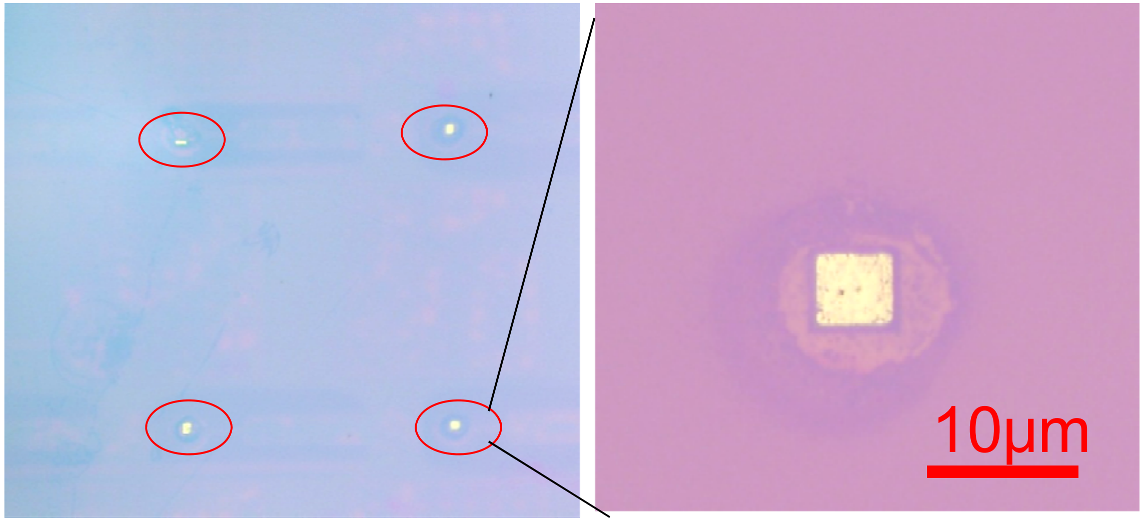
MEMS-DM – Fabrication results(2)



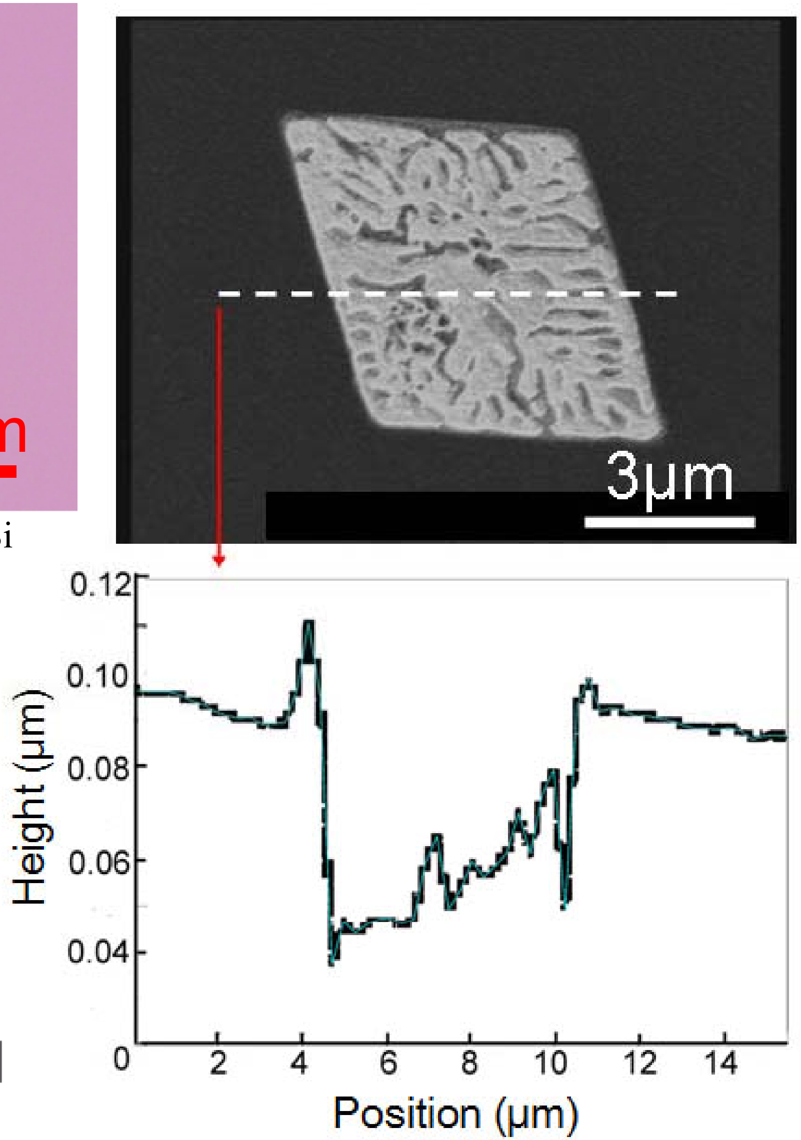


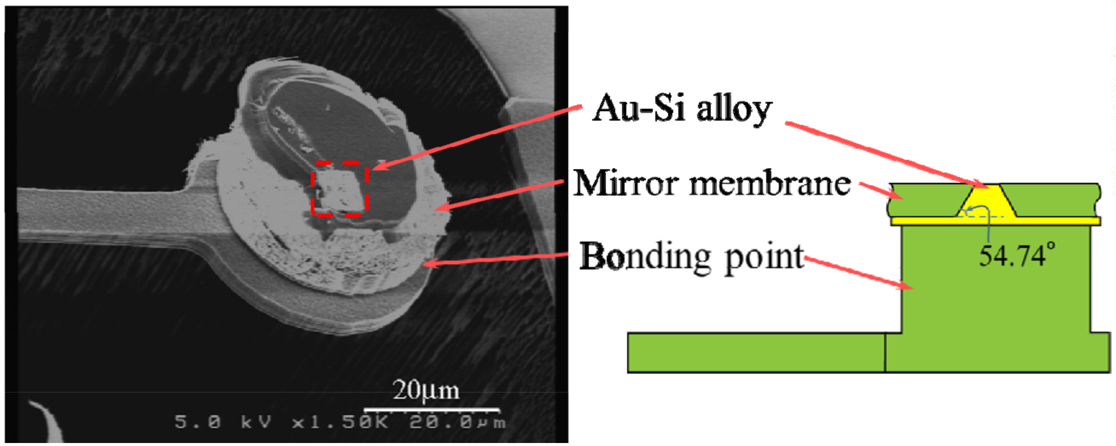
4×4 pixel mirror

MEMS-DM – Fabrication results(4) –



The optical micrograph of the mirror membrane with the square Au-Si reaction area



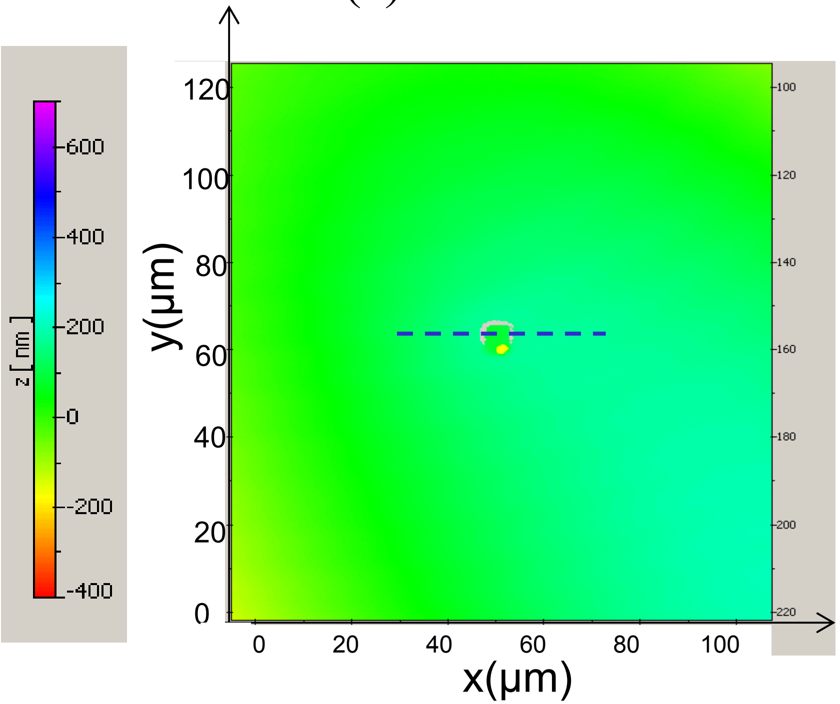


SEM image of the bonding point after peeling the mirror membrane

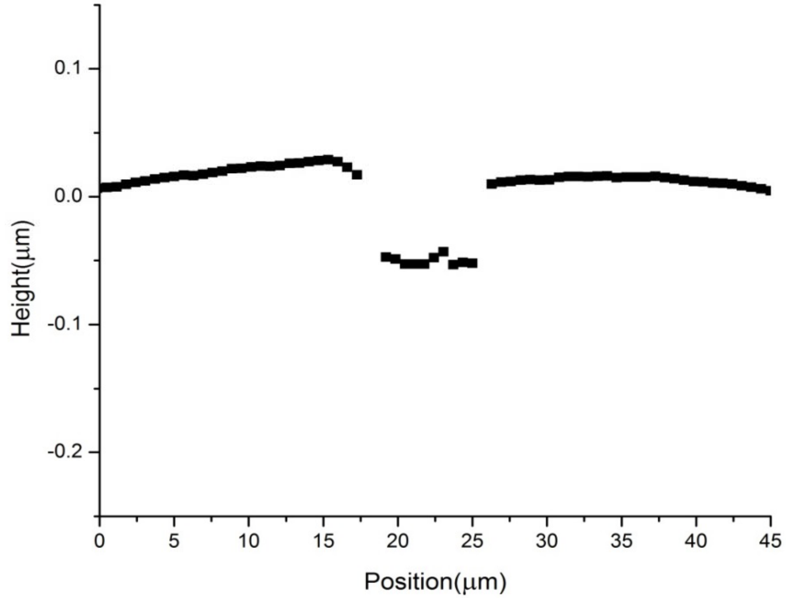
The SEM image and the surface profile of the bonding reaction area

MEMS-DM – Fabrication results(5) –

(a)

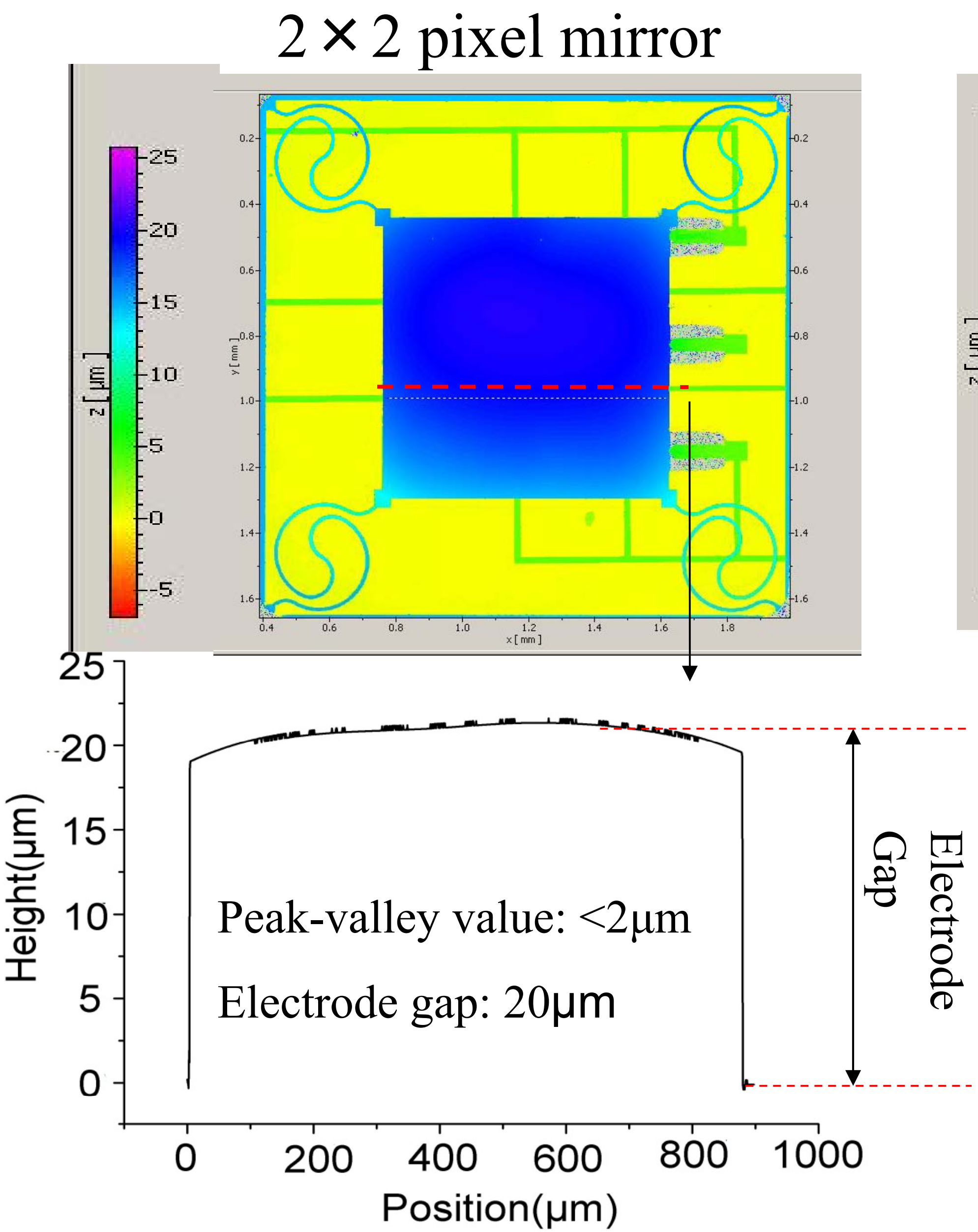


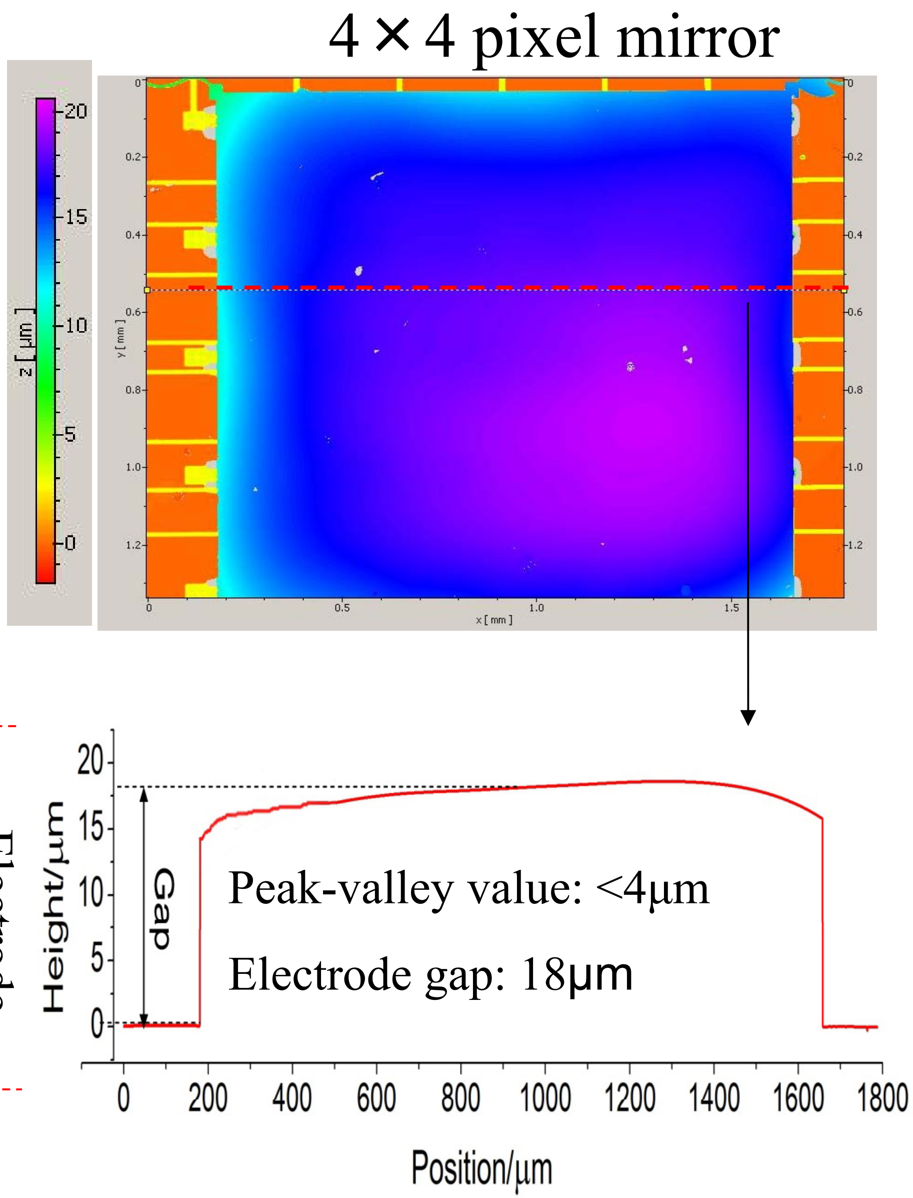
(b)



