MATERIALS REQUIREMENTS FOR OPTOELECTRONIC PACKAGING

-- FIBER SOLDERING

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Abstract – Fiber metallization is the first step to realize the hermeticity in optoelectronic package. The thickness of Au plating is dependent on the solder applied. The raw material of housing could be chosen from Kovar, Invar with lower C.T.E. The Ni/Au coating should also be plated to achieve the hermeticity. The solder 63Sn37Pb dissolves the Au substantially and will form brittle$AuSn_4$, which contributes to joint weakening and eventually cause the lose of hermeticity. However, Au dissolution in Au-rich solder 80Au20Sn is almost negligible. And the brittle $AuSn_4$ is not formed, the experiment shows the solder joint with 80Au20Sn can endure 1250 thermal cycles without losing of hermeticity. Meanwhile, in optoelectronic package, the fiber misalignment is another critical issue because of the optical coupling efficiency. The ferrule material could be chosen from Invar or Kovar, again the gold-plating is needed. The creep deformation and stress induced from C.T.E. mismatch contribute the fiber shift. Both fiber-solder-ferrule with solders of 63Sn37Pb or 80Au20Sn are found fiber shift after temperature cycling. However, the joint with solder 80Au20Sn exhibits shifts two times less than with 63Sn37Pb solder. And in the soldering process, the fiber needs to be soldered near to the center of the ferrule tube to reduce the initial fiber eccentric offset, and hence, to minimize the undesired thermally induced fiber shift.

1) INTRODUCTION

Optoelectronic devices used for telecommunications or military application are usually required operation for 20-25 years in field with potentially humid, corrosive, and mechanically turbulent environments. Long-term reliability in such hostile operating conditions requires hermetic sealing of the optoelectronic devices inside a metal hybrid housing. In a typical configuration, the optical signals are transferred to and from the housing by an optical fiber. The fiber is solder sealed inside a nose tube which is brazed to the sidewall of the package. The fiber here is referred to as “fiber pigtail” and the type of hybrid optoelectronic package is usually referred to as a “fiber pigtailed” hybrid package.

In this type of optoelectronic package, the optical fiber is held in proper alignment to achieve good coupling efficiency by a joint (by soldering or laser welding). After this operation, the feedthrough joint where the fiber enters the package is sealed hermetically.

Basically, there are two sealing methods to realize hermetic package: the one is solder glass, the other is metal solder alloys. The solder glass can produce good hermeticity if the bond is ideal. However, glass seal package requires ideal surface conditions, uniform surface flow in the process. Those conditions are difficult to meet in “fiber pigtailed” packaging. What’s more, solder glass has the disadvantage of poor mechanical shock and impact properties, and has relatively low resistance to attack by many chemicals. Another technical difficulty is that the solder glass liquidus temperature is too high (>350°C) to implement because the package usually contains other optical parts, such as die attach, optical components, which are soldered below 350°C. The solder joints inside the package will melt when the solder glass is reflowed at the seal nose tube. Due to these difficulty, the solder glass seal technique is not suitable in “fiber pigtailed” packaging.

On the other hand, the metal solder sealing technique is proved good hermeticity and long-term reliability and used commonly in industry. There are a lot of advantage compared with solder glass method: (1) lower melting temperature (<300 °C), which will not melt solder joint inside the package; (2) good resistance to chemicals; (3) good mechanical shock and impact properties. However, we need carefully select the solder and feedthrough materials to overcome some other problem, like CTE mismatch induced stress, Au dissolution issue.

Before the solder sealing process, the fiber end inside the optoelectronic package should be aligned with laser or other optical parts to achieve low coupling loss, then bonded (by laser welding or soldering) to the substrate. Before alignment, the fiber end is usually sealed into ferrule by soldering. The fiber-solder-ferrule (FSF) assembly is critical in optoelectronic package, because any micrometer level misalignment will drop the coupling efficiency significantly. The fiber alignment shift of FSF joint will be discussed, too.

2) OPTICAL FIBER METALLIZATION

As we known, the optical fiber, which is SiO_2 , can't be directly soldered with metal housing. Although recently the scientists in Agere systems demonstrated the if the 2-2.5wt.% rare elements (such as Lu, Er, or Ge) were doped into Au-20 wt.% Sn, the new solder can be solderable to most optical materials (GaAs, SiO2, Si) [1]. Those solder are still in the research stage, not commercially available. So optical fiber metallization is usually required for the purpose of wetting and solderability. Some important requirement for the optical fiber metallization are:

1. metal to silica adhesion;
2. metal solderability / wetting;
3. fiber strength is not degraded much;
4. fiber fatigue.

