Self-Positioning Micromachined Structures Made by Micro-Origami

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Introduction

•Recently, we proposed and demonstrated a method to make self-positioned micromachined structures by using hinges that bend due to the strain in a pair of lattice-mismatched epitaxial layers [1].

•This method was applied to fabricate a standing mirror and a retro-reflector using epitaxial growth of III-V compound semiconductors [2].

• We demonstrated a method to make hinges that bend upward, called “tani-ori” (valley-fold) in origami, the Japanese paper folding art, and downward, called “yama-ori” (mountain-fold) from the same epitaxial layers, opening the way to fabricate more complex three-dimensional structures [3].

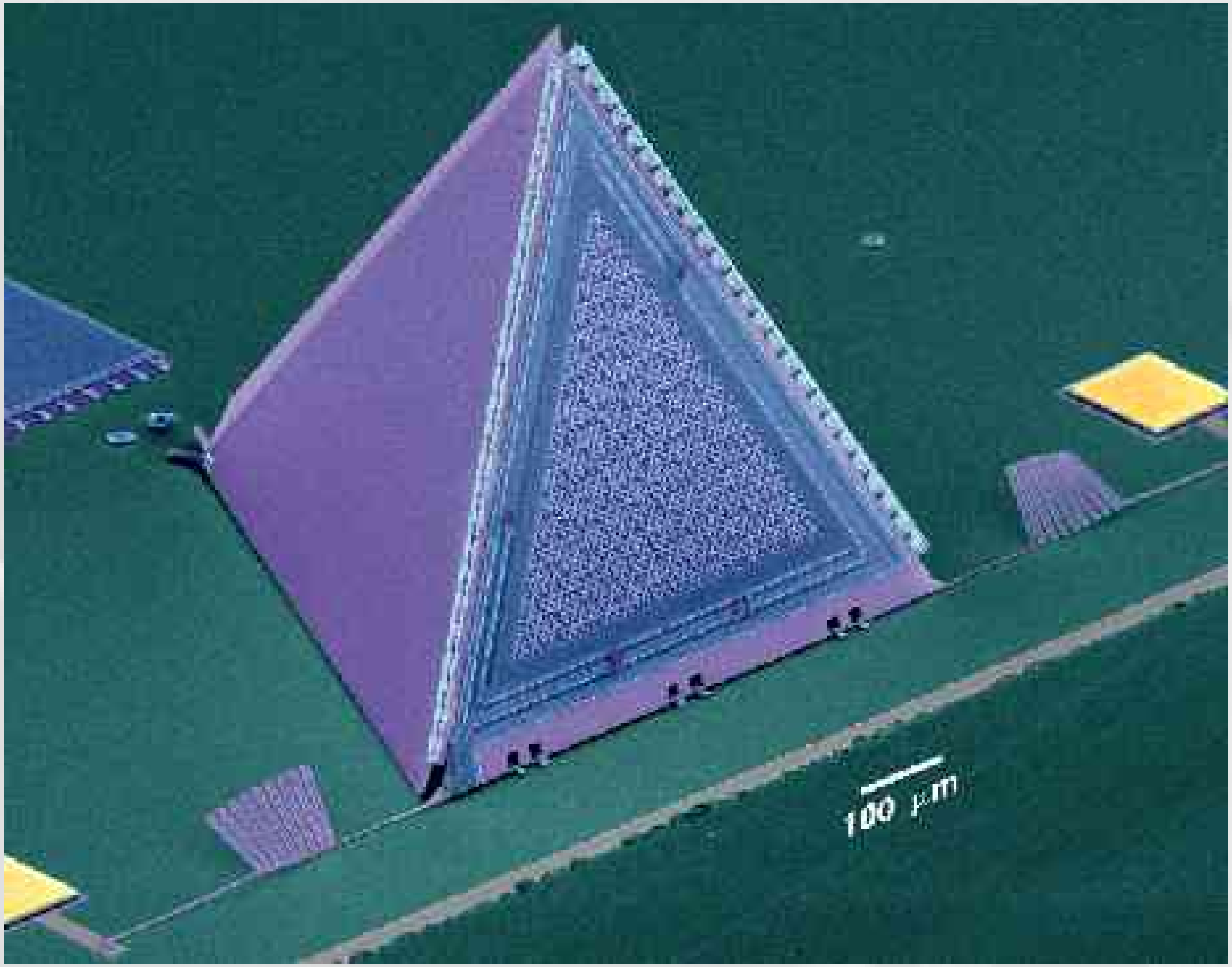
• Currently, we are working in electrostatic actuation of micro-origami devices and fabrication with SiGe epitaxial layers on SOI substrates.

[1] **P. O. Vaccaro**, K. Kubota and T. Aida, Applied Physics Letters**78**, 2852-2854 (2001).

[2] **P. O. Vaccaro**, K. Kubota and T. Aida, 28th International Symposium on Compound Semiconductors (ISCS-28), Tokyo, Japan, October 1-4, 2001.

[3] **P. O. Vaccaro**, K. Kubota, T. Fleischmann, S. Saravanan, T. Aida, Microelectronics Journal, 34 (2003) 447.

First all-surface micromachined microphone



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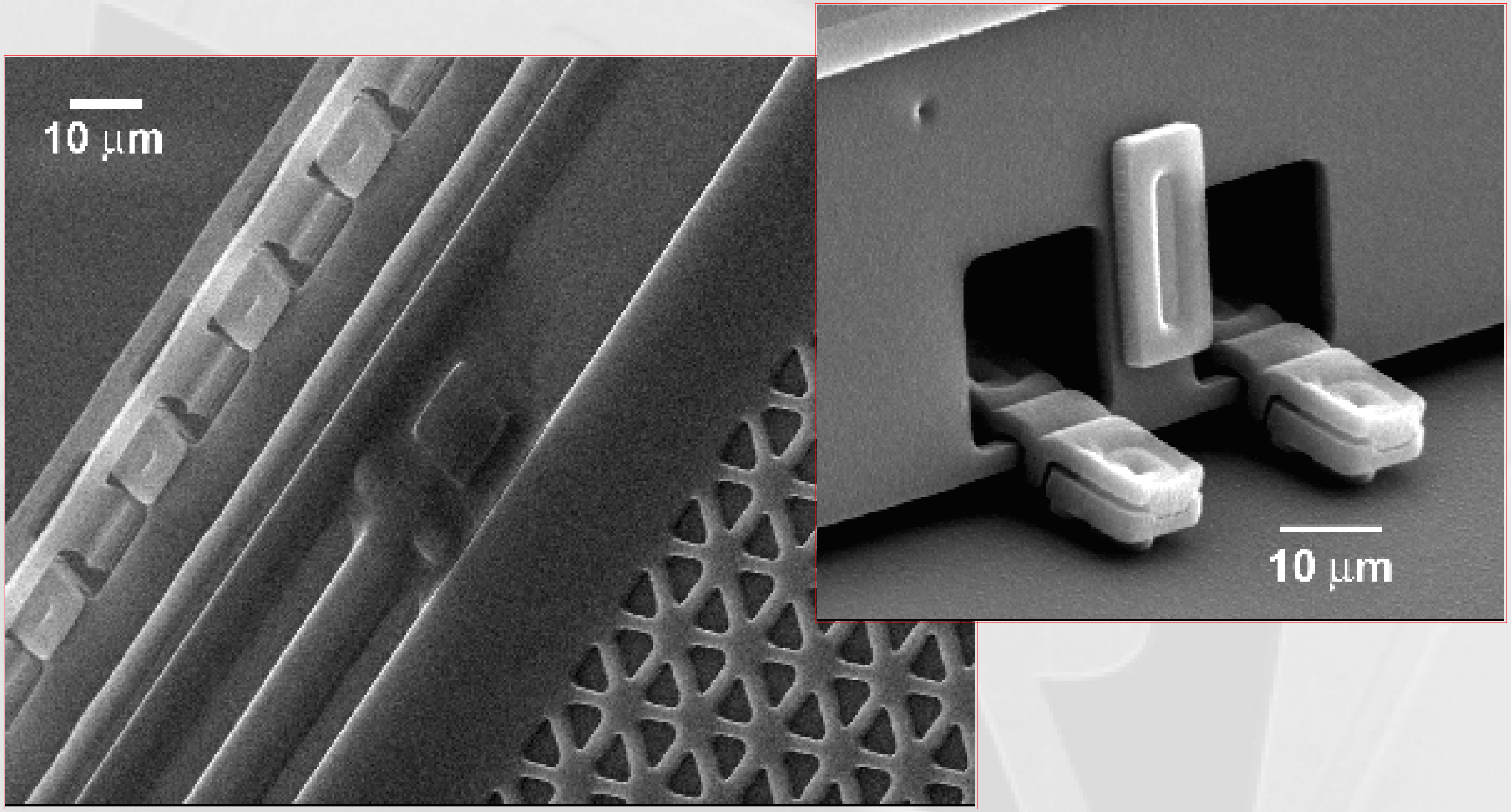
Detail of the hinges



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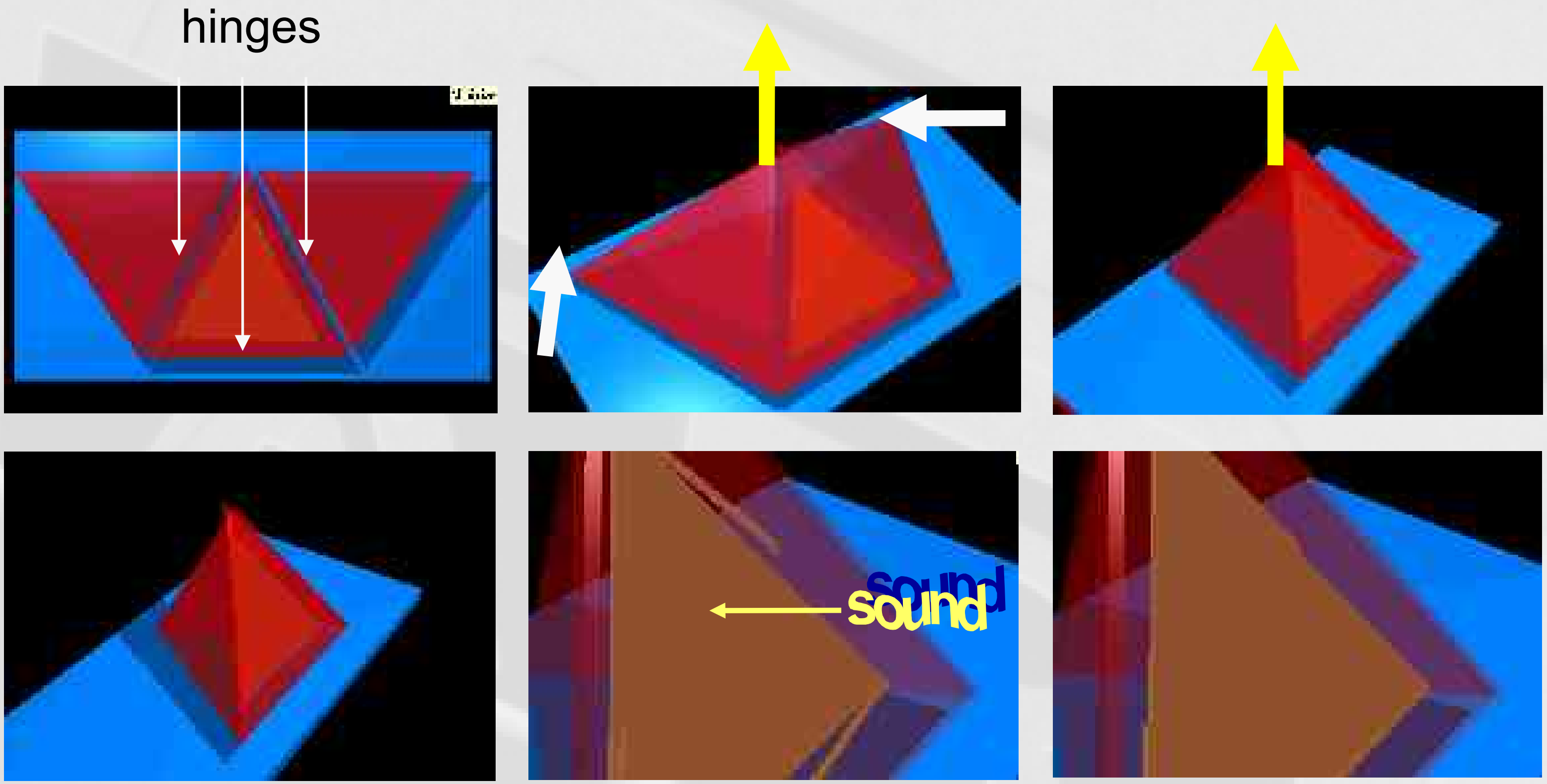
Assembly and working principle



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Purpose

Overcome perceived limitations in the surface micro-machining method used to fabricate MEMS (Micro Electro Mechanical systems)

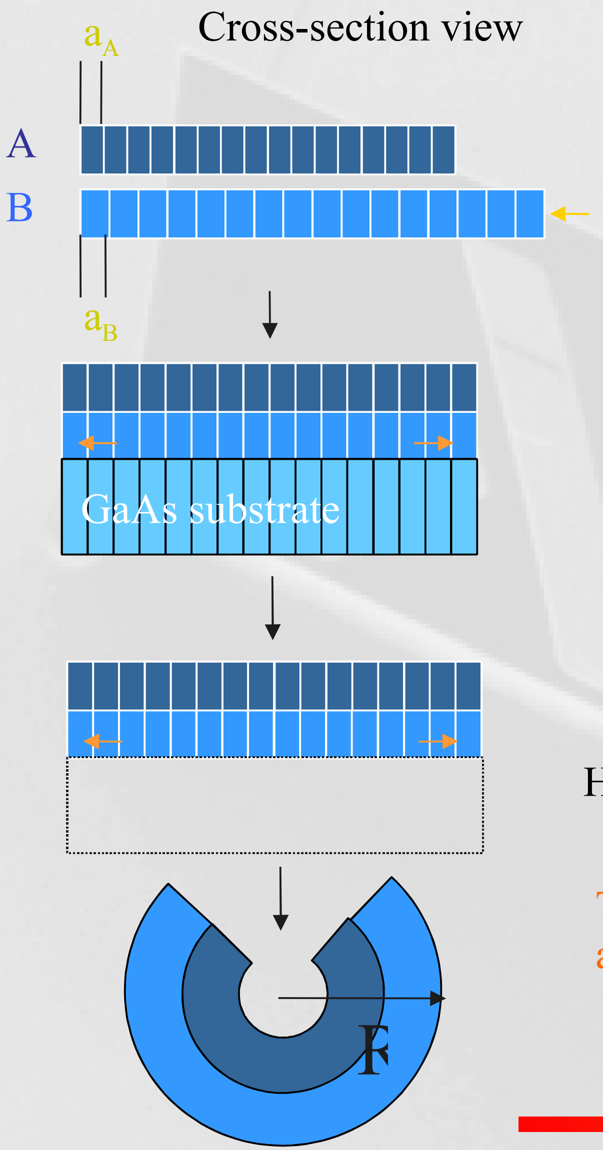
Surface Micromachining

3. Polycrystalline plates: surfaces are not very smooth or flat, mechanical strength is reduced, fatigue and corrosion increases (at grain boundaries).
4. Complex hinge structure: hinges are made with multiple parts, that require more precise lithography, become easily stuck, degrade by friction.
5. Manual or complex actuators to position and assemble structures: plates and other components have to be positioned manually, or complex electrostatic engines or scratching actuators have to be fabricated together.
6. Optoelectronic devices have to be added and aligned later: surface micromachining is made on silicon substrates by piling up polycrystalline layers. These materials are not suitable for active optoelectronic components.
7. Scalability limited to plates of 10 microns order when using standard tools due to smaller mechanical components in hinges.