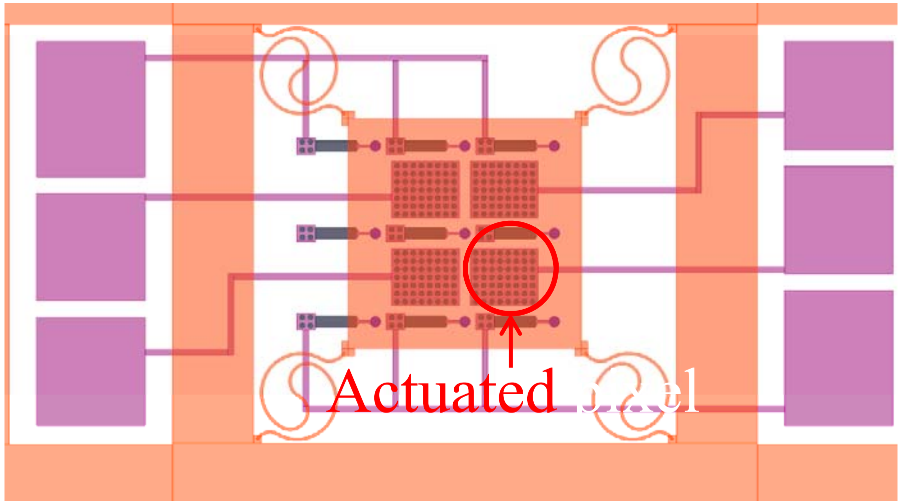
The surface around the bonding point is flat and smooth except the ~5μm reaction area. By removing the area of reaction point, the fill factor of the fabricated mirror is calculated to be 99.9%.

MEMS-DM – Device initial deflection





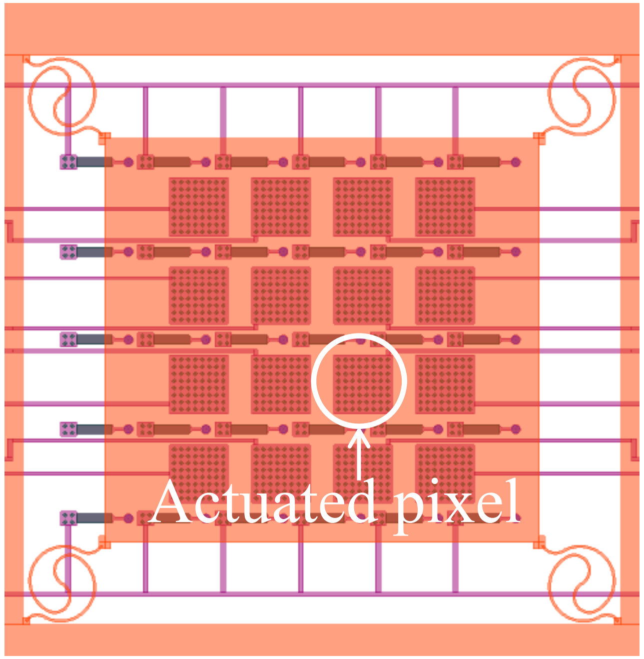
MEMS-DM – device driving experiment(2×2 pixel mirror)

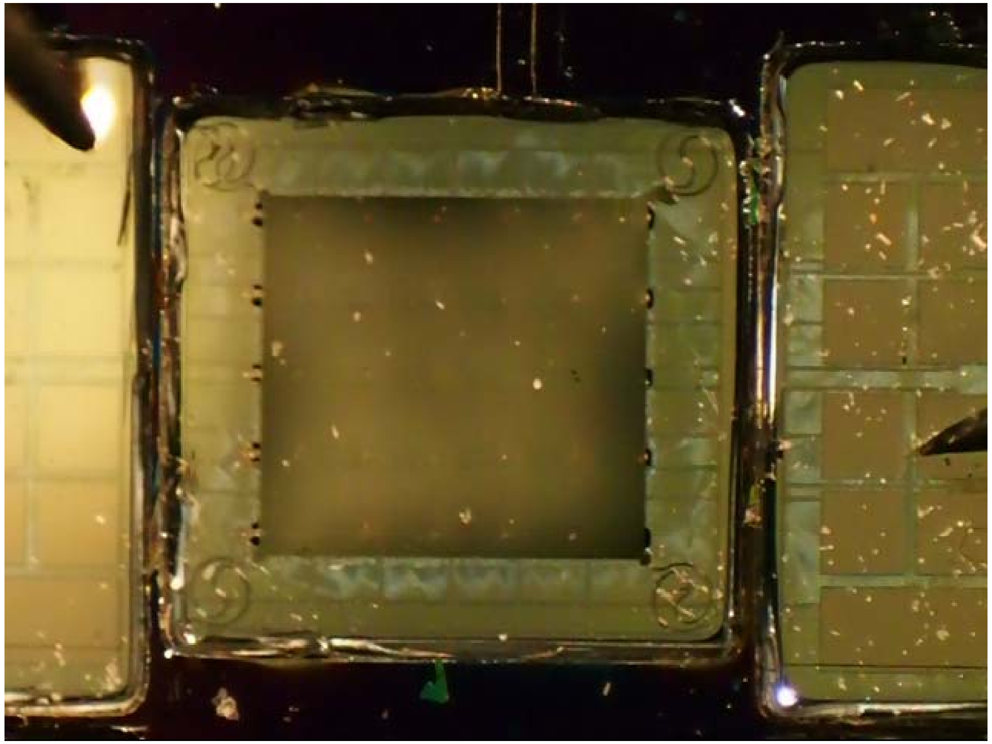


Sine wave driving test: Frequency:1Hz→20Hz→1Hz A pull-in voltage(~120V) is applied.

MEMS-DM – device driving experiment(4×4 pixel mirror)

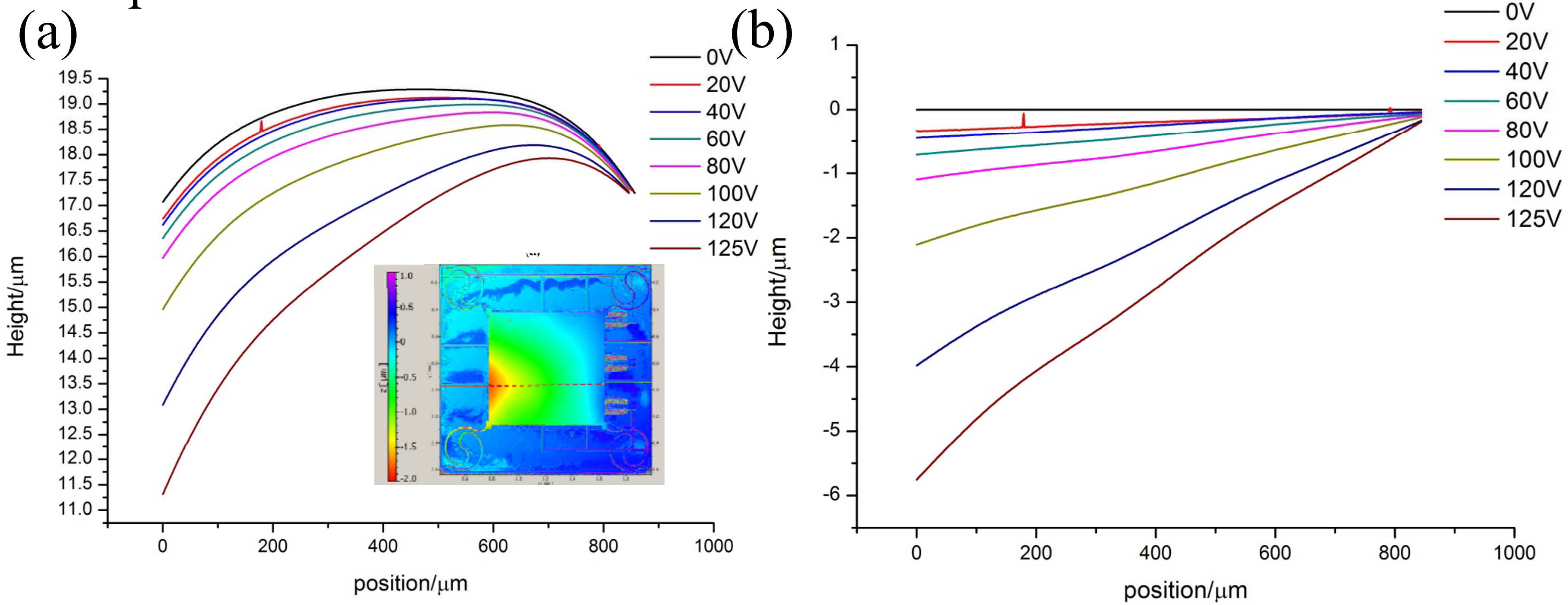
Sine wave driving test: Frequency:1Hz→20Hz→1Hz 80V(peak-peak)





MEMS-DM – static deflection measurement

2×2 pixels mirror

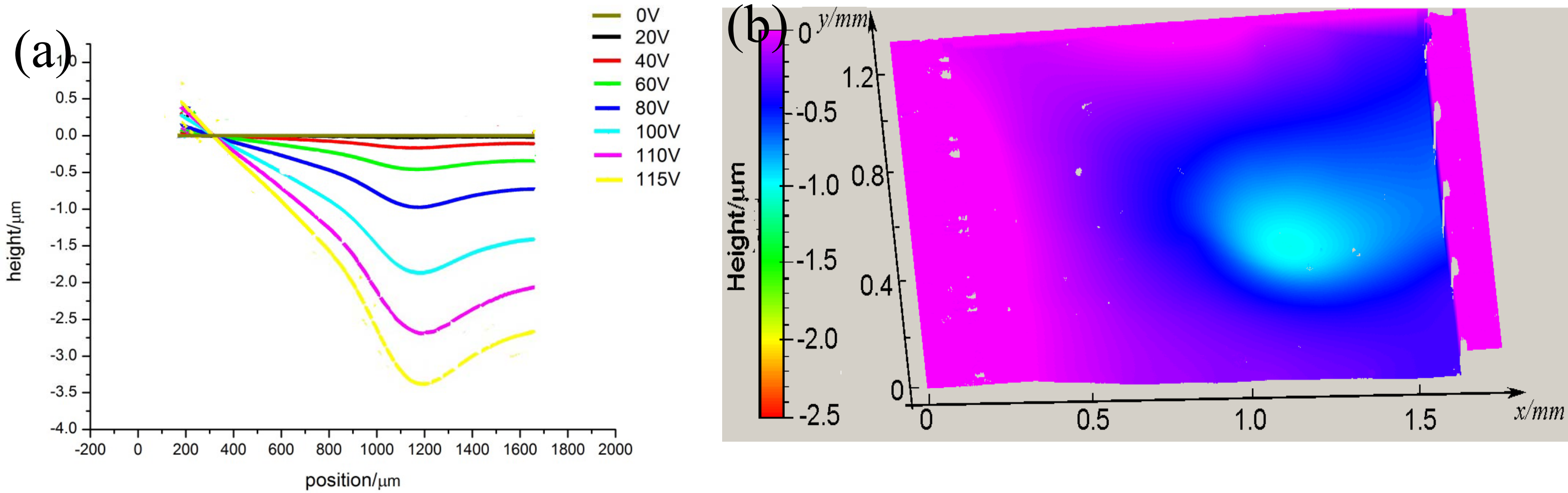


(a)deflection profile of the 2×2 pixels DM with a single pixel actuated at different voltage

(b)deflection profile of the 2×2 pixels DM with a single pixel actuated at different voltage with zero-voltage profile subtracted;

MEMS-DM – static deflection measurement

4×4 pixel mirror

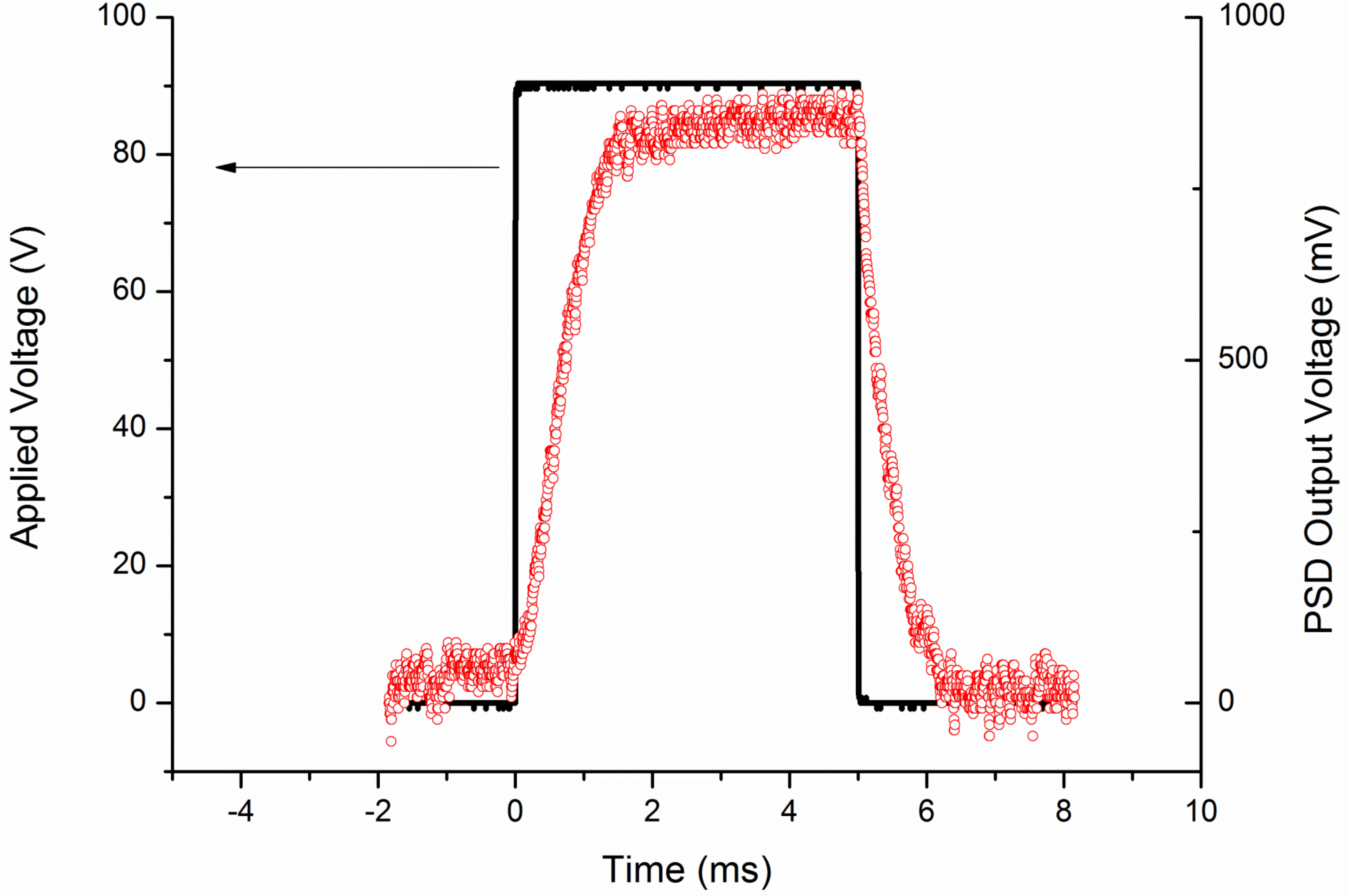


(a)deflection profile of the 4×4 pixel DM with a single pixel actuated at different voltage with zero-voltage profile subtracted;

(b)color-coded surface profile of the 4×4 pixel DM at 80V with zero-voltage profile subtracted.

