Appendix 1

Capacitive Sensors in Silicon Technology

Reprinted with permission from R. Puers, "Capacitive sensors: when and how to use them," in *Sensors and Actuators*, A 37–38, pp 93–105, 1993.

Authors	Type	Size (mm^2)	C_0 (pF)
Sander, Knutti and Meindl, A monolithic capacitive pressure sensor with pulse period output, *IEEE Trans. Electron Devices, ED-17* (1980) 927–930	pressure	3 × 3	22
Ko, Bao, and Hong, A high sensitivity integrated circuit capacitive pressure sensor IC, *IEEE Trans. Electron Devices, ED-29* (1982) 48–56	pressure	2 × 4	?
Lee and Wise, A batch-fabricated silicon capacitive pressure transducer with low temperature sensitivity, *IEEE Trans. Electron Devices, ED-29* (1982) 42–48	pressure	4 × 4	12
Ko, Shao, Fung, Shen and Yeh, Capacitive pressure transducers with integrated circuits, *Sensors and Actuators, 4* (1983) 403–411	pressure	2 × 4	6
Smith, Prisbe, Shott and Meindl, Integrated circuits for a capacitive pressure sensor, *Proc. IEEE Frontiers Eng. Comp. in Health Care*, 1984, pp. 440–443	pressure	2 × 6	22
Hanneborg and Ohlkers, A capacitive silicon pressure sensor with low TCO and high long-term stability, *Sensors and Actuators, A21-A23* (1990) 151–154	pressure	4 × 4	?
Smith, Bowman and Meindl, Analysis, design, and performance of capacitive pressure sensor IC, *IEEE Trans. Biomed. Eng., BME-33* (1986) 163–174	pressure	2 × 6	22
Chau and Wise, An ultra-miniature solid-state pressure sensor for a cardiovascular catheter, *Proc. 4th Int. Conf. Solid-State Sensors and Actuators (Transducers '87), Tokyo, Japan,* June 2–5, 1987, pp. 344–347	pressure	1 × 5	0.5
Miyoshi, Akiyama, Shintaku, Inami and Hijikigawa, A new fabrication process for capacitive pressure sensors, *Proc. 4th Int. Conf. Solid-State Sensors and Actuators (Transducers '87), Tokyo, Japan,* June 2–5, 1987, pp. 309–311	pressure	?	8
Shoji, Nisase, Esashi and Matsuo, Fabrication of an implantable capacitive type pressure sensor, *Proc. 4th Int. Conf. Solid-State Sensors and Actuators (Transducers '87), Tokyo, Japan,* June 2–5, 1987, pp. 305–308	pressure	2 × 3	10
Furuta, Esashi, Shoji and Matsumoto, Catheter-tip capacitive pressure sensor, *Tech. Digest, 8th Sensor Symp., Japan,* 1989, pp. 25–28	pressure	3.5 × 0.7	3.5
Puers, Peeters, Vanden Bossche and Sansen, A capacitive pressure sensor with low impedance output and active suppression of parasitic effects, *Sensors and Actuators, A21-23* (1990) 108–114	pressure	2 × 3.5	10
Bäcklund, Rosengren, Hök and Svedbergh, Passive silicon transensor intended for biomedical, remote pressure monitoring, *Sensors and Actuators, A21–A23* (1990) 58–61	pressure	3 × 3	25
Kandler, Eichholz, Manoli and Mokwa, CMOS compatible capacitive pressure sensor with read-out electronics, H. Reichl (ed.), *Microsystems*, Springer, New York, 1990, pp. 574–580	pressure	array 81 × 100 µm	2
Matsumoto, Shoji and Esashi, An integrated miniature capacitive pressure sensor, *Sensors and Actuators, A29* (1991) 185–193	pressure	2 × 1.7	
Puers, Peeters, VanDen Bossche, and Sansen, Harmonic response of silicon capacitive pressure sensor, *Sensors and Actuators, A25-27* (1991) 301–305	pressure	2 × 3.5	10
Puers, VanDen Bossche, Peeters and Sansen, An implantable pressure sensor for use in cardiology, *Sensors and Actuators, A21-23* (1990) 944–947	pressure	1.8 × 2.2	10
Artyomov, Kudryashov, Shelenshkevich and Shulga, Silicon capacitive pressure transducer with increased modulation depth, *Sensors and Actuators, A28* (1991) 223–230	pressure	4.5 × 4.5	7

