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# AUSN THIN FILM SOLDER LAYERS FOR ASSEMBLY OF OPTOELECTRONIC DEVICES

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**Abstract**

In this contribution, an innovative deposition and patterning technique for AuSn layer deposition is presented. The technique allows the deposition of alloys in the Au-Sn-system with a broad range of composition and melting points to address various chip metallizations and solder hierarchies. The layers can be patterned with high precision photolithography down to feature sizes of twenty microns at a thickness of up to five microns. For the use in submounts the solder layers are applied to thin film metallized substrates with different substrate materials, e. g. $Al_2O_3$, AlN and Si. The fabrication method for the layers is presented as well as the methods for quality control in a volume production. Various applications for AuSn thin film solder layers are shown.

## 1. Introduction

### 1.1 Overview

Eutectic gold tin alloy is commonly used for soldering of optoelectronic devices and microsystems. The main reason is the possibility of fluxless soldering. Flux, even after removal, would contaminate optical and other surfaces and would have a strong impact to performance and reliability of optoelectronic devices. Most often the solder is used as preform and has to be placed on the solder pad prior to die bonding. Typically the preforms are fifty or twentyfive microns in thickness and have approximately the size of the die. This means a difficult pick and place step prior to the alignment and soldering of the device. In contrast, thin film solders are already deposited on the substrate. The lower thickness and the possibility of patterning thin film solder pads make completely different assembly approaches possible, e. g. area array interconnects using flip chip technology and AuSn bumps.

### 1.2 Phase diagram and solder reactions

The phase diagram of the binary Au-Sn sytem was first described by Vogel [1]. In the meanwhile several papers were published on this topic because of the complexity of this system. Fig 1 shows the phase diagram published by Okamoto and Massalski [2].

The Au-Sn system has two eutectic points and four intermetallic phases. The eutectic alloy used for soldering applications has an eutectic temperature of 278°C at a composition of eighty weight percent of gold and twenty weight percent of tin. This composition is named Au80Sn20. If an eutectic Au80Sn20 melt freezes an eutectic reaction occurs with the formation of intermetallic AuSn phase (also called δ-phase) and ζ-phase. At temperatures below 190°C a congruent reaction occurs and the ζ'-phase is formed. This is a stable intermetallic phase with the composition $Au_5Sn$. If an Au80Sn20 solid alloy is heated up to the eutectic temperature melting starts at each interface between gold rich and tin rich phases. More details are described in Vogel[1], Hansen [3], Okamoto and Massalski[2] and in Matijasevic et al.[4].

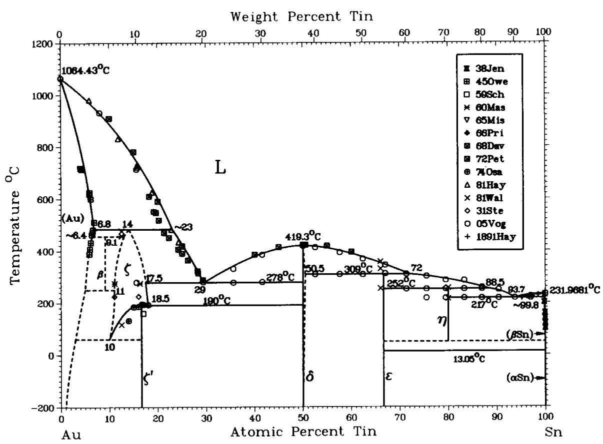



**Fig 1: Phase diagram of the Au-Sn system according to Okamoto and Massalski[2]**

During the soldering process the eutectic melt dissolves gold and forms ζ-phase. This phase is stable up to 519°C, has good mechanical properties, a decreased thermal resistance and excellent reliability [5]. It is possible to achieve pure ζ-phase interconnections [6].

Tests performed with the other eutectic composition Au10Sn90 are described in Aschenbrenner et al[6]. He reports bad results with this composition. It is brittle and often cracks appear directly after the reflow. Shear values are lower compared to dice bonded with Au80Sn20. Further, he found a strong degradation of an LED soldered with the Au10Sn90 eutectic during aging.

### 1.3 AuSn thin film deposition

Several authors[4-15] describe the deposition and application of AuSn thin film solder. Aschenbrenner et al.[6] describes a process where the chip pad is metallized with gold and the substrate is coated with tin. The eutectic reaction takes place during the die bonding process. ζ-phase can be observed on both sides of the joint. Disadvantage is that layers of brittle intermetallic phases might be formed and that Kirkendall voids can appear.