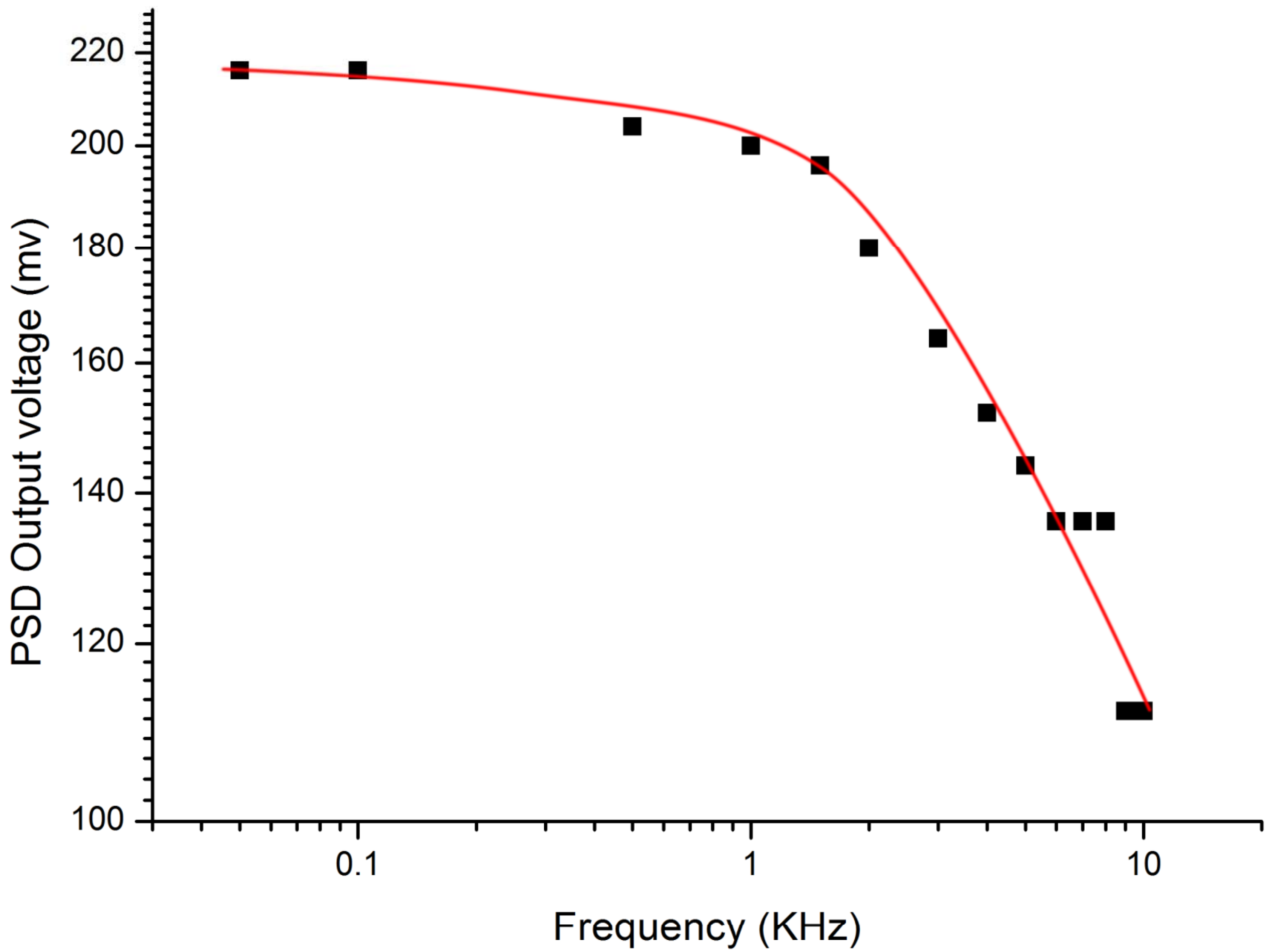
MEMS-DM – response time measurement

Rise time: 1.3ms Fall time: 0.9ms



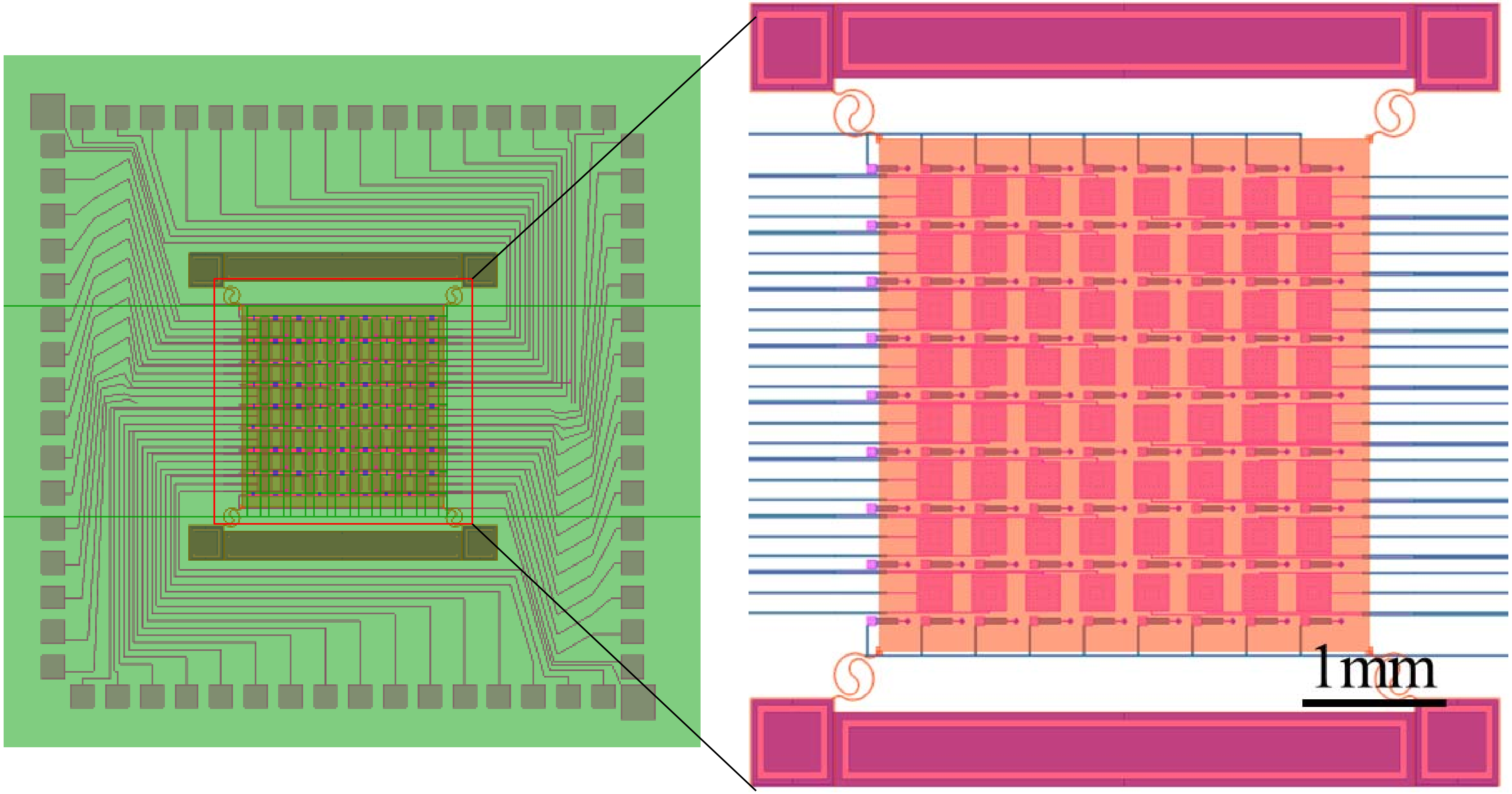
Dynamic response of the fabricate 4 × 4 DM with a single pixel actuated

MEMS-DM – frequency response



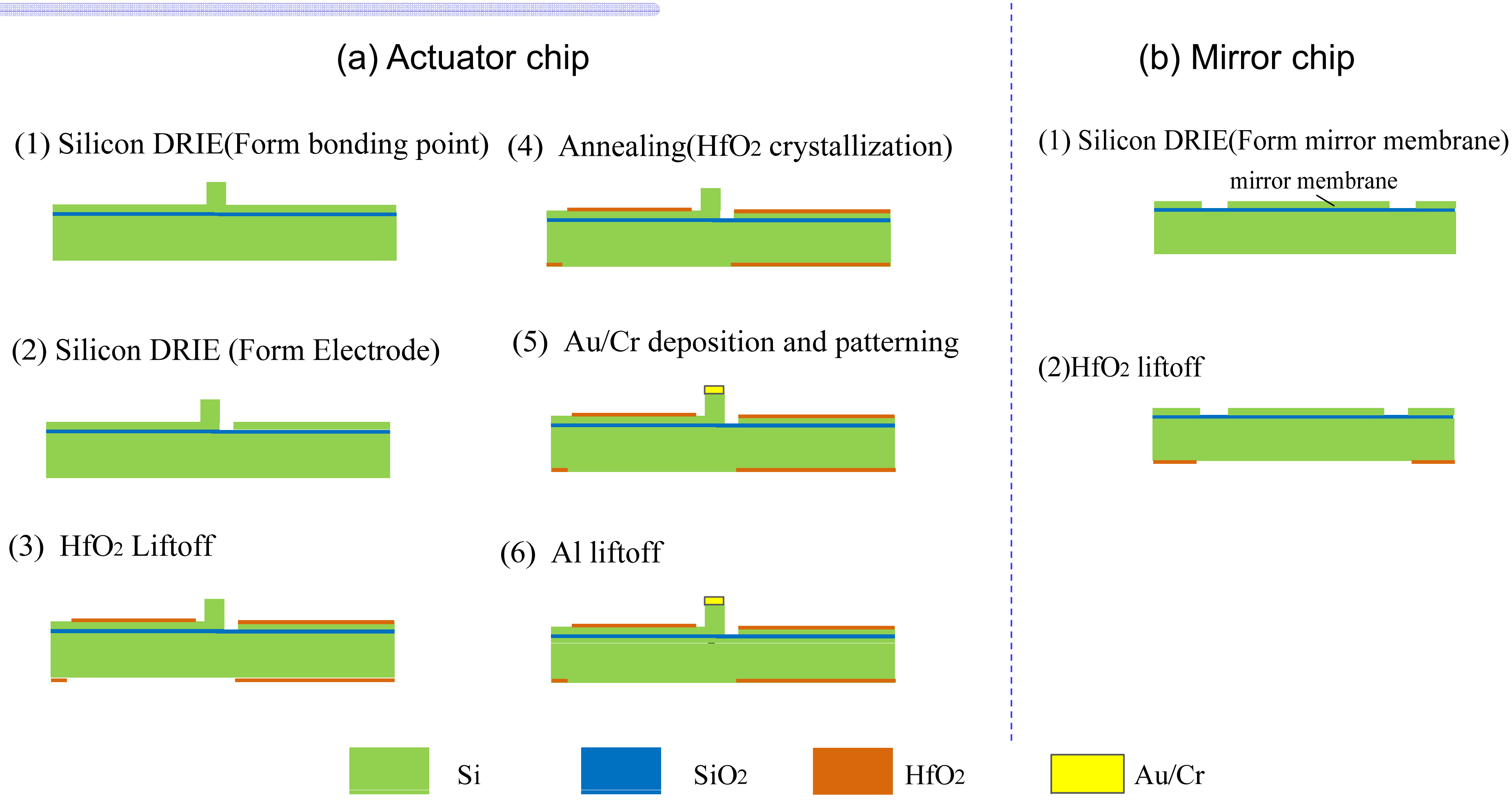
frequency response of the fabricated 4 × 4 pixel DM

