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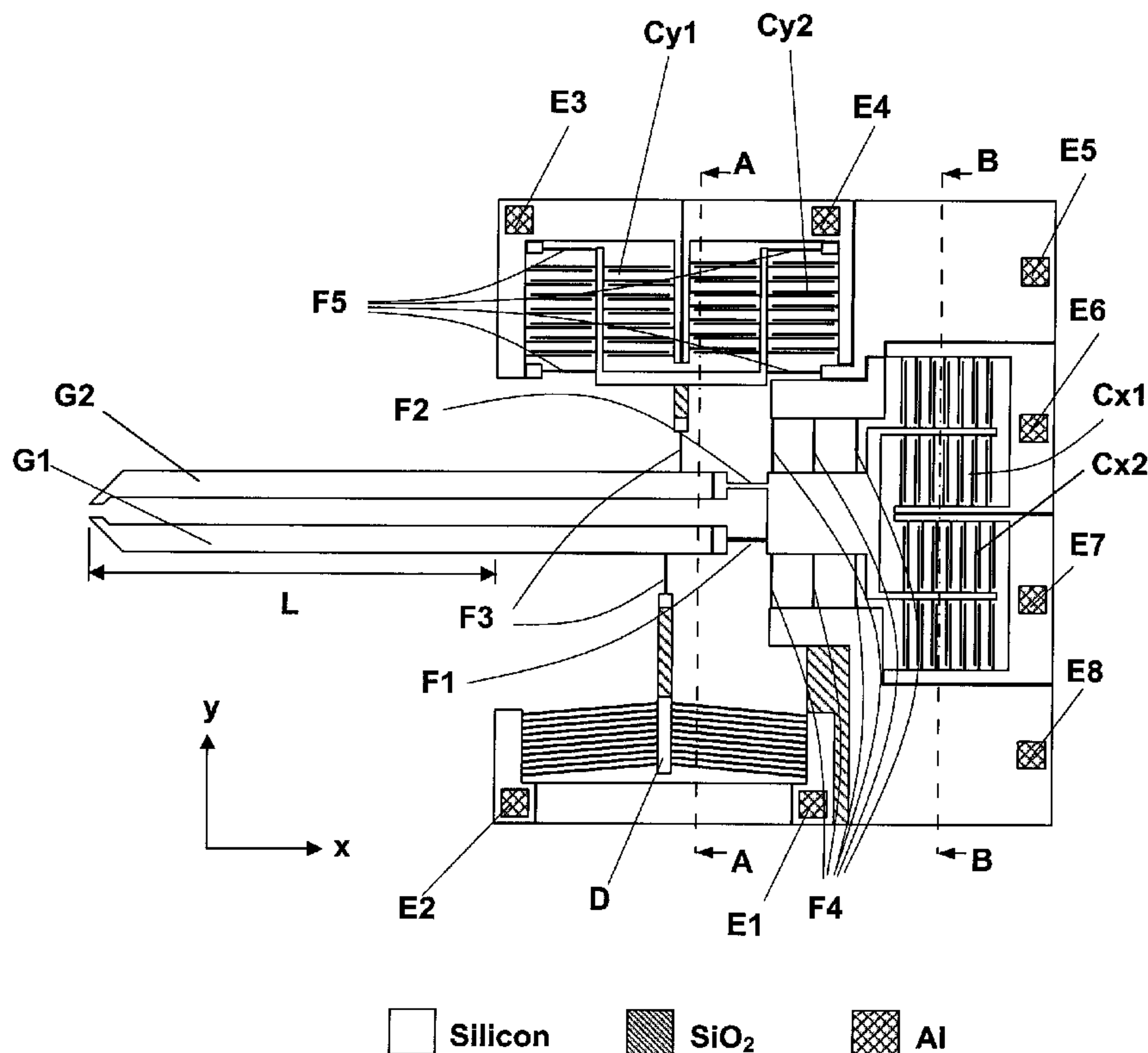
(54) Title: ELECTROTHERMALLY-DRIVEN MEMS MICROGRIPPERS WITH INTEGRATED DUAL-AXIS CAPACITIVE FORCE SENSORS



(57) Abrégé/Abstract:
The present invention relates to a design and microfabrication method for micrograppers that are capable of grasping micro and nano objects of a large range of sizes and two-axis force sensing capabilities.

