SILICON ACTIVE MICROVALVES USING BUCKLED MEMBRANES FOR ACTUATION

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SUMMARY

Design considerations and experiments have been made for obtaining a new type of active microvalves using silicon buckled membranes. The properties of the buckled membranes permitting to obtain high deflections and to actuate them more convenient are demonstrated. A thermal actuation using an aluminium ring layer heated with a polysilicon resistor is analysed. The polysilicon and the aluminium ring layers have been deposited in the region of the membrane having the minimum internal stress. The fabrication process consist of photolithography, LPCVD depositions, diffusion, Al sputtering, isotropic, anisotropic etching and anodic bonding. The design and experiments show a convenient low temperature range necessary to actuate the microvalve.

INTRODUCTION

Microvalves have been realised, using electrostatic actuation [1] and thermal actuation [2]. Thermal actuation was the most performant, obtaining fully proportional control of flows in the range of 0-300 cc/min at input pressures from near zero to over 6 atm. The temperature of the heated layer was rather high, more than 150°C, [2].

This work is on a new type of microvalves using for actuation a silicon buckled membrane. Buckled membranes permit to obtain high deflections and they have a smaller shiftiness after buckling in comparison with non-stressed membranes. A cross section of the silicon active microvalve is presented schematically in Fig. 1:

Fig.1 Cross section of the silicon active microvalve

The microvalve is a sandwich of three structures obtained in three different wafers finally assembled by anodic bonding. The central structure contains the silicon buckled membrane. The membrane is initially buckled under the compressive stress of a thermally grown SiO₂ layer. The deflection can be grown until the valve is closed, by applying a supplementary compressive stress to the silicon membrane, stress obtained using the thermal expansion of an aluminium ring layer. For its heating first a polysilicon resistor is deposited without internal stress, also with a ring pattern.

THEORY

1. Membrane actuation analysis:

The buckling of the membrane is achieved when the compressive stress is greater than a critical value S_{cr} . We have from [3] the value of the critical stress:

$$S_{cr} = 4.38 \cdot \frac{h^2}{a^2} \cdot \frac{E}{1-\nu^2} \quad (1)$$

where: h - is the thickness of the membrane
 a - the size of the membrane
 E - the Young modulus.

After buckling the deflection at the centre of the buckled plate under a compressive stress $S > S_{cr}$ is given by [3]:

$$W_0 = 2.3 \cdot h \cdot \sqrt{\frac{S}{S_{cr}} - 1} \quad (2)$$

where S is the compressive stress due to the internal stress in the SiO₂ layer.

From [3]:

$$S = \frac{h_{SiO_2}}{h_{SiO_2} + h_{Si}} \cdot S_0, \quad S_0 = 0.3 \cdot 10^9 \frac{N}{m^2} \quad (3)$$

with: h_{SiO_2} , h_{Si} , the thickness of the SiO₂ and Si layers,
 S_0 the internal compressive stress in the SiO₂ layer, thermally grown at 1150°C.

The initial deflection W_0 can be made greater by applying a supplementary compressive stress S_{supl} to the initially compressive stress S due to the SiO_2 layer. We use for obtaining the supplementary compressive stress S_{supl} , the internal tensile stress and the thermal expansion of an aluminium ring layer deposited on the membrane on the top of the SiO_2 layer and above a polysilicon ring layer used as the heating resistor. Aluminium is very convenient due to its large thermal coefficient.

In according with eq.1 the deflection will be given by:

$$W = 2.3 \cdot h \cdot \sqrt{\frac{S + S_{supl}}{S_{cr}}} - 1 \quad (4)$$

We obtained for the ΔT - the temperature difference above ambient, necessary for a total deflection W of the membrane:

$$\Delta T = \frac{(h_{SiO_2} + h_{Al} + h_{Si}) \cdot 1.28 \cdot 10^{11} \cdot \frac{W^2 - W_0^2}{a^2} + S_0 \cdot h_{SiO_2}}{E_{Al} \cdot \alpha_{Al} \cdot h_{Al}} \quad (5)$$

with α - the coefficient of thermal expansion.

For: $a = 4000\mu m$, $h_{Si} = 16\mu m$, $h_{SiO_2} = 1\mu m$, $h_{Al} = 3\mu m$ we can calculate:

$W_0 = 37\mu m$, and:

a) For $\Delta W = W - W_0 = 5\mu m$ is necessary

$\Delta T = 17.7^\circ C$.

b) For $\Delta T = 150^\circ C$, result $\Delta W = W - W_0 = 33\mu m$

2. Distributions of the stresses

For long-term operation is necessary that the polysilicon and the Al ring layers to be placed on the membrane in the minimum stress position. We obtained distributions of the stresses like that plotted in Fig. 2.

Fig.2 Distributions of the stresses at the edges and in the middle of the buckled membrane

3. Heat transfer analysis:

In the steady state there is an equilibrium between the rate of development of the thermal energy in the polysilicon resistor and the rate of heat transfer from conduction, convection and radiation towards the aluminium layer on the top side and from the silicon membrane towards the thick silicon surroundings.

