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Micromachined Sensor and Actuator Research at the Microelectronics Development Laboratory

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ABSTRACT

An overview of the major sensor and actuator projects using the micromachining capabilities of the Microelectronics Development Laboratory at Sandia National Laboratories will be presented. Development efforts are underway for a variety of micromechanical devices and control electronics for those devices.

Surface micromachining is the predominant technology under development. Pressure sensors based on silicon nitride diaphragms have been developed. Hot polysilicon filaments for calorimetric gas sensing have been developed. Accelerometers based upon high-aspect ratio surface micromachining are under development. Actuation mechanisms employing either electrostatic or steam power are being combined with a three-level active (plus an additional passive level) polysilicon surface micromachining process to couple these actuators to external devices.

The results of efforts toward integration of micromechanics with the driving electronics for actuators or the amplification/signal processing electronics for sensors is also described. This effort includes a tungsten metallization process to allow the CMOS electronics to withstand high-temperature micromechanical processing.

Keywords: sensors, actuators, microsensors, microactuators, accelerometers, pressure sensors, resonant sensors, hydrogen sensors, microengine, surface micromachining, polysilicon

1. FACILITIES

The Microelectronics Development Laboratory (MDL) shown in Figure 1 at Sandia National Laboratories is a 30,000 square foot, class 1 semiconductor fabrication facility located in Albuquerque, NM. Its various missions can be categorized into four technology areas: 1. CMOS, 2. Radiation-hardened nonvolatile memories, 3. Smart Sensors, and 4. Micromechanical sensors and actuators. This paper discusses the laboratory's development effort in the area of micromechanics and how that relates to the laboratory's other development efforts in smart sensors and CMOS.

The MDL is a modern, well-equipped CMOS fabrication facility with both 2 micron and 0.5 micron CMOS design rules. The facility has been adapted to enable the development of other technologies in addition to the continued development of the baseline CMOS. These other technologies benefit from the wide variety of equipment and processes in existence to support the baseline CMOS, but these other technologies must also maintain a degree of compatibility with the CMOS line so that they do not contaminate that line.

In the area of micromechanics, the MDL has development projects in both surface and bulk micromachining. Because bulk micromachining raises a number of contamination issues and does not take full advantage of the capabilities of the facility, the majority of the work underway at the MDL is being performed in the surface-micromachining area. Both undoped and in-situ phosphorus-doped polysilicon films as well as low-stress silicon nitride can be deposited for use as structural layers. A variety of glasses (for use as sacrificial layers) such as TEOS, PSG, and BPSG can be deposited by both conventional chemical vapor deposition (CVD) and plasma-enhanced CVD (PECVD). Both wet and dry etch processes are available for patterning of these films. Additional materials such as tungsten and copper can be deposited in both blanket and selective CVD processes.

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2. SENSORS

The MDL has developed or is in the process of developing a number of sensors based on micromechanical technologies. The development of these sensors is driven by applications in industry as well as defense. Surface micromachined polysilicon filaments for use as catalytic gas sensors, flow sensors, and thermal-conductivity pressure gauges have been fabricated and characterized. These filaments are fabricated using a single-level doped polysilicon process. TEOS-based glass is patterned to form both the anchor layer and a stiction-reducing dimple level. Filaments over 1 mm in length have been fabricated without stress or sticking problems. A scanning electron micrograph (SEM) of a small array of these filaments is shown in Figure 2. Figure 3 is an individual element of that array with a bias applied so that the filament glows.

In order to better understand the thermal properties of these filaments, a spice model has been developed to describe the distribution of temperature on the filament during operation. This model also allows the simulation of the current-voltage characteristics of the device under operating conditions. Figure 4 compares the results of this model for a 100 micron long filament with the terminal characteristics measured on an actual device.

