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TIN-BASED LEAD-FREE SOLDER BUMPS FOR FLIP-CHIP APPLICATION

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ABSTRACT

This paper reviews the processing of tin-based lead-free solder bump for flip-chip application. Some of the processes, electroplated, stencil printed, evaporated, injection moulded and solder spheres shall be highlighted, while the technology on electroplating technique shall be reviewed. In general, the obstacle in the usage of tin-based lead-free solder alloy is due to the toxicity of lead. This has led to a legislation and control in the usage of lead as an alloying element. The solder bumping methods were compared relatively in terms of cost, quality, bump pitch, applicability and lead-free challenge. Electroplated process produces high quality, fine pitch bumps and has, however, low flexibility in handling with lead-free alloys and has relatively high production cost. On the contrary, the stencil printing method is a low-cost, producing coarse bump pitch and handles easily with lead-free alloys. Evaporation process provides high quality bumps at medium to high cost but is poorly suited for larger wafers and most lead-free alloys. Among the two processes, the electroplating method is the most suitable process to fabricate tin-based lead-free solder bumps, and has proven to be the most cost effective and versatile in application.

INTRODUCTION

Advances in chip scale packaging technology have prompted a rapid increase in the density of solder joints in micro-electronics products. Consumer demands for lighter, cheaper, smaller and smarter products is a reality and are pushing the electronic industry to utilize the smallest packaging footprint possible. In this respect, flip-chip packaging is seen as the ideal packaging platform to satisfy the driver of portable electronics for more, faster and denser electrical I/O's. Flip-chip technology has been around for decades and has not seen a wide spread adoption until recently as the primary interconnection technology. This is due to high cost coupled with constant advances in alternative packaging technologies. It offers many advantages such as high number of interconnects per unit area, faster device speed and lighter weight compared to conventional interconnection technologies such as wire bonding and metallized leads.

Flip-chip is the fastest bonding technique used in electronics to achieve high-density assembly on to printed circuits boards. Flip-chip can be generally described as an

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active component, as IC's, directly connected face-down to substrate by means of conductive bumps on the chip bond pads. The cost, performance, and application determine which varieties of flip-chip best suit it. Sketch of flip-chip technology is shown in Figure 1. The structures of flip-chip involve I/O pads, passivation layer, under-bump metallurgy (UBM) and solder bumps. The UBM system is important to the overall structure with its' functions as a layer which promotes adhesion, a barrier to diffusion and a layer which provide wettability and solderability layer for solder bumping.

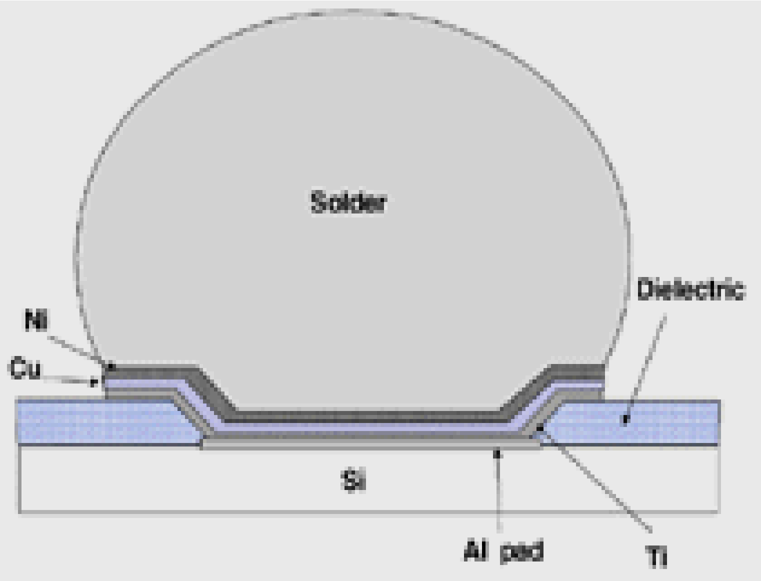

Figure 1: Illustration of UBM applied on silicone wafer prior to bumping.