8×8 pixel MEMS-DM -Design



Design of the 8×8 Pixels DM

8 × 8 pixel MEMS-DM –Process flow

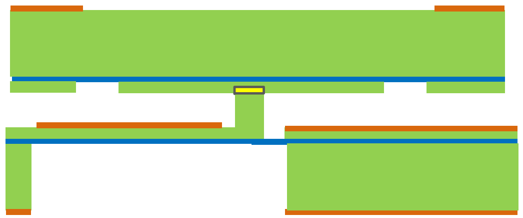


8×8 pixel MEMS-DM –Process flow

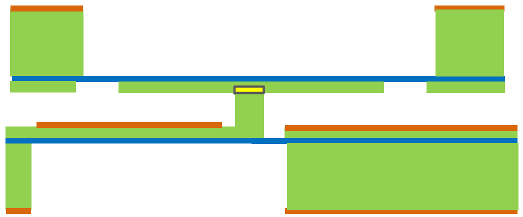
(c) Bonding and release

(1) Au-Si eutectic bonding

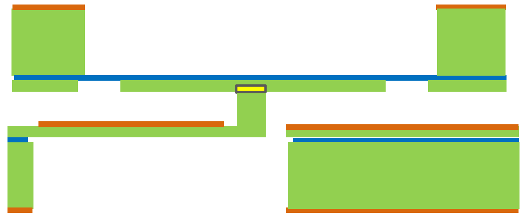
(2) Actuator chip handle layer etching



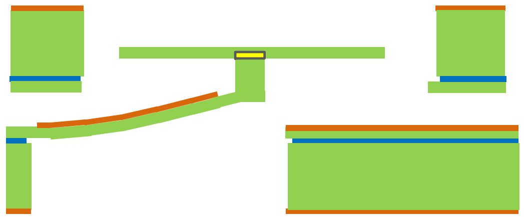
(3) Mirror chip handle layer etching



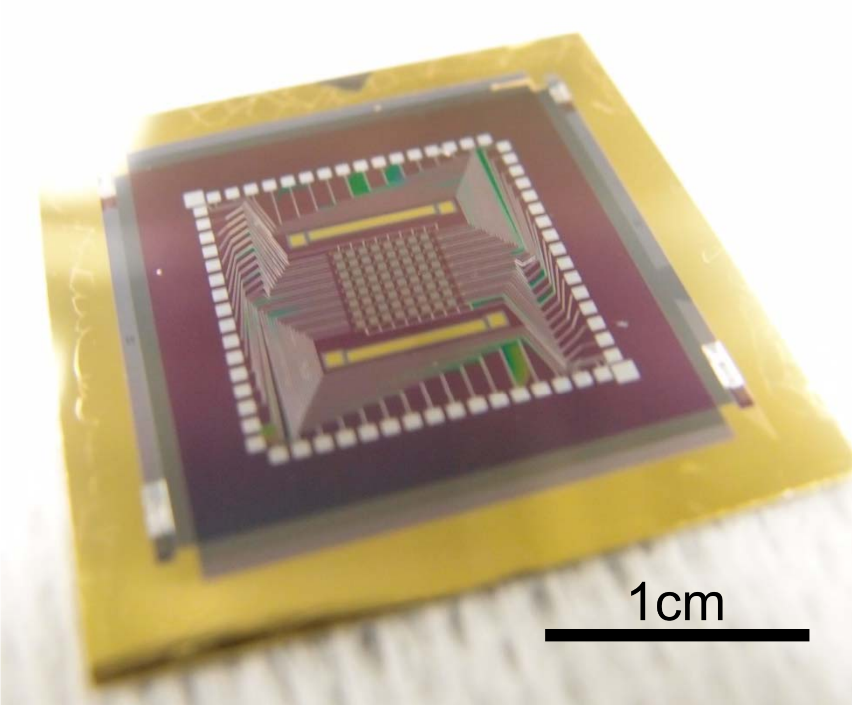
(4)SiO_2 Dry Etching (CHF_3)

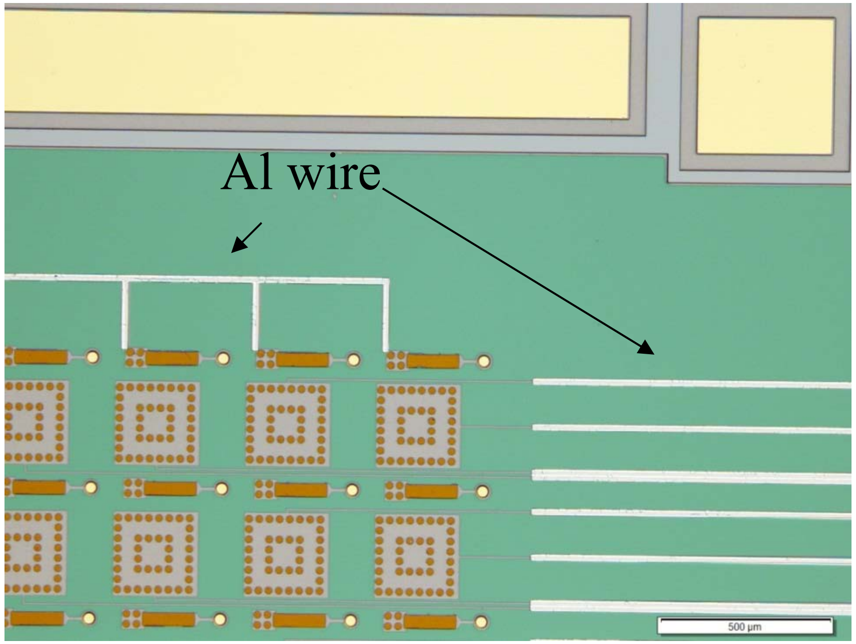


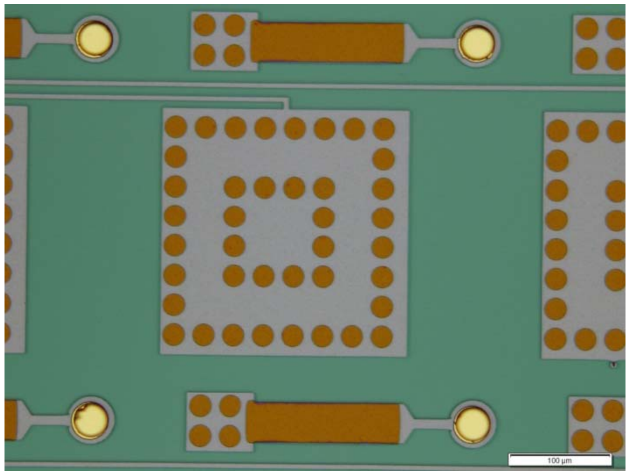
(5) SiO_2 Dry Etching (CHF_3)



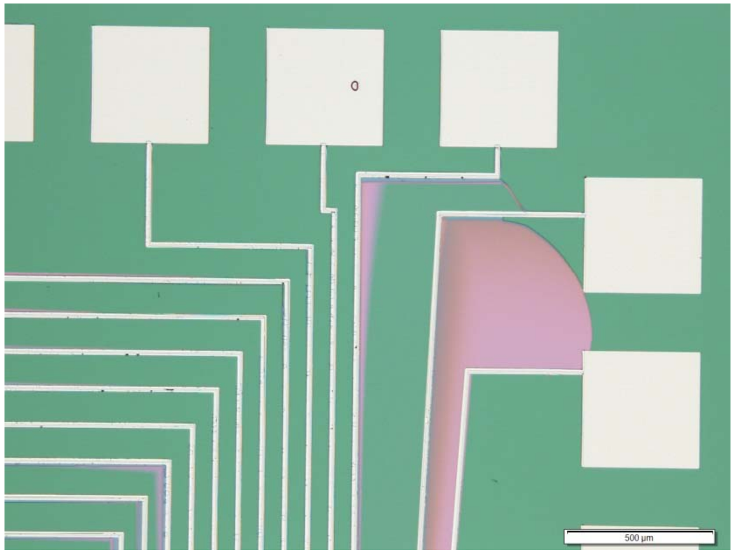
8×8 pixel MEMS-DM –Fabrication result (1)





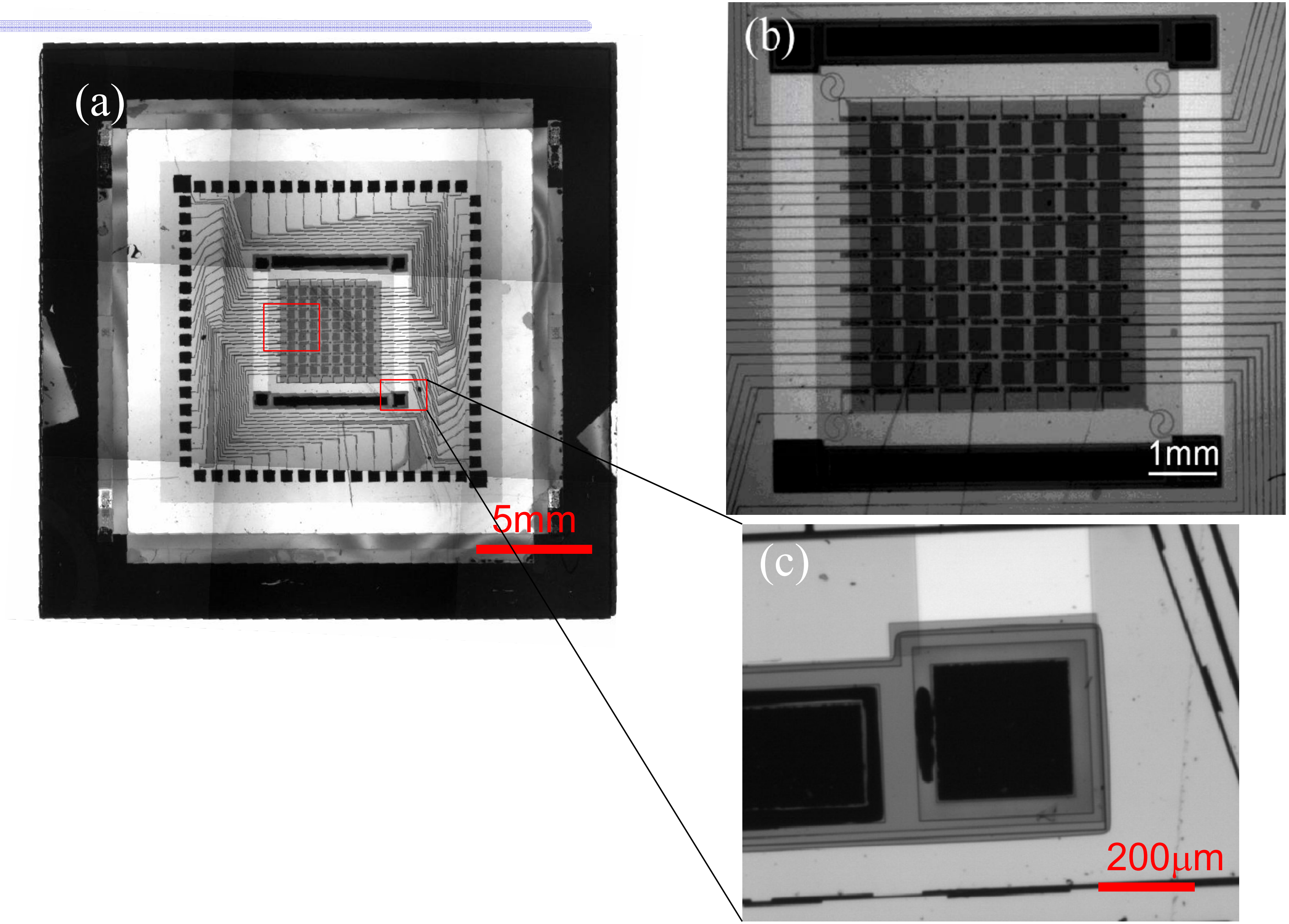


Bimorph springs with bonding pad



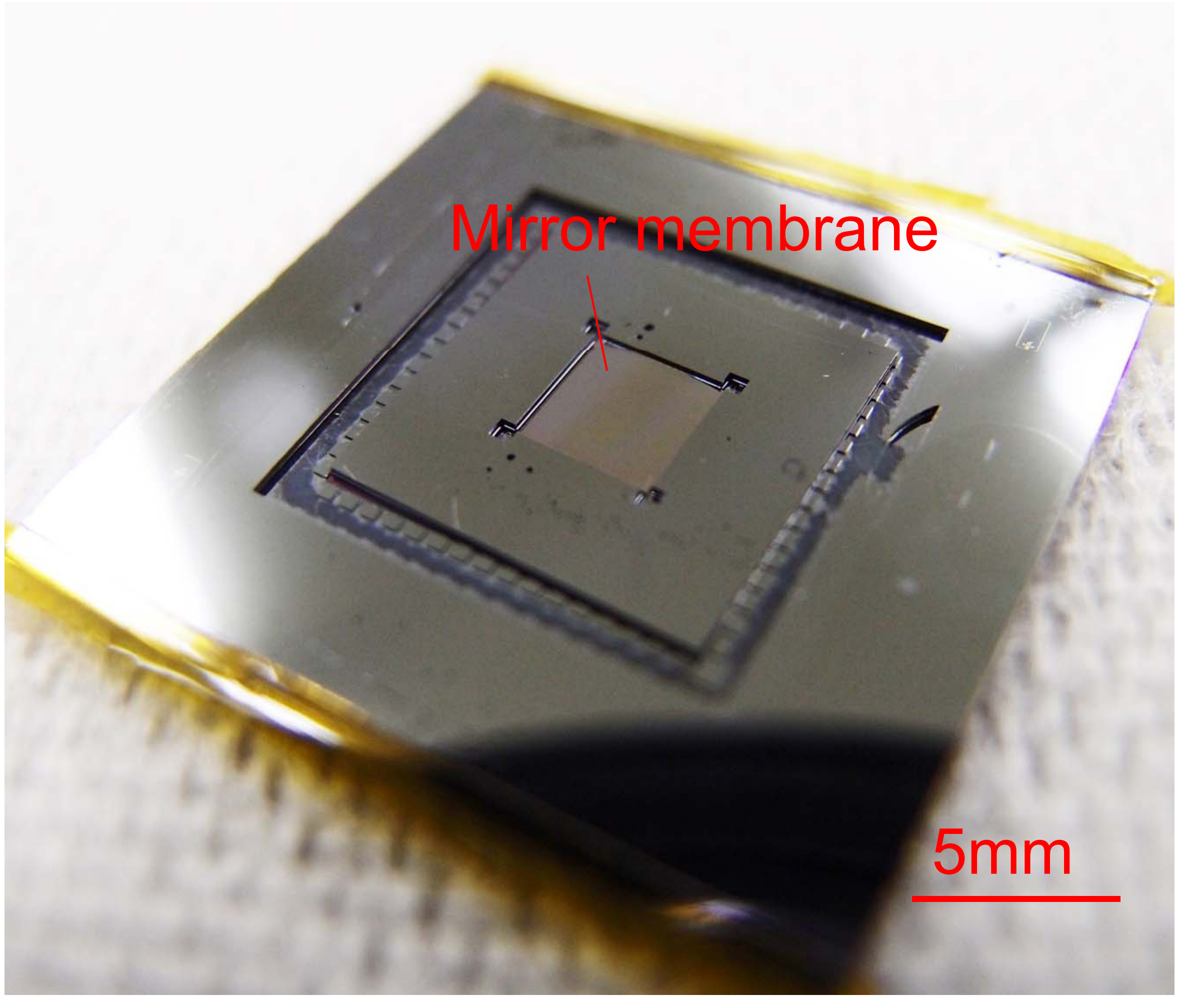
Al electrode pad for wire bonding

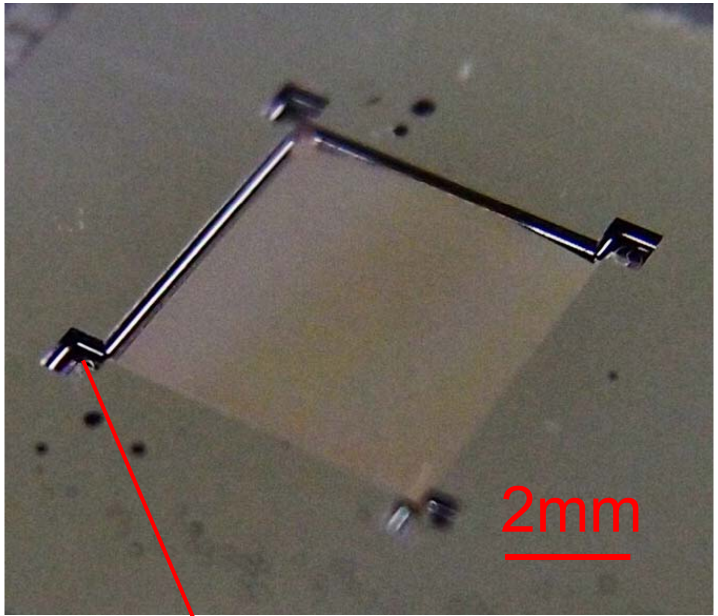
8 × 8 pixel MEMS-DM –Fabrication result (2)