It's difficult that all the requirement can be met by a single metal coating process. In industry, most commonly used materials for metallization is Au and Ni. One study finds that the metals with oxygen affinity achieve good adhesion to silica fiber, so the nickel is usually used as first layer coated outside the silica fiber[2]. The gold plating is coated outside the nickel plating. The advantage of gold coating is obvious:

1. gold has minimal surface oxide, then it can allow for the use of a fluxless soldering technique, which is a must for seal application;
2. good corrosion resistance;
3. good solderability;
4. good protection from environmental moisture;
5. good fiber strength.

The metallization sequence relative to the glass optical fiber is nickel followed by gold as illustrated schematically in Figure 1 and a typical metallized fiber layout in Figure 2. The thickness of coated metals depends on what kind of solder is used. Detailed analysis will be done in following section. But usually, the thickness of 1~7um nickel and 0.1~1um is often seen from industry vendors

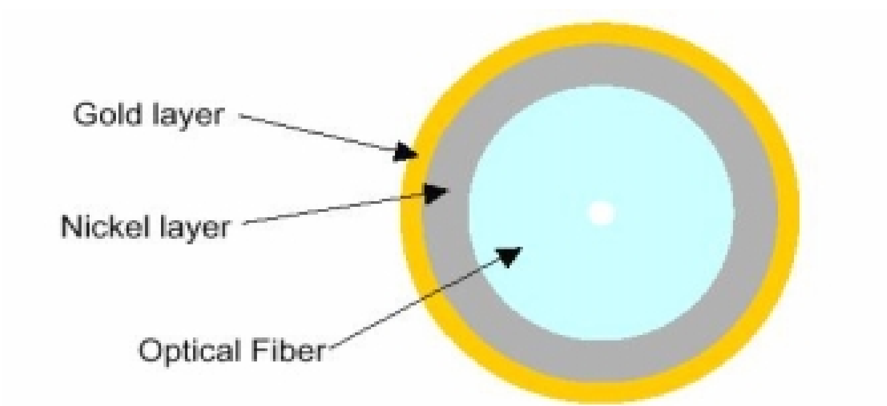

Figure 1. Cross section of a metallized fiber showing the metallization sequence relative to the glass optical fiber. Drawing not to scale.

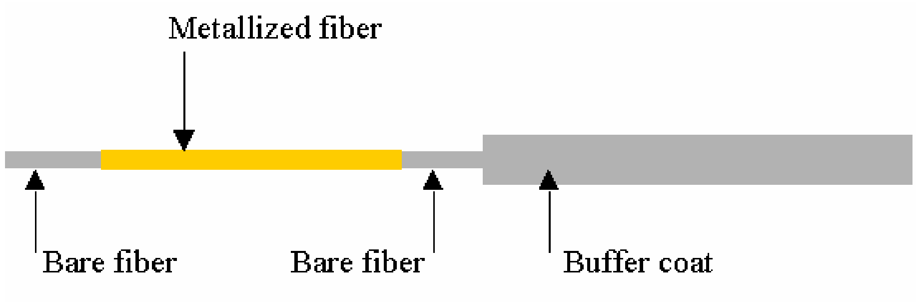

Figure 2. Side view of a metallized fiber illustrating the typical physical layout.

3) SOLDER SELECTION FOR FIBER JOINT

Different solders show different mechanical and thermal properties, and of course, different joint metallurgy, which will influence significantly the performance and reliability of soldering joint. So it becomes extremely important to select a suitable solder for a specified application.

In the case of soldering to gold coated surfaces, About 13% Au will dissolve into the molten **63Sn37Pb** at 50K above the liquidus temperature.[3] $AuSn_4$ crystals will be formed within the solder if Au content of the solder joint exceeds ~5 wt.%,. The AuSn4 phase embrittles the solder joint, thus often resulting in a mechanical failure. This is particularly serious in cases of thermal cycling. The use of extremely thin Au film (<1um) has been studied to reduce the Au available to the SnPb solder joint. However, the so thin plating is easy to be very porous, which will shorten shelf life of coated substrate and barely meet the requirement for good solderability.