Micro-origami

3. Single-crystalline plates: very smooth and flat surfaces, high mechanical strength, no fatigue and decreased corrosion.
4. Simple hinge structure: hinges are formed by a thin flexible layer, with no sliding parts that could stuck or degrade by friction.
5. Self-positioning, self-assembling: plates and other components move to their final position by the strain force built in the layers during the crystal growth.
6. Integration with optoelectronic devices: technology based on III-V compounds, is the standard to make optoelectronic devices.
7. Scalability: plates down to submicron order are feasible because the simple structure of the hinge does not impose limitations due to the lithographic process.

How does it work?



Choose two crystalline materials A and B with different lattice constant a ($a_A < a_B$)

Grow epitaxial layers of materials A and B on a substrate of material A

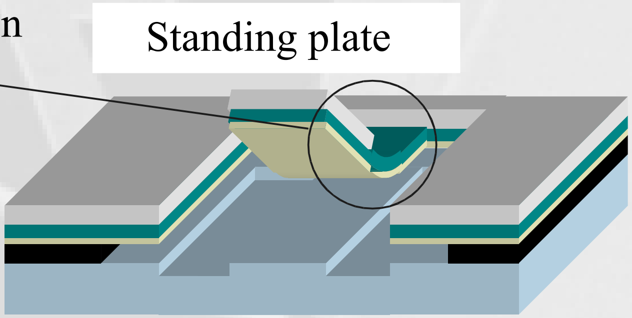
Layer B becomes biaxially compressed in the plane of the substrate

Adjusting material composition and thickness, and the size of the hinge allows control of the standing angle

Layers A and B are released by selective etching from the substrate and bend with a curvature radius R.

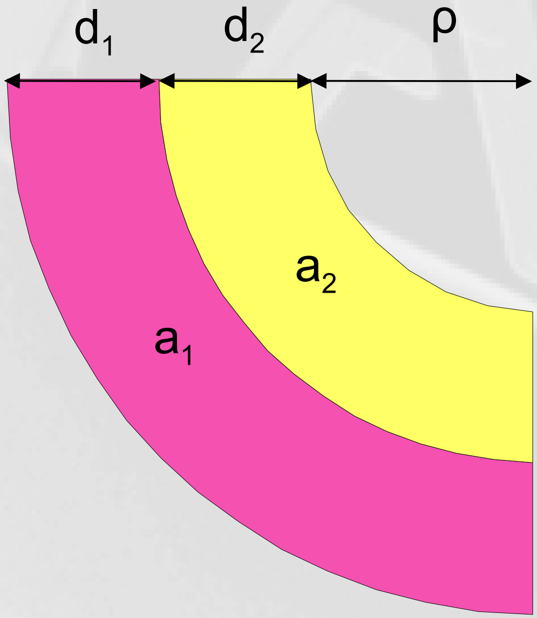
Hinge bends to release the strain

These layers can be used as a hinge between flat plates.



Curvature radius of a strained bilayer

$$\frac{1}{\rho}=\frac{6\varepsilon\,(1+m)^2}{d\left[3(1+m^2)+(1+m\times n)\left\{m^2+(m+n)^{-1}\right\}\right]}$$



ρ: Curvature radius

a_1, a_2 : Lattice parameter

d_1, d_2 : Layer thickness

Y_1, Y_2: Young modulus

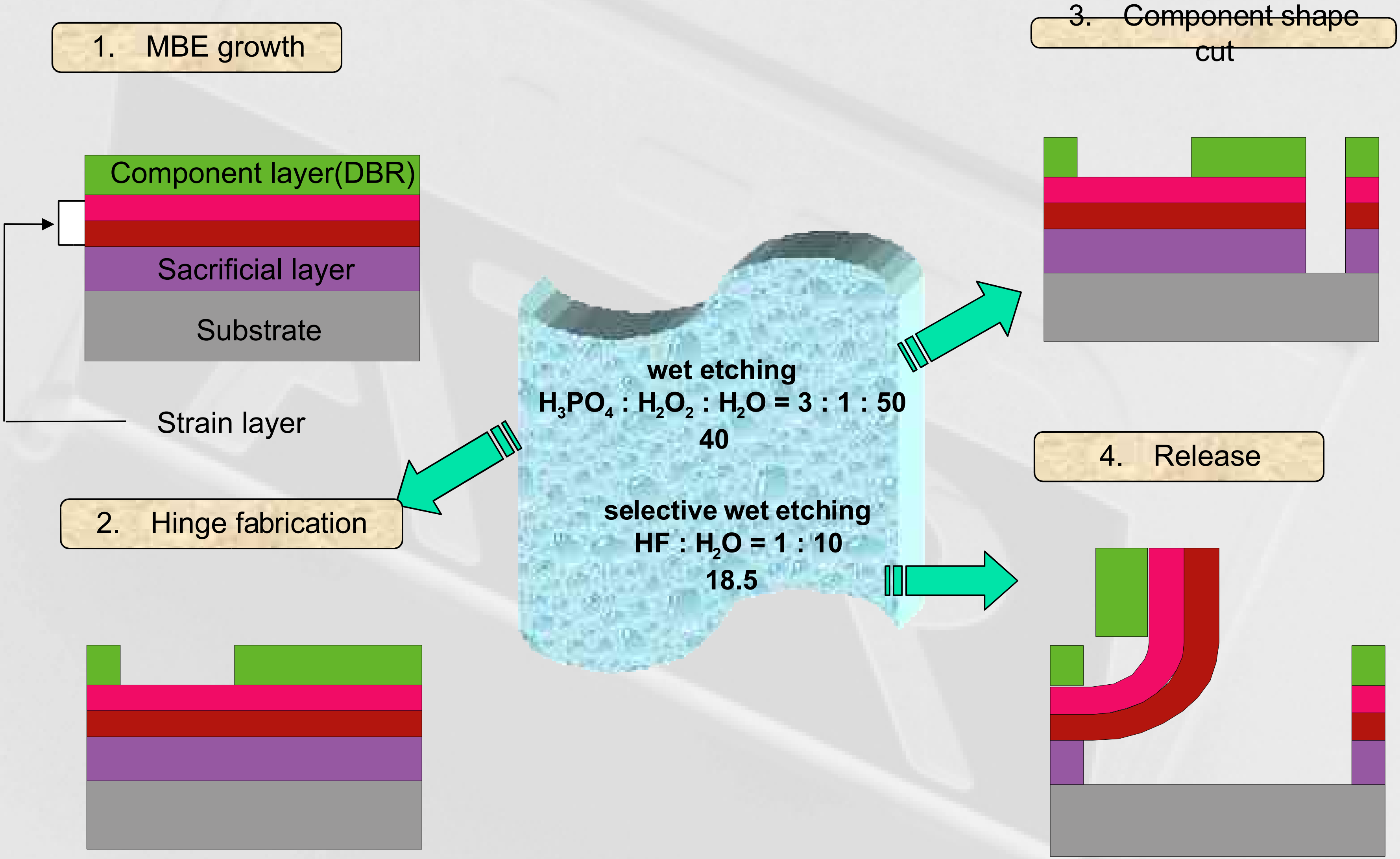
$\varepsilon=(a_1-a_2)/a_1$

$d=d_1+d_2$

$m=d_1/d_2$

$n=Y_1/Y_2$

Fabrication process of a standing plate



1. MBE growth

2. Hinge fabrication

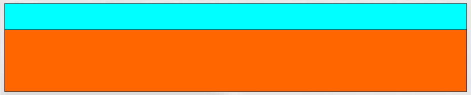
3. Component shape cut

4. Release

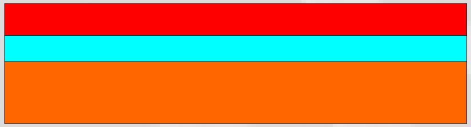
wet etching
$H_3PO_4 : H_2O_2 : H_2O = 3 : 1 : 50$
40

selective wet etching
$HF : H_2O = 1 : 10$
18.5

Conventional surface micromachining

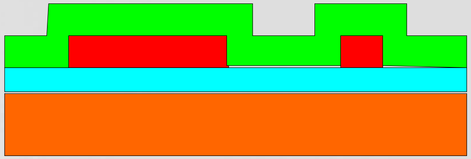


1. Oxide 1

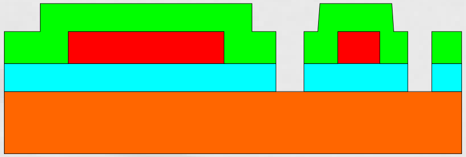


2. Poly 1

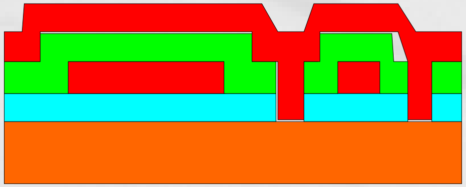
3. Litho 1



4. Oxide 2

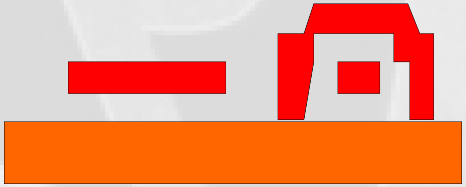


5. Litho 2



6. Poly 2

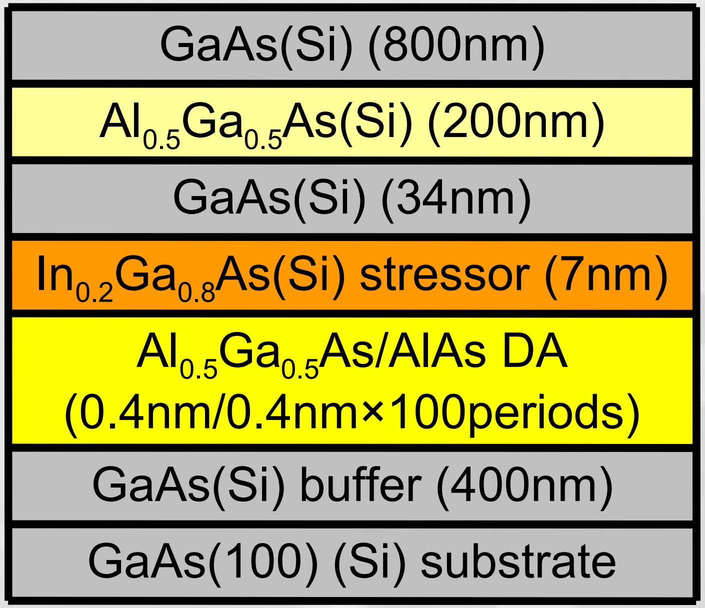
7. Litho 3



8. Release

Fabrication of a plate connected through a hinge to the substrate

Valley-fold: Epitaxial structure for a micro-plate



GaAs(Si) (800nm)

$Al_{0.5}Ga_{0.5}As$(Si) (200nm)

GaAs(Si) (34nm)

$In_{0.2}Ga_{0.8}As$(Si) stressor (7nm)

$Al_{0.5}Ga_{0.5}As/AlAs$ DA (0.4nm/0.4nm×100periods)

GaAs(Si) buffer (400nm)

GaAs(100) (Si) substrate

The epitaxial structure is grown by MBE on a GaAs (100) oriented substrate. Starting from the surface, it is composed by:

Components layer that will remains nearly flat when released from the substrate. In this example, it is just a GaAs “thick” layer.

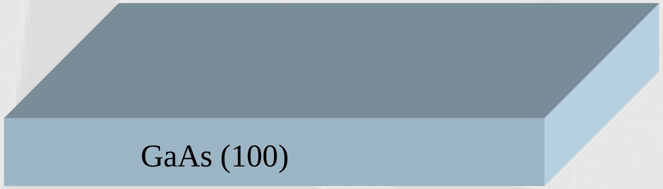
Selective etching layer to stop etching precisely on top of the hinge bilayer.

Hinge bilayer ($In_{0.2}Ga_{0.8}As$(Si) (7nm) and GaAs(Si) (34nm)) that will bend when isolated from neighbouring layers.

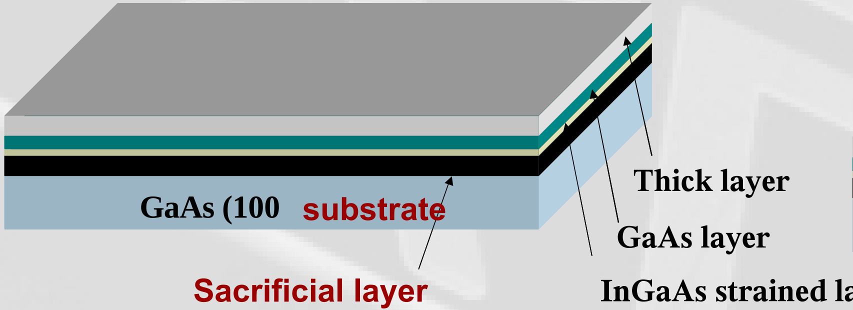
Sacrificial layer (digital alloy with high Al content) that will be etched to released the components.

