Sealing in Success: The Role of Perfluoroelastomer Seals in Advanced IC Production

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With advanced IC processes using more aggressive chemistries and higher operating temperatures, performance requirements have become much more stringent for the sealing components and o-rings used within capital equipment. At stake is the productivity of entire multibillion-dollar wafer fabs.

Today's aggressive chemistries include process gases such as NF_3 for chamber cleaning as well as many others used for optimizing film deposition in high-density plasma CVD processes. In all applications where gases are ionized using plasma, the reaction of the plasma is greatly enhanced. While this makes the ionized gases more effective in removing materials during cleaning processes or reacting with substrates during deposition, this increased aggressive action also makes seals more susceptible to attack by the process chemistries. Selecting the right seal, with the correct material composition and design suited for a given application, has become critical in providing much-needed resistance to such aggressive environments.

Seals are used throughout virtually all etch and deposition equipment to safeguard the ultraclean processing environments within. Although seals have been used in semiconductor equipment for decades, it was not until the 1990s that perfluoroelastomer materials were developed to overcome the shortcomings of FKM, EPDM, nitrile and silicone in high-temperature and aggressive chemical environments. When it became clear that the early perfluoroelastomer seals needed additional improvement, the industry began to create specialized base polymers, fillers and curatives to achieve the best performance for a given set of process conditions. These conditions can include high and low temperatures, acid and base resistance, resistance to solvents, tensile strength, elongation, tear resistance, permeability, and abrasion resistance.

The use of FEA (finite element analysis) for seal design optimization has been a major contributor in improving seal performance. An FEA can simulate the stresses and strains that a seal encounters when installed in a gland, and can indicate areas where design modifications to the seal or gland shape can reduce those stresses. In this way, FEA is very useful when evaluating ways to improve a seal's useful life or when designing seals and glands for new equipment.

Most seal manufacturers provide gland diagrams and gland dimensions for use with their seals, but most of these dimensions are still based on gland designs for older-generation standard compound static seals. Since perfluoroelastomers have different nonlinear coefficients of expansion, these designs may not be appropriate for their current intended use. Other considerations such as allowable gland fill and compression set also must be taken into account for today's sealing applications.

This is especially true for dynamic seals, which may have to operate under varying loading conditions and act as mechanical stops. Gland design as well as seal shape and height become critical issues in dynamic seal design. Here is where FEA can be of great benefit to help optimize designs for long life and minimal particle generation.

Polymers, Fillers and Curatives

The many new materials being used in semiconductor manufacturing create new challenges for sealing components, which must not only withstand exposure to the new materials and their deposition, etching and cleaning, but also deliver long life and minimal-to-no particle generation.