A variety of flip-chip interconnection technologies have been developed by the electronics manufacturing industry, as well as research institutes, such as, electroplating, screen printing, evaporating, solder spheres, injection moulding, stud bumping and adhesive dispensing. Evaporating bumps were the original flip-chip approach which contains high-lead solder. The geometry of evaporators for directing stream of materials from a small source to an entire wafer does not readily scale up to accommodate larger wafer. However, evaporators will remain important for smaller wafers in many specialty applications.

Electroplating has long been preferred as a method to produce excellent quality, fine pitch solder bumps but it is a difficult process to proposed lead-free alloys. Electroplating of ternary and quaternary lead-free alloys will further increases process complexity and cost. This is due to the difficulties in controlling bath chemistry and in avoiding contamination with the number of bath required.

Stencil printing easily adapts to lead-free solders, since the paste is available in a

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wide range of alloys, however, it is limited to bump pitches greater than 200µm. The use of molten solder must be well separated during reflow to avoid solder bridging. The important thing to be aware is to maintain the stencil alignments across the wafer. Some advantages and disadvantages of electroplating and screen printing methodology are highlighted in the paper.

Materials

Packaging trends moving toward the smaller, faster, lighter and cheaper packages, which from fine-pitch Surface Mount Technology (SMT) towards Area-Array Packaging and Ball Grid Array (BGA), Chip-Scale Packaging (CSP) and Flip-Chip (FC). The choice of solder alloys is determined by the requirements of both processes and the reliability. Chosen solder alloys shall be able to maintain its physical and mechanical integrity while in application.

To be a viable lead-free solder alternative, it has to meet criteria such as having melting temperature similar to SnPb solders, particularly 63Sn37Pb solder. The physical properties shall be no poorer than those of SnPb solder, exhibiting good fatigue resistance, compatible with existing liquid flux systems; it shall also be non-toxic and relatively low in cost (Ning 2004). The following are some possible lead-free alloys and pastes which could be used in wafer bumping processes.

- Sn99.3/Cu0.7 (melting temperature: 227°C)

Soldering qualities must equal to eutectic SnPb, however, wettability is reduced and fillet exhibits rough and textured appearances. This alloy has the poorest mechanical properties among all lead-free solders. It is best suited for use in wave soldering because of relatively low material cost.

- Sn/Ag/Cu (melting temperature: 217°C)

Copper (Cu) is added to SnAg to lower the Cu dissolution and melting temperature. It has improved wettability, creep and thermal fatigue characteristics. Brite-Euram (Ning 2004) project reported better reliability and solderability than SnAg and SnCu alloys and recommended as general-purpose solder alloy. The alloy meets economic and availability requirement, as well as other acceptance criteria.

- Sn/Ag (melting temperature: 221°C)

The alloy has good solderability and mechanical properties. However, the alloy is prone to tin-whiskers formation due to higher tin content.

- Sn/Sb (melting temperature: 232°C)

An alternative solder alloy for relatively high temperature application. However, Sb has same toxicity level as Pb.

METHODOLOGY

Electroplating

Electroplating starts after application of under bump metallization (UBM) and

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preparation of designed template. This method offers excellent control on deposition rates and uniformity of bumps for void-free formation. Bath chemistry and composition must be carefully controlled since these parameters affect deposition properties. For example, electroplate composition; electroplate surface roughness or hardness and the crystalline structure. The main steps involved in plating solder bumps are: (a) incoming wafer inspection, (b) wafer cleaning, (c)UBM and seed deposition, (d) photo-resist patterning and developing, (e) plating (UBM), and (f) electroplating (for example: Sn, SnAg or SnCu) (g) resist stripping, (h) UBM/seed etching, (i) fluxing/reflow, (j) flux cleaning , (k) physical and materials characterization (EBARA 2004).

