

Consumable Anode Process for SnAg Electroplating

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Abstract

Near eutectic tin-silver (SnAg) is currently the alloy of choice for electroplated lead-free solder bumping and Cu pillar capping. While lead-tin (PbSn) is still used in some applications, there has been considerable momentum in moving away from the use of lead in semiconductor packaging. Both solders are normally electroplated as alloys with specific compositions to target a desired melting point. Since the deposition potentials of lead and tin are very close together, they plate with similar characteristics. This makes it possible for PbSn plating systems to use a consumable anode system where the anode composition matches the desired deposit composition. Metals are replenished into the bath in much the same ratio they are consumed. In a SnAg plating bath, the deposition potential of Ag is much more positive than Sn, so very low potential is required for Ag deposition. The plating rate of Ag is generally mass transfer limited. The plating rate of Sn is current controlled. While similar in concept to systems using consumable anodes for plating other metals, the SnAg alloy system presents some unique challenges. Because it is more noble, the Ag^+ will deposit onto the Sn anode material by displacement reaction, and passivation will occur. Thus, the Sn anodes cannot come in contact with the Ag^+ in the bath. Historically this problem is overcome by using an inert anode and metals replenishment by liquid concentrate. This paper outlines a method for plating SnAg using a consumable Sn anode, thereby reducing cost of ownership (CoO) and increasing bath stability compared to conventional SnAg wafer level packaging (WLP) plating.

Key words

Lead-free solder, SnAg, Electroplating, WLP, bumping

I. Introduction

As IO counts increase to support growing device capabilities, demand for smaller plated solder bumps and solder capped copper pillars will increase. Improved ball placement and screen-printing techniques will continue as viable solder placement systems for large bumps attaching packages to substrates ($>500\mu\text{m}$ pitch), but most chip stacking applications require increasingly tighter pitches, and electroplating solder through resist is the norm. While cutting edge Cu pillar technologies move forward to decrease demands for SnAg plating volumes, the market for SnAg electroplating will remain strong in the foreseeable future [1].

Like most industries, the electronics industry is coming under pressure to “commoditize” products and processes

more quickly. As the internet makes knowledge immediately and widely available, it generally becomes more difficult to differentiate on the basis of technology alone. Across many industries, large end customers are able to drive prices lower, squeezing suppliers at all levels to provide functional products with lower and lower margins, and the electronics industry is no exception. In view of this trend, great efforts are being made to decrease tool costs and cost of ownership (CoO) at all levels of chip manufacture. Wafer level packaging, in particular, is an area where there has historically been a drive to provide “good enough” processes at low cost, forcing commoditization. Now, as we reach a focus of bandwidth and speed on handheld devices, we must ratchet up the definition of good enough, but frequently the drive is still to reduce costs even as complexity increases.

Good enough in this case means improvements in coplanarity within die to support chip stacking, reductions in contact resistance and RDL line resistance variations, and a wide variety of integration improvements to increase overall reliability in increasingly complex packages. In light of this drive, introducing a cost saving measure such as change to a consumable anode system makes sense, even if the savings become offset by adjustments in other costs (liquid concentrates) as all players struggle to maintain markets or increase market share. The net result is a series of “nudges” toward higher efficiency and more robust processes. In keeping with the incremental march toward CoO improvement, even subtle areas of inefficiency or high cost can become a focus for belt tightening.

II. Background

As the drive to replace lead in electronic applications became stronger in view of RohS in the late 80’s, several manufacturers of solder electroplating baths and plating systems began a search for alternate materials that could replace PbSn solders. In the end, SnAg surfaced as the most viable alternative. Probably the greatest enabler for SnAg plating was the use of proprietary complexing agents in the catholyte to control the deposition potential of Ag to gain some control of plated alloy composition. As part of these catholyte systems, metals replenishment of Sn and Ag was accomplished by direct addition of acidic metal concentrates based on methanesulfonic acid (MSA). From a bath manufacturer’s standpoint, these solutions were essentially a drop-in replacement to PbSn systems, but with a few more controls on the bath to ensure composition consistency. From a plating tool manufacturer’s perspective, these baths were somewhat problematic in that the low deposition potential of the Ag in the plating bath would cause immersion/autocatalytic deposition of Ag onto a consumable SnAg or Sn anode and cause passivation. The default and simple solution at the time was to use an inert anode (platinized titanium or similar) and full replenishment of metal by liquid concentrate. Ag is a small part of the deposit (1.5-3.0% by weight), so Ag consumption overall is low. Sn replenishment is much higher, often approaching 10 liters of concentrate per day in high volume manufacturing. This creates several issues including an up-concentrating of MSA in the bath (introduced as the carrier for Sn in the concentrate), and maybe more critical from the tool manufacturer’s perspective, finding a means to make room for this addition in a bath that is becoming Sn depleted, but is still roughly at target volume. Two approaches to solving this problem are to bleed off existing bath volume to make room and then feed an appropriate

solution to maintain concentration targets, or to increase bath evaporation of water from the bath continuously so that incremental additions can be made as volume allows. Each of these has associated costs and maintenance issues. Bleed and feed increases bath life overall, but increases cost by bleeding away bath material that was viable only moments before. Evaporation incurs lower cost than B&F but allows upconcentration of nontarget materials (like MSA) that are dosed along with the Sn. Other options for dosing are possible, but these two are the current standards in production using inert anodes.

