TRANSDUCTION MECHANISMS AND THEIR APPLICATIONS IN MICROMECHANICAL DEVICES

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ABSTRACT

Transduction mechanisms and their applications in micromechanical actuators and resonating sensors are presented. They include piezoelectric, dielectric, electro-thermo-mechanic, opto-thermo-mechanic and thermo-pneumatic mechanisms. Also advantages and disadvantages with respect to technology and performance are discussed.

INTRODUCTION

In this paper we give an overview of the transduction mechanisms in sensors and actuators which are being developed in the micromechanics group of the Sensors and Actuators Research Unit at the University of Twente. The micromechanical sensors we are concerned with are based on the observation that the resonance frequency of a mechanical structure is changed upon interaction with its surroundings [1,2]. A resonating sensor generally comprises two transducers, one to excite and another one to detect the vibrational motion of the structure. The signal from the detection transducer is fed back, via an electronic amplifier, to the excitation transducer. This way we obtain an oscillator which vibrates at the resonance frequency of the mechanical structure.

This concept requires at least three different types of transduction: (i) excitation, (ii) detection and (iii) modulation of the vibration. The former two have to connect the electrical to the mechanical domain and vice versa respectively, while the latter connects the measurement domain to the mechanical one; examples are the resonant diaphragm pressure sensor [3,15], the vibrating membrane mass flow sensor [4] and Greenwood's vibrating sensor [5]. In this paper we focus on excitation and detection mechanisms.

It is obvious that for the excitation, energy has to be supplied to the vibrating structure. Therefore a transduction of the

generator type is required. If this transduction is reversible (dielectric, piezo-electric), it is obvious to consider the same mechanism for detection purposes. If the transduction contains a non-reversible element (e.g. a "heater" to induce thermal expansion) however, this is not possible. It is therefore natural to choose a detection mechanism which is technologically compatible with the excitation mechanism.

In this paper we describe the theory, technology and performance of some excitation and detection mechanisms used in devices developed in our laboratory.

PIEZOELECTRIC TRANSDUCTION

Piezoelectric transduction can be used both for detecting a mechanical deformation as well as for exciting a structure into vibration. The former effect is called the piezoelectric effect: a deformation of the piezoelectric material causes an electric response; the reciprocal effect is the so called inverse piezoelectric effect: an electric field inside the material causes a deformation.

Figure 1 shows how the inverse effect is used to bend a silicon cantilever with a thin piezoelectric layer on top of it. The exciting voltage V_{ex} causes the piezoelectric

Fig.1 Piezoelectric excitation on a silicon cantilever.

layer to elongate resulting in a bending moment M which acts on the structure. If the thickness of the piezoelectric layer t_{pe} is small compared to the thickness of the silicon cantilever t_{Si} we find for this moment:

$$M = E_{pe} d_{31} V_{ex} w t_{Si} / 2 \quad (1)$$

where E_{pe} is the Young's modulus and d_{31} is the piezoelectric coefficient of the piezoelectric layer.

From (1) it is clear that the piezoelectric effect is a linear transduction between the mechanical and the electrical domain.

In our group thin films of ZnO are used as the piezoelectric material. Although ZnO is not compatible with IC technology, it is the thin film material with the largest piezoelectric coefficients.

The films are deposited by means of RF magnetron sputtering of a pure zinc target in a 100% oxygen atmosphere. The films show a highly oriented c-axis, perpendicular to the substrate, as measured by XRD. SEM photo's show a columnar structure.

The electric properties are determined by CV-, IV- and Van-der-Pauw-measurements. The most important properties are listed in table 1.

Table 1. Properties of ZnO thin films.

piezoelectric coefficient d_{31}	$-5 \cdot 10^{-12} \text{ C/N}$
free electron density n_z	$5 \cdot 10^{17} \text{ cm}^{-3}$
barrier height ϕ_b	$0.2 - 1 \text{ eV}$
grain size (SEM)	$0.4 \mu\text{m}$
Seebeck coefficient	$-80 \mu\text{V/K}$

To exploit the piezoelectric effect in these films, it is necessary to create a depletion region inside the semiconducting ZnO. This is accomplished by using a Schottky- or an MOS-structure which is driven into depletion with a DC bias voltage. The AC voltage for excitation is superimposed on the DC voltage.

Measurements on silicon cantilevers with a metal-SiO₂-ZnO-metal structure on top excited with an AC voltage of 1 mV and no DC bias show a tip deflection at resonance of 75 nm. In this case the built-in charge in the SiO₂ layer supplies the required offset voltage. From these measurements a d_{31} of $-5 \cdot 10^{-12} \text{ C/N}$ is calculated, a value which approximates the value for bulk ZnO ($-5.12 \cdot 10^{-12} \text{ C/N}$ [6]).

