可視赤外線観測装置技術ワークショップ
2月23日　14:30 -15:00

光MEMS
:Deformable mirror

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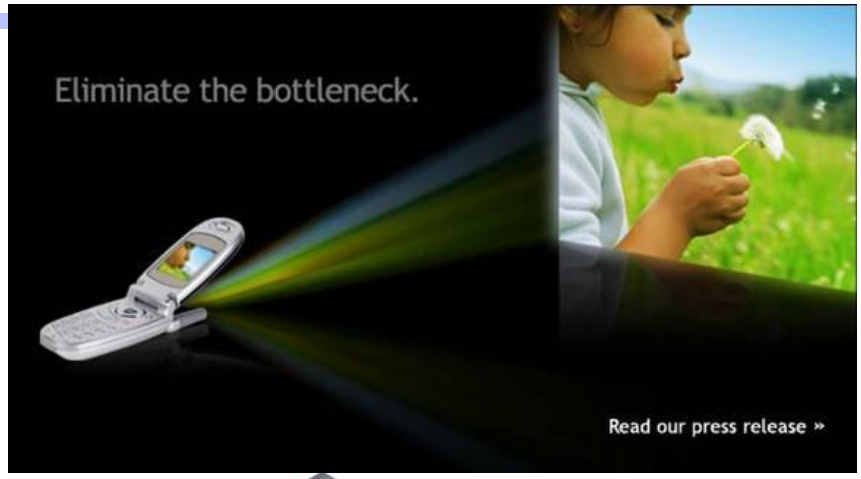
発表内容

1. 光MEMSの紹介
   - マイクロミラー
   - 可変格子
   - 集積型センサ
   - Si導波路干渉計

2. 焦点可変デフォーマブルミラーの製作
   - 曲げモーメント駆動による焦点可変ミラー
   - 焦点可変ミラーを備えた光スキャナー
   - 波面補償デフォーマブルミラーの製作

Applications of laser scanning to display

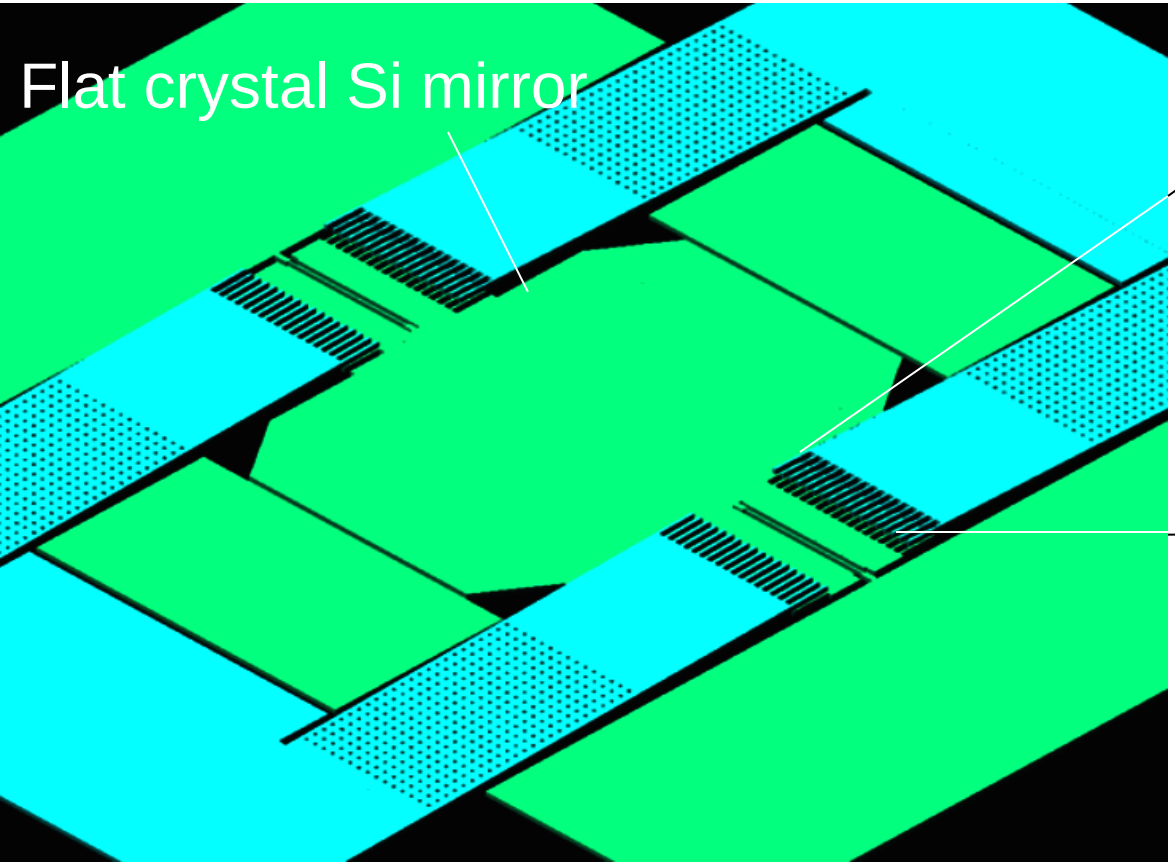
Automobile application

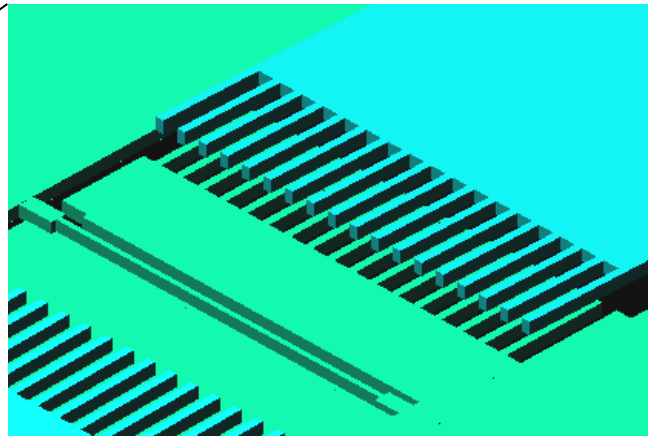


Bi-axial MEMS scanner

Mobile phone application

Crystal Si micro mirror fabricated from SOI wafer

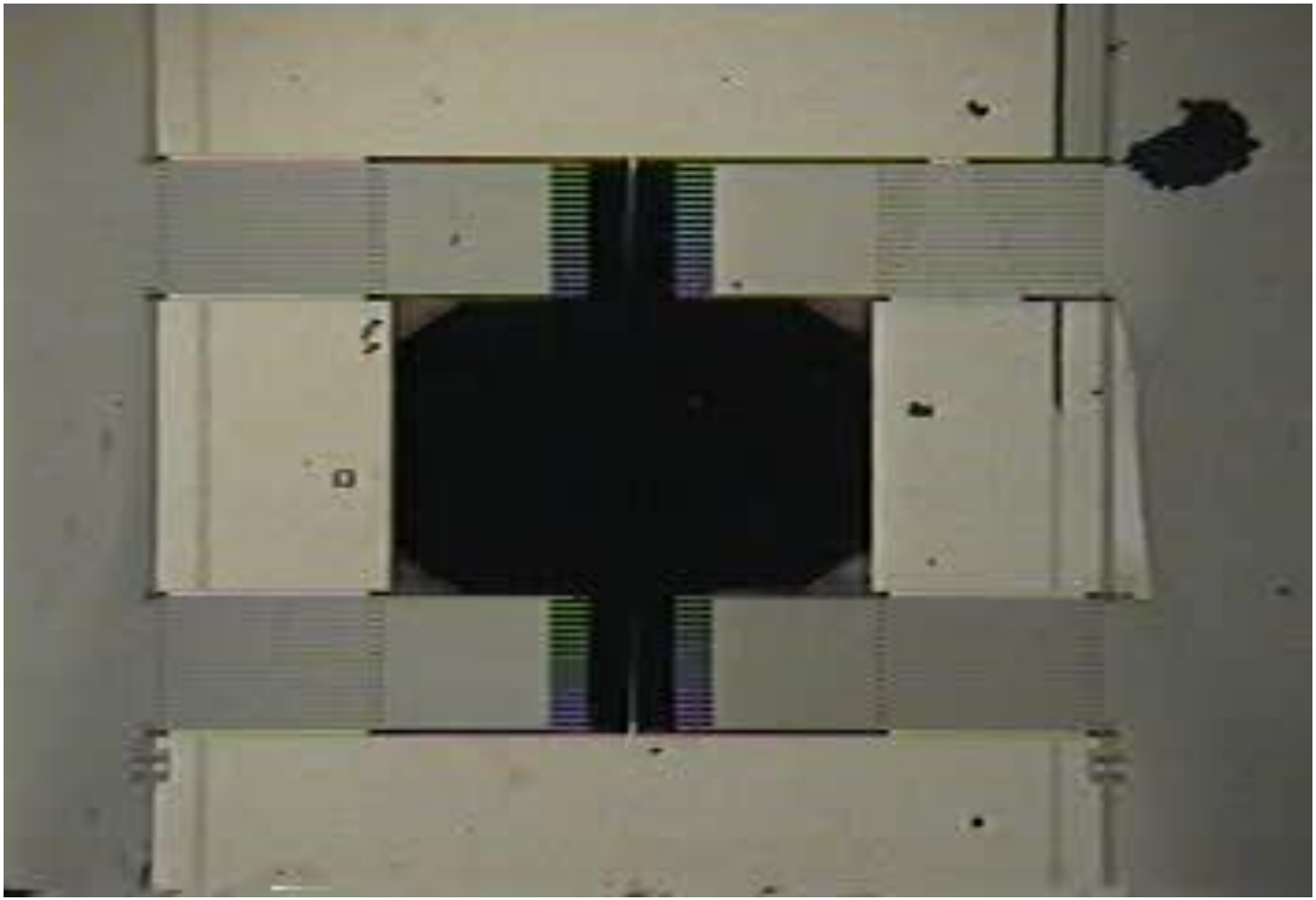




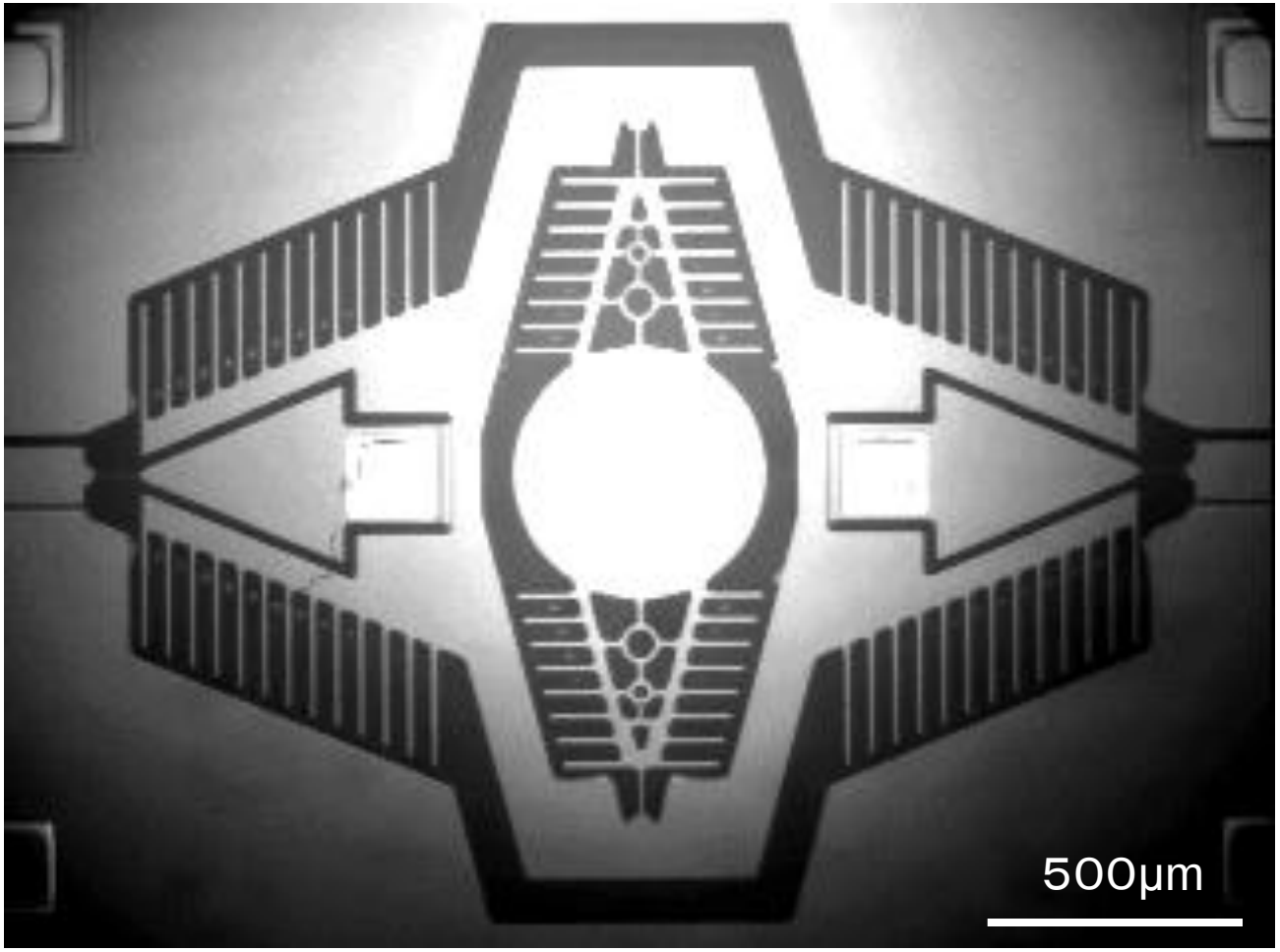
Vertical comb drive actuator

While view of the micro mirror

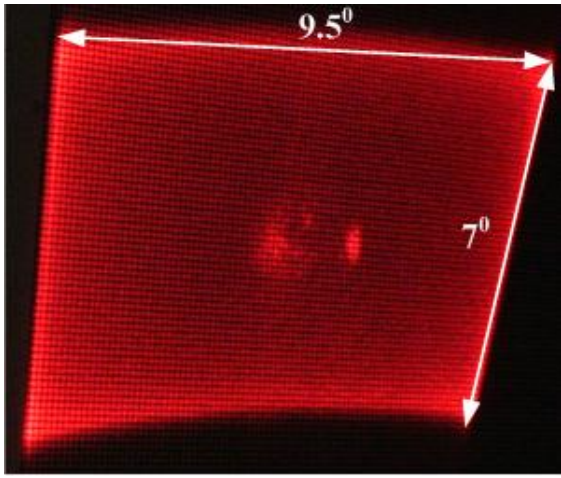
Motion of Micro mirror



2軸静電くしスキャナ



2軸静電くしスキャナ

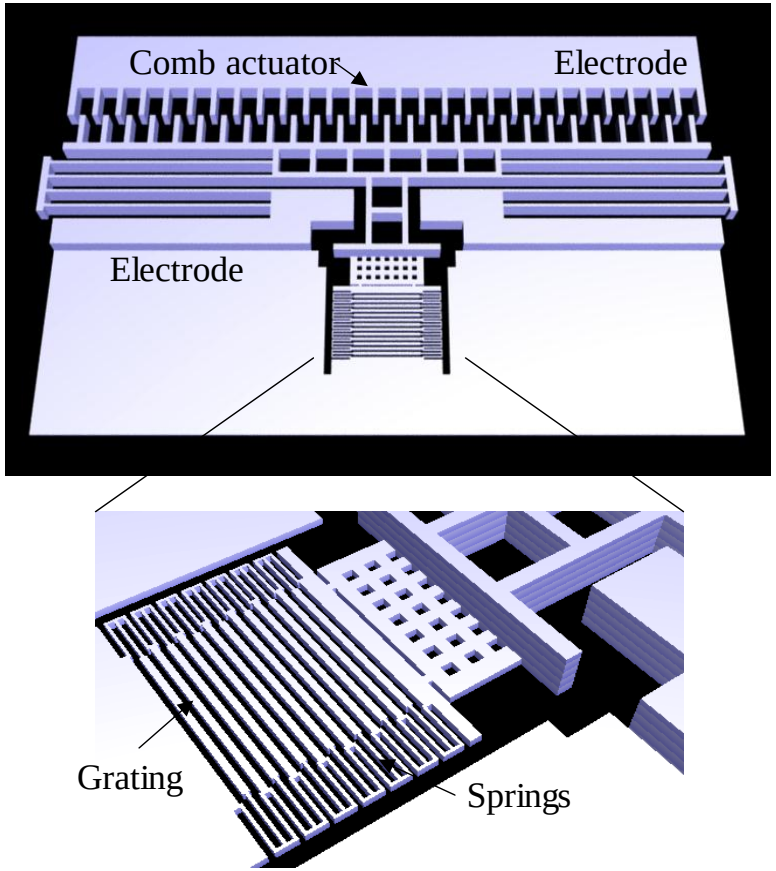


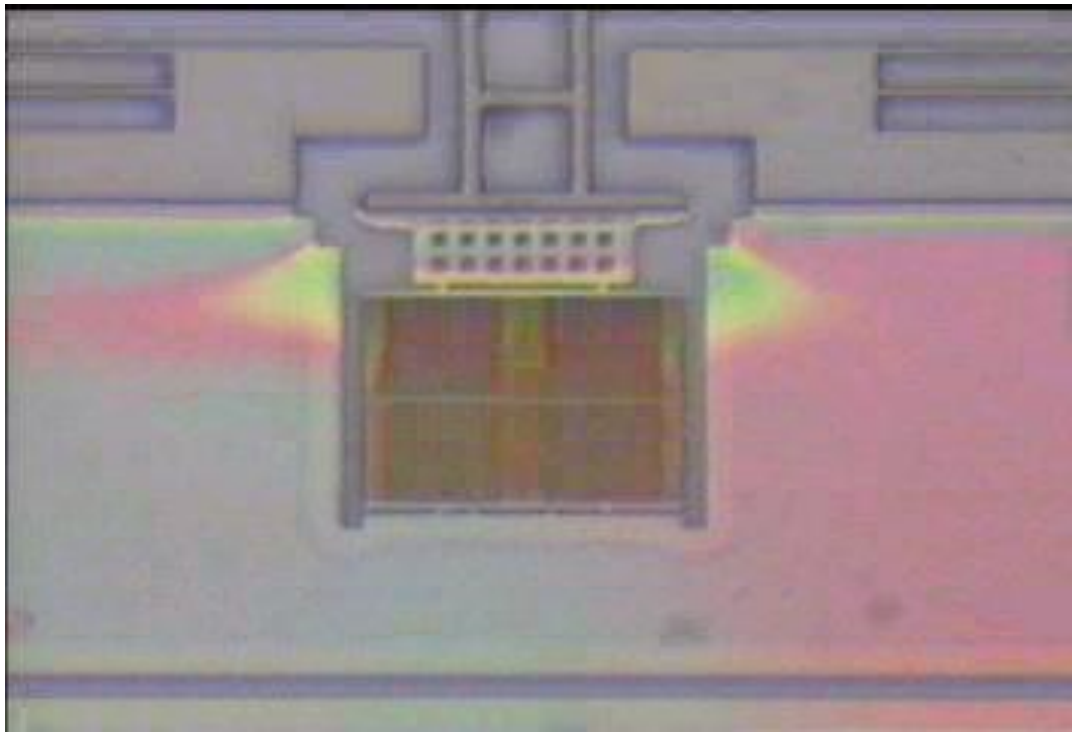
スキャンイメージ

ミラー共振周波数：40kHz
フレーム共振周波数：162Hz
ミラー電圧：12V(11.5度)
フレーム電圧：10V(14度)
圧力：1Pa 真空

H.M.Chu, K.Hane, Sens.Actu.(2011) in press

Tunable gratings

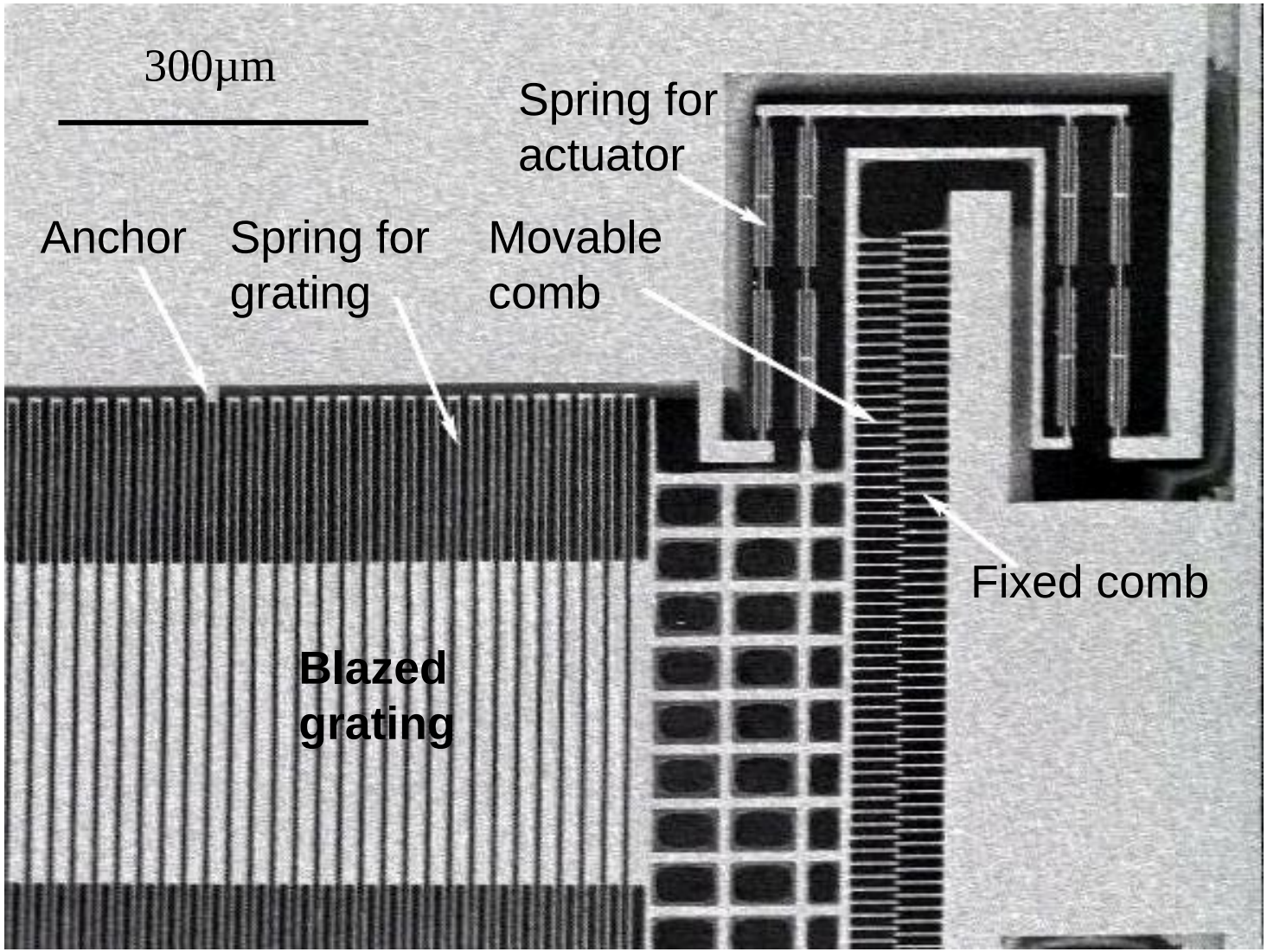




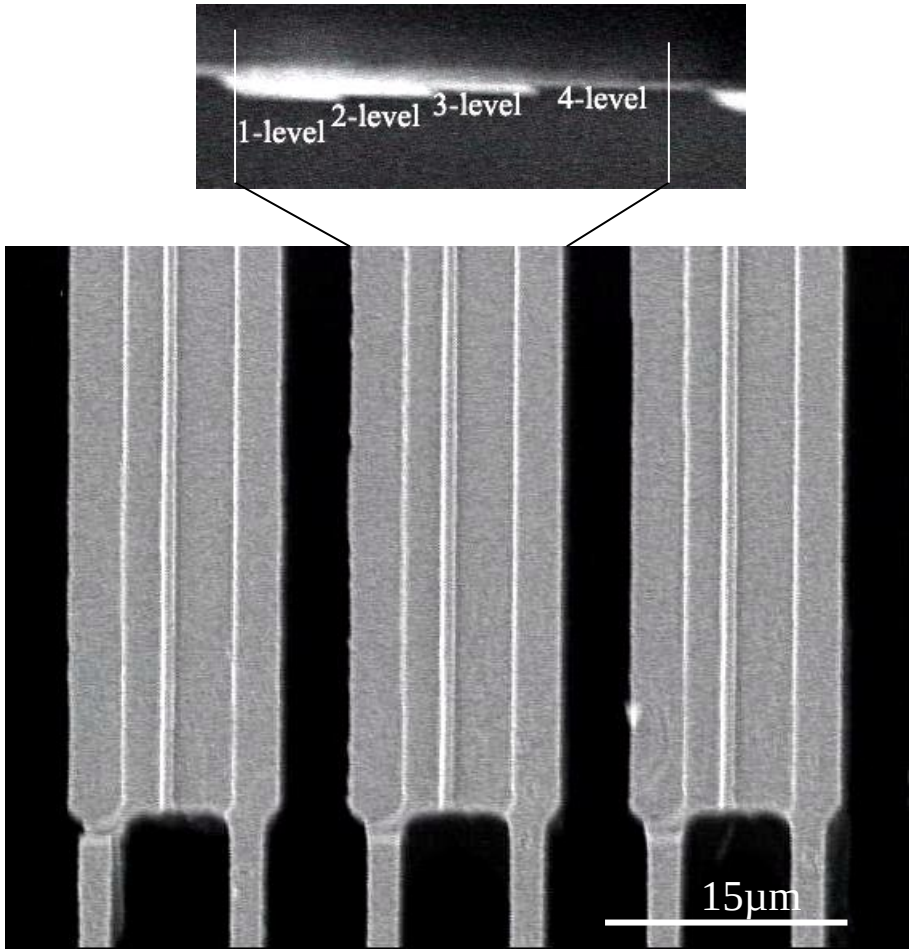
Design
*Self-suspended thin grating (300nm)
*Grating period : 600nm

