Novel Electroformed Ni-Au Alloy for High Temperature Semiconductor Test Structures

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Abstract

The ongoing reduction in semiconductor and package pitch leads to challenges for engineering suitable miniaturized test and measurement contact vehicles. Traditional probe card approaches for miniaturization may reach fundamental limits for reduction in scale and pitch. Direct electroforming of conductive electrical contacts at pitch using LIGA technology can allow for direct registration to the test points, the simultaneous formation of all contacts and an opportunity to extend the roadmap for miniaturization.

We report here on a new and novel nickel-gold alloy (one to three percent gold by weight) that can be produced by electroforming. This new material was computationally designed to optimize the thermodynamics of the two alloy components such that the alloy has a temperature stable nanocrystalline grain structure which produces highly desirable mechanical and physical properties. Specifically, the alloy is highly electrically and thermally conductive with a resistivity of 10 micro-ohm-cm, while also having a yield strength in excess of 1.5 GPa and an elastic modulus of 130 GPa. This combination of high strength and moderate elastic modulus creates and optimum for mechanical elastic stored energy in a formed contact beam. That is to say, contacts engineered from this material are flexible and strong enough to remain in the elastic regime and have sufficient normal force to maintain low and stable contact resistance, which boosts their long term service life. Further, the alloy shows a fixed cantilever beam bending fatigue limit of more than 1 GPa, further enhancing its viability for long term service. For applications requiring even more strength a 2 GPa yield strength version has also been produced, however this version leads to minor trade-offs in terms of ductility and electrical resistivity and cost.

Since these contacts will be used at elevated temperature, the alloy has been designed to be nearly as electrically conductive as plated unalloyed nickel and thermodynamically stable under long term high temperature storage conditions of 400 C. Characterization of the microstructure shows that it is a supersaturated solid solution of Au in a Ni host matrix with evidence of preferential Au segregation to the Ni grain boundaries. Xray diffraction analysis confirms a nanocrystalline grain structure whose size varies as a function of the alloying content. By segregating the Au to the grain boundaries, we extend the electron mean free path and boost electrical conductivity. We also reduce the grain size of the metal leading to improvements in mechanical properties such as yield and fatigue.

The electroplating solution is environmentally friendly with no significantly hazardous materials and is REACH compliant. We have shown chemical compatibility with a limited test set of standard photo-resists and masks used for the LIGA process. The plating process is reasonably fast and has shown the ability to plate layers as thick as 400 um without cracks, defects or voids.

For some applications it may be desirable to add more plated layers to engineer the contact surface. Gold and other precious metals can be plated on top of the Ni-Au layer with good adhesion and lead to improvements in long term low level contact resistance.

Key words

Electroforming, Materials, Plating, Test Probes

I. Introduction

Moore's law predicts the ongoing reduction in size required to manifest the improvement in semiconductor technology that we all enjoy. This size reduction has impacts on many aspects of semiconductor design and manufacturing. An often-overlooked area of technology is in semiconductor test

methods.

A standard approach to semiconductor test relies upon the use of electrical contact probe pins that are assembled into a test fixture and allow for direct contact to the semiconductor package. These are so called "top-down" methodologies where discrete contacts are fabricated then assembled into the test vehicle. Scaling this solution to ever smaller pitch and size is problematic in terms of assembly and the degree of ultimate miniaturization. Assembly requires each contact to be held or managed while it is bonded so some amount of physical space is needed to grip the contact. This inhibits miniaturization progress.

One design approach to reinvent this process relies on the use of LIGA technology to electroform monolithic electrical contacts. These can be made discretely, then assembled in the traditional sense, or then can be fabricated directly on the test device which would then allow for photolithographically defined accuracy and precision in terms of placement.

A challenge in using this approach is leveraging an alloy that meets the electromechanical demands of the application. The ideal material would be highly electrically conductive to ensure that the contact can have enough ampacity to handle 1 A of power without excessive joule heating. Further, the alloy should have the highest elastic stored energy as possible. This is best represented by the dimensionless ratio of the yield strength/elastic modulus, where a higher value means more elastic stored energy. Ideally this value is greater than 0.01. Lastly, the alloy needs to be suitable for electroforming.

In this work we leverage our licensed knowledge and tools for alloy design to create an optimized metal for semiconductor test.[1] Nickel is a reasonably good starting place for the alloy but on its own it lacks the strength required to obtain satisfactory elastic stored energy. Reducing the grain size of the nickel has been shown to very effectively increase the strength of the alloy.[2]

Traditional nano-forming alloying additions such as W are added in relatively high concentrations and lead to an increase in electrical resistivity and thus are not preferred for this application. The computational model showed promising results for the use of Au as a minor alloying element. The Au segregates to the grain boundaries quite efficiently, and thus there is little Au remaining in the crystal matrix. Residual alloying elements in the matrix lead to electron scattering and reduced electron mean free path. By eliminating this scattering when we alloy with Au, the core of the grains remains substantially free of gold, and hence the electrical conductivity of the alloy remains quite close to that of pure nickel.