Some authors [7],[8],[9] electroplate gold with a tin cap on top. In this case, excessive gold is used. The solder layer has to be reflowed before use in order to achieve an eutectic alloy on top of the solder pad. This reflow step is critical because the excessive gold can lead to dentritic growth of ζ-phase before the soldering process. Therefore, there is less eutectic left which would be needed for the soldering process. Further, Kirkendall voids can lead to failure of the solder joint.

Other papers [10],[11],[12],[4] describe stacks of a few layers of evaporated gold and tin. Here the formation of the eutectic takes place due to the fast diffusion even at room temperatures [13],[14],[15].

This paper discusses the technique of co-sputtering of gold tin solder alloys. Composition control, patterning and application of such thin films are described.

## 2. Experimental

### 2.1 AuSn Layer Deposition and Control

Here, an Alcatel SCR850 is used for the deposition of sputtered metal layers. This is an RF sputter tool with six targets and two RF generators. It has the capability of cosputtering, i. e. the operation of two targets at the same time. The substrates are placed on a table rotating underneath the targets. In principal, very thin layers of the two target materials are deposited alternately. The theoretical thickness of each layer with the chosen sputter parameters is in the range of one nanometer. In practice, surface mobility and diffusion leads directly to the formation of the alloy with very fine grains.

The gold tin layers described in this paper are deposited by cosputtering of gold and tin.

The composition of the gold tin solder can be adjusted by chosing appropriate sputter rates for the gold and the tin. The appropriate parameter for selecting an independent sputter rate for both targets is the RF power. The sputter rates can be determined independently in a test run. Thus, the solder composition can be determined preliminary. Much more practical is to control the sputter rate of the gold tin layer. A change in this rate indicates the necessity of a composition check.

Calculation of the film thickness ratio x:

$$r = \frac{m}{A \cdot d}$$

$$A = \frac{m}{r \cdot d}$$

$$x = \frac{d_{Au}}{d_{Sn}} = \frac{m_{Au}}{m_{Sn}} \cdot \frac{r_{Sn}}{r_{Au}}$$

with:

| | |
|---|---|
| d: | film thickness |
| A: | substrate area |
| m: | mass |
| ρ: | density, $\rho_{Au}=19.3gcm^{-3}$, $\rho_{Sn}=7.3gcm^{-3}$ |
| x: | film thickness ratio |

For solder alloy containing 80 weight percent of gold and 20 weight percent of tin the film thickness ratio is x=1.5.

Another advantage of six targets in one tool is the possibility to deposit a stack of different metals without exposing the substrates to atmosphere in between. This gives the possibility to use diffusion barriers and adhesion layers which would oxidize at ambient atmosphere. Such metals can also be used as solder stop layer around the solder pads. Underneath the AuSn they are protected from oxidation and therefore the solder shows a good wettability to this layer. Whereas the unprotected underlayer metal is oxidized leading to no wettability.

### 2.2 AuSn patterning

Gold tin alloys can hardly be etched by wet chemistry. Especially, if the applied photoresist mask should not be attacked. For this reason, gold tin is patterned by dry etching, lift off or using shadow masks. Here, the two latter processes are used depending on the requirements of pattern tolerances. In the case of shadow mask, the positioning tolerance is ±200µm and the edges of the pads are not very sharp defined. If more accuracy is required, photolithography and lift-off is used for patterning the AuSn solder pads. Using this technique, a tolerance in dimensions of ±3 µm and a tolerance in alignment of ±10 µm is achived in standard production. Using this technique it is possible to pattern layers up to a thickness of 5µm. The smallest feature size is 20 µm. It is also possible to produce AuSn solder bumps with a width of 30 µm and a height of 5 µm.

