

Clad Solder for Semiconductor Devices

The favorable soldering characteristics of tin-rich solders are combined with the strength and heat resistance provided to joints by lead-rich solders

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Semiconductor devices such as diodes or transistors consist essentially of a silicone disc, which performs the electronic functions, and appropriate lead wires, which connect the silicone disc to the electronic circuit. The enormous use of such devices naturally resulted in a plethora of designs, which vary not only according to their application, power specification, etc., but also among the individual manufacturers. However, one common feature is the need to provide strong and reliable joints between the lead wires and the silicone discs. In a great number of semiconductor devices, soldering is employed for this purpose.

Figure 1 shows the cross section through the main part of a typical power diode and serves to illustrate the basic features of such devices. In this special case, the silicone disc is soldered with a Pb-5%Sn solder to a hook-shaped lead wire and to a copper base, which serves as a ground connection. It is easily visualized that the reliability of such semiconductor devices depends to a large degree on the quality and soundness of the soldered junction.

During the manufacture of semiconductor devices a large percentage of the rejects can be traced to faulty soldered joints. The main reason seems to be the poor wetting and flow characteristics of the lead-rich solders usually employed. This results in only partial bonding between the solder and the silicone disc or the lead wires. In some cases small voids can be detected microscopically at the soldered interfaces and serve as evidence for the deficiencies of the solder and the soldering process.

Because of these problems, an investigation was started on the

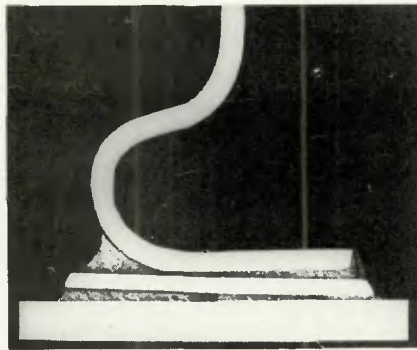


Fig. 1—Section through the main part of a diode assembly; a silicone disc is soldered to a lead wire and a copper base with a clad solder

soldering characteristics of a Pb-5%Sn solder. The results obtained led to the development of a clad solder, which shows improved wetting and flow while retaining the essential properties of the lead-rich solder. The present paper describes the basic ideas leading to this development as well as the main characteristics of the new clad solder.

Soldering of Semiconductor Devices

The soldering of semiconductor devices is a highly specialized process. Although the soldering practice may vary among the manufacturers, the

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following features are considered a common characteristic and distinguish it from conventional soldering of copper parts with soft solders:

1. Lead-rich solders such as Pb-5%Sn are used to ensure sufficient strength and heat resistance of the joint.

2. Due to the solder composition, the soldering temperature is comparatively high and may reach up to 400 C (752 F).

3. Soldering is carried out in a furnace under a reducing atmosphere such as hydrogen. Fluxes are not used.

4. As pure silicone does not alloy with the solder, the silicone disc has to be plated with a thin layer of metal such as nickel, silver, etc., in order to realize a metallurgical bond with the solder.

From these features the main requirements to be imposed on the solder can be deduced. First of all, the solder should sufficiently wet the metal plating on the silicone disc and the lead wires. In conventional soldering, wetting is ensured by the selection of an appropriate flux. Fluxless soldering used for semiconductor devices relies on the intrinsic wetting and flow properties of the solder.

A further requirement is that the metallurgical reaction between the solder and the metal plating on the silicone disc should not lead to a complete dissolution of the plating. As soldering temperatures are high and the thickness of the plating is in the order of some microns, special attention has to be paid to the diffusion rates of the plating metal into the molten solder and their control via solder composition and soldering times.

Finally, with respect to the application of semiconductor devices, a solder with comparatively high melting point is required in order to ensure sufficient heat resistance of the soldered junction during service.

