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A Compact and Fast Measurement System for the Detection of Small Capacitance

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A new technique to measure low level capacitance variations of a gyroscope is proposed. It is based on the improved CVC(capacitance to voltage converter) biased by a d.c. current source and the peak detector without any low pass filter. This setup of the measurement system makes it possible to provide higher speed of measurement and wide operation range. The d.c. drift of the conventional CVC and stray capacitances are automatically compensated. Key parameters that affect the performance of the measurement system are illustrated and computer simulation results are presented. The demonstrated measurement system for micromachined gyroscope applications shows a linearity of 0.99972 and a resolution of 0.67fF from 10 fF to 120 fF at 10 kHz.

Keywords : Gyroscope, CVC(capacitance to voltage converter), Peak Detector

1. INTRODUCTION

Conventional gyroscopes such as mechanical gyroscopes and fiber-gyros have a high accuracy, but their systems are commonly large-sized, complex, very expensive and have a short lifetime. Thus, there is a need for simple and mass-producible micromachined gyroscopes[1]. The development of micromachined vibrating gyroscopes having a polysilicon resonator makes it possible to use them in consumer products such as portable video cameras(compensation of unintentional movement) and automobiles(suspension control and navigation system), because they are simple, small and inexpensive compared to conventional gyroscopes[1, 2]. Moreover, they can be improved to intelligent sensors where a signal processing circuit is combined with the sensor chip itself. In conventional measurement systems, a signal from the CVC is amplified and processed by a synchronous demodulator implemented with a multiplier and a low pass filter[1-5]. But their disadvantages are the d.c. drift of the conventional CVC, the high sensitivity to a stray capacitance [1], the parametric drift of the classical synchronous demodulator and the need for filters at the output which limit the speed of measurement[3].

In this paper, we present a improved measurement system using peak detection technique instead of demodulation technique. Moreover, the methods for modifying the operating range are discussed. The proposed system is implemented with the CVC biased by a d.c. current source and the peak detector without a low pass filter. This technique can be used to measure capacitance variations of capacitive sensors of this kind.

2. MEASURING SYSTEM

2.1 Structure and Basic Operation

Micromachined gyroscope is a laterally driven comb actuator used for the detection of an angular rate. The structure shown in Fig. 1 is a micromachined gyroscope having a resonator suspended by the folded beams. IC-compatible sacrificial layer technology was employed for the realization of the polysilicon structure.

The fabrication process is shown in Fig. 2. A n-type silicon wafer was used for the substrate. After etching the silicon substrate, an insulation layer of Si_3N_4 and a polysilicon layer were formed on the silicon surface. After patterning polysilicon, a phosphosilicate glass (PSG) layer was formed as a sacrificial layer. Then, a 6 μm thick polysilicon layer was deposited by low-pressure chemical-vapor deposition (LPCVD), and etched by reactive ion etching (RIE) into the features of the resonator. The sacrificial layer was then removed by wet etching with HF. Each chip was rinsed with DI water

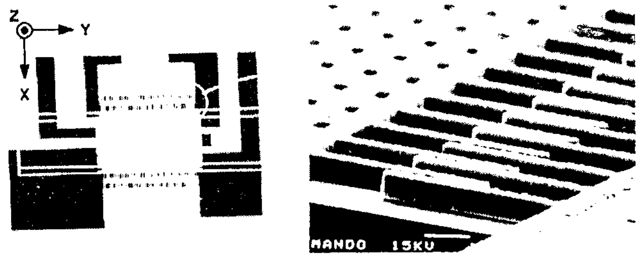


Fig. 1. SEM photograph of a microgyroscope.

