Design of Micro robotic Detector Inspiration from the fly’s eye

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ABSTRACT

This paper describes the design and testing method of a micro robotic detector. The detector was implemented with capacitors. The chip employs the concept of an ultrasonic rangefinder. The fly can detect and locate objects in all directions easily. The micro robot needs to have this capability. In order to implement this, detectors was built to resemble a “soccer ball”. A robust fabrication process is required for the ultrasonic transducer. Since its resonant frequency will shift as function proportional to the membrane thickness. The fabrication process described in this paper also allows the integration of electronics into the capacitive-micromachined ultrasonic transducers [1]. The method of testing is also presented.

INTRODUCTION

Detection is an important issue in the design of micro robot in MEMS (micro-electro-mechanical systems) technology. Different from the detection issue in our daily life, the detection for micro robot requires a short-range, high resolution and low power consumption implementation. Inspired by the structure of fly’s eye and radar technology, we are going to implement the ultrasonic micro robot detector.

Ultrasonic rangefinder is composed of a capacitor with one fixed plate and one moveable plate. A high frequency voltage is applied across the two plates of the capacitor. An ultrasonic wave is sent out from the transmitter to an object (if there is any). By calculating the time difference t, of transmitted and received signal, the distance D, of the object is located.

$$\text{Distance}=\text{Velocity} * \text{Time}/2 \qquad (1)$$

We choose capacitive ultrasonic transducers over piezoelectric transducers because the performance of piezoelectric transducers is limited by its strict geometric tolerances, array configurations and electrical characteristics. Micro capacitive detector has an advantage in size reduction and potential electronic integration.

The successful design of capacitive acoustic transducers composed of a suspended silicon nitride membrane was reported within the past decade [8]. Instead of using a nitride membrane with a layer of aluminum as the top electrode, our design of a capacitive ultrasonic rangefinder consists of an aluminum layer, which acts as the top electrode that is suspended above a silicon bulk, which acts as the bottom electrode. The supporting structure is composed of Silicon nitride, which is a non-conducting layer. By closing the air gap between the two plates, we are able to change the output voltage.

The parameters involved in the calculations are the thickness of the movable top plate, air-gap thickness and sidewall spacing. We apply a dc voltage between the two electrodes; the law of charge force predicts that the plates will attract each other, closing the air gap. However the two plates will also repel each other due to their residual stress. Ultrasound is generated by applying an ac voltage to the structure.

In this paper, we report on the theory and calculations behind our design decisions and the fabrication process used to build the structure. We will also include the test structure so as to verify the performance of our design. 5 by 5 arrays of micro detectors are shown in Figure 0 as to illustrate how they can be aligned after industrial fabrication.

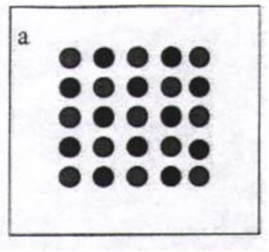

Figure 0. 5x5 array of micro-detectors

THEORY

This Micro robot detector serves as an emitter and a receiver at the same time. On one hand, the detector needs to emit a relatively large signal, in order to transmit the signal as long as possible. Here we are going to do the analysis for both the emitter and the receiver. And we will do the verification after the fabrication.

We do some approximations in the analysis. At first, we assume the restoring force is linear to the displacement. We only consider the forces between the poly-silicon layer and metal membrane and ignore others. Here we use a model consisting a spring (representing the restoring force), a mass (representing the weight of the metal membrane) and a capacitor [4].

Spring

Mass

Capacitor

Figure 1. Simplified Model of micro-detector

$$F_{capacitor} + F_{spring} = F_{mass}$$

$$F_{capacitor} = \varepsilon SV^2 / 2(d_0 - x)^2$$

Here x is the displacement of the upper membrane, S is the surface area of the capacitor, and V is the voltage on the capacitor.

$\varepsilon = 8.854 * 10^{-14} F/cm$. V is time dependent, but in order to simplify the calculation, we use $V(t) = V_{dc}$. Also, we ignore the acceleration of the upper membrane and get:

$$\varepsilon SV^2 / 2(d_0 - x) = kx$$

The breaking point is at $x = d_0 / 3$, and then

$V = \sqrt{8kd_0^3 / 27\varepsilon S}$.

If we use $d_0 = 2\mu m, S = 2500\mu m^2$ here, and the thickness of Aluminum layer equals 2um. With Aluminum's Young's modulus 69Gpa. The largest allowed voltage that can be applied to the capacitor is about 125V. In our design, we set the thickness of the nitride layer to 0.5 um, but in the actual fabrication, it is hard to control. So this is the case without considering the capacitance caused by the nitride layer. The actually allowed voltage should be higher. For example, with nitride's relative permittivity 7.5, we can consider the capacitor is air gap with d=5.75um, the maximum voltage will be 612V.

Furthermore, since x is small compared to d0, we have

$$F_{capacitor} = \varepsilon SV^2 / 2d_0^2$$

And $F_{ac} \propto 2V_{dc}V_{ac}$

FABRICATION

The capacitive-micromachined ultrasonic detector was fabricated by standard (semiconductor) CMOS processing techniques. To obtain good conductivity at the wafer surface, an n-type silicon wafer was doped with phosphorus gas phase drive in at 1000C. [7] And then a thin layer of LPCVD (Low-pressure chemical-vapor deposition) nitride is deposited at 800C as an etch stop in the potassium hydroxide sacrificial etching procedure. Thermal oxide is then deposited at 560C as the sacrificial layer. The sacrificial layer is later dry-etch patterned into rectangle shapes to define the active transducer regions, which will act as the gap of the capacitor with a dielectric material of air. Another layer of nitride is deposited by LPCVD at 800C to form a non-conducting layer surrounding the active transducer regions. Vias are dry etched to allow sacrificial etching in KOH at 75C. The final step is to sputter and web-etch pattern the aluminum to form the top electrode. The aluminum deposition defines contacts to the bottom electrode through a lithographically defined channel in the silicon wafer.