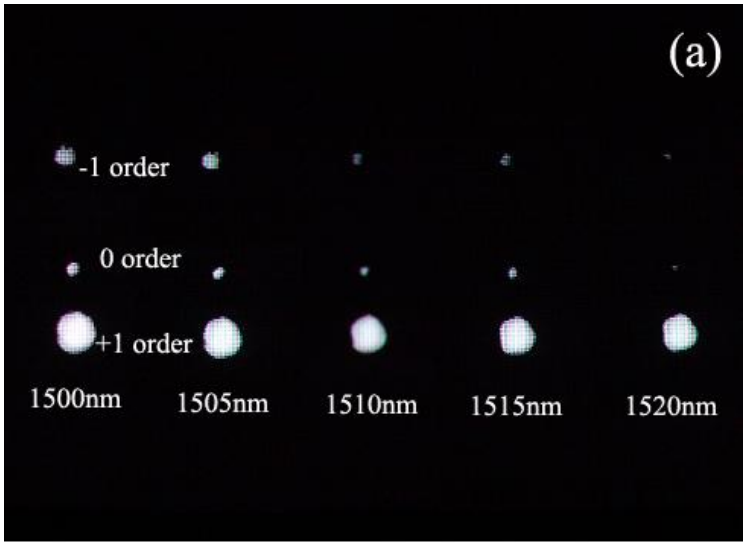
Fabrication
*Self-suspended thin grating is connected a thick (5um)actuator

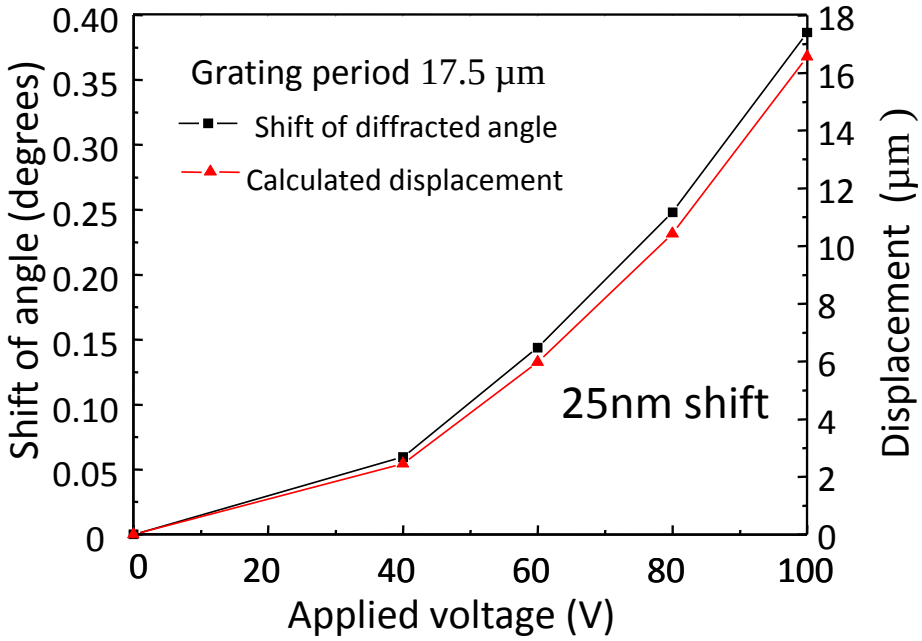
ブレーズのある周期可変回折格子(1.5μm帯)



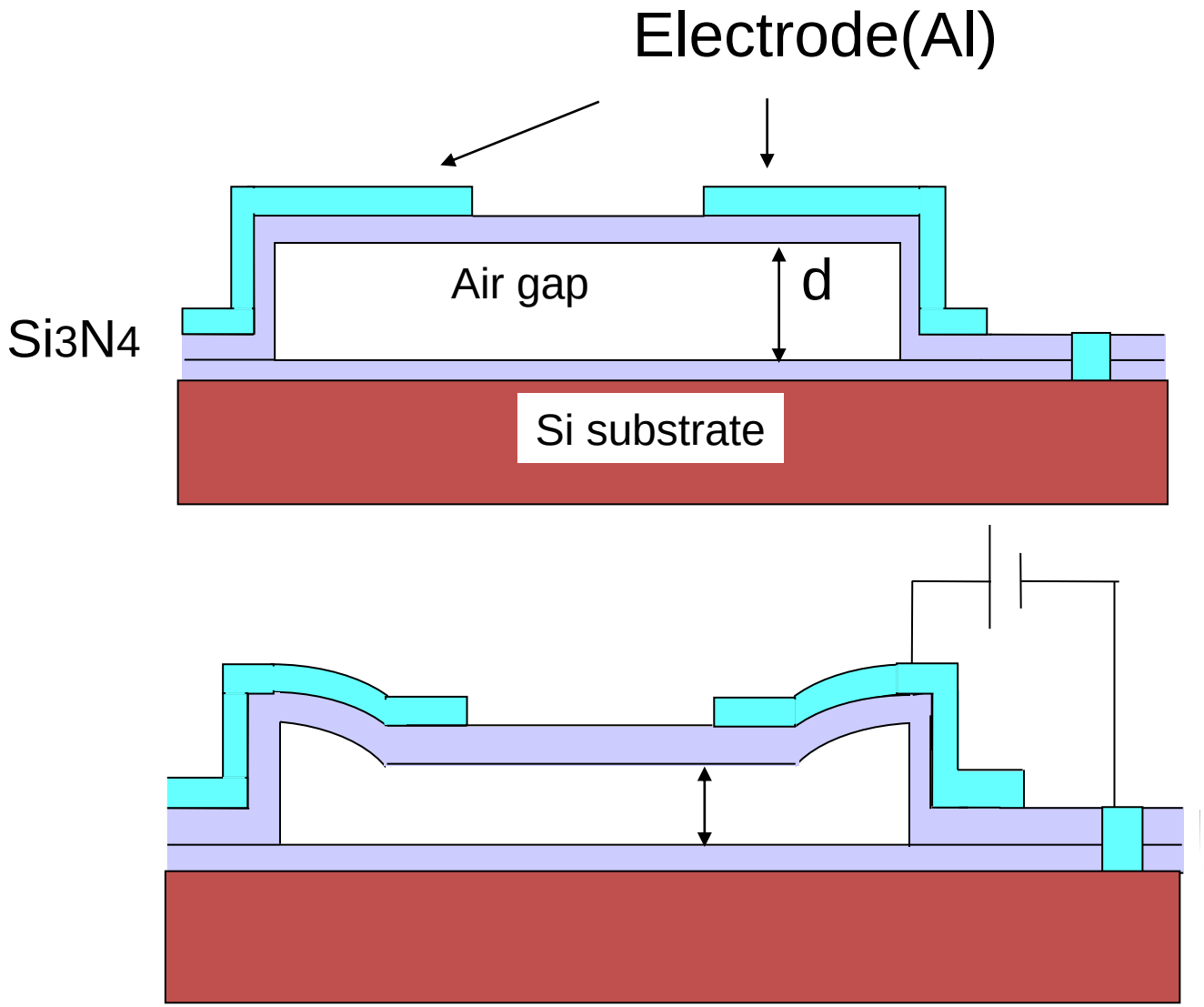
製作結果(ブレーズ格子部)と測定結果





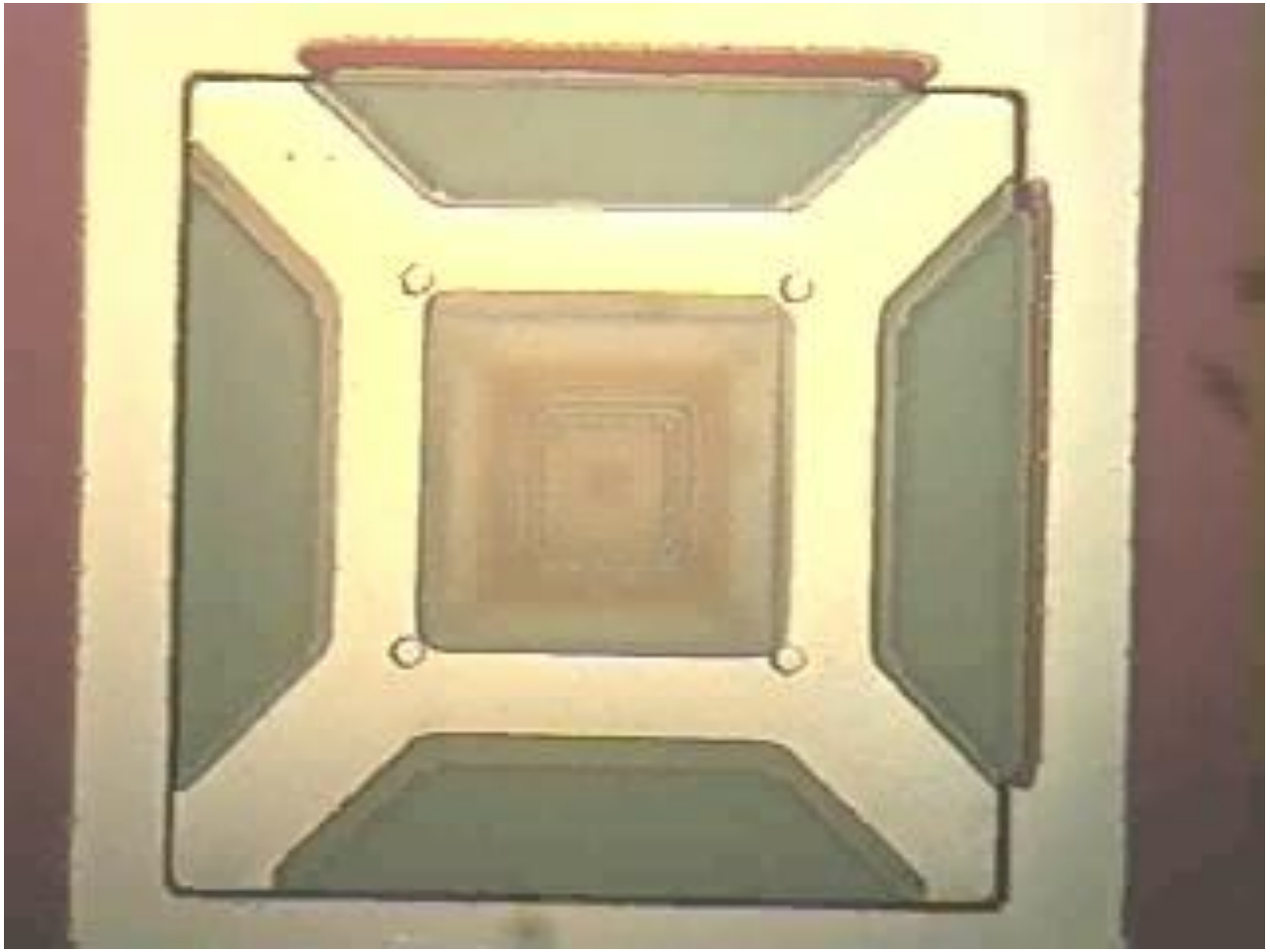


Principle of tunable Fabry-Perot filter



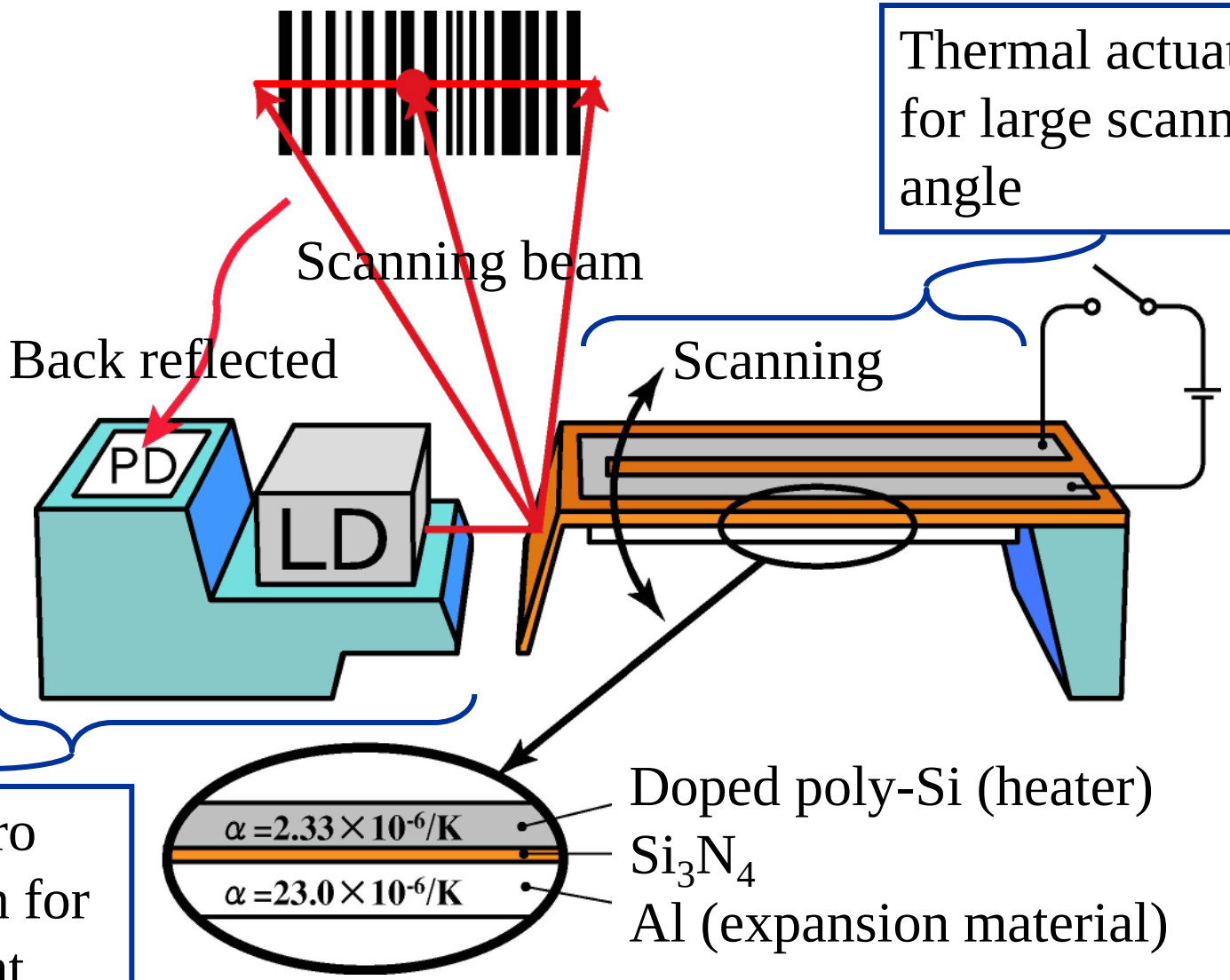
Reflection is controlled by changing gap

Movement of suspended membrane



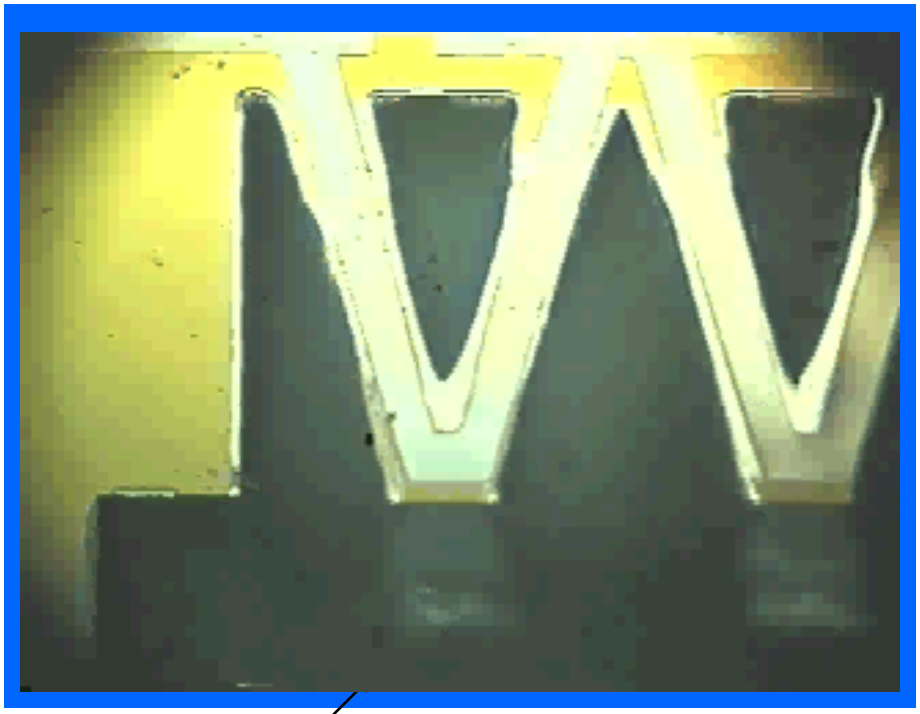
White light illumination, d_1=170μm d_2=70μm

3D integrated optical scanner



Actuator motion

Twin type



Micro-mirror

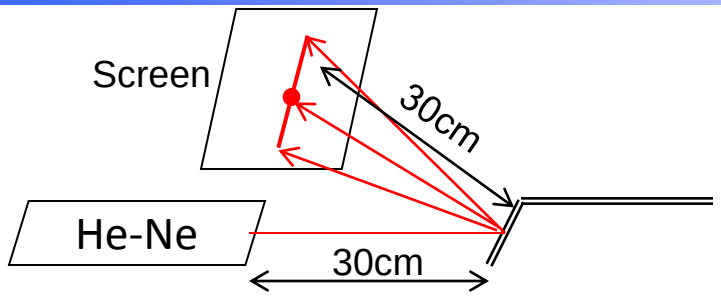
Single type

Mirror angle over 15 deg. is obtained.

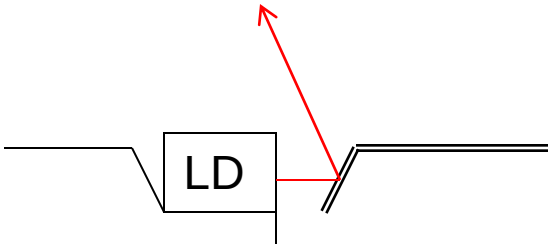
Driving voltage is 20 V.

Current is 6mA.

Beam scanning

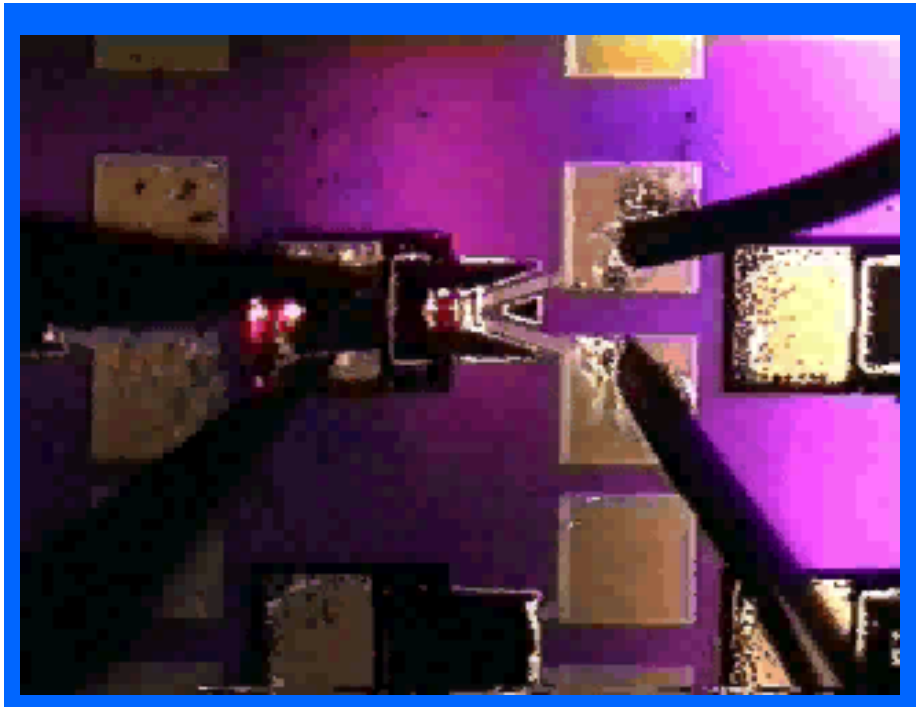


Scanning with He-Ne laser beam



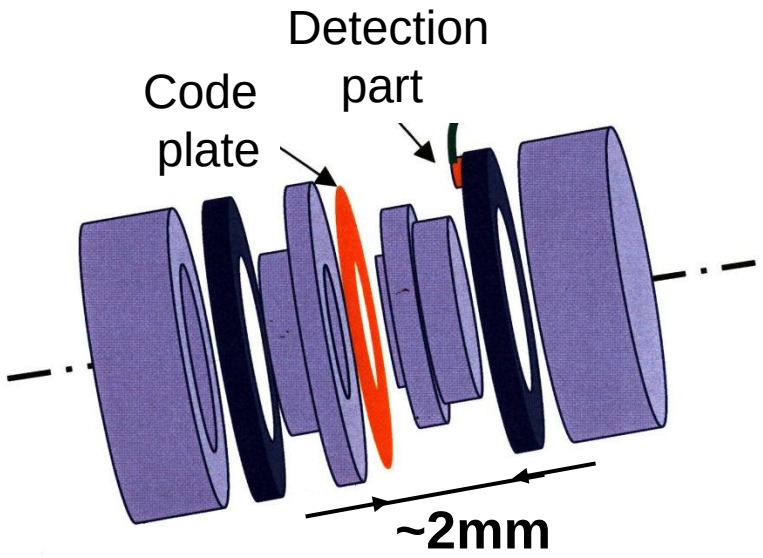
Scanner integrated with LD

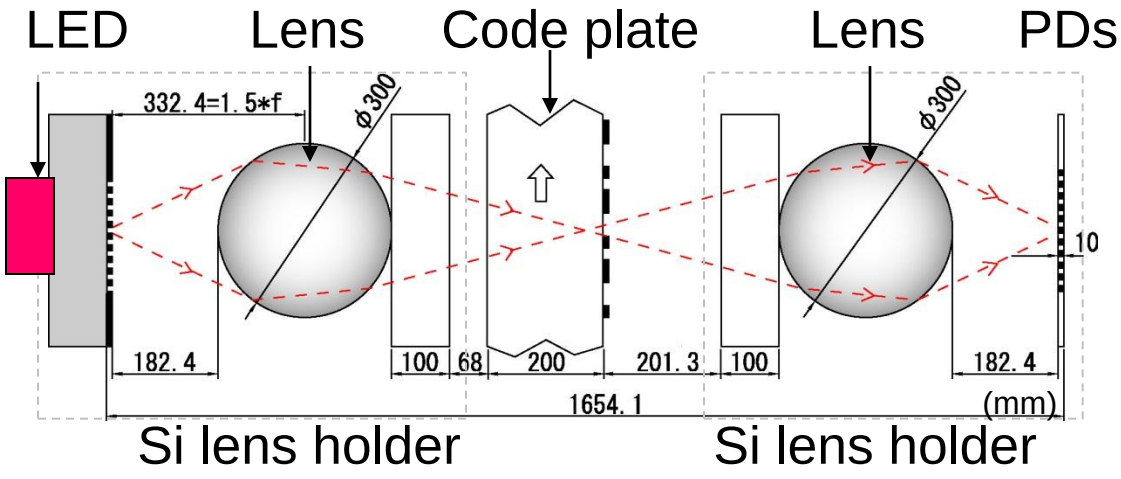
Flat micro-mirror generates small spot.

