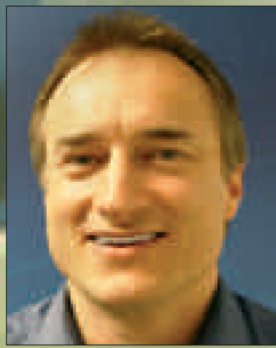
MEMS microvalves: the new valve world



Mark Luckevich.

Anyone who has studied electronic circuits may recall that the concepts of current, resistance and capacitance were often taught using analogies to fluid flow in pipes with orifices (resistors) and storage containers (capacitors) influencing the current in the circuit. It is unlikely that the professors at that time had any idea that a day would come when an electronic semi-conductor device would actually have fluid flowing through it. Microstaq Inc. has developed such a device and is producing innovative valve designs that can provide macro flows with a micro device. The technology is based on MEMS: Micro Electro Mechanical Systems, which utilizes relatively standard silicon processing to create electromechanical systems. At present the MEMS industry has been flourishing and growing at an annual average growth rate of over 20% a year and MEMS devices have been penetrating the marketplace primarily in the form of microfluidic devices (ink jet print heads), telecommunication components and sensors. Microstaq is the first company to develop the technology and commercialize it for macro-flow control applications. The time has now come to design electronic circuits with microprocessors, integrated circuits, resistors, capacitors and micro-valve flow control devices all on the same circuit board.

By Mark Luckevich, VP Engineering, Microstaq

▶

The technology

MEMS is an approach to fabrication that uses the materials and processes of micro-electronic fabrication. It facilitates and conveys the advantages of miniaturization, multiple component integration, and microelectronics to the design and construction of electromechanical systems.

The MEMS microvalves developed by Microstaq are assembled by combining multiple layers of silicon wafers each with a unique geometric structure etched into it or through the silicon surface. The valve design is only limited by one's imagination for structures that will operate as a flow control device. The silicon wafers are bonded together with a technique known as fusion bonding. Wafer cleanliness, surface roughness and alignment are the critical factors in fusion bonding. The bond is completed with a high temperature anneal process.

Standard silicon wafers are used in the manufacture of the MEMS micro valves. The voltage characteristics of the valves are determined by selecting an appropriate resistivity of the silicon wafer. The resistivity of the wafer is controlled through a boron doping process when the wafers are made. The resistivity, specified in ohm-cm, is only critical in wafers intended to carry current. The resistivity is high in the non-conducting layers.

The primary steps of the etching process are photolithography, deep reactive ion etch (DRIE) and KOH etch. These processes are used selectively depending on the features being etched into the silicon wafer. Through hole etch depths are dependant on the wafer thickness and are in the range of 675 µm. Typical feature depths are in the 50–100 µm range with some surface tolerances being controlled to 1–2 µm with sub-micron accuracies possible.

Valve size or die size will depend on the valve design, but will typically be in the range of 1 cm^2. The thickness of the valve will vary based on the thickness of the wafers used and the number of wafers used in the valve stack. A typical three layer stack valve, like the valve depicted in Figure 1, will result in a valve thickness of approximately 2 mm. Since the valve size will vary based on the design, so will the number of valves yielded per wafer stack. Additionally, silicon wafer diameters of 4, 6 and 8 inches (or higher) can be used which will also determine part count per stack.

The Microstaq design

Microstaq has already developed two basic types of Silicon Control Valves (SCV). The first type is a spool valve which is operated by controlling the pressure on either side of the spool. This can be done with a micro valve pilot or by using pressures in the system. The second type of valve is a direct acting device where electrical current is used to directly drive the valve mechanism. The microvalves operate similarly to a conventional spool valve in that a sliding element is used to block or open a port. Conventional spool valves use a spool in a cylindrical bore. The MEMS micro valve uses a sliding plate valve where a silicon plate moves in a cavity over openings in a 'port plate'.