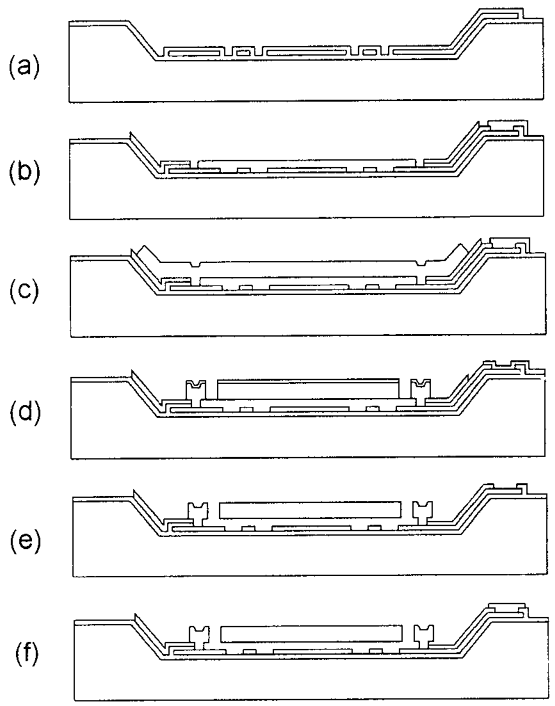
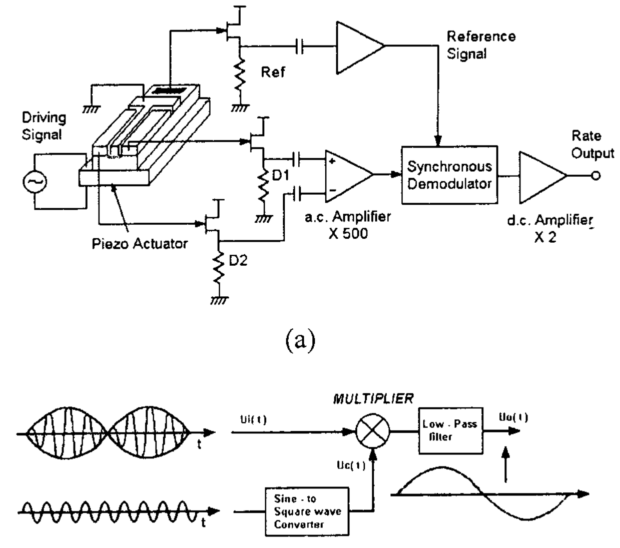


Fig. 2. Fabrication sequence :

(a) Patterning polysilicon;
(b) Patterning anchor;
(c) Polysilcon deposition;
(d) Patterning polysilicon;
(e) Sacrificial layer etching;
(f) Patterning Al.

and dried in the vacuum chamber. To avoid sticking problem, the water was replaced with isopropylalchohol after rinsing.

The polysilicon resonator 375 μm wide (including the combs on both sides), 500 μm long and 6 μm thick is suspended by the beams afloat on a single-crystal silicon substrate. The driving direction is lateral (in the x-direction) to obtain a large deflection amplitude. The resonator is driven by electrostatic force generated by an a.c. voltage applied across the comb-actuators on both sides of the resonator.



(a)

(b)

Fig. 3. (a) Conventional measuring circuits, (b) Block diagram of a synchronous demodulator.

The Coriolis force produced by an angular rate around the y-axis causes the resonator to vibrate in the z-direction. This vibrated deflection is very small and can be detected from the change in the electrostatic capacitance of the gap between the resonator and the substrate. The gap is designed to be 1.5 μm to detect the change with high sensitivity. Because one of capacitance leads should be connected to ground, conventional capacitance sensing technique and differential capacitance mesuring technique can not be applied to measure capacitance variations of the gyroscope[7-10].

The conventional measurement system for the sensors with vibrating resonator shown in Fig. 3 (a), adopted the CVC using FETs[1]. Capacitance variations result in the oscillations of the output voltage without appropriate d.c. bias and the signal from the CVC is amplified and processed by a synchronous demodulator implemented with a linear multiplier and a low pass filter[3]. The synchronous demodulator multiplies the two waveforms, and the output is shown in Fig. 3 (b). A low pass filter extracts the d.c. average value. The filter must rejects the double frequency and all harmonics. The synchronous demodulator can reject parasitic signals and extract the amplitude of the in-phase signal. But the conventional CVC is sensitive to stray capacitances due to high output impedance[1] and the d.c. drift of this interface circuit is rather high. The disadvantages of the classical synchronous demodulator are the parametric drift due to temperature, aging of the multipliers and the need for filters at the output which limit the speed of measurement[3]. The last is a severe disadvantage when the settling time is critical, as in the case of real-time data acquisition systems.

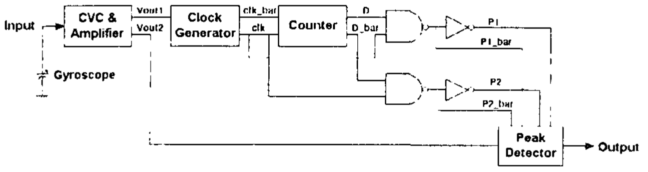


Fig. 4. Block diagram of the proposed detecting circuit.