Valley-fold: Fabrication process of a micro-plate

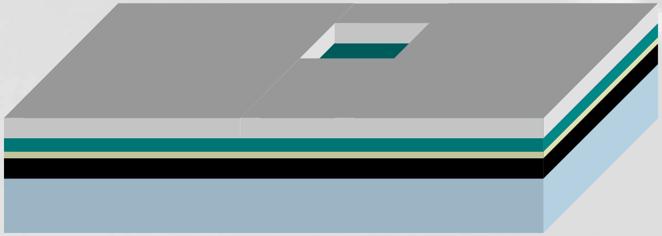
GaAs (100) substrate



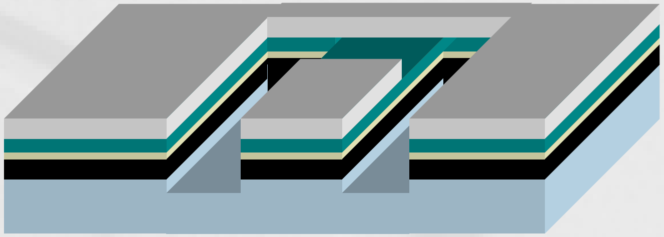
Epitaxial growth



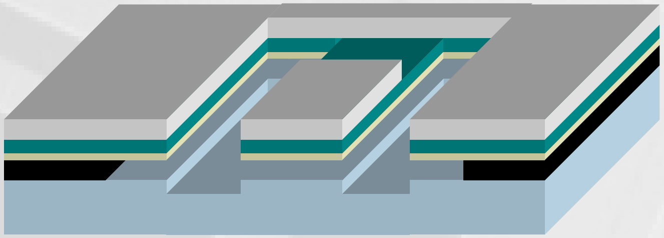
Hinge definition



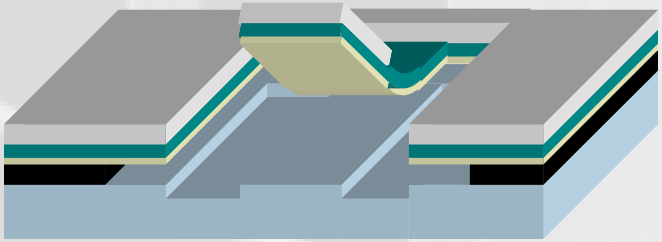
Etching of the plate`s shape



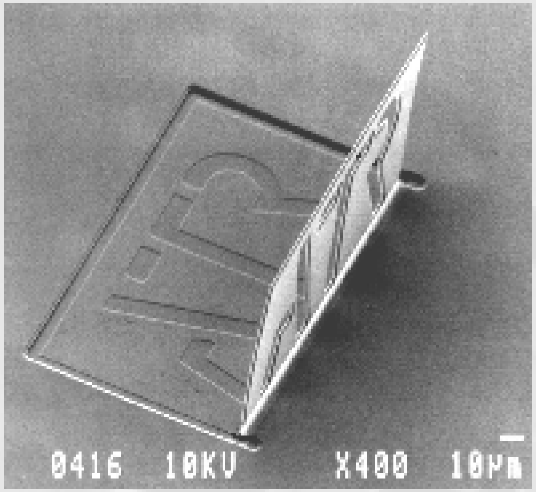
Etching of sacrificial layer

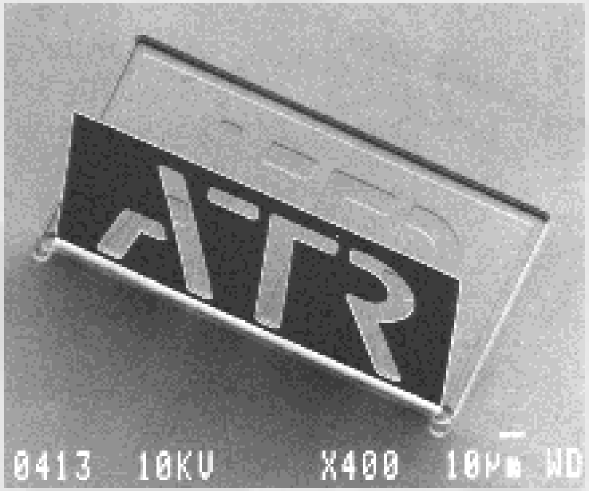


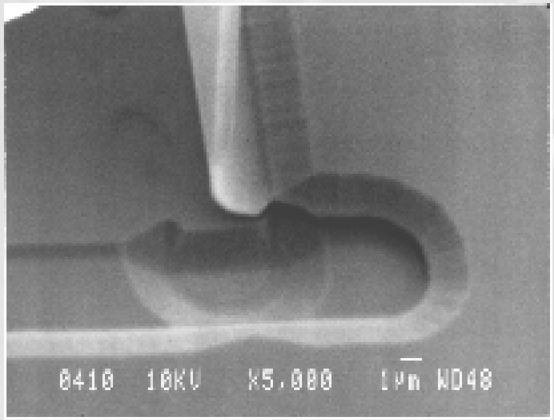
Micro-plate moves up



SEM images of a micro-plate



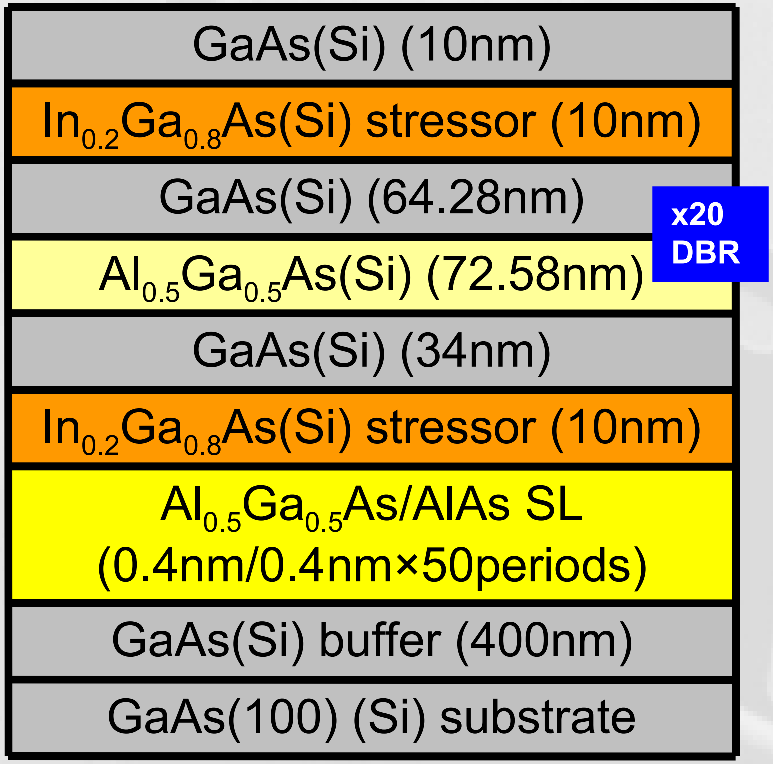




The standing angle of the plate is defined by the hinge length and the relative thickness of InGaAs and GaAs in the hinge bilayer

The plate itself is slightly curved due to the strain from the InGaAs layer

Valley-fold with a strain-compensation layer



GaAs(Si) (10nm)

$In_{0.2}Ga_{0.8}As$(Si) stressor (10nm)

GaAs(Si) (64.28nm)

$Al_{0.5}Ga_{0.5}As$(Si) (72.58nm)

x20 DBR

GaAs(Si) (34nm)

$In_{0.2}Ga_{0.8}As$(Si) stressor (10nm)

$Al_{0.5}Ga_{0.5}As$/AlAs SL (0.4nm/0.4nm×50periods)

GaAs(Si) buffer (400nm)

GaAs(100) (Si) substrate

The epitaxial structure is grown by MBE on a GaAs (100) oriented substrate. Starting from the surface, it is composed by:

Thin GaAs cap layer to protect the underlying strained layer.

Compensation layer, to balance the strain from the hinge layer when the components layer is released.

Components layer that will remains flat when released from the substrate. In this example, it is a distributed Bragg reflector (DBR) with 10 periods.

Selective etching layer to stop etching precisely on top of the hinge bilayer (In this case, it is the last AlGaAs layer of the DBR).

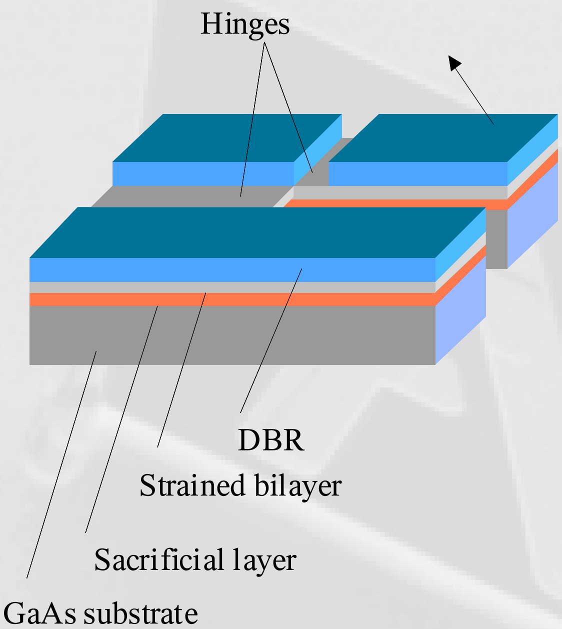
Hinge bilayer ($In_{0.2}Ga_{0.8}As$(Si) (7nm) and GaAs(Si) (34nm)) that will bend when isolated from neighbouring layers.

Sacrificial layer (digital alloy with high Al content) that will be etched to released the components.

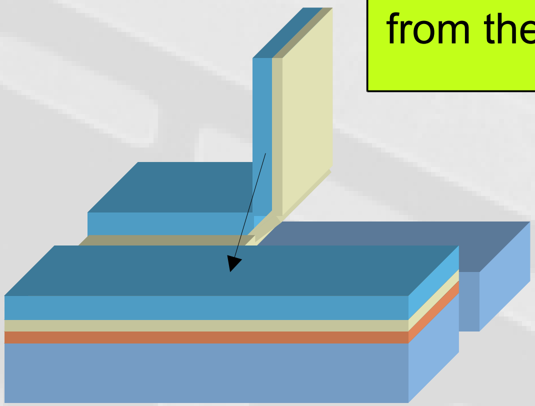
Design and geometry of a retro-reflector

This retro-reflector is composed by two square plates, each 50 microns of side. The surface is a highly reflective dielectric mirror (DBR). The plates are connected with hinge bilayers that bend to the required angle when become free from the neighbouring layers.

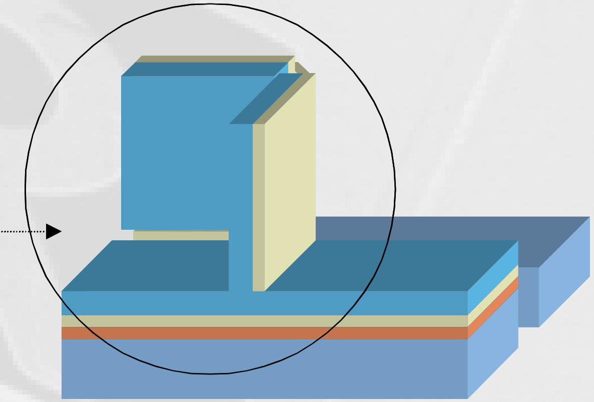
Step 1



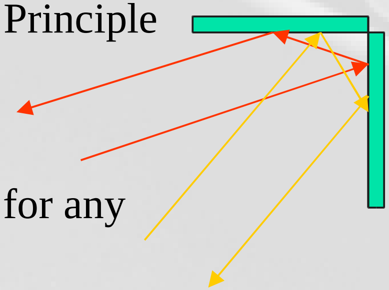
Step 2



Step 3

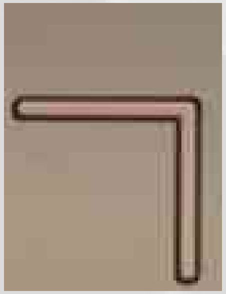


Principle

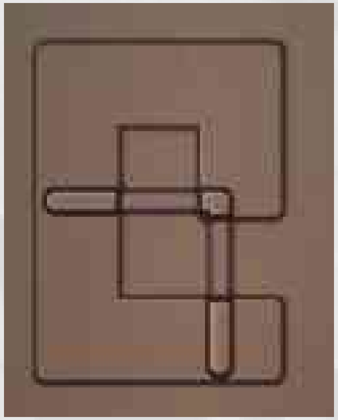


Light is reflected back for any angle of incidence

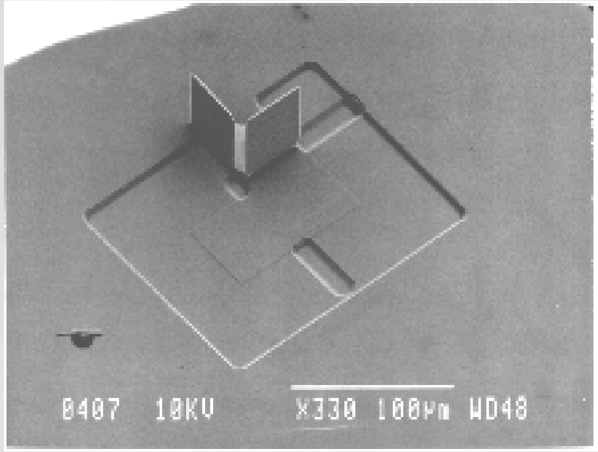
Fabrication process of a retro-reflector



Hinge definition



Component shape cut



SEM picture of a retro-reflector

Fabrication process

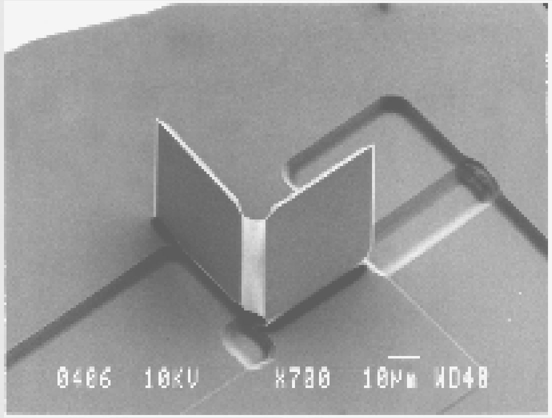
a. MBE growth

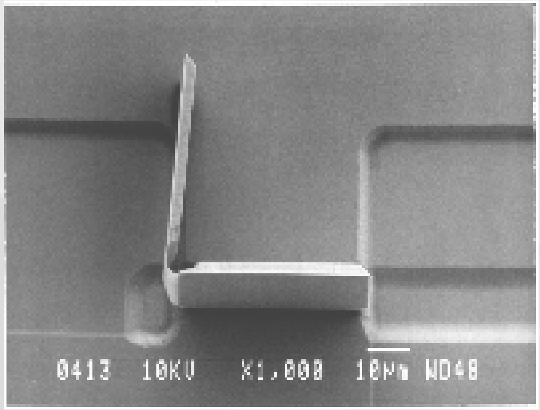
c. Hinge definition
Photolithography and wet etching
Hinge : $In_{0.2}Ga_{0.8}As$(Si) and GaAs (Si)