The completed cross-section of one air-transducer is shown in Figure 2. We start with a highly doped silicon wafer, shown as the bottom layer. The second layer is formed by the nitride deposition. The T-shaped section shown in Figure 2 is formed by the processing steps of deposition, lithography and etch of thermal oxide. The area besides the T-shaped active transducer region is resulted from nitride deposition, via and sacrificial etch. Metalization and electrode patterning is shown as the top layer in Figure 2.

Figure 2. Final cross-section of fabricated transducer

FABRICATION DISCUSSION

The bottom nitride layer acts as a KOH etch stop. However it reduces the effective gap of the capacitor and thus the electric field applied across the capacitor. This will result in reducing the optimal transducer performance. This nitride layer should be thick enough to sustain the etching process, yet it also should be as thin as possible so not to cause a large reduction in the electric field applied to the device. A conservative value of 4000 Angstroms is recommended [7]. The thermal oxide is used as a sacrificial layer in this process; the thickness of this sacrificial layer is chosen to be 1 um so as to produce favorable transducer efficiency and considering the limit on the maximum top plate displacement. The suspended capacitor plate should be as thin as possible for best efficiency of the transducer. Yet it has to be thick enough to provide enough stress for release after sacrificial etching. A typical value of this layer is 0.5-2um [7].

TEST STRUCTURE

The Testing of the structure is performed using a custom electronic setup shown in Figure 3 [2]. The digital section is an 8-bit digitized oscilloscope used to capture time domain data. A network analyzer is used to capture frequency domain data and these data are displayed on a computer or terminal. A pulse function generator labeled as the clock in figure 3 provides the input signal. Analog circuitry consists of a transconductance amplifier that amplifies the received signal.

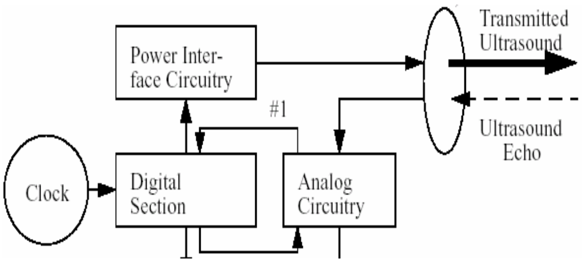

Figure 3. The test structure setup – Transmit and receive

The expected result is graphed in Figure 4. A 20-cycle 1mV ac excitation signal is sent at the calculated resonant frequency is transmitted from the transmitter. When it hits the object and bounces back, the signal is received. The time of signal traveling from the transmitter and back to the receiver is detected. Using formula (1), We can calculate the distance of the object from the detector.

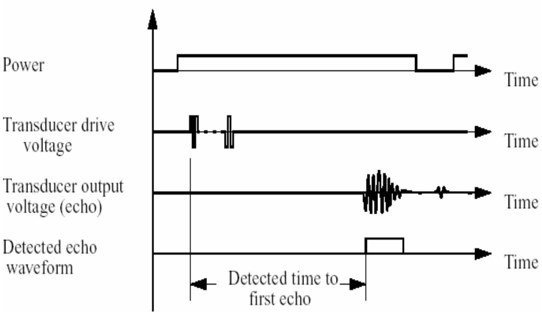

Figure 4. Timing and signal waveforms

RESULTS AND DISCUSSION

The dynamic range of this micro robot detector will be determined by future experiments. The detecting distance is depended on the frequency, the absorption coefficient, and the resolution of the receiver. Usually if a reflected signal as low as 0.2mV can be distinguished from noise, it is a pretty good result. The classical absorption coefficient has the form: [2]

$$\alpha_c = \frac{\omega^2 \eta}{2\rho_0 C^3}(4/3 + \frac{(\gamma - 1)}{P_r})$$

Where ω is the angular frequency. We consider air at $20^0 C$ and 1 atm, η is the coefficient of shear viscosity, $1.85 * 10^{-5} Pa \cdot s$. γ is the ratio of heat capacity, 1.402. ρ_0 is the equilibrium density, 1.21 kg/m^3. Pr is the Prandtl number, at $20^0 C$ and 1 atm, it is about 0.75.

From the table in [5], $A = 1.64 dB \times 10^{-12} s^2 / m$, where $A = \alpha / f^2$. At frequency of 3MHz, we have $\alpha = 5.82 dB / cm$. Suppose we put 16V AC voltage on the capacitor, the minimum detectable voltage is 0.2mV, therefore, it provides about 98dB dynamic range. So if we ignore the loss in reflection, circuits, etc. The maximum detection range is $98/(2 \times 5.82) = 8.42 cm$. The actual detecting range will be lower than that.

CONCLUSION

We have design a Micro robot detector in a small scale yet with reasonable detecting range. With assembling several detectors together, the micro robot can actually detect objects in all dimensions. This detector can also be used in a wide variety of other applications. Examples include medical imaging, nondestructive evaluation, ranging and gas-flow metering. The next step is to actually fabricate this detector and verify the performance. In the future, we are going to optimize the design for this detector. Also, we are going to try on different medias for this detector, such as, laser, infrared, etc.

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