The addition of a membrane in inert anode SnAg plating systems has also become common in the last 8-10 years [2]. In a fountain type reactor with face down plating, a membrane serves several useful functions: 1) it isolates the catholyte bath from the anode, thereby limiting anodic breakdown of organic materials in the bath, and 2) it provides a means to keep hydrogen bubbles generated at the anode from reaching the face down wafer surface, where they can cause bubble/masking defects.

In the case of an inert anode system, the membrane and anolyte need only pass current. Typically an inert anode system uses an anionic membrane to prevent diffusion of positive ions into the anolyte, as any leak of platable ions into the anolyte is component loss that must be replenished.

III. Experimental

Several different approaches have been put forth to implement a consumable anode system for SnAg plating [3]-[5]. The basic system for implementing consumable Sn anode on Applied Materials plating systems is based directly upon our experience plating Cu in similar systems (patent reference). As noted above, plating an alloy introduces some complexity, but normally only Sn is replenished from anodic dissolution. The Ag component of the catholyte is replenished by other means, usually acidic concentrate, but consumption is relatively small compared to Sn. Fundamentally the method is to use an anolyte and catholyte separated by a cationic membrane, and drive ions that are dissolved at a Sn anode through the membrane to replenish those consumed at the cathode. The subtle system configuration differences between inert and consumable anode systems are noted in Figure 1.

Inherent in this configuration is the need to drive Sn across the membrane from anolyte to catholyte. Concentration gradient is not a sufficient means to drive ion transfer across

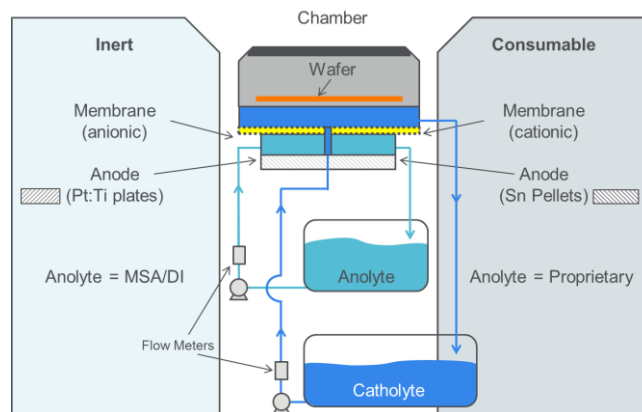


Figure 1. The differences between the inert anode and consumable Sn processes are in the choice of membrane material, type of anodes used, and anolyte chemistry.

a membrane in the case of large, complexed metal ions. It is necessary to drive the ions across using the push of an emf from the plating current. Small, agile protons are not so limited, so key to strong Sn ion transfer is the need to maintain a relatively high ratio of Sn ions to protons, thus pH control of the anolyte is critical (Fig 2). By appropriate choice of anolyte, Sn ion transfer efficiencies of >85% can be realized. The remaining deficit in Sn in the catholyte must still be replenished by liquid addition.

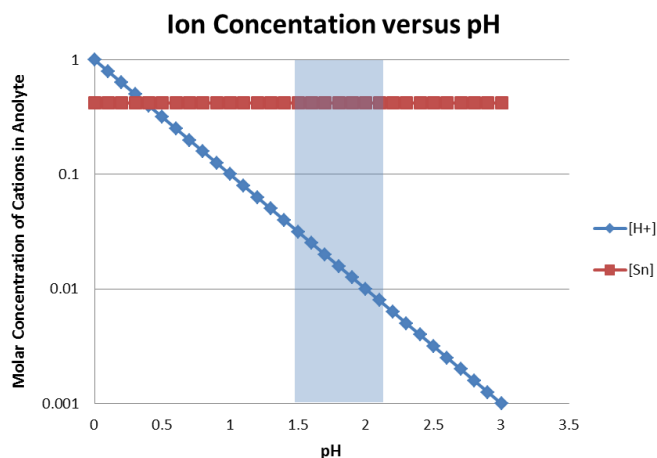


Figure 2. Shows relative concentration of Sn ions versus protons as a function of pH. Shaded blue region represents roughly the region where $[H^+]$ is low enough that Sn^{2+} becomes the dominant charge carrier.