To accommodate all the different operating parameters for seals in semiconduc-

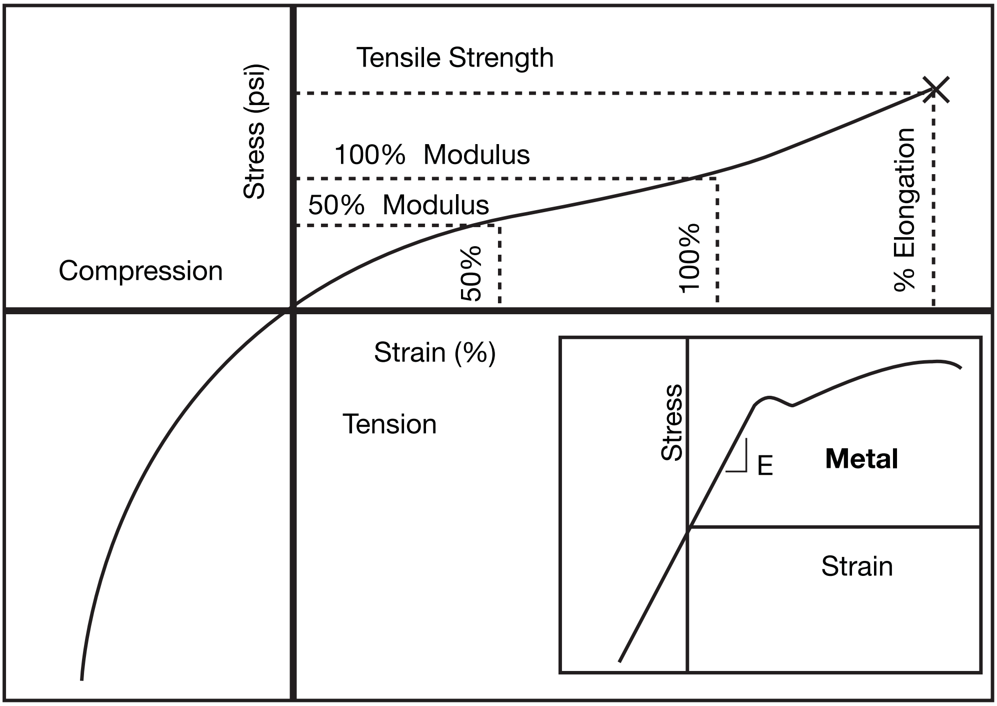

Figure 1. Stress-Strain Characteristics of Elastomer Seals

Source: ISSM Optimization of Semiconductor Manufacturing Equipment Seals for Enhanced Performance

By: John Foggiato, Aaron Thrash, Fred Freerks, Furat Al-Saleem tor equipment, seal manufacturers have had to develop unique seals for different equipment applications. For etch and cleaning processes, they have created seals that can withstand harsh environments such as NF_3 plasmas. Similarly, they developed seals that can tolerate the high temperatures of RTP. To give each seal its unique capability, different base polymers, fillers and curatives were developed and optimized for specific applications. Most perfluoroelastomers are based on tetrafluoroethylene compounds, such as perfluoro(alkyl vinyl ethers). These base polymers are then compounded with fillers to give them the mechanical properties and chemical resistance required for the application. The filler materials include carbon black, $BaSO_4$ (barium sulfate), TiO (titanium oxide), Al_2O_3 (aluminum oxide) and silica. The base polymer and the amount and type of filler depend on the particular performance requirements for the seal.

Once the seal is formed to the right shape and size, the molecular structure of the seal must be cured to assure that the seal holds its shape during use. This is done by cross-linking the seal molecules with one of several possible curing agents such as peroxide, triazine and many others. Curing is carefully controlled and done at high temperatures to assure complete and uniform linking. The combination of base polymer, filler and curing gives the seal its characteristic hardness, tensile strength and modulus.

Performing Finite Element Analysis

To use FEA and understand how a seal will perform, it is necessary to understand the seal's ability to compress (bulk modulus) and deform (elastic properties).

Bulk modulus is the property of a material that defines its resistance to volume change when compressed. Knowing the compressive response of the elastomer is very important. Bulk modulus can be expressed as the derivative (slope) of the pressure-strain curve. Under tension, modulus is determined by a measure of the load at a given elongation. For example, "modulus at 100 percent" is a stress value

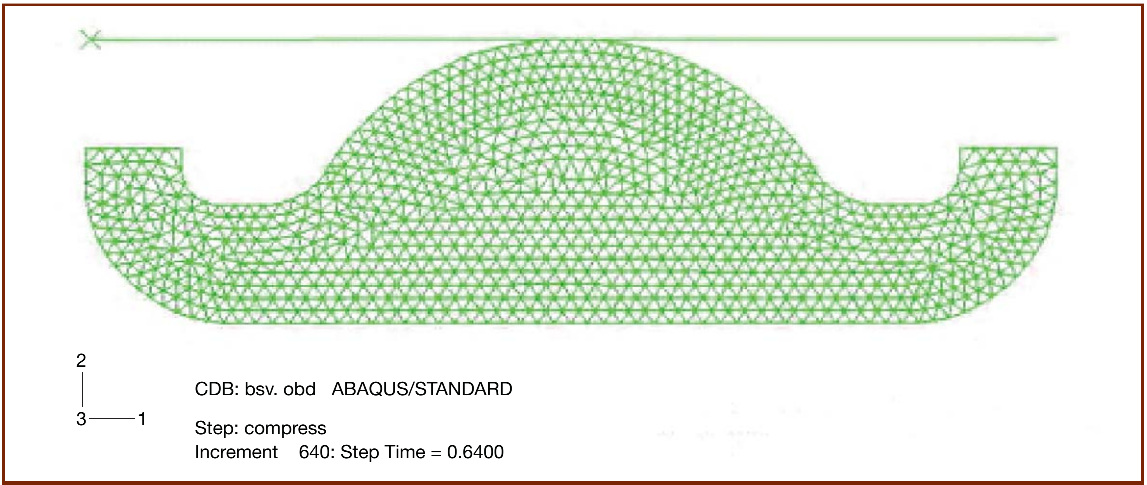

Figure 2. Mesh From Specialty Seal (bonded gate)

Source: Fred Freerks Consulting

for the material at an elongation of 100 percent (i.e., at twice the original length).