The UBM layers were designed to be lead-free alloys and it must fulfill the design of having an adhesion layer, a diffusion layer and as a base for electroplating work. Sputtered titanium (Ti) promotes adhesion of layers, sputtered Cu as plating base, and a diffusion layer was obtained using a thick electroplated nickel. Figures 2 and 3 show solder bump formation and process flow in electroplating

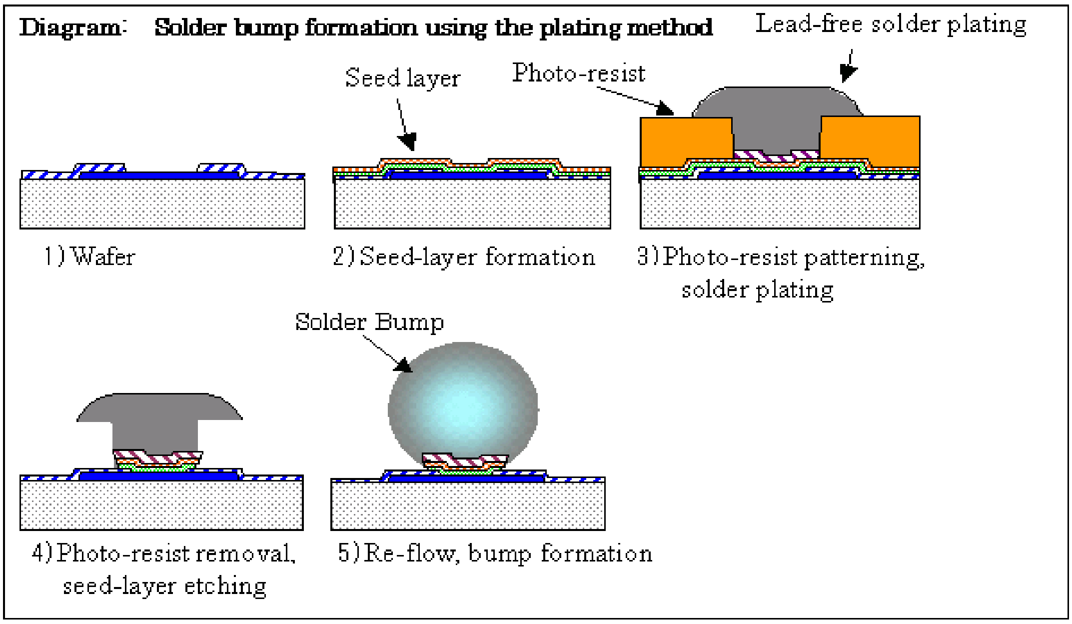

Figure 2: Solder bump formation by electroplating processes [4].

Stencil Printing

The bumping process requires UBM to be clad with the new solder material. The printing processes normally followed by reflow at a temperature of about 20°C above the melting temperature of the solder. It is then followed by cleaning and final inspection [1;2]. Solder printing requires fine-pitch stencils, solder pastes adapted for fine-pitch applications and optimised printing parameters. The following factors have to be considered in order to achieve high quality and reproducible precision of ultra-fine pitch printing.

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- *Printing equipment*: printer, wafer holder
- *Stencil:* aperture quality, wall smoothness, thickness, size, geometry
- *Machine set-up*: print speed, pressure, snap-off, separation speed, alignment.
- *Squeegee*: squeegee material, hardness, angle (45°)
- *Solder paste*: particle size, distribution, viscosity, thixotropy, flux vehicles, slump characteristics and metal content.
- *Environment*: temperature, humidity, dust,

The process involves squeezing solder paste through a screen stencil to deposit bumps directly to die pads on the wafer. Volume and height of the deposited solder depends on the thickness and size of the openings the applied stencil and squeegee material.

Solder bump must undergo a reflow process to become fully stabilized. The bump reflowed in a convection oven under nitrogen atmosphere. Figure 4 shows the recommended profile for solder reflow. The composition of the bump material may be high-lead content, eutectic or lead-free. The equipment and the process must be capable of handling a wide range of temperature profile variation to maintain thermal uniformity within each process profile [6].

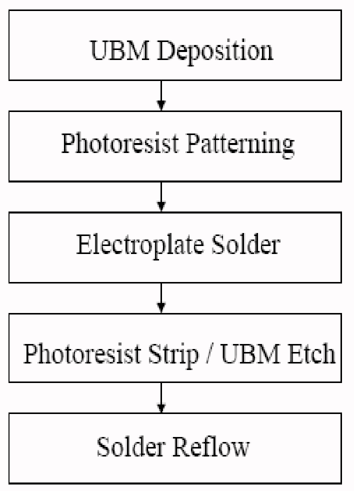

Figure 3: Electroplating processes [5].