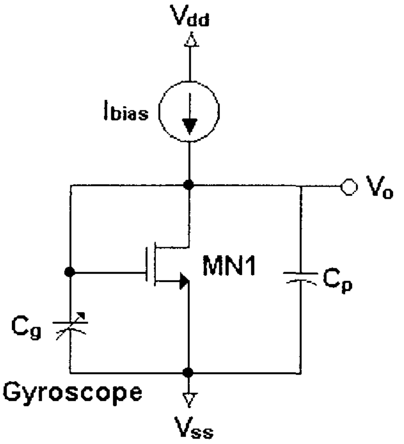


Fig. 5. Circuit diagram of the CVC including micromachined gyroscope.

2.2 Design of the Measuring Circuit

The proposed measurement system is designed and constructed in accordance with the block diagram shown in Fig. 4. The applied rate round the y-axis generates the Coriolis force and the resonator moves to the z-direction. The capacitance variation of the gyroscope, ΔC_g produces the output signal with the amplitude propotional to the amount of variations. A clock generator and a counter generate the clock pulses and control pulses from the output signal of the CVC. These pulses are used to control the peak detector. Instead of demodulation, the proposed measurement system uses the peak detection technique.

The proposed CVC is shown in Fig. 5. It is biased by a d.c. current source, I_{bias}. The gate-source capacitance of MN1 is charged up to the appropriate value that can make MN1 to sustain the bias current, I_{bias}. The equation of the output voltage, $V_o(t)$ can be described as

$$V_o(t) = Q / (C_g+C_p) = \sqrt{\frac{2LI_{bias}}{KW}} + V_T \qquad (1)$$

where C_g is the capacitance of the gyroscope, C_p is the lumped capacitance which all parasitic capacitances at the output node are combined into, Q is the charge stored in C_g and C_p, K is the transconductance parameter, W is the channel width and L is the channel length. Its nominal output voltage is determined only by the bias current and is independent of C_p because the value of Q varies according to C_p. The amount of the capacitance variation, ΔC_g varies directly with the applied angular rate. If the capacitance of the gyroscope(C_g) increases, $V_o(t)$ decreases because Q can not be changed instantaneously. So the variation of $V_o(t)$ will be:

$$\begin{aligned}\Delta V_o(t) &= Q / (C_g+C_p - \Delta C_g/2) - Q / (C_g+C_p + \Delta C_g/2) \\ &= Q \Delta C_g / \left((C_g+C_p)^2 - \Delta C_g{}^2/4 \right) \qquad (2)\end{aligned}$$

The dependence of $\Delta V_o(t)$ on C_p can be neglected by adjusting the gain of the amplifier. When $V_o(t)$ is decreased, the bias current source, I_{bias} will charge the capacitance at the output node so that MN1 can hold its current, and $V_o(t)$ will return to the nominal value. So when the vibration frequency is low, the output voltage can be distorted. But the operating frequency is sufficiently high and this dependence is automatically neglected by using the peak detector. The proposed CVC is insensitive to other stray capacitances because of a low output impedance($1/g_{mn1}$), does not show the d.c. drift of the conventional CVC[2] because it is biased by a d.c. current source and provides excellent linearity.

The capacitance to voltage conversion and the signal amplification are performed using the circuit shown in Fig. 6. The output signal of the CVC is amplified by the two-stage amplifier, and then passes through a level shifter and a non-inverting amplifier to a peak detector. For performing the capacitance detection, it is essential to have a large amplitude of the output voltage enough to generate reference signals for all possible values of ΔC_g. Noise can be drastically reduced by inserting load capacitances(CL1, CL2). V_{out1} is shifted by $V_{dd}/2$ and amplified again. A careful level shifting and amplifications have to be done to translate the output voltage levels to the voltage levels appropriate for the peak detector. Fig. 7 shows output waveforms of the CVC and amplifiers.

The amplified signal, V_{out1} is used to generate the reference signal and the control signal of the detection circuit. Sine to square wave converter generate reference clock pulses, clk and clk_bar, from the sinusoidal output

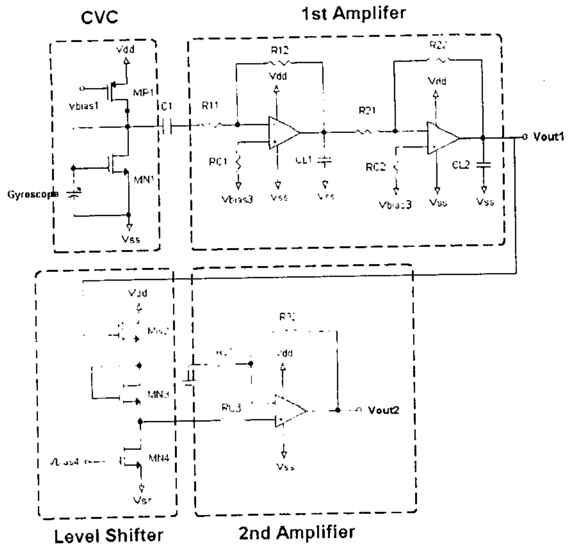


Fig. 6. Circuit diagram of the CVC, amplifiers and the level shifter.