The volumetric compressibility of the material also must be examined. This is typically done by placing a cylindrical specimen in a fixture and compressing it. The actual displacement during compression is very small and great care must be taken to measure only the specimen compliance and not the stiffness of the instrument itself. The initial slope of the resulting stress-strain function is the bulk modulus.

Elastomers are typically nearly incompressible. As such, compression in one direction leads to significant strains and stresses in all directions. Special elements in the FEA software must take this into account. Also, most elastomers do not exhibit a linear region from which a modulus of elasticity can be measured. The stress-strain curves tend to be significantly nonlinear. This requires that most material models need to define the properties of elastomers with one or more stress-strain data sets, which are then translated by the FEA software to define the material model. Most FEA software packages have several choices for material models. Depending on the software, some models are very general and very capable, but typically require more extensive data sets to define the material model.

There are additional effects and sensitivities that are unique to elastomers, including strain rate sensitivity, temperature sensitivity, softening and thermal

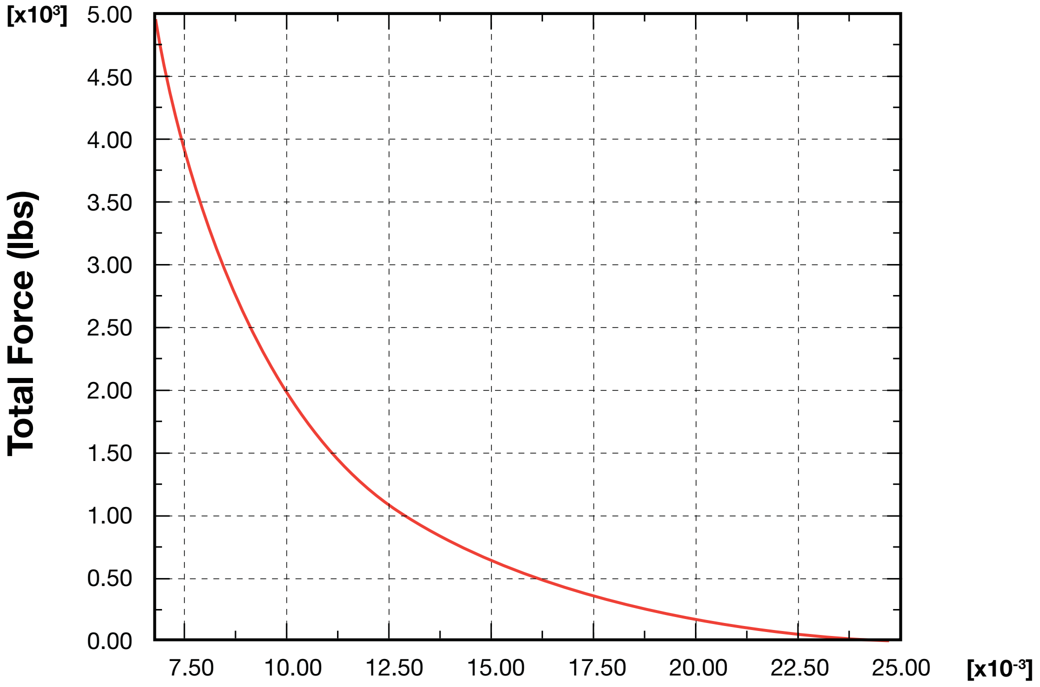

Figure 3. Force/Deflection Curve (bonded gate)

Source: Fred Freerks Consulting

expansion as well as others with lesser effects. All of them can affect the design of an optimal seal.

In most cases, the methodology for FEA will focus on the seal and gland cross section. For static seals, the constraints for the seal are defined by the gland and cover. The cross-sectional area of the seal and gland define the amount of gland fill and the seal deformation. It is in this confined space that the seal must provide sufficient push-back to provide the sealing force. For dynamic seals, not only are the constraints of the gland important, but also the motion of the seal and/or cover.

