

11.7 Integrated Multiple-Device IMU System with Continuous-Time Sensing Circuitry

Hao Luo, Gary Fedder, L. Richard Carley

ECE Dept. Carnegie Mellon University, Pittsburgh, PA

Post CMOS-MEMS processes [1] have advantages of multi-layer routing in mechanical structures and the potential to integrate inertial measurement units (IMUs) with supporting circuitry in a conventional CMOS process. Multiple IMUs are integrated into a single chip to improve the system performance and significantly decrease the cost. In contrast to previous work [2], this system integrates two lateral accelerometers and a vertical gyroscope with all signal processing circuits. A direct-coupled continuous-time sensing buffer for MEMS capacitive sensing has a -3dB frequency corner lower than 10Hz . The integration of multiple sensors makes cross-device compensation possible.

Figure 11.7.1 shows the post CMOS-MEMS process and the SEM of the integrated vertical gyroscope fabricated with this process. After the foundry fabrication of a conventional CMOS chip, the CMOS die undergoes two processes to release the mechanical structures: (a) an anisotropic RIE to define the sidewalls of the microstructures, and (b) an isotropic RIE to remove the silicon underneath the mechanical structures. During the micromachining processes, the top metal layer acts as an etch mask to protect the circuits underneath.

Figures 11.7.2 and 11.7.3 show the implementation of the continuous-time capacitive sensing preamplifier and the unity-gain sensing buffer. The amplifier is for acceleration signal sensing while the unity-gain buffer is for the gyroscope driving mode sensing. Both circuits have their inputs biased by small transistors working in the subthreshold range. The input impedance is so high that even though the MEMS capacitance is extremely small (around 100fF) the circuit corner frequency is lower than the mechanical structure's natural frequency (normally around tens of kHz). This continuous-time sensing simplifies the gyroscope driving mode sensing because no modulation voltage is needed. To avoid large input parasitic capacitance the allowable input transistor size of the circuit is very limited. The sensing amplifier has cascade transistors in series with the input transistors to reduce the Miller capacitance. Compared to the acceleration signal, the gyroscope driving mode signal is very strong and no gain is needed for its sensing. The continuous-time capacitive sensing unity-gain buffer can easily sense the vibration signal ($\sim 100\text{mV}$).

The integrated system is fabricated in the AMS $0.6\mu\text{m}$ CMOS technology. Figure 11.7.4 depicts the ac transfer function of the sensing preamplifier with a 600fF input coupling capacitor. The sensing preamplifier has a gain of 22.8dB and a white input-referred noise of $110\text{nV}/\sqrt{\text{Hz}}$. (Note the measurement active probe has a -7.2dB attenuation).

Since there are multiple sensing devices integrated together, and since pads are very limited, all the accelerometer and gyroscope circuits are integrated with dc coupling. Figure 11.7.5 shows the switched-capacitor (SC) demodulator which is not sensitive to the dc offset from the front-end circuit. During each sensing signal cycle (vs) the signal from the front-end sensing preamplifier is sampled twice with inversed polarity. Thus even large dc offsets ($\sim 100\text{mV}$) are canceled while the acceleration signal (ac sub-mV signal) is sensed.

The IMU system occupies a 6.25mm^2 area with 40 pads (Fig. 11.7.6). It is tested in the open air with a 5V supply. Each accelerometer has a noise floor of $500\mu\text{G}/\sqrt{\text{Hz}}$ and the gyroscope has a noise floor of $0.5^\circ/\text{sec}/\sqrt{\text{Hz}}$.

Integration of multiple inertial sensors has the benefits of guaranteed relative alignment, allowing easy cross sensor compensation for performance improvement. The two lateral accelerometers integrated on the chip have orthogonal orientations. They compensate each other to compress the cross-axis sensitivity by 20dB . The accelerometer can also compensate the gyroscope to reduce its non-ideal sensitivity to linear acceleration interference.

Acknowledgments

This work was supported by DARPA.