### 2.3 Melting tests

The thin film solder of each batch is controlled by a melting test on samples from this batch. This test is performed on a Linkam THMS600 heating stage with a

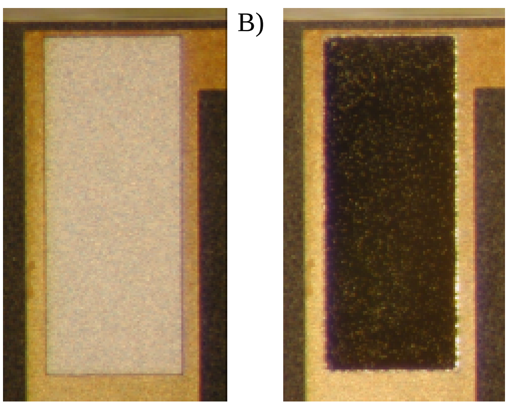
TMS94 programmable temperature controller. This heating stage consists of a small silver block with integrated heater and temperature sensor. The samples are placed in a crucible on the silver block. The whole arrangement is in a closed chamber. The temperature profile is controlled very accurately with a time constant in the range of one second. It is possible to calibrate this setup, so that the temperature reading is close to the real temperature on the sample surface. This is especially true, if the same type of sample is consistently used.

Melting of the thin film solder is observed with a stereomicroscope at 50x magnification. For detailed observations, the heating stage can also be mounted on the stage of a wafer microscope (Olympus MX50) with up to 500x magnification.

The melting behaviour indicates deviations from the eutectic composition. An eutectic alloy melts exactly at the melting temperature and shows a homogeneous melt. In case of any deviation from the eutectic composition, only a part of the alloy melts at the eutectic melting temperature. The other parts keeps solid until the temperature reaches the liquidus curve. In practice, two further effects have to be considered. An oxide layer is grown if the melting is not performed in reducing atmosphere. If the solder layer is close to a layer of gold the interdiffusion and change of composition can be observed (see figures). Fig 2A shows an Au80Sn20 solder pad on a submount after solder deposition and patterning. Between the gold layer and the solder layer is a diffusion barrier with the same lateral shape as the solder pad. Fig 2B shows the same solder pad directly above the melting temperature of the eutectic. Since the solder pad is not surrounded by the diffusion barrier, gold from the layer underneath is able to diffuse from the edge into the pad and forming the gold rich ζ-phase. This effect is shown in Fig 2C. The same effect happens during soldering a die to the submount. In this case the gold originates mainly from the metallization of the die. If the AuSn pad deposited on a diffusion barrier and a solder dam is present around it is possible to perform several melting and freezing cycles without any negative influence to the melting and soldering characteristics.

The appearance of a non eutectic solder composition between liquidus and solidus is shown in Fig 2D and E.

A) B)



C) D) E)

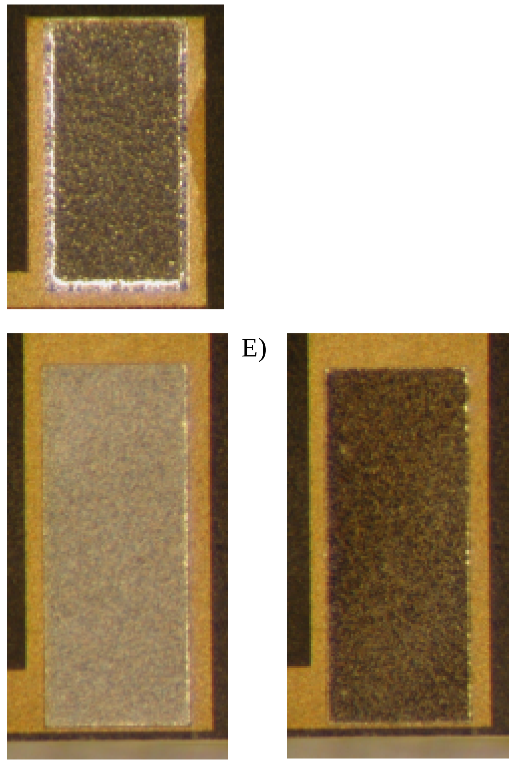


**Fig 2: Photographs from gold tin solder pads. The width of the pads is 500μm:**
**A) Au80Sn20 after deposition**
**B) sample A) just after melting at the eutectic temperature**
**C) without solder dam after one minute at T=290°C**
**D) non eutectic composition at T=280°C**
**E) same as D) but at T=285°C, t=30s later**

### 2.4 Applications of AuSn thin film solder

AuSn thin film solders can be used for the bonding of two components with planar surfaces. The planarity of the surfaces should be better than one third of the solder thickness. Otherwise, gaps and voids will result. This planarity condition can easily be fulfilled in the case of bonding small dies to a substrate. E. g. as in the case of bonding laser diodes or photo diodes to a submount. The main advantage of a thin film solder compared to solder preforms is its ease of use during the soldering process. The solder is already attached to one of the two parts to be assembled. Therefore, the cumbersome handling of small solder preforms is eliminated. This saves a lot of money for the die bonding process. Further, the thickness of the solder joint is reduced drastically. This reduces the thermal resistance of the solder joint dramatically. Also, a nice solder meniscus is formed nearly without squeezing excessive solder out from under the die.

