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Manifold destiny: Gas systems go modular

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Several modular gas distribution system designs are currently available, all promising reduced cost of ownership (COO). Depending on the system requirements, modular designs can occupy as little as 25% of the volume of conventional welded gas systems. Current modular systems are extremely simple to install, field-modify, and troubleshoot. Modular systems are enabled by recent developments in seals and fasteners, machining technology, and modularity concepts. The critical sealing element in the "Z-Bloc" design is a narrow nickel gasket that plastically deforms within the gland; gland design isolates external forces from the gasket.

After years of incremental improvement, modern semiconductor gas systems provide a high degree of performance and reliability. Fundamentally, these systems interconnect discrete components with stainless steel tubing. Straight tubing segments are orbitally welded to machined elbows, tees, and the components themselves. Fittings with metal gaskets provide joints for assembly and service. The ratio of welding to fittings varies considerably between designs, trading off the serviceability of a system with many fittings against the compactness and leak integrity of an all-welded system.

The recent introduction of modular or integrated gas systems challenges nearly all of the assumptions of conventional (welded tubing/VCR fitting) designs. The fundamental interconnecting element in modular gas systems is a machined passage in a block of stainless steel. This article reviews the issues that modular systems address, explains why these systems are coming forward now, and illustrates in detail how one design implements a solution.

Design challenges

Several factors make modular gas systems attractive to both original equipment manufacturers (OEMs) and semiconductor fab end users, including ease of maintenance, and low cost and size. While some processes may benefit from modular designs, process improvement is not the main reason for the adoption of the technology in most instances. The advent of 300-mm process tools has opened the first window in years for fundamentally rethinking gas system architecture.

End users want systems that are easier and faster to maintain and upgrade in the field. Modern gas systems are now quite reliable, but service can be difficult and time consuming when systems eventually require maintenance. Making a design change in an operating tool usually requires a complete retrofit.

OEMs and users want to limit system cost, particularly where the user or the process dictates custom features. Users particularly despise the current charges for "engineering specials," which they view as excessive. OEMs want "building-block" systems that are easier to design and require less inventory because they have shorter manufacturing cycle times.

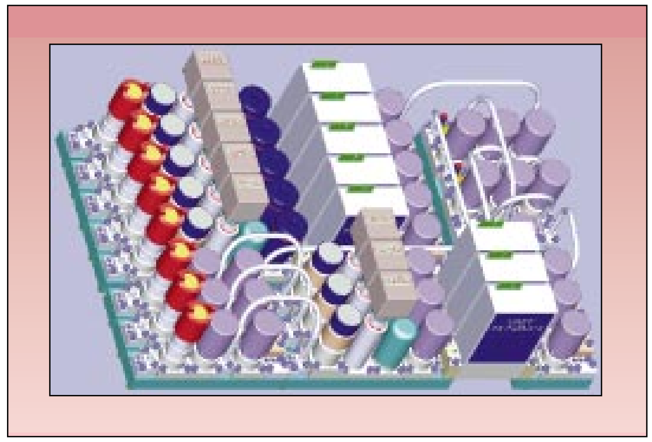

Figure 1. By eliminating welded tubing, modular gas distribution systems occupy significantly less space.

Both OEMs and users applaud the smaller size of modular systems (Fig. 1). Both want to limit tool footprint, and with the migration toward 300-mm wafers almost everything else in the tool is getting larger. Users also see an opportunity to retrofit modular systems into existing tools, because more features can be fit into the existing space while improving maintainability.

Modular systems are currently hot because enabling technology and market hunger have converged. Seals, fasteners, machining technology, and modularity concepts have evolved tremendously in the past five years. For 20 years, seals have been the most likely parts of the gas system to leak. Modern metal sealing systems, including the fasteners holding them together, now compare favorably with welded joints. New CNC multiaxis machine tools can economically produce complex stainless parts with very good surface finishes directly from computer-aided design files. Modular gas system architectures can now compete in versatility and cost with welded tubing.