References

- [1]G. K. Fedder, et al, "Laminated High-aspect-ratio Micro-structures in a Conventional CMOS Process," *Sensors and Actuators*, 1996, vol. A57, no. 2, pp.103-110.
- [2]Hao Luo, et al, "A Post CMOS-MEMS Micromachined lateral Accelerometer," *Journal of Microelectromechanical Systems*, vol. 11, no. 3, pp. 188-195, June 2002.

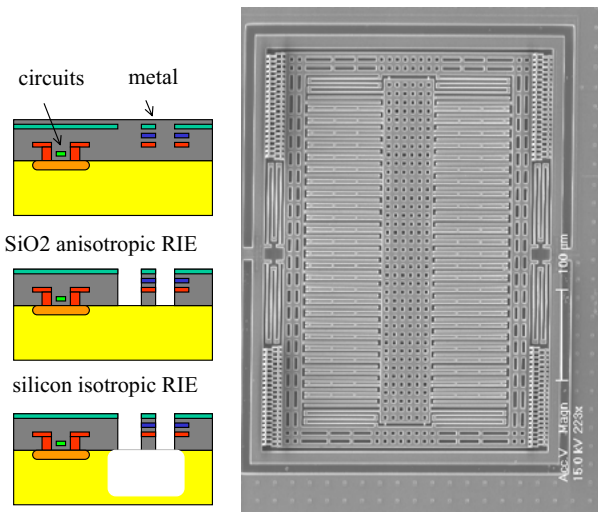


Figure 11.7.1: Post CMOS-MEMS process and a gyroscope fabricated in this process.

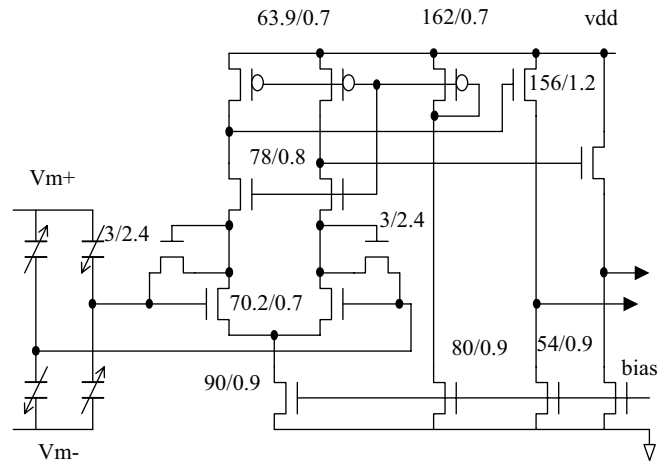


Figure 11.7.2: Continuous-time sensing amplifier.

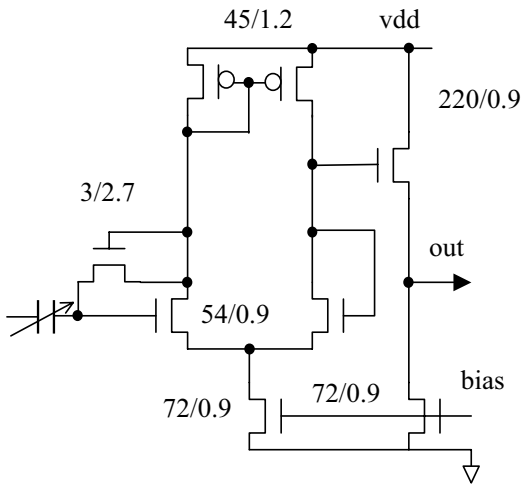


Figure 11.7.3: Continuous-time unity-gain buffer.

