New Advances in Silicone-based Thermal Insulation

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Abstract

Silicone foam is currently used as the thermal insulation material of choice for many heating applications. However, silicone foam has disadvantages that limit its use in many applications. These disadvantages include: a thickness requirement that is unmanageable to meet specified temperature gradients; complicated manufacturing processes; poor thermal stability; particulate contamination after degradation; and high cost. The semiconductor industry is moving towards a thinner profile insulation that still maintains required thermal gradients, operates at higher temperature, has excellent thermal stability, and is lower in cost. Review of the semi-conductor industry indicates that there is a need for an all-new silicone-based thermal insulation material to mitigate the limitations of silicone foam in heating assemblies. Arlon has developed a next generation silicone-based thermal insulation material to replace silicone foam. The new thermal insulation material is 70% thinner but can still maintain specified temperature gradients, is thermally stable up to 250°C, and has excellent long term application integrity at a moderate cost.

Content

1. Background

Many gases (BCl_3, ClF_3, SiH_2Cl_2, WF_3, $AlCl_3$, NH_4Cl, etc.) are used in semiconductor wafer processing. Condensation and particle buildup in gas carrying pipelines can occur at cold spots often resulting in expensive maintenance and tool down time [1]. It is necessary to use silicone flexible heaters around these pipelines to maintain higher temperatures (up to 220°C for current designs, and 300°C for future designs).

Silicone foam, or sponge, is currently used as thermal insulation material of choice in a silicone, flexible heater assembly. A number of composites can be designed by combining silicone flexible heater substrates and silicone foam [2-3], as shown in **Figure 1**.

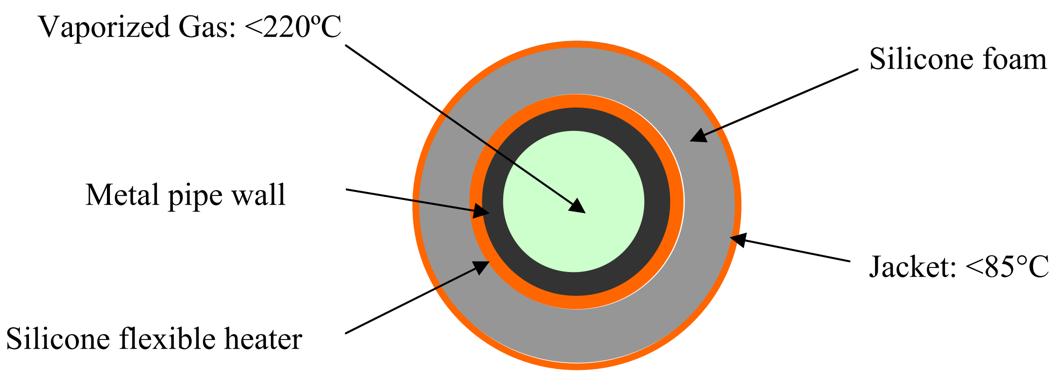

Figure 1 Heating assembly for gas pipe in the semiconductor industry

Silicone foam has been used as thermal insulation material for decades. However, applications have been limited because silicone foam can be too thick, expensive, and in many applications an unstable insulator. The semiconductor industry is pushing for higher processing temperatures (250 to 300°C). An all-new thermal insulation material is needed to replace silicone foam. Silicone foam is becoming obsolete.

This paper introduces Arlon's new silicone-based thermal insulation material that can replace silicone foam for current applications up to 220°C and meet new industry requirements for temperatures up to 250°C and possibly beyond.

2. Heat Transfer Fundamentals [4]

Heat transfer can take place in one of three ways --- conduction, convection, and thermal radiation.

2.1 Conduction

Conduction is thermal energy being transferred within a single body or between two bodies in direct contact on an atomic-particle level, as shown in **Figure 2**. The heat flow rate is proportional to the temperature difference across an object and the area available for heat to flow through, but inversely proportional to the thickness of the object, as described in

Equation (1).