New, small, high-quality metal seals have been perfected over the past several years. For a long time, elastomeric O-rings, now recognized as prime sources of contamination in ultra-high-purity gas systems, were the only practical seals for compact assemblies of machined parts. Serviceable metal fitting seals, such as the classic VCR design, have certainly been available. Fitting seals and bonnet seals, with their large, robust, threaded mating parts, apply the necessary high forces to a conventional metal gasket very evenly. However, these seals are difficult to adapt to compact, complex assemblies.

Modular design challenges

Modular gas systems differ principally in how they achieve modularity and in their choice of sealing system. The sealing system includes the gaskets, the machined patterns (glands) in the mating parts that contact the gaskets to seal the joint, and the fastening system that holds the parts and the sealed joint together.

All modern modular systems meet or exceed established standards for ultra-high-purity gas systems, including leak integrity, low volatile contaminant and particulate levels, corrosion-resistant surfaces, and rapid dry-down following exposure to moisture. Most modular systems have lower internal volume and surface area than welded systems, though all gas control panels have much lower volume than the facility gas lines and the other interconnecting lines within a tool.

Faced with significantly different competing modular designs, many OEMs and end users desire standardization such as the de facto current standard of welded/VCR systems. The choice would be easy and safe if everyone agreed on an initial design approach. Standardized modular systems would probably be less expensive, since the competition to manufacture essentially interchangeable components would relentlessly drive prices to the commodity level. A SEMI-SEMATECH group is earnestly looking into modular system standardization.

Modular designs

The degree of modularity in a gas system design is a crucial choice. Every modular system has a base or "substrate" that provides both physical mounting for and interconnecting passages between valves, flow controllers, and other components. The substrate can

Figure 2. Cross section through a Z-Bloc system shows the "V"-shaped passages through the substrate that connect the top-mounted components. A jumper between substrates is shown on the left.

be all one piece or many modular pieces connected together. For modular systems, a mounting plate beneath the modular substrates provides mechanical support and rigidity.

Single block. Both Tylan and Innovus fielded very compact systems in the mid 1980s by machining the substrate for four flow loops from a single block of steel. However, this choice drove up the substrate costs, making inventory and spares very expensive. The amount of machining time invested in a single piece of steel, in addition to the high cost of scrap if mistakes or damage occurred late in the manufacturing cycle, increased system costs. Modern CNC tools and techniques make it much easier to machine complex flow passages with excellent surface finishes, but the costs and risks associated with cutting the entire substrate for each unique system out of a single block remain.

Components as modules. Conventional gas systems, in which each fundamental element such as a valve, filter, regulator, or mass flow controller (MFC) connects to an adjacent component with a VCR fitting, are the opposite extreme in modularity.

Component to component (C^2). Compressing the modularity of VCR/welded designs so that separate tubing and fittings are eliminated and the interconnecting seals are on the components' base surfaces results in dense modular systems. As a further refinement, each module can have more than one component machined into it. The base block/substrate contains component features and features that provide mounting and connection to adjacent blocks.

Once the space between active components is eliminated, effectively holding the parts together in such component-to-component (C^2) systems presents a design challenge. C^2 designs raise serviceability issues because component replacement can require substantial disassembly. However, the ability to machine both component functionality and interconnection into the same component block makes C^2 designs inherently simple. Additional seals are not necessary if the interconnect substrate is not separated from the components.

Top mount. Separating fully functional subcomponents from a modular interconnecting substrate results in a family of top-mount designs. The substrate only supports and interconnects the components. Some components, such as valves, are actually simpler if the connections come out the bottom rather than the sides. All top-mount systems provide access to each active component from one direction for improved serviceability, but they differ significantly in how they treat the substrate and in their sealing systems. As with C^2 designs, individual substrate elements can mount and interconnect more than one component. Substrate elements can connect directly to each other or a bridge can be used between them.