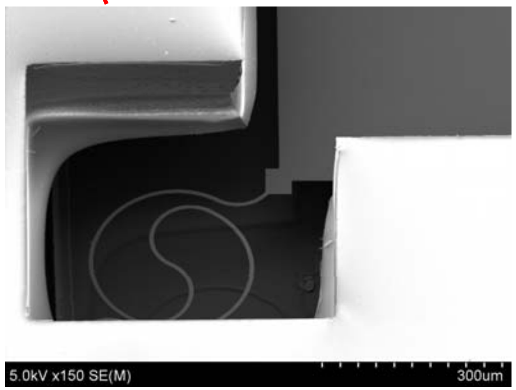


Infra red micrographs of the DM after bonding process

8×8 pixel MEMS-DM –Fabrication result (3)





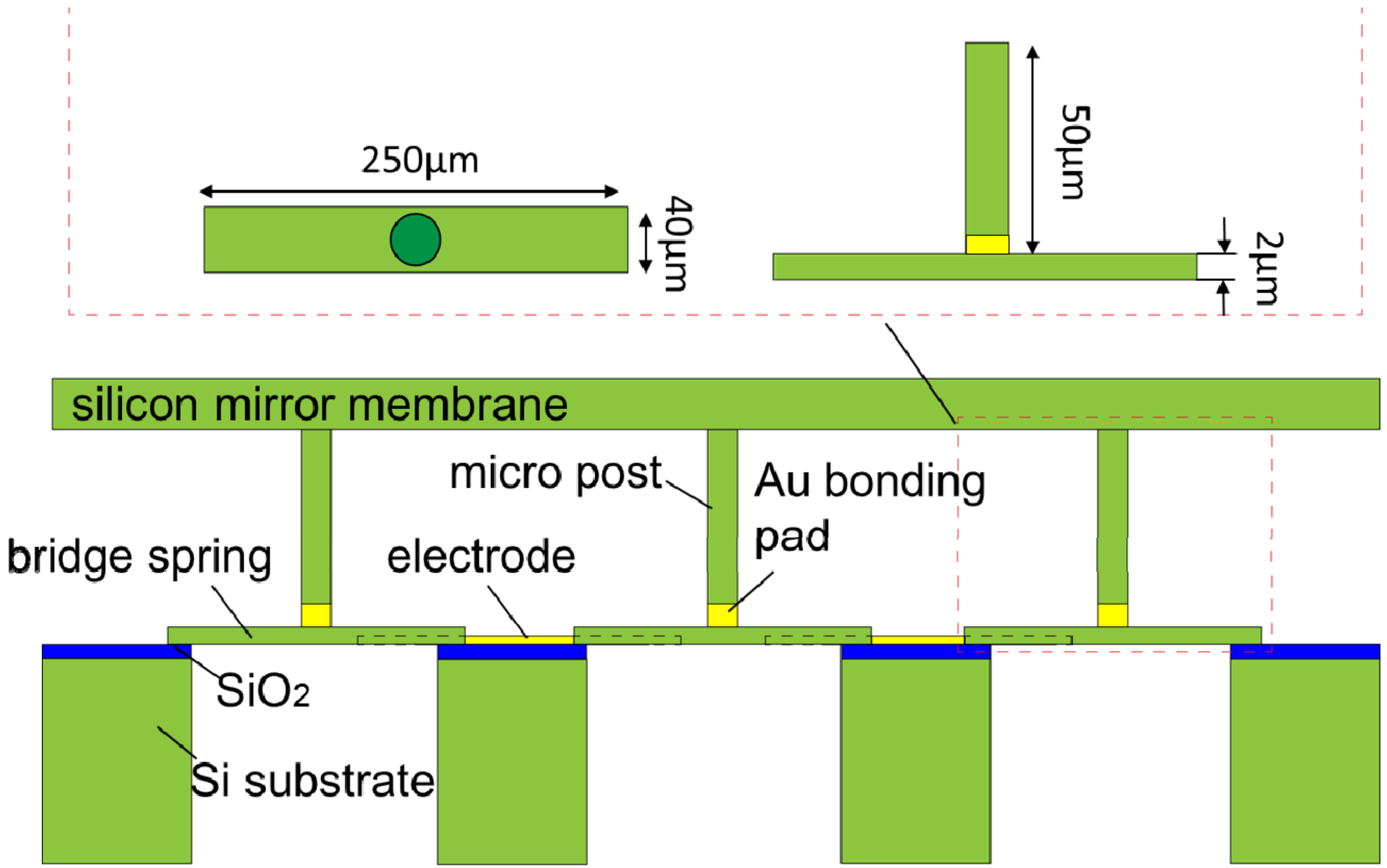


Conclusions

An improved membrane transfer process for large-stroke continuous membrane DM is proposed and demonstrated

- A 2μm-thick membrane is transferred to a flexible bimorph array by combining bulk micromachining and Au-Si eutectic bonding technology;
- Au-Si eutectic bonding shown a reliable bonding quality for transferring large scale mirror membrane;
- The stroke of the DMs are 4.0μm at 125V(2×2 Pixel DM) and 3.5μm at 115V(4×4 Pixel DM), respectively. The fill factor of the fabricated mirror is ~99.9%.
- A freestanding 4mm×4mm×2μm mirror membrane is successfully fabricated.

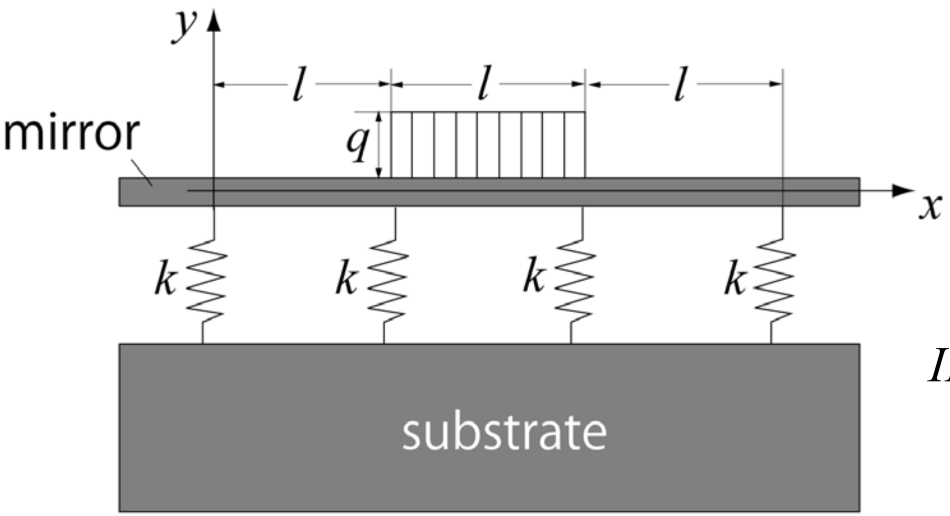
New design



250µm
40µm
50µm
2µm
silicon mirror membrane
micro post
Au bonding pad
bridge spring
electrode
SiO2
Si substrate

MEMS-DM – Influence function(IF) at adjacent actuator

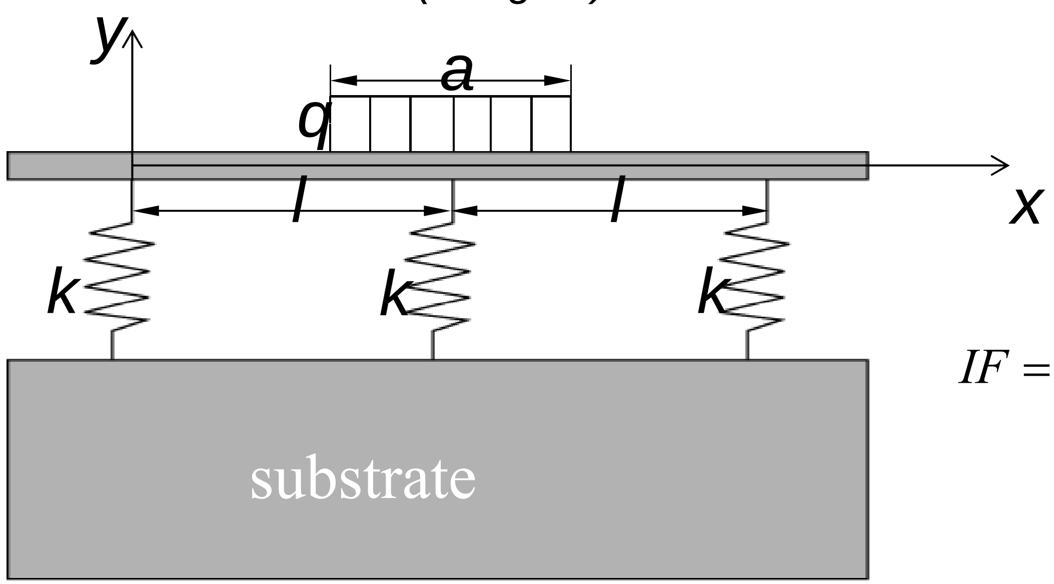
Previous calculation modle(design 1) :



$$IF = \frac{y|_{x=l/2}}{y|_{x=3l/2}} = \frac{552EIkl^3 + 1152E^2I^2 - 6k^2l^6}{1260EIkl^3 + 1152E^2I^2 + 13k^2l^6}$$

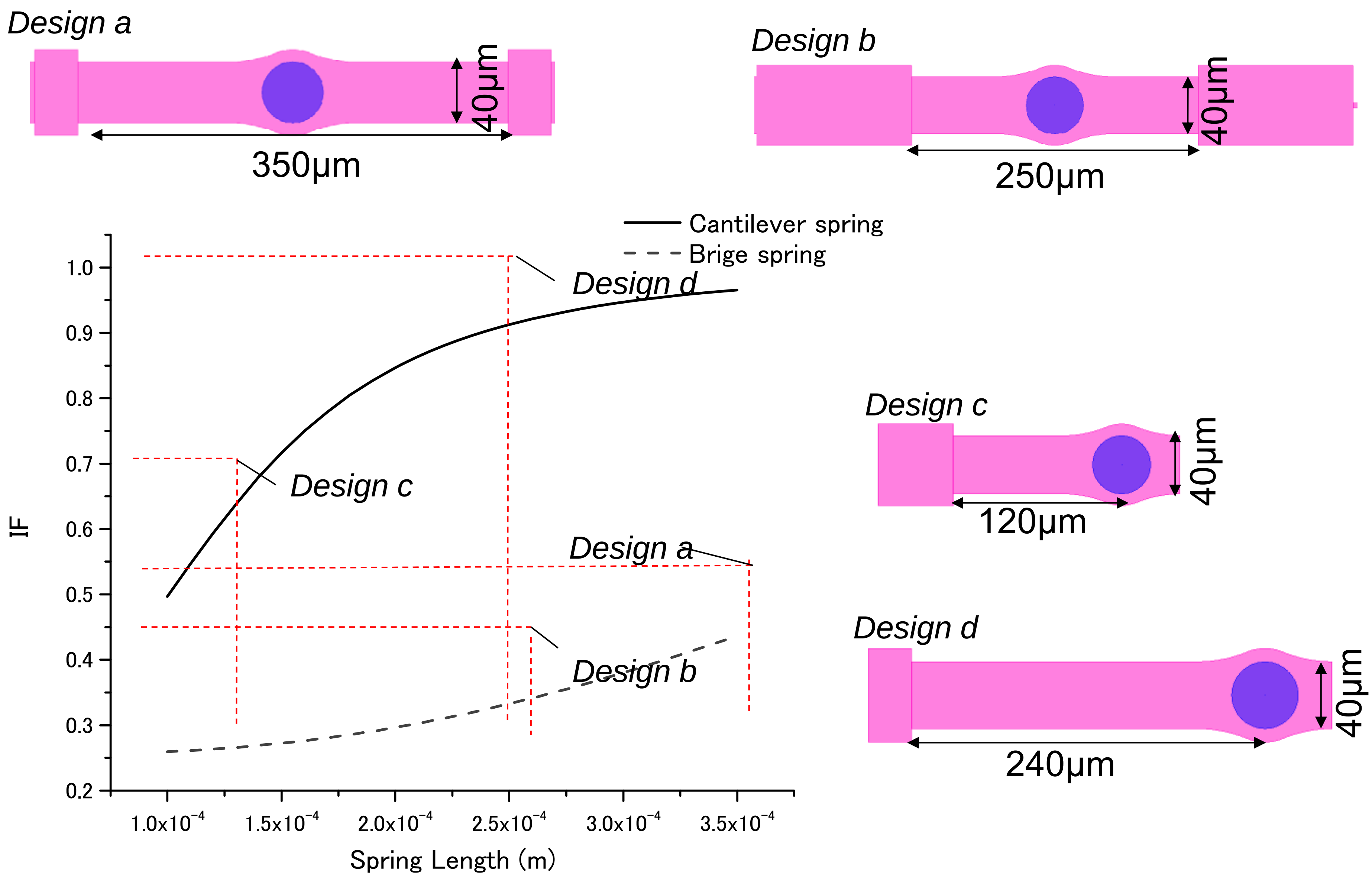
Current calculation model(design 2) :

(*EI* is the flexure rigidity)

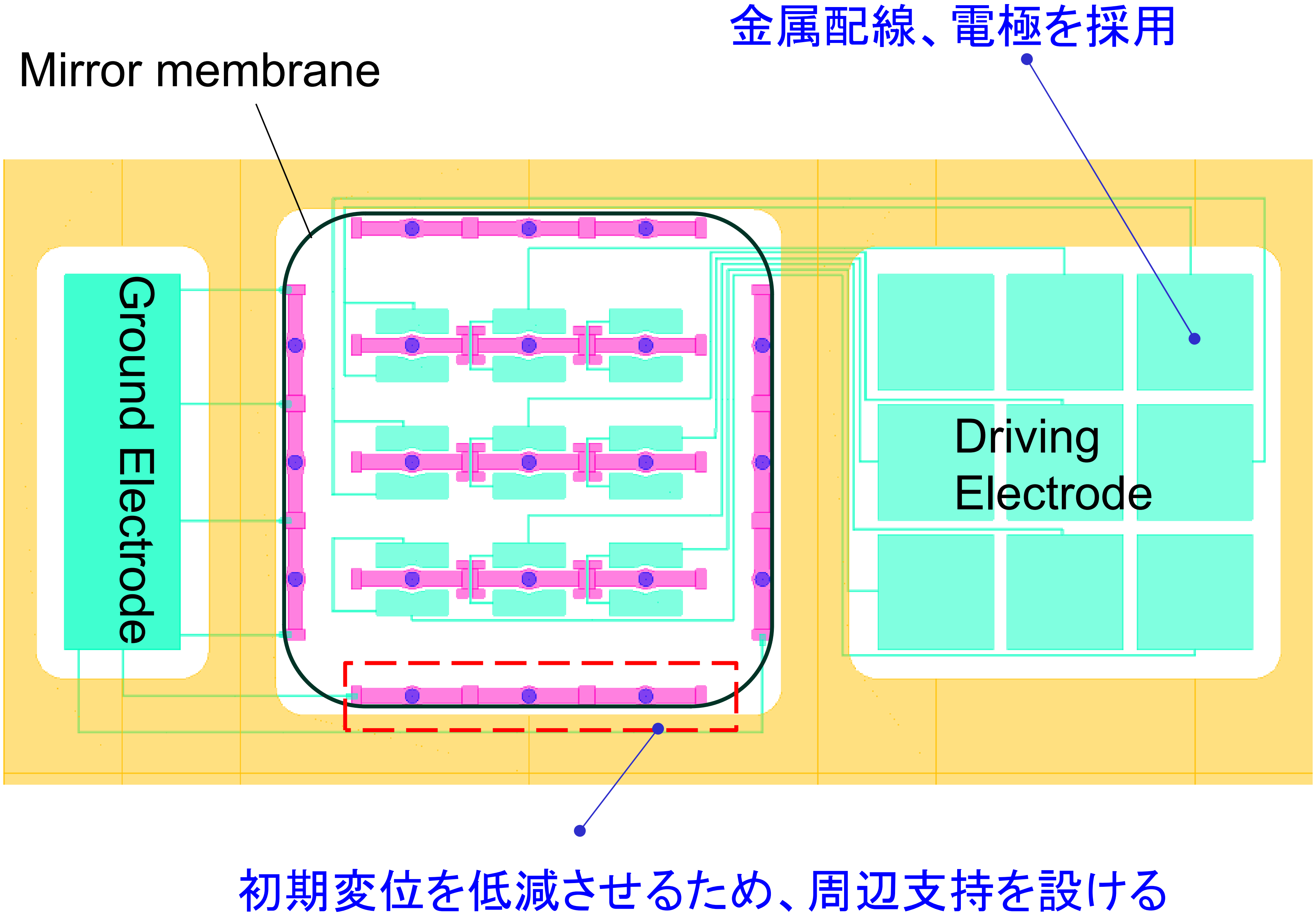


$$IF = \frac{y|_{x=2l}}{y|_{x=l}} = \frac{3ka^3 + 16kla^3 + 384EI}{-39ka^3 + 96kla^3 + 384EI}$$

