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Performance of Ni-alloy MEMS-probes coated with PdCo films in semiconductor wafer test

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Abstract: A novel electroplating system and approach for selectively coating of probe tips for wafer and package testing are presented. A Ni-alloy probe tip with an overcoat layer of 3.5um thick PdCo provided less tip wear and better electrical contact resistance performance in wafer testing. Microstructures of films resulting from different conditions of electroplating process were analyzed, most uniform films were obtained at 5 mA of plating current conditions. The probe tip wear throughout probe life testing was monitored which indicates PdCo film with Au underlayer establishes good electrical contacts.

Keywords: Wafer test; electroplating PdCo films; probes;, contact resistance

Lastnosti MEMS sond iz Ni litine in prevlečenih z PdCo filmom pri testiranju polprevodniških rezin

Izvleček: Predstavljen je nov sistem selektivnega nanašanja prevlek na konice sond za testiranje rezin. Konica sonde iz Ni litine, ki je prevlečena za 0,35 um debelo plastjo PdCo predstavlja boljši električen kontakt in manjši vpliv dotika pri testiranju rezin. Analizirane so mikrostrukture plasti, ki nastajajo pri različnem procesu nanašanja z elektriko. Najbolj homogene plasti so bile dosežene pri toku 5 mA. Spremljana je bila obraba konic sond, pri čemer smo ugotovili, da dober električen kontakt zagotavljajo konice z PdCo plastjo, ki je nanešena na plast Au.

Ključne besede: testiranje rezin; nanos PdCo plasti z elektriko; sonde; kontaktna upornost

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1 Introduction

In wafer and package testing, spring connectors are utilized to transmit test signals from a testing system and the semiconductor device by an electrical contact on the device pads or bumps. The probes shown in the probe card structure in Fig. 1 or spring pins shown in Fig. 2 are used in wafer and package testing respectively. Spring pins are used in flip-chip bump testing in sockets and conventional probes are typically made of Pd-alloys or beryllium-copper (BeCu) [1-3], and can potentially have outer layers of overcoat, while more advanced style probes produced lithographically are made of Ni-alloys, or MEMS (Microelectromechanical systems) probes [4-7]. Outer layers coated on those probe types can be pure or alloys of nickel, gold, or rhodium and palladium, intended to increase the hardness and decrease wear of the probe or pin. In testing, it is required for probe tip to pierce the oxide layer on the pad or bump consistently to secure good electrical connection. A very hard probe tip, achieved with an overcoat, is needed for long probe life. This type of coating on the spring section of the probe is undesirable since it may peel off during cycling operation of a probe or lead to an unwanted change in the spring characteristics of a probe and also it is more expensive to coat the whole probe.

The spring section of the probes are typically electrodeposited from nanostructured Ni-alloys, NiMn or NiCo, utilized as structural spring members and contact tips may have various coatings for reliable electrical contacts needed in fine pitch Cu pillar and other test requirements [7-11]. These types of alloys were used for their strength, ductility and thermal stability as well as good electrical conductivity necessary for good electrical contacts. In addition, these two alloys are electroformable and lend themselves to MEMS processes allowing creation of small structures and probe geometries.

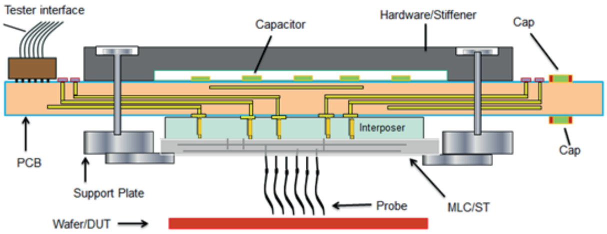
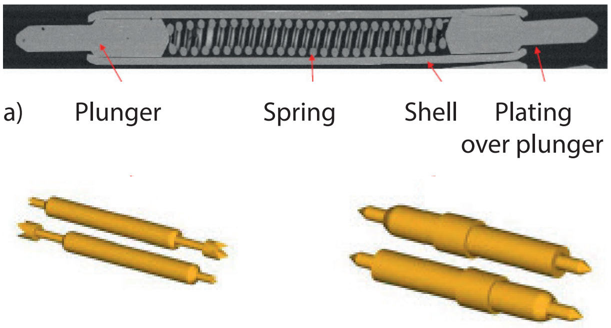


Figure 1: The probe card structure showing the test system, probes and the wafer. Cap refers to capacitor and MLC/ST refers to multilayer-ceramic and the space transformer.



b) Spring pin types

Figure 2: Spring pins in two different designs typically used in package testing. The spring in the middle is typically made of stainless steel and the other components are made of brass or BeCu.

