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AN 8x8 ROBUST CAPACITIVE PRESSURE SENSOR ARRAY

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Abstract

In this work, robust substrates, such as stainless steel, have been studied as substrates for rnicromachiped devices. The use of robust substrates may allow for the co-fabrication of micromachined IdeVices and sensor packages. Lamination process techniques combined with traditional micro machining processes have been investigated as suitable fabrication technologies. To illustrate these principles, a capacitive pressure sensor array has been designed, fabricated, and characterized using stainless steel substrate, Kapton polvimide film as a suspended movable plate, and an electroplated nickel fixed back electrode. The net capacitance change o.f this sensor aver the applied pressure range (0 to 34 kPa) was approximately 0.14 aF. Multivibrator circuitry has been integrated with pressure sensors in a hybrid fashion and used for frequency-modulated output measurements. An important attribute of this design is that only the steel substrate and the pressure sensor inlet is exposed to the flow; i.e., ilie sensor is self-packaged.

INTRODUCTION

Since the root of micromachining technology is in integrated circuit processing technology, micromachined devices have been primarily realized using silicon substrates [1-3]. In many applications, me use of traditional silicon-substrate micromachined devices may be limited, for example by the lack of ability of the surrounding silicon substrate to absorb large mechanical shocks.

In this work, we have investigated the use of more robust substrates as suitable starting points for both bulk and surface micromachined structures, as well as investigated the possibility of the substrate forming essential structural components of the device package. Alternative fabrication techniques, such as techniques more commonly used in either conventional machining as well as electronic packaging fabrication (e.g.~ lamination), are combined with more additional integrated circuit-based microelectronics processing techniques to create micro machined devices on these robust substrates.

One of the advantages of the use of robust substrates is the possibility of co-'fabrication of the micromachined devices and their package using, e.g., the robust substrate itself as an integral part of the sensor package. Another advantage is that due to substrate robustness, these co-packaged devices may be able to be used in mechanically Harsh environements as aerospace and oceanography applications.

To illustrate these principles, a robust capacitive pressure sensor array has been fabricated using stainless steel as a substrate, Kapton polyimide film as a pressure-sensitive flexible plate, and electroplated nickel as a back electrode. An important attribute of this design is that only the stainless steel substrate and the pressure sensor inlet are exposed to the flow; i.e., the sensor is self-packaged.

THOERY AND DESIGN

The sensor device concept is based on the pressure-induced deflection o f a metallized flexible plate and the subsequent measurement of the capacitance between this deflecting plate and a fixed backplate surface micromachined over the deflecting plate.

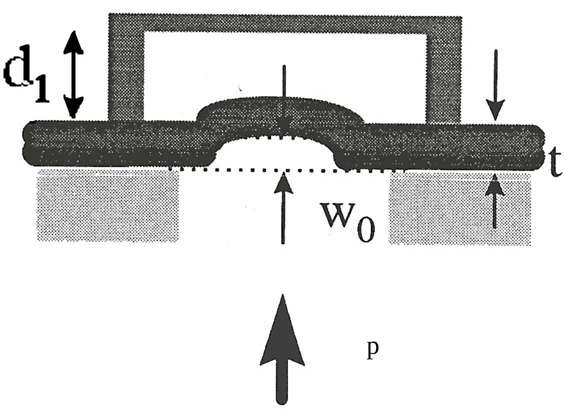


Figure 1. A schematic diagram of the side-view of the capacitive pressure sensor.

