Self-Positioning Micromachined Structures Made by Micro-Origami

P. O. Vaccaro, K. Kubota, T. Fleischmann, A. Vorobev, J. M. Zanardi Ocampo, S. Saravanan, and N. Saitoh

ATR Wave Engineering Laboratories
2-2-2 Hikaridai, “Keihanna Science City”, Kyoto 619-0288, Japan

Email: vaccaro@atr.jp
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.


First all-surface micromachined microphone

Flavio Pardo, Bell Labs. Lucent Technology
Detail of the hinges

Flavio Pardo, Bell Labs. Lucent Technology
Assembly and working principle

hinges

Flavio Pardo, Bell Labs. Lucent Technology
### Purpose

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

#### Surface Micromachining

1. **Polycrystalline plates**: surfaces are not very smooth or flat, mechanical strength is reduced, fatigue and corrosion increases (at grain boundaries).
2. **Complex hinge structure**: hinges are made with multiple parts, that require more precise lithography, become easily stuck, degrade by friction.
3. **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.
4. **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.
5. **Scalability limited to plates of 10 microns order when using standard tools due to smaller mechanical components in hinges.**

#### Micro-origami

1. **Single-crystalline plates**: very smooth and flat surfaces, high mechanical strength, no fatigue and decreased corrosion.
2. **Simple hinge structure**: hinges are formed by a thin flexible layer, with no sliding parts that could stuck or degrade by friction.
3. **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.
4. **Integration with optoelectronic devices**: technology based on III-V compounds, is the standard to make optoelectronic devices.
5. **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 \( a_A < a_B \)

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

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

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

These layers can be used as a hinge between flat plates.
Curvature radius of a strained bilayer

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

\( \rho \): 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

- Component layer (DBR)
- Sacrificial layer
- Substrate
- Strain layer

2. Hinge fabrication

3. Component shape cut

- Wet etching
  \[ \text{H}_3\text{PO}_4 : \text{H}_2\text{O}_2 : \text{H}_2\text{O} = 3 : 1 : 50 \]
  \[
  \begin{align*}
  \text{HF} : \text{H}_2\text{O} & = 1 : 10 \\
  & = 18.5
  \end{align*}
\]

4. Release
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

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\textsubscript{0.2}Ga\textsubscript{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

1. **GaAs (100) substrate**
2. **Epitaxial growth**
   - GaAs (100) substrate
   - InGaAs strained layer
3. **Hinge definition**
4. **Etching of sacrificial layer**
   - Thick layer
   - GaAs layer
   - Sacrificial layer
5. **Etching of the plate’s shape**
6. **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.
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 remain 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 ($\text{In}_{0.2}\text{Ga}_{0.8}\text{As(Si)}$ (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.

Light is reflected back for any angle of incidence.
Fabrication process 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

Hinge definition
Component shape cut

SEM picture of a retro-reflector
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.
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.
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

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs(Si) (10nm)</td>
<td></td>
</tr>
<tr>
<td>( \text{In}<em>{0.2}\text{Ga}</em>{0.8}\text{As(Si)} ) stressor (14nm)</td>
<td></td>
</tr>
<tr>
<td>GaAs(Si) (450 nm)</td>
<td></td>
</tr>
<tr>
<td>( \text{Al}<em>{0.5}\text{Ga}</em>{0.5}\text{As(Si)} ) (150 nm)</td>
<td></td>
</tr>
<tr>
<td>( \text{In}<em>{0.19}\text{Ga}</em>{0.81}\text{As(Si)} ) stressor(12nm)</td>
<td></td>
</tr>
<tr>
<td>GaAs(Si) (100nm)</td>
<td></td>
</tr>
<tr>
<td>( \text{In}<em>{0.2}\text{Ga}</em>{0.8}\text{As(Si)} ) stressor (5nm)</td>
<td></td>
</tr>
<tr>
<td>( \text{Al}<em>{0.5}\text{Ga}</em>{0.5}\text{As/AlAs SL} ) (0.4nm/0.4nm×50periods)</td>
<td></td>
</tr>
<tr>
<td>GaAs(Si) buffer (200nm)</td>
<td></td>
</tr>
<tr>
<td>GaAs(100) (Si) substrate</td>
<td></td>
</tr>
</tbody>
</table>