DISCUSSION

The two processes selected for wafer bumping were briefly discussed here. The methods selected are electroplating and screen printing. Both of them were chosen because of their advantages in the flip-chip applications. Electroplating achieved by using electrical current through a solution containing dissolved metal ions and the metal object to be plated. The metal object serves as the cathode in electrochemical

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cell and attracts metal ions from the solution. Electroplating starts at UBM level and performing template, plate, and strip to form the bump interconnections. Process flow of electroplating solder bump begins on wafer with aluminium bond pad and having passivation layer. The UBM system was sputter on top of aluminium pad and coated with photoresist film. The electroplated solder bumps were deposit and photoresist were removed for the reflow process.

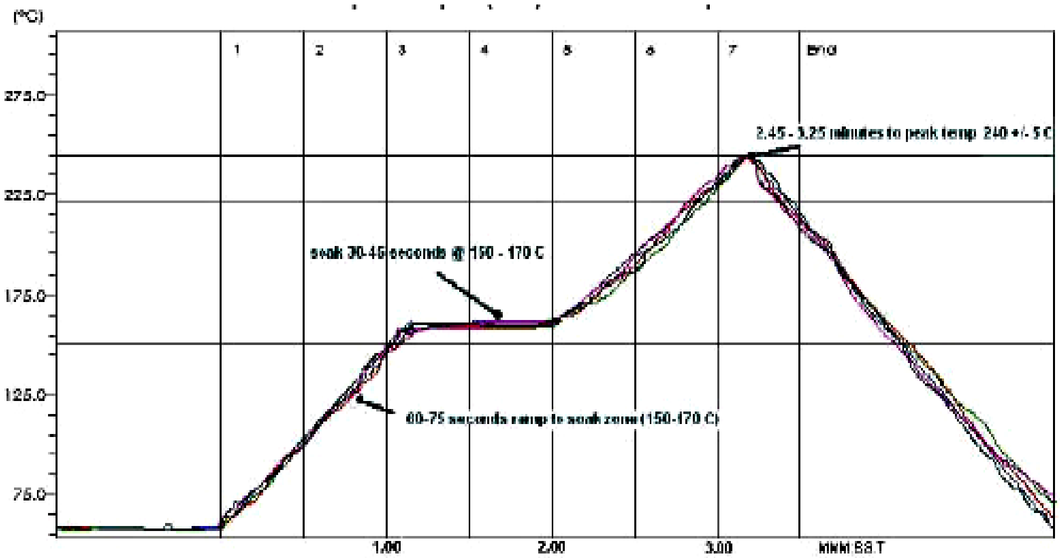

Figure 4: Recommended profile for SnAgCu for solder reflow.

Figure 5 shows the schematic diagram for deposition of metals on silicon wafer. The process needs power supply to deliver an electrical connection, anode and cathode as a wafer-plate to receive ions from anode.

Referring to Figure 6, there are different steps in plating binary, ternary and quaternary alloys. It is not surprising that it is significantly easier to plate pure metallic bumps than SnAg or SnAgCu bumps. The main limitation for electroplating is the difficulty in depositing ternary and quaternary alloys. Basic electroplating can be done on binary system and it can be reflowing as normal step. Ternary compositions of alloys need to be deposited layer by layer and reflowed in the oven to form bumps. Electroplating process is applicable for pitches down to 40µm. The ITRS predicts a decrease of bump pitch for flip chip touch in general, from 160µm in year 2002 towards 90µm in year 2010 and 70µm in year 2016 for high I/O and high power chips. Bump height uniformity is the range of ± 1µm which means better uniformity with stencil printing technique [3].

This process offers the widest set of material choices and compositions of any deposition processes used today. It also offers the broadest range of bump sizes, pitches, pattern and also the most cost effective. The challenges electroplating faced in the lead- free are wafer contamination, uniformity, sputtered film etch and

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reliability. Wafer contamination can be described as an exposed wafer with metal bond pads, having a thin oxide layer on the surface and need to be removed to make successful bumping.