In times of plating, general motion of positive ions is toward the cathode (wafer surface). This inhibits backstreaming of protons into the anolyte which would poison Sn transfer, as well as further decreasing the possibility of Ag ions from crossing into the anolyte to passivate the Sn anode. In times

of non-plating, the hardware is capable of creating an air gap between the anolyte and the membrane to effectively isolate anolyte from communication with the catholyte.

As long as relatively high transfer efficiency is maintained, this configuration requires no bleed and feed function, instead depending on evaporation to create the volume necessary for the small Ag and Sn ion additions to maintain the bath. Increasingly, bath maintenance is provided by inline monitoring systems. These systems frequently provide both analysis of the bath and dosing of components back into an active slipstream. Extension of bath life is another important area of cost savings, and considerable efforts have been made by bath vendors to investigate failure modes, and analytics suppliers to identify/control the conditions that cause bath degradation [6].

Data

A large part of what a plating tool manufacturer brings to the plating process is the capability to deliver a wafer to a plating bath that can be controlled well to create consistent on-wafer performance in a high volume production environment. Fortunately, as long as the catholyte stays fundamentally the same, the plating process generally will continue to deliver acceptable results. While this may sound easy because of advanced analysis and bath control, a poorly designed plating tool can make bath maintenance all but impossible. By transferring primarily only ionic Sn from anolyte to catholyte during replenishment, our approach to SnAg plating with a consumable Sn anode has demonstrated stable performance in laboratory tests.

Marathon plating tests using commercially available catholyte solutions and a custom anolyte solution were undertaken in the lab. In these tests, patterned wafers were plated and measured on a fresh catholyte bath using inert anodes (standard system) and a baseline was established. The system was then converted to the consumable anode configuration, the baseline results verified, and extensive bathlife testing using both dummy wafers for amp*time accumulation and interspersed patterned wafers for on wafer performance verification were plated. As-plated on wafer bump height and Ag uniformity results are shown in Figure 3. The baseline data is enclosed by the dashed box at the beginning of the data set, and the results after converting the system to the consumable Sn anode process show stable plating performance to 80 amp hours per liter and counting, sufficient to release the process for beta site testing at a customer site.

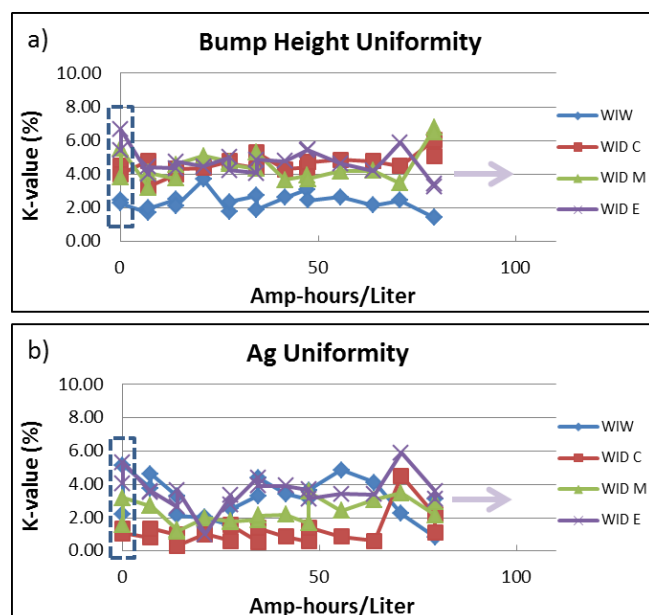


Figure 3. a) Bump height and b) Ag uniformity data as a function of bath age. The data includes within wafer (WIW) uniformity, as well as within die (WID) uniformity at the center, middle, and edge of the wafer. The dashed box at the beginning of the data set contains the baseline inert anode data; all subsequent data is from the consumable anode marathon. The arrow at the end of the data indicates ongoing data collection and analysis.

Metrics of plating performance include bump morphology and post reflow voiding. Shown in Figure 4 are SEM/FIB images of as-plated and reflowed Ni/SnAg bumps using our consumable Sn anode approach. Fig. 4a is a SEM image from an as-plated wafer, demonstrating uniform bumps and standard morphology. Fig. 4b is a FIB cross section of an as-plated bump showing very limited micro-voiding, while Fig. 4c shows that any voiding is essentially eliminated after reflow.