Abstract

The present invention relates to a design and microfabrication method for microgrippers that are capable of grasping micro and nano objects of a large range of sizes and two-axis force sensing capabilities.

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ELECTROTHERMALLY-DRIVEN MEMS MICROGRIPPERS WITH INTEGRATED DUAL-AXIS CAPACITIVE FORCE SENSORS

Field of the Invention

5 The present invention relates to micro and nanosystems, and micro and nanotechnology.

Background of the Invention

Intelligent manipulation (e.g., grasping/gripping) of micro- and nanometer-sized objects requires the use of miniaturized microgrippers with integrated force sensors. Currently, micro- and 10 nanomanipulation typically relies purely on visual feedback either from an optical microscope or an electron microscope. The lack of force feedback at the microNewton and nanoNewton level severely limits intelligent micro- and nanomanipulation.

Besides miniaturization and electrical control, microgrippers must be capable of providing multi-axis force feedback to satisfy the following requirements: (i) to protect the microgripper and 15 detect the contact between the microgripper and the object to be manipulated; and (ii) to provide gripping force feedback during grasping to obtain secured grasping while protecting the object to be grasped.

The vast majority of existing microgrippers lack force feedback due to the difficulty of integrating force sensors with microgrippers. The lack of force feedback does not permit force-20 controlled manipulation and easily causes breakage of microgrippers and damage to the object to be manipulated.

A recently reported electrothermally driven microgripper design is integrated with a single-axis piezoresistive force sensor that is only capable of measuring gripping forces. (See K. Molhave and O. Hansen, "Electrothermally actuated microgrippers with integrated force-feedback," *J. of* 25 *Micromechanics and Microengineering*, 15(6), pp. 1265-1270, 2005.) However, the gripping force sensing resolution is poor, on the order of milli-Newton that is orders of magnitude worse than what micro-nanomanipulation requires.

A recent paper reports a design of an electrostatically driven microgripper with a single-axis capacitive force sensor that is only capable of measuring gripping forces. (See F. Beyeler, D.J. Bell, B.J. Nelson, Yu Sun, A. Neild, S. Oberti, and J. Dual, "Design of a micro-gripper and an ultrasonic manipulator for handling micron sized objects," IEEE/RSJ International Conference
5 on Intelligent Robots and Systems, Beijing, China, October, 2006.) Due to the limitation of electrostatic actuation (low force output and small displacements), the microgripper design is only capable of grasping objects of a small range of sizes.

The lack of force sensing capabilities along a second-axis down to nanoNewton in existing designs does not allow for the protection of microgrippers and the detection of contact between
10 the microgripper and object to be manipulated. What is needed is the design and microfabrication of microgrippers that are capable of grasping micro and nano objects of a large range of sizes and having two-axis force sensing capabilities.

Summary of the Invention

15 In one aspect, the present invention employs MEMS (microelectromechanical systems) technology in the design and microfabrication of microgrippers that are capable of grasping micro and nano objects of a large range of sizes and two-axis force sensing capabilities.

In a preferred embodiment of the present invention, integrated, single-chip, batch microfabricated MEMS devices are disclosed that are electrothermally-driven microgrippers
20 with integrated dual-axis force sensing capabilities. The gripping motion is produced by a bent-beam electrothermal actuator. The designed bent-beam actuator requires little power and is capable of producing a large range of gripping forces and displacements. Integrated force sensors along the in-plane x and y directions using transverse differential capacitive comb drives enable the measurement of gripping forces as well as the forces applied at the end of
25 microgripper arms along the normal direction, both with a resolution down to nanoNewton.