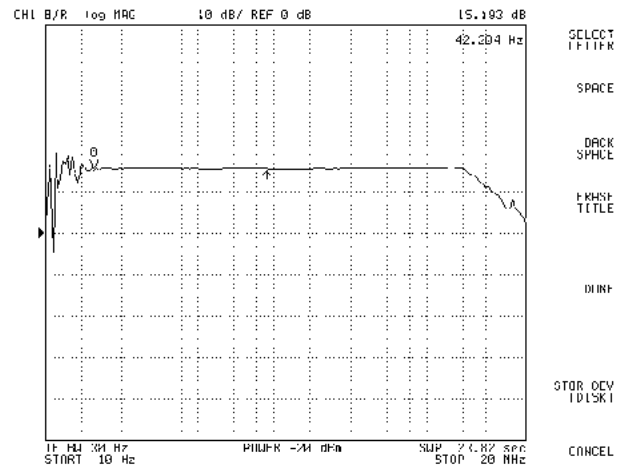


Figure 11.7.4: AC response of continuous-time sensing amplifier with 600fF input coupling capacitor.

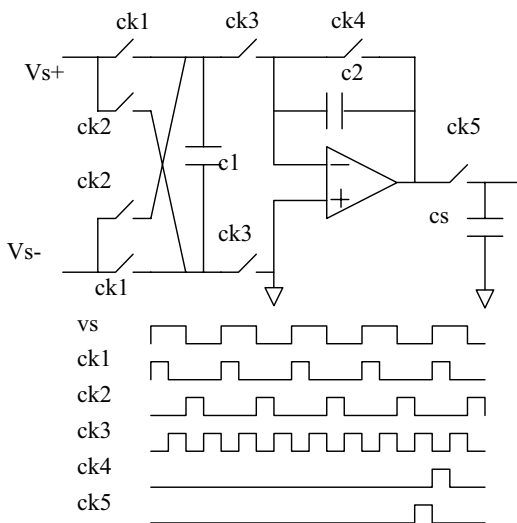


Figure 11.7.5: Switched-capacitor demodulator.

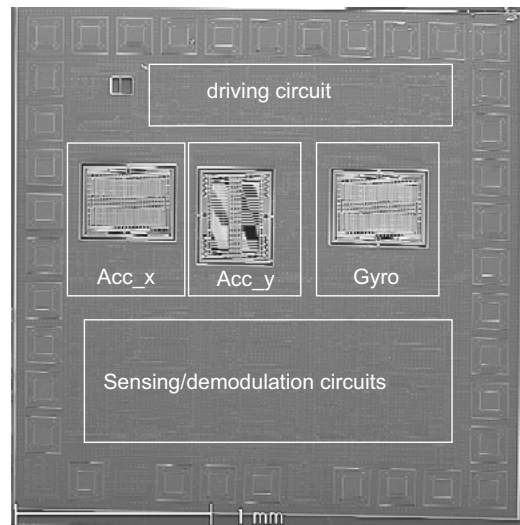


Figure 11.7.6: The 3 DOF die SEM.