It seems that the electrical properties of our ZnO thin films differ considerably from those described by Polla and Muller [7]. They characterize their films by a Debye length of $120 \mu\text{m}$ which implies that the free electron density is much smaller than n_z given in Table 1.

The piezoelectric transduction mechanism is used in several devices developed at the University of Twente:

(i) Resonant diaphragm pressure sensor [3]. The resonance frequency of a silicon diaphragm is a function of the applied pressure difference: 0.11 Hz/Pa at low pressures ($<0.1 \text{ bar}$).

(ii) Laser beam deflector [8]. A rotating silicon mirror is driven into resonance by four bending bars. Result: a scanning angle of 1° at a resonance frequency of 3600 Hz .

(iii) Resonant force sensor [9]. A force acting on a silicon beam shifts its resonance frequency. The resolution can be as high as 1 part in 100,000 at a maximum load of 1 N.

DIELECTRIC TRANSDUCTION

An alternative technique for excitation and detection makes use of a dielectric film [10]. As in the previous case the film is sandwiched between lower and upper electrodes, located on top of the vibrating structure. By applying a DC with superimposed on it AC voltage, electrostatic forces result which excite the structure (see Fig. 2a).

The compression of the dielectric film in the transverse direction is accompanied by a lateral expansion, which causes the multilayer to bend.

The detection of the vibration is capacitive. When the multilayer is vibrating, the upper layers are harmonically stretched and compressed. This causes a fluctuation of both the area and the thickness of the dielectric film capacitor (Fig. 2b). With a DC voltage applied across the electrodes, the (re)charging of the capacitor yields the detection current.

Fig. 2 Dielectric excitation (a) and detection (b).

We have derived formulas for both mechanisms. The amplitude of the electrostatically excited vibration is proportional to the product of the applied DC and AC voltages, the Poisson ratio and the dielectric constant of the film. The detection current is proportional to the

vibration frequency, the dielectric constant, the amplitude of vibration and the applied DC voltage.

Measurements were done on silicon cantilevers of various dimensions with a 95 nm thick stoichiometric silicon nitride film sandwiched between a p⁺⁺-silicon lower and a chromium-gold upper electrode.

The amplitude of vibration of a number of dielectrically excited cantilevers was measured for various DC and AC voltages. A typical result of a single measurement sequence is shown in Figure 3a.

Fig.3 Results of the dielectric transduction: (a) excitation and (b) detection.

The amplitude of vibration proves to be proportional to the product of the applied voltages. An offset U_0 of 5.5 V occurs which is probably caused by trapped ions within the dielectric film.

The output current of the capacitive detection was measured for a number of externally excited cantilevers for a series of ranges of the amplitude of the vibration and the magnitude of the applied DC voltage (see Fig. 3b). The output current is proportional to the product of the varied parameters, again with an offset of 5.5 V for the DC component. The experimental results for both the excitation and the detection agree well with the model.

The efficiency of the transduction can be increased by decreasing the thickness of the film and by applying a dielectric film with high values for the Poisson ratio and for the dielectric constant (for thin films of $\text{Pb}(\text{Ti,Zr})\text{O}_3$ a dielectric constant of $\epsilon=950$ (!) is reported [11]), and by optimizing the deposition process for the capacitor's built-in charge.

The simple fabrication technology, with a wide scope of materials, geometries and etching techniques to choose from, can be

made compatible with IC-technology. Power consumption is low due to the high resistivity of the dielectric film.

This excitation - detection technique will be used in a resonating micro-bridge force sensor [12], as well as in a resonating pressure sensor [13].

ELECTRO-THERMO-MECHANICAL TRANSDUCTION

Another way of exciting a micro-mechanical structure is by means of an electro-thermo-mechanical transducer (Fig.4). The transduction mechanism is a combination of two mechanisms: an irreversible electro-thermal transduction combined with a reversible thermo-mechanical transduction.

This technique of electro-thermo-mechanical excitation was first described by Wilfinger et al. [14] in 1968. The excitation is based on the thermal expansion of the beam material. The periodic heat dissipation results in a periodic thermal gradient, which results in a driving mechanical moment.

Because the heating effect of the electrical current is proportional to the square of the current, the frequency of the AC driver signal must either be at half the resonant frequency of the structure or in case the AC signal is superimposed on a DC bias, the AC frequency can be the same as the resonant frequency.