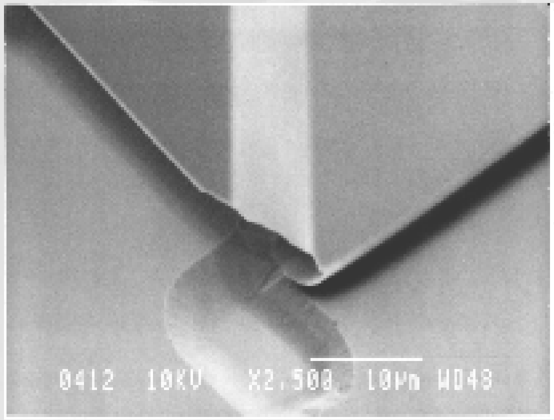
g. Component shape cut
Photolithography and wet etching

j. Release
Selective wet etching
Sacrificial layer : $Al_{0.5}Ga_{0.5}As/AlAs$

SEM images of a retro-reflector



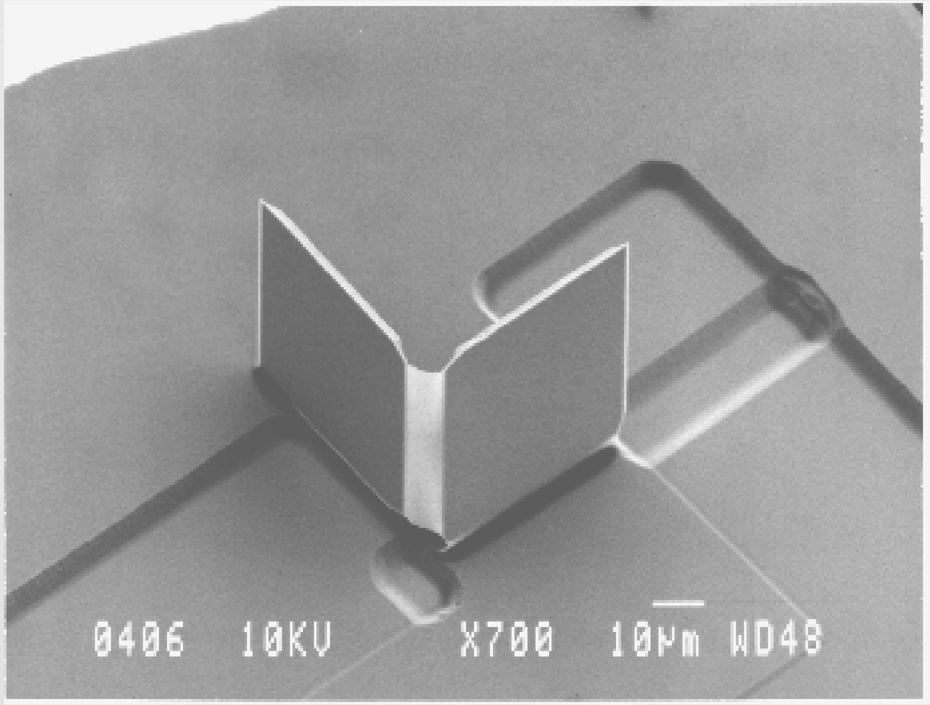


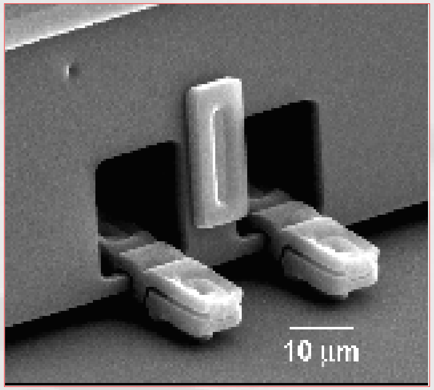


The plates are completely flat because strain from the InGaAs layer in the hinge is compensated by the InGaAs layer on top of the structure (compensation layer).

In the top view, the angle between plates is smaller than 90 degrees, however, the plates are perpendicular to the substrate due to the structure geometry.

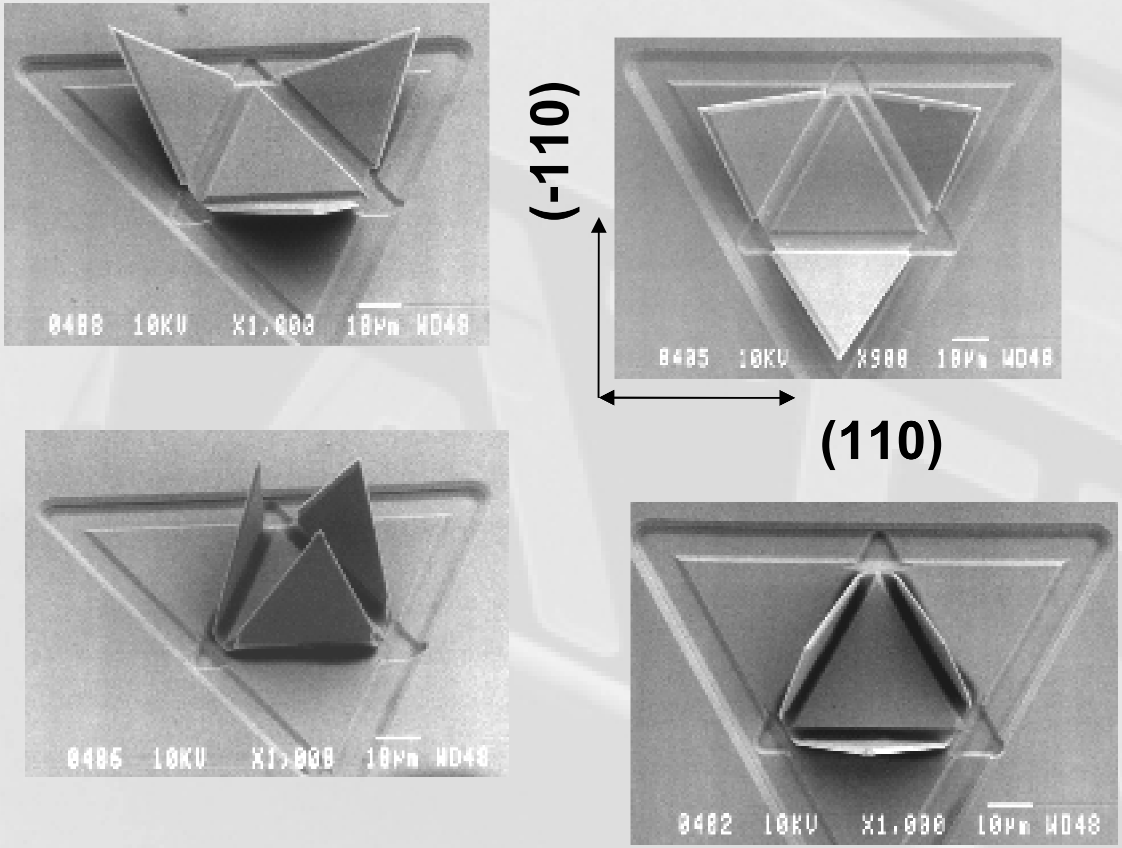
Micro-origami and conventional micromachining





This typical hinge made by conventional surface micromachining is as large as the total size of a corner-cube device made by micro-origami. Much smaller devices are easily fabricated by micro-origami even using standard tools.

SEM Images of flowers



Triangular plates structure. It would form a triangular pyramid when completely closed.

Valley-fold hinges: comparison with models

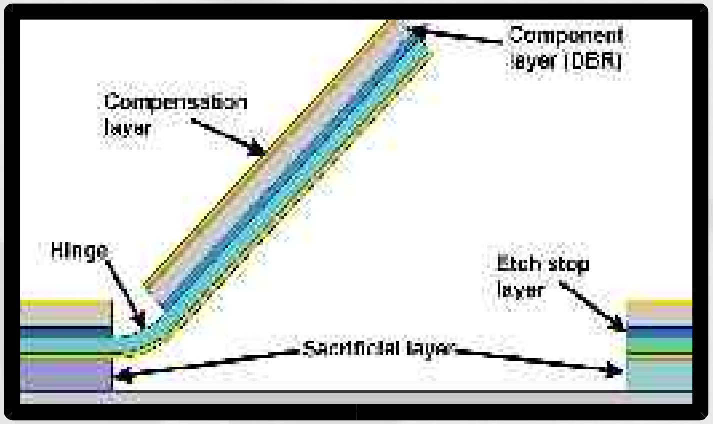


Figure 1: Origami process schematic

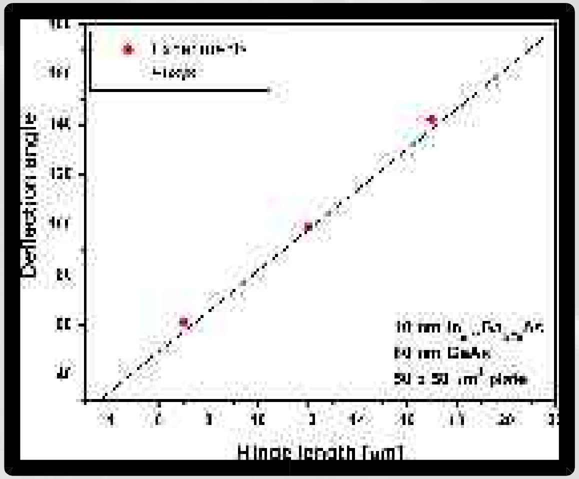


Figure 2: Calculated and experimental deflection angle versus hinge length

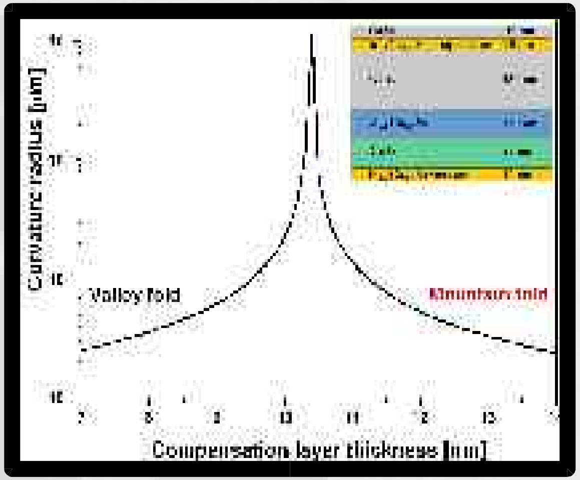
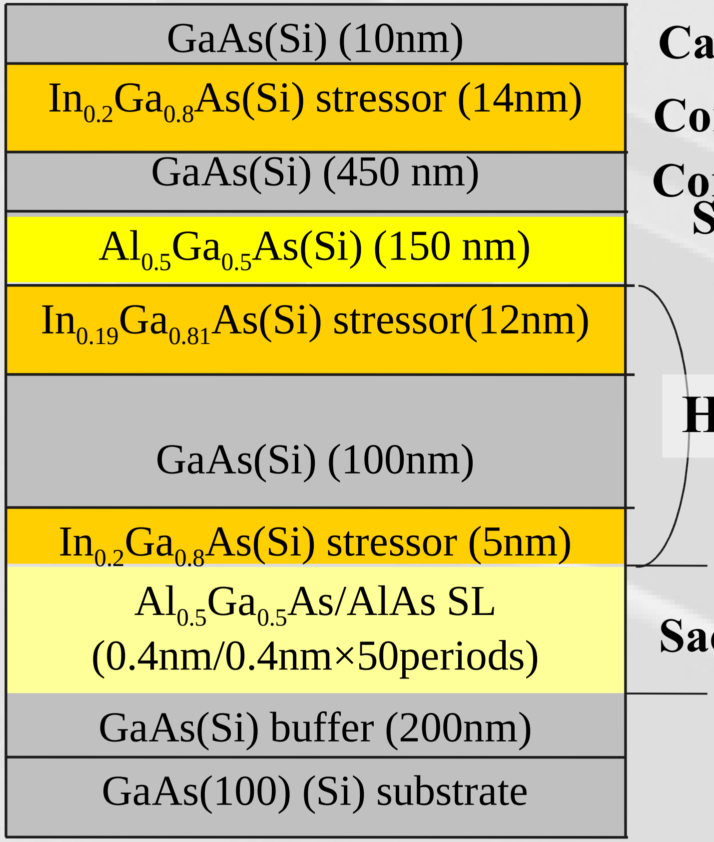


Figure 3: Curvature of the plate region versus compensation layer thickness

Epitaxial structure for “valley-fold” and “mountain-fold” hinges



GaAs(Si) (10nm)
$\mathrm{In_{0.2}Ga_{0.8}As}$(Si) stressor (14nm)
GaAs(Si) (450 nm)
$\mathrm{Al_{0.5}Ga_{0.5}As}$(Si) (150 nm)
$\mathrm{In_{0.19}Ga_{0.81}As}$(Si) stressor(12nm)
GaAs(Si) (100nm)
$\mathrm{In_{0.2}Ga_{0.8}As}$(Si) stressor (5nm)
$\mathrm{Al_{0.5}Ga_{0.5}As/AlAs}$ SL (0.4nm/0.4nm×50periods)
GaAs(Si) buffer (200nm)
GaAs(100) (Si) substrate