Cap layer
Compensation layer
Component layer
Selective etching layer
Hinge
Sacrificial layer
Fabrication process for valley- and mountain-folds

**Step 1:** (H$_3$PO$_4$:H$_2$O:$H_2$O = 3:1:50 at 40),

**Step 2:** (HF:H$_2$O = 1:6)

**Hinge #1 (mountain fold) definition by wet etching**

**Hinge #2 (valley fold) definition by wet etching**

Component shape cut by wet etching
(H$_3$PO$_4$:H$_2$O:$H_2$O = 3:1:50 at 40)

Selective wet etching of sacrificial layer

Release

MBE growth

Component Layer

Etching stop Layer (AlGaAs)

Sacrificial layer

GaAs substrate (100)

Upper Strained layer (InGaAs)

Hinge (GaAs)

Lower Strained layer (InGaAs)

Selective wet etching of sacrificial layer
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.

Hinge #1 (Mountain fold)

Hinge #2 (Valley fold)

a) before assembling
b) after assembling
After etching the two types of hinges and components shape, the sample is immersed 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) $L = 7\, \mu m$, (b) $L = 27\, \mu m$
Directional sensing-photodetector

- **Current technology**
  - hybrid assembled sensor
  - big size
  - not integrated with detection circuit

- **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

Defence Research Establishment Valcartier, Canada
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.

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

Top view
(before releasing)

Red: photodiodes
Yellow: top contacts
Green: flexible hinges
Grey: walls to be standing up
Fabrication of directional-sensing photodetector

**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.

**MBE-grown heterostructure**

<table>
<thead>
<tr>
<th>Material</th>
<th>Layer Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-GaAs</td>
<td>isolation layer</td>
</tr>
<tr>
<td>n-GaAs</td>
<td>PIN-diode</td>
</tr>
<tr>
<td>i-GaAs</td>
<td>p-GaAs</td>
</tr>
<tr>
<td>p-AlGaAs</td>
<td>stop layer</td>
</tr>
<tr>
<td>p-GaAs</td>
<td></td>
</tr>
<tr>
<td>p-InGaAs</td>
<td>strained layer</td>
</tr>
<tr>
<td>p-AlAs/AlGaAs</td>
<td>sacrificial layer</td>
</tr>
<tr>
<td>p-GaAs (100)</td>
<td>substrate</td>
</tr>
</tbody>
</table>

**Photographs of the sample (top view):**

- Before releasing
- After releasing
Electrostatic actuation of micro-origami devices

Introduction

- Ansys was used to model electrostatic actuation of a corner cube reflector.
- Forces required for actuation were estimated to be below 1 µN.
- Influence of metallization on the hinge was studied.

Electrostatic deflection

- Up to 10 µm deflection for less than 35 V

Figure 1: Calculated deflection versus applied force

Figure 2: Origami plate in a perpendicular electrostatic field

Figure 3: Deflection versus applied voltage
Electric contacts on released plates

- Metallization on the hinge
- Small effect on hinge deformation for thickness below 20nm

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

Figure 4: Modeling the effect of metallization across the hinge
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
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.

Optical Modeling

Effective optical modulation for free-space applications

Figure 1: Illustration of a dual corner cube reflector

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

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.

Good control over hinge curvature and deflection angle
**Micro-mirror array**

Hinge at 400nm
Ga flow reduced by 30%
Hinge thickness reduced
In comp. increased

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>10 nm</td>
</tr>
<tr>
<td>In_{0.2}Ga_{0.8}As compensator</td>
<td>10 nm</td>
</tr>
<tr>
<td>GaAs</td>
<td>450 nm</td>
</tr>
<tr>
<td>Al_{0.5}Ga_{0.5}As</td>
<td>150 nm</td>
</tr>
<tr>
<td>GaAs</td>
<td>66 nm</td>
</tr>
<tr>
<td>In_{0.2}Ga_{0.8}As stressor</td>
<td>10 nm</td>
</tr>
<tr>
<td>Sacrificial layer Al_{0.5}Ga_{0.5}As / AlAs DA</td>
<td></td>
</tr>
<tr>
<td>GaAs buffer</td>
<td>400 nm</td>
</tr>
<tr>
<td>GaAs(100) substrate</td>
<td></td>
</tr>
</tbody>
</table>
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
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

30 Hz Off

90 Hz On

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.

• Has 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.