Fig. 4. Electro-thermo-mechanical transducer with a NiFe film as the dissipating element.

The transducer is relatively simple. Various materials can be used for the dissipating element e.g. thin metal films like Cr/Au, Al and NiFe, doped poly-silicon films and p or n diffusion areas in single crystal silicon. The choice of the material depends on its mechanical properties, its technological compatibility with other parts of the device and on the desired input impedance.

In principle, the dissipation of heat in the resistor is irreversible, therefore this transduction mechanism cannot be used for detection. A possible detection method makes use of the piezoresistive effect e.g. of

doped polysilicon. This way, both the transducer for the excitation and detection can be identical, which makes the fabrication process less complicated. It appears therefore that from a technological point of view, the excitation-detection pair of poly-silicon resistors is most natural and simple.

The starting material for the thermally excited resonating membrane mass flow sensor [4] is a low doped 2" (100) silicon wafer. Conventional techniques are used for thin film deposition, doping, photolithography and etching. In-situ phosphorous doped poly-silicon is used for the resistors. Anisotropic etching in a KOH/IPA solution is used to form the membrane. As an etch stop a heavily boron doped silicon layer is used, yielding a 3 μm thick membrane (Fig. 5).

Fig. 5. Resonating membrane mass flow sensor. The membrane is 2 mm square and about 3 μm thick.

Finally, from a technological point of view we may state that the electro-thermo-mechanical transduction mechanism is very interesting: realization is relatively simple, the process is compatible with standard IC processing and almost any conducting material can be used for the transducers. However the inherent thermal dissipation might result in unwanted mechanical stresses, causing an error signal in the sensor output.

OPTO-THERMO-MECHANICAL TRANSDUCTION

When the vibrating micromechanical structure is combined with fiber optic links, the micromechanical system becomes a fiber optic sensor. This class of sensors combines advantages of both optical and (micro)mechanical sensors [17,18]. In our group a fiber optic pressure sensor and a fiber optic force sensor are developed [19]. The principle of operation is depicted in Fig. 6.

The micromechanical structure is periodically heated by the absorbed light from an optical fiber 1 (opto-thermal transduction). The thermo-mechanical transduction is already described in the previous section. In contrast to the electro-thermo-mechanical mechanism, the frequency of the optical driving signal is now the same as the resonant frequency of the structure. Fibers 2 and 3 in Fig. 6 form a

Fig. 6. Vibrating mechanical structure with fiber optic links.

sensitive displacement sensor [3]. The light coupled back into fiber 3 is modulated by the displacement of the microstructure.

The opto-thermo-mechanical transducer is just like the electro-thermo-mechanical transducer simple to realize. We make use of bare silicon, although other materials do have a better "figure of merit" for the thermo-mechanical transduction [20]. From a technological point of view the advantages of bare silicon are obvious. An optical coating of the silicon will result in more heating power into the silicon and thus producing a larger bending moment.

We have realized an optical pressure sensor based on this principle [19] (see Fig. 7). A pyramid on the diaphragm acts as a light shutter in the fiber optic displacement sensor, which consists of two optical fibers

Fig. 7. Cross-section of fiber optic pressure sensor.

2 and 3 that form an integral part of the device. V-grooves are used for precision guiding of the fibers. The width of the V-grooves is chosen such that the top of the pyramid lies exactly on the axis of the fibers. The whole structure is realized using anisotropic etching techniques.

The fiber link for the excitation is configured in another wafer. A mirror is etched in this wafer and is used to deflect the light in a direction perpendicular to the diaphragm.

THERMO-PNEUMATIC ACTUATION

A thermo-pneumatic actuator is a device consisting of a sealed cavity filled with a thermally expandable medium that can be heated or cooled, resulting in a pressure change in the cavity. The induced pressure change is used to actuate a flexible or movable part, like a membrane or piston. Gas or a gas/liquid system can be used as the expandable medium.

We have realized a thermo-pneumatic actuator [21] designed to drive a microminiature pump, replacing the original piezoelectric transducer [22]. Figure 8 shows a sketch of the actuator comprising a cavity filled with air, and a built-in aluminium meander which serves as a heating resistor. The resistor is supported by a thin silicon sheet suspended by four silicon beams. The beams are made small in order to minimize the heat losses. Aluminum current leads connecting the meander to the bonding pads run through narrow channels. These channels also serve as a restriction for the gas flow. The actuator is mounted on top of a pump body, such that the flexible membrane can

Fig.8 Thermo-pneumatic actuator (dimensions in mm).

displace liquid present in the pump chamber [23].