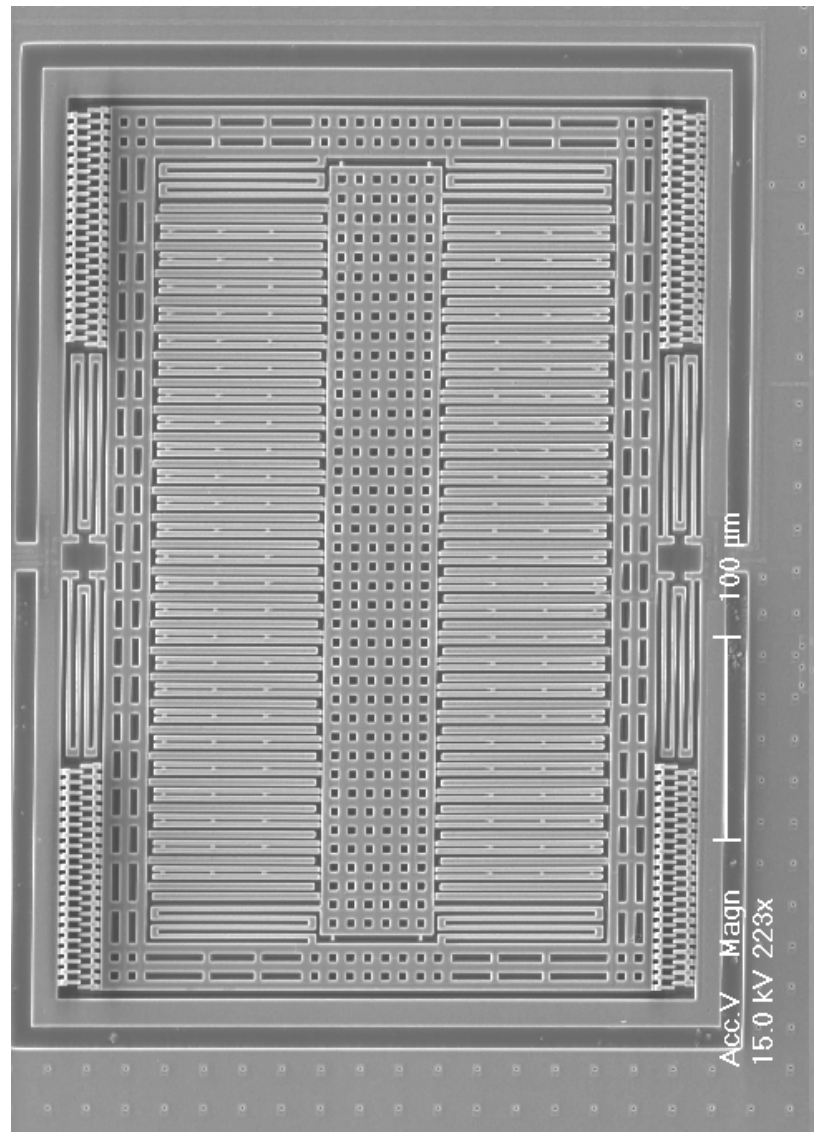
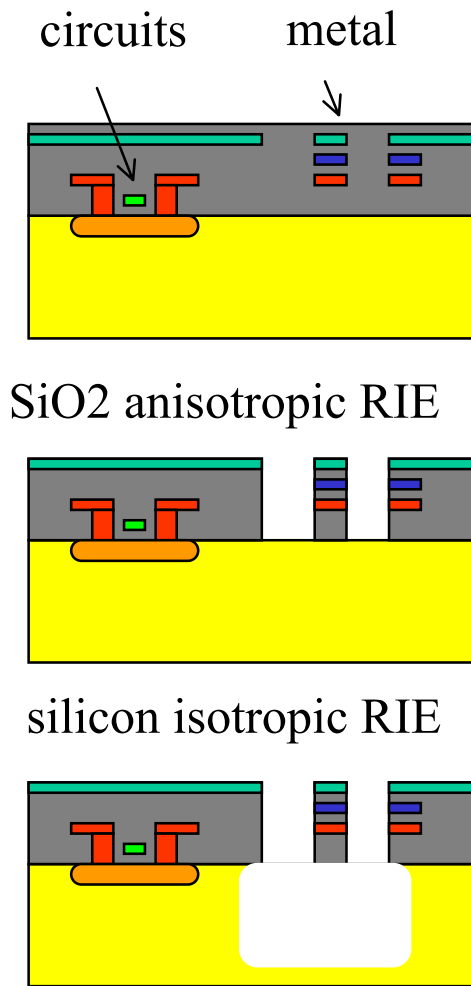


Figure 11.7.1: Post CMOS-MEMS process and a gyroscope fabricated in this process.