The total heat losses by conduction and by convection, P_{tot} , can be written, using [4]:

$$P_{tot} = \frac{T_{poly} - T_{amb}}{\frac{h_{SiO_2}}{k_{SiO_2} \cdot A_{poly}} + \frac{\ln(\frac{a}{2} / (r + L))}{2\pi \cdot k_{Si} \cdot h_{Si}}} + \frac{T_{poly} - T_{amb}}{\frac{1}{h_{conv, fluid} \cdot A_{Al}} + \frac{h_{1, SiO_2}}{k_{SiO_2} \cdot A_{poly}}} \quad (6)$$

where: a - the size of the membrane, r - the inner radius of the polysilicon circular layer, L - the width of the polysilicon resistor, k - thermal conductivity's, $h_{conv, fluid}$ - the convection coefficient of the fluid, T_{amb} - the ambient temperature, T_{poly} - the temperature of the polysilicon layer

For $a = 4000\mu m$, $L = 330\mu m$, $r = 1000\mu m$, fluid = water with $h_{conv} = 1000$ Watts/mK, we obtain the heat dissipated in the polysilicon layer:

For: $\Delta W = W - W_0 = 5\mu m$: $P = P_{tot} = 0.56$ Watts, which is very convenient.

In this analysis the thermal expansion of the polysilicon layer was neglected in comparison with the aluminium layer due to the difference about one order of size between their coefficients of thermal expansion.

4. Fluid flow analysis

The flow from the outlet can be written [1]:

$$flow \cong \frac{h^3 \cdot d \cdot (P_{in}^2 - P_{out}^2)}{24h \cdot P_{out}} \quad (7)$$

where: $h = W - W_0$, the grow of the deflection

d - the outlet hole diameter

P_{in} , P_{out} , the input and output pressures

h - the viscosity of the fluid

The flow can be adjusted from the parameters $h = \Delta W$ and d .

5. Fabrication Process

The main fabrication sequence is the following:

1. Double side polished (100) silicon wafer
Thermally grown $1.5\mu\text{m}$ SiO_2 layer
Front and back faces align
2. LPCVD polySi $0.5\mu\text{m}$.
Bor diffusion for 30 m/sq polySi resistor
Plasma etching polySi
3. LPCVD, HTO SiO_2 $0.5\mu\text{m}$, patterning and etching
4. Al sputtering onto the surface, Al patterning and etching
5. Front face LTO, SiO_2 deposition
Back face SiO_2 patterning and etching
Back face anisotropic KOH etching.
6. Upper and down structures processing by anisotropic etching
- 7 Assembly by anodic bonding

EXPERIMENTS

Experiments were made first to obtain silicon buckled membranes for the microvalve actuation. Silicon square membranes were anisotropically etched in KOH and TMAH with mask of thermally grown SiO_2 having $1\mu\text{m}$ SiO_2 layer at the end of the etching. We studied individual samples like in Fig.4 having the square a between $100\mu\text{m}$ and $5000\mu\text{m}$ and thickness h between $12\mu\text{m}$ and $25\mu\text{m}$.

FIG.4 Cross section of a sample with buckled membrane loaded with a pressure

The membranes buckled into the the direction of the SiO_2 layer. The membranes buckled in time when the ratio a/h was greater than a critical value $(a/h)_{cr}$, given in [3] and membranes with $a/h < (a/h)_{cr}$ remained flat.

We measured the deflection at the centre of the square membrane, $w=f(q)$; q - the difference of pressure was made with a controllable pressure source Wallace @ Tiernan and the deflection was measured with a surface profiler type DEKTAK 3030.

For $h_{\text{SiO}_2} = 1\mu\text{m}$ and $a/h = 5000\mu\text{m}/16\mu\text{m}$, a comparison between the theoretical and experimental behaviour of the plate is shown in Fig. 5.

Fig 5. Theoretical and experimental behaviour of the buckled membrane

A comparison between the pressure needed by the buckled membranes and non-stressed membranes of equal dimensions in order to obtain the same deflections is shown in Table 1 for two samples $a/h = 4000\mu\text{m}/18\mu\text{m}$ and $a/h = 5000\mu\text{m}/16\mu\text{m}$.

We can see that for similar deflections the buckled membranes need much smaller difference of pressure.

Deflection W [μm]	
Pressure [mbar]	Buckled membr.
Pressure [mbar]	Non-stressed membr

a/h=4000 μm /18 μm	a/h=5000 μm /16 μm
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21.5	28.8	37	42	48	56
4	40	100	6	24	54
72	138	255	105	167	253

Table 1. Comparison between pressures needed by buckled and by non- stressed membranes for similar deflections

Experiments were made also for performing the fabrication sequence presented above.

CONCLUSIONS

In this paper a new type of active microvalves based on silicon buckled membranes have been analysed.

Buckled membranes deflect much stronger under an external pressure that non-stressed membranes and this added to the initial deflection make them convenient for using them in microvalves, micropumps actuation.

A thermal actuation of silicon buckled membranes is very convenient.

An initial deflection of 37 μm and a supplementary actuation of 5 μm can be obtained with only about 18 $^{\circ}\text{C}$ heating of an aluminium deposited ring layer for a silicon membrane 4000 μm size and 16 μm thickness.

The dissipated power in a polysilicon ring resistor in order to obtain this actuation is only 0.56W.

The microvalve is a sandwich of three bonded structures with the central structure the actuated membrane.

The modelling of the microvalve, the experiments made for obtaining the new type of silicon buckled membranes and for performing the fabrication process permit us to start now the final structure of the microvalve.

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