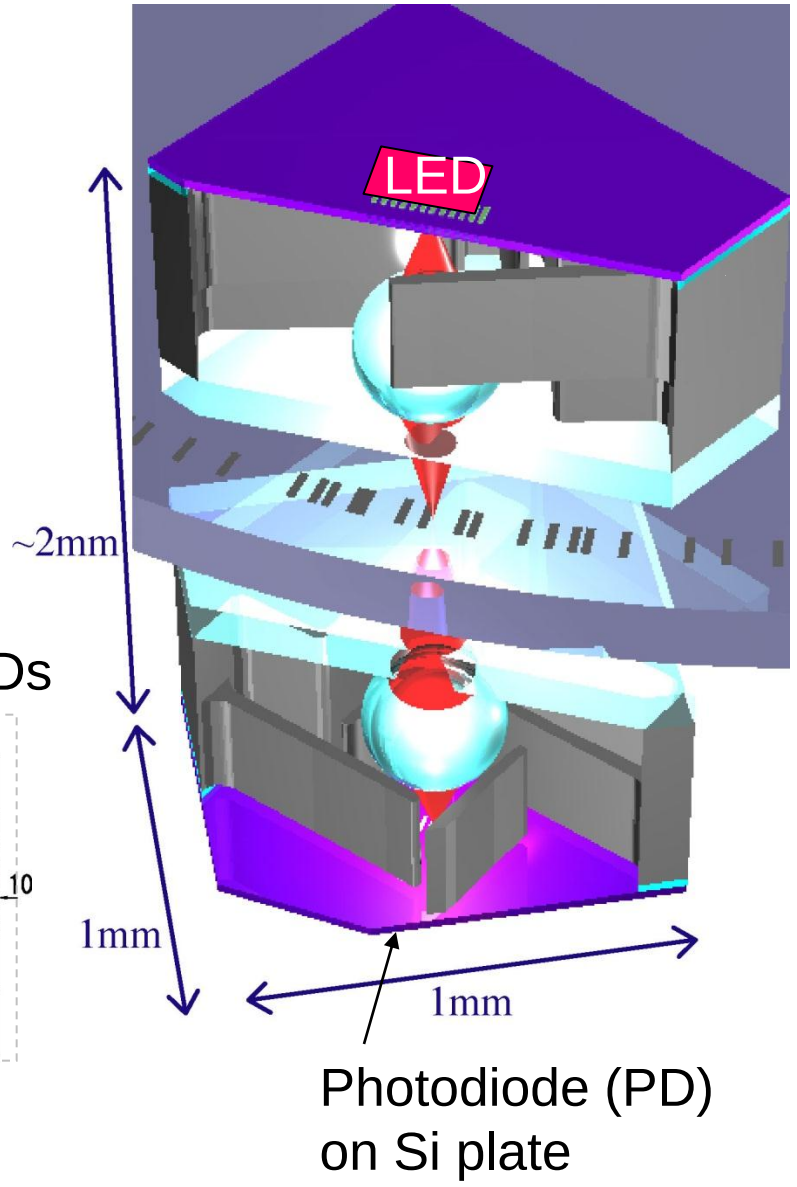


Only putting LD, optical axis is aligned.

Optical configuration of the encoder エンコーダの光学系

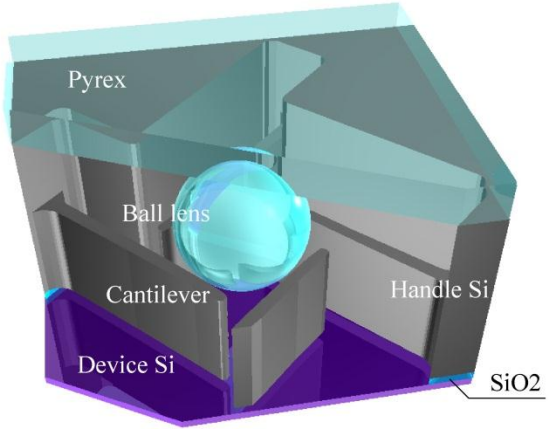




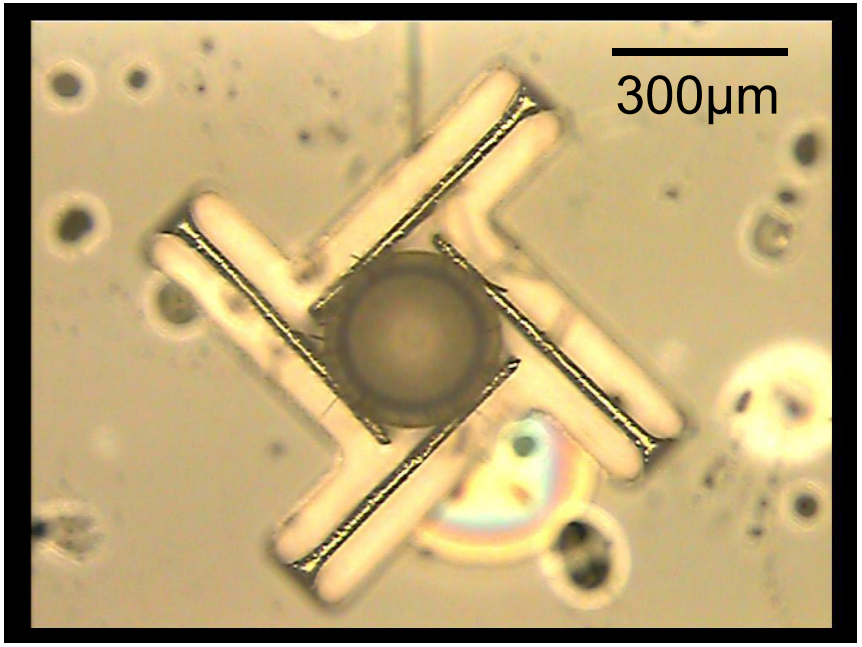


光検出部の製作結果

Silicon lens holder

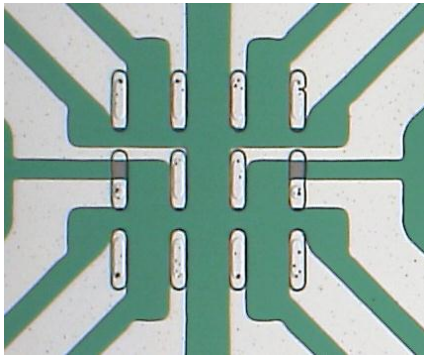


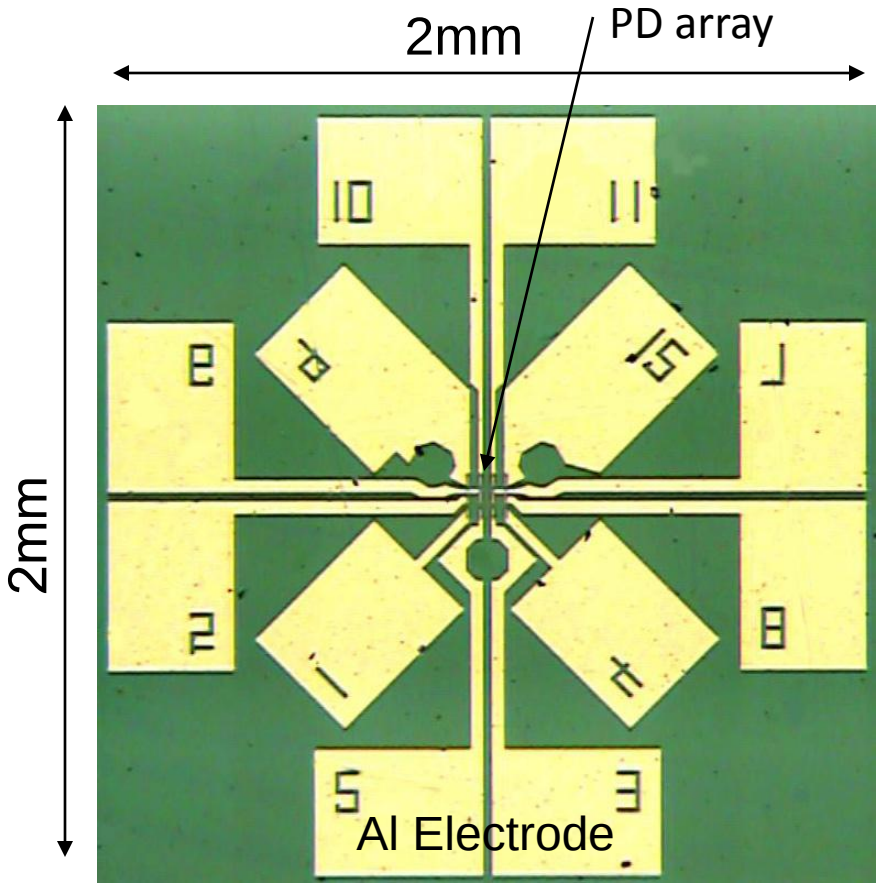
With lens



Alignment errors<±10mm

Photodiode array behind lens holder

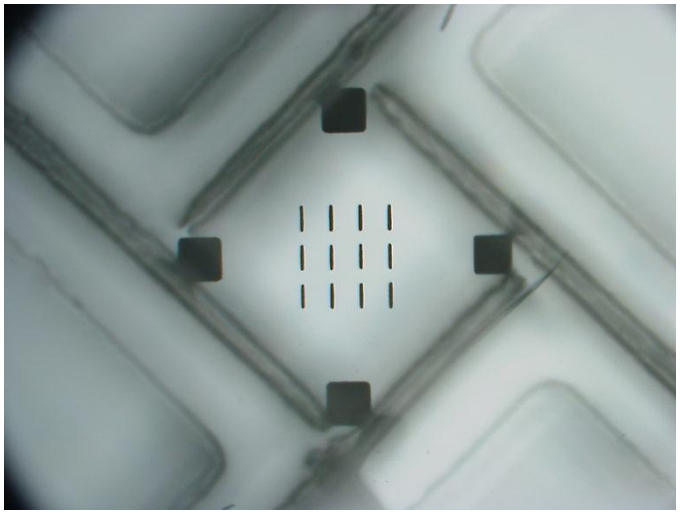


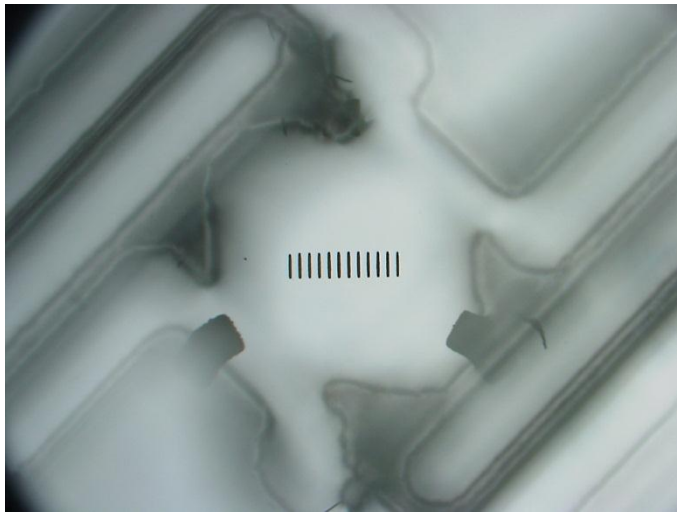


PD array: 2x2x0.6mm, 3 x4 diodes

光源部の製作結果

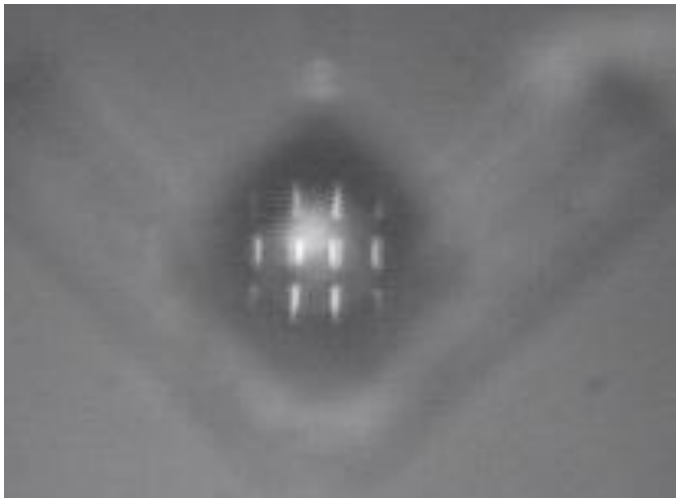
Light source slits on Si top layer of SOI wafer