A coating system for applying a coating to only a tip portion of a probe was developed and used in this study. The coating system includes a container for holding a coating material and a porous plate adjacent the container for receiving a portion of the coating material during a coating process. The system was described in detail elsewhere [12]. The plating solution used was a palladium cobalt solution with a targeted ratio of Pd to Co ranged from 60 wt.% Pd and 40 wt.% Co to 80 wt.% Pd to 20 wt.% Co. Some material properties and contact reliability of palladium cobalt and palladium nickel were previously reported [13,14]. PdCo may offer less porosity and superior finish on the probe surface compared to other coatings. Because it possesses a fine grain structure and a low coefficient of friction, it will prevent metal debris adhering from the contact pad. PdCo-tip plating offers better probing performance in repeated test cycles due to a reduction or elimination of debris buildup on the probe tips. Probes typically contact solder bumps such as PbSn, Cu or SnAgCu bumps and Al or Cu pads on wafers. Various Pd-alloys or films with nanocrystalline microstructures have been investigated using different physical and chemical approaches towards sensors or fuel cell catalyst applications in the past [15-17]. Nanostructured and nanoporous Pd materials were synthesized by electrochemical methods for various fuel cell studies and for its some magnetic properties [18-23].

In this work, different conditions of electroplating process of PdCo coating on NiMn probes were analyzed, and plated probe tip microstructures were studied. It must be stated that PdCo coatings applied on the plunger (contacting ends of pins) or shells of spring pins, manufactured by final machining processes, are produced in a lot immersed in plating solution, quite different than the present proposed process. In this process, MEMS probes are produced by lithographic electrodeposition of NiMn alloy first, subsequently the ends of probes which contact the bumps on wafer are overcoated with series of steps with PdCo. Selective plating of vertical style probes with PdCo overcoat with an underlayer of Au is presented here for the first time. The probe tip wear throughout life testing in test cards was monitored and presented.

2 Experimental

Probe sets as strips for the study were manufactured through lithographic methods. Probes are electroplated from NiMn alloy. The probe formation process begins with laminating the desired material, masking the laminated material to define the probe set and UV imaging this, remove the mask and then develop the imaged material. Subsequently probes are formed from this photoresist pattern defined shape in the plating process. The strip used in PdCo plating is illustrated in Fig. 3 a. One method of getting the PdCo plating applied only to the tips, a resist coating may also be applied to the probes. The resist coating such as NIT215 or NT250 dry films available from Morton Electronic Materials Chicago, Illinois or Intermountain Circuit Supply, Scottsdale, Arizona, were applied by a lamination process. The resist coating may have a thickness of between approximately 30 μm and 50 μm, other than the probe tip. A sketch showing a cross-section of probe tip section with the resist coating prior PdCo electroplating operation is shown in Fig 3 b.

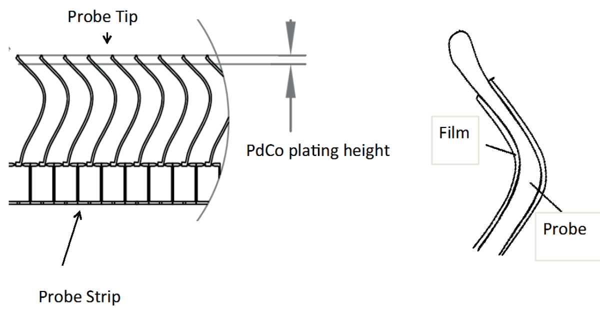
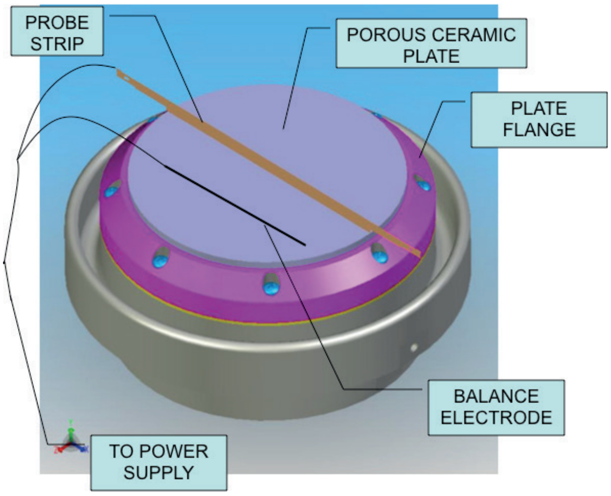
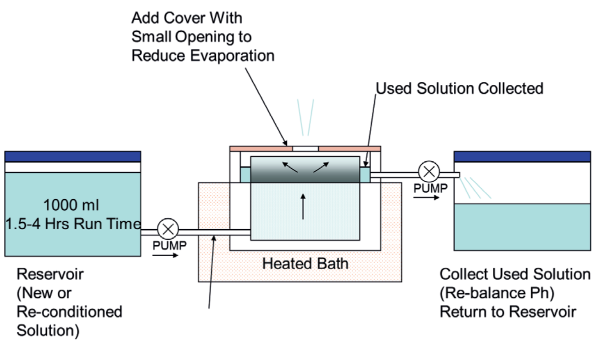


Figure 3: The probe strip used in PdCo plating is illustrated (A on the left) and the probe tip section and the resist coating (film) in (B on the right).



a



b

Figure 4: The plating system.