Figure 2 is a scanning electron microscope (SEM) photograph of two separate spool designs. The devices shown are part of the center (or mechanical) wafer and constitute the sliding element of the spool valve. The top device is part of a 3-way normally closed spool valve and the device shown below is used in a 2-way normally open valve. In both devices, a spring is one of the mechanical features of the spool. The spring provides a number functions for the devices but generally does not have a large enough spring constant to be used as a constant force balance mechanism in the valve control function. Spool positioning is achieved by controlling the pressure balance across the spool. Feedback mechanisms can be integrated into the device by strategically placing holes or slots in the spool, which create

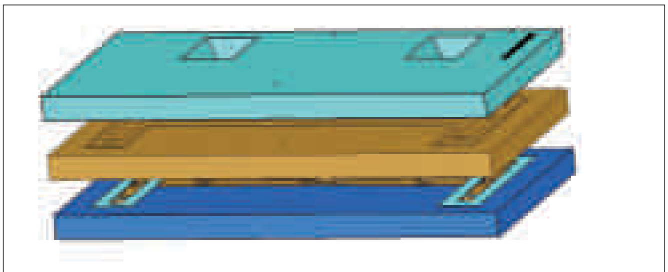


Fig. 1. Microvalve sketch showing the three layers of the valve stack. Cover plate, mechanical layer and port plate.

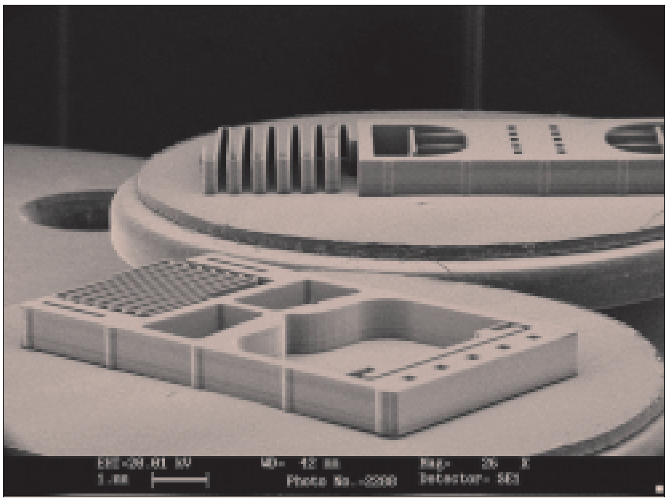


Fig. 2. Scanning electron microscope photo of a microvalve spool. Top: 3-way closed center. Bottom: 2-way normally open. (Photograph courtesy of Micralyne, Inc.)

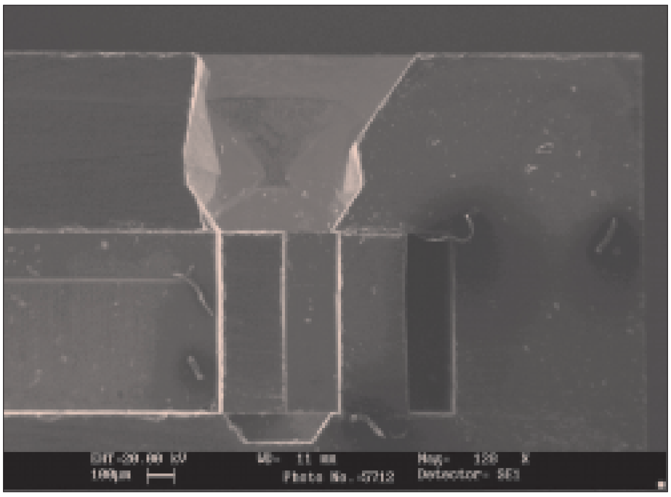


Fig. 3. Scanning electron microscope photo of a direct acting microvalve. Photo shows a cross section of the normally closed port. (Photograph courtesy of Micralyne, Inc.)

Fig. 4. Direct acting microvalve in comparrison to a typical automotive solenoid valve.

variable feedback orifices that are a function of the spool position. Other holes and features are designed into the device to facilitate proper function of the valve and to ensure that the leakage paths are kept to a minimum.
The second type of valve noted is a direct acting device that provides a proportional flow control capability. The valve provides a variable orifice that is proportional to the power applied. The most common method of driving the device is to provide a fixed voltage and then pulse width modulate (PWM) the signal to provide a range of 'average voltages' that will stroke the valve. The valve will then have an opening that is proportional to the PWM signal.