Sn-Ag eutectic alloy is sometimes considered for solder processes on gold films. Au has a larger solubility of up to 30% into **Sn-3.5Ag** at 50 K above the liquidus temperature (versus ~ 13 % for eutectic Sn-Pb)[3]. Therefore, the $AuSn_4$ intermetallic becomes the primary phase until the Au content exceeds 10% in Sn-3.5Ag eutectic (versus ~5% for Sn-Pb eutectic). As mentioned before, 5 wt. % Au in Sn-Pb solder will deteriorate seriously mechanical properties of solder joint; the Sn-3.5Ag, on the other hand, can keep good mechanical properties if the Au concentration in solder is less that 8 wt. %. [3]

The normal way to avoid scavenging the metal from the surface is by loading the solder with this material, thus shifting the tendency from a strong rate of solution to a slow rate of solution[4]. To apply this principle to our case, Au rich solder, such as **80Au20Sn** is a good candidate to solder on the gold surface. The most important advantage is that the gold dissolution into molten 80Au20Sn is almost negligible. So the embrittling intermetallics are not expected to form, which enables a more durable hermetic feedthrough joint, compared with 63Sn37Pb and Sn-3.5Ag solder. More details will be discussed in following section about thermal cycles influence to solder joint. Some of the data of related materials are listed in the table 1.

SnPb solder has lower elastic modulus (~ 35GPa, versus 137GPa of AuSn solder). For a given strain (external added or induced because of CTE mismatch), the stress induced in the solder joint will be lower, based on Hooke's law. So for some stress sensitive package, such as polarization maintaining fiber pigtailed package, we should choose "soft" solder SnPb as first trial. How to choose a suitable solder is dependent on the materials contained in specified package.

Table 1 material parameter [3,5,6]

Parameters	63Sn37Pb	Sn-3.5Ag	80Au20Sn	Ni	Au	Invar	Kovar	Silica
Melting temperature (ºC)	183	221	280			1445		1750
Elastic (Young) modulus (GPa)	39, 30.5		137.2	214			137.9	73
Yield strength (MPa)								
UTS (MPa)	19 @20C, 4 @100C				108			
Poisson Ratio				0.3			0.32	0.17
Shear modulus (GPa)		18.8						31
Shear strength (MPa)	34 @20C, 21 @100C	27 @25C						
C.T.E. (ppm/K)	21	22	15.93	13	14	1~2	5.86	0.56
Thermal conductivity (W/mK)		36.2 @ 23C				16.4	17	1.38

4) HOUSING MATERIAL REQUIREMENT

Figure 3 illustrates schematically the side view of typical feedthrough with soldered optical fiber. FEM simulation prediction shows that the feedthrough (housing) and its coefficient of thermal expansion or contraction (C.T.E.) contribute much to the stresses both in the fiber and in the solder [7]. Low expansion materials (Invar, C.T.E. = 1.4 ppm/°C) result in elevated tensile radial and tangential stresses in the glass and in the solder (both on its inner and outer boundaries) because of the big mismatch of C.T.E.. So Invar is not suitable for the housing. On the other hand, high expansion materials, such as aluminum (CTE = 25ppm/°C), result in high compressive stresses and therefore should also be avoided. However, materials of moderate expansion, such as Kovar (C.T.E. = 5.86 ppm/°C), lead to moderate relatively low stresses in both the fiber and solder, if gold-tin or silver-tin solder is used. In industry, most popular material used in optoelectronic packaging is Kovar because of the lower stress induced to fiber in soldering process. Of course, the housing is nickel-gold plated. The thickness of Ni is usually 1 – 4 µm, Au is 0.5 – 2 µm, depends on different requirement.