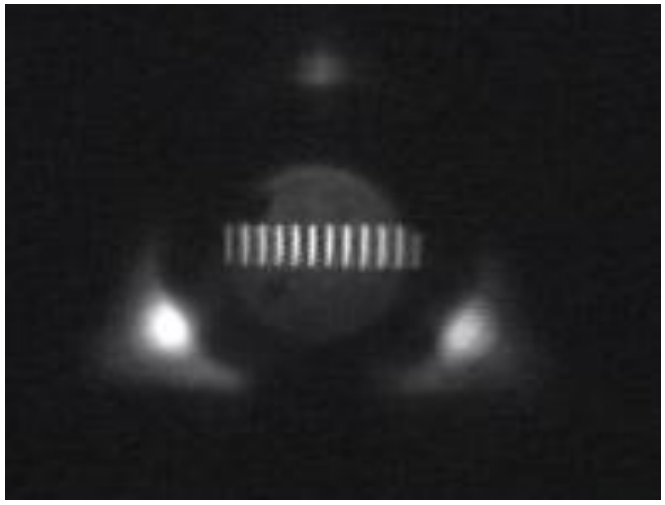




300μm

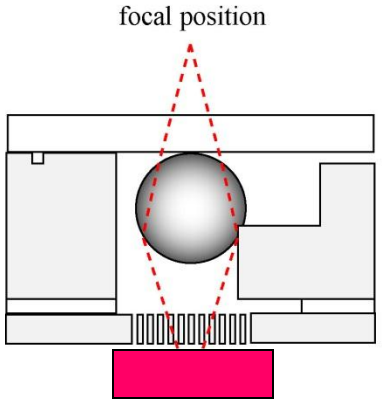
Images of slits through ball lens



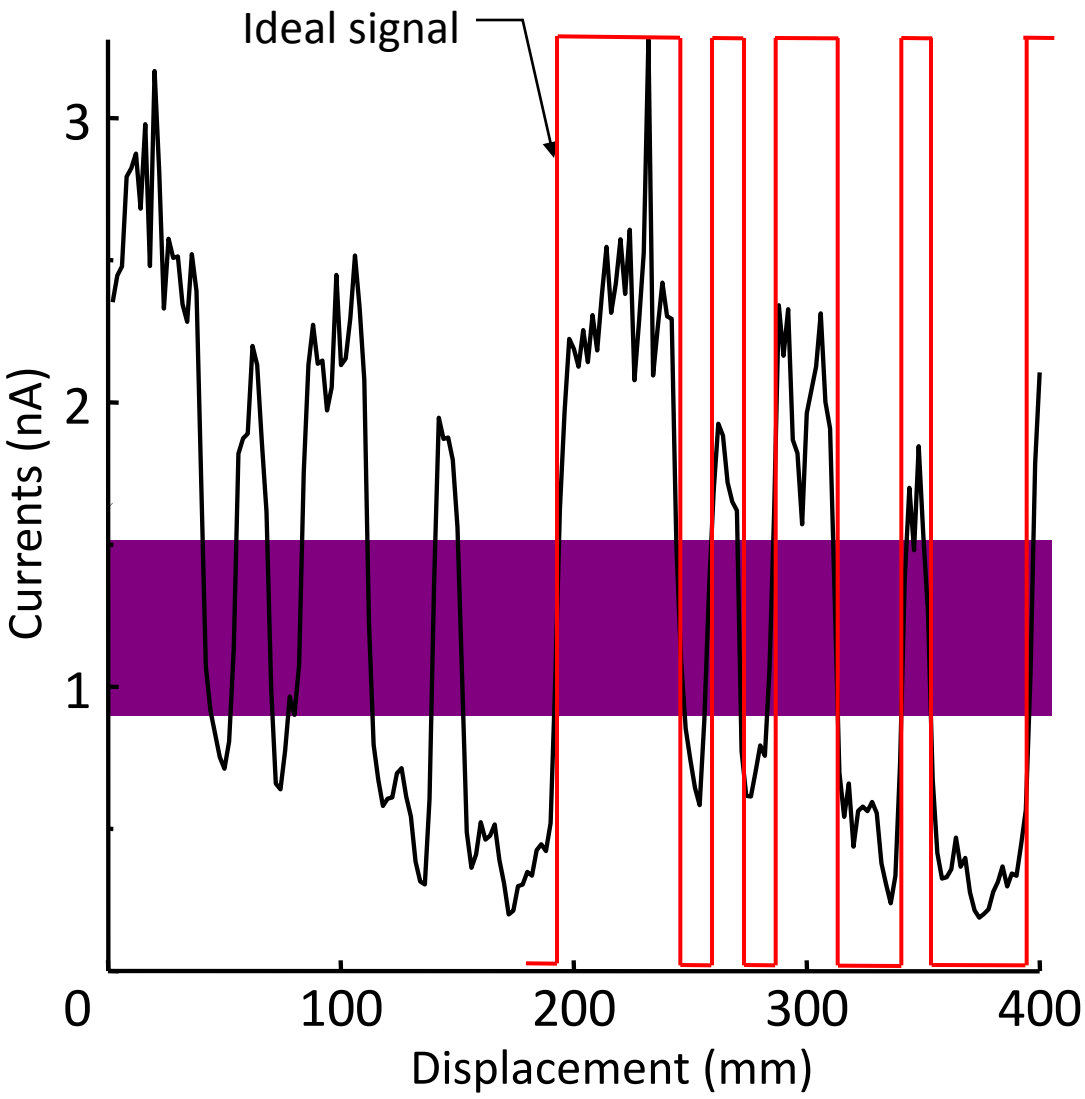


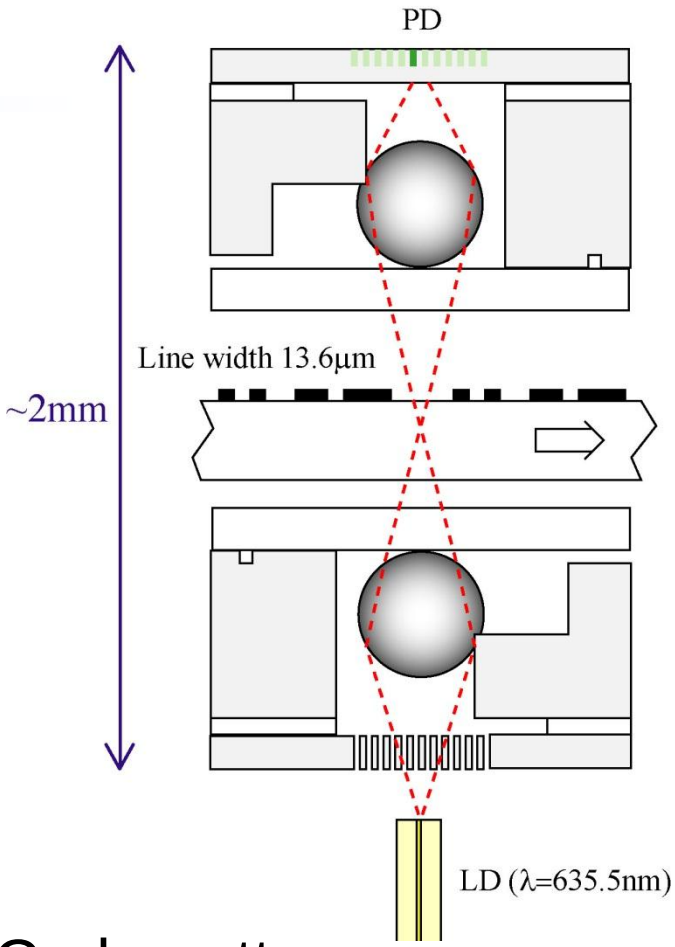
Slit size

5μm wide
30μm long



測定したエンコーダ信号

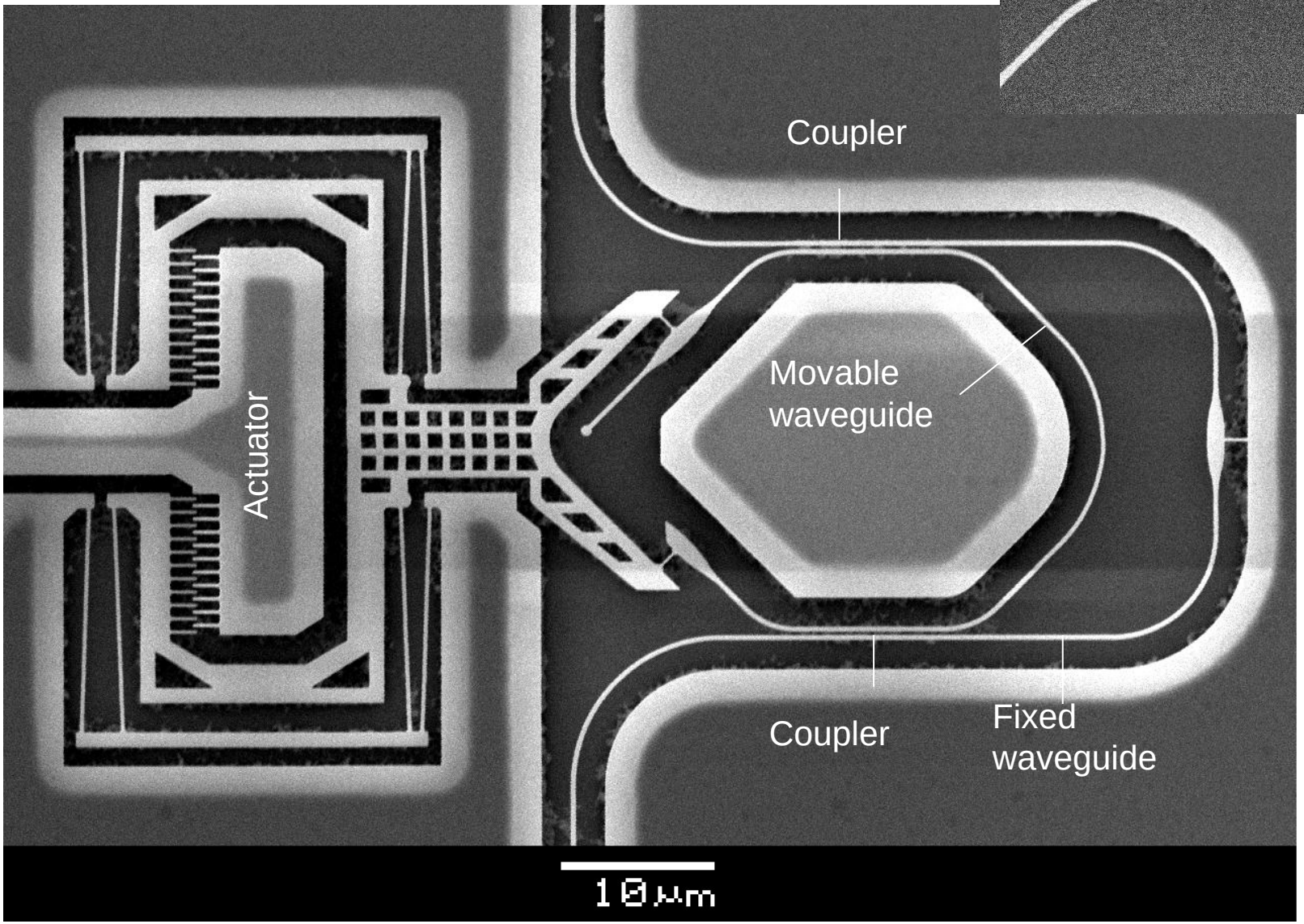


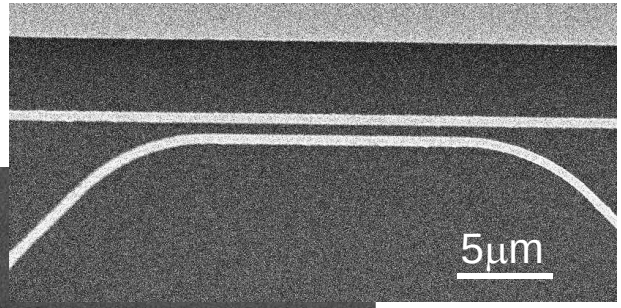


Code pattern

M-series: 12 bits,
13.6mm wide line

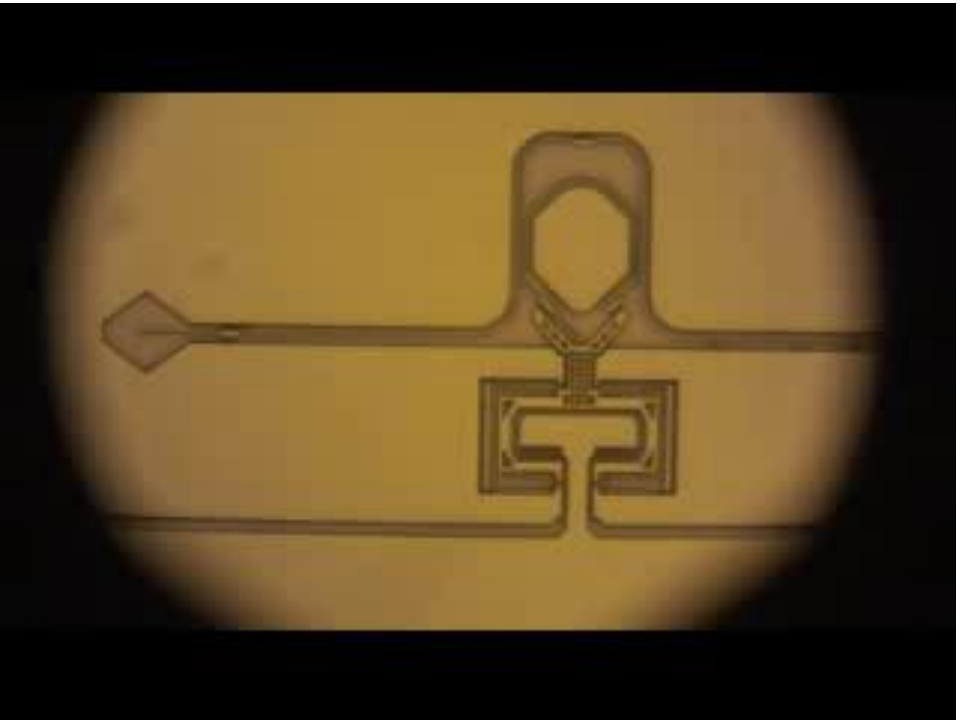
Fabricated MZI



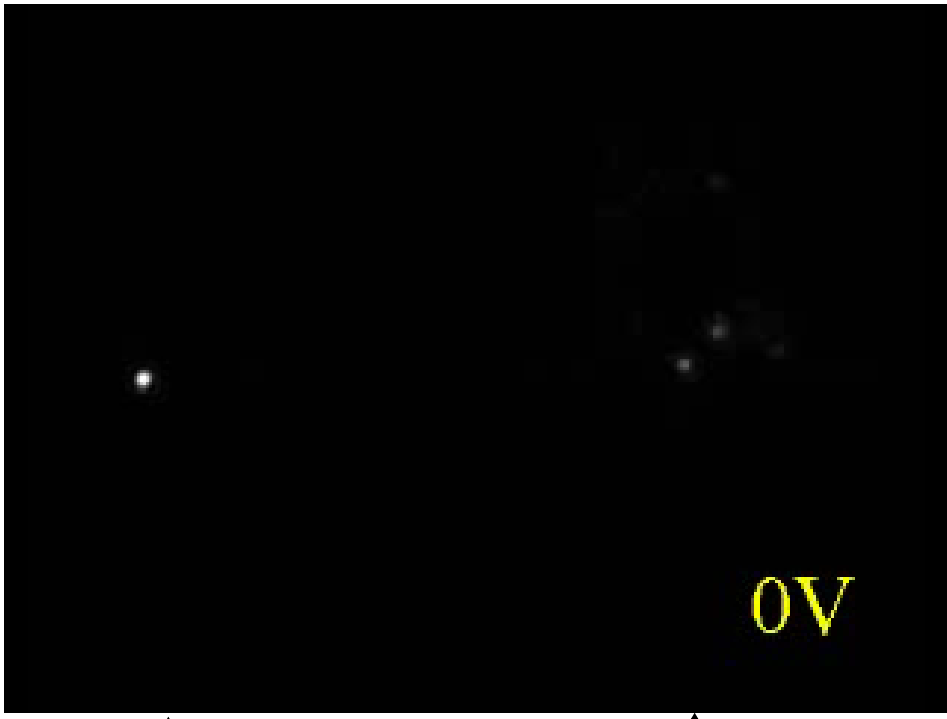


Optical measurement

Opitcal image



Infrared signal image



Through port Drop port

- 1μm displacement at 31V
- Mechanical resonant frequency:197.8kHz (Wide type), 212.4kHz (Narrow type)
- 1.5μm optical output modulation is observed

曲げモーメント駆動による焦点可変ミラー

MEMS Deformable Mirrors

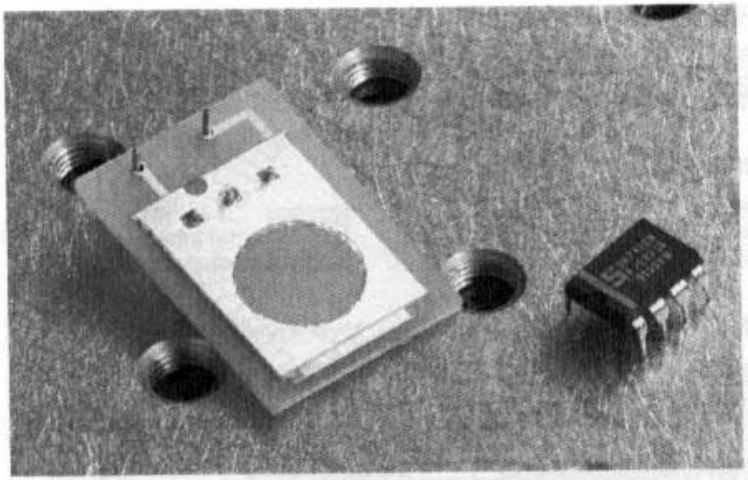


Figure 5. Defocus corrector mounted on a PCB.

or:

$$\varepsilon/\delta a = a/R.$$

From the latter expression, we see that the demands on the shape of the membrane contour are very strict. For example to achieve $\varepsilon = 0.1\ \mu$m with a membrane mirror having diameter of 1 cm, when the deformed membrane has a focal distance of one meter, the deviation from the circular contour must be less than 20 μm.

The compensation reported can be applied for the fabrication of more complex shapes, for example for elliptical mirrors for correction of astigmatic beams emitted by semiconductor lasers.

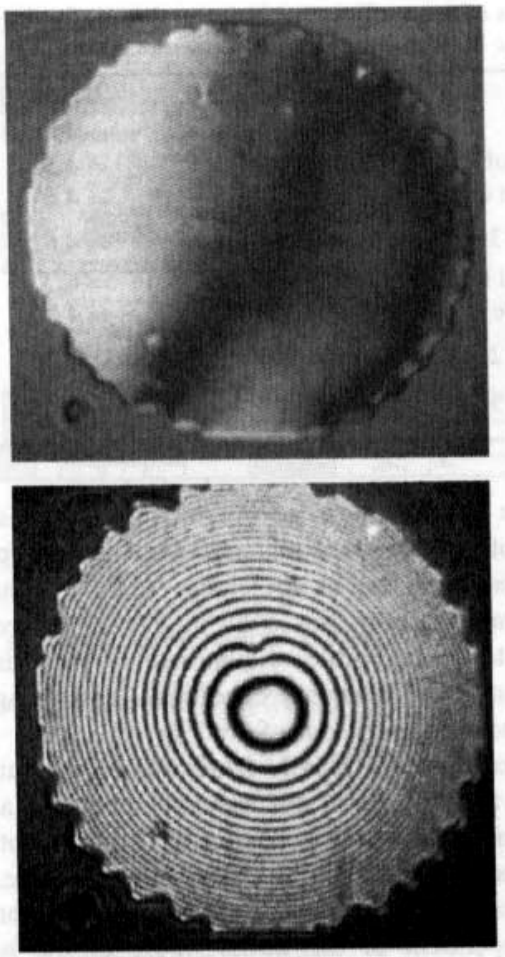
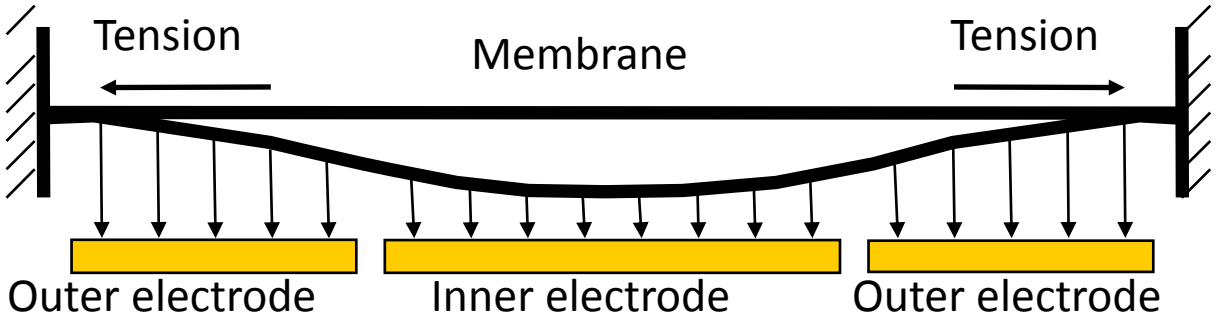


Figure 6. Interferogram of the initial mirror surface with an active diameter of 10 mm (top), the same surface deformed by a control voltage of 90 V, corresponding to a focal distance of 1 m (bottom).

G.Vdovin et al. JMM 9(1999) R8-R20

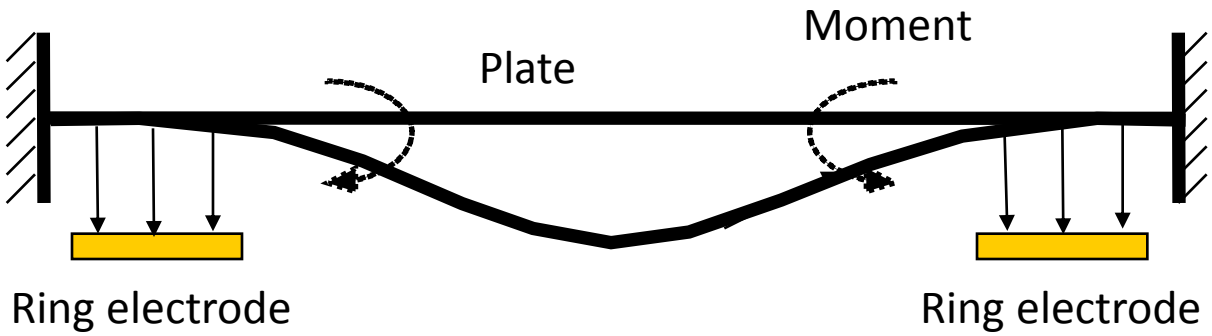
Varifocal mirrors

Membrane mirror



Distributed force is needed to obtain parabolic shape

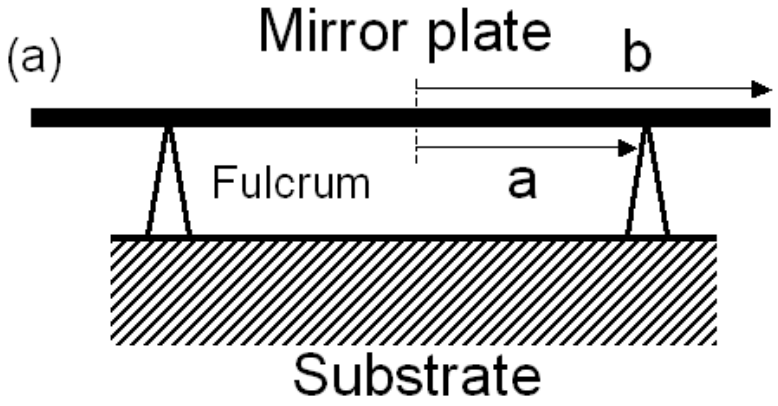
Plate mirror

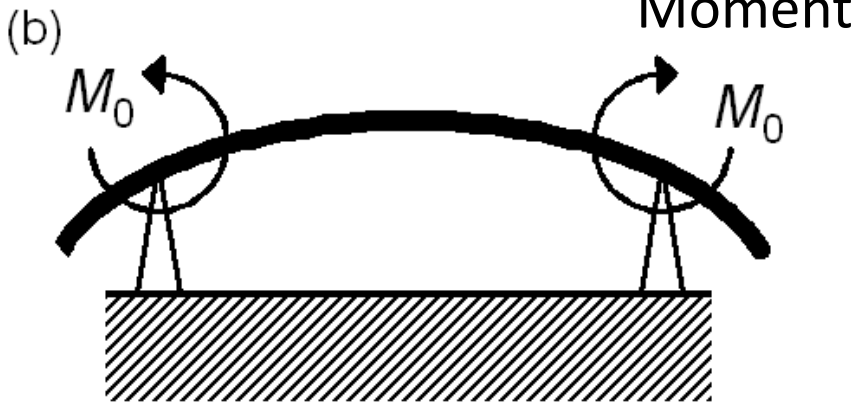


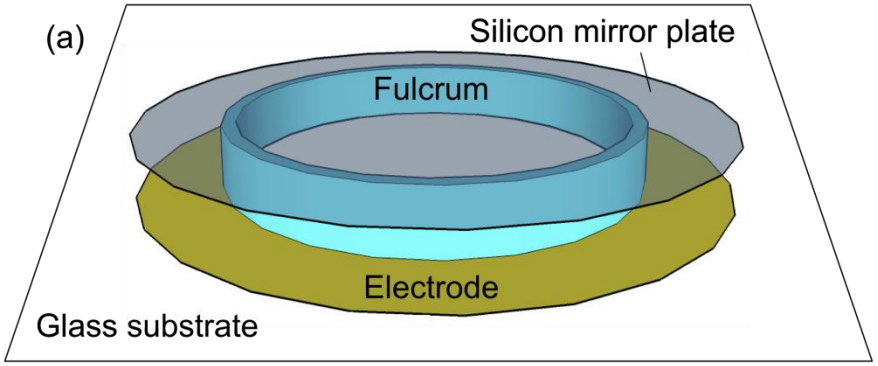
Ring electrode is effective to generate parabolic shape inside the ring electrode

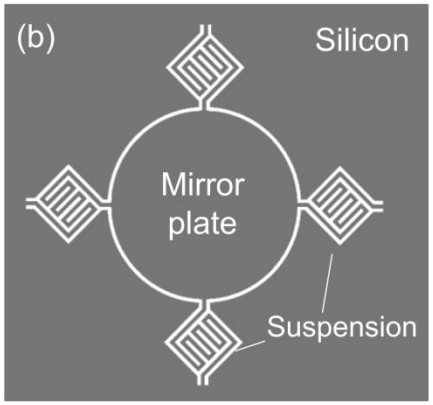
Support conditions affect the region of the parabolic shape

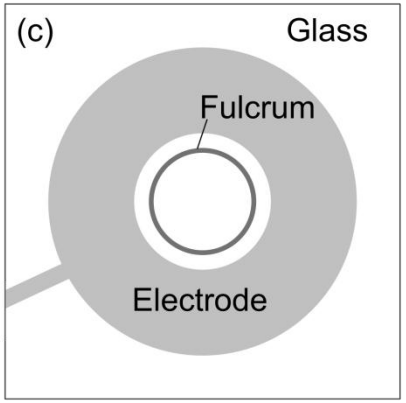
Deformable mirror by bending moment drive





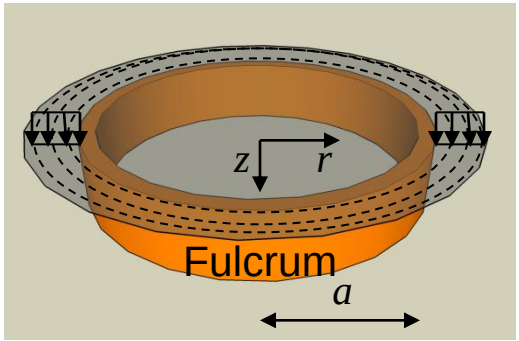






焦点可変ミラーの動作原理

Circular mirror



Ring-shaped load distribution

円板のたわみ曲線の微分方程式 （材料力学）

$$\frac{d^4z}{dr^4}+\frac{2}{r}\frac{d^3z}{dr^3}-\frac{1}{r^2}\frac{d^2z}{dr^2}+\frac{1}{r^3}\frac{dz}{dr}=\frac{P(r)}{D}$$

E: Young's modulus

h: mirror thickness

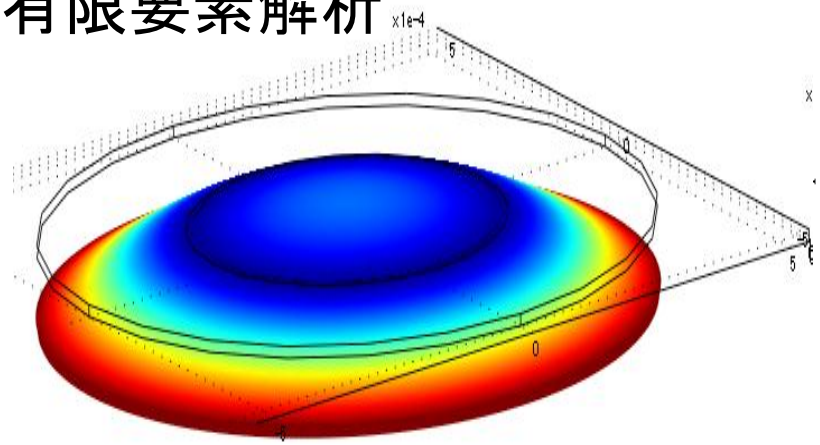
v: Poisson ratio

$$P(r):\ Distribution\ of\ load,\quad Bending\ stiffness:\ D=\frac{Eh^3}{12(1-\nu^2)}$$

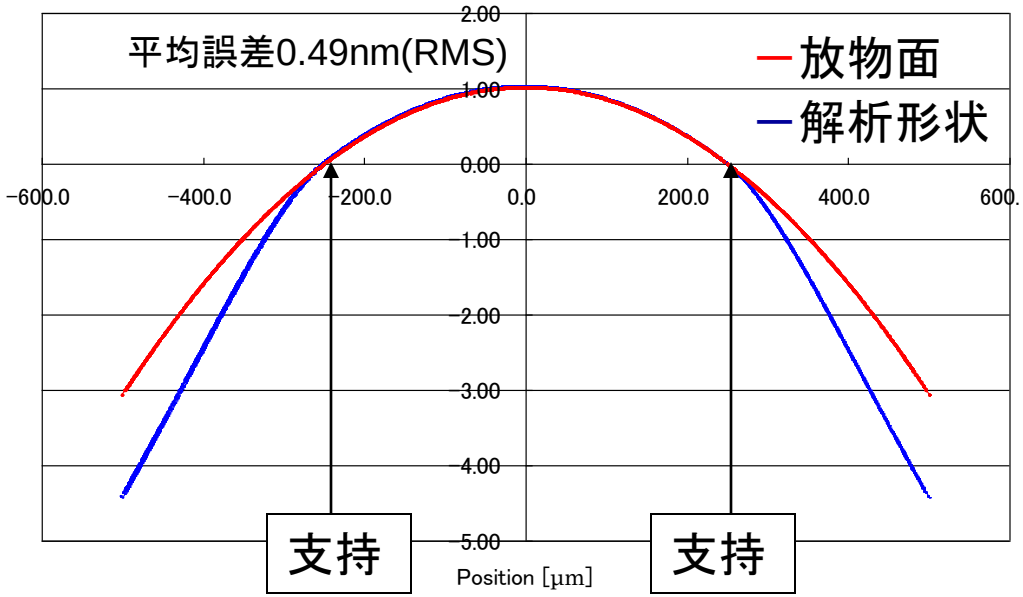
たわみ曲線の近似解

$$z=\frac{M_0}{2D(1+\nu)}\left(r^2-a^2\right)=\frac{6(1-\nu)M_0}{Eh^3}\left(r^2-a^2\right)\quad parabola$$