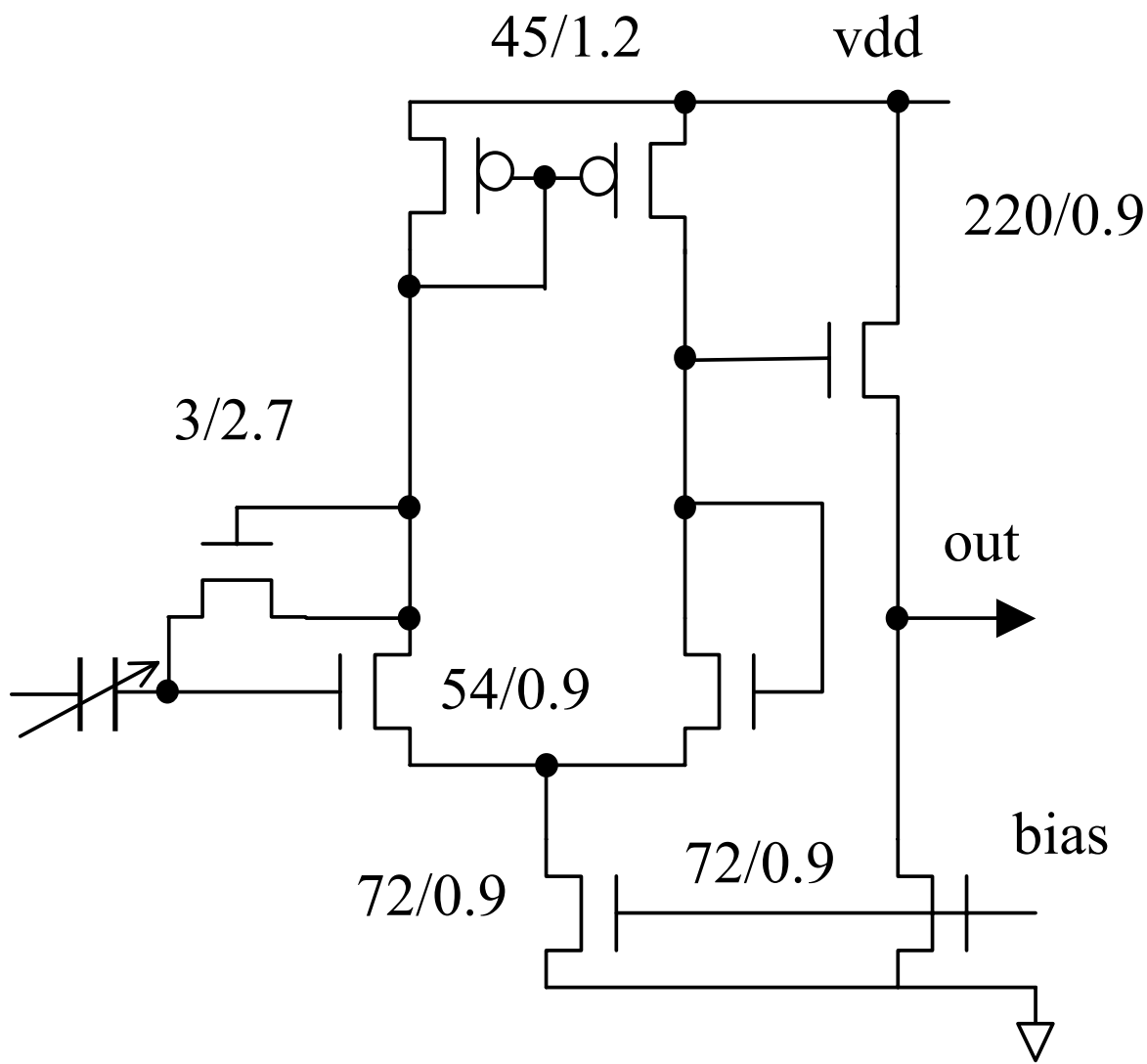


Figure 11.7.3: Continuous-time unity-gain buffer.