Z-Bloc design

The Z-Bloc system is a top-mount design with each substrate block interconnecting up to five individual components (Fig. 2). Only one surface of the substrate block contains any machined features for gas connections or physical mounting. Mounting posts from the base plate travel up through holes in the substrate, bottoming on flat caps fastened to the component mounting surface (Fig. 3). In this unusual way, the substrate is supported above the base plate from its top surface, which makes the thickness of the substrate irrelevant. Space between the base plate and the substrate makes it straightforward to run heaters along the bottom of individual loops.

Several millimeters separate each block from its counterparts. Therefore, dimensional tolerances on the substrate blocks can be very loose and do not accumulate either within a block or across the gas system. With only one vulnerable surface, it is relatively easy to handle blocks without physically damaging them. Most other commercially available designs butt the substrate elements against each other, making flow path connections on more than one surface of each block.

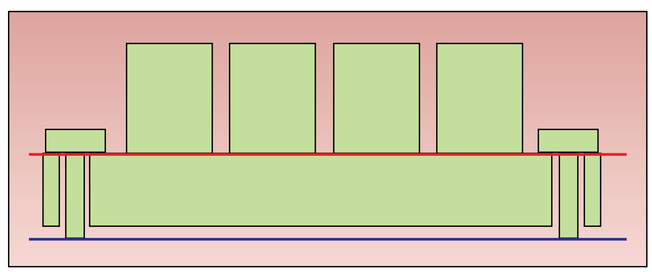

Figure 3. Both components and the substrate are referenced from the same plane (red). Spacers connect to the top surface of the substrate and support it above the mounting plate (blue).

Short, machined "V" channels interconnect components through the substrate (Fig. 2). Overhead jumpers and bridges provide interconnection between substrate blocks, placing all flow path seals in a single plane. Machined top jumpers connect adjacent blocks (Fig. 2), while tubing and flanges create bridges between more widely separated parts of the system. These bridge connections are mechanically compliant, so they do not create dimensional tolerance problems across the assembly. Separate jumpers connect each side of a flow loop to its adjacent neighbors. Continuous passages across gas loops through these alternating blocks and jumpers form purging or process manifolds.

All modular designs handle simple configurations well, such as identical parallel loops connecting together to form a process manifold. The ability to interconnect any two points by bridging above the substrate helps Z-Bloc systems handle unusual plumbing requirements. Using bridges and jumpers between substrate blocks allows detachment and removal of any number of interconnected blocks and their attached components for service without disturbing the remainder of the system. Likewise, it is possible to add gas loops in the field by extending manifolds with jumpers.

Except for MFCs, all components mount on the same pattern. The system contains only five surface patterns: component, bridge, manifolding jumper, MFC, and substrate mounting. These patterns and the appropriate interconnections can be machined into a substrate block in almost any order. The system design philosophy does not strive to minimize the number of different substrate blocks. Rather, the objective is to construct a particular design with the fewest total number of substrate blocks, each optimally patterned to deliver the required functionality in the smallest space. The interconnected Z-Bloc substrate is a balance between a system within a single, massive, substrate block, and a system containing many small substrate blocks mounted to individual components. This balance, together with the simplicity of the block design, minimizes machining costs.

The Z-Bloc system uses a component mounting pattern with symmetrical ports, which simplifies the drilling of passages within the substrate. Components are keyed to prevent backward installation. Components come with gaskets and all mounting hardware fastened in place. Mounting screws are captured so that the entire part can be installed in any position without any hardware falling out (Fig. 4). On removing a component, the gaskets and screws exit with the part. Reinstallation of a component requires only replacement of the gaskets.

Many OEMs and end users have strong preferences for particular component brands. The Z-Bloc system accommodates any component that can be mounted on a 1.48 × 1.48 in. (37.6 × 37.6 mm) square flange. At present, more than 20 component suppliers in the US, Europe, and Japan produce valves, regulators, MFCs, and other components ported for the Z-Bloc system.

Sealing requirements

An all-metal sealing system must meet a number of demanding criteria. Components of the system, the seals and the sealing glands machined into the mating surfaces, should be simple and inexpensive. Both seals and glands should forgive physical damage from handling or be well protected. Sealing must be reliable and highly predictable. Otherwise, gas systems with several hundred seals become difficult to manufacture or repair.