Cost Analysis

Having the on wafer results from the consumable Sn anode process match or exceed those of the standard inert anode process is a necessary but insufficient requirement. An additional factor for success is cost savings. Our cost benefit analysis is shown in Figure 5 based on a bath lifetime of 65 amp-hours/liter; the longer a bath lasts the more savings will be realized. The savings shown in the figure are calculated from comparing a 100% efficient inert anode process to our consumable Sn anode marathon consumption data. The initial catholyte bath and Ag dosing are the same for both processes, so their costs are also identical. The consumable Sn anode process requires a specialized anolyte chemistry which incurs

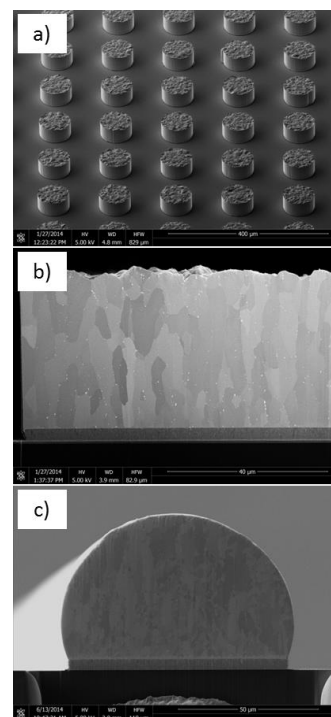


Figure 4. a) SEM image of as-plated SnAg bump; b) FIB cross section of an as-plated Ni/SnAg bump; and c) post-reflow FIB image of Ni/SnAg bump.

additional costs over the inert anode process, as does the use of Sn pellets. However, the cost difference between the Sn pellets used in the consumable Sn anode process and the liquid Sn concentrate necessary to replenish the Sn plated in the inert anode process, as well as the efficiency of our technique more than offset the additional costs of the anolyte chemistry and the Sn pellets, providing substantial cost of ownership savings using our consumable Sn anode process.

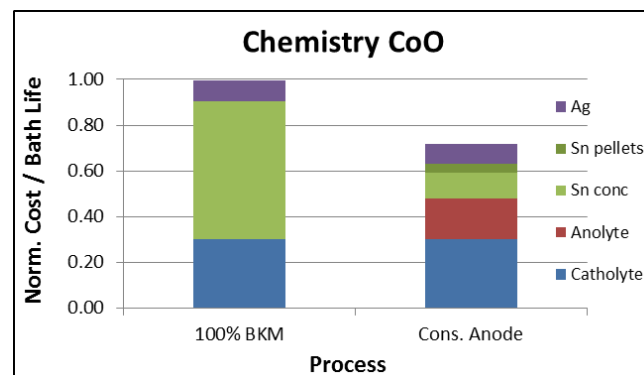


Figure 5. Estimated cost of ownership savings using a consumable Sn anode process versus a 100% efficient inert anode process. The Ag dosing and up front catholyte costs are the same. The consumable Sn anode process incurs additional costs from the specialized anolyte chemistry and Sn pellets, but the extra costs are more than offset by the savings from dosing less Sn concentrate.

IV. CONCLUSION

Gram for gram, solid Sn is considerably less expensive than Sn replenished from concentrate, so using a consumable pure Sn anode and a cation selective membrane to replenish plated metal, significant cost savings can be realized. The first metric for success of a new process is to generate on wafer results that meet or exceed the current process. In order to address this concern, we established baseline plating performance data using a standard inert anode process, converted the system to our consumable anode process, verified the baseline results, and proceeded with extensive bathlife testing. The data collected over the course of the marathon has shown results better than or equal to the baseline data. Furthermore, our cost of ownership analysis, based on a modest 65 amp-hours/liter and which will only improve with longer bath lifetimes, estimates a substantial savings advantage.

Acknowledgment

The authors would like to acknowledge Ian Drucker, Grey Roh, Jeff Dennison, Graeme Bell, all of Applied Materials PPC.

REFERENCES

- [1] J. Baron, L. Cadix, P. Garrou, C. Zinck, Yole Equipment for 3DIC & Wafer Level Packaging Report June 2011.
- [2] R. Baskaran, et al. "Electrolytic Process Using Cation Permeable Membrane." Patent US 8,236,159 B2. 7 August, 2012.
- [3] Ibid. Baskaran.
- [4] S. Mayer, D. Porter. "Electroplating Apparatus and Process for Wafer Level Packaging." Patent Application US 2012/0138471 A1. 7 June, 2012.
- [5] J. Chiu, D. Guarnaccia, J. Hander, A. Kiegler, D. Papapanayiotou. "Electro Chemical Deposition and Replenishment Apparatus." Patent Application WO2012142352 A1. 18 October, 2012.
- [6] C. Arvin, "Optimization of Lead Free Plating for Flip Chip Applications." IMAPS 10th International Conference on Device Packaging, March 10-13, 2013. Fountain Hills, Arizona.