To verify that sufficient sealing force is available and that the stresses on the seal are low enough to enable maximum design life, FEA analysis is a helpful tool to optimize design. With round cross-section seals, the initial contact with the sealing surface is tangential. But as the seal is compressed, a greater footprint is made with the sealing surface. It is this footprint and the residual force of the seal that provides the sealing force. In custom seal designs, all operating parameters will affect the seal and gland design, so the designer must have a good understanding of the operating environment as well as the seal's limitations.

Figures 2-4 show typical analyses for a complex custom seal design. This design was based on customer input and thorough understanding of the operating conditions. The FEA shows that the seal's compressibility and deformation were sufficient to provide the required sealing.

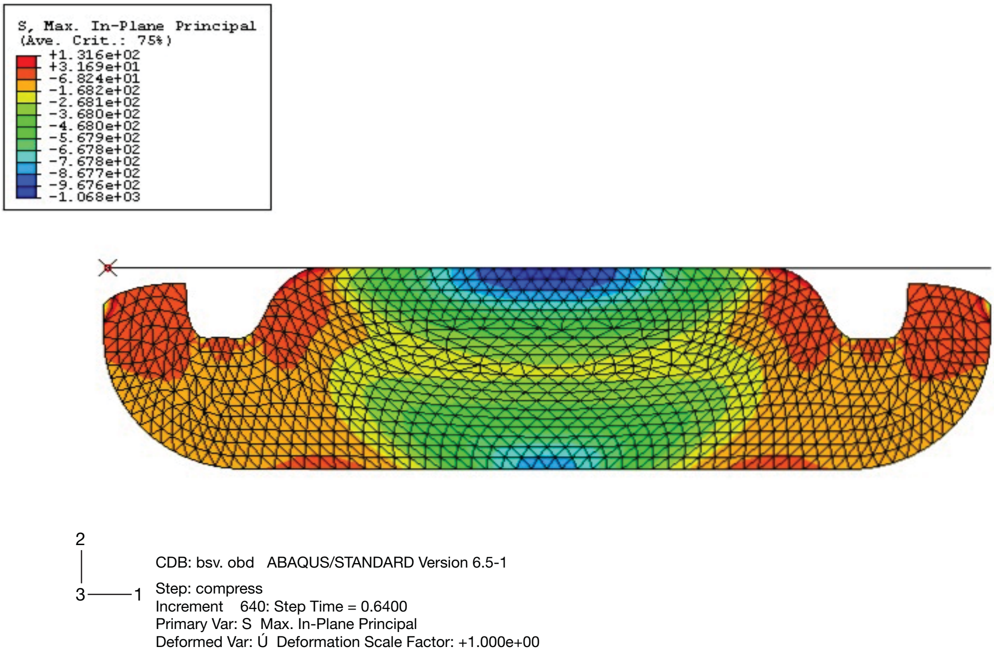

Figure 4. FEA Showing Deformed Mesh and Internal Seal Stress (bonded gate)

Source: Fred Freerks Consulting

When comparing the compressed mesh with that of the uncompressed, you can visualize the deformation stresses.

Summary

Due to the variety of chemistries, temperatures, cycle times and cleanliness requirements for different process steps, there is no single "universal" seal. From the gland to the seal material to the seal cross section, there are several critical factors that make all the difference – not just in seal life or optimization, but also in creating the ultraclean processing environments on which multibillion-dollar fabs depend.

Many key industry challenges – from yield to contamination control to extending preventive maintenance cycles – are impacted by often-overlooked seals. Increasing the industry's understanding of available sealing solutions and how they are best used with various new materials can go a long way in helping to bring advanced manufacturing processes online more quickly and efficiently.

Figure 5. Seal Engineer Verifying Seal Dimensions to Specification

Source: Applied Seals North America, Inc.

About the Authors

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Fred Freerks is the principal in Fred Freerks Consulting, providing technical solutions to semiconductor equipment manufacturers and users. He has worked for leading companies in semiconductor equipment design for over 30 years and has been awarded eight U.S. and five foreign patents. He holds a B.S. degree from the University of San Francisco.

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