This microgripper design features two-axis force sensing capabilities suitable for use in intelligent micro and nanomanipulation. Additionally, the employment of bent-beam electrothermal microactuators permits the grasping of objects of a large range of sizes.

Brief Description of the Drawings

A detailed description of the preferred embodiments is provided herein below by way of example only and with reference to the following drawings, in which:

5 Figure 1 illustrates a microgripper with integrated 2-axis capacitive force sensors.

Figure 2 is a cross sectional view of the microgripper corresponding to Figure 1 along axis A-A.

Figure 3 is a cross sectional view of the microgripper corresponding to Figure 1 along axis B-B.

Figure 4 illustrates microfabrication steps for the construction of a microgripper.

In the drawings, one embodiment of the invention is illustrated by way of example. It is to be
10 expressly understood that the description and drawings are only for the purpose of illustration and as an aid to understanding, and are not intended as a definition of the limits of the invention.

Detailed Description of the Invention

In a preferred embodiment of the present invention, an electrothermally actuated microgripper
15 comprises four parts, as illustrated in Figure 1: (i) bent-beam electrothermal microactuator D to drive gripper arm G1; (ii) driving arm G1 and sensing arm G2 used together to grasp micro/nano objects; (iii) linear beam flexures F1, F2, F3, F4, and F5 used to transform forces into displacements; and (iv) pairs of capacitor plates forming capacitors Cx1, Cx2, Cy1, and Cy2 to transform displacements into capacitance changes.

20 Electrothermal bent-beam microactuator D produces forces to deflect the microgripper arm G1 through flexure F3. When electrothermal forces are produced by applying voltages/current between electrodes E1 and E2, the translational movement of F3 is converted into a rotational movement of the driving arm G1. The displacement and driving force from a single bent-beam of the electrothermal microactuator are

$$U = \alpha \Delta T l_d \frac{\sin\theta}{\left(\sin^2\theta + \cos^2\theta \dfrac{12I_d}{A_d l_d^{\,2}}\right)}$$

$$F_d = \alpha \Delta T E A_d \frac{\cos\theta}{\left(\sin^2\theta \dfrac{A_d l_d^{\,2}}{12I_d} + \cos^2\theta\right)}$$

where α is the coefficient of thermal expansion of the beam material, E is Young's modulus, l_d is the beam length, A_d is the beam cross sectional area, I_d is the moment of inertia, and θ is the
5 bending angle of bent beams. The bending of flexure F1 increases the reaction force of G1; however, this contribution from the bending of flexure F1 is trivial and thus, can be neglected. The displacement of the end of G1 is amplified by an amplification factor from the displacement of the bent-beam microactuator.

The second microgripper arm G2 is supported by flexures F2 and F5 and is connected to the
10 capacitive force sensor Cy1 and Cy2. G2 transmits gripping forces to the movable capacitor plates of the transverse comb drive Cy1 and Cy2 that together form a differential comb drive. As a gripping force F_g is applied, flexure F5 is deformed and the capacitance change of Cy1 and Cy2 can be measured through electrodes E3, E4, and E5. The bending force of flexure F2 converts the rotational motion of G2 into a translational displacement that is small and can be
15 neglected.

$$F_g = 4\frac{Etw_g^{\,3}}{l_g^{\,3}}x$$

where l is the length of the flexures F5, t is the out-of-plane thickness, w_g is the in-plane width, and x is the deflection. The capacitance C for each comb drive is

$$C = \frac{\varepsilon_0 n A}{d}$$

20 where ε_0 is the dielectric constant, n the number of capacitor plate pairs, A is the overlapping area, and d is the gap distance. Changing the gap d instead of the overlapping area A provides a

high change of capacitance for a small displacement Δd and thus increases the resolution of force sensing.