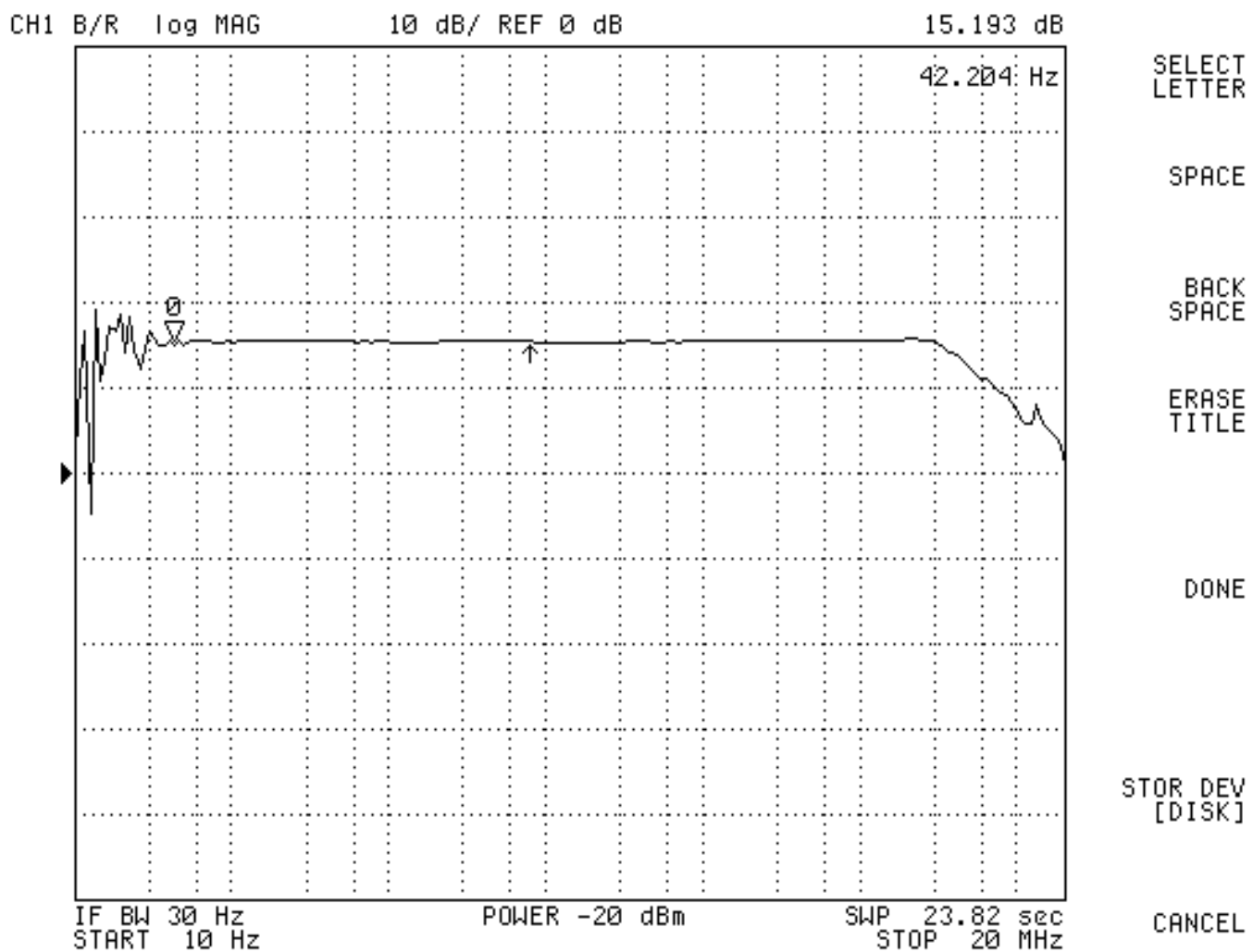


Figure 11.7.4: AC response of continuous-time sensing amplifier with 600fF input coupling capacitor.