A pressure sensor technology has been developed at the MDL based upon a silicon nitride layer as the diaphragm material. A sacrificial oxide underneath this diaphragm layer is etched away using HF-based chemistries. This leaves a cavity beneath the diaphragm. An additional silicon nitride layer is used to seal the cavity in near-vacuum conditions (approx. 200 mTorr). Polysilicon piezoresistors are deposited on the diaphragm to sense the diaphragm strain that results from changes in ambient pressure. A completed, 100 micron diameter pressure sensor is shown in Figure 5. The response of that sensor to pressure changes is shown in Figure 6. This project is described more thoroughly in a later paper in this proceeding.[1]

Micromachined force feedback accelerometers and gyroscopes are also being investigated. Approaches to improve the sensitivity of such structures by increasing the proof mass and decreasing parasitics while maintaining batch fabrication of the devices are being pursued. Additionally, force feedback sensors are being used as a technology development vehicle for monolithically integrating micromechanical structures with CMOS in a batch fabricated process. This integration will be discussed later in this paper.

Bulk micromachining of single crystal quartz was used to produce the volatile organic sensor shown in Figure 7. This sensor has been described in more detail elsewhere[2]. This sensor uses three bulk acoustic wave resonators to sense mass changes in films deposited on those resonators. The quartz resonant elements are 1.2 mm in diameter and approximately 75 microns thick. They have a resonant frequency of 22 MHz. Figure 8 illustrates the time-dependent response of one of these resonators coated with 0.1 microns of poly-isobutylene to varying concentrations of trichloroethylene. The magnitude of the frequency shifts for this coated sensor to five different organic solvents and water is shown in Figure 9. Additionally, a custom driver chip[3] attached to the quartz contains circuitry for temperature compensation, frequency counting, and signal multiplexing.

In addition to these micromechanical sensing technologies, the MDL also has developed a robust, wide-range hydrogen sensor[4] with integrated control and interface electronics. This chip shown in Figure 10 illustrates the ability of the MDL to integrate sensing technologies with controlling CMOS. The controlling electronics include analog control elements, A/D converters, D/A converters, and a network communication interface. The sensor utilizes a Pd/Ni alloy in both a chemi-resistor and a chemFET to sense hydrogen concentration from the PPM level to pure hydrogen. The chip also contains heaters, a thermometer, and the necessary control electronics which enable the chip to maintain a constant temperature under changing environmental conditions. Figure 11 shows the response of the chemi-resistor and chemFET on the hydrogen sensor.

3. ACTUATORS

Micromechanical actuators have not seen the wide-spread industrial use that micromechanical sensors have achieved. Two principal stumbling blocks to their widespread application have been low torque and difficulty in coupling tools to engines. The MDL has two development projects that are overcoming these issues. A steam-based actuation mechanism generates orders of magnitude higher force per unit chip area than conventional electrostatic actuators. Also, a new three-level polysilicon micromachining process greatly enhances the ease at which one can couple to microengines.

The MDL has produced the world's smallest steam engine[5]. This device, shown in Figure 12, incorporates a polysilicon piston that moves inside a polysilicon cylinder. The seal between the piston and cylinder is provided by the meniscus force of a drop of water covering the device. A small amount of water is pulled into the boiler through capillary action. It is then heated with a polysilicon heater inside the boiler, causing the formation of a bubble which pushes the piston out of the cylinder. Springs provide a return force for the piston when the heat is removed and the bubble collapses.

More intricate actuation mechanisms require advanced mechanical designs coupled with additional levels of structural materials. A new micromachining process described elsewhere in detail[6] includes three movable levels of polysilicon in addition to a stationary level for a total of four levels of polysilicon. These levels are each separated by sacrificial oxide layers. An additional friction-reduction layer of silicon nitride is added between the layers that form bearing surfaces. Figure 13 illustrates a bearing formed between two layers of mechanical poly. A total of 8 mask levels are used in this process. This process has first been applied to the microengine shown in Figure 14. Here, two comb-drive actuators[7] drive a set of linkages to a rotary gear. This gear can be rotated by applying sinusoidal driving forces 90° out of phase with each other to each of the comb-drive actuators. Rotational speeds in excess of 100,000 RPM have been achieved with this device. Presently, work is underway to couple this gear to perform additional functions.