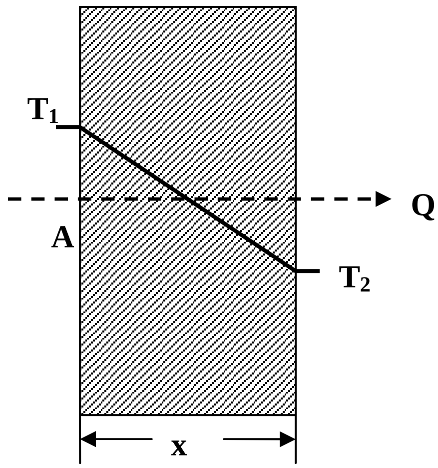

Figure 2 Schematic of thermal conduction

$$Q = kA\frac{T_1 - T_2}{x}$$ **Equation (1)**

Q is heat flow rate in Watts
k is thermal conductivity in W/(m-K)
A is the area in m^2
T_1 and T_2 are temperature in K
x is thickness in meters

R-value is commonly used in industry when choosing thermal insulation material during design. See **Equation (2)**.

R-value = x/k **Equation (2)**

R-value is in m^2-K/W

2.2 Convection

Convection involves transferring energy by physically transporting a mass of fluid or gas from one place to another. Two major types of convection can occur. Free convection takes place when a temperature difference causes pockets of fluid to be more buoyant, or less dense, than the surrounding fluid. Forced convection is the result of mechanical work such as when pumping a fluid.

2.3 Thermal Radiation

Thermal radiation is electromagnetic energy emitted from the surface of a thermally excited object. All bodies that have a temperature greater than absolute zero have internal energy. Some energy is released as thermal radiation from the surface of the body. The rate of energy emission per unit area of surface is called the emission power, which is proportional to the fourth power of the absolute surface temperature, as described in **Equation (3)**.

$$W = \sigma \varepsilon T^4 \qquad \textbf{Equation (3)}$$

ε is the emissivity of a surface, (a constant between 0 and 1)
σ is the Stefan-Boltzmann constant, $5.6\times10^{-8}\ W\cdot m^{-2}\cdot K^{-4}$

3. Semi-conductor Industry Thermal Insulation Requirements

Semi S2-93 is the most important guideline for the design of thermal insulation for heating assemblies used in the semi-conductor industry [5]. **Table 1** below shows surface temperature limits for different insulative materials based on human safety touch criteria. The flexible heater assembly, which is the focus of this technical paper, falls into the category of "slightly conductive (plastics)". Other important requirement for semiconductor heating assemblies, including thermal insulation, are the UL94V-0 flame resistance specification and the ability to be particle free for clean rooms.

Surface temperature limits		Material type		
		Highly conductive (metal)	Moderately conductive (glass)	Slightly conductive (plastics)
Operator accessible area	Hand-held	50°C	55°C	65°C
	Will touch	55°C	65°C	75°C
	May touch	70°C	75°C	90°C
Service area	Will touch	55°C	65°C	75°C
	No need to touch	80°C	100°C	120°C

Table 1 Surface temperature limits in Semi S2-93 [5]

4. Arlon Thermal Insulation Characteristics

4.1 Thermal Conductivity

The thermal conductivity of different thermal insulation materials was determined by ASTM E1530. The instrument utilized is a Thermal Conductivity Analyzer (TCA, Holometrix Model TCA-300). The test results of thermal conductivity are shown in **Figure 3**. The "Silicone rubber base" data set is the baseline and consists of pure silicone rubber with ~25% fumed silica by weight. It has the highest thermal conductivity, 0.20W/(m-K) at 200°C. Seven types of silicone foams manufactured by various vendors were tested. The range of thermal conductivity for all silicone foam materials evaluated is between, 0.10-0.14W/(m-K), at 200°C test temperature. Thermal conductivity of silicone foam is about half the value of pure silicone rubber. Arlon's new thermal insulation material has a thermal conductivity of only 0.03W/(m-K) at 200°C, which is approximately seven times less than pure silicone rubber or approximately three to four times less than silicone foam.