Figure 3 shows a SEM photograph of the side view of a direct acting valve that has been cross sectioned through the port area. The top portion of the valve clearly shows the port. The center wafer mechanism can be seen closing off the port to the flow path on the left. When the valve opens, the center mechanism moves to the right which in turn opens the flow port above to the common flow area within the valve. The direct acting valve is currently available in 2 and 3 port configurations and can be used either as a digital or proportional flow control device.

Valve operation and capabilities

The differences between a standard solenoid valve and the MEMS micro valve are vast and are measured in orders of magnitude. The most significant difference is the size and weight of the micro valve, which is obvious just by visually comparing the valves as shown in Figure 4. Since the valve is made entirely of silicon, there is no longer concern over susceptibility of seals and metals to fluids. The valves can operate with any fluid that is non-corrosive to silicon and at temperatures that challenge the materials used to interface the micro valve to the system.
The fundamental operating mechanism of the direct acting micro valve is a flow of electrical current through silicon 'ribs' which in essence are multiple resistive elements. These silicon ribs expand due to the resultant thermal expansion of the silicon and translate into a linear displacement of the valve mechanism. Unlike the inductive solenoid device, the micro valve has no electro-magnetic interference (EMI) emissions and does not require any elaborate valve drive electronics. There is the added benefit of not interfering with sensors that may be located near the flow control device. In addition, the MEMS based valve technology lends itself to integration with MEMS based pressure transducers as well as other sensing technologies. Valve and sensing elements can be affixed to the same manifold with a common electrical interface.

A summary comparison of the MEMS direct acting micro valve to a typical solenoid valve is given in Table 1.

Table 1: Microvalve to solenoid valve comparison chart

Key Metric	SCV	Solenoid	Impact
Size	0.8cm³	41.2cm³	98% Reduction
Weight	0.35g	170g	99% Reduction
Power	1A @12v	3A @12v	66% Reduction
Reliability	High	Limited	Longer Life
System	Silicon	Metal	Significant cost reduction
Electronics	Resistive	Inductive	Low driver complexity
EMI	None	High	Low design complexity
Interface	Simple	Multiple Bore	Low manufacturing complexity

As with most valves, the performance and operational capabilities will be a function of the type of fluid, the operating temperature as well as a number of other environmental factors. The following is a summary of some of the operating capabilities of the microvalve in current applications. This list does not define the limitations of the technology.

Direct Acting Valve: Several versions of this valve are available with flow areas ranging from 0.05 mm² to 2 mm² and operating voltages of 6 and 12 volts. The valves can operate at pressures in excess of 2,000 psi and over a temperature range of –40 to 150°C. A flow capacity test using nitrogen (N2) at 100 psi yields flows from 6 l/min to 40 l/min. Valve leakage will vary with operating conditions and will be greater than zero.

Spool Valve: The spool valve has similar operating capabilities to the direct acting valve. This design has provided orifice areas in the 2 mm² to 4 mm² range. Flow capacity tests in nitrogen at 100 psi yielded flows in the range of 150 to 175 l/min. To operate at the high pressure limit of the direct acting valve, the spool valve must either be encapsulated with a metal cap or designed into the system such that it is surrounded by the high pressure fluid.

Packaging

The mounting or interfacing of the micro valve into the flow control system is relatively straight forward using conventional

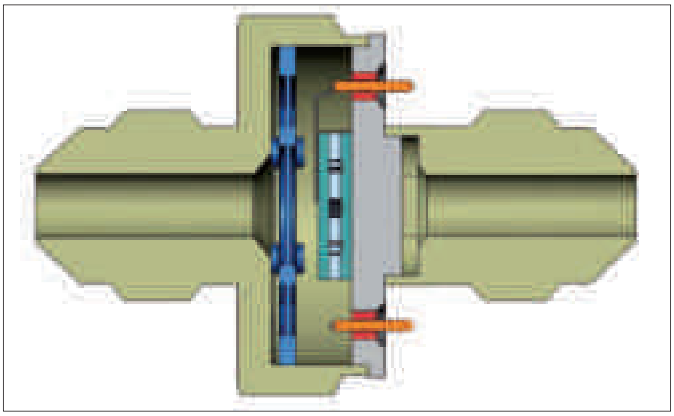


Fig. 5. Flow through microvalve mounted in a typical pipe fitting. Electrical interconnect via a glass bead insert. Integral filter shown on the inlet side.

electrical and mechanical technologies. With a flow through valve configuration, the flow enters on one side of the microvalve and exits on the other. With this type of valve configuration the valve can be affixed to a metal plate which is then integrated into the flow system. Alternately, the silicon can be captured by the edges, eliminating the need for any kind of mounting plate or manifold. Figure 5 demonstrates a mounting concept where a flow through microvalve is mounted on a plate inside of a standard pipe fitting. Note that the fitting also includes a filter element and provides for the electrical interconnect with (glass bead) feed through wire technology.