Figure 1 shows a schematic diagram of the side-view of the device, where *d]* is an initial (undeflected) gap distance between the fixed back electrode and the flexible plate electrode, *Wo* is the deflection at the center of the plate, *t* is the thickness of the plate, and*P* is the uniform applied pressure. For analytical modeling [4], several assumptions have been made: (a) stretching of the plate has been neglected, since the plate will not be undergoing deflections large compared with its thickness; (b) the thickness of the metallic electrode on the plate has been neglected, since this thickness is small compared with the plate thickness; (c) residual stress in the plate has been neglected, since (as will be discussed later) the plate is formed using lamination; and (d) electric field fringing effects have been neglected, since the gap between the flexible plate and the fixed backplate is small compared with their lateral extents. Under these conditions, the deflection of a circular plate with fully clamped perimeter as a function of radius, $w(r)$, is given by:

$$w(r) = w_0\left[1-\left(\frac{r}{a}\right)^2\right]^2, \qquad (1)$$

where a is the radius of the plate ($0\leq r\leq a$) and the deflection at the center of the plate w_0 is given by:

$$w_0 = \frac{Pa^4}{64D}. \qquad (2)$$

In equation (2), D is the flexural rigidity of the plate which is given by:

$$D = \frac{Et^3}{12\left(1-\nu^2\right)}, \qquad (3)$$

where E is the elastic modulus and ν is the Poisson ratio of the plate. The resultant sensor capacitance can be obtained by integration:

$$C_{sensor} = \varepsilon_0 \int_0^{2\pi}\int_0^{a} \frac{r dr d\theta}{\left(d_1 - w(r)\right)}. \qquad (4)$$

Equation (4) can be nondimensionalized by substituting $\xi=r/a$, $\gamma=w_0/d_1$, and $f(\xi)=[1-\xi^2]^2$, yielding:

$$C_{sensor} = 2C_0\int_0^1 \frac{\xi d\xi}{1-\gamma \bullet f(\xi)}, \qquad (5)$$

where C_0 is the capacitance when the plate is undeflected. In equation (5), since $f(\xi)$ is bounded between zero and one, and γ is by definition less than one, the integrand can be expressed as a Taylor series expansion and the solution of equation (5) can be described as follows:

$$C_{sensor} = C_0\left(1+K_1P+K_2P^2+\cdots\right), \qquad (6)$$

where K_n are constants given by:

$$K_n = \frac{1}{(2n+1)}\left[\frac{a^4}{64Dd_1}\right]^n, \qquad (7)$$

for $n\geq1$.

FABRICATION

The fabrication sequence of the robust capacitive pressure sensor array is shown in Figure 2. The process starts on square 5.7 cm (2 ¼ inch) on a side, 0.5 mm thick stainless steel substrates. An array of 8x8 pressure inlet holes with a diameter of 2mm, with 5mm center-to-center distances, are milled through the stainless steel substrate. Kapton polyimide film (Dupont, Kapton HN200, 50µm thick) is laminated onto the milled stainless steel substrate using a hot press. The pressure sensitive flexible plates will be the Kapton polyimide film in the regions suspended over the milled pressure inlet holes.

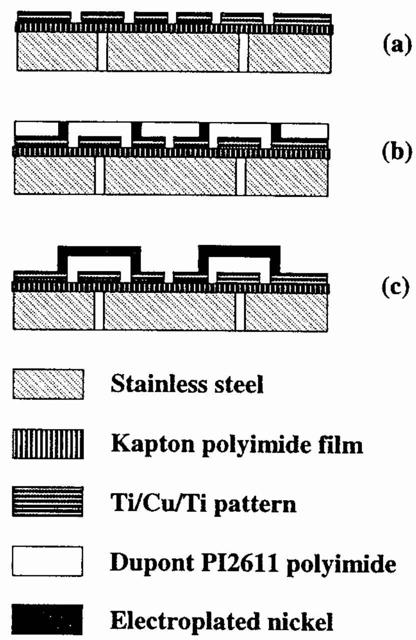


Figure 2. Fabrication sequence: (a) lamination of milled stainless steel and Kapton polyimide film and bottom electrode patterning; (b) polyimide deposition and electroplating of nickel posts; (c) backplate electroplating and removal of polyimide sacrificial layer.