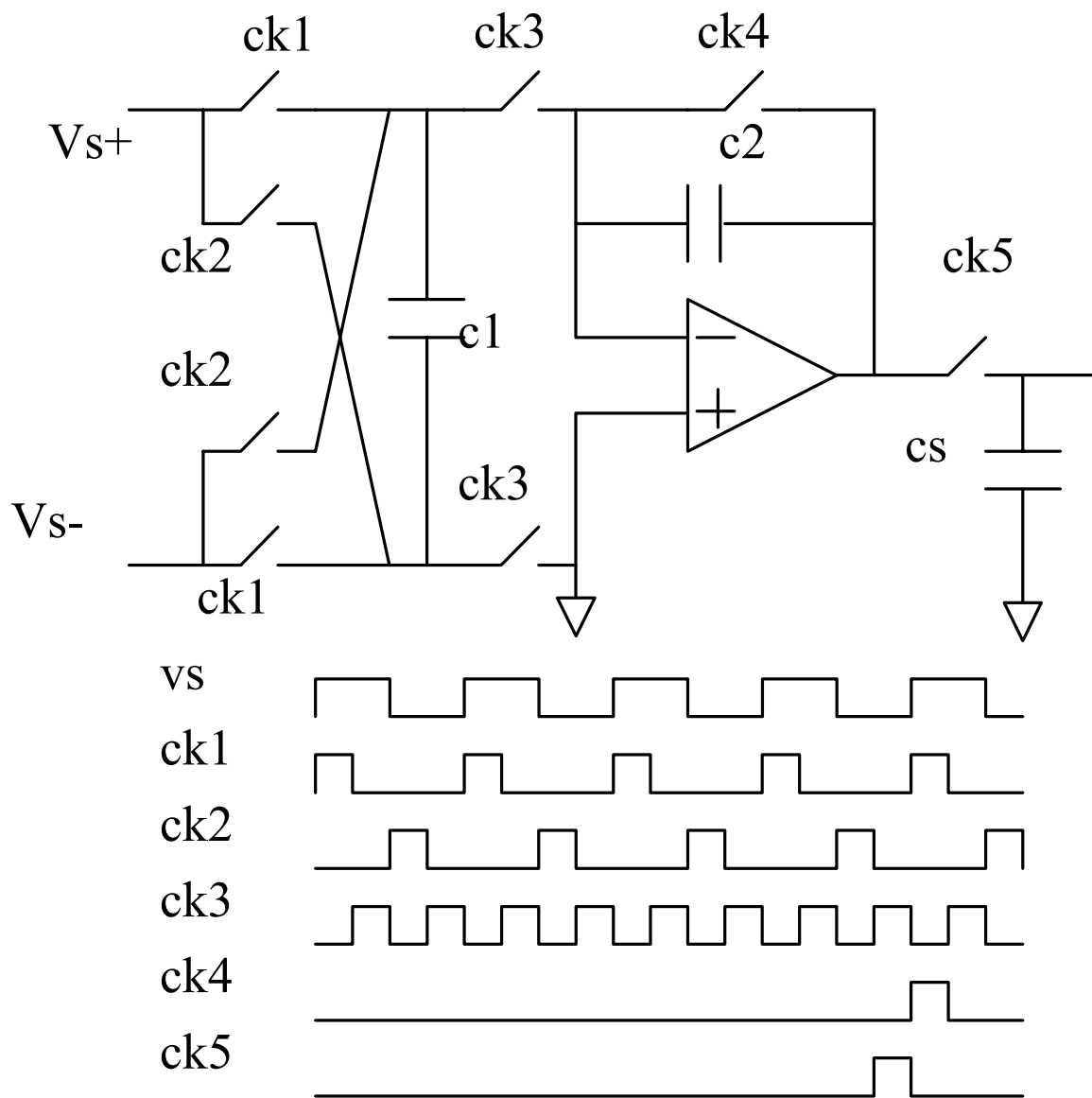


Figure 11.7.5: Switched-capacitor demodulator.