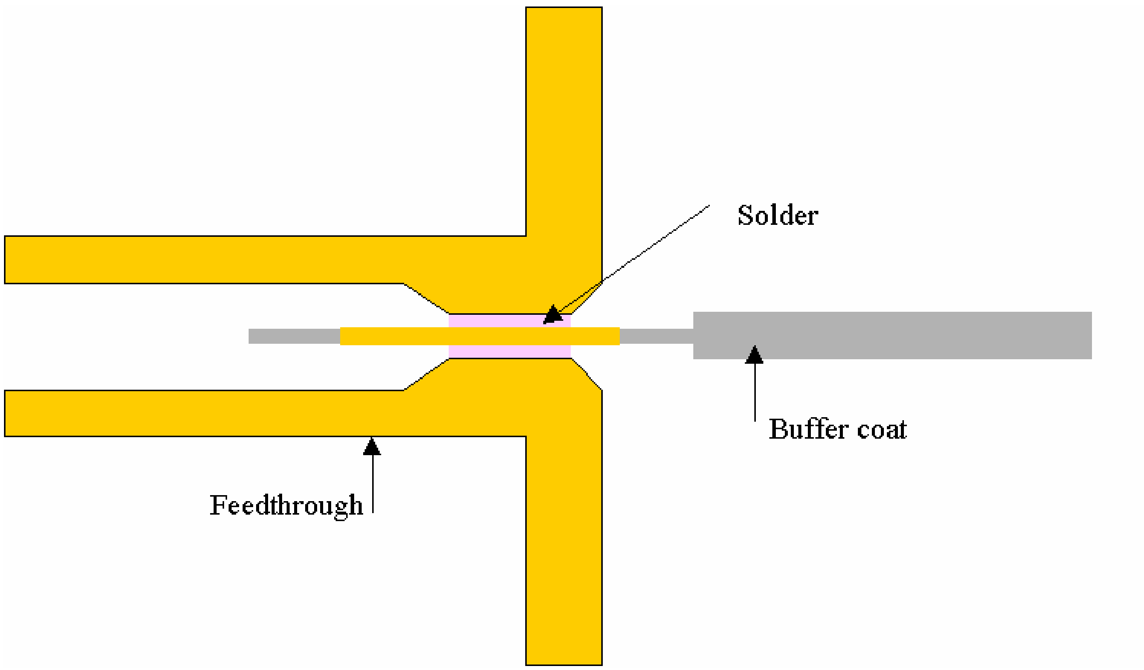

Figure 3. Side view of feedthrough with soldered fiber

5) THERMAL CYCLING INFLUENCE ON HERMETICTY

Lead solder 63Sn37Pb is widely used in industry in past decades. The melting point is 183ºC. As mentioned before, the Au will dissolve into 63Sn37Pb solder substantially. The new phase $AuSn_4$ will embrittle the solder joint, which is extremely serious if the samples go through the thermal cycles. The figures 4-7 show that the SEM images of samples after 230 thermal cycles [5]. Experiments showed the feedthroughs sealed with 63Sn37Pb begin to lose hermeticity between 130 to 230 cycles. EDX (energy dispersive x-ray) analysis indicates that the Sn-rich layer at the interface between the 63Sn37Pb solder and the Au-plated surfaces is primarily AuSn4, as showed in figure 6 and 7. A crack happens between the brittle AuSn4 layer and Kovar is complete. It is the crack that causes the feedthrough to lose the hermeticity. The reason of crack formation is that CTE is mismatched between solder and the nosetube and the presence of brittle $AuSn_4$ intermetallic layer.