Etch	Seal	Circuit	Application	Discussion
bulk	anodic	Schmitt oscillator, bipolar	cardio	early device
bulk, hydrazine	anodic	integrated, bipolar	general	ring vs. square membrane, drift aspects
bulk, KOH	anodic	separate	general	effect of sealing on TCO and TCS
bulk, hydrazine	anodic	integrated, CMOS	biomedical	ref. capacitor integrated with sensing capacitor
bulk	anodic	integrated, oscillator, bipolar 10 μm	cardio	temperature compensation
bulk	sputtered glass	separate chip	general	low TCO and drift
bulk	anodic	integrated, oscillator, bipolar 10 μm	cardio	comparison with piezoresistive devices
EDP, bulk	anodic	separate	cardio	miniaturized
surface etch	n.a.	no	general	Ni diaphragm, sacrificial layer, cheap large batch prod.
bulk, EDP	Si-Si fusion	CMOS	biomedical	direct fusion bonding
bulk, KOH	anodic	separate, CMOS	cardio	small assembly, compete backside etch
bulk, KOH	anodic	no	general	FEM analysis & linearization
KOH, bulk	fusion bonding	*LC* circuit only	eye-pressure	*LC* tuned by pressure-transponder system
sacrificial layer, polysilicon	n.a.	SC CMOS	general	preliminary results
bulk, KOH	anodic	integrated, CMOS	cardio	throughhole connection, backside etch
bulk, KOH	anodic	separate, CMOS	biomedical	parasitic capacitance rejection
bulk, KOH	anodic	separate	cardio	miniaturized biocompatible package
bulk	?	no	general	three electrode, linearization by reducing electrode

Authors	Type	Size (mm^2)	C_0 (pF)
Ji, Cho, Zhang, Najafi and Wise, An ultraminiature CMOS pressure sensor for a multiplexed cardiovascular catheter, *Proc. 6th Int. Conf. Solid-State Sensors and Actuators (Transducers '91), San Francisco, CA, USA*, June 24–28, 1991, pp. 1018–1020	pressure	1.4 × 0.4	0.3
Kudoh, Shoji and Esashi, An integrated miniature capacitive pressure sensor, *Sensors and Actuators, A29* (1991) 185–193	pressure	2.3 × 3.7	
Kung and Lee, An integrated air-gap capacitor process for sensor applications, *Proc. 6th Int. Conf. Solid-State Sensors and Actuators (Transducers '91), San Francisco, CA, USA*, June 24–28, 1991, pp. 1010–1013	pressure	0.4 × 0.5	
Nagata, Terabe, Fukaya, Sakurai, Tabata, Sugiyama and Esashi, Digital compensated capacitive pressure sensor using CMOS technology for low pressure measurements, *Proc. 6th Int. Conf. Solid-State Sensors and Actuators (Transducers '91), San Francisco, CA, USA*, June 24–28, 1991, pp. 308–311	pressure	5 × 5	
Rosengren, Söderkvist and Smith, Micromachined sensor structures with linear capacitive response, *Sensors and Actuators, A31* (1992) 200–205	pressure	2 × 2	3
Schnatz, Schöneberg, Brockherde, Kopystynski, Mehlhorn, Obermeirer and Benzel, Smart CMOS capacitive pressure transducer with on-chip calibration capability, *Sensors and Actuators, A34* (1992) 77–83	pressure	8.4 × 6.2	6
Suminto, Yeh, Spear and Ko, Silicon diaphragm capacitive sensor for pressure, flow, acceleration and altitude measurements, *Proc. 4th Int. Conf. Solid-State Sensors and Actuators (Transducers '87), Tokyo, Japan*, June 2–5, 1987, pp. 336–339	press., accel.	2 × 3	8
Puers and Vergote, A subminiature capacitive movement detector using a composite membrane suspension, *Sensors and Actuators, A31* (1992) 90–96	motion	1 × 1	4
Petersen, Shatel and Raley, Micromechanical accelerometer integrated with MOS detection circuitry, *IEEE Trans. Electron Devices, ED-29* (1982) 23–27	accel.	0.3 × 0.1	0.004
Rudolf, A micromechanical capacitive accelerometer with a two-point inertial mass suspension, *Sensors and Actuators, 4* (1983) 191–198	accel.	1.5 × 2.6	1
Rudolf, Jornod, and Bencze, Silicon microaccelerometer, *Proc. 4th Int. Conf. Solid-State Sensors and Actuators (Transducers '87), Tokyo, Japan*, June 2–5, 1987, pp. 395–398 Rudolf, Jornod, Bergqvist, and Leuthold, Precision accelerometers with μg resolution, *Sensors and Actuators, A21-23* (1990) 297–302	accel.	8 × 6	20
Olney, Acceleration measurement using variable capacitance, *Proc. Sensors Nüremberg '88, Germany*, 1988, pp. 149–160	accel.	2.8 × 3.6	10
Schlaak, Arndt, Steckenborn, Gevatter, Kiesewetter and Grethen, Micromechanical capacitive acceleration sensor with force compensation, H. Rechl (ed.), *Microsystems*, Springer, New York, 1990, pp. 617–622	accel.	7 × 7	16
Seidel, Riedel, Kolbeck, Mück, Kupke and Königer, Capacitive silicon accelerometer with highly symmetrical design, *Sensors and Actuators, A21-23* (1990) 312–315	accelero-meter	35 × 3.5	10
Suzuki, Tuchitani, K. Sato, Ueno, Yokata, M. Sato and Esashi, Semiconductor capacitance-type accelerometer with PWM electrostatic servo technique, *Sensors and Actuators, A21-23* (1990) 316–319	accelero-meter	3 × 4.5	9
Kloeck, Suzuki, Tuchitani, Miki, Matsumoto, K. Sato, Koide and Sugisawa, Motion investigation of electrostatic servo-accelerometers by means of transparent ITO fixed electrodes, *Proc. 6th Int. Conf. Solid-State Sensors and Actuators (Transducers '91), San Francisco, CA, USA*, June 24–28, 1991, pp. 108–111	accelero-meter	3 × 4.5	9