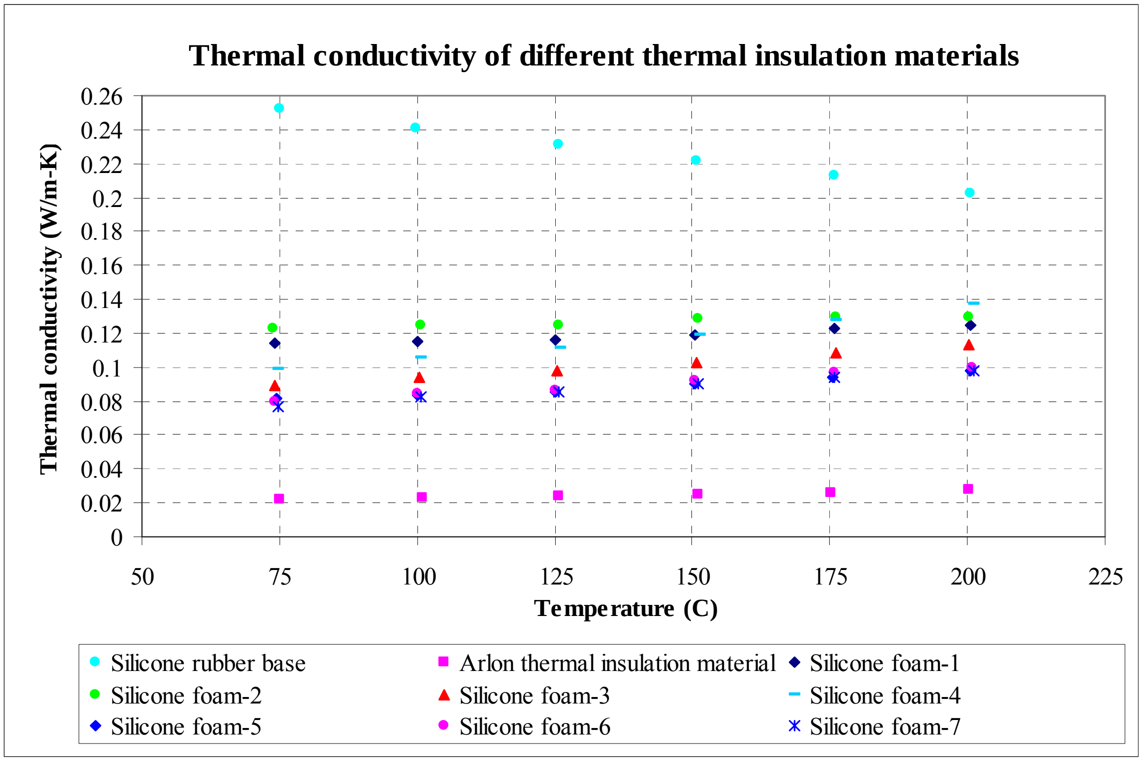

Figure 3 Thermal conductivity of different thermal insulation materials

Lower thermal conductivity indicates that a thinner thermal insulation product can be used in designs to meet the same surface temperature requirement for a given application. Heat loss is reduced so that less energy is transferred to a surface at the same comparative insulation thickness. See **Section 4.2 and 4.4.**

4.2 Surface Temperature and Thickness

Arlon designed and built a hot pipe test apparatus to test the outside surface temperature of thermal insulation materials. The temperature of the hot pipe can reach 300°C. The test specimens were designed as shown in **Figure 4**. This test simulates a typical heating application in the semi-conductor industry. In the experiment, the internal temperature in the vicinity of the hot pipe, T1, and the outer surface temperature of the insulation, T2, were tested. Ambient temperature was controlled at ~21°C and was allowed to flow freely around the test fixture and test specimen. The thickness of thermal insulation material was precisely determined between T1 and T2 so that insulation performance was accurately determined and compared.