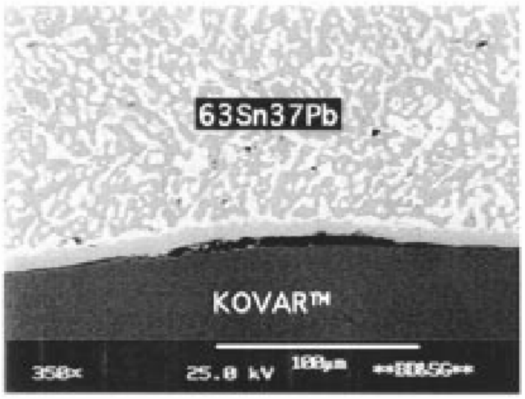

Figure 4 63Sn37Pb/Kovar interface after 230 thermal cycles (-40-125ºC), 350X

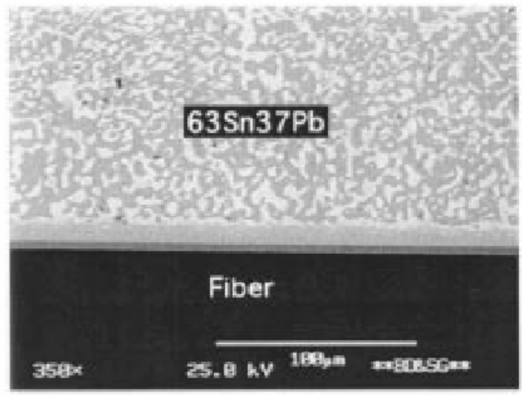

Figure 5 63Sn37Pb/fiber interface after 230 thermal cycles (-40-125ºC), 350X

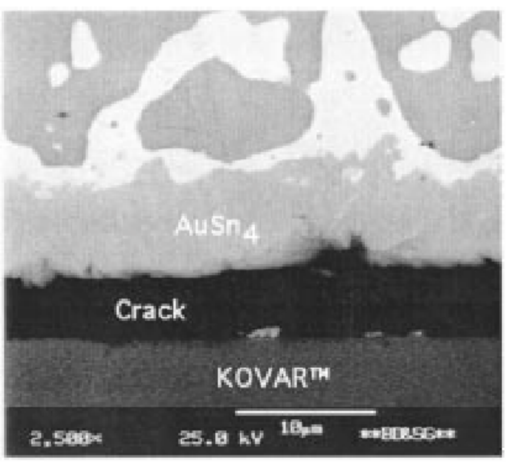

Figure 6 63Sn37Pb/Kovar interface after 230 thermal cycles (-40-125ºC), 2500X

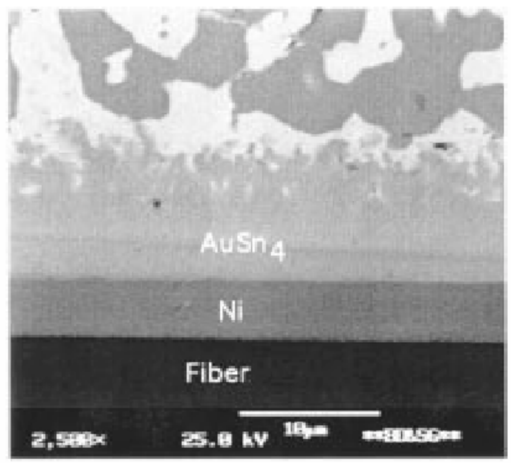

Figure 7 63Sn37Pb/fiber interface after 230 thermal cycles (-40-125ºC), 2500X

Lead-free Au-rich solder 80Au20Sn has higher melting point, 280ºC. As we mentioned before, the dissolution of Au in 80Au20Sn solder is negligible. The figures 8-11 show that the SEM images of samples after 1250 thermal cycles (-40-125ºC)[5]. The experiment demonstrates that the feedthrough solder with 80Au20Sn can keep the hermeticity and there is no crack found after 1250 thermal cycling. The absence of $AuSn_4$ intermetallic layer and closer CTE match with Kovar relative to make the 80Au20Sn more suitable in the aspect of hermeticity.