A triple metallic layer of Ti/Cu/Ti with a thickness of 100/2,000/500 Å is deposited on the surface of the Kapton polyimide film by electron-beam evaporation and then patterned to create bottom electrodes, electroplating seed layers, and bonding pads with a lift-off process (Figure 2a and Figure 3). Multiple layers of PI2611 polyimide (Dupont) are spun onto the patterned layer with a spin speed of 1,200 rpm for 60 seconds, and hard-cured in a N_2 ambient at 300 °C yielding a final thickness of polyimide of approximately 44~48 μm. The polyimide layer is anisotropically etched using reactive ion etching to create electroplating molds for the support posts of the fixed backplates, and to remove the uppermost titanium layer of the seed layer. Nickel supports are then electroplated through the polyimide molds (Figure 2b).

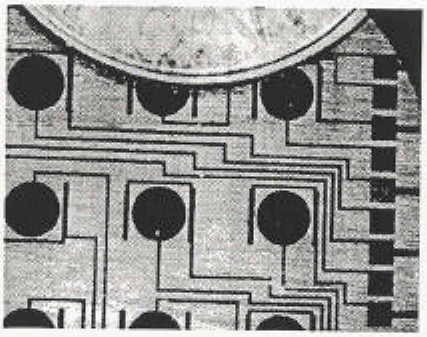
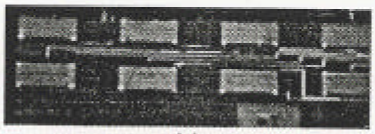
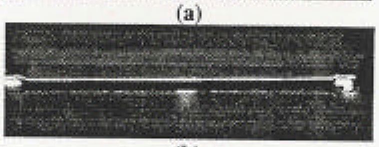


Figure 3. A photograph of top-view of the metallic seed layer which corresponds to the fabrication sequence shown in Figure 2 (a). The pressure-sensitive flexible plates are located underneath the circular metallic patterns.



(a)



(b)

Figure 4. Photographs of fabricated pressure sensor array: (a) A side-view of the pressure sensor array; (b) a close-up view of the gap (approximately 44 μm) defined between electroplated nickel backplate and pressure sensitive Kapton flexible plate.

A Ti/Cu/Ti metallic triple layer with a thickness of 300/2,000/300 Å is deposited using DC sputtering to act as a seed layer for the deposition of the backplate. Thick photoresist (Shipley PR 5740) is spun on the seed layer with a spin speed of 1,100 rpm for 30 seconds (yielding a final thickness of approximately 15 μm) and patterned to act as electroplating molds for the backplates. After removal of the uppermost Ti layer, nickel is electroplated through the thick photoresist electroplating molds to create the backplates. The thick photoresist electroplating molds and the remaining seed layer is removed. Finally, the polyimide molds for the backplate posts as well as polyimide sacrificial layers are isotropically etched to create air gaps between the fixed backplates and the pressure sensitive Kapton polyimide flexible plates (Figure 2c and Figure 4). The isotropic dry etch is carried out in a barrel plasma etcher using CF_4/O_2 plasma with a RF power of 120W. Figure 4 shows photographs of a fabricated pressure sensor array, where (a) shows a side-view and (b) shows a close-up view of the gap defined between the fixed backplate and the flexible plate.

MEASUREMENT

The capacitance of individual pressure sensors has been measured using a Keithley 3322 LCZ meter. Measured capacitances for undeflected pressure sensors were in the range from 11.35 pF to 13.97 pF depending on the length of interconnections between bonding pads and sensors. It has been observed that capacitance monotonically increases with increasing applied pressure, meaning that the pressure sensitive Kapton plate deflects toward the fixed backplates. Over an applied pressure range from 0 to 34 kPa, the net capacitance change was approximately 0.14 pF. Theoretical prediction of the sensor behavior is determined by taking the first three terms of equation (6) (i.e., up to n=2). Theoretical and measured net capacitance change over the applied pressure range are compared in Figure 5. Theoretical data shown in Figure 5 is based on an initial gap (d_i) of 40 μm. There is approximately a 10~20 % difference between the measured physical gap and the 40 μm gap value used to provide a best fit between theory and experiment. This difference could be explained by the fringing effects of the sensor capacitance (since the flexible plate is circular and the backplate is a square the side length of which exceeds the diameter of the flexible plate). The measured values of relative capacitance change are in the range from 1 % to 1.34 %.