Figure 5 compares the performance of Arlon thermal insulation materials versus an industry leading silicone foam, which has a thermal conductivity 0.1 W/m-K. Four steady state hot pipe temperatures, 180°C, 200°C, 220°C, and 250°C, at T1 were precisely controlled. Thermal insulation materials with different thicknesses were evaluated so that an extrapolated regression line predicts the thickness needed to meet any surface temperature requirement. The results show that if the surface temperature goal is T2 = 65°C for a pipe temperature of T1 = 250°C, then Arlon's thermal insulation material can achieve this with a thickness of 0.240” (6mm) compared to a thickness of 0.787” (20 mm) for silicone foam. Arlon’s thermal insulation material is able to reach the same surface temperature goal as silicone foam and yet is 70% thinner.

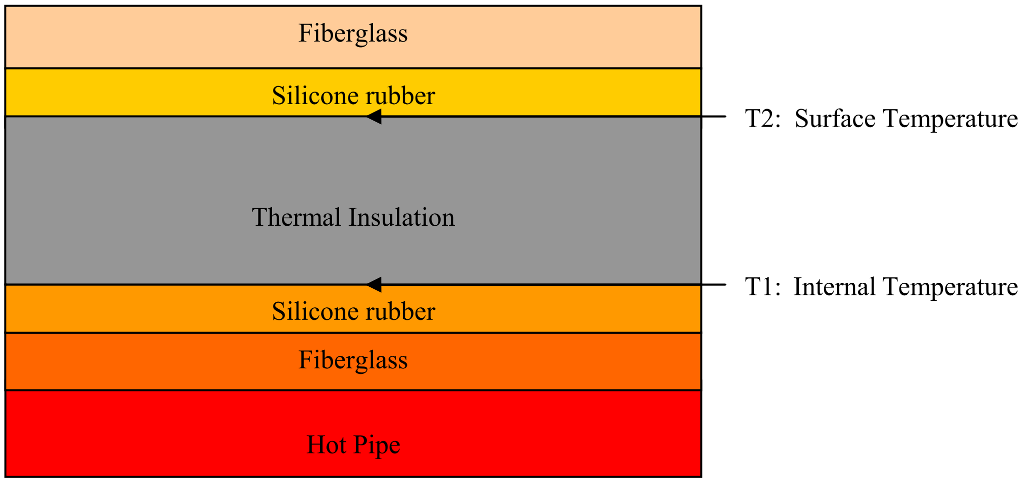

Figure 4 Specimen structure for the surface temperature test

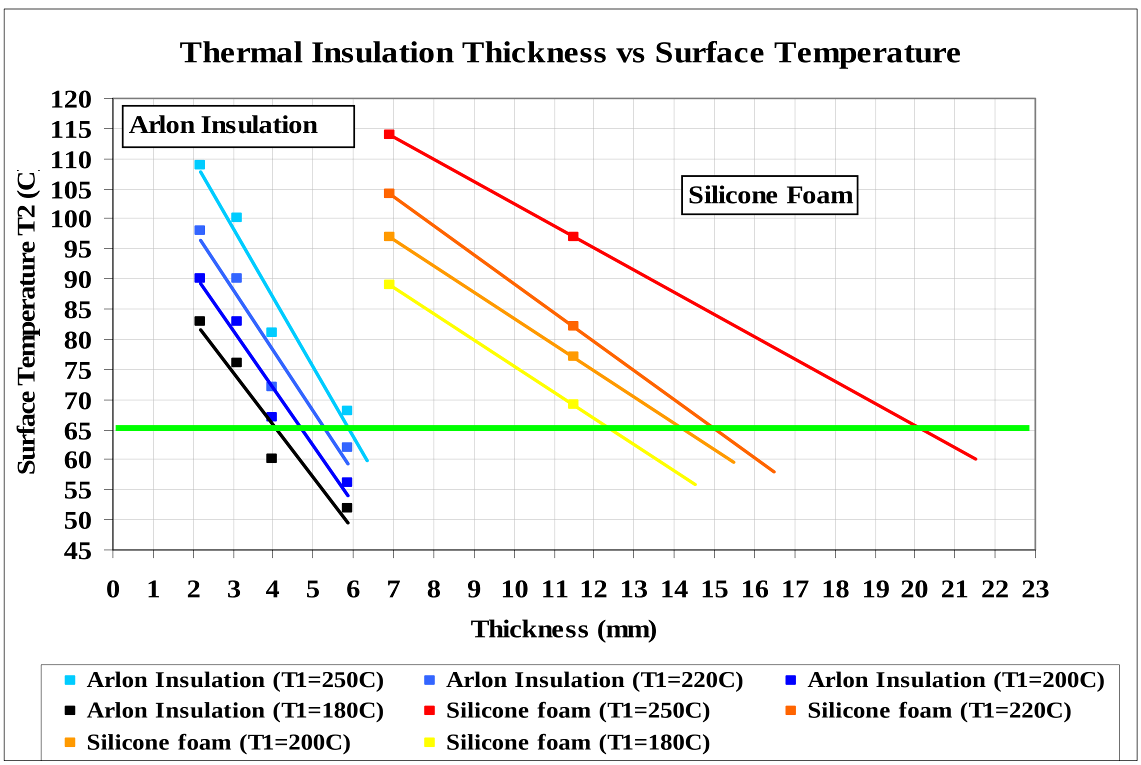

Figure 5 The effect of thickness on outside surface temperature for different thermal insulation materials

4.3 Thermal stability

Arlon 0.084” thick, thermal insulation material was evaluated in a highly accelerated thermo-oxidative stability study at 300ºC, 275ºC, and 250ºC in forced convection ovens. After a certain aging period, the specimens were tested in for thermal conductivity and T2 using the hot pipe method described in **Section 4.2**. The test results for thermal conductivity are shown in **Figure 6**. Arlon thermal insulation material has excellent thermal stability at high temperatures. Thermal conductivity does not change after 300ºC*14days, 275ºC*28days, and 250ºC*56days. Surface temperature test results, T2, when T1 equals 250ºC hot are shown in **Table 2**.