The sealed joint must withstand vibration, shock, and temperature excursions encountered in shipment or service. Technicians should be able to make up joints properly with readily available tools and a minimum of training. Joints should reliably reseal repeatedly to accommodate design changes and maintenance. They should not produce particles when assembled or disassembled. The design should facilitate isolating a leak in a dense assembly with many seals; leak detection would otherwise present a formidable challenge.

The Z-seal. The Z-Bloc system derives its name and its most distinctive characteristics from the unique sealing system used — the Z-seal, developed by Unit Instruments in 1993. The seal tests to 1×10^{-11} atm-cc/sec (He) with quality rejects of less than 1000 ppm (Fig. 5). The sealing glands are undamaged in the process of making up the seal.

The Z-seal gasket is a narrow nickel shoulder washer that deforms within the gland (Fig. 6). Bringing the parts together creates very high compression forces in the center of the gasket, causing the relatively soft gasket material to flow into small imperfections in the glands and creating a gas-tight seal. A thin "keeper" that also functions as a compression stop, retains the seal in place before assembly. Machine screws hold the parts together with approximately 3700 lbs. of force.

The glands of a Z-seal are quite simple, consisting basically of opposing 90° corners. The intersection of a counter bore and the surface of the part forms one corner. The mating part where a circular groove or trepan intersects the part surface forms the other corner. Both the counter bore and the trepan are deeper than necessary, allowing for resurfacing of a scratched part.

Once compressed, the gasket is isolated from external mechanical stresses. Although it plastically deforms, the Z-seal gasket retains enough elasticity to maintain the seal over a wide temperature range.

In VCR fittings, the mating parts never bottom out and external forces on the parts transmit directly to the gasket. Consequently, VCR fittings can loosen up when shipped or otherwise subjected to vibration. External force further compresses the gasket, which then loosens and leaks when the force relaxes.

Because the Z-seal gasket begins to shear when compressed, the force required to make up the seal is comparatively low and

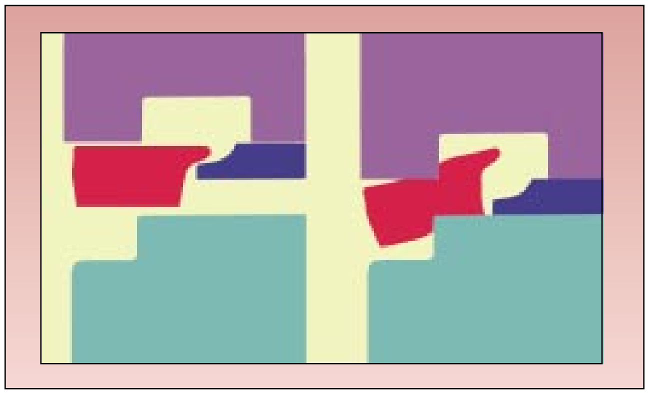

Figure 6. Cross-sectional drawing of the Z-seal before and after sealing. The soft nickel gasket deforms to make the seal, while the portion of the keeper in contact with the substrate isolates the seal from external forces.

during assembly. A thicker gasket allows proper sealing with significant dimensional variation in keepers and mating parts.

The seal makes up with a torque of 20–30 in.-lbs. on the screws. As the components bottom out, the torque increases sharply. Further torquing the screws to 45 and 55 in.-lbs. provides the high clamping force that isolates the gasket from external forces. The screw will not break until torqued to 135 in.-lbs., providing a large safety factor.

In virtually every commercially available metal sealing system, the gasket must be very evenly compressed in order to achieve a high-quality seal. This requires tightening the four mounting screws on an ordinary component in gradual stages and in a particular sequence. Z-seal screws should be torque-checked twice, but they can be tightened down in any order.

Fasteners. Fasteners are the final critical element in modular gas systems. The ultimate reliability of the metal seal depends on the mating parts adhering under any conceivable environmental stress. Massive interthreaded parts (i.e., those that secure fittings) are robust but difficult to design into compact modular systems. Threaded fasteners are compact, simple, and relatively inexpensive, so machine screws hold most modular gas systems together. Threaded fasteners, however, can be surprisingly unreliable.