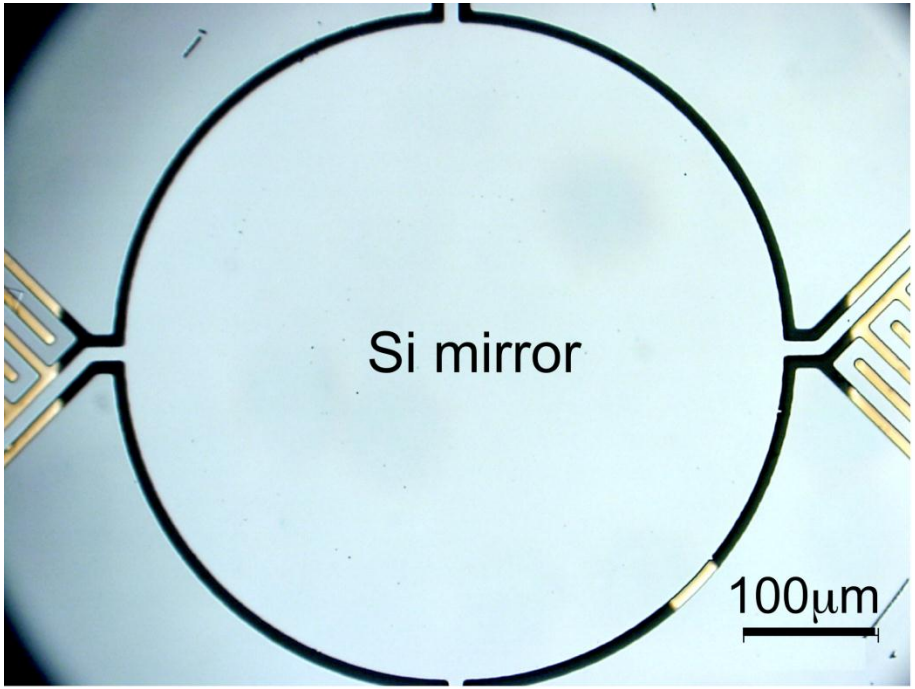
有限要素解析



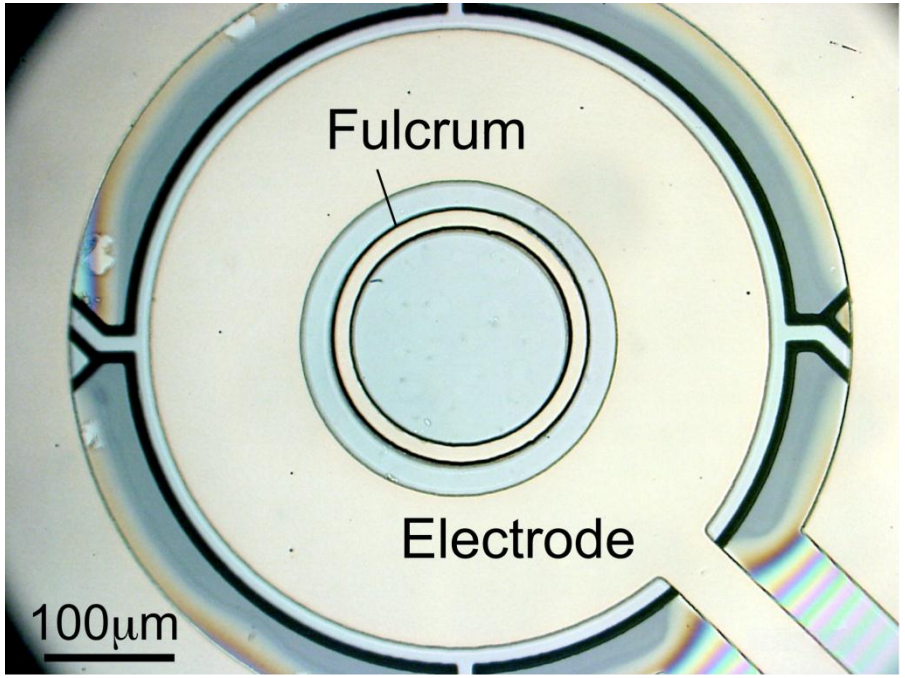
材料：シリコン，支持外部に分布荷重



Fabricated circular varifocal mirror

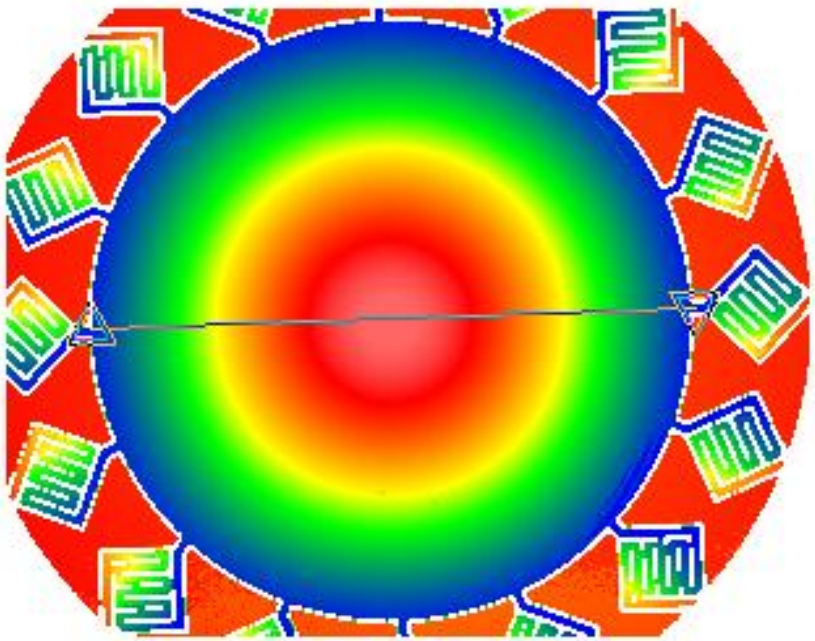


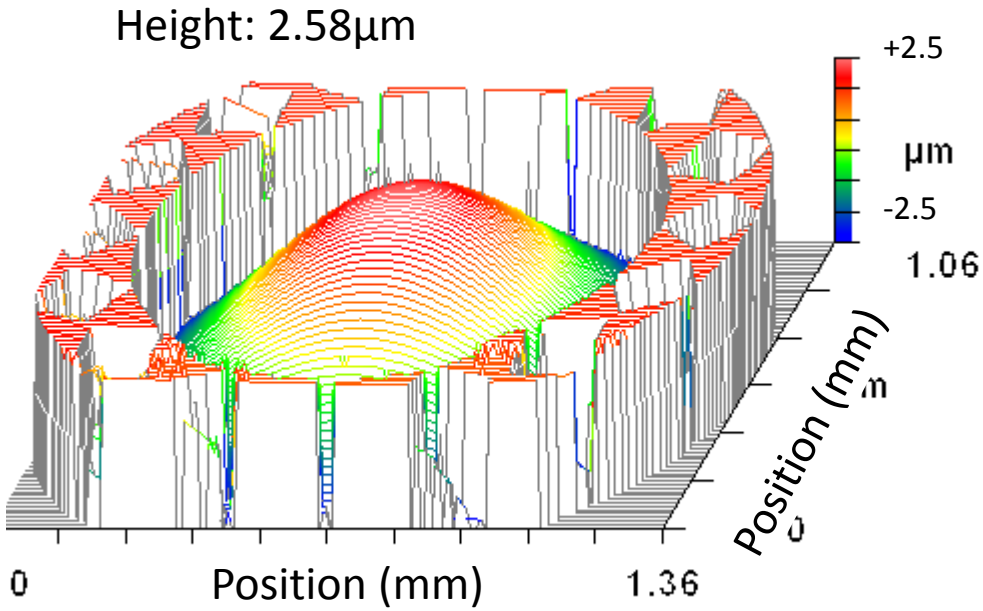
Si mirror side

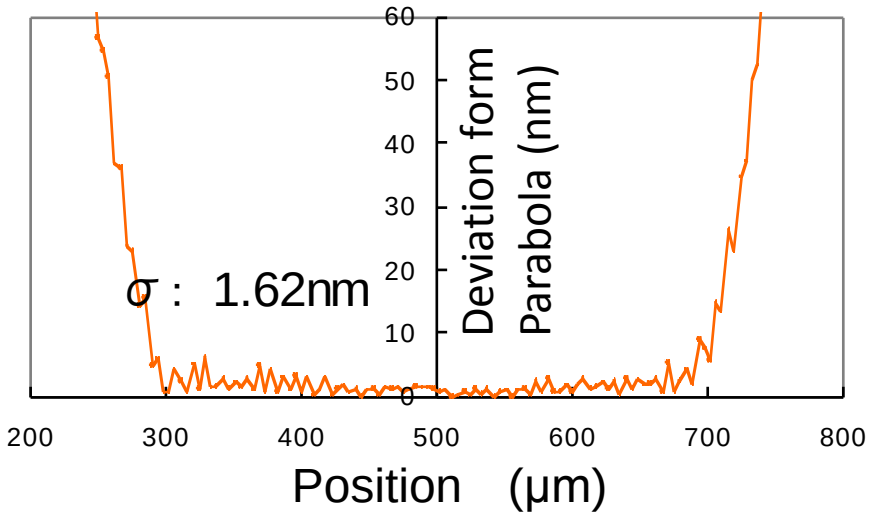


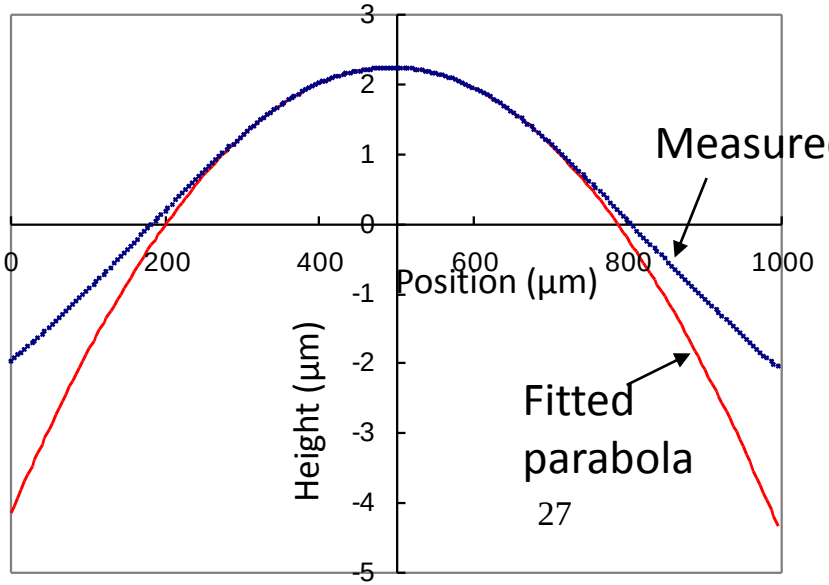
Glass side

Deformation by voltage





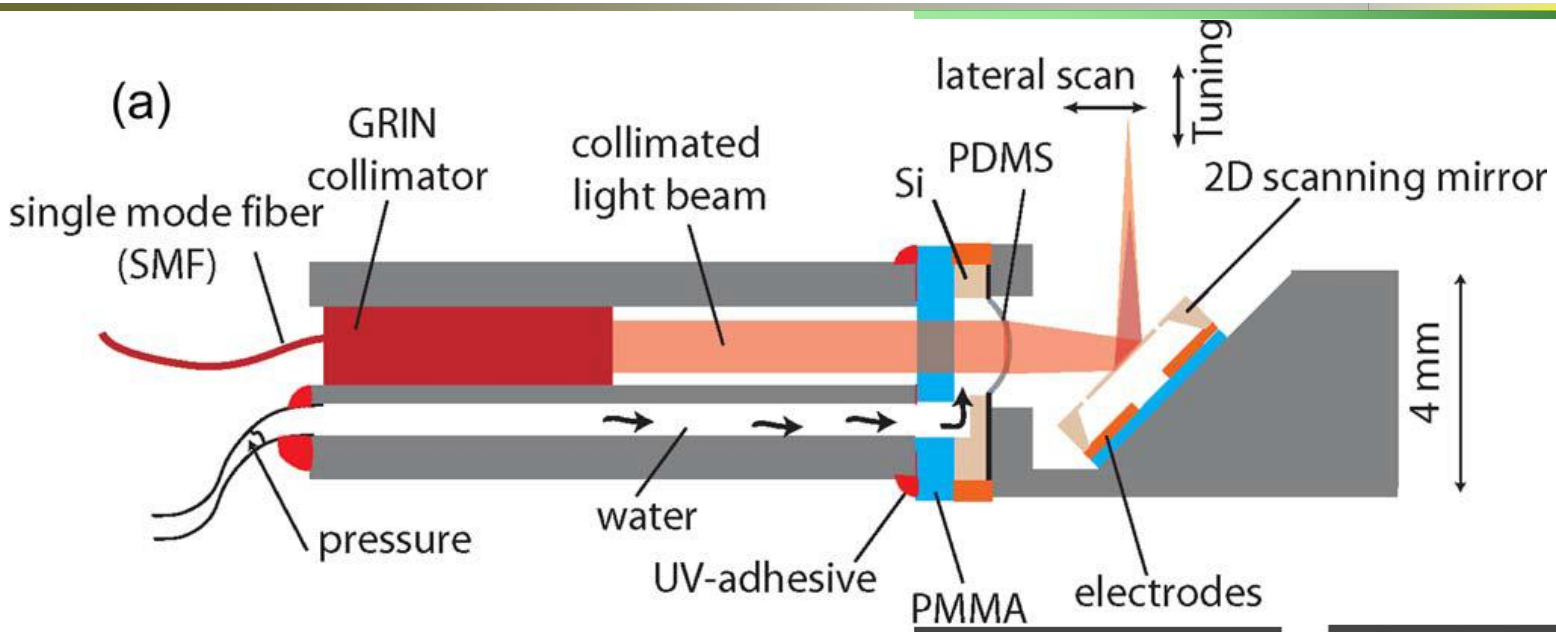




焦点可変ミラーの動作

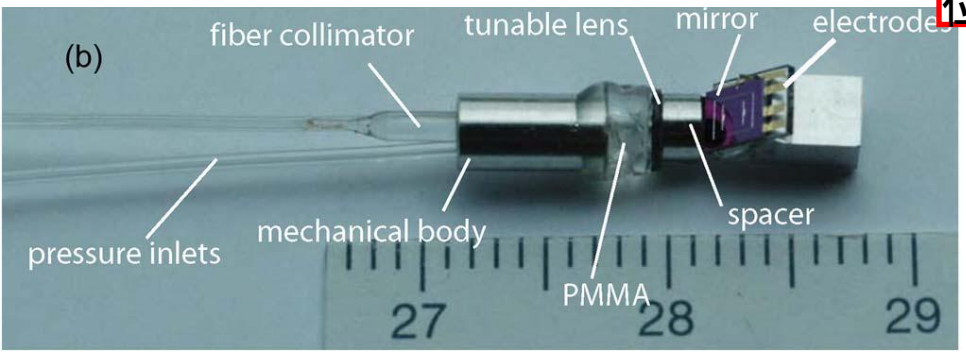
焦点可変ミラーを備えた光スキャナー

焦点可変と光走査機能を搭載した内視鏡

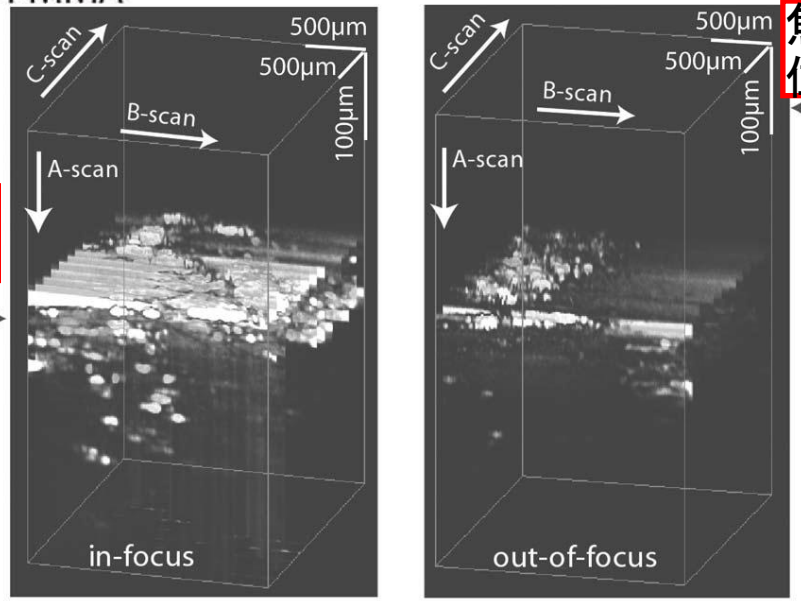


K. Aljasem et al., IEEE J. Microelectromech. Syst., 20, pp.1462–1472, 2011.

焦点可変と光走査は内視鏡用途で良い画像を得るために必要な機能であることが示されている。

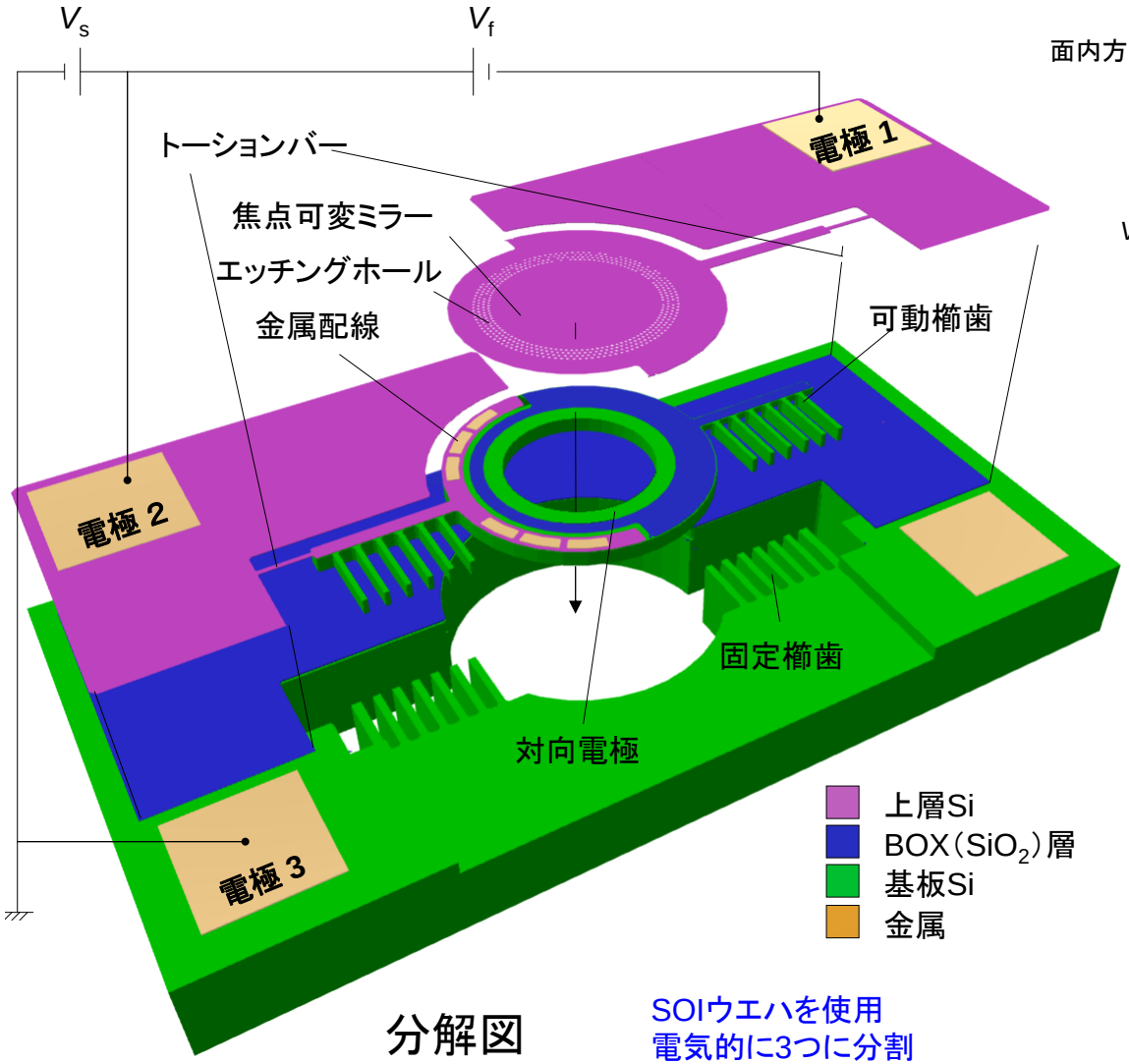


写真



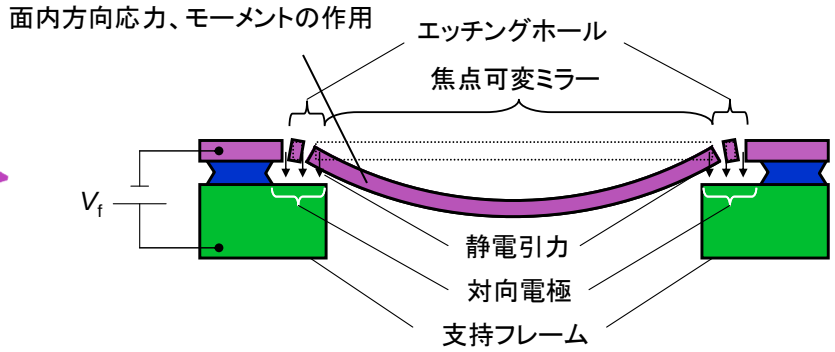
(a) ねぎの皮のOCT画像

提案する焦点可変走査ミラーの構造



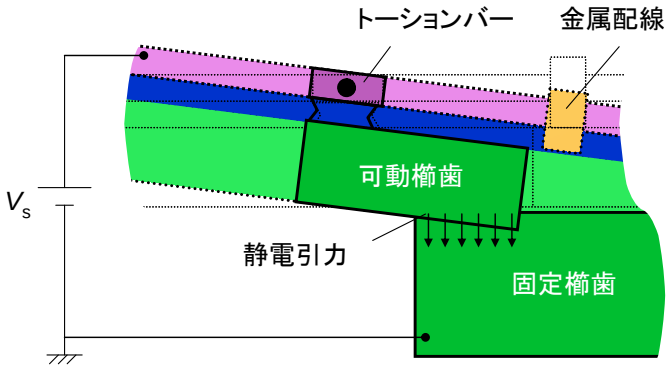
分解図

SOIウエハを使用
電気的に3つに分割



焦点可変ミラーの断面図

焦点可変電圧 V_f の印加によりミラー変形

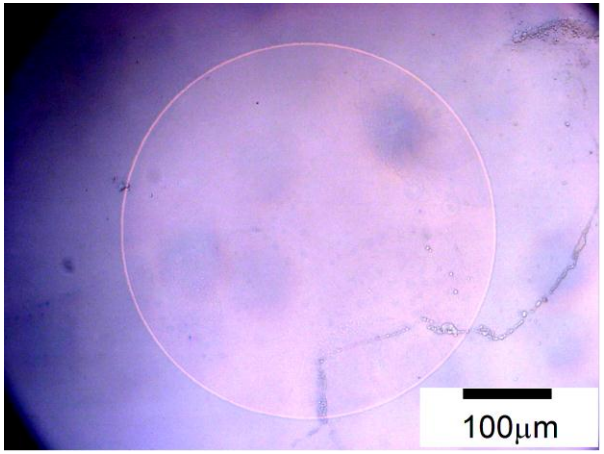


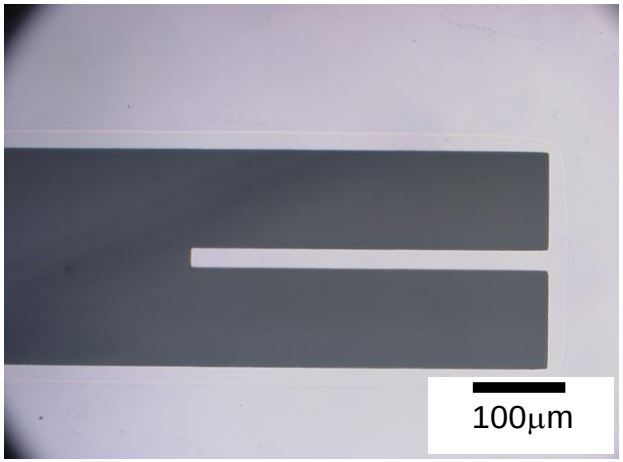
スキャナアクチュエータの断面図

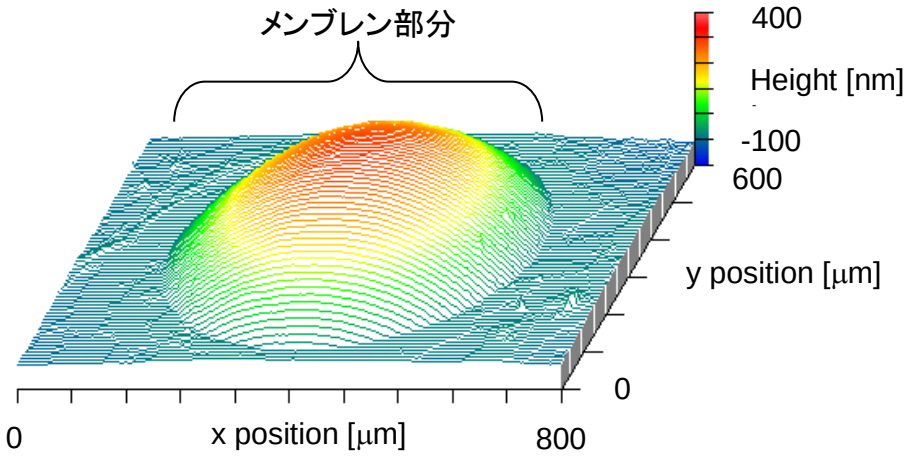