Cap layer

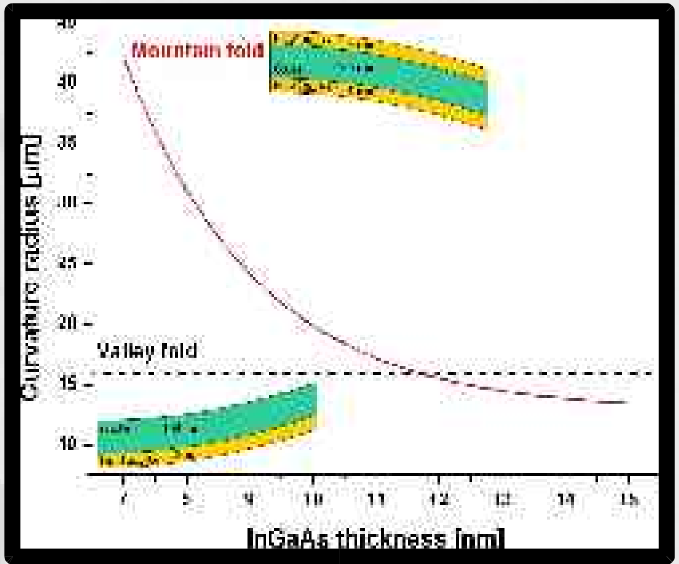
Compensation layer

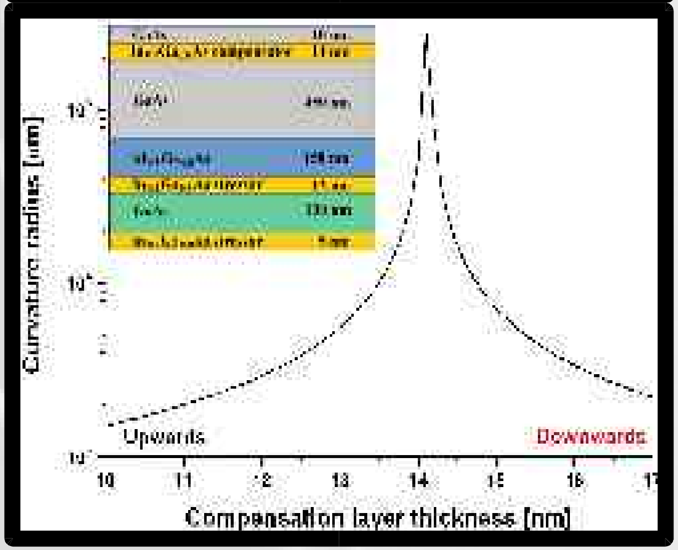
Component layer

Selective etching layer

Hinge

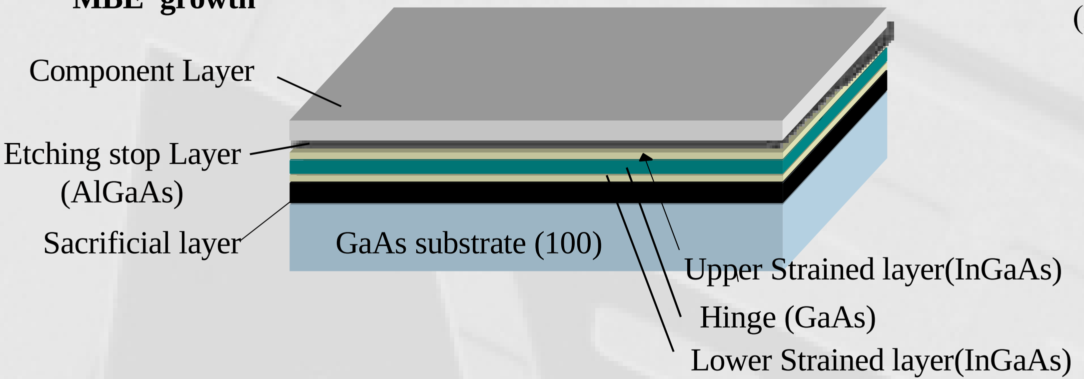
Sacrificial layer





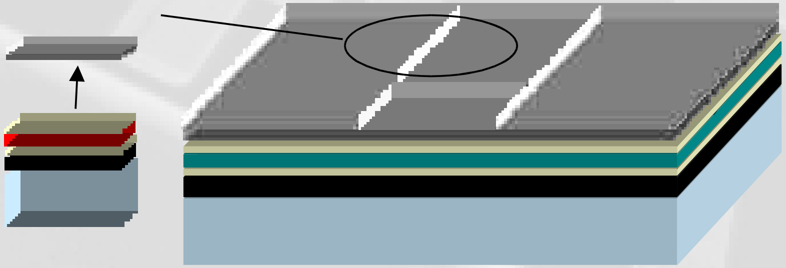
Fabrication process for valley- and mountain-folds

MBE growth

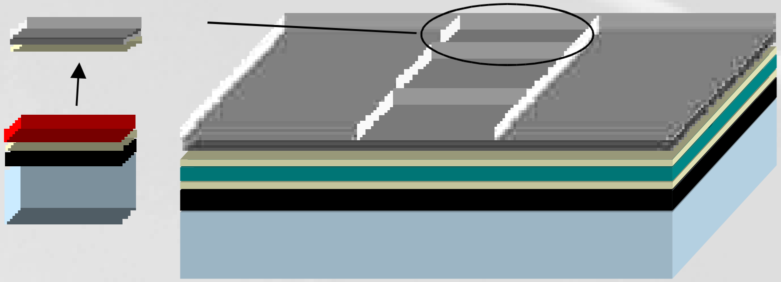


Hinge #1 (montain fold) definition by wet etching

Step 1 : (H_3PO_4:H_2O_2:H_20 = 3:1:50 at 40), *Step 2* : (HF:H_2O = 1:6)

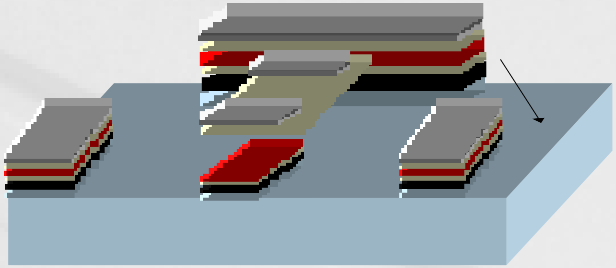


Hinge #2 (valley fold) definition by wet etching

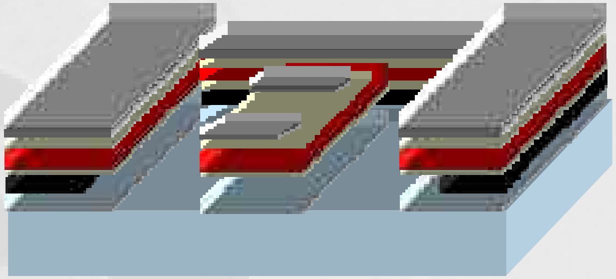


Component shape cut by wet etching

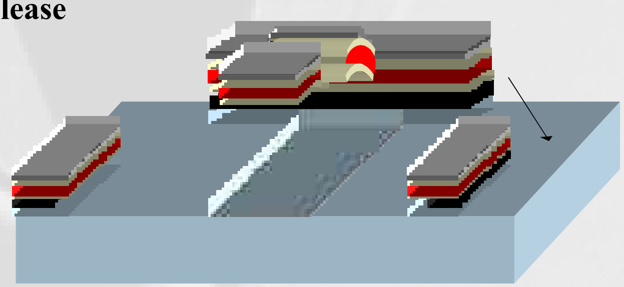
(H_3PO_4:H_2O_2:H_20 = 3:1:50 at 40)



Selective wet etching of sacrificial layer

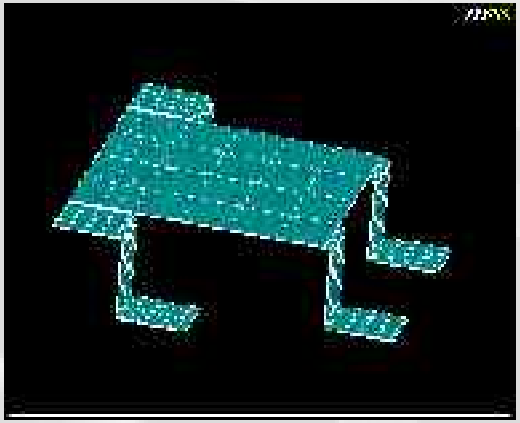


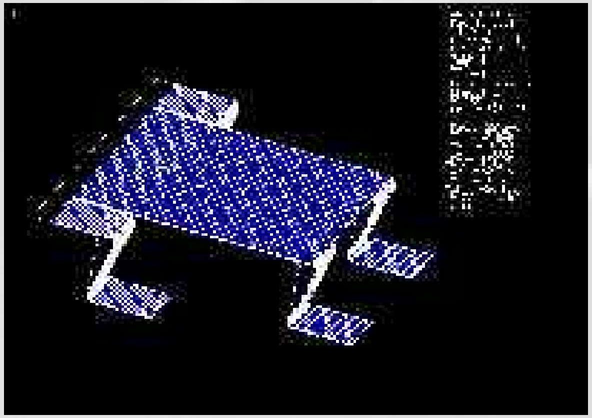
Release

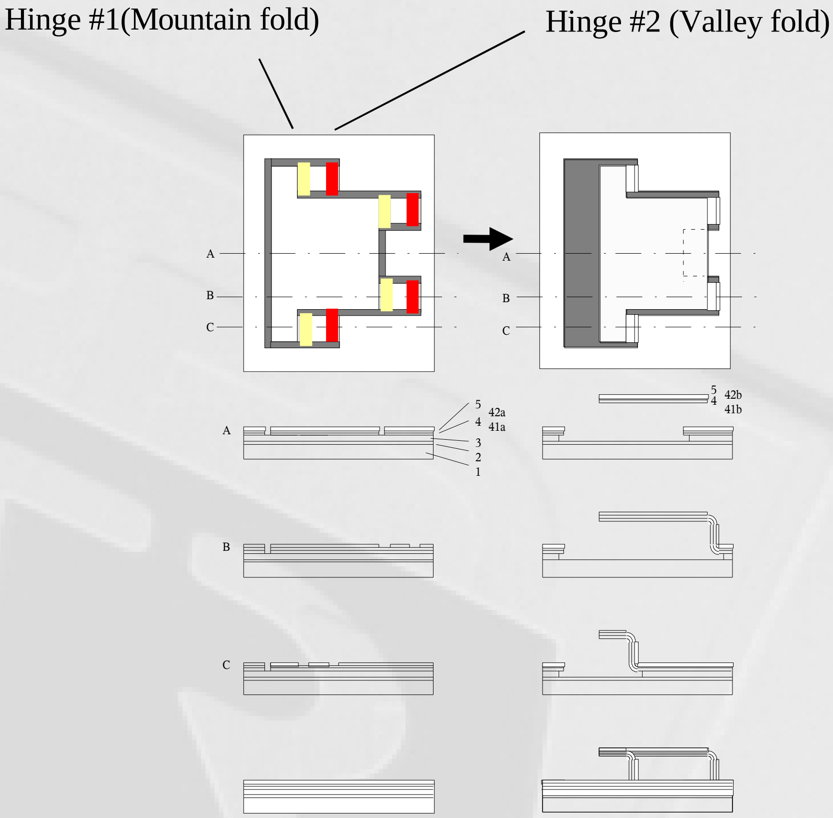


Combination of valley and mountain folds to make a micro-stage

A micro-stage with four legs remains parallel to the substrate while distance is adjustable





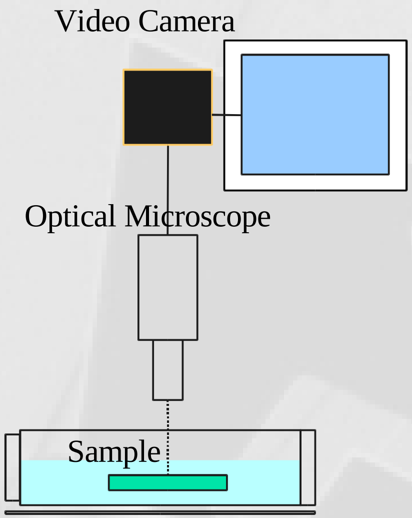


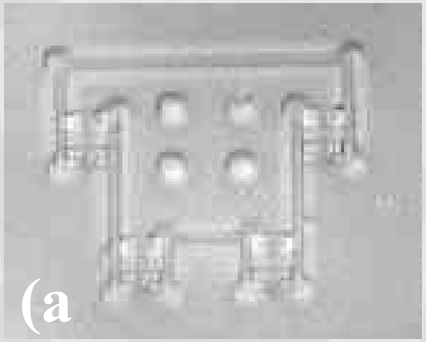
a) before assembling
b) after assembling

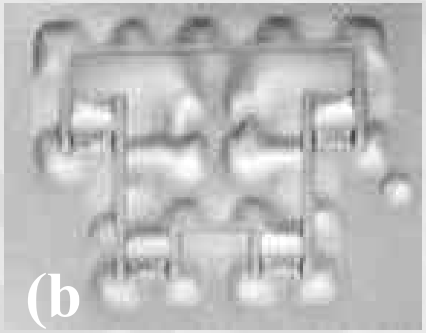
1 GaAs
2 DBR
3
4 41a, 42a, 41b, 42b)
5 DBR

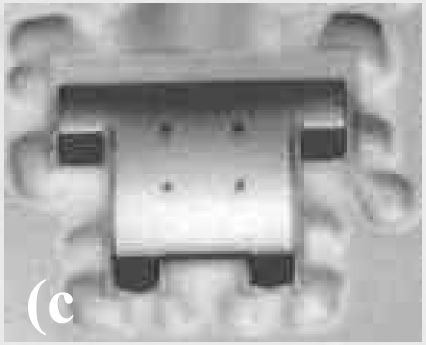
41a, 41b InGaAs
42a, 42b GaAs

Self-assembling of the micro-stage



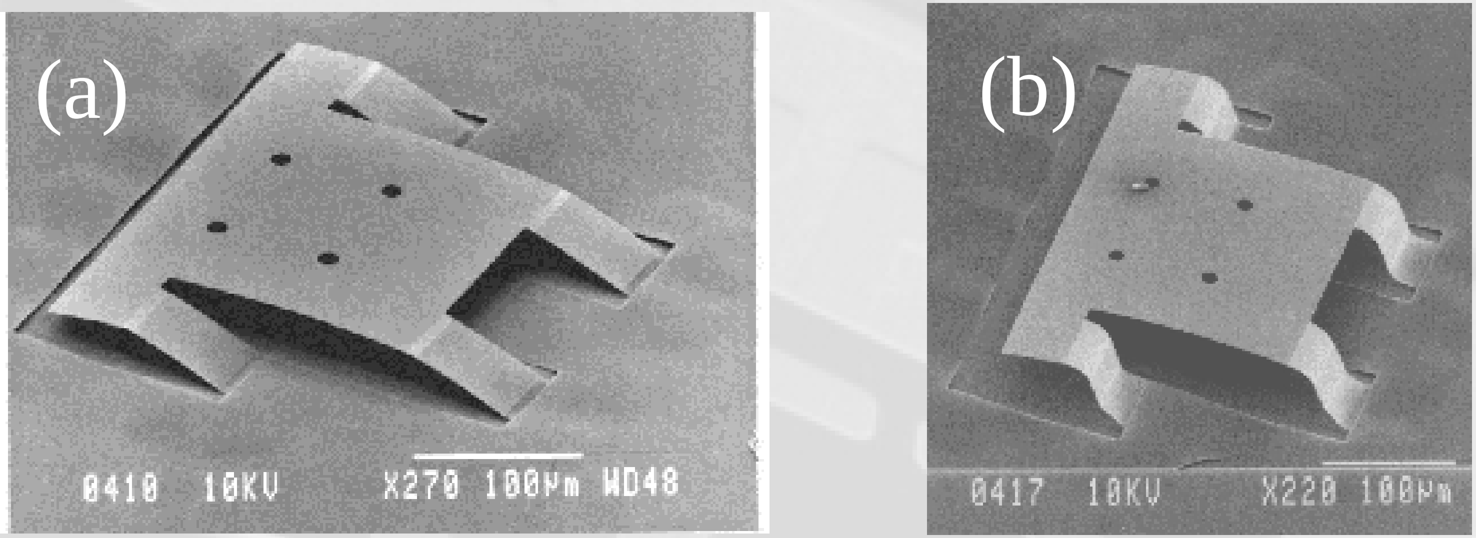

(a)


(b)


(c)

After etching the two types of hinges and components shape, the sample is inmersed in diluted HF to etch away the sacrificial layer. The optical-microscope pictures show, from left to right, the progress of the etching until the structure is released and moves to the standing position. The micro-stage surface is not completely flat after release due to remaining unbalanced strain in the epitaxial layers.