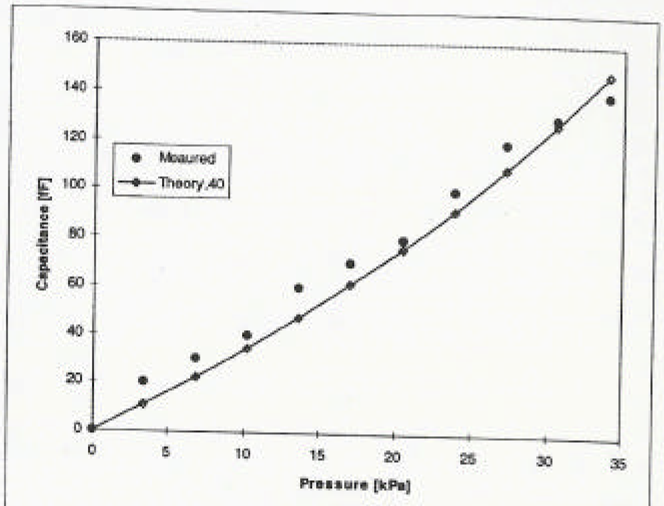


Figure 5. A comparison of theoretical and measured values of net capacitance change over the full range of applied pressure ranging from 0 to 34 kPa.

An OP-amp-based astable multivibrator circuit has been integrated with the pressure sensors in a hybrid fashion to create a frequency-modulated voltage output. Figure 6 shows a schematic diagram of such an astable multivibrator circuit, which consists of an LF351 operational amplifier, and three external resistors.

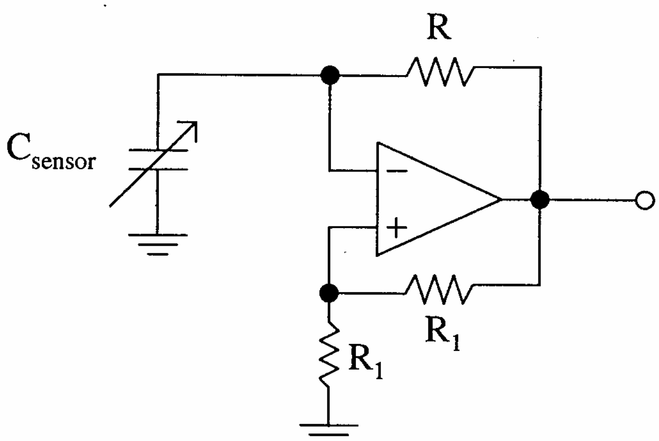


Figure 6. Schematic diagram of the astable multivibrator circuit.

The capacitance of the pressure sensor is the frequency-determining capacitance, which modulates the frequency of the voltage output on the output of the amplifier. The output frequency of the OP-amp is given by:

$$f = \frac{1}{2RC_{sensor}\ln 3}, \tag{8}$$

where RC_{sensor} is the time constant of the circuitry. In this work, external resistors R and R_1 have been selected as 1 MΩ, resulting in a base frequency of 12.544 kHz for the output of the OP-amp. Figure 7 shows the frequency output of the OP-amp circuit as a function of applied pressure from 0 to 30 kPa. The measured value of relative frequency change is 0.93 % over the applied pressure range from 0 to 30 kPa.

The values of capacitance and/or corresponding frequency change produced by the sensors are easily measurable in their current form; however, in order to achieve higher sensitivity, elimination of parasitic capacitance is essential. Primary sources of parasitic capacitance include capacitance between bonding pads and substrates and capacitance between interconnection lines and substrates. Parasitic capacitance from those primary sources can be eliminated by using integrated on-chip circuitry which has a reference electrode, which has same length of interconnection line and same structure as that of a pressure sensor with a pressure insensitive (immovable) circular plate. With a goal of achieving such an integrated on-chip circuitry, a physical demonstration example has been fabricated (Figure 8). In this figure, a 14-pin surface-mount chip has been integrated on patterned metallic lines on Kapton polyimide film which is laminated on the stainless steel substrate. Patterned metallic lines interconnect from an array of sensors and a reference electrode to multiple inputs of the chip. This physical demonstration shows the feasibility of the concept of the parasitic capacitance elimination circuitry directly integrated on the robust pressure sensor array. By doing so, the relative capacitance change over the applied pressure range could be increased to 22.3%.