4. INTEGRATION OF CMOS WITH MICROMECHANICS

Finally, the task of integrating micromechanics with the controlling CMOS is also being undertaken. The MDL has successfully integrated CMOS with the chemFET sensing technology of the hydrogen sensor, but the issues involved in integrating CMOS with micromechanics are much more involved due to the intricacy of the micromechanical processing. Basically, good micromechanical structures require long, high-temperature anneals to assure that the stress in the structural materials of the micromechanical structures has completely relaxed. Additionally, a good CMOS technology requires good planarity of the substrate in order to achieve the needed accuracy of the photolithographic process. If the micromechanical processing is performed first, the substrate planarity is sacrificed. If the CMOS is built first, it (and its metallization) must survive the high-temperature anneals of the micromechanical processing. This second alternative was chosen by researchers at Berkeley[8] and is being developed further at the MDL. In this approach, the standard aluminum metal used in CMOS is replaced with tungsten. Since tungsten is a refractory metal, it survives the high-temperature processing well, but a number of issues remain unsolved dealing with adhesion of the tungsten layer and the unwanted formation of tungsten silicides. Despite these issues, the MDL has fabricated integrated devices with functioning control electronics. One such device, an accelerometer with on-chip amplifiers, is shown in Figure 15.

5. SUMMARY

Sandia's Microelectronics Development Laboratory has developed and is developing a broad range of sensors and actuators using micromechanical processing techniques. Combustible gas detectors, flow sensors, and vacuum gauges based on hot polysilicon filaments are under development. Accelerometers and gyroscopes with integrated feedback and amplifying circuitry are also being developed. A micromachined steam engine, a volatile organic sensor technology and a pressure sensing technology have been developed. A new three-level polysilicon process has enabled the development of an intricate coupling mechanism linking linear comb-drive actuators to a rotating output gear.

6. REFERENCES

[1] W. Eaton and J. Smith, "A CMOS compatible surface micromachined pressure sensor for aqueous applications", accepted for publication in *Proceedings of Smart Structures and Materials '95*, SPIE (1995).
[2] J. Smith, T. Ricco, S. Martin, and D. Koehler, "Miniature Quartz Thickness-Shear Mode Resonator Sensor Array with Integrated Control Electronics", presented as a Late News Paper at *The IEEE Solid-State Sensor and Actuator Workshop '94* (1994).
[3] J. Smith and S. Senturia, "Self-Consistent Temperature Compensation for Resonant Sensors with Application to Quartz Bulk Acoustic Wave Chemical Sensors", submitted to *The 8th International Conference on Solid-State Sensors and Actuators*, IEEE Press (1995).
[4] J. Rodriguez, R. Hughes, W. Corbett, and P. McWhorter, "Robust, wide-range hydrogen sensor", *Proceedings of the 1992 International Electron Device Meeting*, p. 521, (1992).
[5] J. Sniegowski, "A microactuation mechanism based on a liquid-vapor surface tension," *Abstracts of Late News Papers of the 7th International Conference on Solid-State Sensors and Actuators*, IEEE press, p. 12 (1993).
[6] J. Sniegowski and E. Garcia, "Microfabricated actuators and their applications to optics", accepted for publication in *Proceedings of SPIE Photonics West '95*, SPIE (1995).
[7] W. Tang, T-C. Nguyen, and R. Howe, "Laterally driven polysilicon resonant microstructures," *Sensors and Actuators*, vol. 20, pp. 25-32 (1989).
[8] W. Yun, R. Howe, and P. Gray, "Surface micromachined, digitally force-balanced accelerometer with integrated CMOS detection circuitry", *The IEEE Solid-State Sensor and Actuator Workshop '92*, p. 126 (1992).

Figure 1. The Microelectronics Development Laboratory at Sandia National Laboratories in Albuquerque, NM.

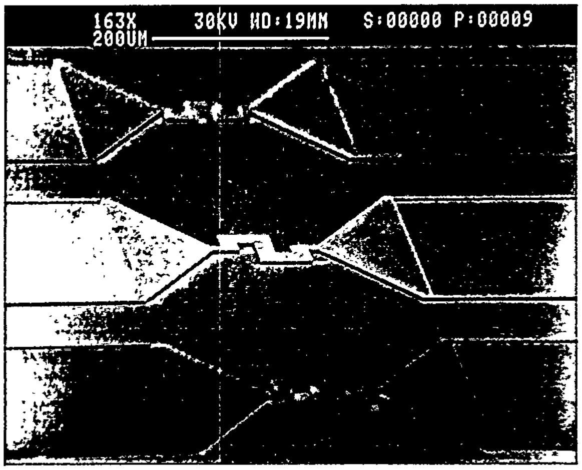

Figure 2. A scanning electron micrograph of an array of polysilicon filaments suspended 2 microns above the substrate.

