論文の内容の要旨

Title A Study on Monolithic Integration of Electroplated MEMS Actuators with CMOS Digital Control Circuits
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This study is about integration of micromirror and its control circuits for self oscillation at the resonant frequency of the scanner. The integration process is perfectly CMOS compatible electroplating.

Micromachined scanners have a lot of applications. One powerful candidate application is optical coherent tomography (OCT) of which merits are high resolution and penetration up to millimeter range of human tissue. OCT system with micromachined scanner makes miniaturization and large tilting angle possible. The larger tilting angle, the wider range of human epidermis or retina with small energy. On the opposite side of the advantages of the microscanner in OCT system, electro-statically actuated scanners require high voltage for large displacement, which is not suitable internal operation. In recent researches, external power is not supplied through copper wire. They adopt solar cell inside the OCT head units instead. Because of low efficiency of the present solar cell, it is much difficult to obtain high voltage for driving.

As shown at the above, low voltage actuated scanners are the first demand. This study takes another route to get large tilting angle not by high driving voltage but by resonance oscillation. The scanner should be equipped with its control parts for resonance vibration. At the same time the control parts and the scanner have to be merged in a form of a system on a chip (SoC) for internal body operation. Control algorithm and fabrication process for integration are considered as the target of this study.

Among pre-CMOS, intermediate-CMOS and post-CMOS methods for integration, the last one is adopted as the integration style of this study. It is to make micromachines on top of the multi user service CMOS chip. All the area of the chip can be used for micromachines. The main process is electroplating. Electroplating is low temperature process and does not have high power of plasma which may damage to CMOS circuits. By use of closed loop control circuits, the mechanical resonance is achieved by tracing the Eigen frequency. The close loop is a modified phase locked loop (PLL) which is composed of a voltage controlled oscillator (VCO), a phase shifter, a phase detector, and a displacement sensor.

The micromachined devices with PLL algorithm for resonant vibration and CMOS-MEMS integration through electroplating is MEMS gyroscopes. The PLL has capacitive sensors for feedback. They are linear, small, sensitive, consuming low power, insensitive to temperature drifts, and it is easy to be integrated with other micromachines. Moreover, they do not need special material like piezoresistive/piezoelectric method although their drawback is measurement of very small differential capacitances meaning that they are very sensitive to parasitic capacitances and electromagnetic interference, and that the pick-off electronics may be complex. Moreover, most widely used capacitive sensing method, charge amplifier technique, must be equipped with amplifier. It is usually an operational amplifier which is supposed to have high power consumption.

A novel but simple sensing method is presented in this study, which is digital sensing method as an original idea. A protrusion at side of mirror plate or hinge touches bottom electrode, then the contact resistance between the stud and the electrode changes from infinity to finite value. By connecting external resistor in series between power line and ground, a voltage divider is built. The output of the voltage divider becomes VDD or ground when the protrusion does not touch bottom electrode and indicates a certain values determined by the serial resistors ratio when it hard contact the bottom.

By the digital sensing method, perfectly digital control blocks which promise more reliability are achieved and integration process on top of a chip fabricated by standard CMOS will provide a universal platform of CMOS-MEMS integration to other researchers.

As the first step of the research, analysis by computer aided design was done by MATLAB Simulink and HSpice. On the basis of both the force equation at parallel plates and the equation describing quadratic oscillation, the scanner model was built by for MATLAB Simulink blocks. The frequency response of the model showed the same result with the quadratic oscillation even the model is nonlinear. As the next step of modeling and analysis, HSipice simulation was carried out. It is meaningful because HSpice tells exactly the designed chip would work correctly or not in real world. Before employment of HSpice, analogies between mechanical system and electrical system were introduced. HSpice does not have parameters for mechanical simulation. Therefore, mechanical parameters were converted into electrical parameters based on the analogies. The HSpice model also reflected correct result as the MATLAB model showed. Thereafter the two previous models were combined with other control blocks. Both cases were obvious that the VCO input was maintained at a certain DC value which produces constant frequency. The amplitude plots of the scanner models stay at maximum and 90 degree delay compared to driving signal. The modified PLL algorithm was expected to work correctly.

The temperature at each unit fabrication process was observed and the highest temperature is photoresist bake temperature. The proposed electroplating step is safe for post-CMOS process. The first step is bottom metal interconnection and electrode patterning. Material is Cr/Au or Ni for protection of aluminum pad of CMOS circuits. The second step is sacrificial layer deposition by evaporation. Material is copper for selective etching. The thickness was 1.4um and it is so precisely controllable that the driving signal level has high degree of freedom in mechanical design. The third step is nickel structure electroplating. The recommended temperature is 55 degree, which does not affect any degradation to aluminum interconnection in CMOS chip. The mold for electroplating should be thicker sufficiently than target metal height. The forth step is release by nickel compatible copper etchant. It is diluted mixture of acetic acid and hydrogen peroxide. After release, it should be very careful not to happen stiction by wafer vaporization between structure and substrate.

The scanners were actuated by less than 5V, which means pull in happened around 4V. The contact resistance is very important value to determine proper value of external resistance. It was 3.3 kΩ, which should be reduced much more. Preferable value is less than 10Ω. By surface coating with gold can enhance contact resistance.

Main CMOS circuit blocks are VCO, phase shifter, and phase detector. When VCO has very high output frequency, a frequency divider is needed. The VCO is a ring oscillator with a variable resistor which is an NMOS transistor. By input voltage resistance change becomes time constant variation of the ring oscillator. Large value of time constant causes low frequency VCO output and vise versa. The divider is a series of a D flip flop which has D input and negated Q connected. It is called half divider. The half dividers were also used in phase shifter instead of Hilbert transform. One half divider and an XOR gate made a phase shifter. Phase detector is well known phase/frequency detector with a charge pump.

The design chip will be delivered by July. The measurement of the chip and integration process will follow to prove the idea of the study, which is that presentation of digital sensing method for simple position detector and that CMOS-MEMS monolithically integrated system on standard CMOS process will become a universal platform for researches on CMOS-MEMS integrated system.