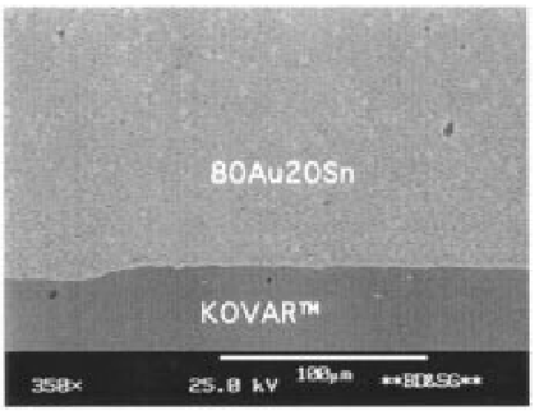

Figure 8 80Au20Sn/Kovar interface after 1250 thermal cycles (-40-125ºC), 350X

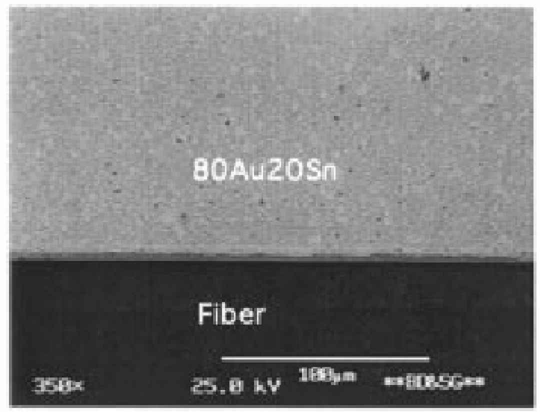

Figure 9 80Au20Sn /fiber interface after 1250 thermal cycles (-40-125ºC), 350X

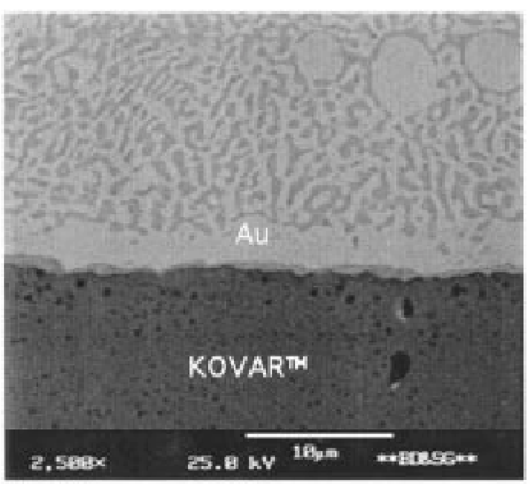

Figure 10 80Au20Sn/Kovar interface after 1250 thermal cycles (-40-125ºC), 2500X

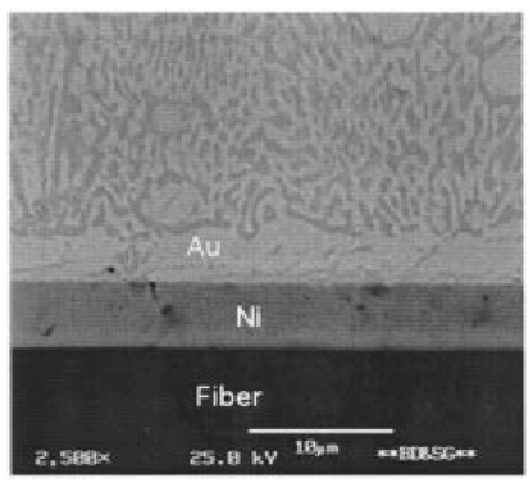

Figure 11 80Au20Sn/fiber interface after 1250 thermal cycles (-40-125ºC), 2500X

6) FIBER ALIGNMENT SHIFT IN FIBER-SOLDER-FERRULE ASSEMBLY

A typical laser module construction is shown in figure 12[8]. Actually, some optical MEMS packaging also require this type to realize precise alignment, then fix the fiber with so-called U-channel to keep the alignment. Basically, the low C.T.E. materials, like Kovar, Invar, are selected to build the ferrule.

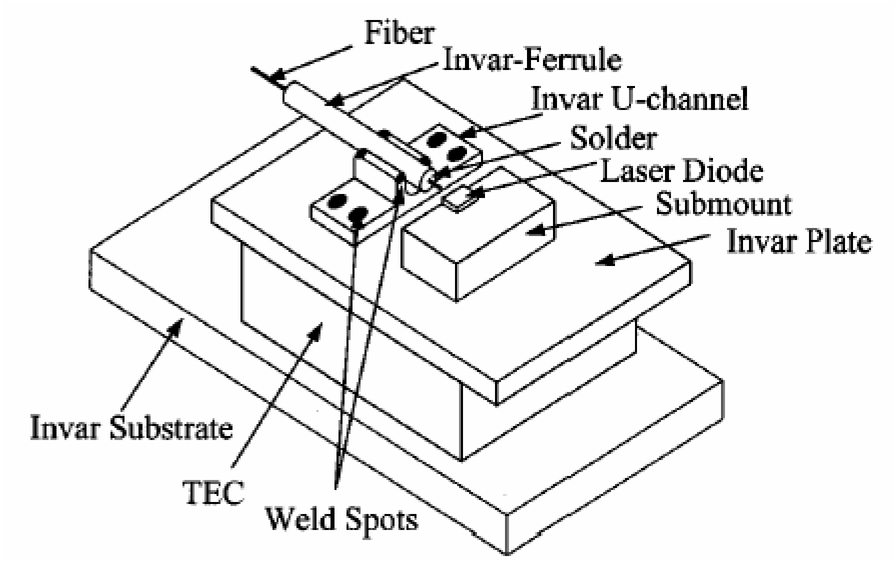

Figure 12 schematic diagram of a laser showing the fiber pigtail

The detailed fiber-solder-ferrule (FSF) assembly is shown in the figure 13. Obviously, the solder joint in an FSF assembly should be able to withstand the stress under the condition of thermal cycling and field operation. Similarly, we will discuss two solders: 63Sn37Pb and 80Au20Sn in this application. During the process of inserting the fiber to ferrule and soldering, the fiber is difficult to locate at the exactly geometrical center of the ferrule tube. The figure 14 specified the offset of an FSF assembly, which is the eccentricity between the center of the fiber and the ferrule.