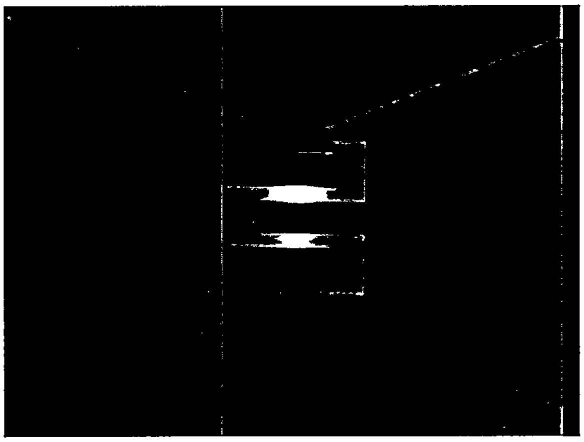

Figure 3. An individual polysilicon filament glowing due to the application of an electrical bias.

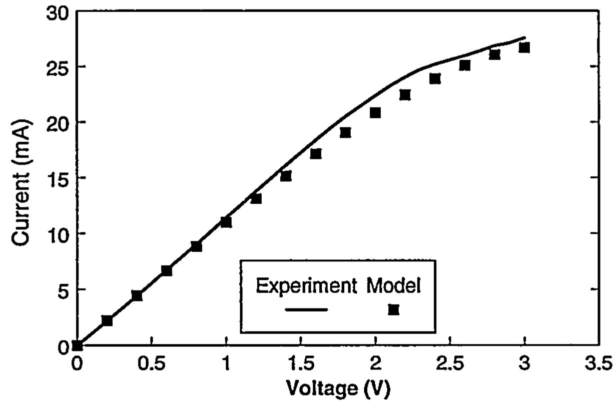

Figure 4. The current-voltage characteristics of a 100 mm long polysilicon filament. The line (experimental) is data measured on an experimental device in air. The squares (model) represent data from a spice model for the filament that accounts for the self-heating of the filament and the changes in resistance of the polysilicon filament with temperature.

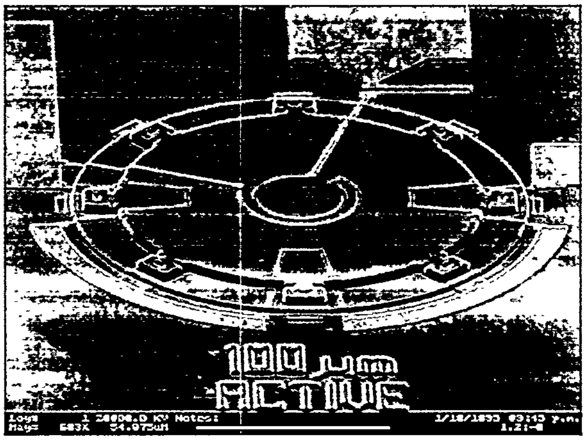

Figure 5. An SEM of a surface micromachined pressure sensor. The pressure sensor uses polysilicon piezoresistors on a nitride diaphragm over a vacuum cavity to sense changes in ambient air pressure.

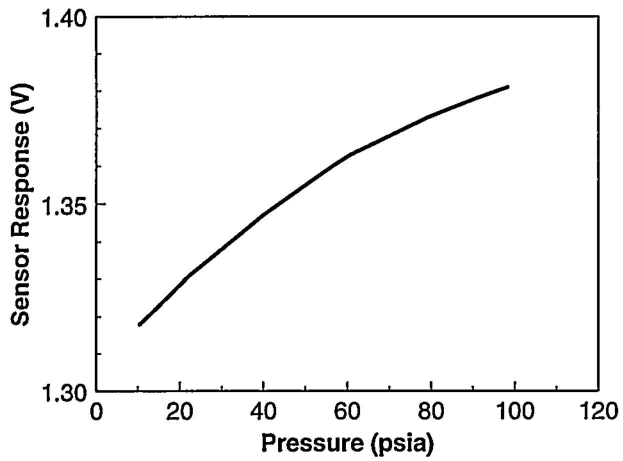

Figure 6. The response of a surface-micromachined pressure sensor with a 100 micron diameter diaphragm to changes in applied pressure.