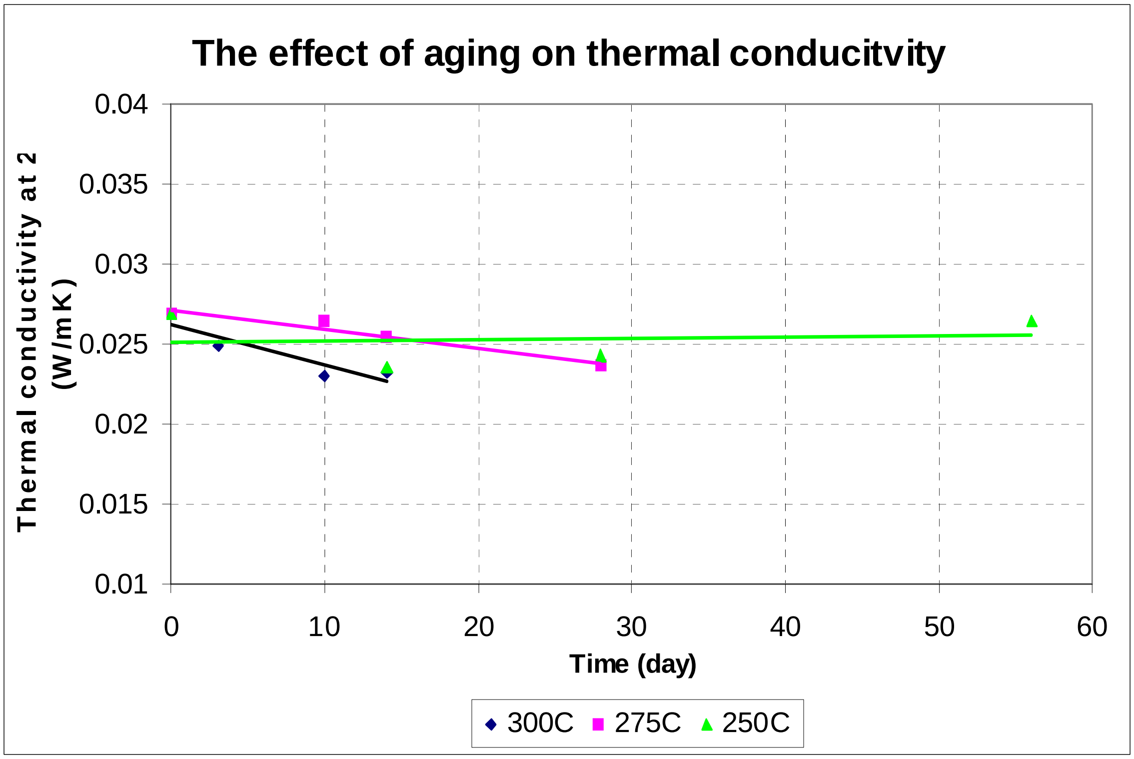

Figure 6 Thermal conductivity at 200ºC after highly accelerated thermal aging

		Surface temperature T2 (ºC) when T1 = 250°C					
Aging time (day)		0	3	10	14	28	56
Aging temperature	300ºC	125	99	116	102	/	/
	275ºC	125	/	108	114	102	/
	250ºC	125	/	/	107	105	127

Table 2 Surface temperature, T2, when hot pipe temperature, T1 = 250ºC.
(0.084" thick Arlon thermal insulation material after highly accelerated thermal aging)

4.4 Heat Loss and Energy Consumption

No known thermal insulation material can effectively insulate hot pipes adiabatically. When the surface temperature of a hot pipe is higher than ambient temperature, there is always heat loss. Silicone flexible heaters compensate for this heat loss. The cost of electricity can be a factor when deciding to insulate a silicone flexible heater. If the choice of thermal insulation material is thinner, at the same surface temperature, T2, and hot pipe temperature, T1, a silicone flexible heaters will consume less electricity to maintain pipe temperature and subsequently internal gas temperature. An example is calculated as follows:

Arlon thermal insulation material (three layers of 0.084" thick insulation) that is 0.252" (~6 mm) thick and silicone foam that is 0.79" (20 mm) thick are used on the same two inch diameter pipe (diameter = 2" (~51mm)). From **Figure 5**, they both have the same outside surface temperature, T2 = 65°C, when the hot pipe temperature is T1 = 250°C. The diameter of the hot pipe with Arlon thermal insulation is 2.50", and 3.58" with silicone foam. The ambient temperature (T3), outer surface temperature (T2), and the insulation convective surface properties are the same in both cases so heat transfer rate per unit area is the same.

$$\frac{Q_1}{A_1} = \frac{Q_2}{A_2}$$

Equation (4)

Q is the heat flow rate in Watts
A is the surface area in meters squared and the calculation is shown in **Figure 7**
"1" is for the design with Arlon thermal insulation
"2" is for the design with silicone foam

$$\frac{Q_1}{\pi * 2.50 * L} = \frac{Q_2}{\pi * 3.58 * L}$$

$$Q_1 = 0.70Q_2$$

So silicone flexible heaters insulated with Arlon's new thermal insulation for pipe heating applications will consume ~30% less electricity than those with silicone foam. Air conditioning cost for a room with multiple flexible heater installations on piping is also reduced when Arlon's new material is used to insulate flexible silicone heaters.