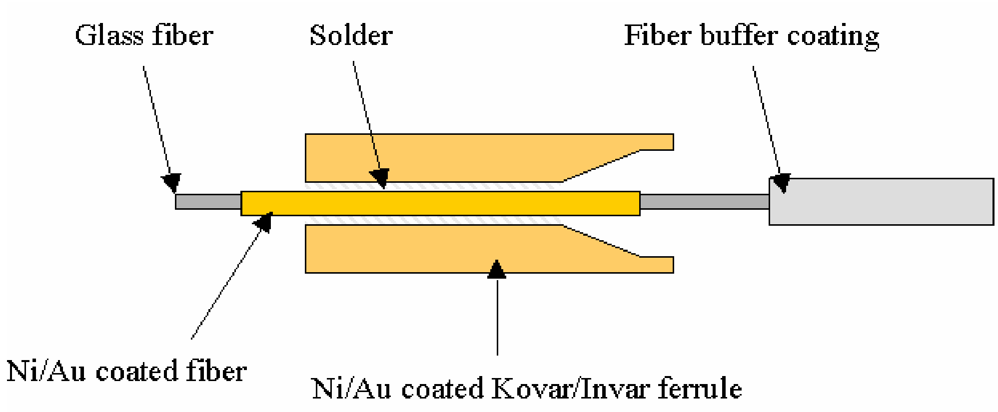

Figure 13 a fiber-solder-ferrule assembly

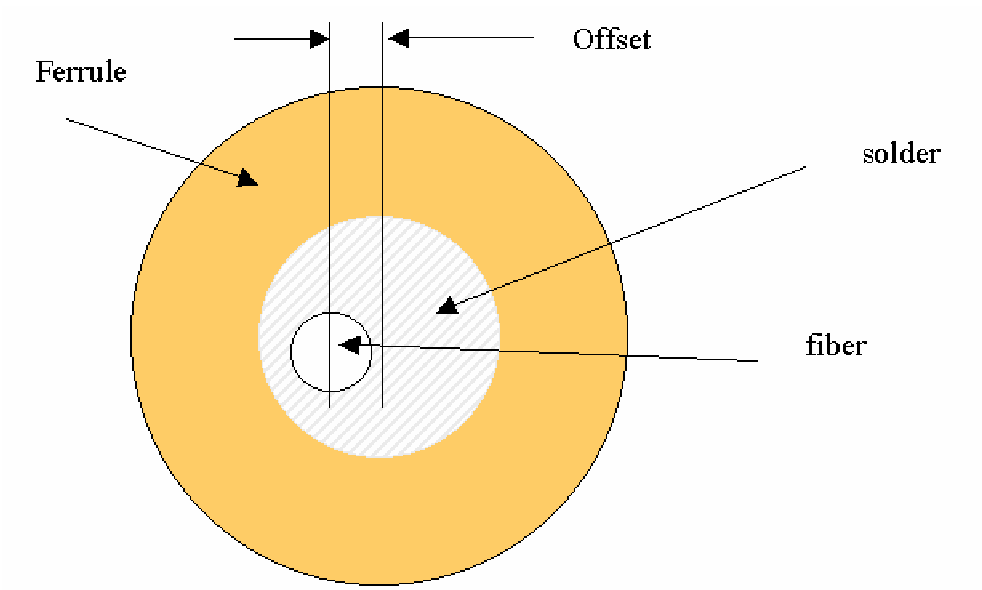

Figure 14 offset definition

The fiber shift with different offsets inside the ferrules were measured under different thermal cycles. Combined with the FEM simulation results are shown in the figure 15 and figure 16[8].

As widely known that the creep deformation becomes critical when the temperature exceeds half the absolute melting temperature of the soldering materials. As far 63Sn37Pb, at the room temperature 300K, the ratio is 300/456 = 0.66 > 0.5, so we can expect that the creep deformation is serious in the thermal cycling. However, the solder of 80Au20Sn, the ratio is 300/(280+273) = 0.54 > 0.5. So we can expect that the creep deformation of Au-Sn solder will much better than Sn-Pb solder. The creep deformation will help release the stresses at the stress concentration points. This stress relaxation in 63Sn37Pb plays more important role than 80Au20Sn solder because 63Sn37Pb has bigger creep deformation.

If we apply a nonlinear FEM of the coupled thermal-elasticity-plasticity model, and considering the creep deformation as mentioned before, we could get the fiber displacement shifts as shown in figure 15, 16 for 63Sn37Pb, and 80Au20Sn solder respectively. It's clear that the shift of fiber of 80Au20Sn based FSF can keep under 0.5um if the offset is below 50um, however, for the same level offset of 63Sn37Pb, the shift could reach more than 1um. So in order to keep good alignment, the 80Au20Sn solder is more suitable for this application.