The length of microgripper arm L can be larger than 3.0mm for the purpose of operating in an aqueous environment, such as for handling biological cells. To make the arms mechanically connected and electrically insulated, the gripper arms are preferably connected using the handle layer of an SOI (Silicon on Insulator) wafer as shown in Figures 2 and 3. The buried
5 oxide layer, device layer, and handle layer are used together to form the structure and achieve electrical signal routing.

Figure 4 shows a microfabrication process of the microgripper, as an example. According to application needs, an SOI wafer having a 200-500 μm thick handle layer, 1-2 μm thick SiO_2 and 0.5-300 μm thick device layer can be chosen, as an example. A total of 4
10 photolithography masks are required to construct the microgrippers.

In particular, the specific steps as illustrated include:

A) SiO_2 is deposited on the handle layer of SOI wafer.

B) SiO_2 is patterned to form DRIE (Deep Reactive Ion Etching) etch mask (mask 1).

C) Center part of photo resist is removed (mask 2) and handle layer of the wafer is etched up
15 to 50 μm forming the structure for electrical insulation and mechanical connection.

D) Center part of SiO_2 is etched.

E) Handle layer of the wafer is etched again up to handle layer thickness minus up to half the thickness of the handle layer, e.g., 50 μm.

F) Buried oxide layer is etched.

20 G) Ohmic contacts are formed by e-beam evaporation and patterned by lift-off (mask 3).

H) Device layer of wafer is etched to form the structural elements thereof, including in this case gripper arms, flexures, bent-beam actuators, and comb drives (mask 4), for the microgripper of this example.

Note that changing the tethering spring dimensions and capacitance readout circuits can allow
25 devices in accordance with the present invention to resolve forces down to pico-Newtons. Force resolution at this level enable a larger range of applications, particularly in nano device assembly and biophysics studies in which individual molecules are manipulated and characterized.

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What is claimed is:

1. A mircofabrication method incorporating photolithography masking to produce a microgripper device operable to grasp objects varying from micro to nanoNewton and having two-axis force sensing capabilities, characterized in that the method comprises:

5 (a) depositing a silicon dioxide layer onto a handle layer, wherein the handle layer is resident on a silicon on insulator wafer, the wafer comprising a device layer and a buried oxide layer, wherein the buried oxide layer is between the silicon oxide layer and the device layer;

(b) patterning the silicon dioxide layer using an etching means to form a first mask;

(c) etching an area of the wafer to remove a first portion of the handle layer exposed 10 by the first mask;

(d) etching the area of the wafer to remove the silicon dioxide layer;

(e) etching the area of the wafer to remove a second portion of the handle layer so that a portion of the buried oxide layer is exposed;

(f) etching to remove the portion of the buried oxide layer;

15 (g) forming ohmic contacts; and

(h) etching the deivce layer to form structural elements of the microgripping device.

2. The microfabrication method of claim 1, wherein the structural elements include gripper arms, flexures, actuators, and capacitive force sensors.

3. The microfabrication method of claim 1, wherein the actuators are bent-beam actuators, 20 U-beam electrothermal actuators or electrostatic actuators.

4. The microfabrication process of claim 1, wherein the handle layer is 100 to 500 microns thick.

5. The microfabrication process of claim 1, wherein the silicon oxide layer is 0.5 to 4 microns thick.

6. The microfabrication process of claim 1, wherein the device layer is 0.5 to 300 microns thick.

7. The microfabrication method of claim 1, wherein the first portion of the handle layer is up to half the thickness of the handle layer.

5 8. A method of microfabrication incorporating photolithography masking comprising multiple stages of etching a silicon on insulator wafer having multiple layers to produce structural elements of a gripping device operable to grasp objects varying from micro to nanoNewton and having two-axis force sensing capabilities, said method comprising the steps of:

10 (a) depositing a silicon dioxide layer on the handle layer of the silicon on insulator wafer and forming a deep reactive ion etching etch mask by patterning the silicon dioxide layer deposited on the handle layer of the silicon on insulator wafer;

(b) forming the structure for electrical insulation and mechanical connection by etching the handle layer; and

15 (c) forming structural elements including gripper arms, flexures, bent-beam actuators and combs drives by etching the device layer of the silicon on insulator wafer.