Hinge length dependence



SEM pictures of micro-stage with two different hinge lengths: (a) L = 7 μm,(b) L = 27μm

Directional sensing-photodetector

❑ Current technology

- hybrid assembled sensor
- big size
- not integrated with detection circuit

Defence Reseach Establishment Valcartier, Canada

❑ Applications

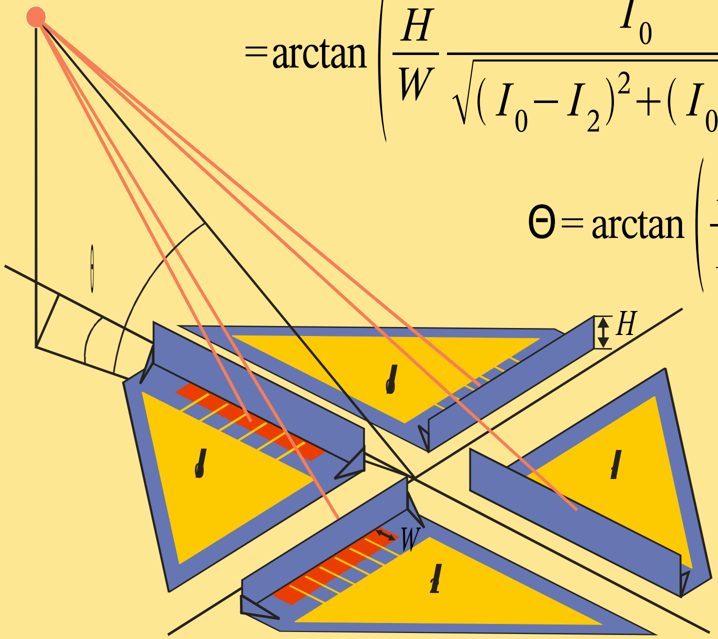
Detecting the collimated radiation that comes from a light source and encoding its angle of arrival for

- positioning devices
- position determining systems
- directional aids
- vehicle guidance
- warning or countermeasure systems against laser-guided weapons and laser-based surveillance systems

Micro-origami applications: directional-sensing photodetector

- **General principle:**

a light-sensing device with electrical output that gives information on the direction relative to the device of the incoming light.

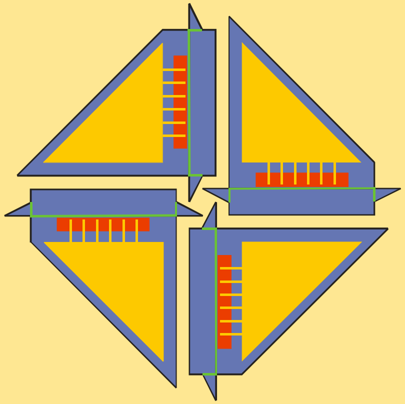


$$=\arctan\left(\frac{H}{W}\frac{I_0}{\sqrt{(I_0-I_2)^2+(I_0-I_1)^2}}\right)$$

$$\Theta=\arctan\left(\frac{I_0-I_1}{I_0-I_2}\right)$$

- **Top view**

(before releasing)



Red: photodiodes
Yellow: top contacts
Green: flexible hinges
Grey: walls to be standing up

Fabrication of directional-sensing photodetector

❑ MBE-grown heterostructure

p-GaAs	isolation layer
n-GaAs i-GaAs p-GaAs	PIN-diode
p-AlGaAs	stop layer
p-GaAs	
p-InGaAs	strained layer
p-AlAs/AlGaAs layer	sacrificial
p-GaAs (100)	substrate

❑ Device fabrication

1. MBE growth.
2. Photolithography and wet etching to define
   a) photodiode regions; b) hinge regions; c) wall shape.
3. Deposition and annealing of contacts on the front and back surfaces.
4. Selective etching of the sacrificial layer to stand up the walls.

❑ Photographs of the sample (top view):

before releasing after releasing

Electrostatic actuation of micro-origami devices

WEL Dept. of Photonics

Advanced Telecommunications Research Institute International

Introduction

- Ansys was used to model electrostatic actuation of a corner cube reflector.
- Forces required for actuation were estimated to be below1μN.
- Influence of metallization on the hinge was studied.

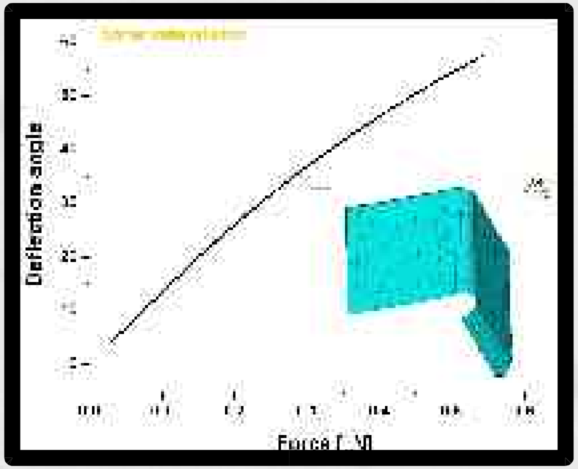


Figure 1: Calculated deflection versus applied force

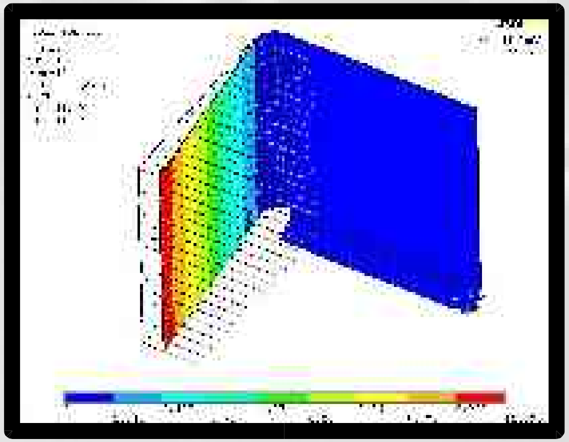


Figure 2: Origami plate in a perpendicular electrostatic field

Electrostatic deflection

Up to 10 μm deflection for less than 35 V

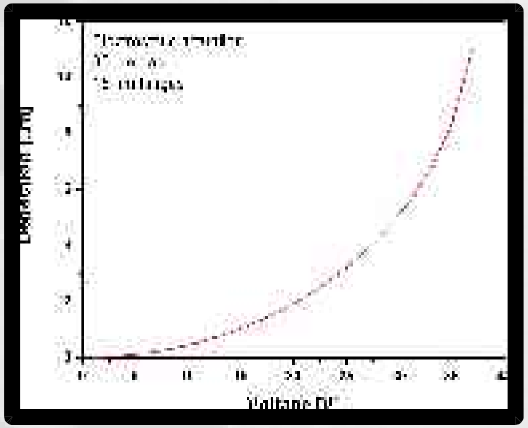


Figure 3: Deflection versus applied voltage

Electric contacts on released plates

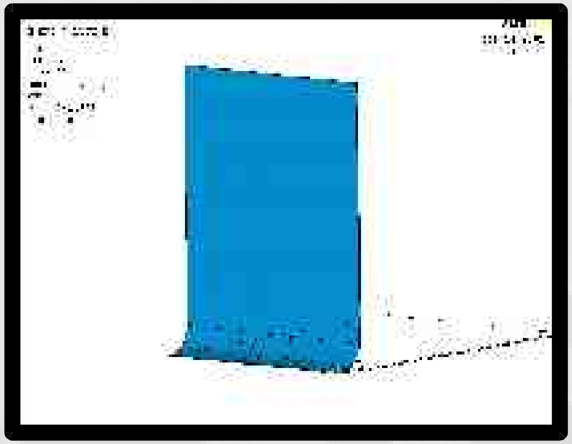
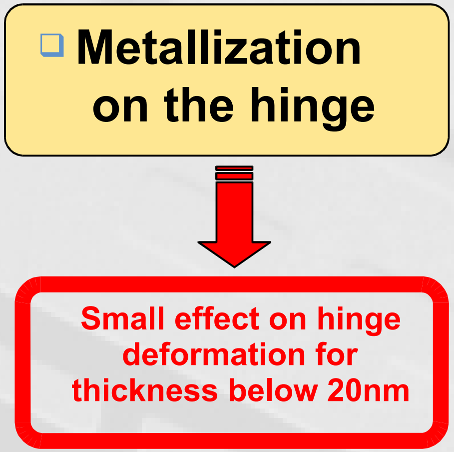


Figure 4: Modeling the effect of metallization across the hinge



- **Metallization on the hinge**

Small effect on hinge deformation for thickness below 20nm

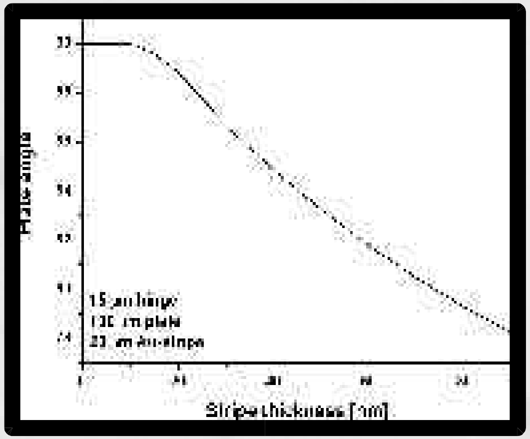


Figure 5: Plate deflection angle versus contact thickness (Ti/Au).

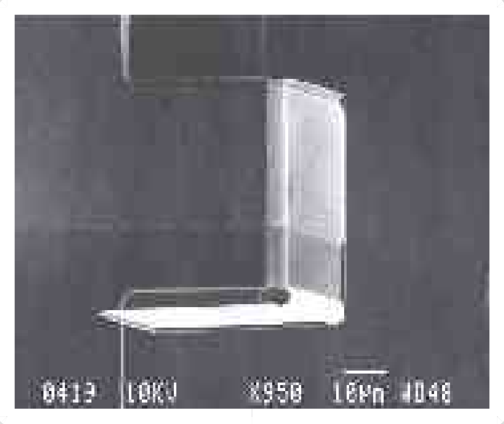


Figure 6: SEM picture of a corner plate with a 20 nm thick Ti/Au contact

Figure 7: SEM picture of the hinge portion covered with a Ti/Au stripe

Future steps

- Integrate metallization with active devices.
- Optimize deposition process.
- Investigate electrical properties.

Corner-cube reflector for free-space commun.

❑ Introduction

Corner cube reflector for passive modulation in free-space optical communication systems using the micro-origami technique.

Electrostatic actuation with low power consumption via parallel plates with metallization.

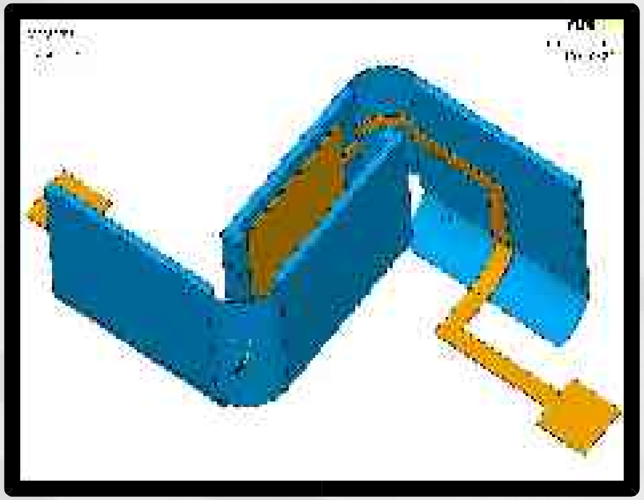


Figure 1: Illustration of a dual corner cube reflector

❑ Optical Modeling

Effective optical modulation for free-space applications

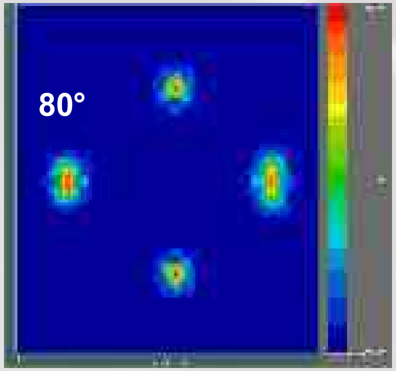


Figure 2: Far-field pattern for 80° between the plates

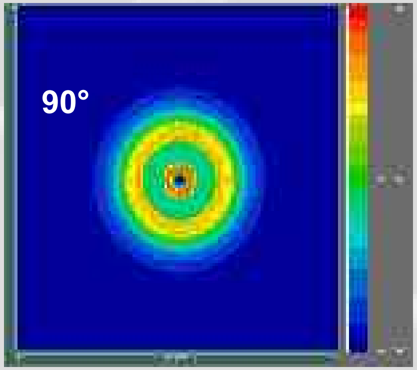


Figure 3: Far-field pattern for 90° between the plates

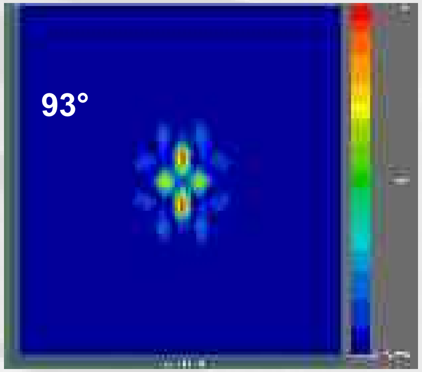


Figure 4: Far-field pattern for 93° between the plates

Calculated using CODE V

Fabrication of the corner-cube reflector

❑ Fabrication

Figure 5: Growth structure

Good control over hinge curvature and deflection angle

Figure 6: Corner plates with a 7µm hinge deflecting 65°.