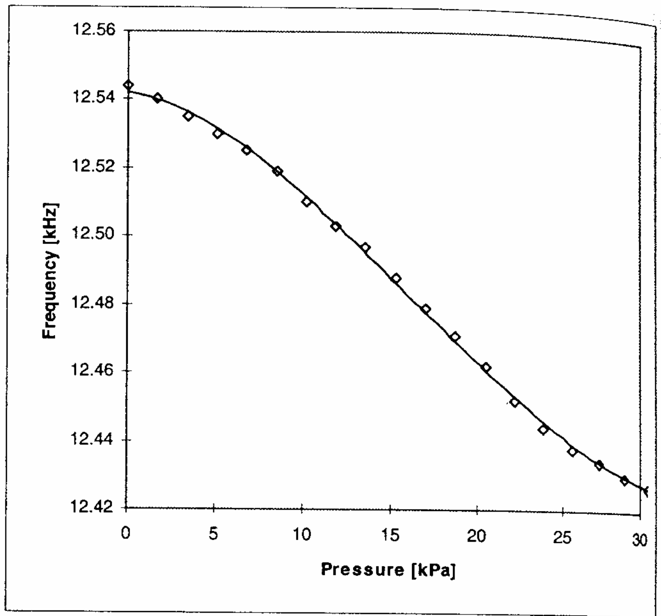


Figure 7. Frequency output of the hybrid multivibrator circuit in response to pressure sensor capacitance change over the applied pressure ranging from 0 to 30 kPa.

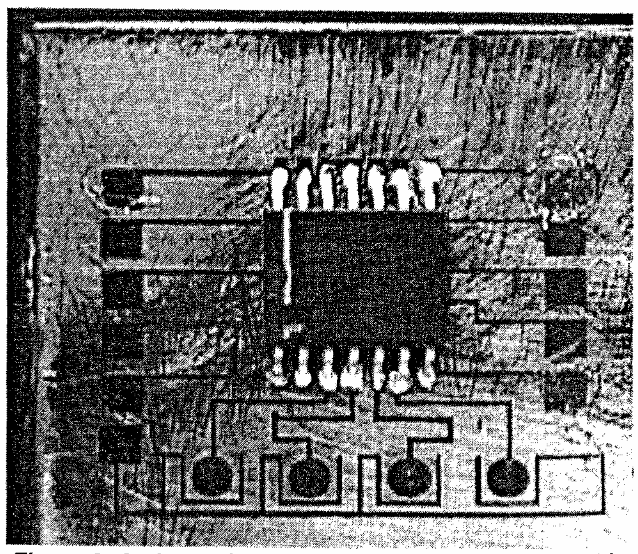


Figure 8. A photomicrograph of the surface-mount chip integrated on laminated Kapton polyimide film. Chip and sensors are all on the underside of the plate.

CONCLUSIONS

Robust materials have been studied as suitable substrates for micromachined devices. Lamination using a hot press, combined with traditional micromachining processes, has been investigated as a suitable fabrication process for the robust substrates. A capacitive pressure sensor array using a robust substrate (0.5mm thick stainless steel shim stock), Kapton HN200 flexible plate, and lamination processing has been designed, fabricated, and characterized. Over the applied pressure range from 0 to 34kPa, the net capacitance change of the pressure sensor is approximately 0.14 pF. OP-amp-based multivibrator circuitry has been integrated with pressure sensors in a hybrid manner to create frequency-modulated outputs. A physical demonstration of a surface-mount chip directly integrated on laminated Kapton polyimide film has been performed to show the feasibility of parasitic capacitance elimination for higher sensitivity.

ACKNOWLEDGMENT

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