9. The method of microfabrication of claim 8, further comprising the step of producing a gripping device to include gripper arms, flexures, actuators and comb drives.

10. The method of microfabrication of claim 8, further comprising the step of forming ohmic
20 contacts by e-beam evaporation and lift-off patterning on the silicon on insulator wafer.

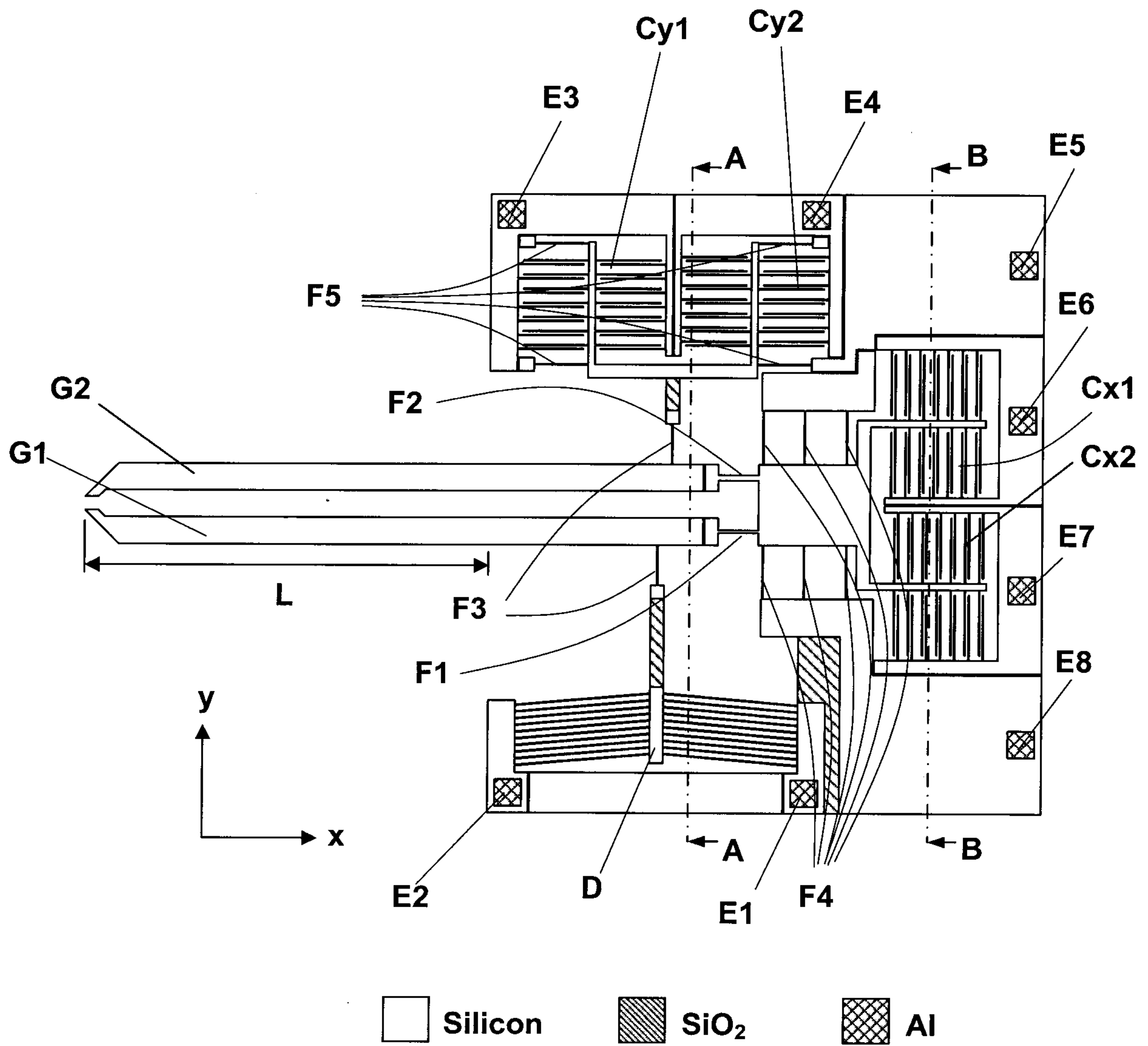
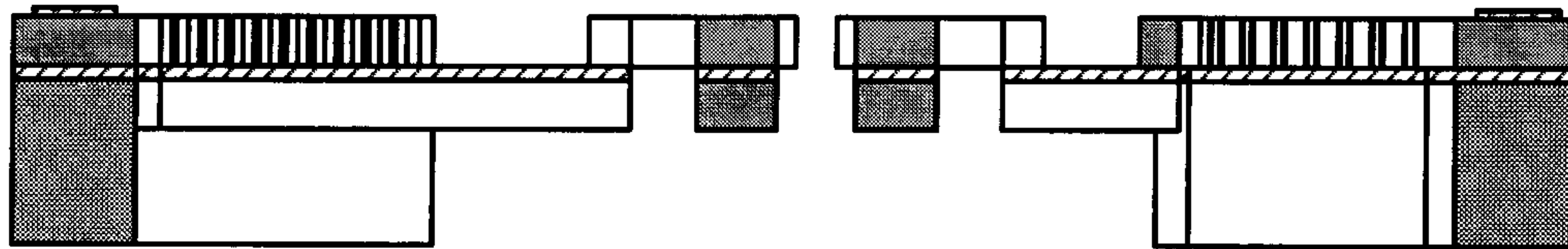
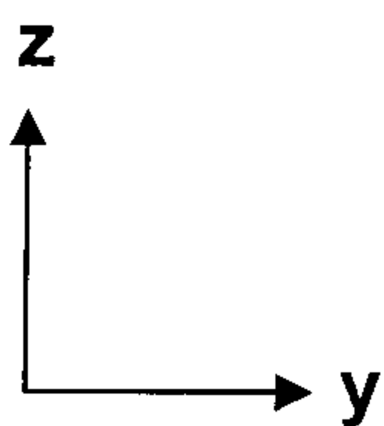