Figure 7: Corner plates with a 12µm hinge deflecting 98°.

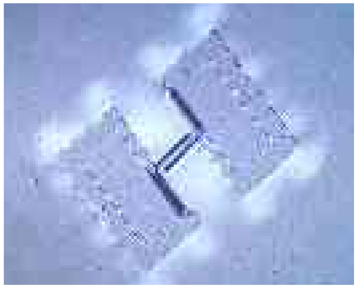


Figure 8: Dual CCR after release, immersed in methanol

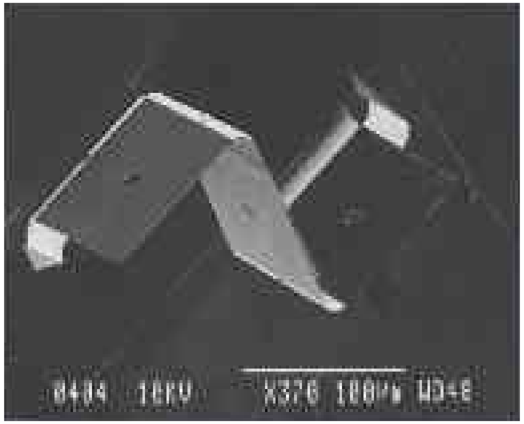
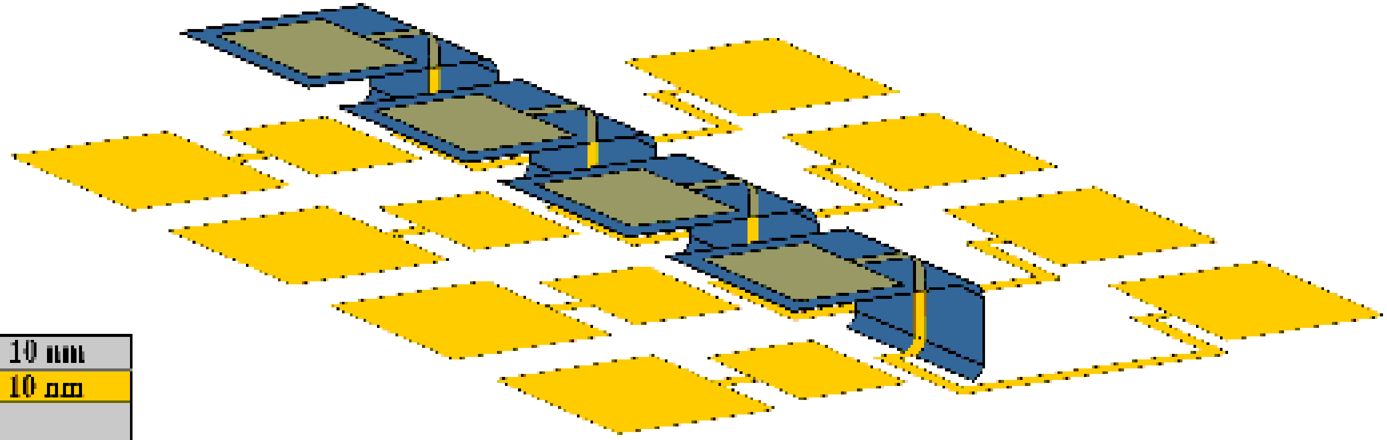


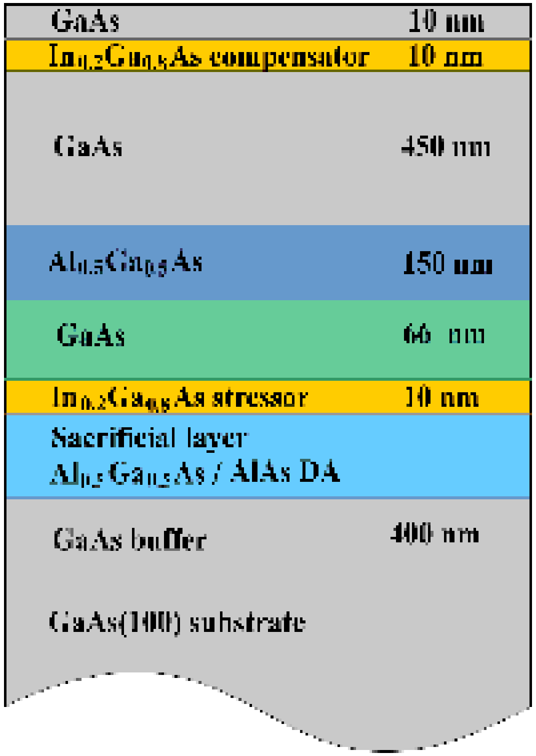
Figure 9: Dual CCR after freeze-dry.

❑ Future steps

- Improve etching process to reduce undercut.
- Improve drying technique to avoid sticking of the plates.
- Integrate electrodes for electrostatic actuation.

Micro-mirror array





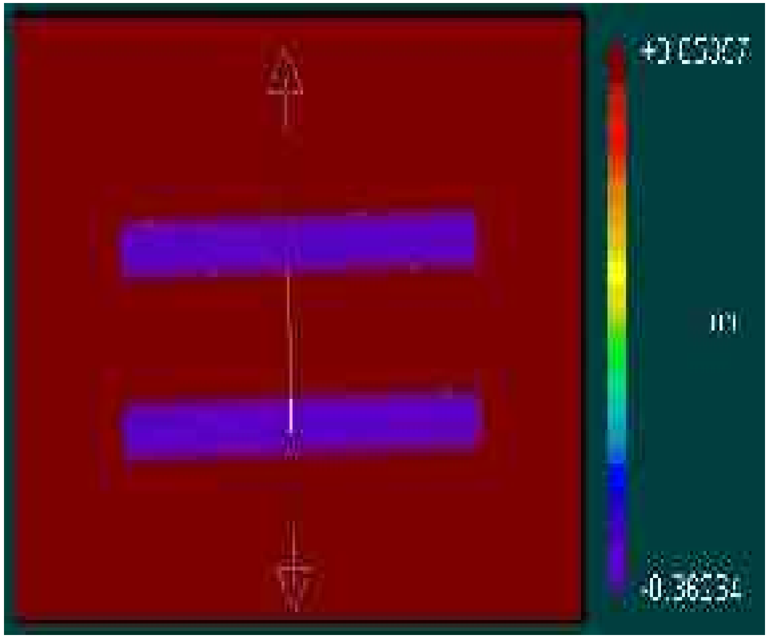
GaAs	10 nm
In$_{0.2}$Ga$_{0.8}$As compensator	10 nm
GaAs	450 nm
Al$_{0.5}$Ga$_{0.5}$As	150 nm
GaAs	66 nm
In$_{0.2}$Ga$_{0.8}$As stressor	10 nm
Sacrificial layer Al$_{0.5}$Ga$_{0.5}$As / AlAs DA	
GaAs buffer	400 nm
GaAs(100) substrate	