Pb-5%Sn solders, because of their low tin content, satisfy the requirements of good heat resistance and low attack on the base metal. On the other hand, for the same reason wetting properties are poor. It is generally known that wetting of Pb-Sn alloy solders correlates with their melting points and is optimum for medium tin concentrations. This is also true for fluxless soldering in a hydrogen atmosphere.¹

Therefore, any improvement in the soldering characteristics of solders for semiconductor devices requires a combination of the wetting properties of low melting point tin-rich solders with the desirable properties of lead rich solders. As these requirements are mutually exclusive, little improvement can be expected from adjustments in the solder composition or the addition of third elements to the basic Pb-5%Sn solder.

However, it was considered that wetting and spreading of the solder occurs during the initial stages of soldering, while attack on the base metal is a function of the total time of exposure to the high soldering temperature. Furthermore, the heat resistance of the solder is of consequence only in the finished joint. Therefore, the present lead-rich solder can be decisively improved by:

- 1) Providing a tin-rich solder at the interface between the solder and the base metal in the initial stages of soldering when wetting occurs.
- 2) Removing this layer during the subsequent stages of soldering through diffusion of lead.

This concept of stepwise soldering

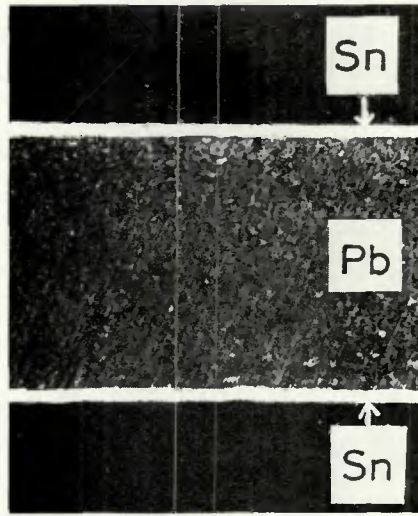


Fig. 2—Cross section of a clad solder sheet. $\times 400$

was realized through the development of clad solders.

The Clad Solder

Structure and Composition

Figure 2 shows the cross section through a clad solder sheet developed in this research. A core of pure lead is covered on both sides with a thin layer of tin metallurgically bonded to the core. The total thickness of the sheet is 0.1 mm (0.004 in.), and the thickness of the tin cladding (4μ) is selected in such a way that the total composition of the sheet material corresponds to Pb-5%Sn.

Such clad solders can be produced by roll bonding. Here a lead sheet is sandwiched between two tin sheets of predetermined thickness and passed through a roll. By applying a large one-pass reduction, the three sheets are effectively cold-welded to each other. The resulting composite material can then be rolled down to the desired

thickness; both the thickness ratio between core and cladding and the composition of the solder sheet remain constant.

The structure of the clad solder provides for a great flexibility to adapt the solder to various requirements by varying the thickness and composition of the clad layer. Especially in cases where attack of the solder on the base metal constitutes a serious problem, the use of thinner claddings or an alloy cladding reduces the time during which the base metal is exposed to tin-rich solder. However, a variation in the type of cladding results in a change of solder composition. In order to balance the overall tin content of the solder, tin has to be added to the core.

Figure 3 shows the relation between the tin content of the core and the clad thickness for clad layers of various tin concentrations. The data in Fig. 3 were calculated for a solder with the standard composition of Pb-5%Sn and a total thickness of 0.1 mm (0.004 in.). The tin content in the core rises nearly linearly with decreasing thickness of the clad layer. It is also seen that a maximum thickness exists for each composition of the cladding, which in the case of pure tin is 4μ . By using this diagram, suitable combinations of the core and the cladding can be selected to produce solders for specific soldering conditions without changing the composition and thus the properties of the soldered joint.

For certain applications the addition of third elements to the Pb-Sn solder may be required to improve the strength or creep resistance of the joint. Such elements can be added to the core. As the surface layer of the clad solder remains unchanged, the basic soldering characteristics are not influenced.