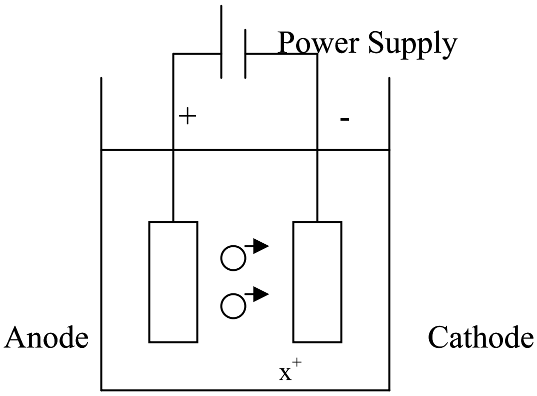

Figure 5: Schematic diagram for deposition of solder bumps.

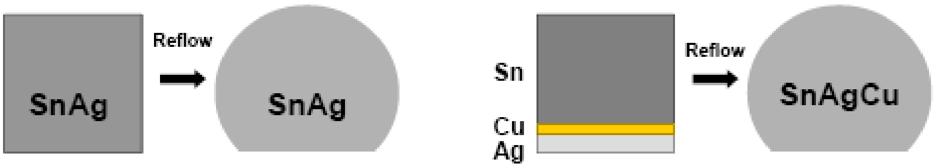

Figure 6: Different steps on plating binary and ternary alloy.

Stencil printing is a low-cost flip-chip bumping method and this method is compatible with surface mounts technology (SMT) processes and flexible with different solder materials. Three general methods exist for stencil fabrications in stencil printing were chemical etching, laser cutting and nickel plate-up. Chemical etching cannot support fine geometry of solder bumps, and considering not a variable process, laser cutting is a variable process for fine-pitch device and the suitable methods to create wafer bumping stencils due to combination of low-cost aperture and smooth surface finish is the nickel plate-up method.

The process flow of stencil printing started from wafer preparation having passivation layer and aluminium bond pads. The electroless Ni/Immersion Au one of the example UBM systems was applying on the wafer. Solder pastes type V and VI were usually used in develop solder bumps because of their fine geometry and smooth. Solder pastes was transfer through the stencil to the wafer by pushing some amount of solder paste across the stencil with a squeegee blade. After applying solder paste, reflow process take part and finally the cleaning process. A few parameter need to be considered when using stencil printing.
Table 1 shows the printing parameters we need to consider before forming a solder bumps. The parameters such as stencil material, thickness, snap-off, squeegee

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material, print speed, squeegee pressure, separation speed and also the print sequence. Stencil material we can choose either metal or plastic but preferring to use metal because it is easy to clean, robust and commercially available. For cleaning purposes, it is recommended to verify the compatibility of the clean-up solvent with the metal stencil frame adhesive.

Stencil thickness is important in stencil design. Paste deposition applying onto a wafer is impacted by the relationship that exists between the pad size, aperture opening and foil thickness. The aperture appropriately sized for a pad, either a stencil too thin or too thick it still cause less than optimal deposition of solder paste. These forces can be quantified and represented as a measurement called the Aspect Ratio. A broad set of rules has been adopted that help us design stencils with appropriate Aspect Ratios depending on the type of stencil ordered.

Table 2 showed the comparisons between electroplating process and stencil printing process. From the table, electroplating process can produce fine pitch solder bump compare to the stencil printing methods which produce more coarsening surface. Comparing in cost, stencil printing was much lower than electroplating because the materials and equipment used compare to the electroplating which need an electrical connection to deposit metals onto solder.

Table 1: Descriptions of stencil design guideline in stencil printing.