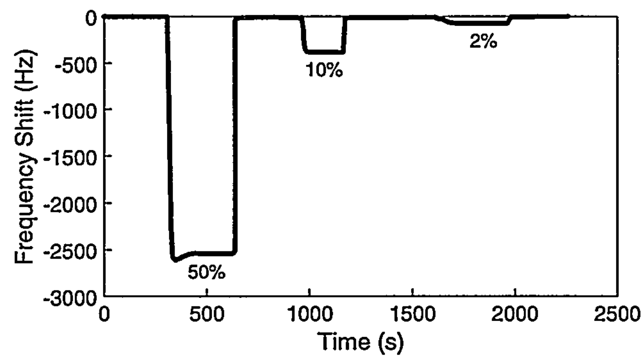

Figure 8. The time-dependent response of the quartz sensor platform coated with 0.1 microns of poly-isobutylene to various concentrations (50%, 10% and 2% of saturation vapor pressure) of trichloroethylene in nitrogen at 20°C.

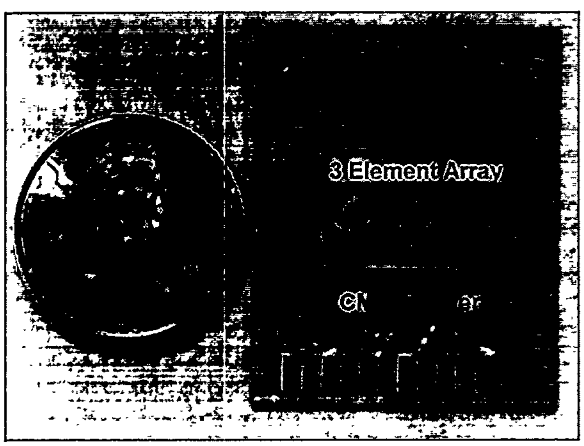

Figure 7. A three element volatile organic sensor with integrated driving, temperature compensation, and multiplexing electronics.

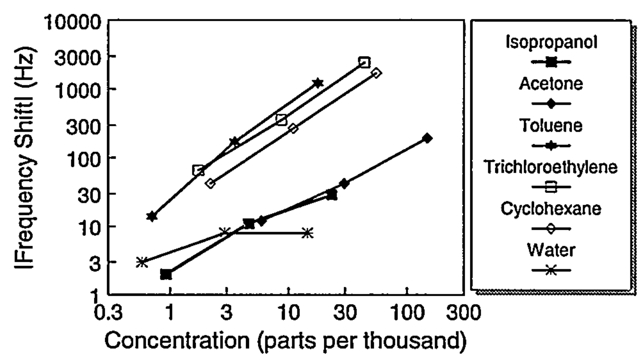

Figure 9. The magnitude of the response of the quartz sensor platform coated with 0.1 microns of poly-isobutylene to various concentrations of 5 organic solvents and water.

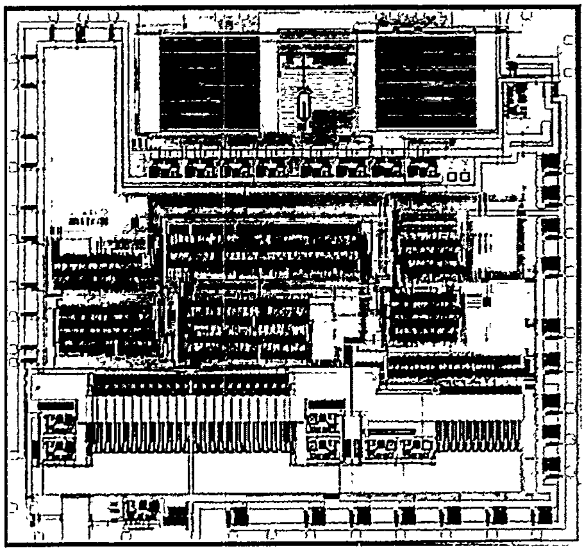

Figure 10. A robust, wide-range hydrogen sensor complete with integrated control and interface electronics.