It is thus possible to design a great variety of clad solders for various

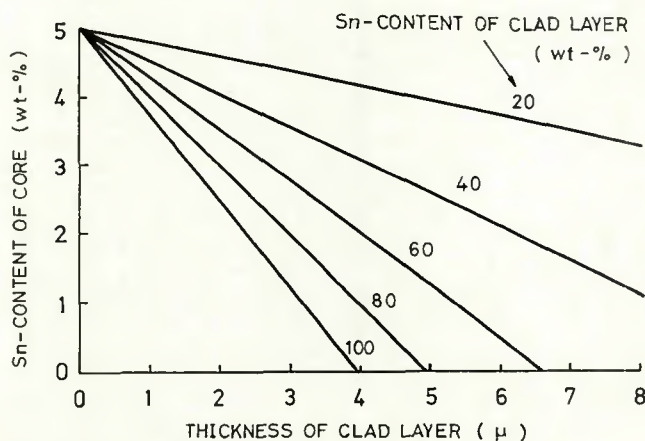


Fig. 3—The core composition of clad solders depends on the thickness and the tin content of the clad layer; curves refer to a clad solder with a total composition of Pb-5%Sn and 0.1 mm thickness

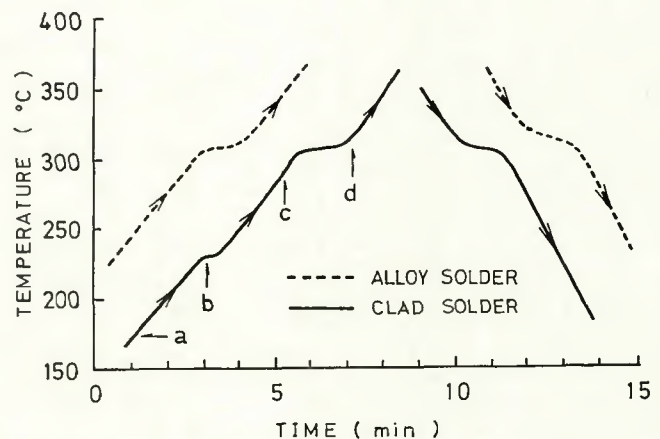


Fig. 4—Heating and cooling curves of clad and alloy solders. The clad solder has a 4μ tin cladding; both solders have a total composition of Pb-5%Sn

requirements. However, further evaluation of the properties of clad solders was done with sheets having a total thickness of 0.1 mm (0.004 in.) and a composition of Pb-5%Sn.

Melting Behavior

During soldering in a furnace, melting of the clad solder proceeds in the following sequence: Upon heating to the soldering temperature, the clad layer, having a lower melting point, melts first and immediately starts wetting the base metal. Subsequently, the molten layer reacts with the core and its thickness increases due to the mutual diffusion of tin and lead. Finally, as the temperature rises, the solder sheet fuses completely and attains a homogeneous composition because of the high diffusion rates in a liquid phase.

The solder layer at the interface thus passes through the whole composition range of the Pb-Sn phase diagram, including those compositions, which show good wetting behavior. At the same time, the increasing lead content at the interface reduces the reaction between the solder and the base metal to a minimum. Finally, as the solder reaches a homogeneous composition of Pb-5%Sn during the soldering process, the properties of the soldered joint are similar to those made with an alloy solder.

The above melting sequence was verified by thermal analysis and metallographic observations on a clad solder with a tin cladding of 4μ. Figure 4 compares the heating and cooling curves of the clad solder with that of a Pb-5%Sn alloy. Upon heating, two thermal arrests are observed for the clad solder. One corresponds to the melting point of tin, while the other is identical with the melting temperature of the alloy solder. This indicates that diffusion of tin into the lead core proceeds fast enough to cause equilibration of the concentration prior to complete melting of the solder. Melting of the clad solder is thus achieved without raising the temperature to the melting point of lead and the same soldering temperatures as for alloy solders can be employed.

On cooling, the clad solder shows only one thermal arrest at the solidification temperature of the alloy solder. This proves that complete homogenization of the clad solder did occur.