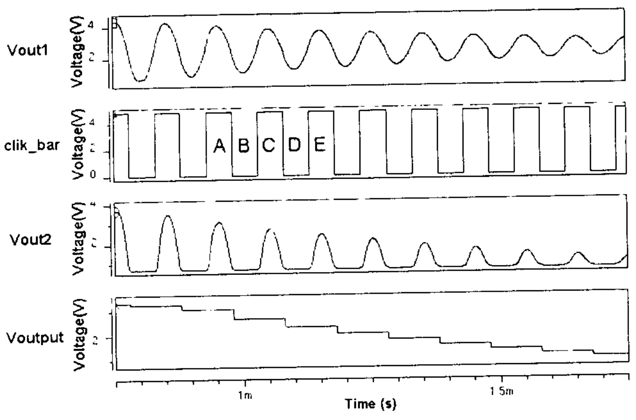


Fig. 7. Waveforms of the output signals.

voltage of the CVC. Divider generates control pulses, D and D_bar, having 2 times longer period than clk and clk_bar. From these pulses, the simple logic gates generate control pulses, P1, P2, P1_bar, P2_bar. Fig. 8 shows waveforms of control signals. In the simplest form, the peak detector shown in Fig. 9 uses these control signals. C1 is charged up to the peak voltage of V_{out2} during A period and C2 holds its voltage during B and C period, C3 discharged in B period is charged up to the new peak voltage of V_{out2} in C period and C2 holds its voltage during D and E period. In E period, new peak value is stored in C1 and from then on, the process repeats itself.

If C1 and C3 are at least one order of magnitude larger than C2, the output voltage does not decrease after charge sharing. The drain junction leakage current of

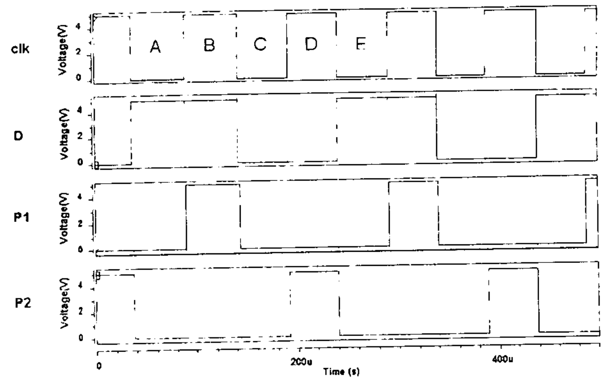


Fig. 8. Waveforms of the control signals.

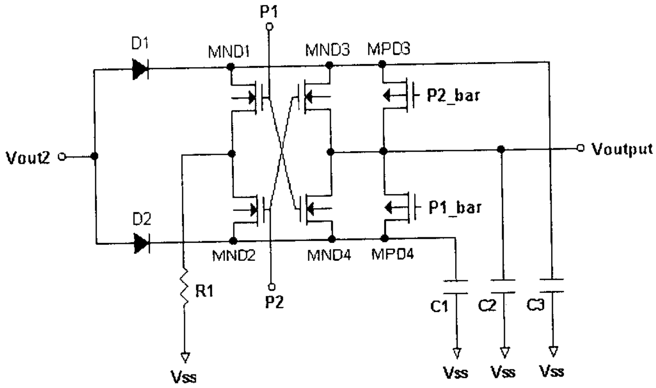


Fig. 9. Circuit diagram of the peak detector.

MND2 during B and C period is the main reason for the gradual depletion of the stored charge on C1. R1 should be small enough to enable C1 and C3 to discharge completely before recharging, but large enough to enable the peak detector to hold the peak value stored in C1 before the output voltage decreases due to the leakage current. Therefore a compromise is inevitable.

Operating frequency of the measurement system can be controlled by selecting appropriate values for C1, C2, C3 and R1. The detectable measurement range can be controlled by selecting the appropriate values for the voltage gain and the shifted voltage. This setup does not require a low-pass filter at the output, resulting in higher speed of measurement.