Figure 4 a shows the designed container with a plating solution. The container may be formed from insulator material and anode may be located within the plating solution. The electrodes and the probes are connected to a power source. The probe strip shown in Fig 3 a. comes into contact with the fiber sheets on top of the ceramic plate on the container. Once the probe tips contact the fiber sheets, the plating solution wets the tip of the probes. Fiber sheets may be cellulosic or other synthetic fibers (or nylon, polycarbonate and glass from Whatman International, Clifton, N.J.) similar to those used as filter papers. In order to minimize surface tension of the plating solution to prevent or minimize wicking of the plating solution between probes. It is desirable to plate only tips of the probes in the strip, and prevent plating over the full length. The plating solution is maintained at approximately 50 degrees °C, by using water bath held in glass bowl warmed by hotplate, while the electrical system is held at approximately 4 volts and the current density at approximately 10 asf (Amps/ft, where 1 ft. equals 30.48 cm). In order to plate the probe tips, the backing plate is lowered so as to submerge the probe tips in the plating solution. Current is supplied from the power source to cause the plating solution to adhere to the probe tips. Fig 4 b shows the system with reservoir connection showing a replenishing scheme for the plating solution. The pH of a solution should be maintained during the plating cycle. When used solution collected in the right reservoir deviates from the plating solution pH, then rebalancing meaning bringing the solution back to original pH is carried out before solution is fed back to main reservoir to keep the total volume.

After the plating has completed on the probe tips as planned, the probes are removed from the plating solution, and the resist coating can be removed using a variety of conventional techniques, for example, through the use of a stripper bath, such as ADC available from RBP Chemical Technology, Milwaukee. Alternatively, it may be removed using another material such as n-methylpyrolidinone (NMP). There may be sources of variations across PdCo plating process steps which will impact final probe plating quality and test results. Table 1 summarizes process steps used in this study and nearly forty steps which may contribute to variations in the manufacturing various strips with coatings and finally qualification testing.

In qualification of the PdCo plating process used for the probe tips, a wafer test card was used at real test conditions of wafers. Test vehicle consisted of a MLC (Multilayer ceramic space transformer) bonded with MEMS (Microelectromechanical systems) style probes. For life-testing, 200 probes with PdCo tips plated were used as electrical contacts touching wafers. Probe tips were coated with PdCo with an underlayer of Au to ensure good adhesion and good electrical contact. Probing recipe is as follows: 0.5 A/B ratio in probing chuck movement of Prober (TEL XL) at 70 µm of probe overtravel (OT) which defines the probe deflection amount. Probes are cycled on a prober touching on a wafer contacting bumps. The contact resistance (Cres) measurements at initial, 90K, 175K, 250K, 340K, 425K, 513K, 595K, 670K, 760K and 844K cycles. Cleaning recipe was applied on probe tips was as follows: Every 87 touchdowns, 25 insertions at 50 µm OT to maintain good contact resistance. Cleaning of debris from probe tips during the testing cycle was carried out using a 3M Tape 0.5 µm-grid Type A on a prober. The term 'Touchdown' used commonly in wafer testing industry is described as the probe making a physical and thus an electrical contact with a wafer pad or a bump and the signal passing through the circuit under testing. The probe, the probe card structure and the wafer were illustrated in Fig. 1.

3 Results

When NiMn probes had no tip coating, the contact resistance (Cres) results were not very stable since probe tip sizes grew as probe cycling on contact pads in-