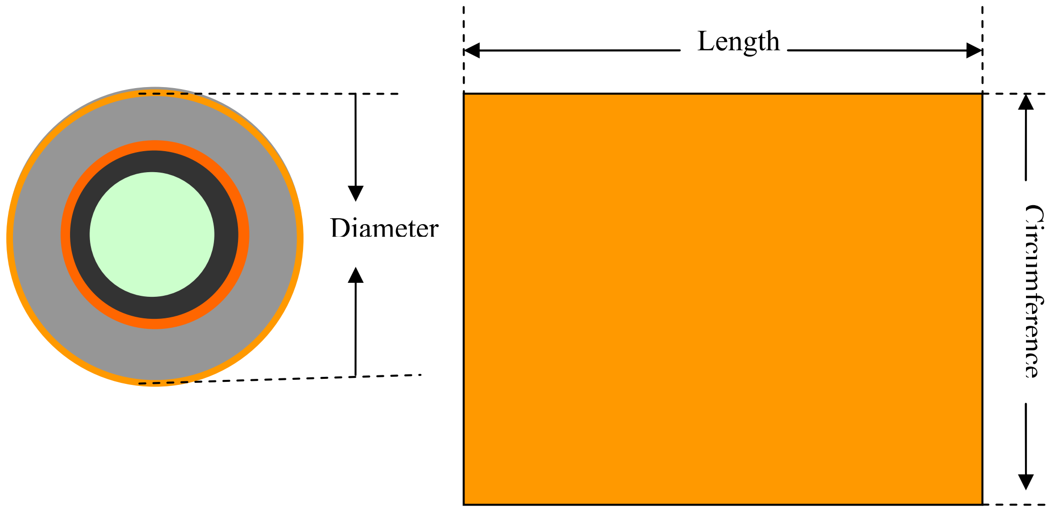

Figure 7 Surface area calculation

5. Processing Methods for Arlon Thermal Insulation Material

The standard thickness of Arlon thermal insulation material is 0.084". **Figure 5** compares the surface temperature test results of Arlon products with that of silicone foam. A 0.084" (~2 mm) thick Arlon product can produce the same thermal gradient as ~0.250" (6.4 mm) thick silicone foam. Two layers of 0.084" (~2 mm) thick Arlon insulation can perform as well as ~0.500" (12.7 mm) thick silicone foam. When the application calls for higher temperatures or narrower temperature gradients, additional layers of the Arlon insulation can be applied to achieve the desired surface temperature.