Figure 5 shows the microstructure of the clad solder samples quenched from various temperatures during heat up. At the temperature of the first thermal arrest, a broadening of the clad layer indicates that interaction between the core and the cladding already started. With increasing temperature, the progressive diffusion of

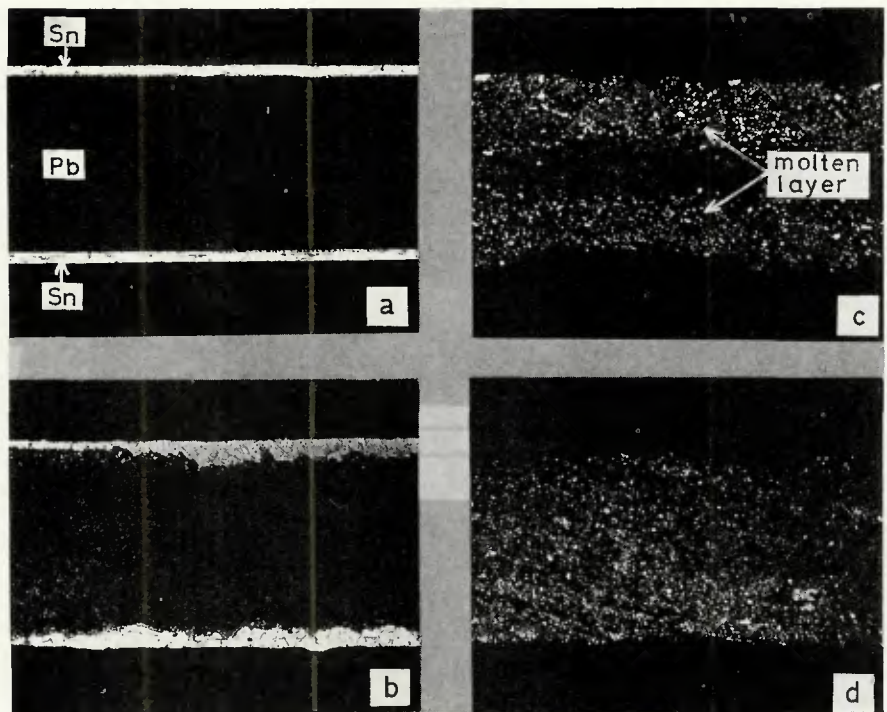


Fig. 5—Cross sections through clad solder samples quenched from various temperatures during heating; letters refer to the temperatures indicated in Fig. 4. ×400

tin into the core and the subsequent growth of the molten layer is recognized from the change in the microstructure. At 312 C (594 F) complete fusion of the solder has occurred.

Microprobe analysis at various locations of the cross section verified the even distribution of the tin.

Spreading Test

The wetting properties of the clad and the Pb-5%Sn alloy solders were

obtained from their spreading on various substrate metals. In these tests small solder discs having a thickness of 0.1 mm (0.004 in.) and a diameter of 3 mm (0.12 in.) were used. These discs were placed on the substrate and heated to 400 C (752 F) in a furnace under a hydrogen atmosphere. The spreading area was measured after a heating time of 5 minutes. Oxygen-free copper and pure nickel served as the main substrate materials. For supporting experiments, silicone discs

| SUBSTRATE | ALLOY SOLDER | CLAD SOLDER |
|-----------|--------------|-------------|
| COPPER | | |
| NICKEL | | |
| SILICONE | | |

Fig. 6—Spreading of alloy and clad solders on various substrates after heating for 5 min at 400 C in a H₂ atmosphere shows superior wetting properties of clad solder; clad solder has 4μ pure tin surface layer