スキャナ電圧 V_s の印加によりミラー回転

スキャナと焦点可変ミラーの機能が集積されている。

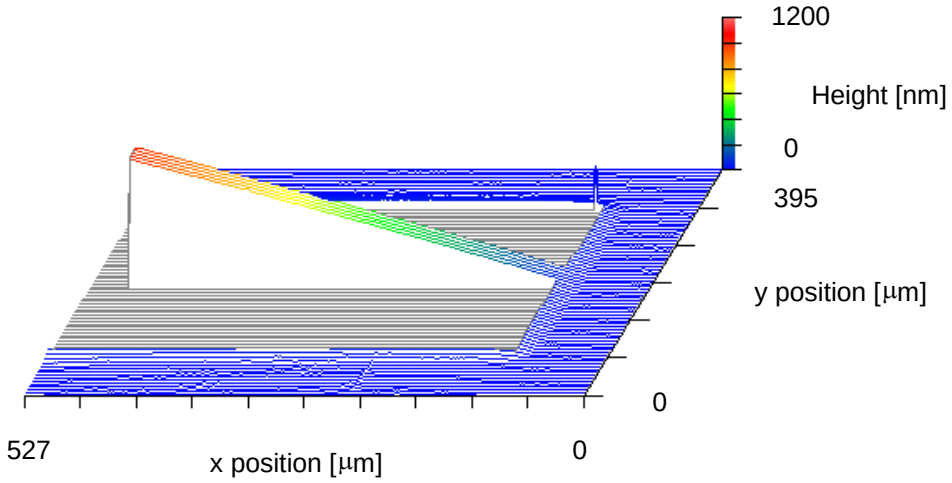
円形薄膜ミラーとカンチレバーの形状





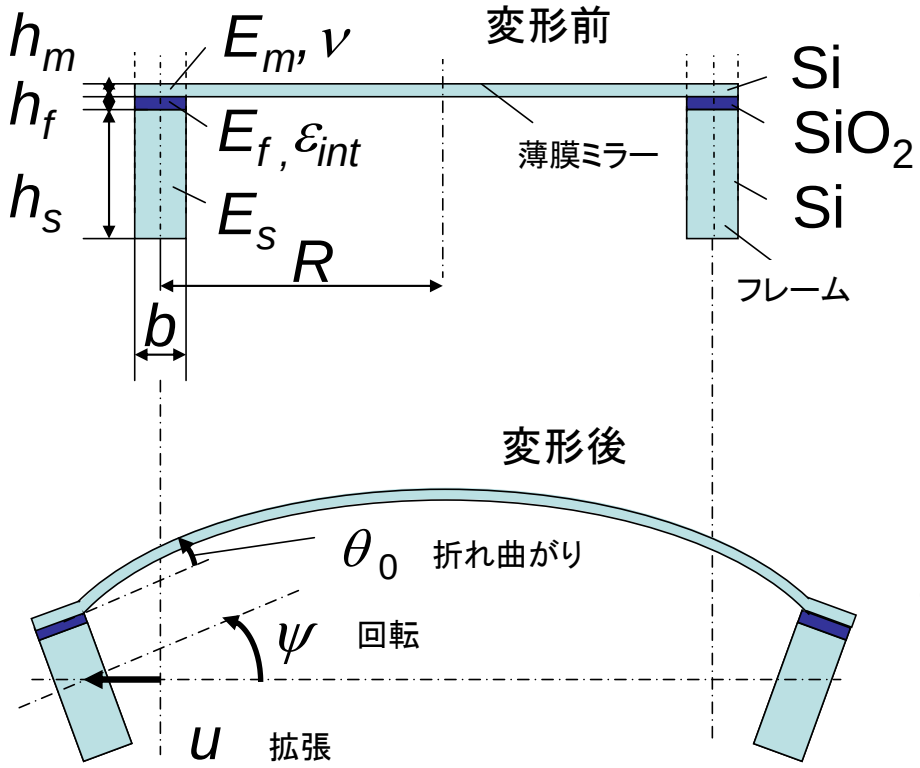


円形薄膜ミラーの形状



カンチレバーの形状

応力による変形の計算



薄膜ミラー断面図

フレーム変形による薄膜ミラー支持条件変化

支持角度	→	増
面内方向応力	→	増

フレーム変形の計算結果

拡張変形

$$u_{r=R-\frac{b}{2}} = \frac{-h_f E_f \varepsilon_{\mathrm{int}} - \frac{1}{b(1-\nu)} h_m E_m \lambda}{\frac{1}{R-\frac{b}{2}}\left(h_f E_f + h_s E_s + h_m E_m\right) + \frac{1}{b(1-\nu)} h_m E_m}$$

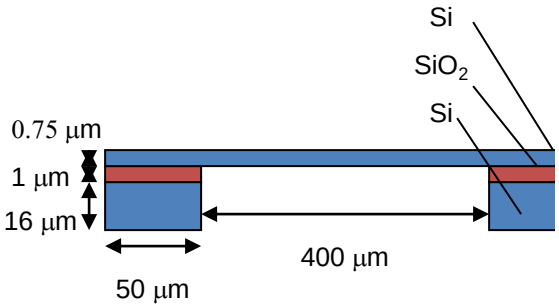
回転変形

$$\psi = -\frac{h_f E_f\left(\varepsilon_{\mathrm{int}} + \varepsilon_a\right) + h_m E_m \varepsilon_a + h_m \sigma_{m\theta} + \frac{2M_{m\theta}}{bh_s}}{\left(h_f E_f + h_m E_m\right)\frac{h_s}{2} + E_s \frac{h_s^{\,2}}{6}} R$$

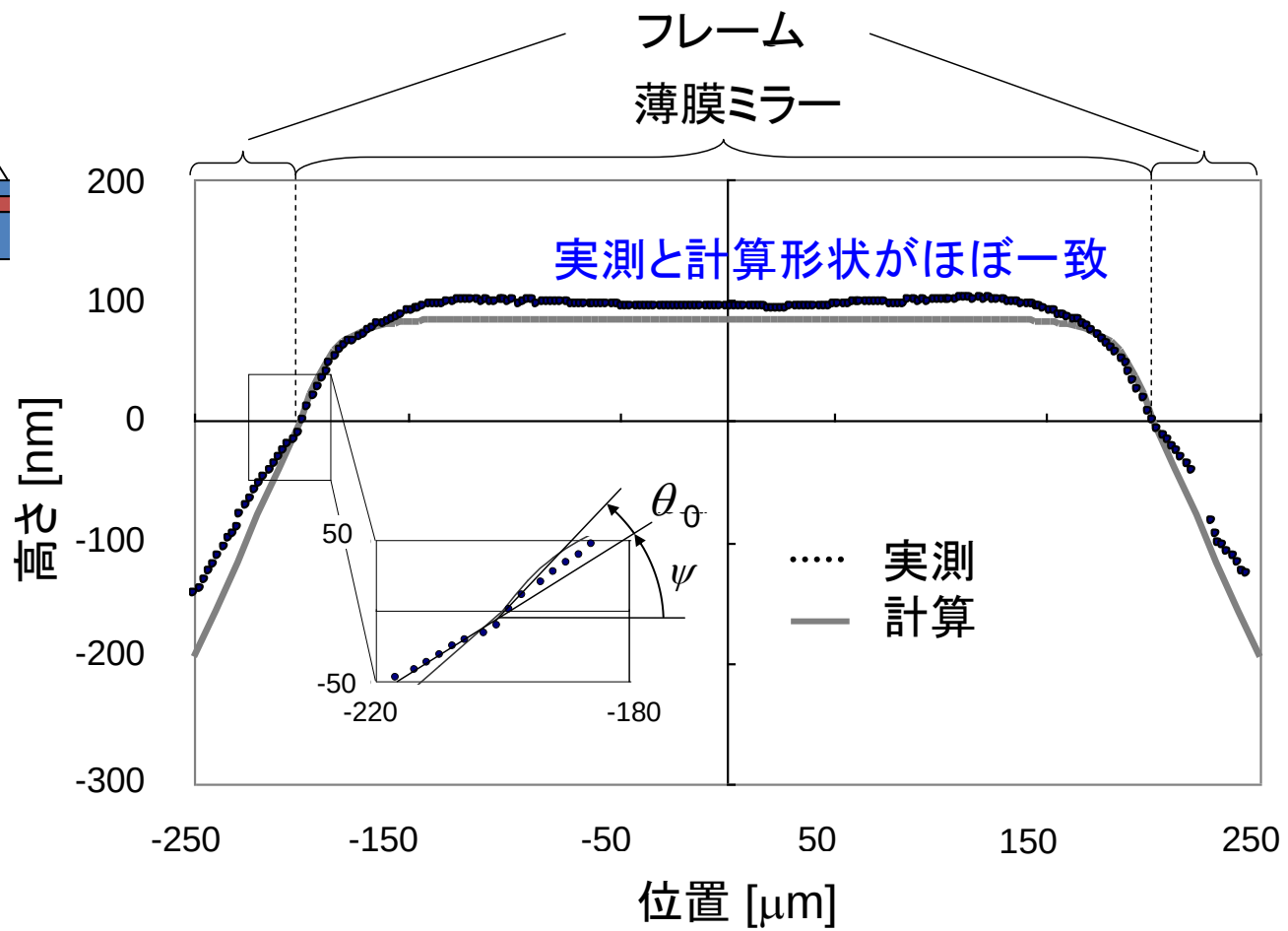
フレーム寸法と面内方向応力の関係

フレーム厚	フレーム幅	面内方向応力
大	小	小
小	大	大

薄膜ミラーの変形の実測と計算結果

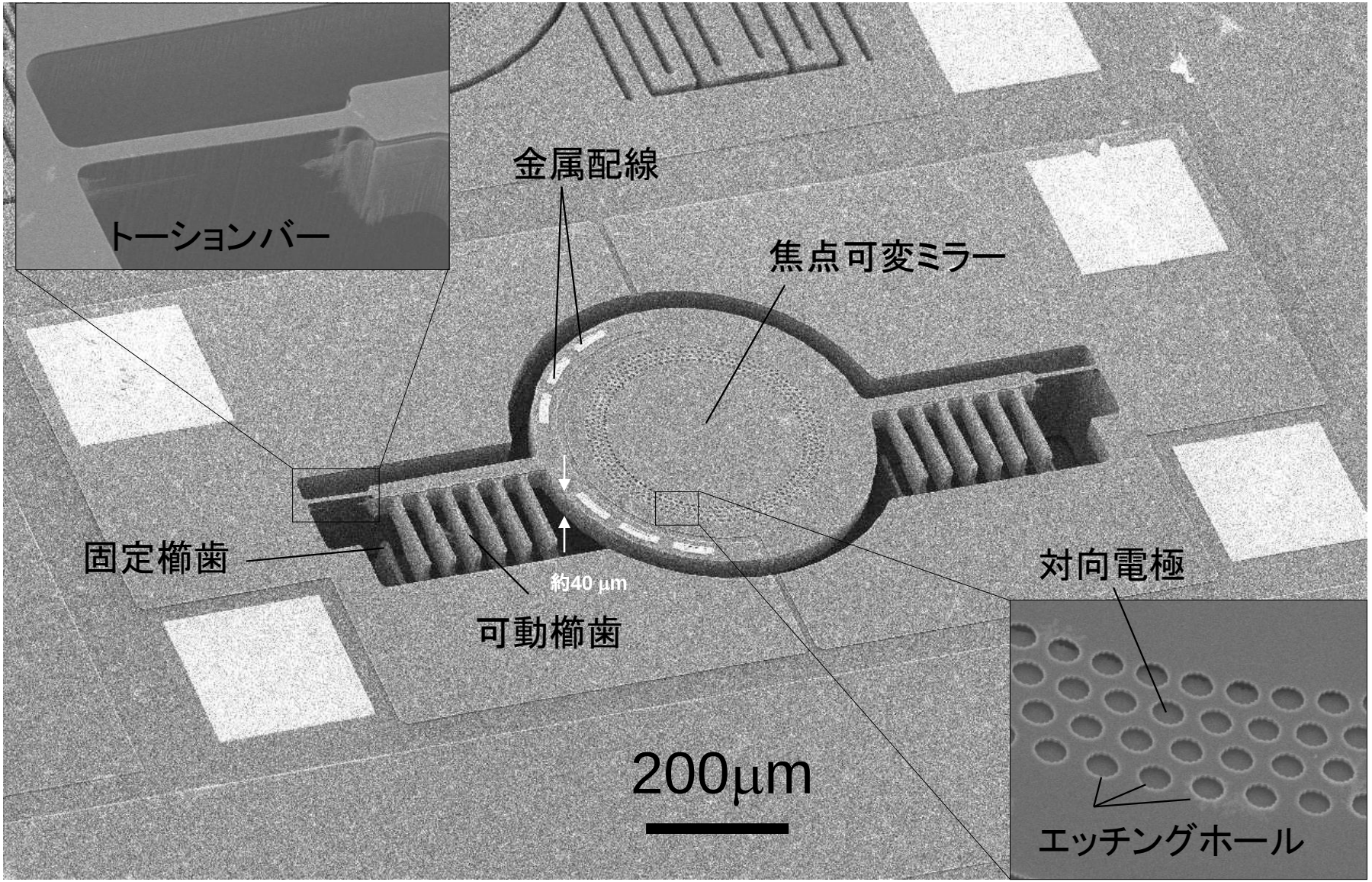


ミラー寸法

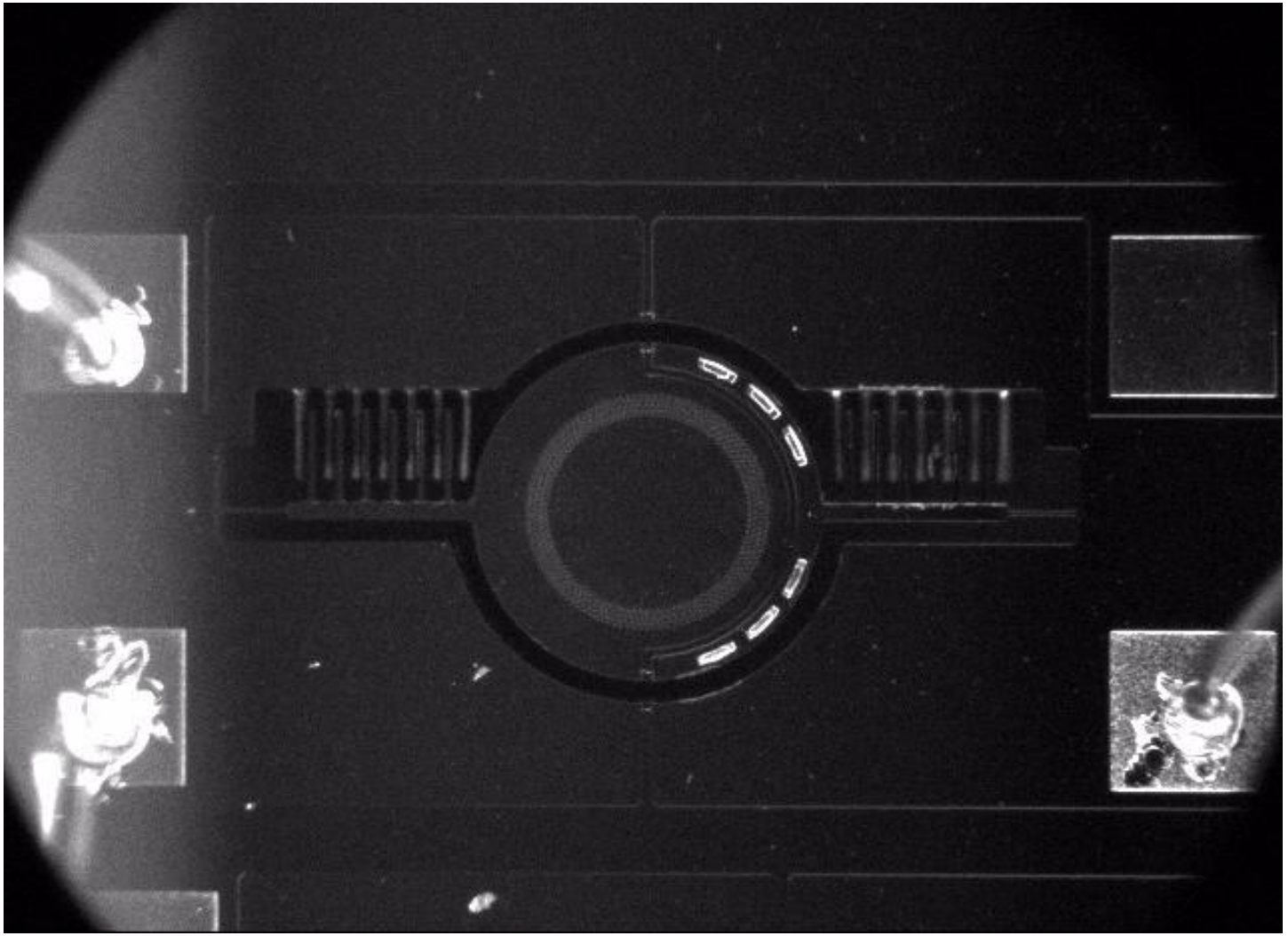


	測定結果	計算結果
フレーム回転角度 ψ	2.8 mrad	3.9 mrad
ミラー支持部たわみ角 $\psi + \theta_0$	4.7 mrad	6.2 mrad
ミラー面内方向応力 σ_0	20 MPa	47 MPa