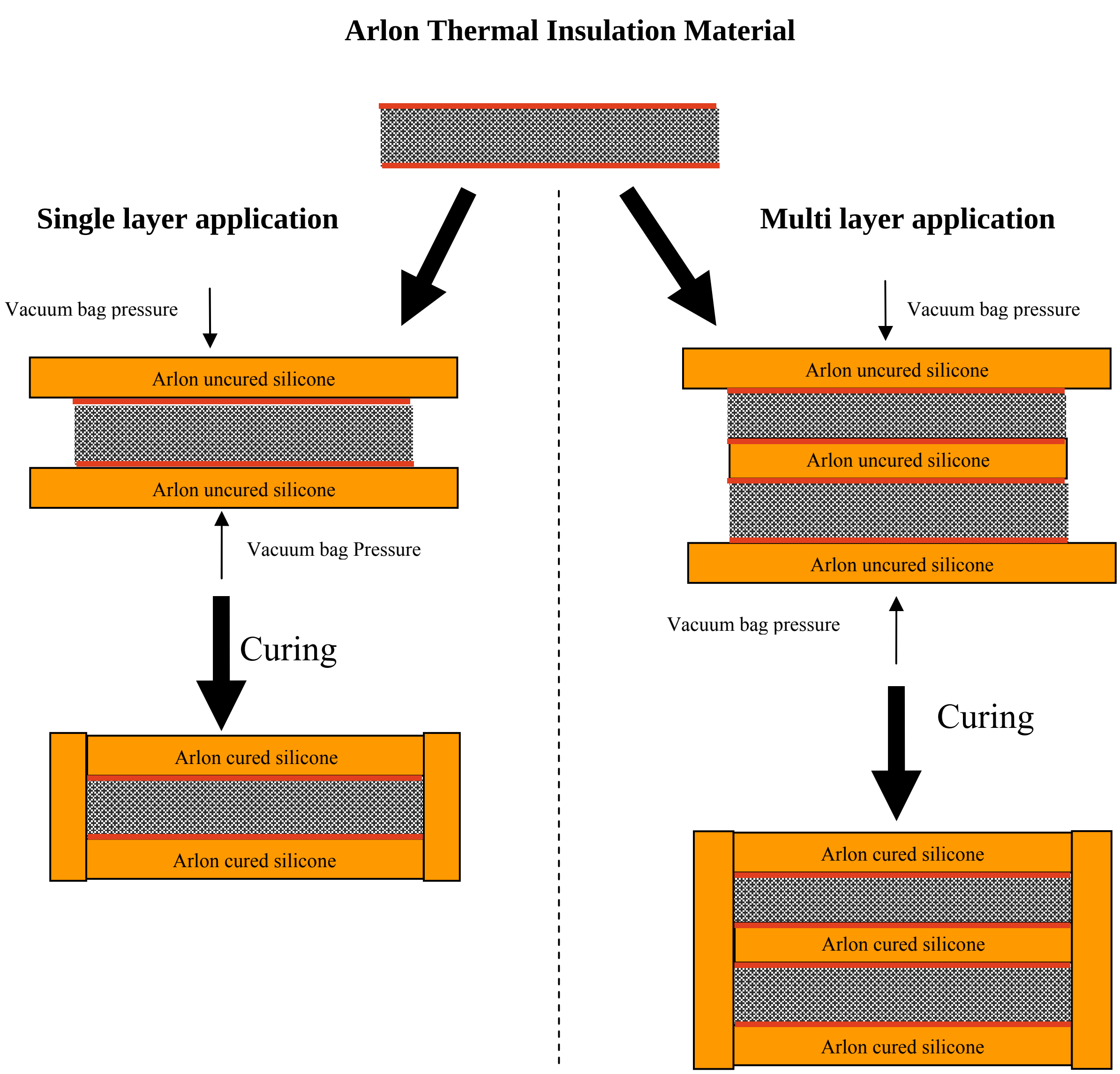

Figure 8 Vacuum bag curing to seal the edges for particle free applications

Figure 8 depicts Arlon thermal insulation material processed for particle free applications utilizing a vacuum bag curing method, but platen press processing is another option. The final product is an Arlon thermal insulation material covered on both sides with layer of fully cured, unsupported silicone. In the process, the uncured, unsupported, silicone sheet stock is cut just larger than the insulation material. The two pieces of oversized, uncured, unsupported, silicone rubber are used to sandwich the entire piece of thermal insulation. The silicone sheets are laminated and cured to the insulation and the edges are sealed during the vacuum bag process. Edge excess can be trimmed as needed from the fully cured product. The