Etch	Seal	Circuit	Application	Discussion
bulk	anodic	separate	cardio	subminiature assembly
bulk, KOH	anodic	integrated CMOS oscillator	general	advanced assembly, electrical feedthroughs
surface etch, KOH through	n.a.	integrated, NMOS	general	polydiaphragm, miniature size
bulk, TMAH	anodic	integrated, CMOS oscillator	general	frequency output, linearized response
bulk, KOH	fusion bond	no	test	linearization techniques by constructions
bulk	anodic	integrated, CMOS SC	general	includes band-gap reference for temp. correction
bulk, EDP	anodic	separate, CMOS	general	membrane with central mass for linearity
KOH, bulk	anodic	separate	animal monitoring	composite suspension membrane
surface etch, EDP	n.a.	one CMOS stage	general	silicon oxide beam, with Au deposited mass
KOH bulk	anodic	separate	general	plate suspended on torsion bars
KOH bulk	anodic	separate	spacecraft	force balancing, μg resolution
bulk	anodic	separate	space, flight control	commercial device
bulk, EDP	anodic	separate	position sensing	μg resolution, symmetric suspension
bulk	anodic	separate	general	good linearity
bulk	anodic	separate	general	servo action
bulk	anodic	separate	general	transparent electrodes on glass allow observation

Authors	Type	Size (mm^2)	C_0 (pF)
Payne and Dinswood, Surface micromachined accelerometer: a technology update, *SAE Int. Automotive Eng. Congr., Detroit, MI, USA*, 1991, pp. 127–135 Goodenough, Airbags boom when IC accelerometer sees 50g, *Electronic Design* (8 Aug. 1991), 127–135	accelero-meter	±5 × 5	?
Peeters, Vergote, Puers and Sansen, A highly symmetrical capacitive micro-accelerometer with single degree of freedom response, *Proc. 6th Int. Conf. Solid-State Sensors and Actuators (Transducers '91), San Francisco, CA, USA*, June 24–28, 1991, pp. 97–100	accelero-meter	3.6 × 3.6	12
Ura and Esashi, Differential capacitive accelerometer, *Tech. Dig. 10th Sensor Symp., Japan*, 1991, pp. 41–44	accelero-meter	5 × 6	15 × 2

Etch	Seal	Circuit	Application	Discussion
surface etch	n.a.	integrated CMOS	automotive	fully integrated device, no bulk micromachining
bulk, KOH	fusion bond, anodic	separate	general	highly symmetrical, tunable damping
bulk, hydrazine	anodic	separate	general	silicon-oxinitride suspension