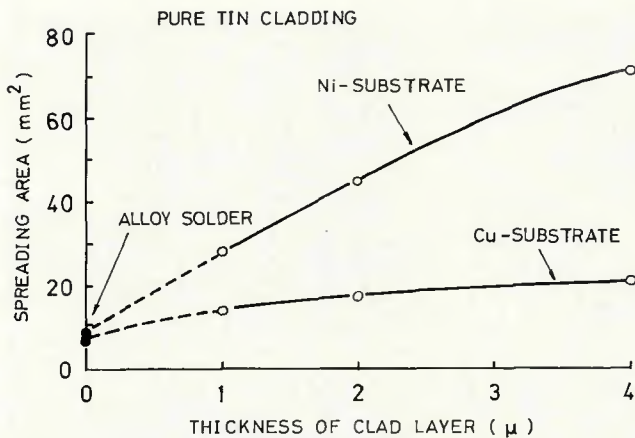


Fig. 7—Influence of clad thickness on the spreading of clad solders. Heating condition: 5 min at 400 C in H₂ atmosphere

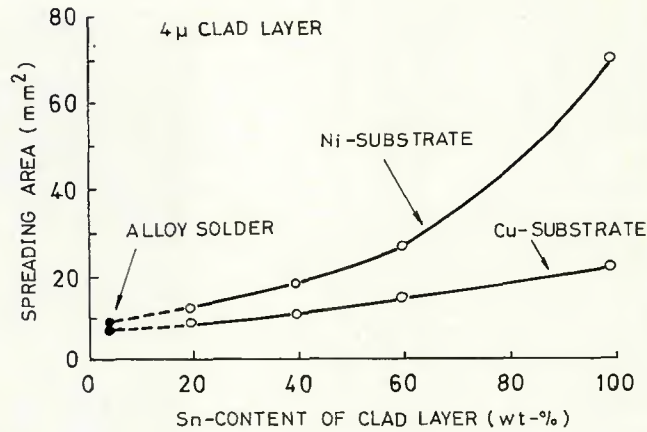


Fig. 8—Influence of clad layer composition on the spreading of clad solders. Heating condition: 5 min at 400 C in H₂ atmosphere

having a 1 μ nickel plating were used.

Figure 6 compares the spreading characteristics of a clad solder having a pure tin cladding of 4 μ thickness with that of the Pb-5%Sn alloy solder. While hardly any spreading occurred for the alloy solder on all substrates, the improved wetting and flow properties of the clad solder is clearly recognized. This improvement is especially significant for the nickel substrate, but even for copper a twofold increase in the spreading area was obtained.

In a more quantitative study, the spreading of clad solders with a total composition of Pb-5%Sn was mea-

sured as a function of the thickness and the tin content of the clad layer. As seen from Figs. 7 and 8 all clad solders show better spreading than the alloy solder. Increasing amounts of tin at the interface promote the spreading on both the nickel and copper substrates. This demonstrates the importance of tin for the soldering characteristics of lead-rich solders. It is also interesting to note that the curves obtained can be extrapolated to the Pb-5%Sn alloy solder which, in this context, can be considered as a "clad solder" having a "cladding" of the same composition as the core.

The exact mechanisms which cause the improved spreading of clad solders and the influence of the substrate material are not yet clearly established. It is considered, however, that the wetting properties of the clad solders are a consequence of their complicated melting behavior.

During heating to the soldering temperature, the solder passes through a series of soldering conditions. These are determined by the instantaneous combinations of temperature and the composition and thickness of the molten layer at the interface. The