Conventional plated, high-strength, steel screws can weaken and fail from hydrogen embrittlement after installation. Plated, nonplated, and stainless steel screws are subject to failure from stress-corrosion cracking. These fasteners can fail if exposed to humidity and small amounts of corrosive gas. Gas systems should never leak, but if they do, a leak must not degrade the fastening system so that it could catastrophically lose containment of hazardous gases. Welds are also subject to stress-corrosion cracking, so this threat is not necessarily new.

Z-Bloc critical fasteners consist of a special nickel superalloy developed for aerospace and marine environments. These alloy #10-32 cap screws are essentially immune to failure from embrittlement or corrosion. To prevent the unwitting substitution of ordinary fasteners, these special alloy screws are shipped already installed in every component.

Overall system performance

Z-Bloc systems are only 25–60% of the size of conventional welded systems, depending on the density of the welded design. Z-Bloc systems are approximately 20% heavier than a welded equivalent. Most of the internal flow passages are 0.188 in. dia., slightly larger than 1/4-in. tubing. There are fewer right angles in the flow path. For every "V" in a substrate block, the design eliminates two "Vs" by converting most components from side porting to bottom porting.

Most of the pressure drop in a complete Z-Bloc system occurs in the components. Also, the pressure drop in the substrate is lower than that in a comparable welded system, because there are fewer acute angles and larger diameter passages.

Standard surface finishes measure 7 micro-in. Ra, and all internal machined surfaces are chromium-oxide passivated for corrosion resistance. Systems emit no measurable particles when monitored on a condensation nucleus particle counter. Atmospheric pressure ionization mass spectrometer measurements show that the seals and interconnecting passages dry down after moisture challenges no differently than an equivalent length of stainless tubing.

Economics. Most modular gas systems are not being produced in sufficient quantity to answer cost effectiveness questions conclusively. Several modular system suppliers say that they expect their designs to compete favorably in price with conventional welded systems as shipments increase. Unless this happens, OEMs and users will lose interest. Component suppliers generally agree that top-mount versions will cost no more than their standard models and may even cost less.

Judging how different modular designs will fare against each other at high production levels is more difficult. Perhaps the best way to judge the ultimate cost of modular systems is to review the material and machine time involved in making the seals and substrates. Most modular designs contain more stainless steel, which makes them heavier than conventional systems, but minimal differences exist in steel content between modular designs. Substrate cost scales principally with total system machining time, including set up, handling, and final finishing processes. Seal cost again scales with design complexity plus the number of seals required in a system. Whether the various feature differences between modular systems will prove compelling is not yet clear.

Summary

Modular gas systems are appealing because of their size, serviceability, and promise of lower total COO. Current systems vary significantly in how they achieve modularity, in their sealing systems, and in the variety of components that are supported. While interest in modular systems for new tool design is very high, practical field experience is low. The relative effectiveness of these designs in use will determine which ones are ultimately successful. Awareness of the design/performance issues involved in modular systems will help potential consumers make vital decisions. ■

Acknowledgment

VCR is a registered trademark of the Cajon Corp. Z-seal is a trademark of Unit Instruments.

David Sheriff is VP and GM of Z-Bloc Modular Gas Systems, a division of Unit Instruments Inc. He joined Unit Instruments in 1989 as director of marketing, after having led the sales and marketing activities at Tylan Corp. Sheriff was for many years cochairman of the MFC standards committee at Semi, where he founded and chaired a task force to develop a digital MFC communication standard and a sensor/actuator bus. A member of several Sematech MFC test-method working groups, he also served on the steering committee that guided the design of the MFC testing laboratory at Oak Ridge National Laboratory. *Unit Instruments Inc., 22600 Savi Ranch Parkway, Yorba Linda, CA 92887-7027; ph 714/921-2640, fax 714/921-1438, e-mail dsheriff@unit.com.*