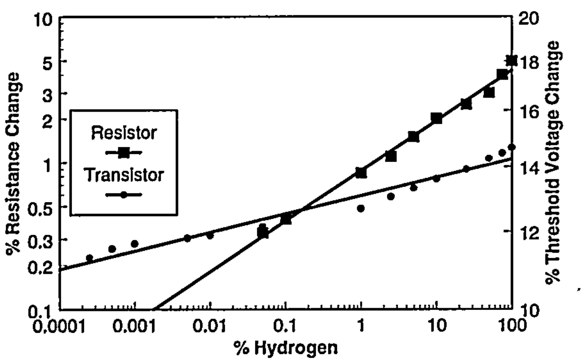

Figure 11. The response of both the resistor and transistor on the hydrogen sensor to various concentrations of hydrogen.

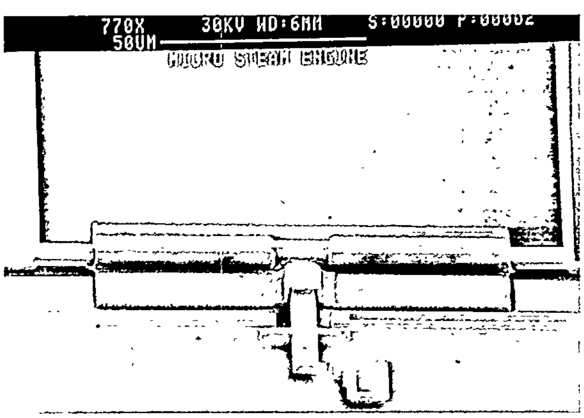

Figure 12. The micro steam engine.

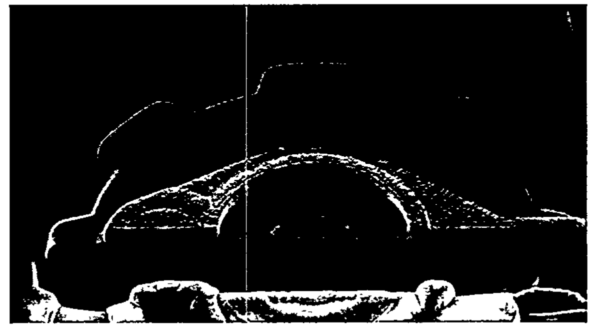

Figure 13. A focused ion-beam cross-sectional image of a gear produced with the MDL's three level polysilicon process.

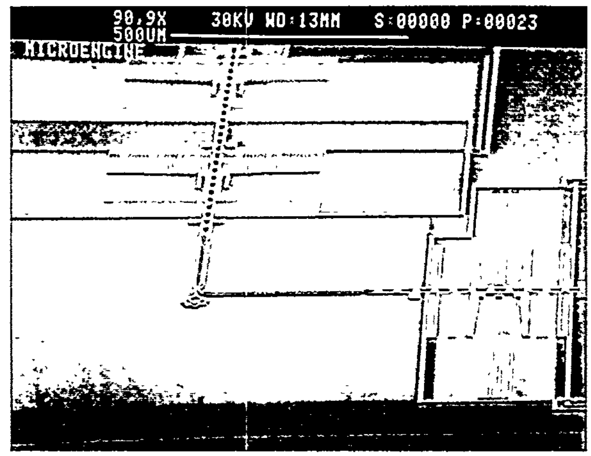

Figure 14. A microengine that drives the gear shown above in Figure 7 with two comb-drive actuators.

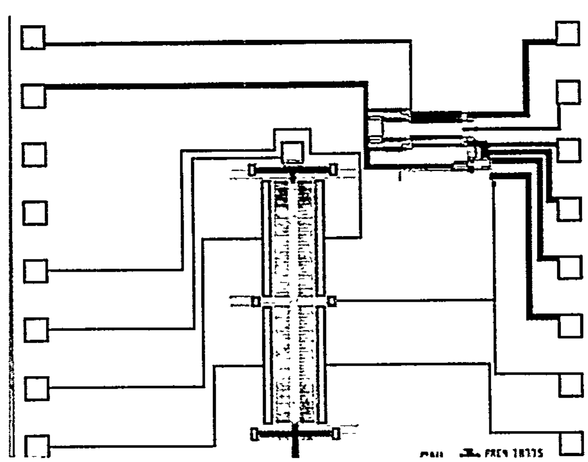

Figure 15. A micromachined accelerometer integrated with an all-tungsten CMOS pre-amp.