When using a diffusion barrier underneath the solder pad it is possible to perform even two solder reflow processes. The first component is attached to the first solder pad. The subsequent soldering process leads in this interconnection to dissolution of gold from this component in the solder and to the formation of ζ-phase. Thus, this joint will withstand at a second reflow process. During the latter, a second component can be soldered.

This way, it is possible to create at least a two step solder hierarchy with only one solder alloy.

AuSn thin film solder can be applied to various materials. Volume production with AuSn thin film solder uses substrate materials like aluminum nitride and aluminum oxide ceramics. Other materials are also tested with success. It is possible to use this kind of solder for silicon and Kovar, e. g.

Another big advantage of thin film solder is the possibility of tacking the chips to the substrate with a die bonder. The reflow is done afterwards in a furnace for a whole batch. This reduces the pick and place cycle time drastically because there is no need to wait for the temperature cycle as necessary in the case of thermode bonding [8].

The high patterning resolution of thin film solders allows the use of area array interconnects technologies with high density.

### 2.5 Analysis of the AuSn composition

Here, gold tin solder layers are analyzed by GD-OES [16] (glow discharge optical emission spectroscopy). This method ablades the metallization by glow discharge and the optical emission is measured by spectroscopy. Hence, even measurement of composition profiles is possible. The relative measurement accuracy is 1% for the gold concentration and 10% for the depth information if appropriate calibration standards are used. A typical profile measured on cosputtered gold tin alloy is shown in Fig 3. It shows a gold rich surface and a very homogeneous composition profile in the bulk. The gold rich surface could be caused by the fact that the shutter of the gold target is closed after the one of the tin target. But a gold rich surface is in contrast to the literature [17] where the segregation of tin to the surface is described.

Quantitative Analysis with EDX shows also a promising measurement accuracy of the concentration within 1%. It is performed in an SEM as top view. By changing the acceleration voltage compositional changes in depth can be detected. But due to the small penetration depth of some tens of nanometers it is still a surface analysis. Here a solder preform is used for calibration.

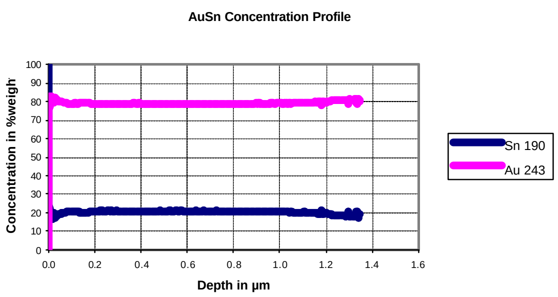



**Fig 3: AuSn-Concentration profile measured by GD-OES**

The gold contents obtained with this method are approximately five weight percent higher than those determined by GD-OES. This could be explained by the gold rich surface detected with the latter method and the fact that EDX is still a surface analysis. Further, the preform used for calibration could show the tin segregation described in the literature. This would introduce an error into the calibration so that the gold contents of the samples are determined to a higher value than realistic. The lateral distribution of the elements shows a fine and homogeneous texture. By variation of the acceleration voltage a very slight increase of the gold content could be interpreted.

Further investigations are necessary to get a congruent picture of the results. Next step will be an EDX analysis of cross sections of sputtered thin films as well as of preforms.

## 3. Conclusions:

A technology for the deposition of gold tin solder alloys with adjustable composition was developed and is introduced into volume production. Process control methods are discussed. The ability to pattern solder layers by photolithography allows a wide range of applications. Together with the flexibility in solder composition application specific products can easily be developed.
Advantages of thin film solder are :
- thin solder joint
- lower thermal resistance compared to solder joints fabricated using preforms
- less excessive solder around the solder joint
- no need to handle preform
- easier die bonding process
- solder hierarchy with one solder alloy possible
- area array interconnects using solder bumps possible

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