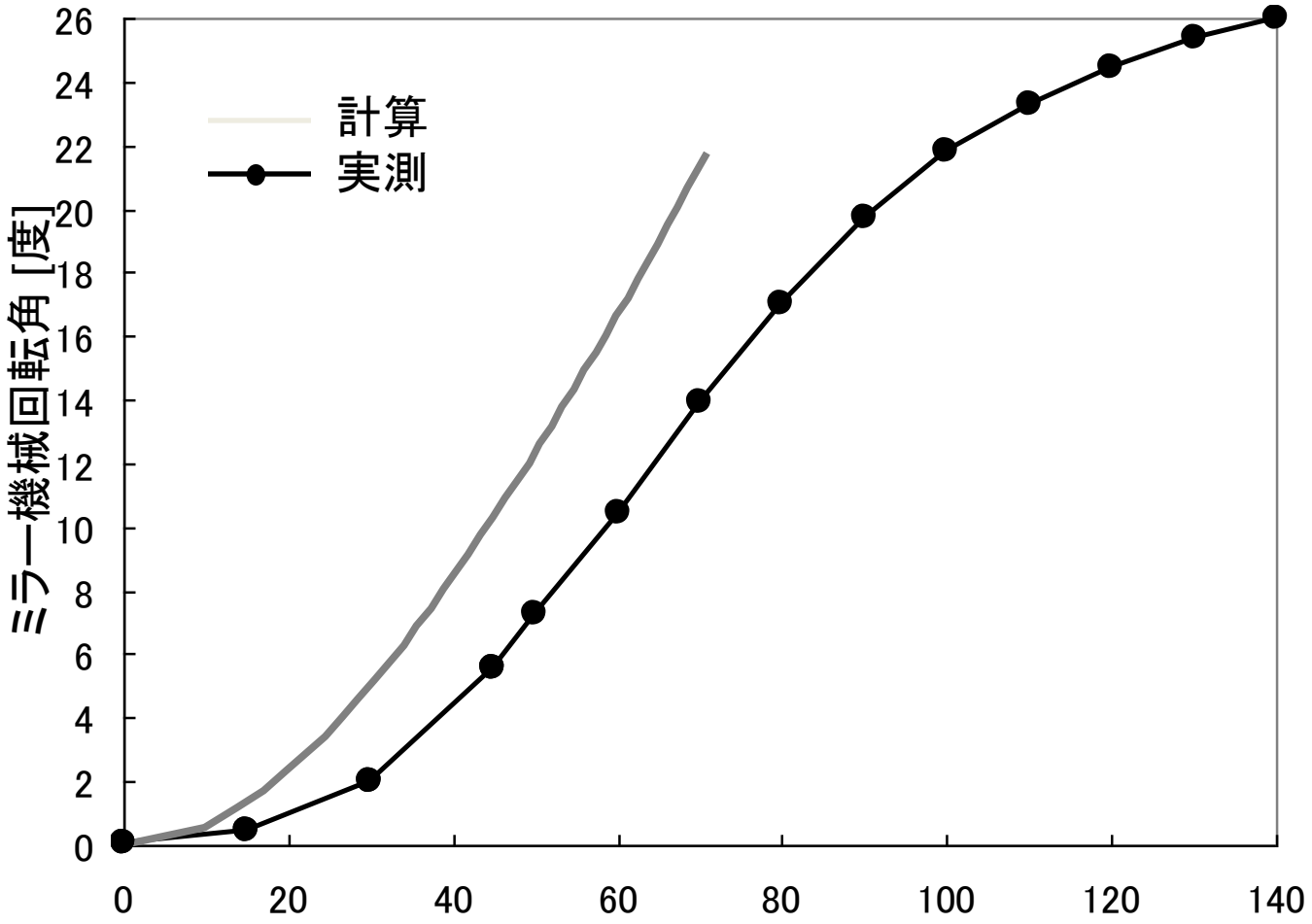
製作したデバイスのSEM写真



スキャナの駆動動画



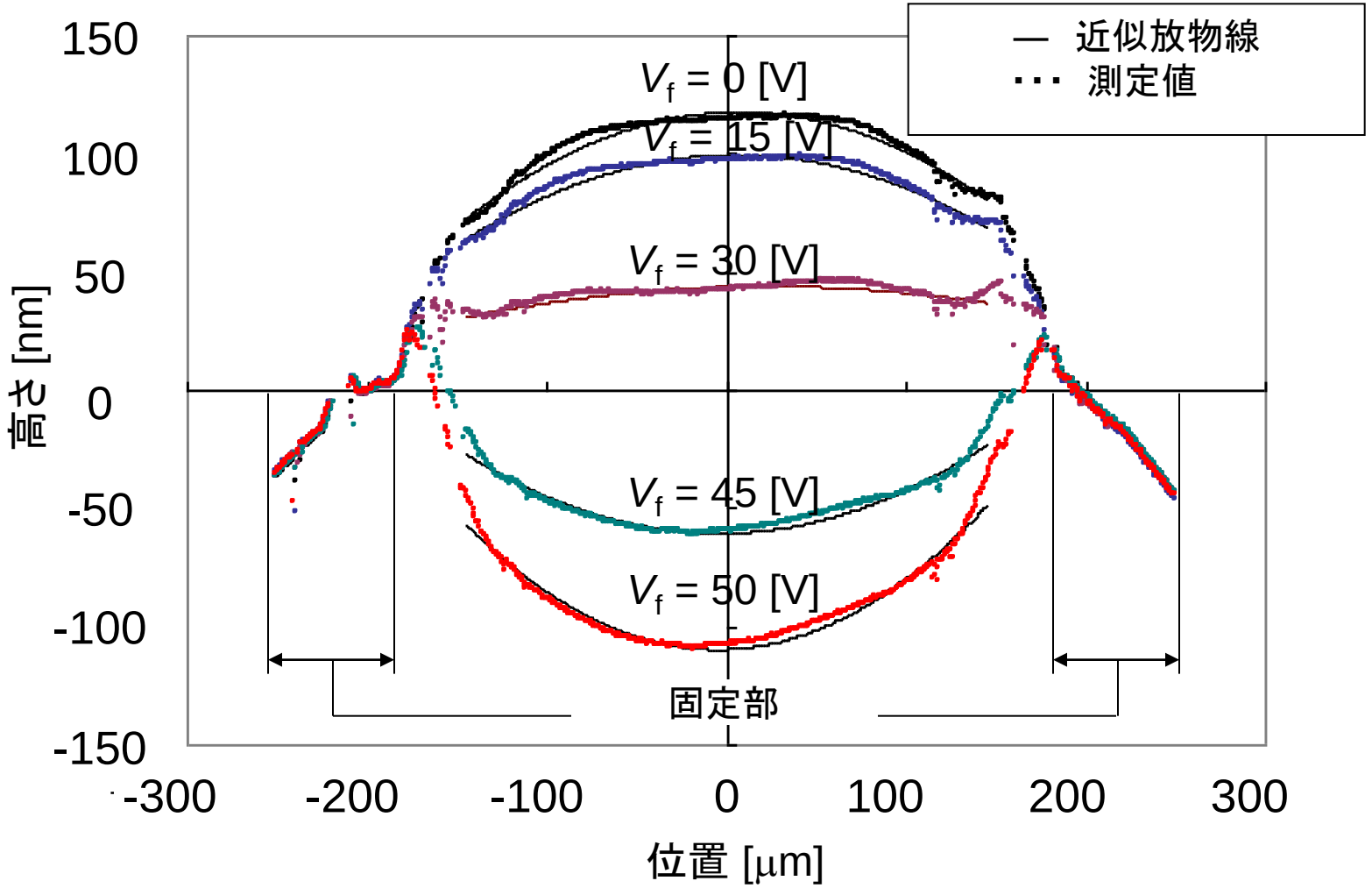
スキャナの静特性



スキャナ電圧V_sに対する回転角

140 Vの電圧印加でも電気的ショートや櫛歯のプルインが発生することなく26度回転した。

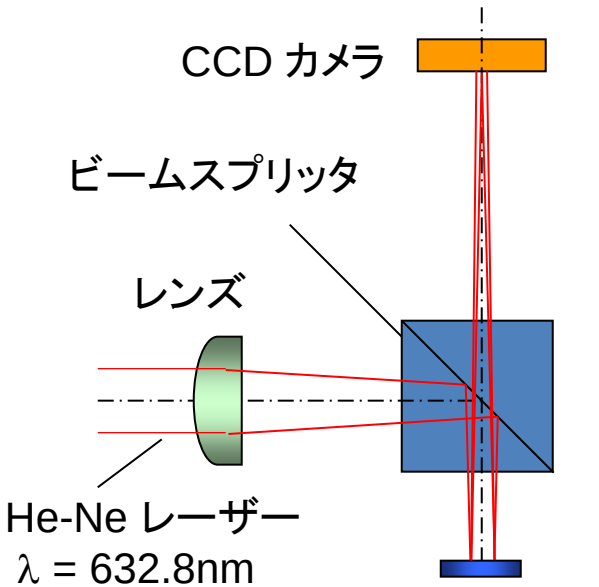
焦点可変ミラーの変形特性



各焦点可変電圧 V_f における焦点可変ミラーの断面形状

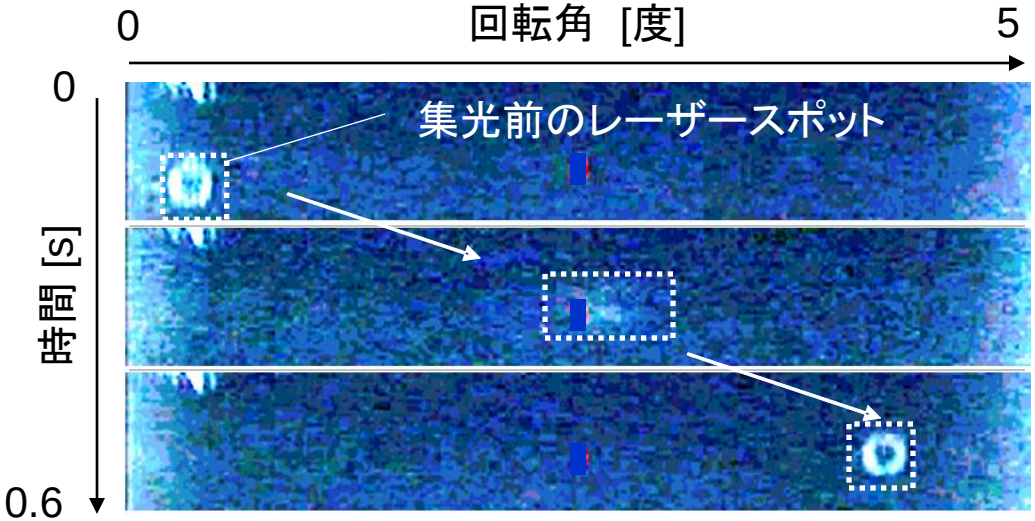
電圧印加と共に徐々に凹面形状に変形した。
座屈変形のような不安定な動作や、電気的なショートは観測されなかった。

焦点と走査の同時駆動実験

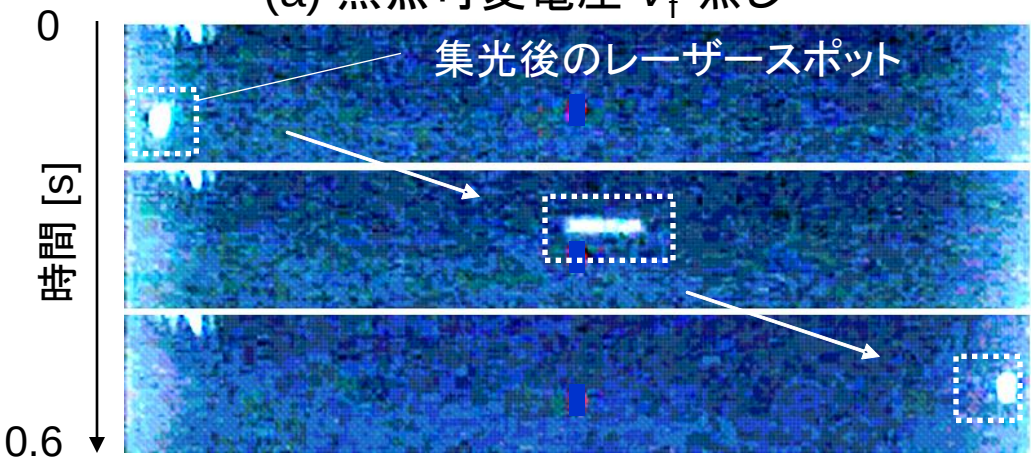


レーザースポット像測定
に用いた光学系

スキャナと焦点可変ミラーの駆動により
レーザー光走査と集光を同時にできることを確認した。



(a) 焦点可変電圧 V_f 無し



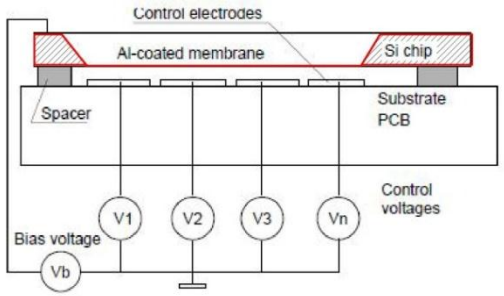
(b) 焦点可変電圧 V_f 有り

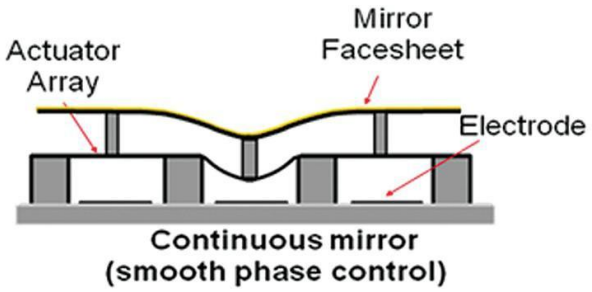
スキャナと焦点可変ミラーの
同時駆動時のビーム走査像

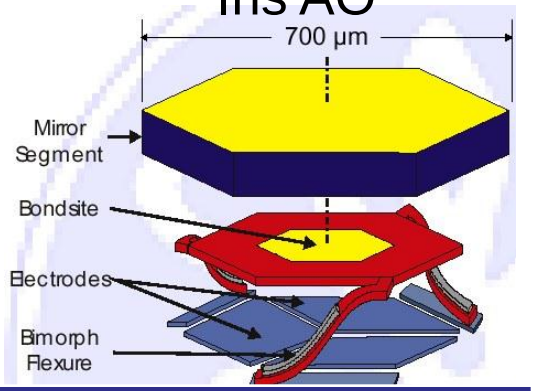
波面補償デフォーマブルミラーの製作

Introduction – MEMS-DM Development-

Single Membrane	laminate Membrane	Segmented
OKO	Boston Micromachines	Iris AO







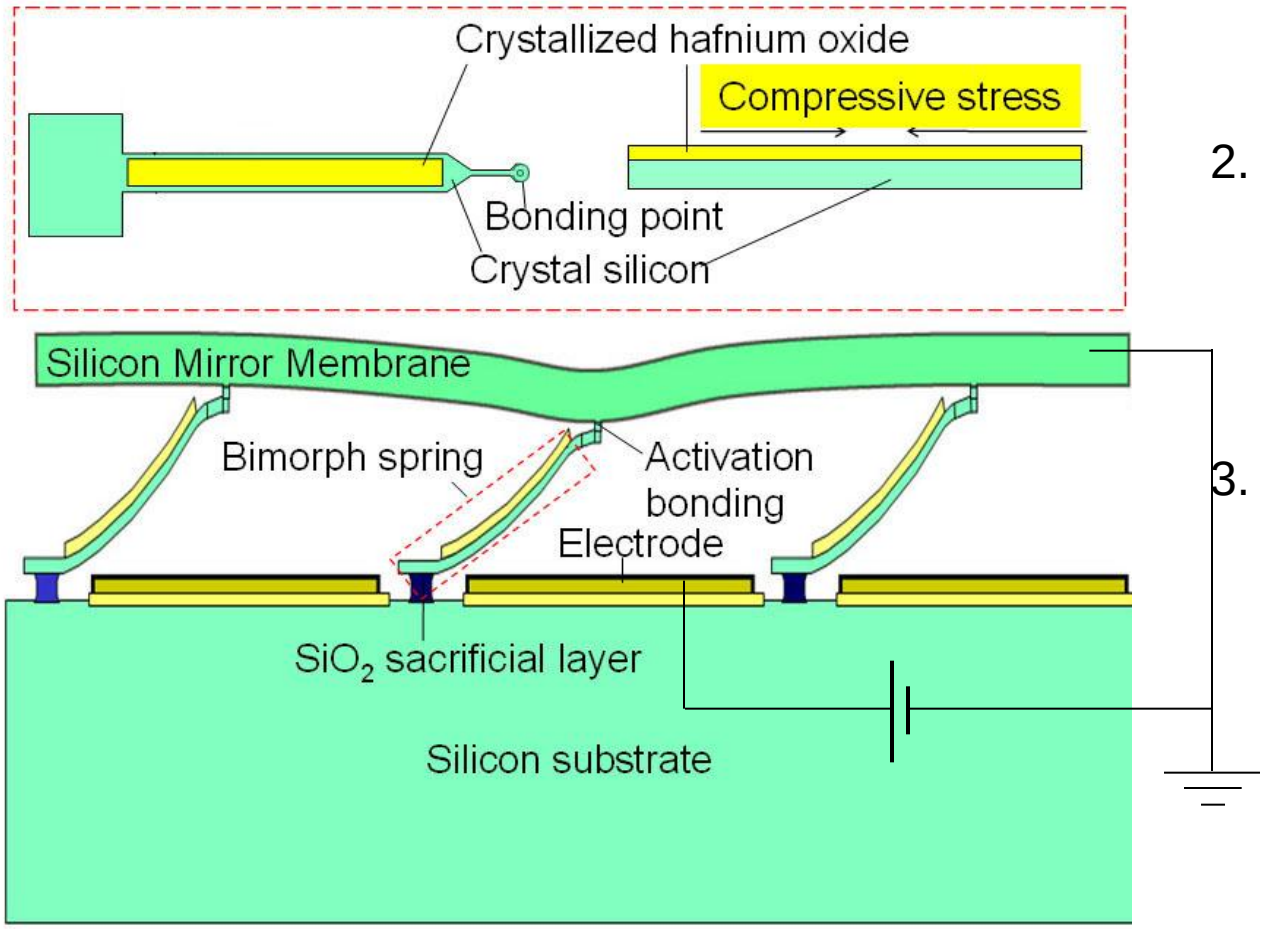
Element count<100 **Stroke>10µm(center)** **Small stroke at edge** **Element count not enough**	**Element count<4096** **Stroke not enough (<5µm)**	**Element count>100** **Stroke>10um** **Diffraction occurs at the pitch between the segmented mirrors**

The stroke of the electrostatic actuated DM is usually limited by the air gap between the electrodes and the mirror membrane. Air gap is usually generated by

1. Surface micromachining(sacrificial layer deposition → etching) cannot generate a big vertical gap which is limited by the thickness of the sacrificial layer.
2. Wafer bonding process can generate a large air gap by bond a mirror membrane to a micro-post array.

MEMS-DM – Main design -

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

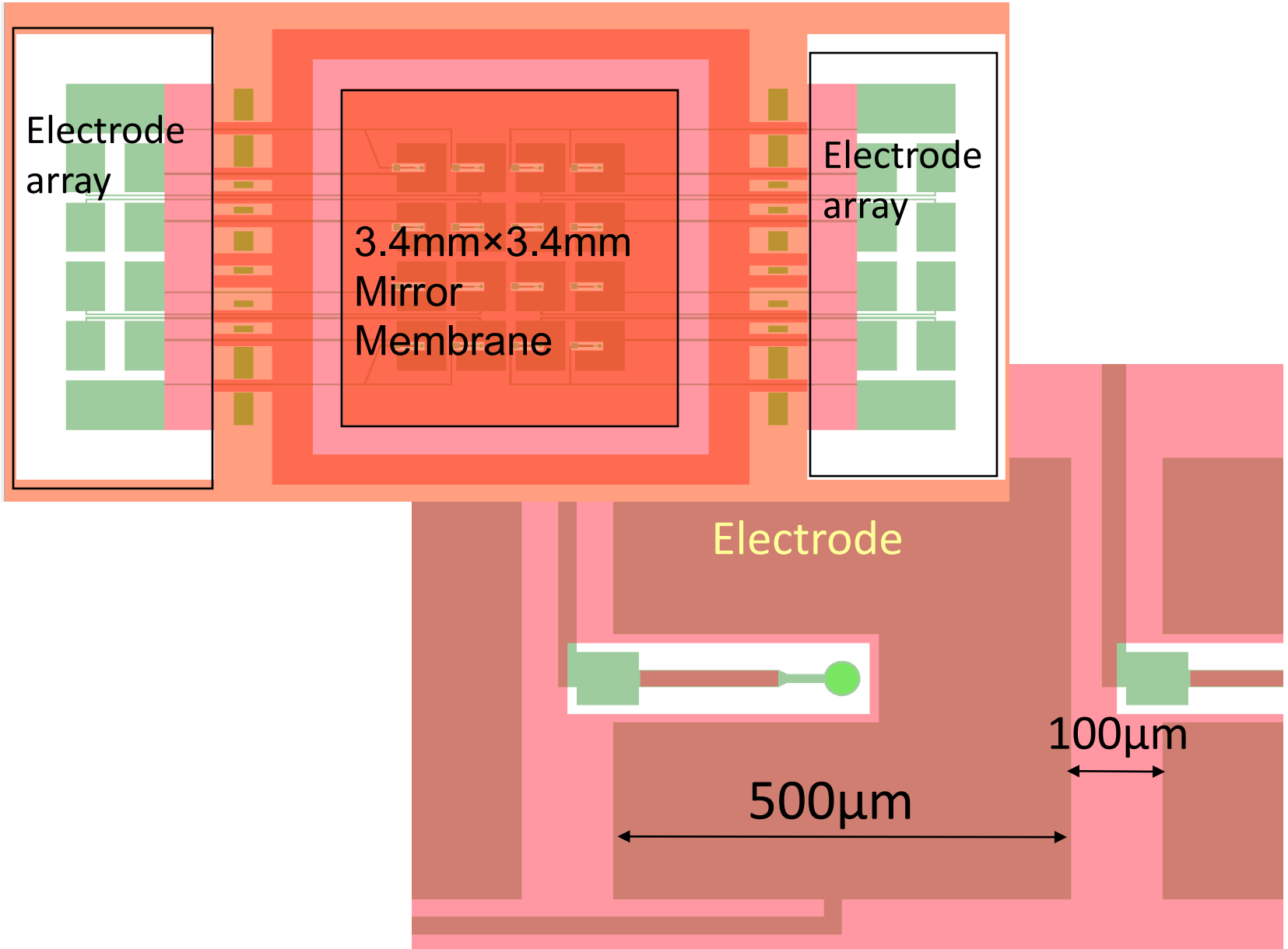


1. HfO_2 crystallization-induced stress is used to introduce large air gap.
2. Relatively soft spring structure (small spring constant) instead of fixed posts is used to increase the stroke.
3. High optical quality mirror surface is guaranteed by the top layer of SOI wafer and the wafer bonding process.

High-stroke MEMS-DM Structure

MEMS-DM – Design -

3. design overview



MEMS-DM – Design -

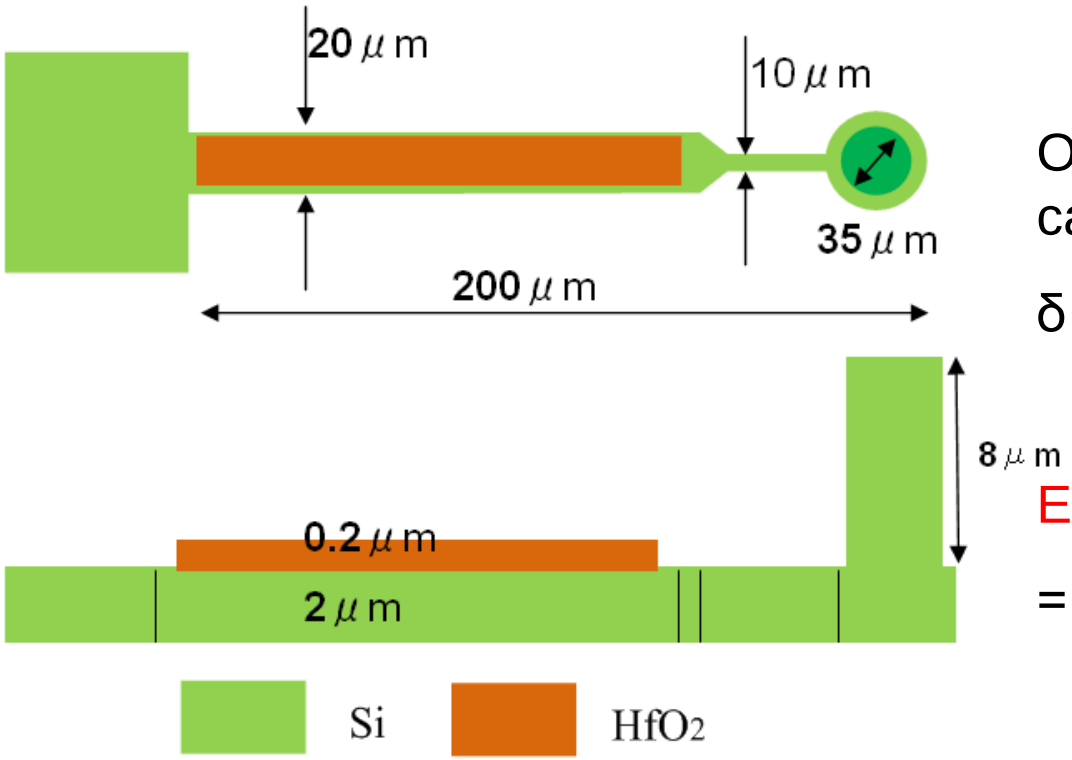
1.The dimension of bimorph spring for MEMS-DM

Target stroke: 20μm

For the Parallel-plate actuator , it is demonstrated that range of motion is limited to less than one third of the initial gap

→ Initial gap>60μm

Length (μm)	Deflection before crystallization (μm)	Deflection After Crystallization (μm)	Film stress of the crystallized HfO_2
100	9.20	33.72	2.11Gpa
200	38.06	131.86	



Out-of –plane Deflection calculated to be :

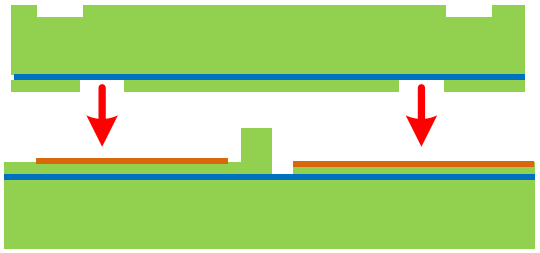
δ= 48.7μm

Electrode gap

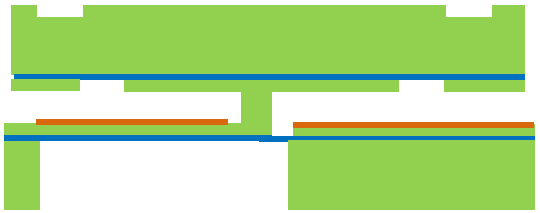
= δ+ 10μm= 58.7μm

MEMS-DM –Fabrication flow：Bonding and Release

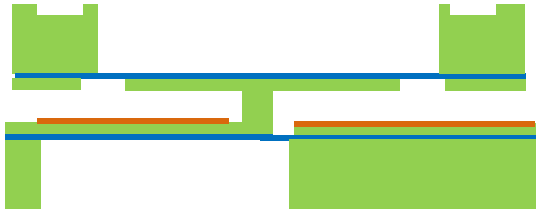
(3-a) Plasma activated bonding



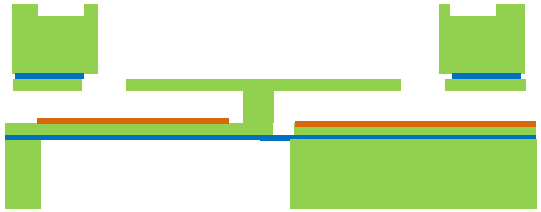
(3-b) Actuator chip handle layer etching



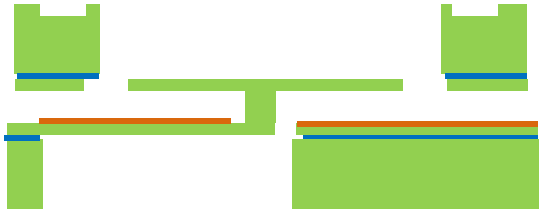
(3-c) Mirror chip handle layer etching



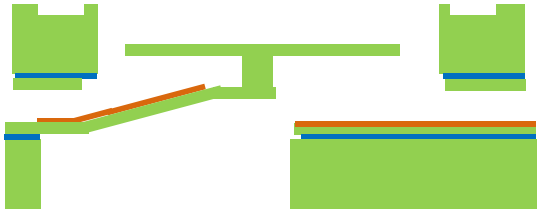
(3-d)SiO_2 Dry Etching (CHF_3)



(3-e) SiO_2 Dry Etching (CHF_3)



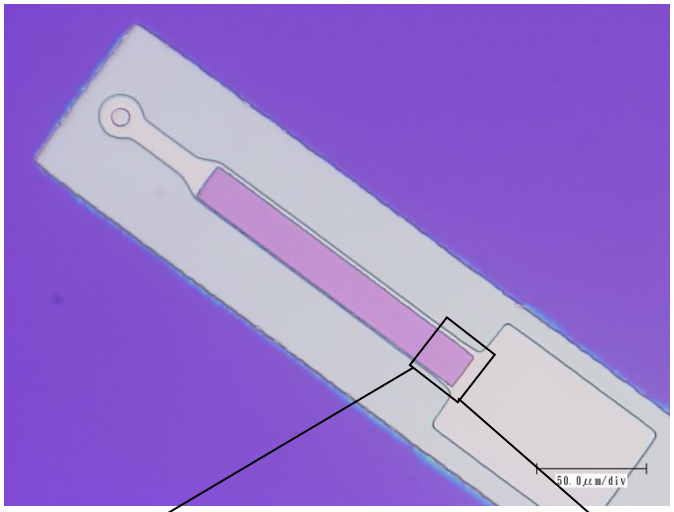
(3-f) Annealing (HfO_2 crystalliztion)