	Description
Stencil Material	- Metal or plastic - Preferred metal because easy to clean, robust and commercially available.
Stencil Thickness	- chips (leadless); 6 mil(152.4 µm) thick stencil. - SOIC's; 10 mil(250.4 µm) thick stencil. * *Possible to obtain dot height of 80 mils(2032 µm) with a 1 mm(40 mils) thick plastic stencil*
Snap-off	- contact print (0 snap-off). - higher dots with same thickness; snap-off up to 1 mm(40 mil) is recommended.
Squeegee Material	- metal blade; metal stencils - polycarbonate blade; plastics stencils
Print Speed	- 25 – 50 mm/sec (1-2"/sec)
Squeegee Pressure	- 0.2 to 0.3 kg/cm
Separation Speed	- slow (0.1-0.5 mm/sec) for 3 mm distance

Regarding to the lead-free issues nowadays, electroplating has a low flexibility to handle with lead-free materials due to the contaminations, intermetallics growth and

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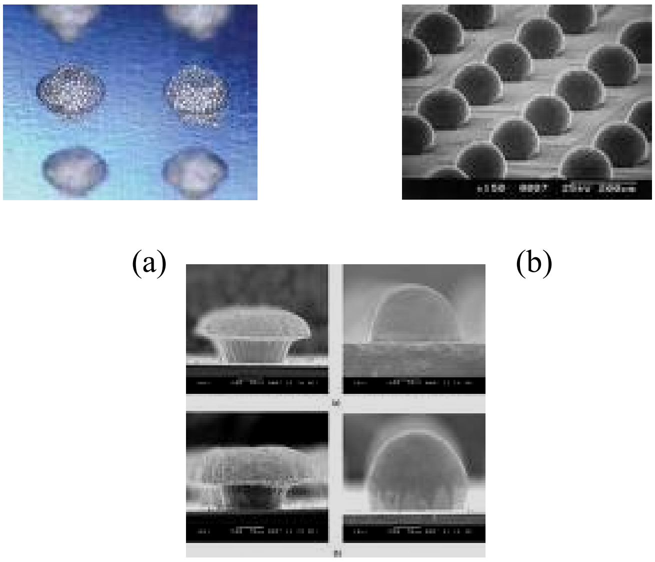
so on. Stencil printing one of the methods easily to handle with lead-free materials. Applying solder paste on the template and then squeeze becoming this methods easy to handle.



(a) (b)

(c)

Figure 7: (a) Solder deposit by stencil printing before reflow (b) Solder deposit after reflow using stencil printing (c) Solder bumps before and after reflow by electroplating process.

Table 2: Comparison between electroplating process and stencil printing process.

Electroplating Process	**Stencil Printing Process**
High cost	Medium/Low cost
High quality bump produce	Low quality bump produce
Having fine pitch	Bump has coarse pitch
Using bath chemistry as a medium to	Stencil template were use as a tool to
deposit solder	deposit paste to form bumps
Used power supply as electrical	Used squeegee blade to squeeze paste
connection	through the template
No need in fabricating	Three general methods in fabricating
	stencil; laser-cutting, nickel plate-up and
	chemical etching
Bump size ≤ 50 μm	Bump size >100 μm
Hard to handle with lead-free	Easy to handle with lead-free

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Figure 7 shows the differential solder deposit between electroplating process and stencil printing before and after reflow. Figure 7a and 7b showed for stencil printing process meanwhile figure 7c refer to the electroplating process. We can see the solder must be heated above its melting point and be completely molten while reflowing process.

Nowadays, the industrial need a fine pitch solder bumps compare to the coarse pitch bumps although the cost for fabricating fine-pitch bumps quite high. Many of the industrial manufacturing company intend to use electroplating process rather than stencil printing because of the having a fine-pitch bumps and also the smaller sizes of bumps without considering on cost although cost is the main priority to consider

CONCLUSIONS

As conclusions, the pros and cons of two lead-free bumping methods selected which are electroplating and stencil printing were discussed. Electroplating intend to be the most effective way to produce lead-free bump size as low as 50 µm whereas the stencil printing limited about 100 µm. However, the electroplating process difficult to deposit especially for ternary and quaternary alloys and also the start-up cost much higher compared to the stencil printing. Besides that, the solder bumps forming by electroplating having high quality due to the stencil printing process. The challenges in lead-free nowadays encourage stencil printing process more easily to handle whereas the flexibility of electroplating process is low with lead-free. The major issue in electroplating is difficulty in controlling alloy stability and requires more tender care and it is suggested that a further studies to overcome the stability of alloys in bath chemistry of electroplating methods.

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