Table 1: Plating process steps

Process Step	
1. SYSTEM PREP	
	Fill heating water bath
	Unplug external thermocouple. Turn hot plate and stirrer on (125 °C / 200 rpm)
	Plug external thermocouple; set hot plate to 65 °C
2. PREPLATE CLEANING	
1. Alconox solution	Pour DI (deionized) water into dish
	Add detergent powder (1%)
	Heat cleaning solution to 45 °C
	Place probes in cleaner 15 min
2. DI Rinse	Prepare DI water rinse baths
	Rinse probes for 5 min
3. H2SO4	30 ml H2SO4, 270 ml DI water, (10% acid)
	Place probes for 5 seconds
4. DI Rinse	Prepare DI water rinse baths
	Rinse probes for 10 min
5. Dry bake	Load baking plate on the hot plate
	Heat to 70 ° C
	Load strips and bake for 15 min
3. PLATING	
1.Mounting the probe strip	Clear Jig (strip holder) of remaining material
	Place strip in the center of jig (probe tip up + curvature left to right)
	Seat strip in bottom of track
	Tighten Set screws
	Place and secure Jig in "Gantry"
2. On sequence	Plug the power source wire to jig
	Turn the data logger on
	Lower the jig (probe tips) into plating fluid
	Adjust planarity if necessary using the level screws
	Make sure the strip is parallel to the Pt anode wire
	Turn on input pump
	Turn on output pump
	Remove the bridge (hydrophilic membrane to promote flow) using Q tips
3. Plating Process	Start the current source and time it for 5 min
	Stop current source
4. Off sequence	Turn off input pump
	Turn off output pump
	Put the bridge back on
	Unplug the power source from jig
5. Dismounting the probe strip	Raise the jig
	Remove the jig
	Remove strip from jig
4. POST PLATE CLEANING	
1. DI Rinse	Rinse probes for 10 min in DI water
2. Dry bake	Load strips and bake for 15 min

creased and the scrub on contact metal pads became smaller and irregular in shape, as shown in Figure 5. This led to higher average Cres values as the testing continued, from less 0.5 Ohms at initial cycling to more than 1 Ohms after 100K cycling and 5 Ohms after 200K cycle testing on pads. The average probe tip diameter grew from 7.5 µm at initial conditions to 18 µm at 100K cycling and 22 µm after 200K cycling. This shows that bare NiMn probe tips do not provide stable Cres necessary for wafer testing, hard and conductive and smooth probe tip materials or coatings are necessary for reliable contact measurements for lifetesting of product wafers. In this study, a relatively inexpensive method of probe tip coating by PdCo is explained. It has only one-step for NiMn electroplating and subsequent single-step PdCo selective plating of just the probe tips. So this process used at this work is radically simpler and cheaper than most widely used existing processes for generating probe assemblies.

Common but more expensive methods for generating probe tips with PdCo or Rh in probe cards have been used in the test industry. Rh tips have been generated on multilayers of Ni-alloys using MEMS process on substrates where up to 25 layers were built up the beams and finally tips, a process also called EFAB [24-25]. In this method, as Ni-alloy beams are electroplated, a sacrificial metal structure made of Cu is also formed. After each layer, a planarization process is employed, then the following thin Ni-alloy layer is electroplated again. The tip made of different metallurgy is done as a final step. Another widely used MEMS-card in the industry involves manufacturing probe beams in many layers and producing PdCo probe tips separately and bonding them together, which is costly and a long process [26-30]. These electrical contacts can be cantilever beams or vertical beams which are also called microsprings. In this method vertical spring starts as a gold bond wire with a spring shape which gets electroplated with Ni-alloy to impart its spring characteristics. After molding and planarization steps, PdCo tips formed separately gets attached in a solder reflow process to wire spring assembly. PdCo tips are generated in an etched silicon wafer.

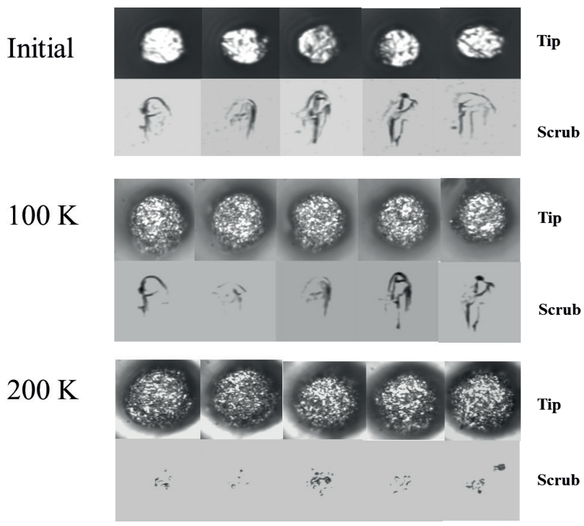


Figure 5: Probes and probe tips made of NiMn and resulting scrub marks are shown at initial touchdown, after 100K and 200K cycling on Al contact pads. As tip diameters grow after cycling, scrub marks start fading.