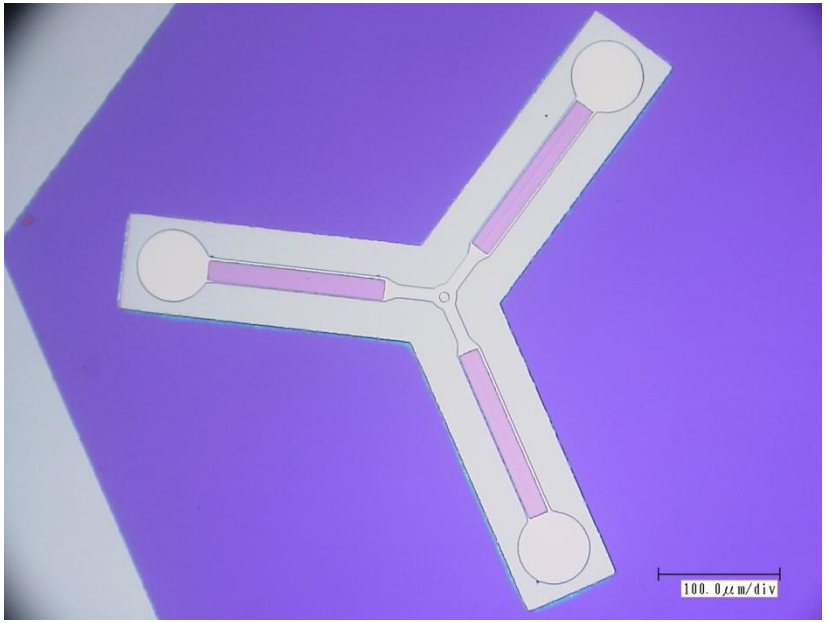


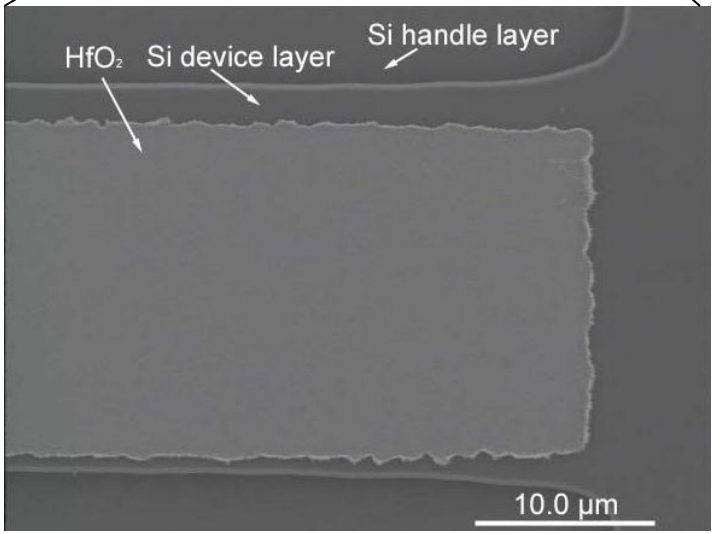
Si SiO_2 HfO_2

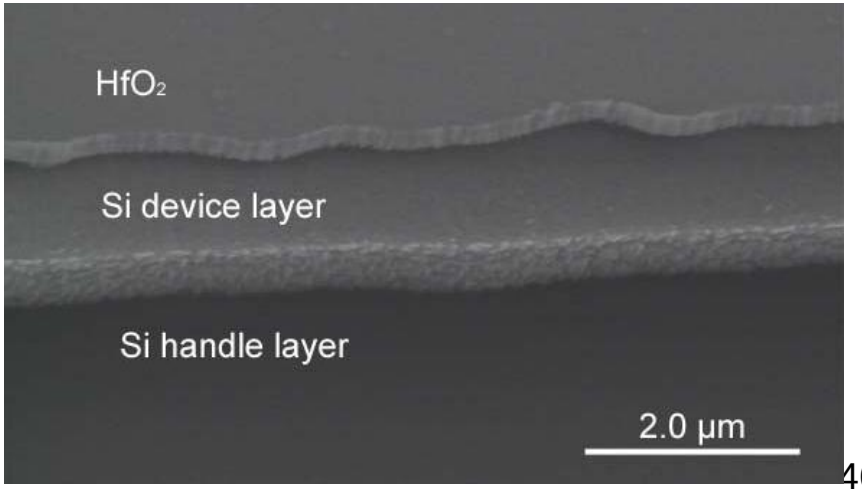
MEMS-DM –Actuator chip-

Actuator Fabrication: Microphotos & SEM Images







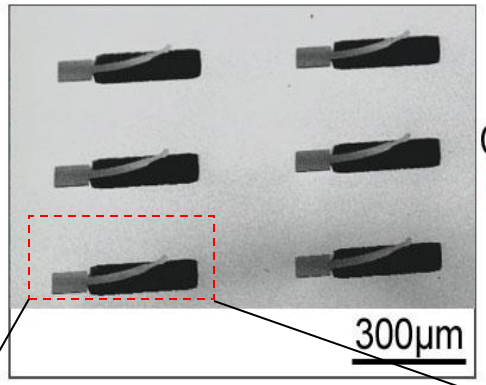


MEMS-DM – Si/HfO2 Bimorph spring

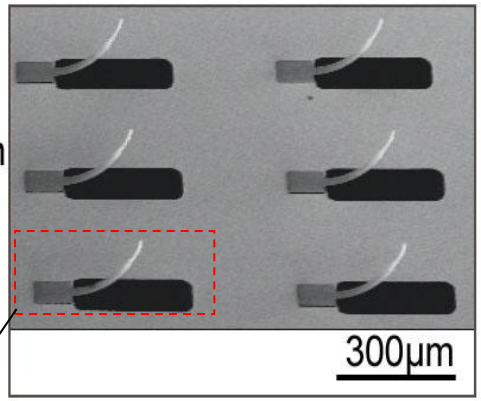
Fabricated bimorph spring

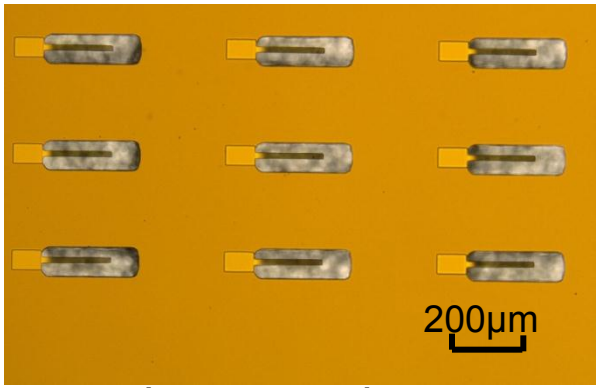
結晶化させる前

結晶化させた後

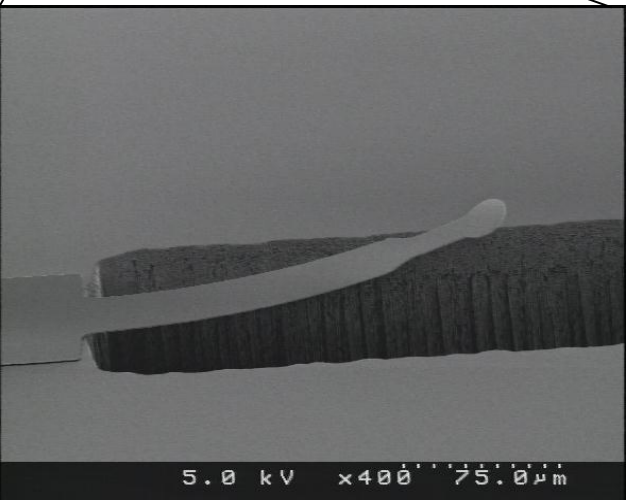


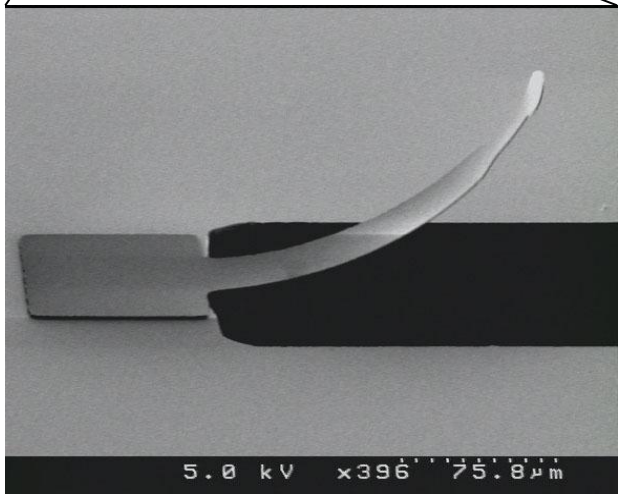
HfO2
Crystallization

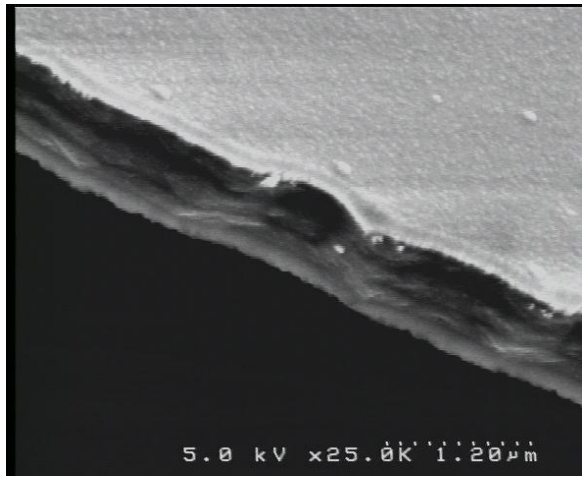




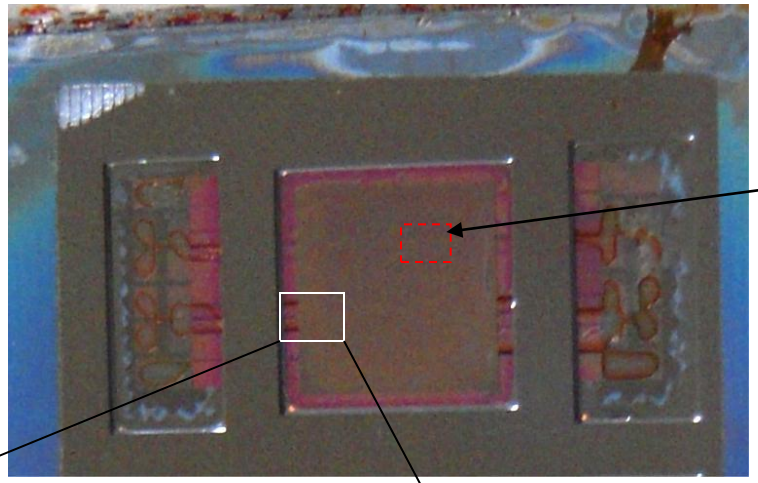
Microscope image







MEMS-DM – Static Deflection Measurement



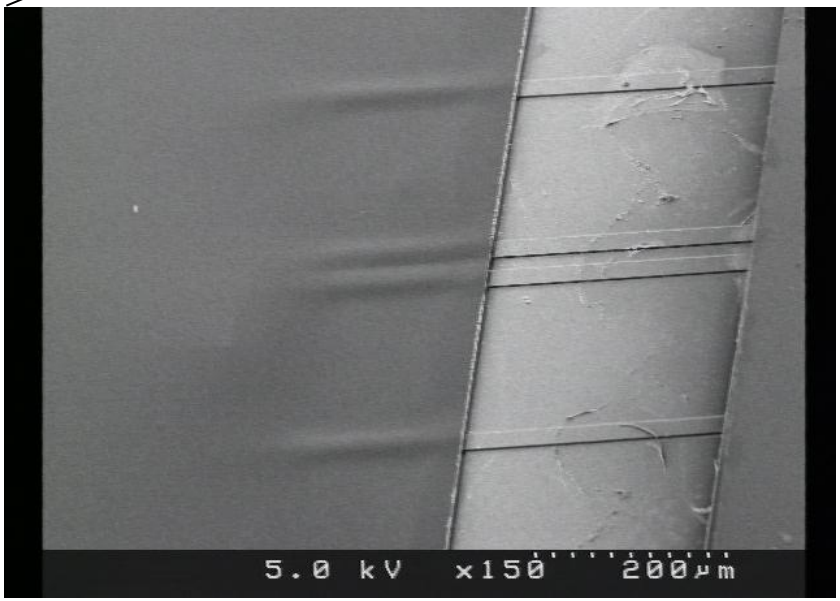
駆動する所

*電極面積 500*μm × *500*μm

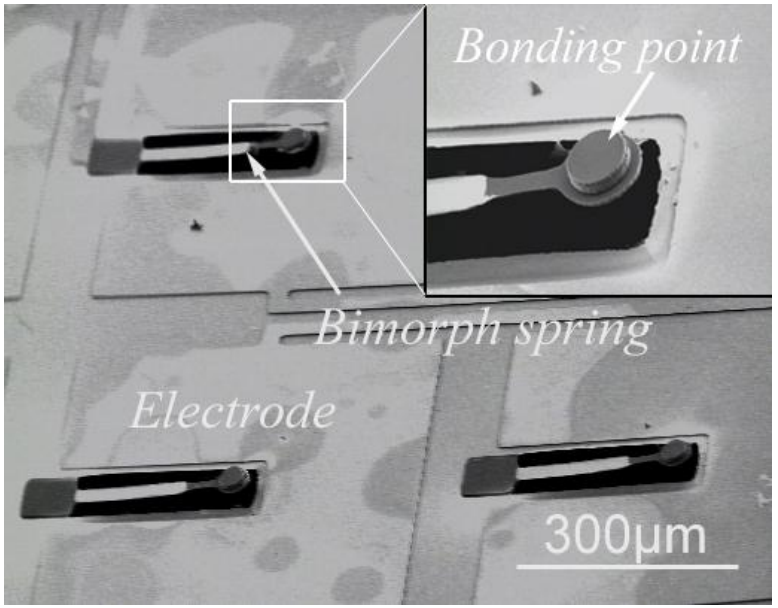
測定したミラーエリア

900μm × 670μm

fabricated Deformable mirror

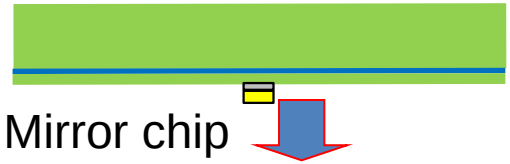


mirror edge sticked to the substrate

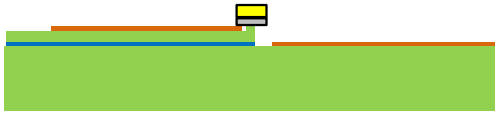


bimorph spring array

Because the plasma activated bonding requires extremely strict conditions(<2nm surface roughness, high surface cleanliness), another stable bonding process is investigated for the fabrication of MEMS-DM.

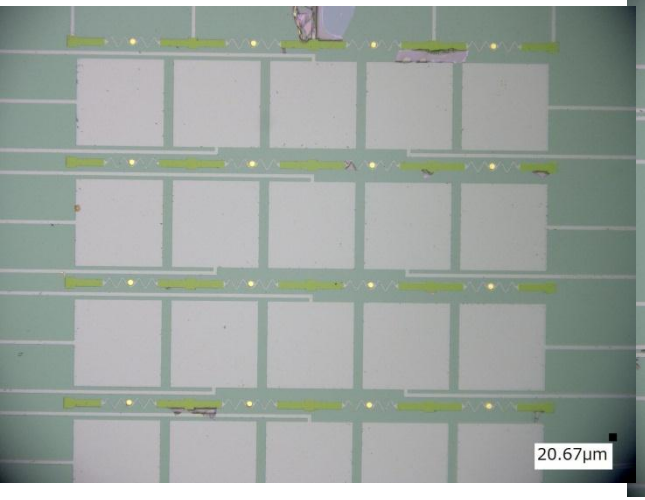


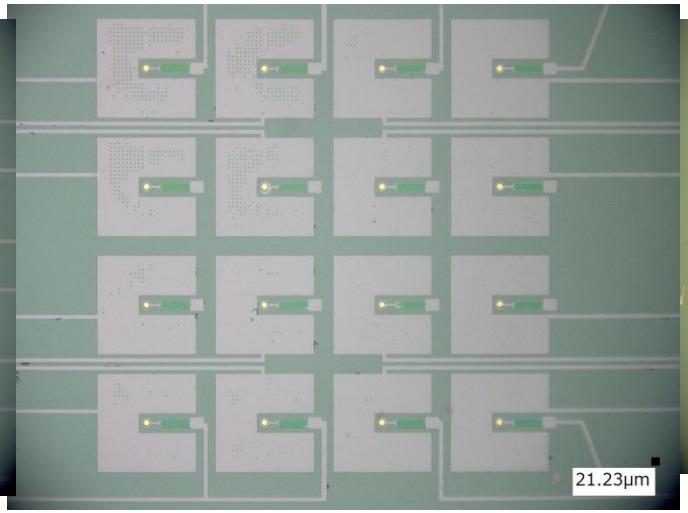
Mirror chip



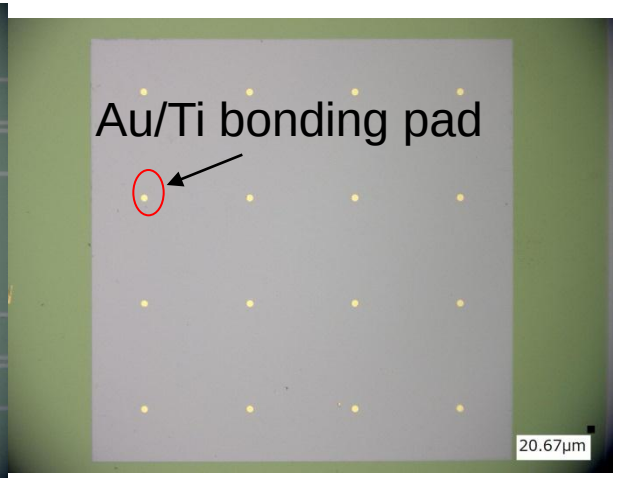
Actuator chip

Bonding pad: Ti/Au , Ti: 50nm, Au: 200nm;
Ti is used to react with the native oxide layer on the bare Si surface which will result in the poor bond quality of the Au/Si bonding structure.



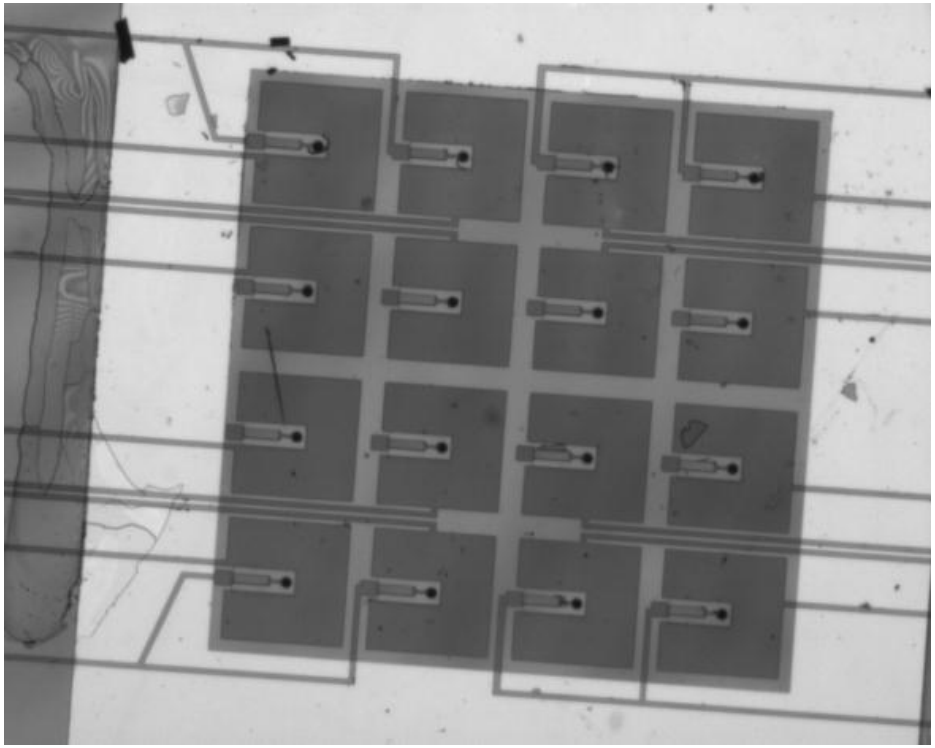


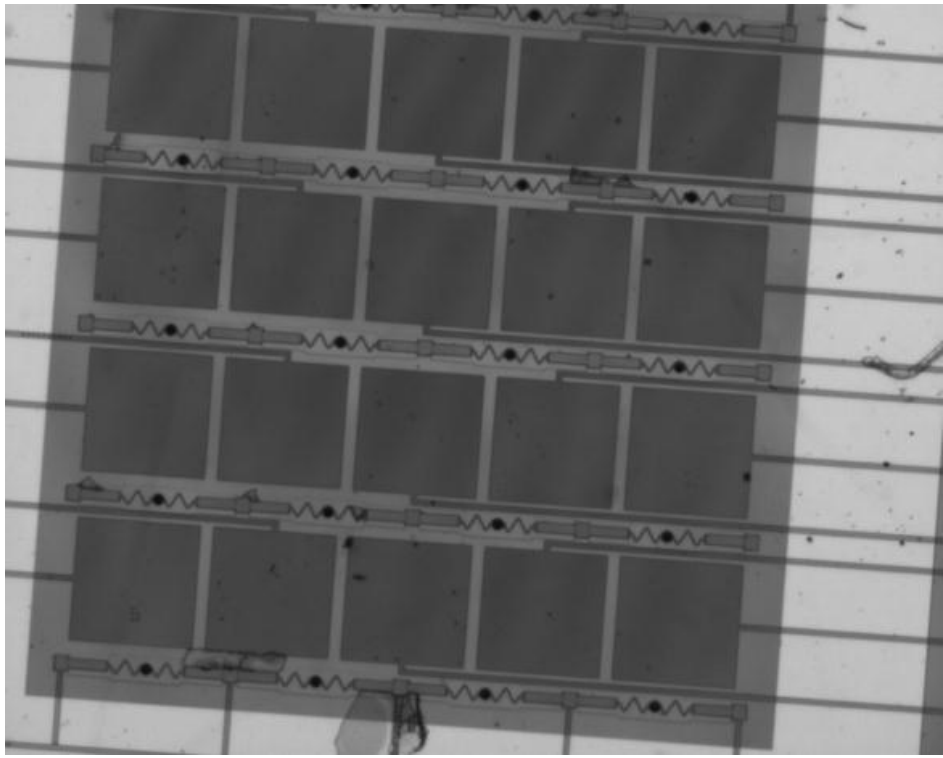
Actuator chip



Mirror chip

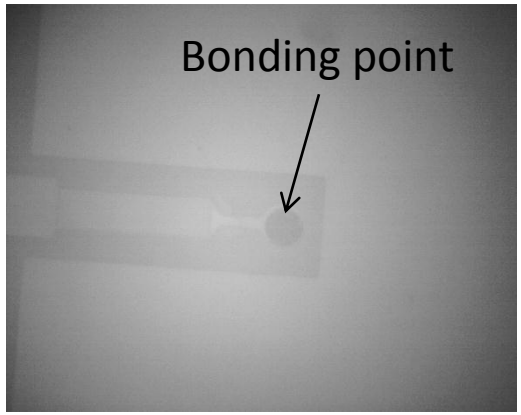
MEMS-DM – IR micrograph

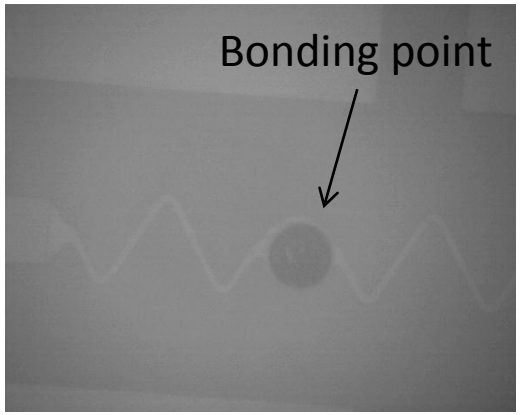




3.4mm×3.4mm continuous mirror

Bonding condition
Temperature: 400℃
Time: 30min
Pressure: 1.7 MPa
(EVG bonder: 0.4MPa)





まとめ

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   - 可変格子
   - 集積型センサ
   - Si導波路干渉計

2. 焦点可変デフォーマブルミラーの製作
   - 曲げモーメント駆動による焦点可変ミラー
   - 焦点可変ミラーを備えた光スキャナー
   - 波面補償デフォーマブルミラーの製作