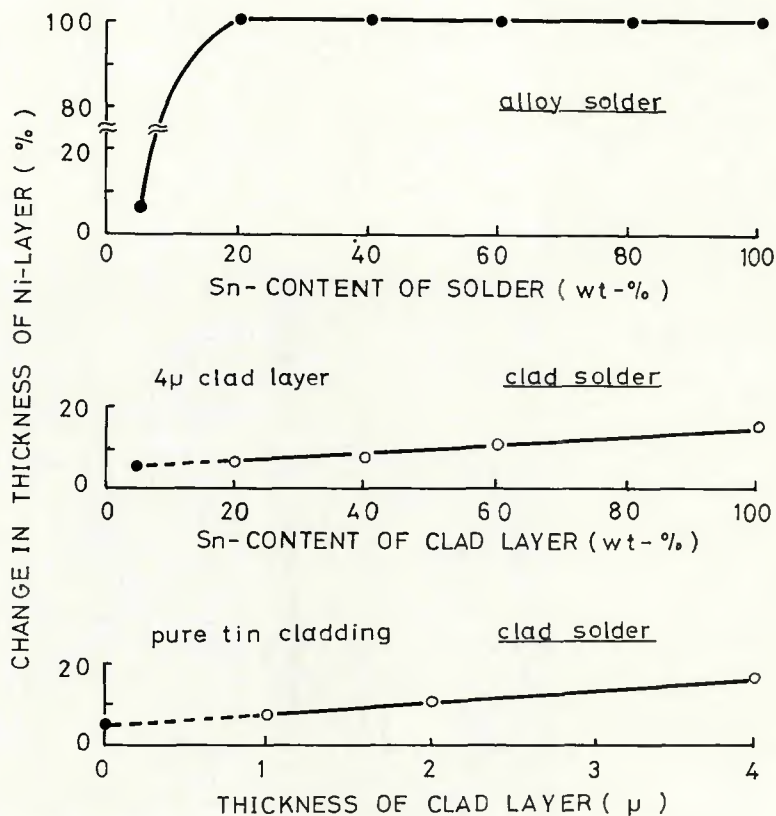


Fig. 9—Change in thickness of a 4 μ nickel plating due to dissolution into various alloy and clad solders; all clad solders have a total composition of Pb-5%Sn. Heating condition: 5 min at 400 C

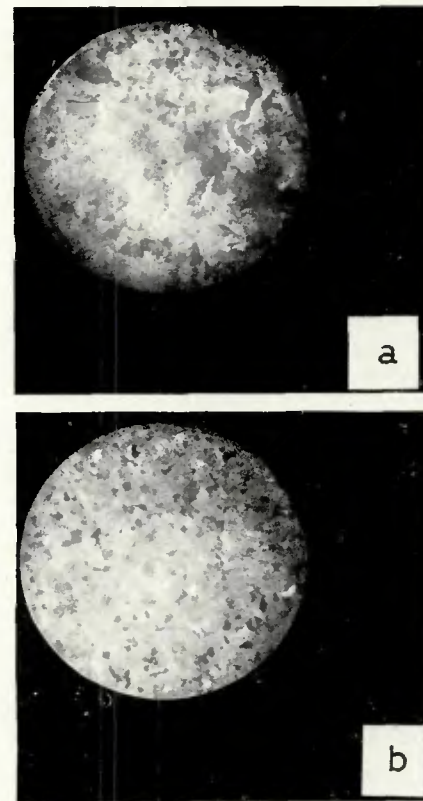


Fig. 10—Solder sheets were melted on silicone discs to show the wetting properties of (a) Pb-5%Sn alloy solder and (b) clad solder of same composition. Melting was done in a furnace under H₂ atmosphere

degree of spreading obtained on each substrate, therefore, depends on how far favorable combinations of these parameters are realized during heat-up.

Interface Reactions

One of the advantages of clad solders is that, despite their excellent wetting properties, the attack on the base metal is very low. To prove this argument the dissolution of nickel into various clad and alloy solders was measured—Fig. 9. In these experiments, small samples of the solder were placed on a copper substrate, which was plated with a 4μ nickel layer. After heating the samples for 5 minutes at 400 C (752 F) under hydrogen, the amount of nickel dissolved was measured metallographically.

It is seen from Fig. 9 that the Pb-5%Sn alloy solder attacks the nickel plating only slightly. However, increasing the tin content strongly accelerates the attack on the nickel plating. For the heating conditions selected, an alloy solder with 20% tin already completely dissolves the nickel layer.

On the other hand, dissolution of nickel into the clad solders having claddings with various thicknesses and compositions is comparatively low. Similar to the spreading tests, the attack on the nickel plating also increases with the amount of tin initially present at the interface. However, since the lead content of the solder cladding rapidly increases after melting starts, the total amount of nickel dissolved is much lower than for the corresponding alloy layers. Even for a pure tin cladding of 4μ thickness, the nickel plating decreases less than 1μ . This is considered tolerable for usual semiconductor device soldering practice.