In this study, the measurements of Pd/Co ratio by weight on the probe strips and corresponding plating thickness readings were made. The palladium content varied from 60 to 78 wt.% in various strips measured by AAS (Atomic Absorption Spectroscopy). Some measurements were initially performed also by WDS (Wavelength Dispersive Spectroscopy). The plating ratios and compositions indicated a range where there is low stress in deposits and no cracking was observed. The plating current was varied to study microstructures and find appropriately uniform microstructures with no sign of cracking in the films. SEM images in Fig. 6-12 show submicron grain structures from different plating current conditions whose duration was approximately 6 minutes. A porous microstructure is observed in Fig. 6 at a low plating current of 3 mA. Most grains have ir-

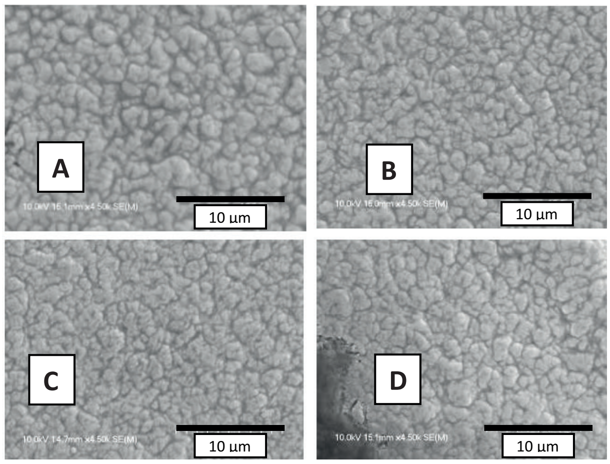


Figure 6: Microstructures produced at 3 mA current conditions.

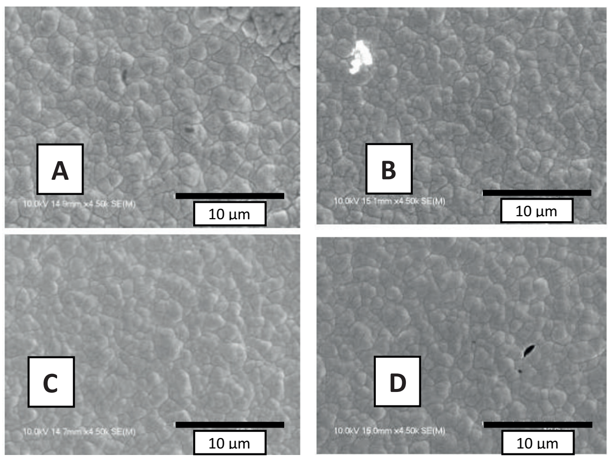


Figure 7: Microstructures produced at 4 mA current conditions.

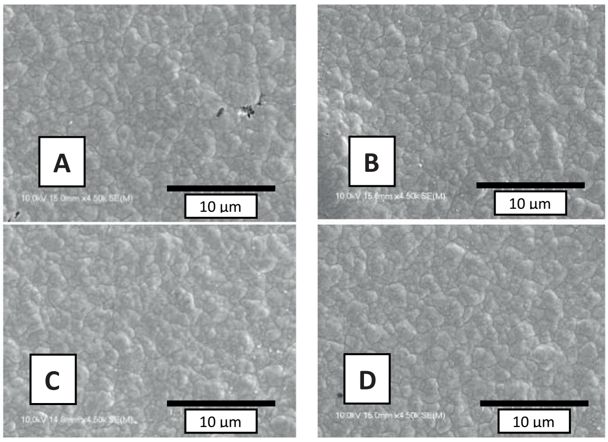


Figure 8: Microstructures produced at 5 mA current conditions.

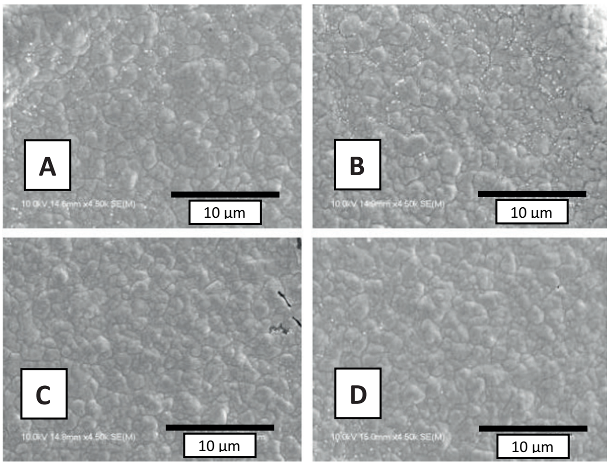


Figure 9: Microstructures produced at 6 mA current conditions.