II. Materials & Methods

A. Ni-Au Electroplating

The nickel gold alloys for this work are made by electroforming. Typical plating process parameters are as shown in Table 1.

Table 1. Ni-Au Plating Process Parameters

Parameter	Value
Temperature	40 C
pH	6-7
Anode	Ni, soluble
Current density	30-90 mA/cm^2
Plating rate	0.2 to 1 um/min
$NiSO_4*6H_2O$	60 g/l
$HAuCl_4$	2 g/l
Complexing agent	0.5M
Leveling additive	2 g/l

The substrates chosen for this work were either monolithic copper foils or patterned PCB substrates. For the foils, the Ni-Au was electroformed onto the foils, then the Cu backing material was selectively etched from the composite. For the PCB patterned samples, the plated parts could be lifted off the substrate after selective etching of the copper substrate.

B. Ni-Au Alloy

The plating process provides the flexibility to make various alloys from the same or similar plating baths. We built alloys with different Au content to optimize the alloy amongst competing key performance indicators.

C. Characterization

X-ray diffraction is an effective tool to quantify the impact of alloying additions on the effective crystallite size of the alloy. We used CuKα x-rays in a theta two theta Siemens D5000 powder diffractometer. Electrical resistivity was measured with a four-point probe with gold contact tips.

III. Results

Hardness and Crystallite Size

One of the goals of the work was to produce small and stable grains in the alloy. Adding Au into the alloy forces segregation which drives a reduction in grain size. Figure 1 shows the relationship between Au content in the alloy and the reduction in crystallite size. Further, the Au additions stabilize the grain size to ensure that grain growth does not occur during normal thermal excursions anticipated in a

semiconductor test application. Table 2 shows a summary of the alloys, hardness and crystallite sizes obtained for preferred alloy configurations.

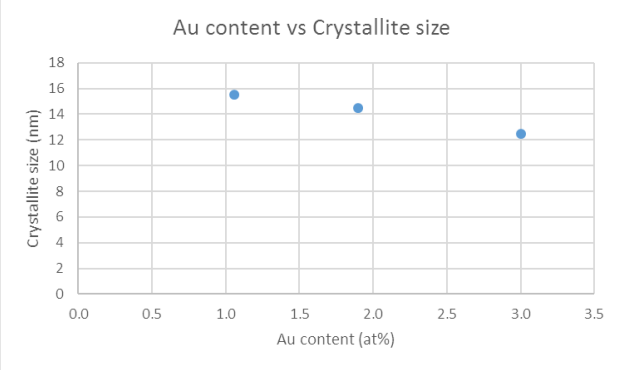

Figure 1. Crystallite size of the Ni-Au alloy as a function of the Au content. Additional Au alloying agent leads to a reduction in crystallite size.

Table 2. Alloy compositions and properties for Ni-Au alloys.

Alloy	Crystallite size (nm)	Hardness (HV10)
Ni-1.2at%Au	15	584
Ni-3.0at%Au	14	644

Resistivity

Several Ni-Au alloys were built then tested for resistivity. There was an essentially linear relationship between Au content and resistivity. For the targeted range of about 2 at%Au, the resistivity is only slightly higher than electroplated pure Ni, as shown in Figure 2.

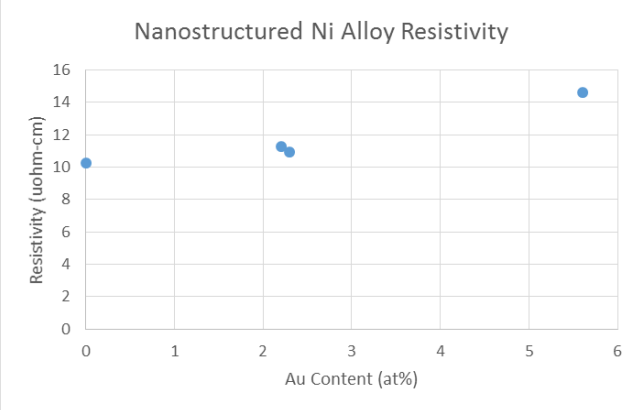

Figure 2. Electrical resistivity of Ni-Au alloys as a function of Au content.

Thermal Stability

Two alloy configurations, 1.2 at% and 3.0 at%, were heat treated to determine the thermal stability of the alloy. Low load microhardness testing (10 g, HV) was performed after one-hour exposure at various temperatures. Figure 3 shows the hardness response as a function of heat treatments.

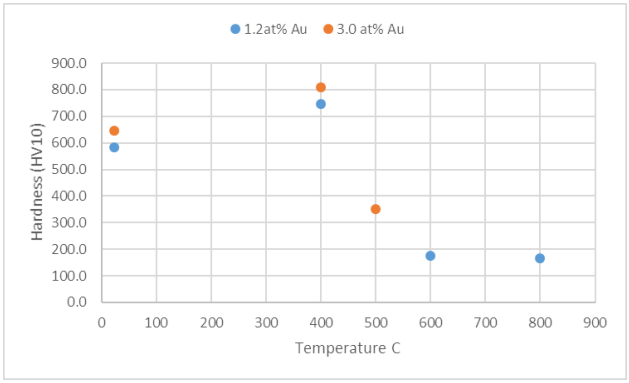

Figure 3 – Hardness of Ni-Au electroformed contacts after one-hour thermal exposure.