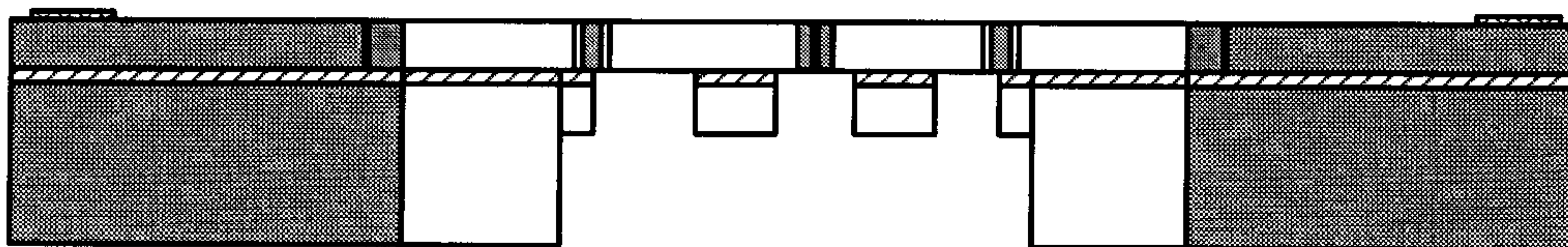
Figure 1



A - A

Figure 2





B - B

Figure 3

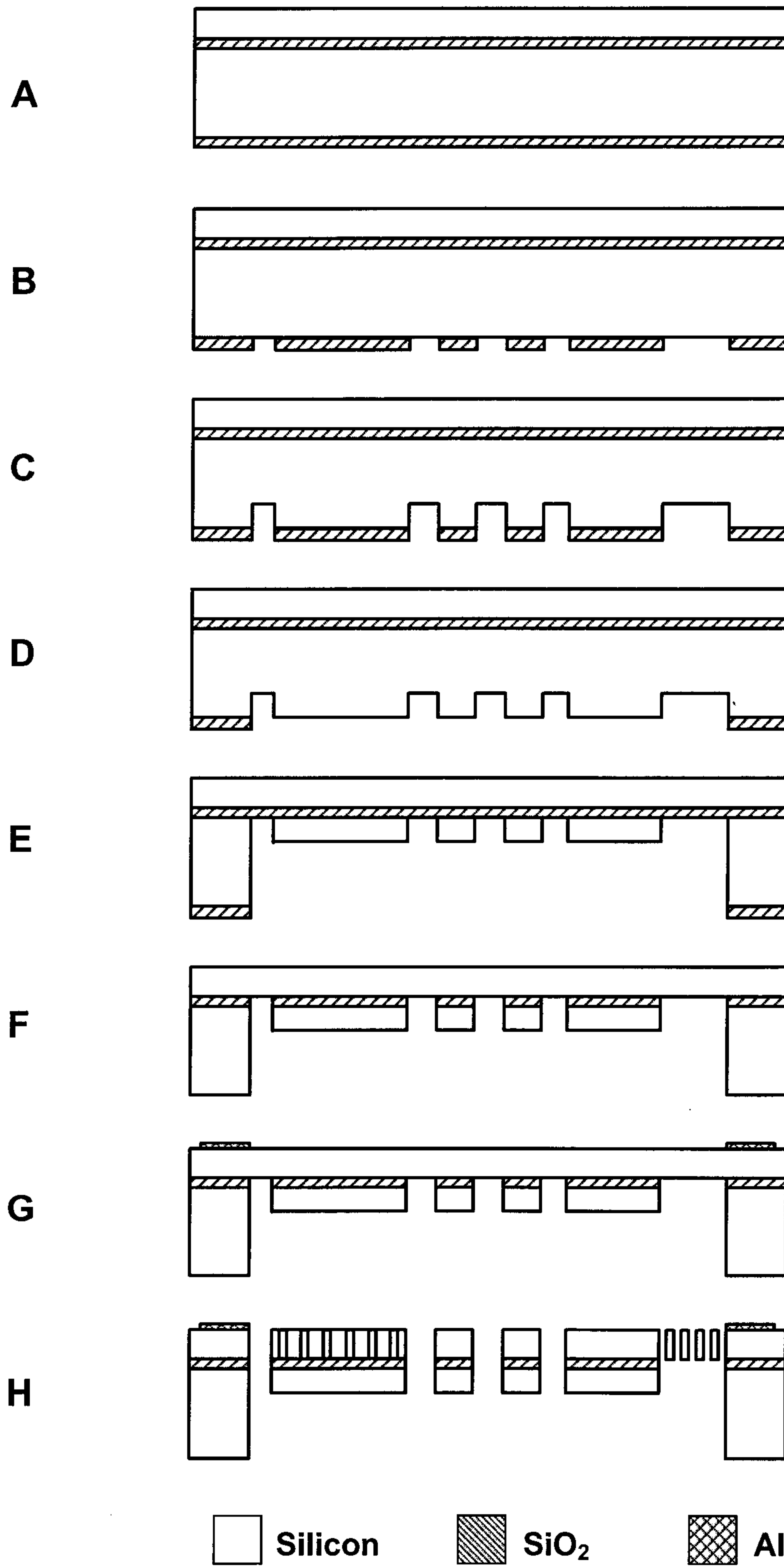