Another method of interfacing utilizes a U-flow microvalve design where the fluid flow enters and exits the valve on the same side. This design requires a multi-layered manifold to provide the proper porting and channeling of the flow. Figure 6(a) and (b) shows two U-flow type mounting configurations. In figure 6(a), the microvalve is mounted on a standard solenoid type interface manifold utilizing a cylindrical bore and o-ring seals. Figure 6(b) shows the microvalve mounted on a flat manifold that would attach to the surface of the device and use a face

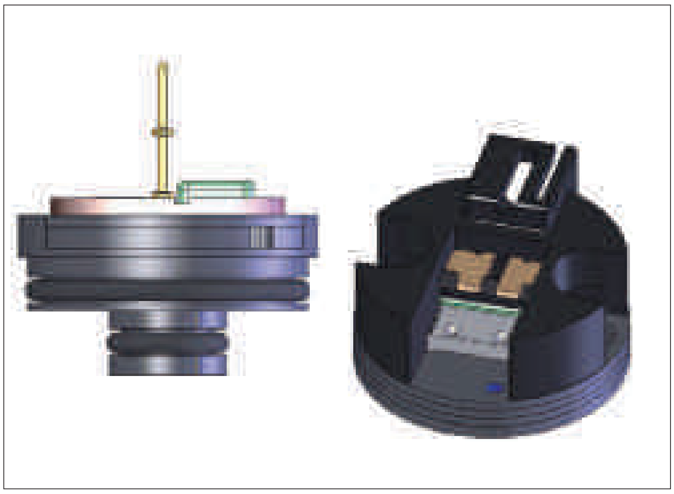


Fig. 6. (a) Microvalve piloted spool with a U-flow installation. External electrical connection and conventional cylindrical bore with o-ring seals. (b) Microvalve piloted spool with a U-flow intallation. Conventional connector on a flat plate manifold using a face seal and integral filter element.

seal. In either case, filters are integrated into the manifold or sealing elements. Note that the round interface manifold is ideal as a direct replacement for a solenoid valve, but further system benefits would likely result by integrating the micro valve directly into the device. With the U-flow valve the electrical connect is on the outside face of the valve and standard connectors can be used as part of the manifold design. Wire bonding, among other techniques, is used to connect the valve to the connector terminal pins.

Industry applications

Since the MEMS microvalve is a flow control device, it has potential applications in many industries. Today's limitations are measured by the flow and pressure capacity of the valve, but these capabilities will grow as the technology is developed. Current applications span across the industrial, process control, automotive and commercial/residential markets. These applications include refrigeration, where microvalves are being developed for variable displacement compressor control and electronic control of the refrigerant thermal expansion. In hydraulics, the micro valve has found a home as a pressure control device for transmission clutches and is also being developed for hydraulic braking applications. The micro valve is also being used to control hydraulic and pneumatic actuators (cylinders).

In many high flow applications solenoid valves are used to pilot much larger valves. Similarly, the micro valve can be used to pilot a larger flow device eliminating the need for a solenoid valve. This 'hybrid' valve concept can be applied to many flow control applications, where the solenoid device is replaced by the micro valve which is used to drive a conventional mechanical valve mechanism. ■

ABOUT MARK LUCKEVICH

As Vice President of Engineering at Microstaq, Mark Luckevich is responsible for the micro valve product and application development. He is a control system specialist with design and development experience in hydraulic and pneumatic flow control. In the automotive industry, Mark was responsible for the design and development of ABS, Traction Control and Vehicle Stability Control systems for the global market. His R&D team developed hydraulic controls for advanced products including by-wire systems, active damping and roll control. In his earlier aerospace work, Mark was responsible for the design and development of cabin pressure control systems along with other flight critical controls. Mark earned his Bachelor of Science degree in Physics from the University Of Waterloo in Ontario, Canada.