Hinge at 400nm

Ga flow reduced by 30%

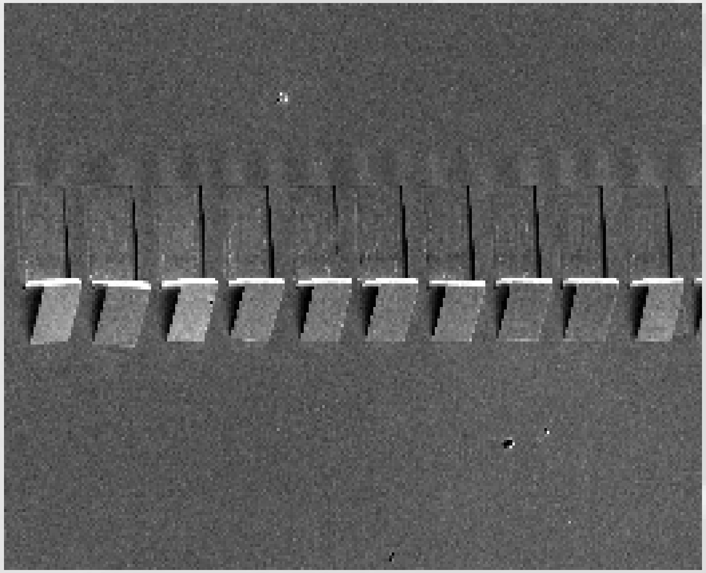
Hinge thickness reduced

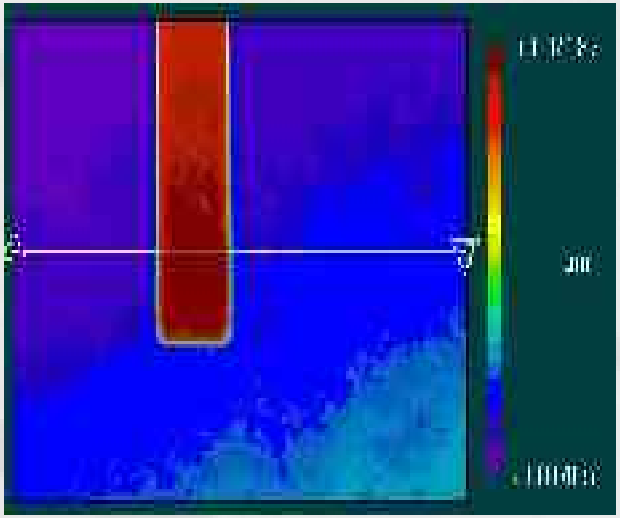
In comp. increased



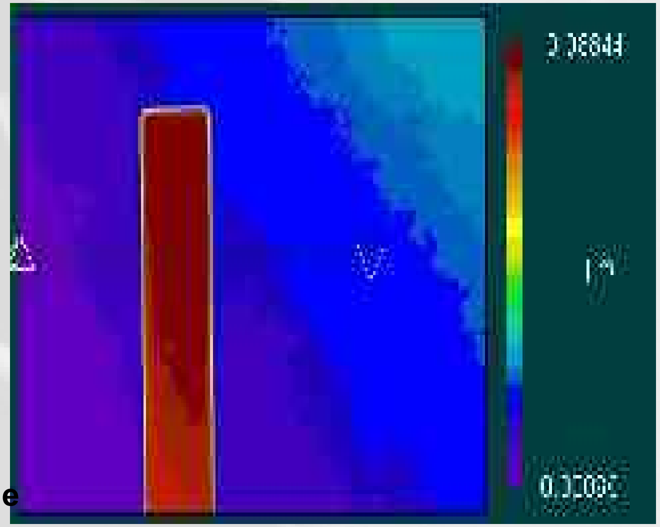
Compensation of hinge deformation

Released mirrors



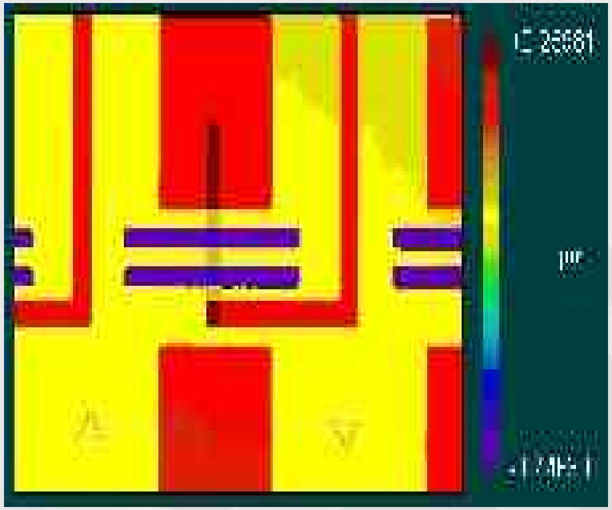


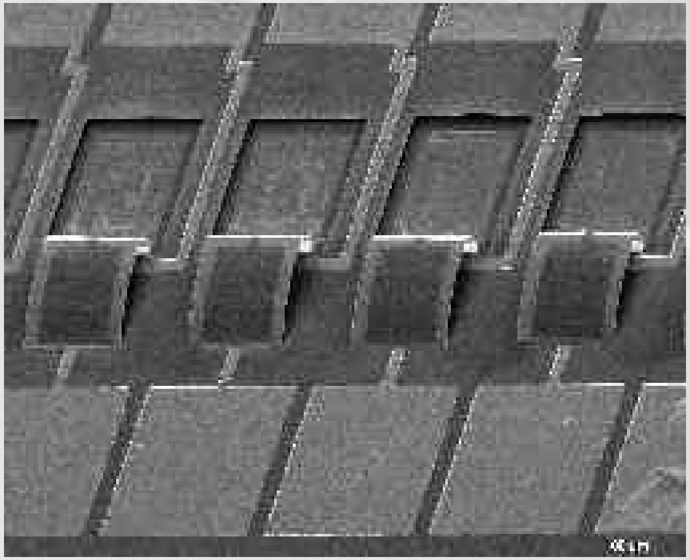
40nm Au stripe on the hinge

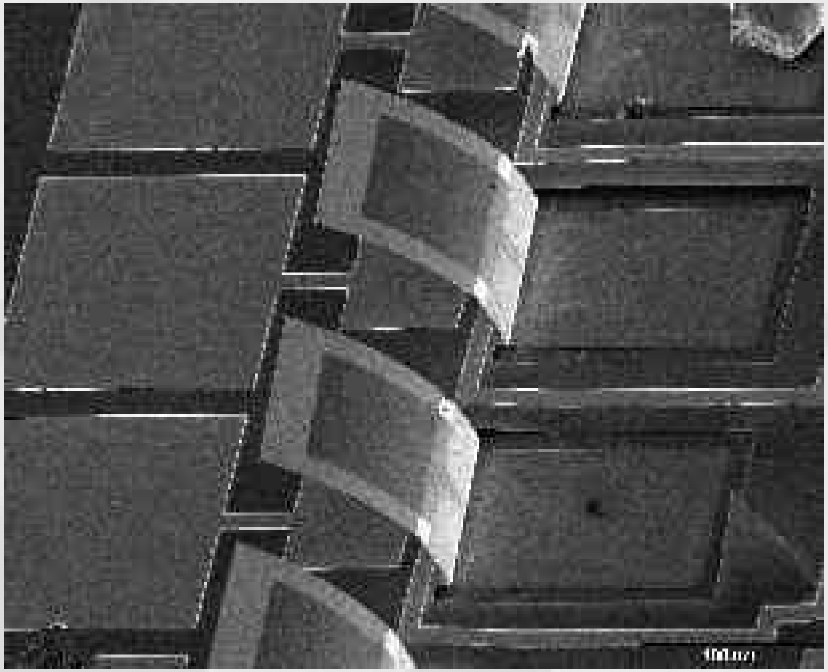


90nm Au stripe on the hinge

Fabrication results



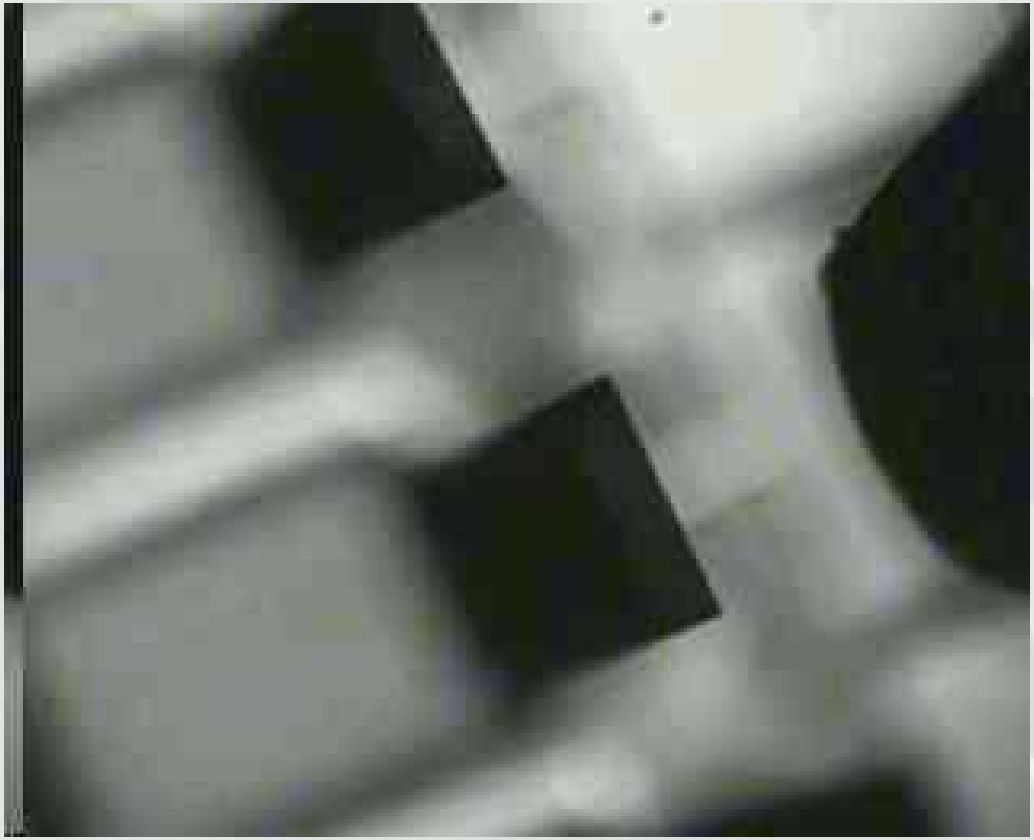




Miss-alignment of electrode blocks upper hinge

90nm Au stripe was not enough
The 200 nm thick electrode has tensile

Mirror actuation



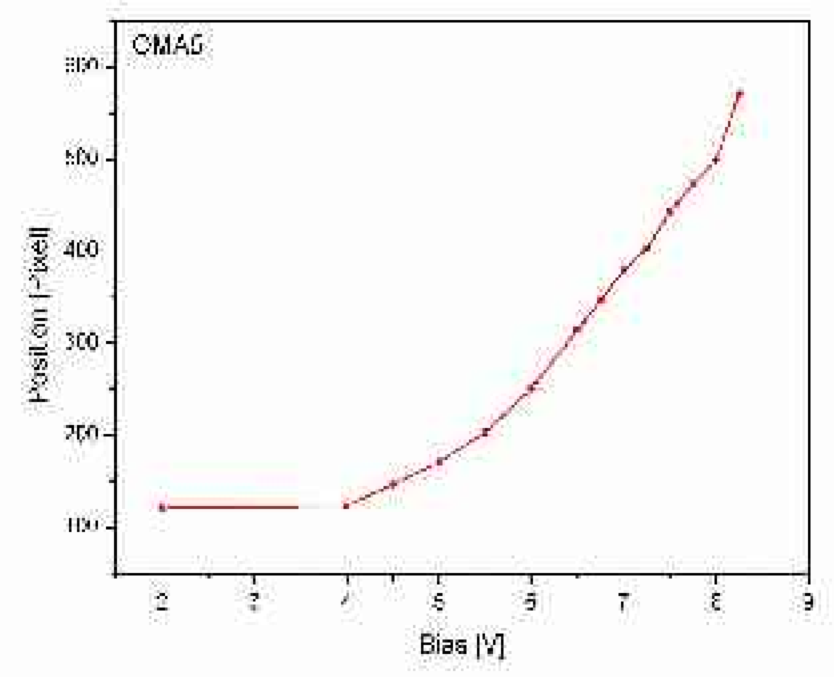
Actuation at 10 Hz with a peak to
Peak voltage of 16V

Mirror actuation

Reflected HeNe beam hitting a CCD chip at 4cm distance

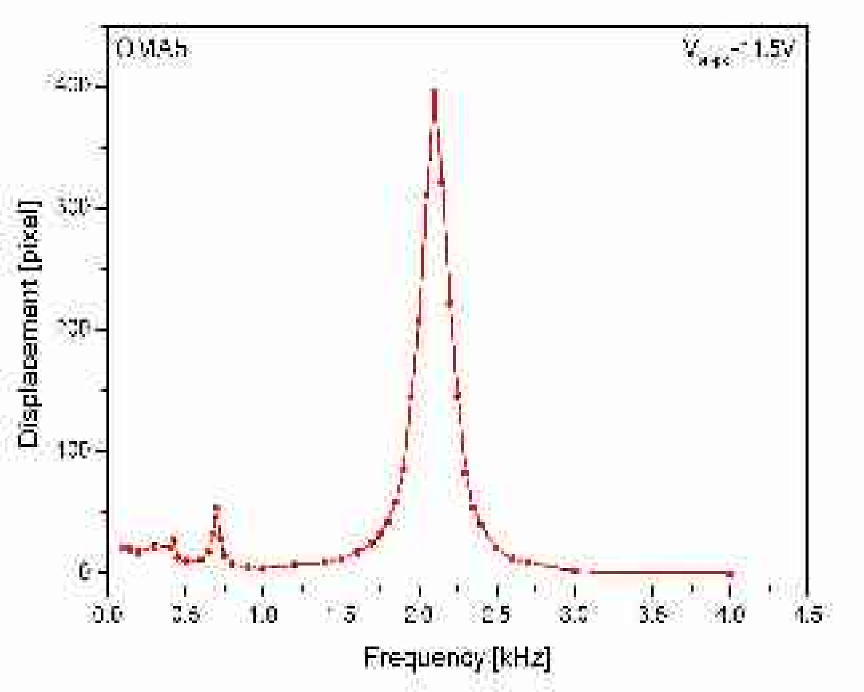
Actuation frequency of 4Hz and peak to peak voltage of 17.5V

Mirror deflection and resonance frequency



Beam displacement on the CCD chip versus applied DC bias. Beam displacement at 8V corresponds to an angular mirror deflection of ~3°.

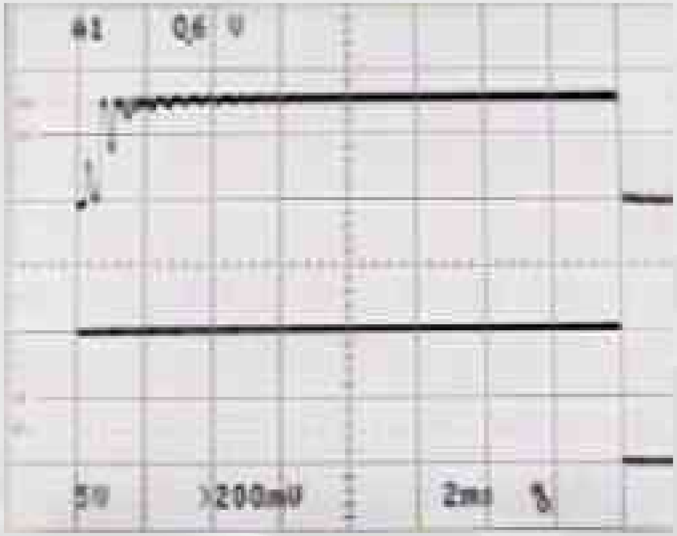
Maximum beam displacement versus frequency for a peak to peak voltage of 10V.



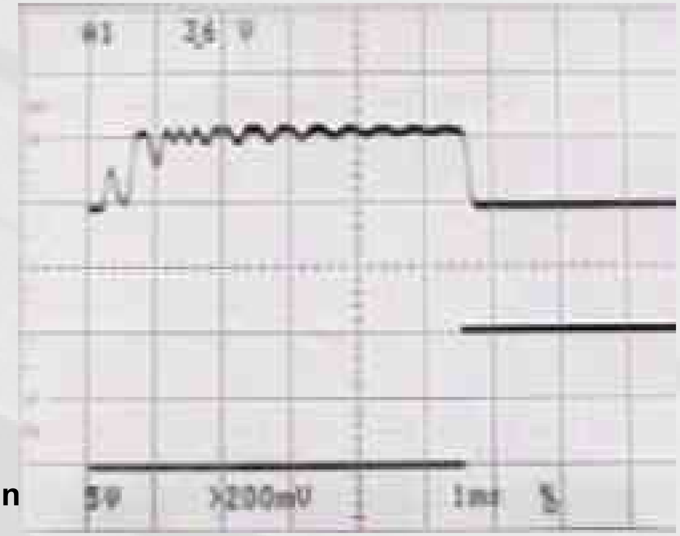
Beam displacement

About 13 cm displacement at
A distance of 120 cm.

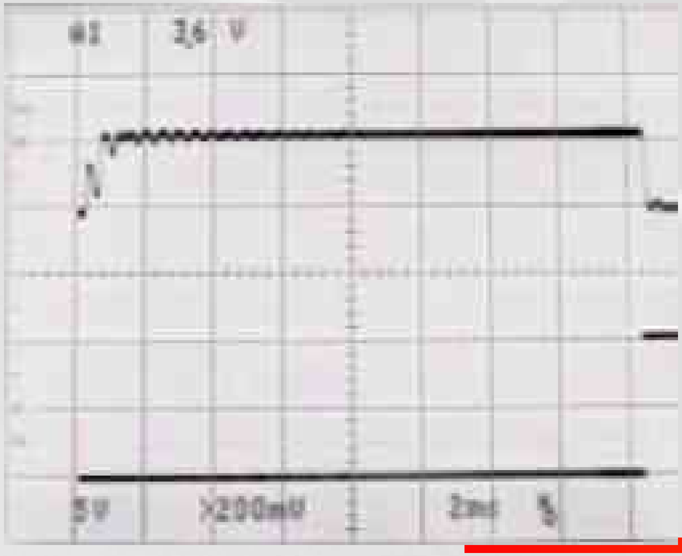
Dynamic response



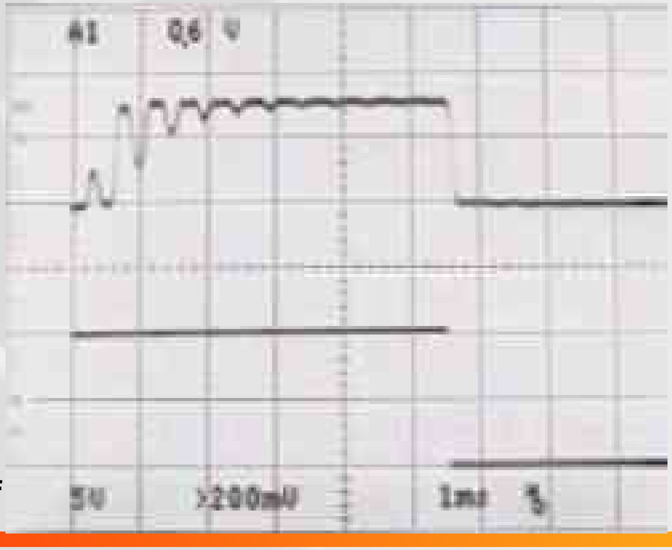
30 Hz On



90 Hz On



30 Hz Off



90 Hz Off

Applications in optoelectronics

- Flat and cylindrical mirrors for integration with optoelectronic devices.
- Micrometer scale optical bench (half and full mirrors, diffractive lenses, etc.)
- Optical attenuators for fiber optical links.
- Movable mirrors for wide tuning of VCSELs.
- Scanning mirrors (moved by magnetic or electrostatic forces, piezoelectricity, thermal dilatation, etc.).
- Free space light beam switching for WDM systems

Fabrication with other materials

•Metallic layers could also be used. The following are promising combinations: zinc/cadmium, copper/silver/gold, nickel/palladium/platinum, cobalt/rhodium/iridium, chromium/molybdenum/tungsten, vanadium/niobium.

•Proper substrates and sacrificial layers have to be found.

Conclusions

- Micro-origami allows total self-assembling of complex 3-D structures in the micrometer scale.
- Reduces the complexity and weakness of hinges used to connect moving and fixed parts, as compared to traditional micromachining methods.
- Ha been demonstrated in III-V compound semiconductors and silicon.
- Will allow fabrication of MEMS with monolithically integrated optoelectronic devices in III-V compound semiconductors.
- Could be scaled down to the submicron or even nanometer scale.
- Applications have to be found not only in optoelectronics but in many other kinds of MEMS.