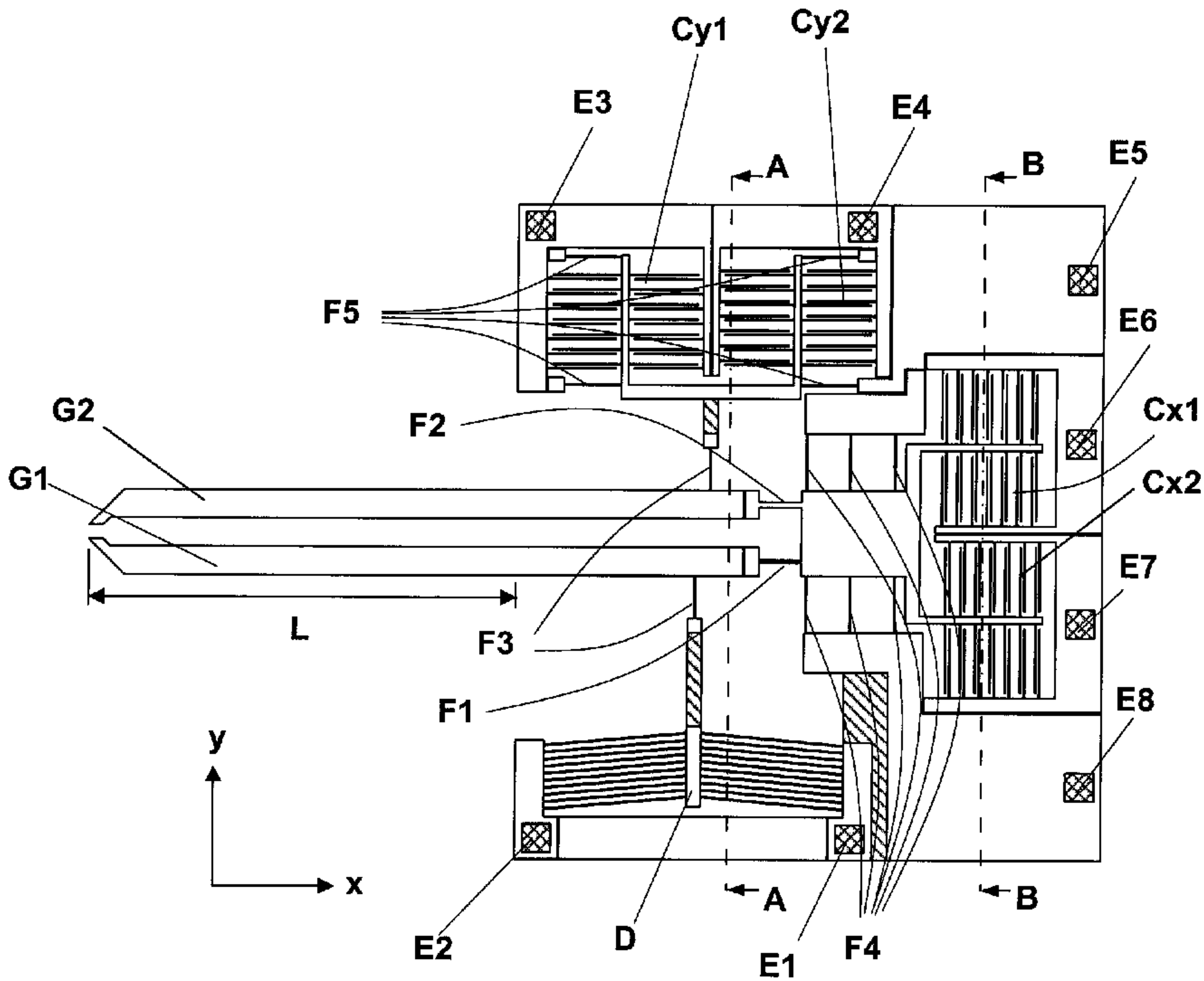


Figure 4


Cy1
Cy2
E3
E4
A
B
E5
F5
E6
Cx1
G2
F2
Cx2
G1
E7
L
F3
F1
E8
y
x
A
B
E2
D
E1
F4
Silicon
SiO2
Al