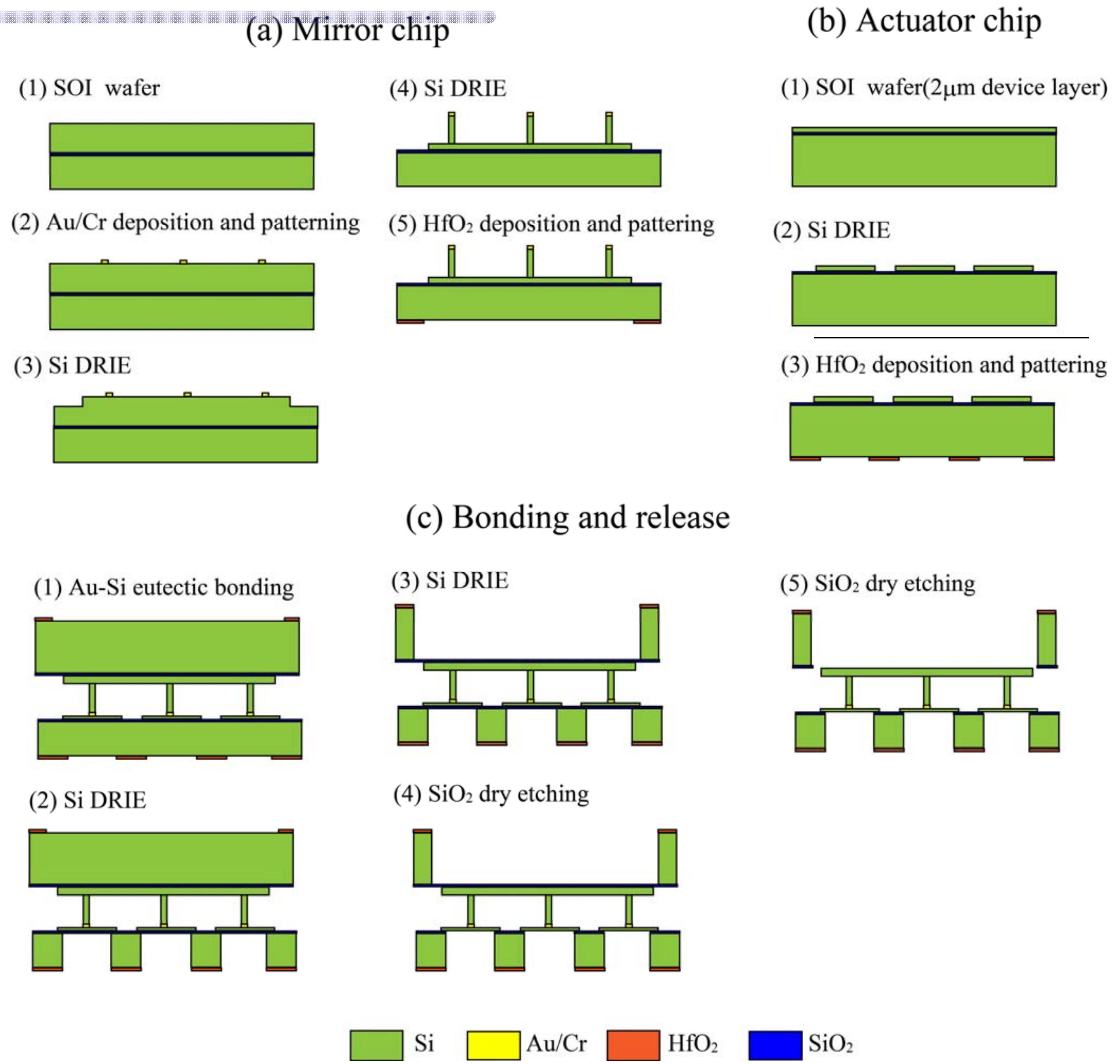
MEMS-DM – Spring design



MEMS-DM – 3 × 3 DM layout



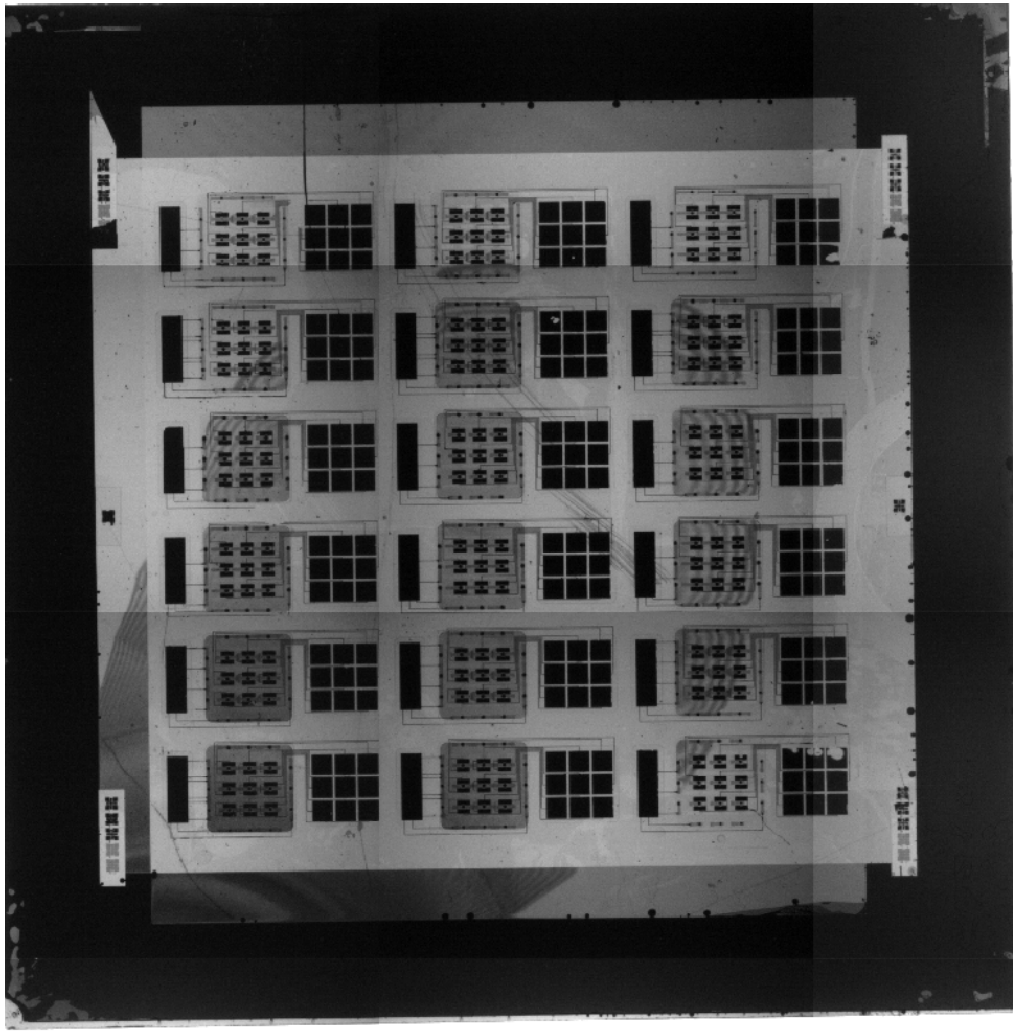
MEMS-DM – fabrication

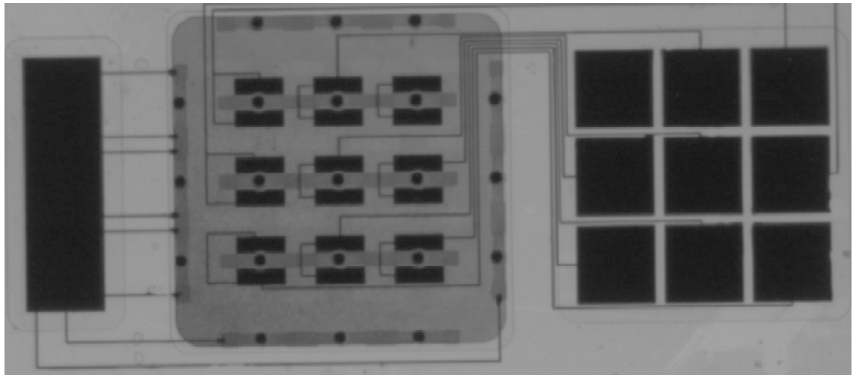


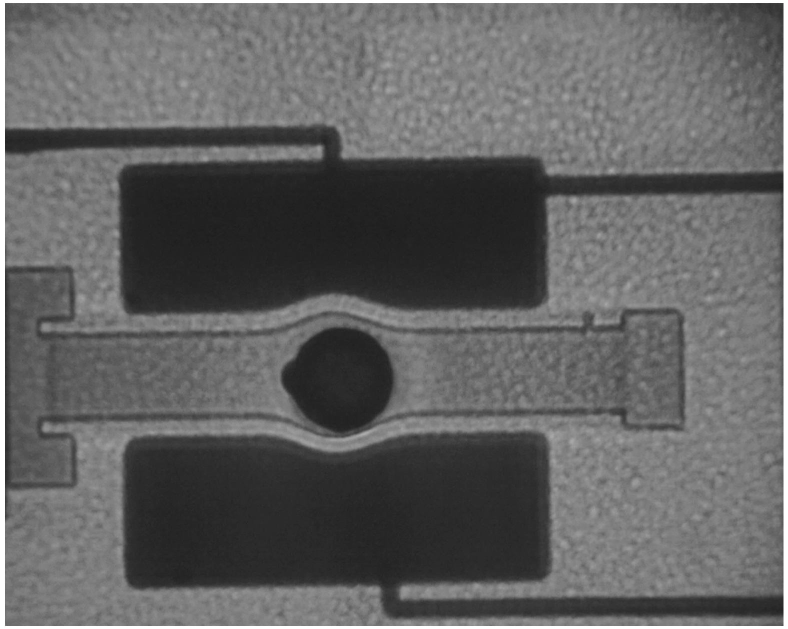
MEMS-DM – Bonding(design 2)

Bonding experiment@Kyoto tou, Suss Bonder SB-6e

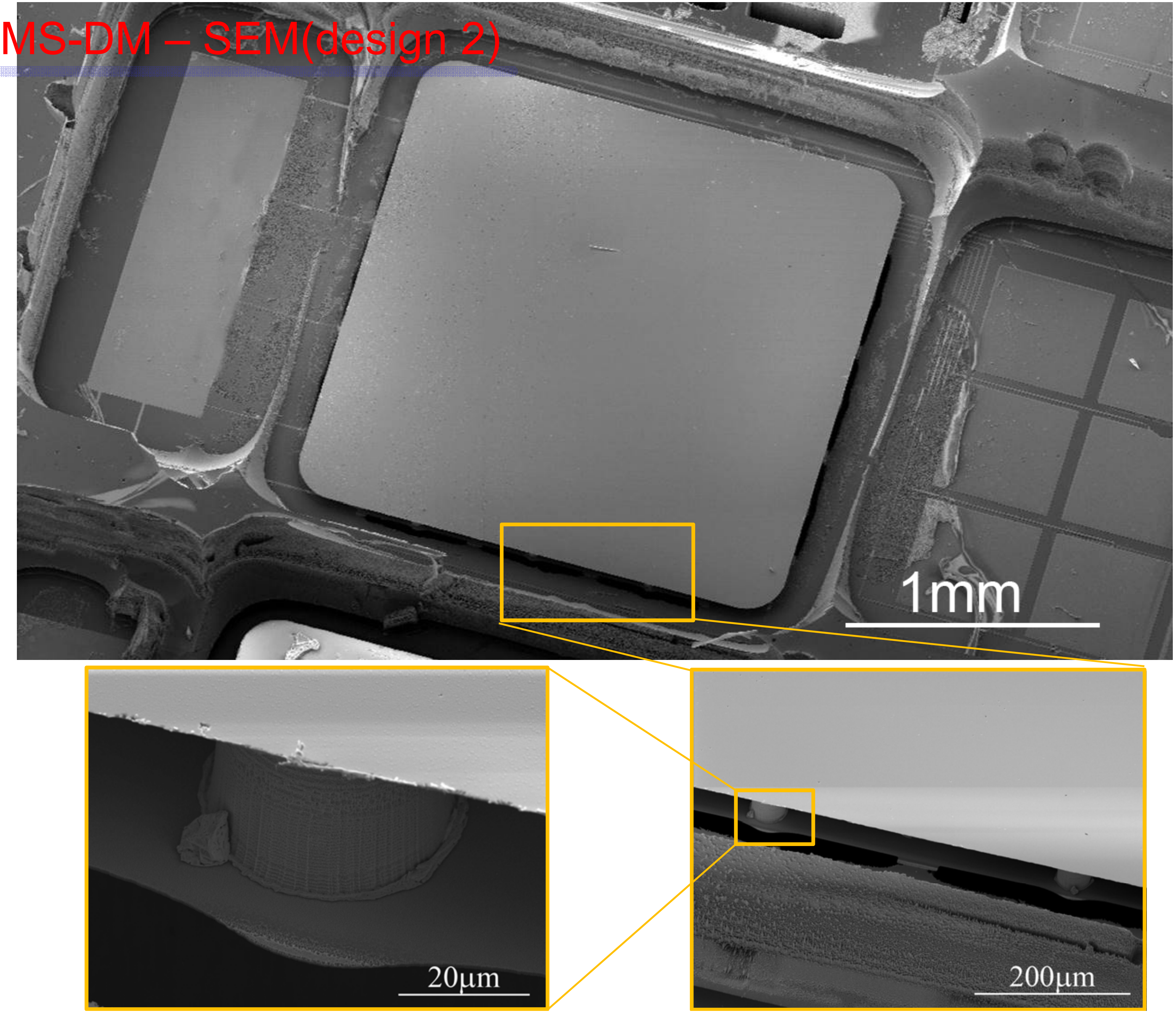
Au-Si eutectic bonding condition :400℃, 12KPa(30min)