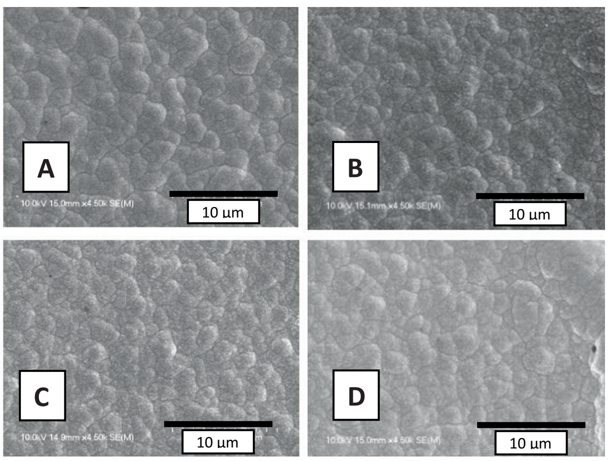


Figure 10: Microstructures produced at 7 mA current conditions.

regular shapes where two or three grains are conjoined together. It appears that grains become more uniform at 4 mA in Fig .7 and at 5 mA Fig. 8 in terms of uniform-

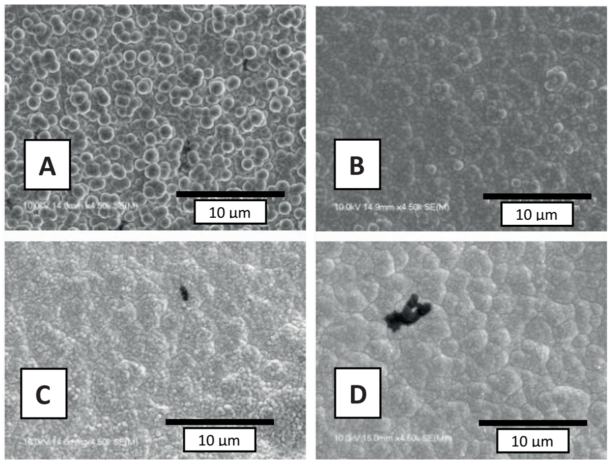


Figure 11: Microstructures produced at 7.7 mA current conditions.

ity of grains and quality of the overplate. Increasing plating current from 6 mA in Fig. 9 to 7 and 7.7 mA in Figs 10-11 changes a fairly uniform size distribution to a somewhat nonuniform or lower quality films. Lower quality films usually have pores or ruptures over the critical surface of probes near their tips. Porous films have typically less integrity and cause delamination of films during aggressive tip cleaning cycles in wafer test. It was noted that as the plating time exceeded 12 min and no stirring was used during the plating cycle, microcracking was observed on the plated surface sections of probe tips as shown in Fig 13. For longer plating time and nonoptimal stirring conditions, microcracking was observed regardless of existence of Au underlayer. Although it is more prevalent to see undesirable microcracking in of PdCo overcoat plated directly over Ni-alloy. It should be noted that the stirring conditions, especially stirring pump-direction was also key to stabilizing the plating quality and compositional uniformity. The compositional variation and grain size variations are less pronounced for stirring condition when operator-to-wall mode is employed. Such mode was used for all plating conditions microstructures are shown from Fig. 6 to Fig. 11. It was seen to produce more uniform microstructures and also compositions of probe beams across the probe strip. The variation of plating composition across a long strip is shown for non-optimal wall-to-operator side stirring direction, as shown in Fig 12, Pd/Co wt. % 60/ wt.% 40 to wt.% 78/ wt.% 22. The pump stirring was optimized to obtain low-stress, compositionally stable uniform grained structures with a uniform and smooth overcoat. In Fig 6-11, images A, B, C, D refer to different locations across a strip analyzed to understand microstructural characteristics. I appears that for these plating conditions, there are no dramatic grain structure or porosity changes within a plating set of conditions. For example, microstructural features in four images of Fig 6 (A, B, C, D) are similar in appearance and porosity. A similar correlation is observed for four images in Fig 7 (A, B, C, D).

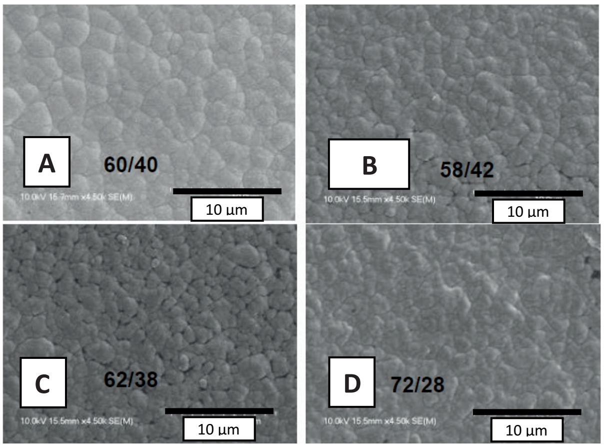


Figure 12: Pd/Co ratio (wt.% of Pd / wt.% of Co) variation for one condition was shown. 6 mA plating current was used. The stirring pump direction was a critical parameter in stabilizing the plating quality and compositional uniformity. Greater variation of plating composition across a long strip is shown for the case of stirring from the wall-side to the operator-side in this case. Pictures labelled as A, B, C, D refer to different locations along the strip.