Similar results were obtained for the reaction of clad solders with other metal substrates such as copper and silver-plated copper. In all cases, dissolution of the base metal was only slightly higher than for the Pb-5%Sn alloy solder.

Application to Semiconductor Devices

The above results demonstrate that the clad solders fulfil the require-

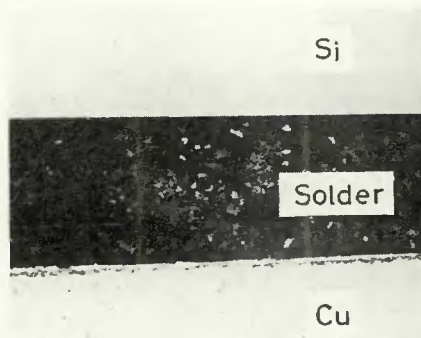


Fig. 11—Photomicrograph of a soldered junction showing good bonding of the solder to the silicone disc and copper substrate and a void-free solder layer. $\times 400$ (reduced by 33% on reproduction)

ments initially set for an improved version of a solder for semiconductor devices. Therefore, after establishing their basic properties, their usefulness for the soldering of silicone discs was evaluated.

The good spreading characteristics of the clad solder with a 4μ tin cladding was shown in Fig. 6. A further example of the problems caused by the poor wetting of the Pb-5%Sn alloy solder is shown in Fig. 10. In this experiment, a solder disc of 50 mm (1.97 in.) diameter was melted on a silicone disc of the same size. Considerable dewetting occurred and caused local exposure of the silicone substrate. In soldered semiconductor assemblies, this phenomenon leads to voids at the soldered interface and thus to faulty junctions. Replacing the alloy solder with an equivalent clad solder having a 4μ tin cladding solved the problem of dewetting.

Silicone disc-lead wire assemblies similar to that shown in Fig. 1 were soldered under conditions resembling those of continuous soldering of diodes. In all cases, the excellent wetting and flow properties of the clad solder were confirmed.

Figure 11 shows the microstructure of such a junction. The solder layer is free of voids, and a perfect metallurgical bond is indicated by the thin diffusion layer at the interface between the copper and the solder. On the silicone side, the nickel plating is too thin to be revealed in the micrograph. However, the void-free interface again is proof of the good wetting by the solder. Electron microprobe

analysis at various locations of the solder layer confirmed that the solder had completely fused and had a homogeneous composition of 5% tin.

The above experiments were carried out with a clad solder having a pure tin cladding of 4μ thickness. However, the most suitable type of clad solder will depend on the type and thickness of the plating on the silicone disc and on the heating conditions during soldering. Further improvements can be expected from an adjustment of the soldering conditions to the peculiarities of the melting behavior of the clad solder.

Considering that the soldering practice for semiconductor devices varies among the manufacturers and much of it is proprietary know-how, it is difficult to propose an optimum clad solder. However, the wide range over which the wetting properties and the reactions with the base metal can be controlled ensures that the clad solders described will meet the various specific requirements.

Conclusion

In order to improve the low wetting properties of lead-rich solders used for the soldering of semiconductor devices, a clad solder consisting of a lead-rich core and thin tin-rich surface layers was developed. During heating to the soldering temperature, the tin-rich layer provides for good wetting and flow of the solder. In the later stages of soldering, the core fuses completely with the cladding and through diffusion a lead-rich solder layer of homogeneous composition is obtained. It is thus possible to combine the favorable soldering characteristics of tin-rich solders with the strength and heat resistance of joints soldered with lead-rich solders.

Although the clad solder described in this paper was primarily developed for the manufacture of semiconductor devices, the basic principle of the clad solder may be applied to other soldering applications where the solder has to meet conflicting requirements.

Reference

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