process can occur as a stand alone process or integral to the manufacture of a insulated silicone flexible heater, as shown in **Figure 9**.

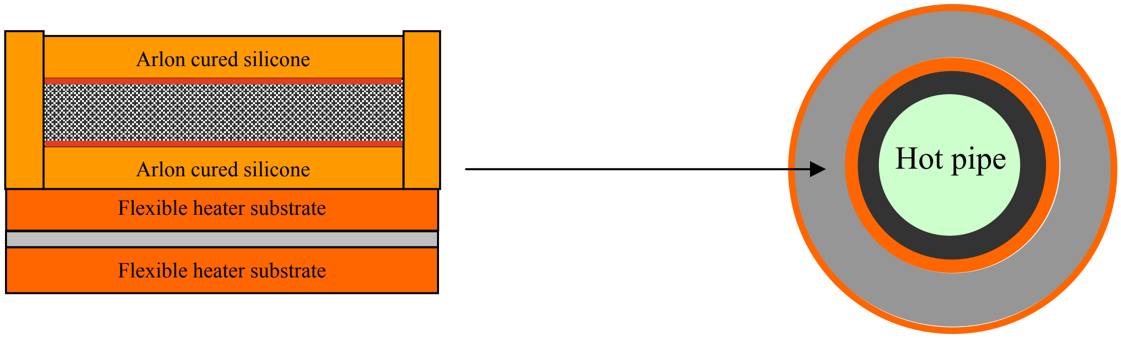

Figure 9 Arlon Flexible Heater Substrates Insulate with Arlon Insulation

6. Summary

There is a need in the semi-conductor industry for a thinner insulation product that can be used at higher temperatures. Arlon thermal insulation material is 70% thinner than silicone foam while offering the same temperature gradient yet has better thermal stability at higher temperatures. A calculation shows a 30% reduction in energy consumption when using Arlon thermal insulation in a pipe heating application compared to using a leading silicone foam.

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7.0 References

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