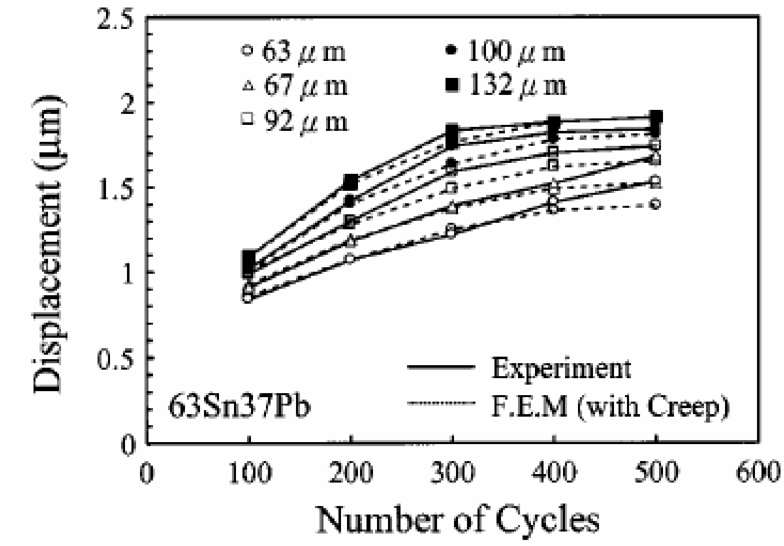

Figure 15 The fiber displacement shifts of FSF joint with SnPb solder as a function of the cycle number for different fiber eccentric offsets

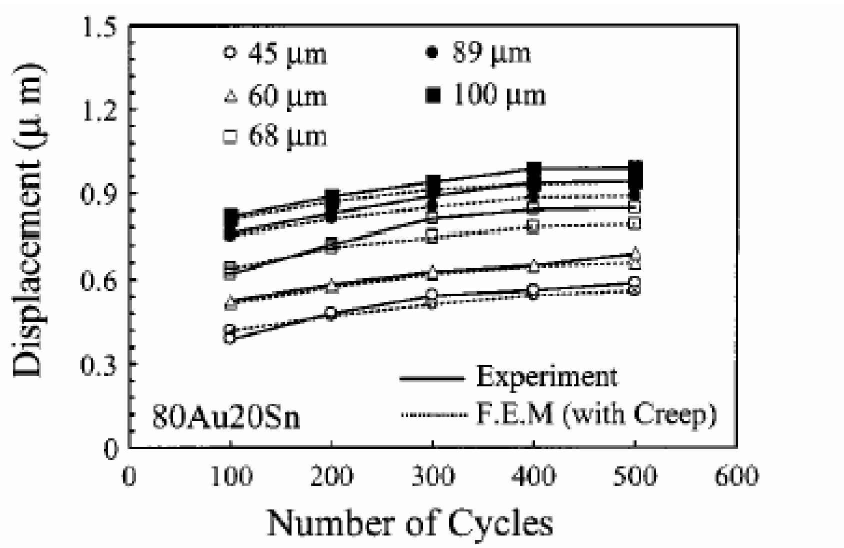

Figure 16 The fiber displacement shifts of FSF joint with AuSn solder as a function of the cycle number for different fiber eccentric offsets

7) CONCLUSION

In conclusion, hermeticity package in optoelectronic industry is one important topic. Some of critical processes are fiber metallization, fiber soldering, and fiber-solder-ferrule assembly. For the fiber metallization, the thickness of gold can't be too thin (<1um) because of porosity and short shelf life. The material requirement of fiber metallization, housing, and solder were discussed from the view of metallurgy. During the fiber seal process, the Au dissolution into solder and form intermetallic $AuSn_4$ will embrittle the solder joint and result in losing hermeticity. The 80Au20Sn has little dissolution of Au and better CTE match with Kovar, which can keep good hermeticity during the thermal cycling. So the 80Au20Sn is good candidate for the hermeticity application in optoelectronic packaging. On the other hand, the fiber shift is another important issue in optoelectronic package because it will reduce the optical coupling efficiency. Different solders show different creep deformation and cause different fiber shift. Again solder 80Au20Sn has smaller fiber shift than 63Sn37Pn solder. However, some special application, such as stress sensitive, we have to choose "soft" solder to decrease stress.

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