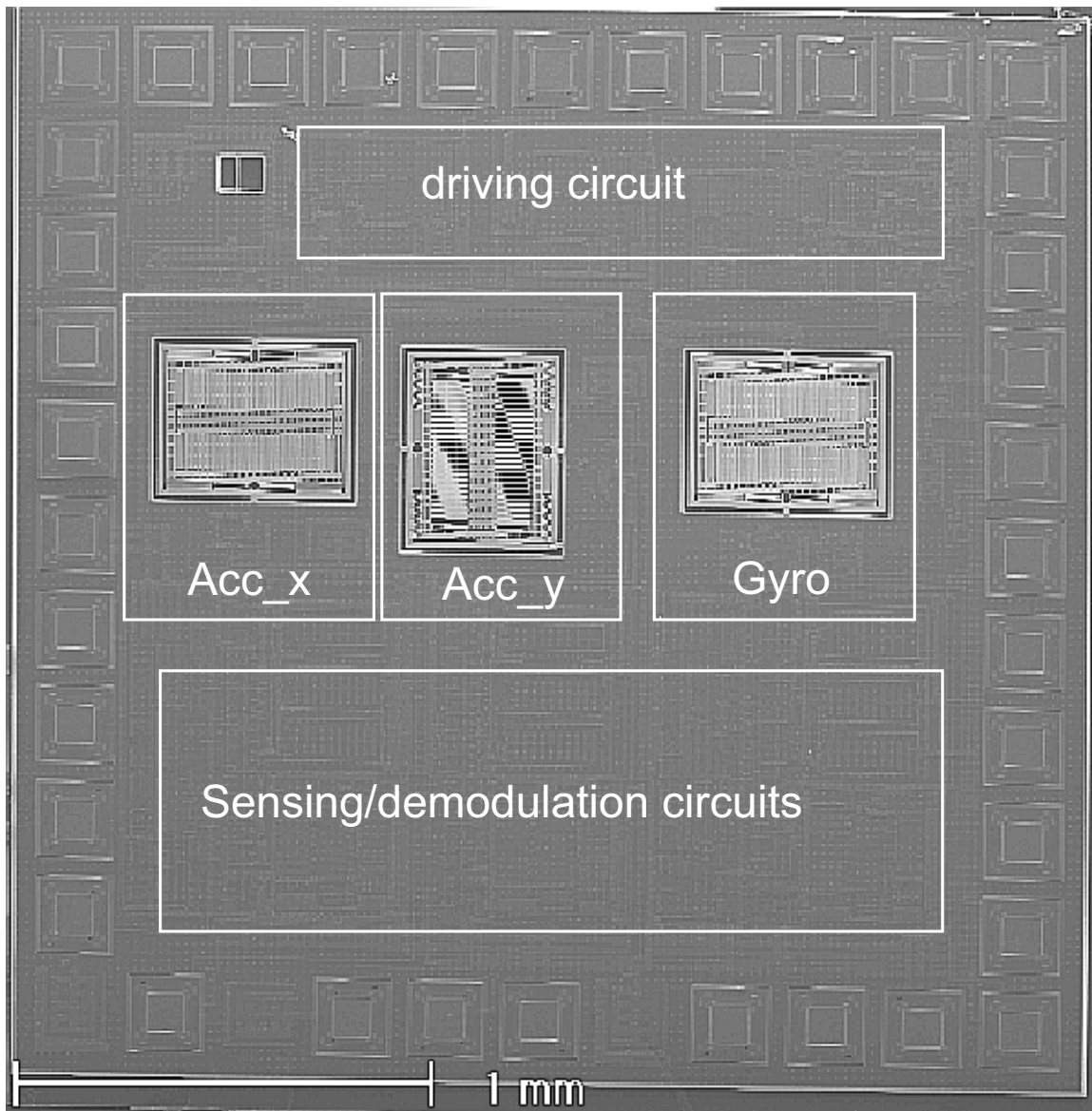


Figure 11.7.6: The 3 DOF die SEM.