The thermal response indicates that the alloy is thermally stable up to a temperature of more than 400 C. This is sufficiently stable at temperature to meet the application of semiconductor continuous use test environments.

We can also evaluate the thermal stability using x-ray diffraction. The Ni-Au alloys will show primary (111) and (200) peaks. The broad spectral response in Figure 4 indicates a nanocrystalline structure which can be quantified using the Debye formula. The blue lines indicate the alloy in the as plated state while orange is after one hour at 300 C. Some minor relation in the structure occurs but no significant grain growth nor recrystallization. Further, the peaks indicate that the alloy is a solid solution of Au in the Ni matrix.

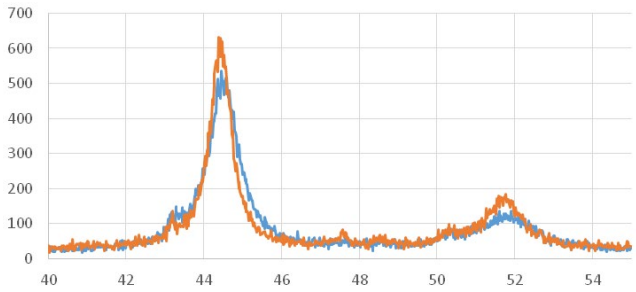

Figure 4. XRD theta-two theta spectra of Ni-Au alloy before (blue) and after(orange) one-hour heat exposure at 300 C.

Mechanical Properties

Strength is a key performance factor in the application, especially relative to the elastic modulus. Miniature tensile bars were electroformed from the Ni-Au alloy. These were tested on an Instron with a non-contact profilometer.

The elastic modulus of the alloys remained constant across various alloying amounts, always at 130 GPa. This is on the low side for nickel, which shows some degree of anisotropy in the elastic modulus. This is attributed to the alloy preferentially depositing along the low modulus crystal planes, and that the bulk of each grain is essentially pure Ni, so we would anticipate the grains to dominate the elastic modulus performance.

The tensile yield strength varied as a function of the alloy content. At 1.2 at% Au the yield strength was 1.5 GPa and at 3.0 at% Au the yield strength increased to 2.0 GPa. There was some ductility loss at the higher Au loading with little post yield deformation.

At a loading of 1.2 at% Au and a yield strength of 1.5 GPa, the ratio of yield strength to elastic modulus is 1.5/130 = 0.0115, which is more than our target of 0.01. At a strength of 2.0 GPa and with the modulus unchanged at 130 GPa, the ratio of strength to stiffness is even larger at 0.015.

Since these materials will be made into contacts that need to see many cycles of durability, the fatigue performance of the springs is critical. Straight rectangular prisms of monolithic Ni-Au were made at the target concentration of 1.2 at%. These samples were then configured into a cantilever bend style fatigue device with a non-reversing applied load required to produce an outer fiber stress on the part of 1 GPa. Parts were cycled to 10k, 40k, 100k, 250k, and 1,000k cycles. Visual inspection and SEM inspection showed no evidence of cracking or fatigue crack growth during these cycles. This suggests the fatigue limit in the alloy is 1 GPa or higher.

IV. Discussion and Application

The Ni-Au alloy has a unique set of mechanical and electrical properties. These properties could enable improved performance and miniaturization in semiconductor testing applications.

Since the Ni-Au alloy is produced by electroplating, the applications for the technology are either in the electroformed state or as an additional plated layer.

For electroformed contacts, the plating solution has to be able to throw down into holes and complex shapes as well as deposit fully dense and with low stress. The deposit and the edges of the formed beams must be crack free in order to ensure optimum mechanical performance, especially in fatigue.

The plating bath operates in a low stress condition. Stress tabs have shown the plating bath to produce a slightly tensile plated deposit.

Plating throwing power relates to the ability of the plating bath to produce an even thickness distribution and alloy composition across the plated part. Some of these challenges can be overcome using well-known plating best practices like shielding, enhanced flow and current thieves. We have found the alloy composition to be reasonably consistent and uniform across plated parts.

The alloy can be plated with good adhesion to various metallic substrates. As such, one other route to performance could be to electroplate a layer of the Ni-Au alloy on top of a lower performing but lower cost substrate. Since many of these electrical contacts are used in bending mode, the application of a strong mechanical material on the outer fiber leads to synergistic boost in strength and stiffness.

V. Conclusion

A novel Ni-Au alloy has been invented and reduced to practice as made by electroplating or electroforming. The alloy has a unique combination of high strength, low elastic modulus, high fatigue limit and high electrical conductivity. These combined properties make the alloy well-suited for high performance electromechanical applications, such as semiconductor test probes.

VI. References

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