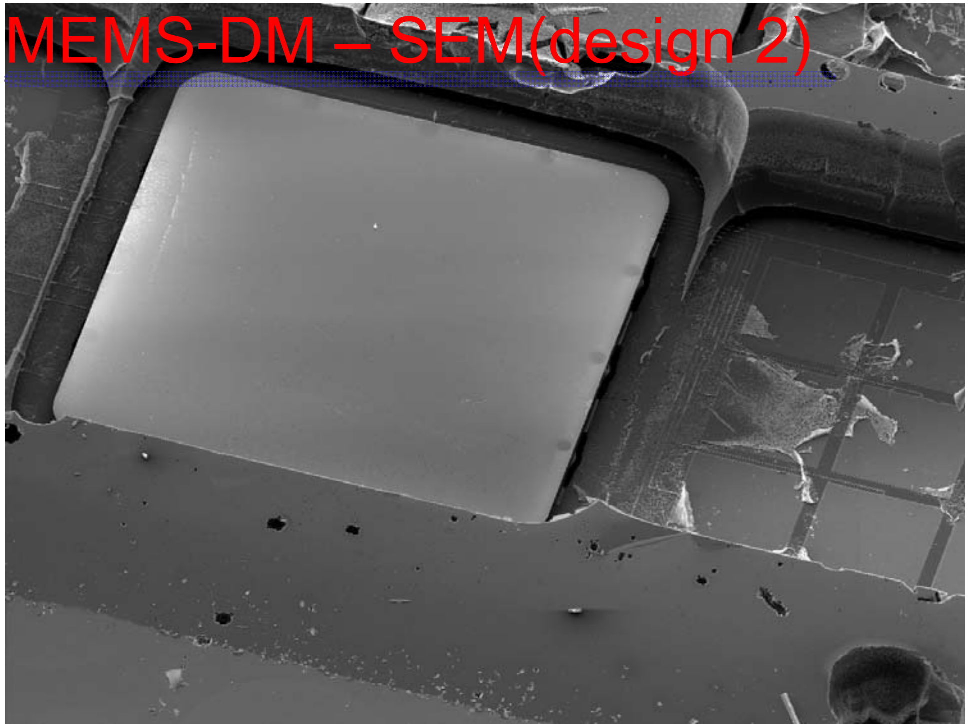


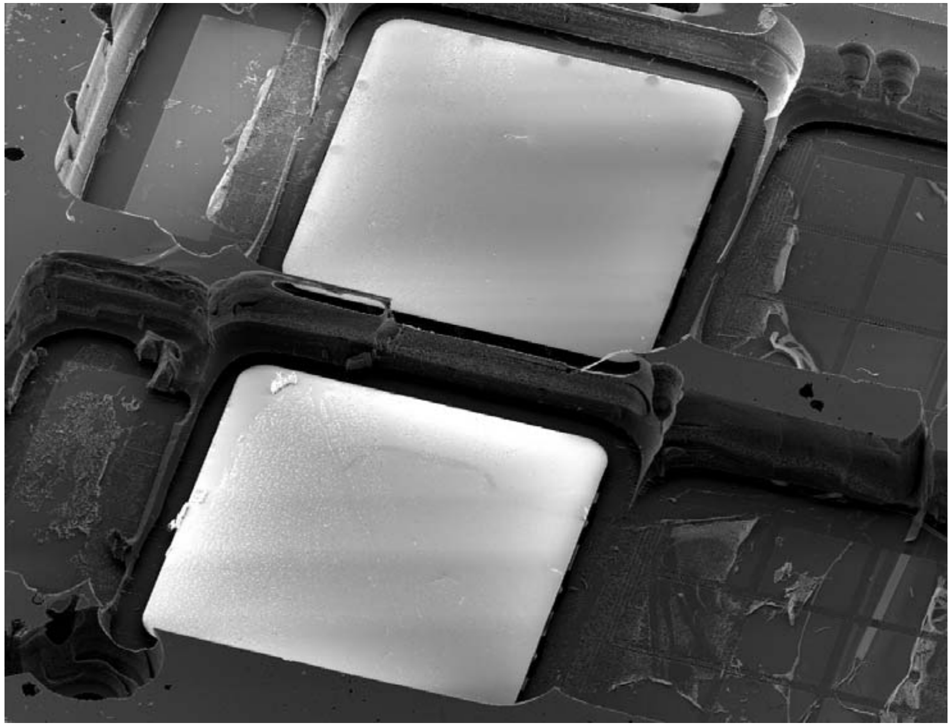


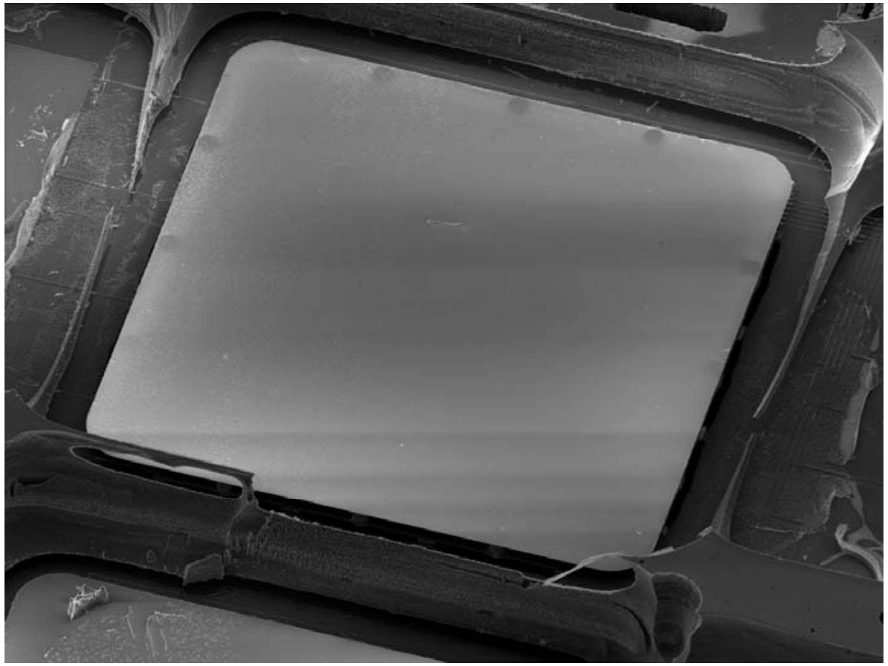
MEMS-DM – SEM(design 2)

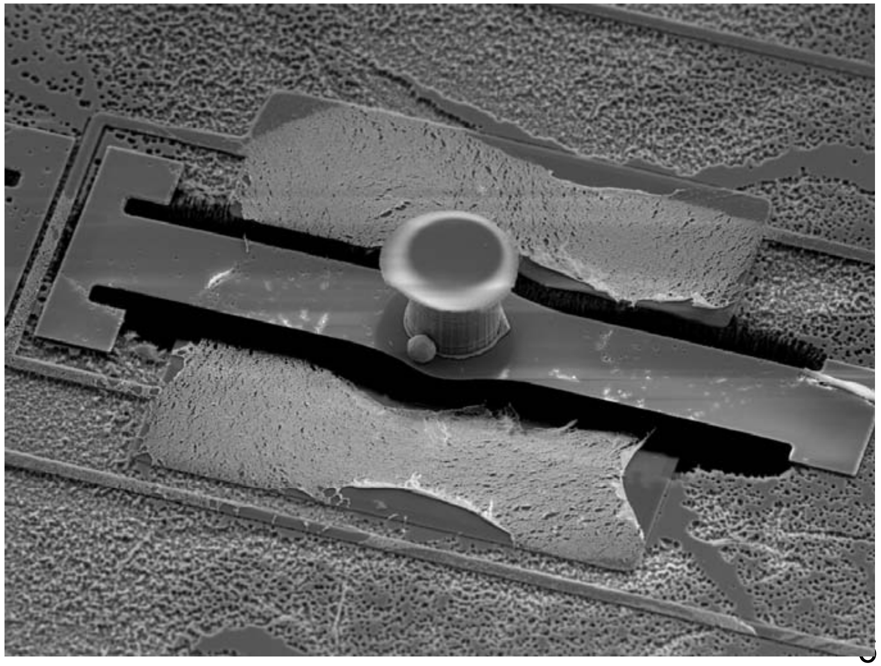


MEMS-DM – SEM(design 2)

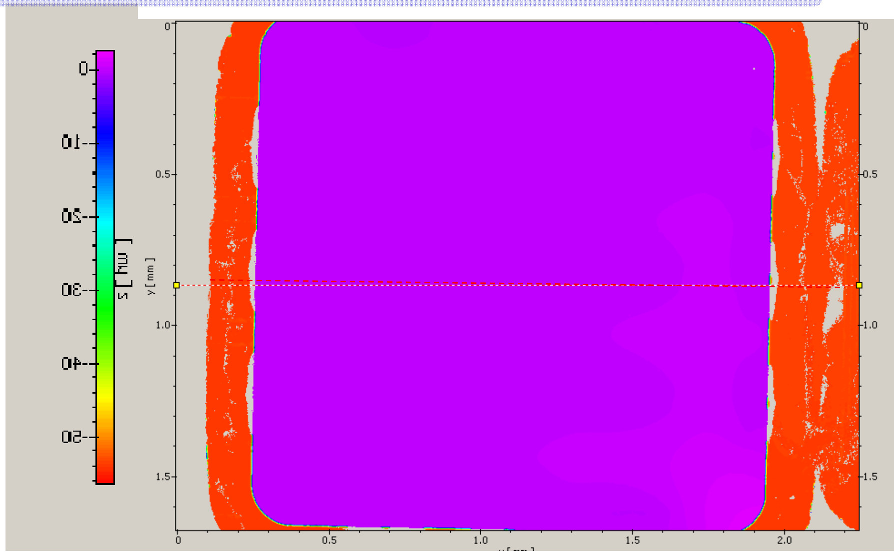


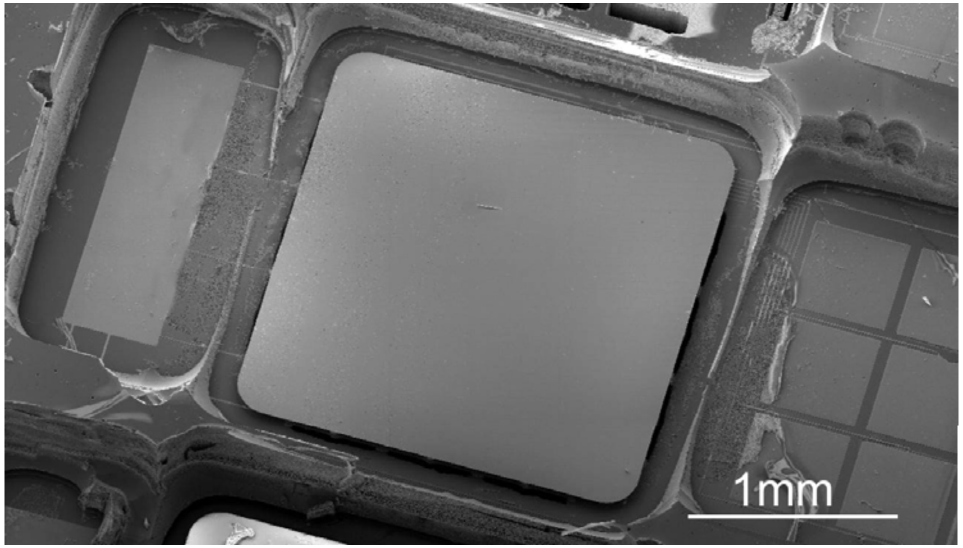


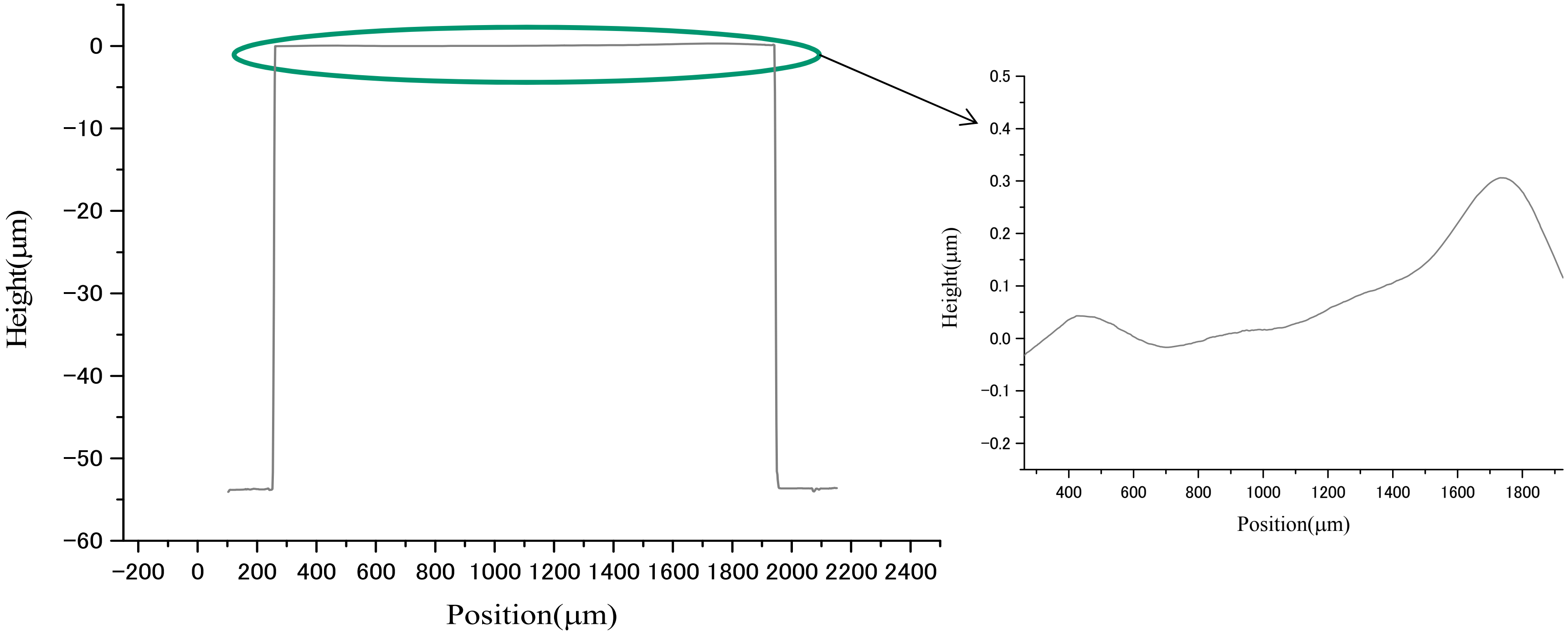




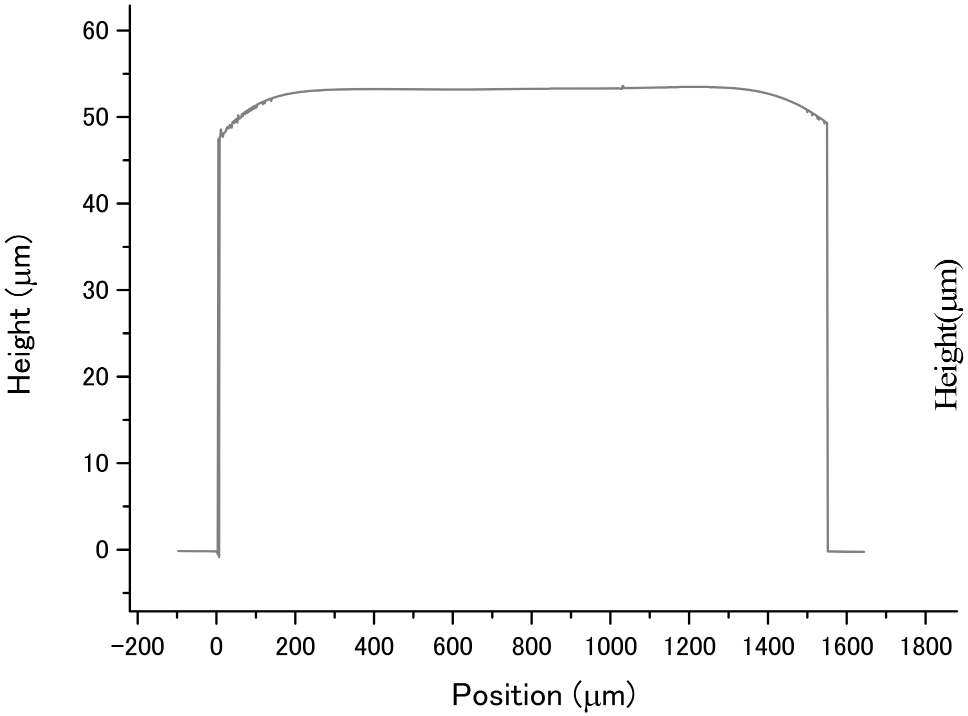
MEMS-DM – initial deflection(design 2)