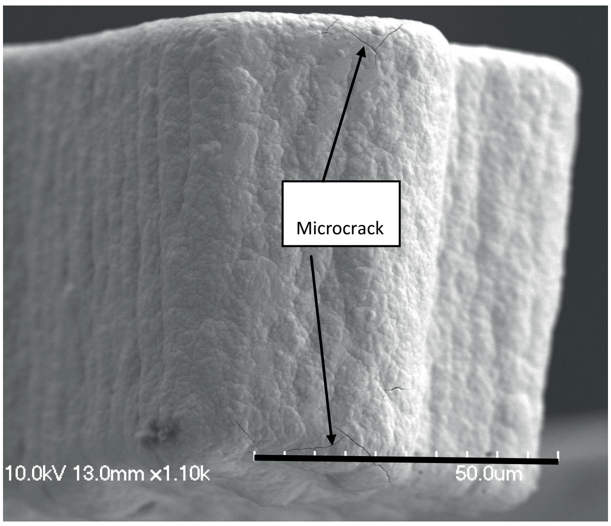


Figure 13: Probe tip microstructure showing microcracks on top and bottom sections.

Figure 14 shows the cross-section of a probe tip where the core is NiMn alloy with electroplated inner Au overcoat layer with an average thickness of 2.9 µm and a PdCo outerlayer with average thickness measured at 5.7µm. Strip 11 in Fig. 14 refers to a strip of probes characterized to exhibit an overcoat chemical composition of Pd/Co 78/22 wt% with a thickness on the high end measured as 5.7 µm on average. This strip was analyzed for Au as well as PdCo coating uniformity and compositions from a total of 14 strips plated in the experiments.

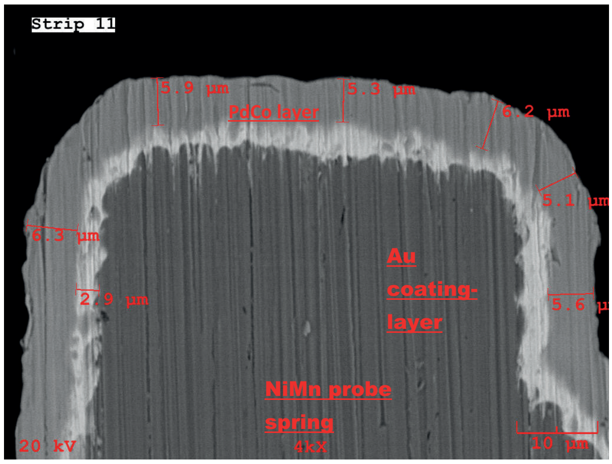


Figure 14: Cross-section of probe-tip is shown for a probe from one of the test strips. Average Pd-Co thickness is 5.7 µm and the average Au innerlayer thickness is 2.9 µm.

Strip probes from selected composition and uniform microstructure lots were used in constructing a test card for lifetest and Cres qualification test. The contact resistance (Cres) is measured using a test system which includes a probe card with contact probes and interface and a test wafer with Al or solder contacts as shown in Fig.1 and in earlier work [4-5]. Signal is sent through one channel which links the prober/probe card and interface which reaches the wafer finally by a probe contact. For some lifecycle and qualification studies, blank wafers coated with Cu or Al or solder materials were used. Bump contact studies were carried out with wafers with Cu pillars or solder-capped copper pillars placed at various pitches, typically daisy chained for contact resistance measurements. Trace resistance was measured for the test vehicle used as the probe card. It contained a probe head carrying probes attached to a space transformer structure including a MLC (multilayer ceramic) and a PCB (printed circuit board), as illustrated in [4]. The trace resistance is calculated as the sum of reistances, $R_{MLC}+R_{probe}+R_{cres}+(R_{probe}+R_{cres})/N$, where R is the resistance and N is the number of probes, i.e. links in the chain being tested. It is more accurate to test many probes due to a negligibly small second term in the equation. For the Cres test, the current is forced through a single probe and all other probes are shorted together and the last probe is sensed.

The average PdCo thickness for test strips was identified to be 3.5 µm. The stability of contact resistance is a very important parameter in wafer test. Probes made from NiMn probes without tip coating did not perform well in lifetest and Cres assessments as the tips wore quickly and Cres became unstable after 100K touchdowns. Therefore a stable, non-corroding, non-oxidizing and hard-tip contact material was needed to improve performance. Coating over the tip should not be adhering to the debris generated during scrub cycle of probe tip on the pad or bump on the wafer. Any accumulating debris on the probe tip must be removed by a cleaning cycle. A smooth, nonporous coating such as PdCo offers opportunities for good electrical contact in repetitive test cycles. Contact resistance and lifetesting on a test card indicated a fairly stable mean Cres of 0.2 Ohms up to 844000 touchdowns on test wafers, as seen in Fig. 15. Initial lifetest and stable Cres target was 500K touchdowns and tests indicated good results. In Fig. 15, each measurement interval represents 10 data points (25 data points at 513K). Each data point represents the average of all 120 Cres probes taken before and after cleaning was applied. Cres mean is well below 0.5 ohms (<0.2 ohms, 15,000 data points).