As a starting material for the actuator, two (100) silicon 2-inch wafers, polished on both sides, and a Duran borosilicate glass plate are used. The silicon wafers are shaped by wet chemical etching in a KOH-H₂O solution using standard photolithographic techniques for pattern definition. A glass wafer is cut out off the plate and is subsequently polished (surface roughness < 0.05 μm). The wafers are attached to one another by means of anodic bonding [24,25]. To achieve a bond between the two silicon wafers, an intermediate layer of silicon oxide and sputtered borosilicate glass is required.

Bond graph techniques [26] and TUTSIM [27] are used for physical modelling and simulation of the dynamic behaviour of the actuator. The model includes the thermal behaviour of the actuator, the thermodynamics of the air, the fluid dynamics of the channels and the mechanics of the flexible membrane.

Fig.9 Deflection w_0 vs. time for a number of applied voltages.

Figure 9 shows the centre deflection w_0 of the flexible membrane, as a function of time t for a number of pulsed voltage levels applied to the resistor. The voltage is switched on at time $t = 4$ s. A fast increase of w_0 is followed by a slower decrease to zero deflection. The first fast increase is caused by a temperature rise in the cavity and a related pressure increase. Maximum temperature and pressure built-up and related deflection w_0 are determined by input power and the thermal conductances of the small suspending beams and the air in the cavity. The subsequent slower decrease of w_0 is due to a flow of air out of the cavity, via the narrow channels, and a related pressure decrease. When the voltage is switched off at time $t = 25$ s, the opposite behaviour is observed. The cavity cools down causing a pressure drop inside the cavity, which results in a fast decrease of w_0 . The

following slower increase to zero deflection is due to a flow of air into the cavity. The dashed lines in Fig. 9 represent simulation results.

At higher frequencies a steady state is reached after 30 s with an amplitude of 23 μm corresponding to a pressure difference over the membrane of 0.02 atm and a volume stroke of 0.5 μl . At frequencies exceeding 0.4 Hz, there is no time to reach maximum or minimum w_0 , resulting in a decrease of the amplitude.

The actuator behaves as expected: measured and simulated results agree within 10 %. Hence the model can be used for optimizing the actuator. Pressure built-up and induced membrane deflection are sufficient to drive the micropump [22]. A better thermal insulation of the cavity will result in an increase in temperature and pressure built-up.

DISCUSSION AND CONCLUSIONS

We have demonstrated that there is quite a number of different transduction mechanisms available for excitation and detection of resonating sensors. All of them have certain advantages and disadvantages. In addition, a thermo-pneumatic actuation principle is described.

The transducers using the thermal domain necessarily produce heat. This can be used to our benefit, e.g. in the vibrating membrane mass flow sensor, where the heat is directly exploited. However, the released heat might cause problems. The steady state temperature not only depends on the design of the device but also on details of the packaging, which determines the heat flow to the surroundings. This is a "performance disadvantage". On the other hand, the technology for the excitation - detection pair of electro-thermo-mechanical excitation - piezoresistive detection is the most simple one. Therefore, there is a technological advantage.

The thermo-mechanical actuation has a number of advantages. The main advantage is that tremendous forces can be produced by employing the thermal expansion of condensed material; examples are the bimorphs of Benecke and his coworkers [28]. The expansion of gases has been suggested to actuate not only pumps as discussed here but also valves [29].

Opto-thermo-mechanical transduction offers the possibility to make all-optic sensors with the important advantage that they are insensitive to electromagnetic interference. Furthermore, it can be used in environments in which electrical signals must be avoided. Integration of optics and micromechanics seems to be extremely difficult, because these sensors are hybrid in nature, and one

is faced with serious (but solvable) fabrication problems.

The dielectric transduction is technologically simple. Moreover, there is a great variety of materials which are suitable. One can choose materials with or without thermal match, depending on the application. A material thermally matching silicon, is silicon nitride [30]. An additional advantage of silicon nitride is that the residual film stress can be controlled [31]. Employing this type of transduction, fabrication of resonating solid-state sensors with a reduced thermal drift is feasible. The disadvantage of this method however is the extremely small gain, making advanced electronics for the feed back loop necessary.

Finally, the piezoelectric transduction has a large gain, and hardly any heat losses. However, the non zero conductivity of the material used so far, i.e. sputtered ZnO, at low frequencies (< 1MHz) still causes some problems e.g. a lowering of the efficiency of the transduction. In an MOS or MS structures this problem can be overcome by creating a depletion region with a very high resistivity.

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