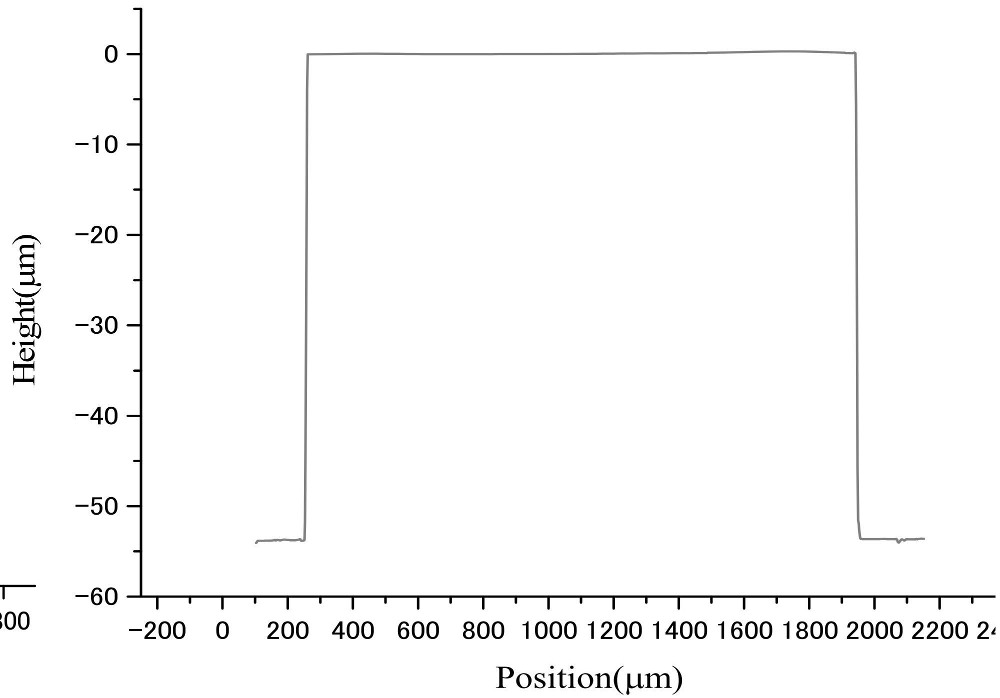






MEMS-DM – membrane initial deformation





Without edge support

Mirror size: 1.5mm × 1.5mm

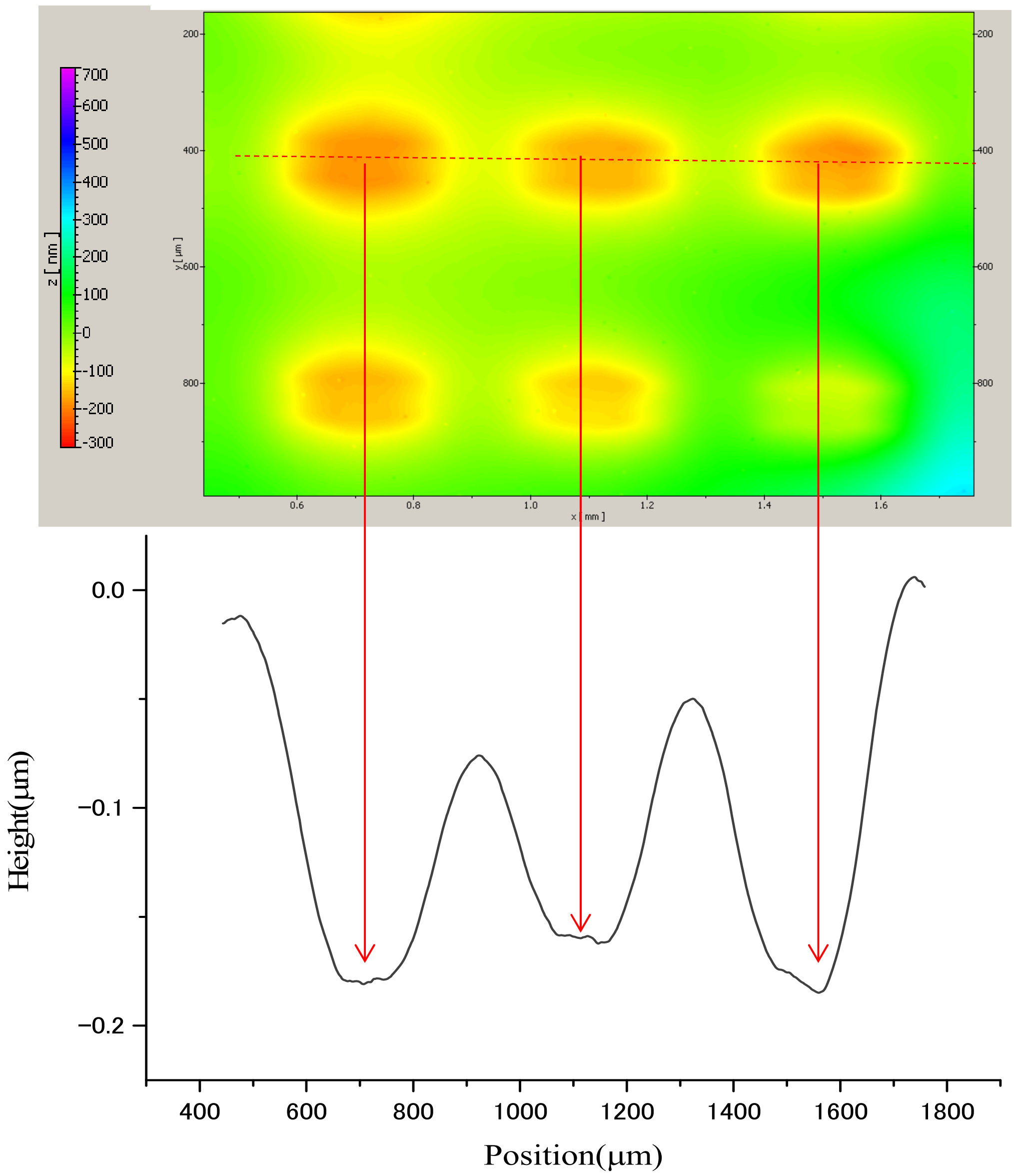
Mirror initial deformation: PV value=3900nm

With edge support

Mirror size: 1.7mm × 1.7mm

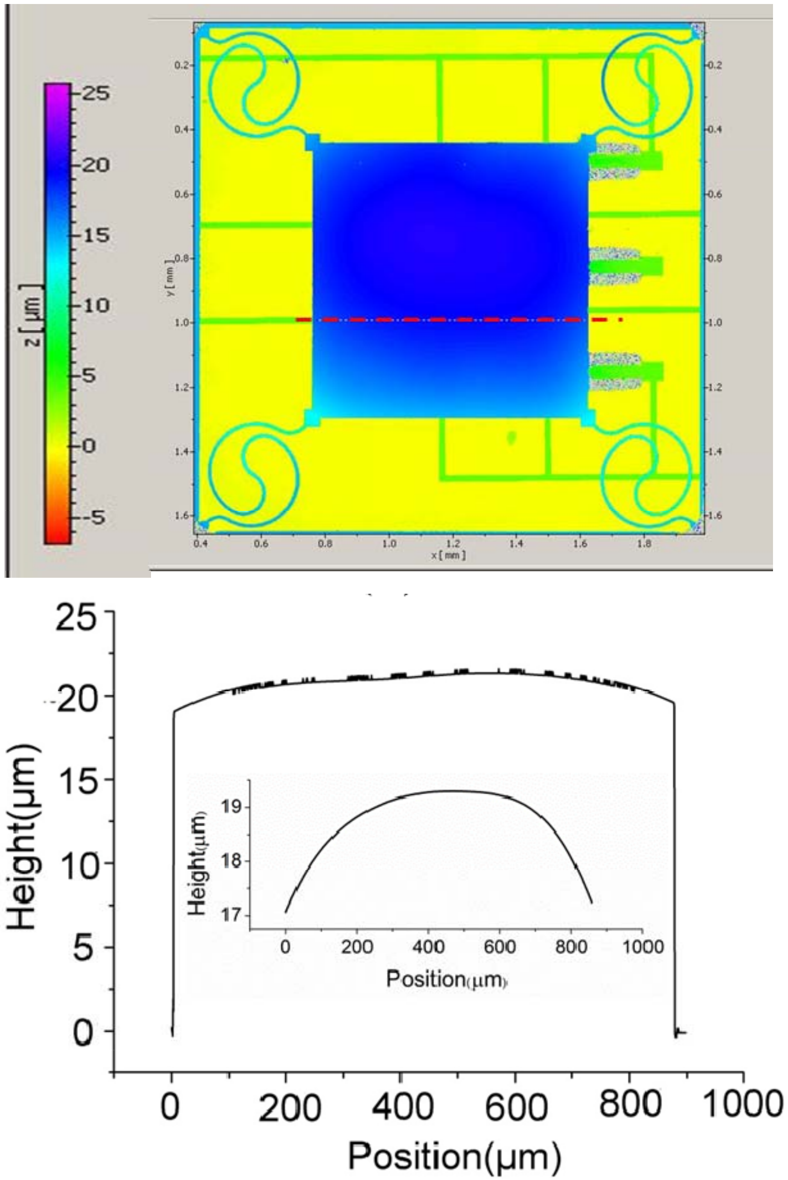
Mirror initial deformation: PV value=350nm

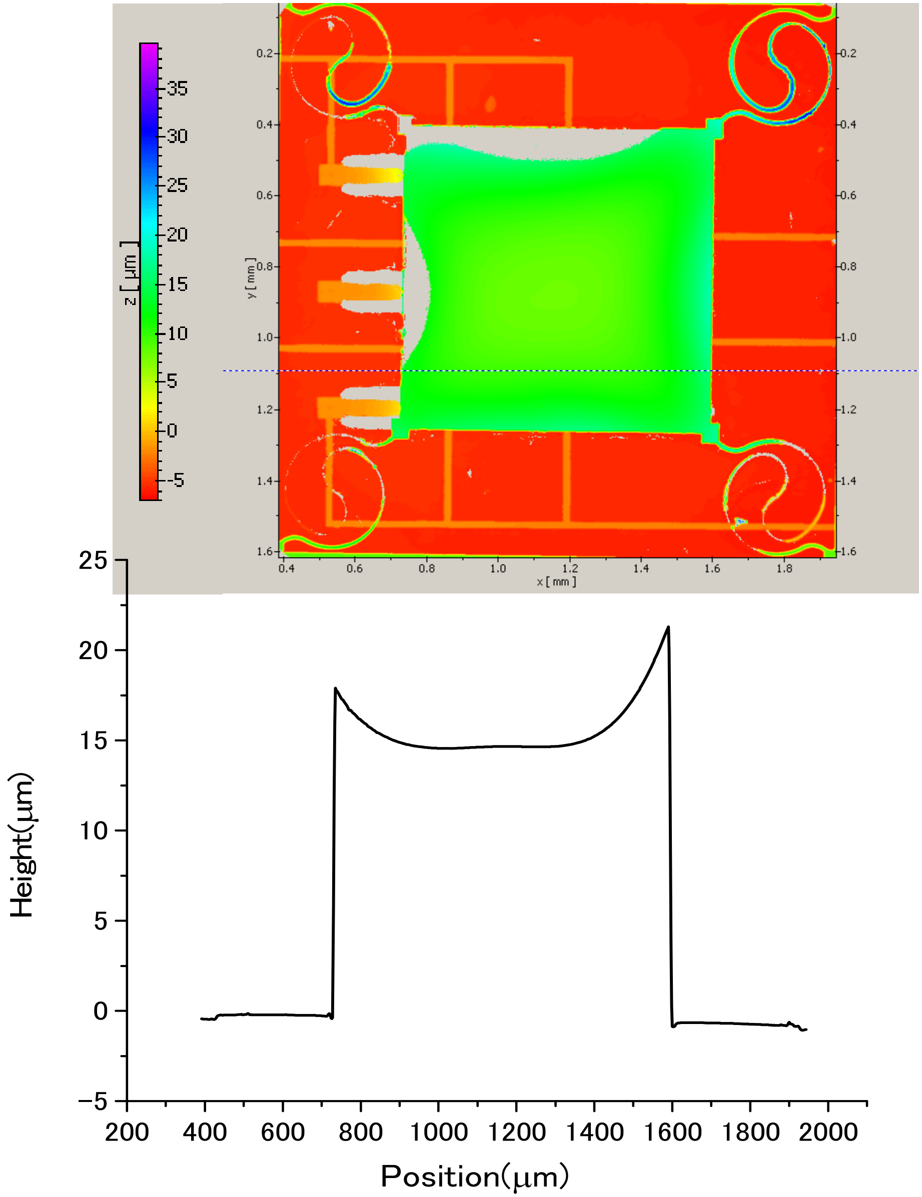
MEMS-DM – initial deflection mirror : bonding point



MEMS-DM – Au/Cr coating

Cr: ~10nm, Au: ~60nm is coated on the mirror by sputtering

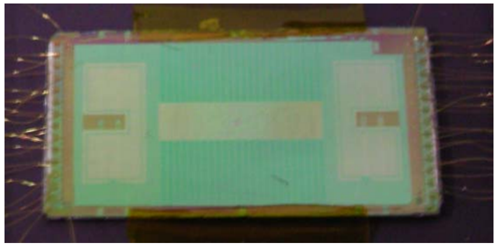


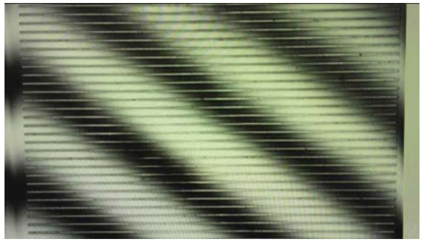


まとめ

1. 集積型MEMSミラーについて

2. LSIと集積した波長選択スイッチ用MEMSミラー





3. Si連続メンブレン-デフォーマブルミラーの開発状況