3. DISCUSSION OF THE RESULTS

A 2.5V d.c. bias voltage and a 250mVp-p a.c. drive voltage, whose frequency was the resonance frequency of the driving mode, were applied across the comb-actuators. The nominal capacitance and the maximum capacitance variation of gyroscope are 530 fF and 120 fF, respectively when the resonance frequency of the

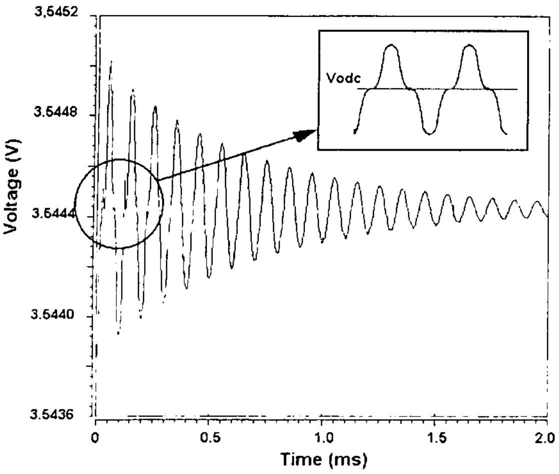


Fig. 10. Peak amplitude of the CVC output signals versus capacitance variations.

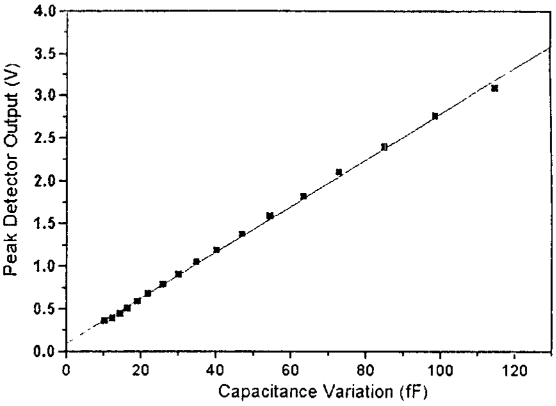


Fig. 11. Output voltage of the peak detector versus capacitance variations at 10kHz.

gyroscope for the x-direction is 10 kHz. Capacitance variations should be at least 3.4 fF in order to generate the reference signal. Fig. 10 shows the output voltage of the CVC as a function of the time when the capacitance variation of the gyroscope decreases exponentially with time. The output signal is nonlinear about $V_0(t)=V_{odc}$ when the amplitude of the output signal is large. This is because I_{bias} charged the load capacitances (C_p, C_g) when $V_0(t)$ deviates from its nominal value and made $V_0(t)$ return to V_{odc}. But this distortion can be neglected by the peak detector because the peak value of $V_0(t)$ is the final outcome. Noise can be reduced by inserting the load capacitance of 50 pF at the output of the each inverting amplifier. The proposed CVC shows excellent linear response from 10 fF to 120 fF at 10 Hz. Fig. 11 shows the output voltage of the peak detector.

The demonstrated peak detector also shows good linear response from 10 fF to 120 fF at 10 kHz. The correlation coefficient and the standard deviation between the measured values and the best straight line are 0.99972 and 0.67 fF, respectively. The correlation coefficient of the total system is lower than that of the CVC. This is because the input voltage of the peak detector is lower than $V_0(t)$ by diode drop. This can be completely neglected by adopting another supply voltage to peak detector.

4. CONCLUSIONS

In this paper, we described the design of the detection circuit for the gyroscope applications which has several advantages compared with the conventional ones. The proposed CVC does not show the d.c. drift and has a low output impedance and good immunity to stray capacitances and the dependence of the CVC upon stray capacitances and the dependence of the CVC upon stray capacitances can be compensated by the peak detector. The peak detector has fast speed of the measurement and can be easily fabricated on-chip because of its simple structure without a mutiplier and a low pass filter. Simulation results show that the proposed CVC provides a linearity of 0.99995 and a resolution of 0.33 fF and the peak detector provides a linearity of 0.99972 and a resolution of 0.67 fF. The detectable range of capacitance variations, the operating frequency and the range of the output voltage can be easily set by selecting appropriate values for a few parameters that affect the performance. The proposed measurement system which is a very simple structure provides a good remedy for the defects of the conventional ones. It is possible that micromachined vibrating gyroscope and its measurement system are fabricated on a single chip. We are now working on such improvements.

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