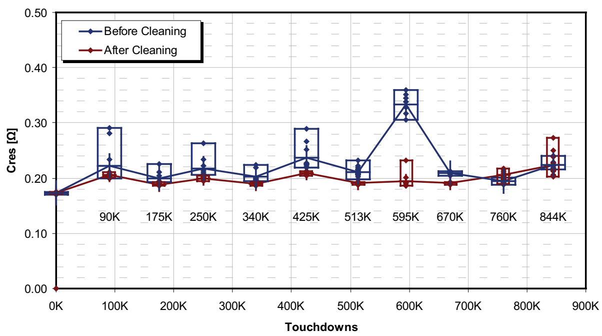


Figure 15: Each data point represents the average of all 120 Cres probes taken before and after cleaning was applied. Cres mean is well below 0.5 ohms.

Figure 16 shows SEM images of probe tips (wedge style) from initial contact on the test wafer all the way up to 854K touchdowns. There is slow progression of tip wear and 12 µm tip width grows to 22um at 250K touchdowns and PdCo and also Au plating on the contacting wedge wears out and NiMn core becomes visible. At 854K touchdowns, the tip width reaches to 33 µm as seen in image 6 in Fig. 16. Despite the tip wear observed, results indicate a good electrical contact based on electrical measurements of Cres as shown in Fig. 15. This was thought to be resulting from the combination of the probe tip composition. The contacting probe surface has both Au and PdCo contacting the bump along with NiMn core and it is possible that current mostly flows from Au plating surfaces in test cycle. Since the gold has the lowest resistivity and no corrosion by products, once the gold plating is exposed, the contact resistance is kept low due to lower resistivity of Au than nickel-alloy. Periodic probe tip cleaning and constant cycling of solder-metal wears out probe tips and breaks through the PdCo overplate, however, this does not seem to cause any significant rise in average contact resistance. Probe tip-pad contact appears to be gold-to-solder pad over lifecycling.

Figure 17 illustrates measurements of the tip width of probes based on SEM photos. The probe tip width reached 16um at 175K touchdowns and Au-underlayer broke through the PdCo overcoat, as the tip growth data shows. The baseline initial tip width was 12 µm. It remained fairly constant at 22 µm from 250K to 550K touchdowns and it grew to 28.6 µm at 760K and 33.3 µm at 854K touchdowns. The graph includes a polynomial which defines the tip wear versus number of touchdown cycles. Probe force stability at initial and final test conditions was also analyzed.

Measurements indicated a constant probe force readings of 8.8 +-0.2 g at 75 µm OT. This suggests that probes survive the test cycle up to 854K touchdown cycle.

It must be stated the PdCo coating can only be applied at tips where it helps good electrical contact between a probe and the bump. It should not be applied over deflecting section of a probe since it can peel off due to insufficient ductility of PdCo coatings over one million cycles necessary. However, underlayer of Au is useful but it is not by itself sufficient for reliable probe contacts over lifetesting. PdCo is harder than Au, leading to decreased wear, increased life and improved reliability in contacting surfaces. PdCo is more stable at higher temperature than the gold. The gold up is stable to 150 °C and the PdCo up to 395 °C under test conditions. During testing, even at high temps, the Cres stays consistent for PdCo plated contacts. Pd oxidizes at high temp ~ 380 °C. Co oxides are thin, self-limiting and conductive. Additionally surface oxides inhibit solder adherence. PdCo has smaller grain size than Au which may lead to lesser potential of diffusion and formation of intermetallic compounds. Intermetallic compound when formed at boundary layer of two dissimilar materials tend to be hard and not very conductive. Pd and Co have higher melting points, 1559 °C and 1425 °C respectively, which show reduced tendency for diffusion and formation of intermetallic compounds. The melting temperature of gold is 1064°C. It was suggested that higher melting point plating material will help inhibit diffusion and formation of intermetallics in earlier research [31]. Also, it was surmised that lower porosity in PdCo does not allow corrosion to penetrate plating and damage base metal. It was reported that PdCo has a lower coefficient of friction than the gold [32]. Solder particles will not adhere to the spring probe surface minimizing excessive contamination or build-up on the probe surface. This provides a consistent contact resistance, allowing for longer periods for testing. NiMn

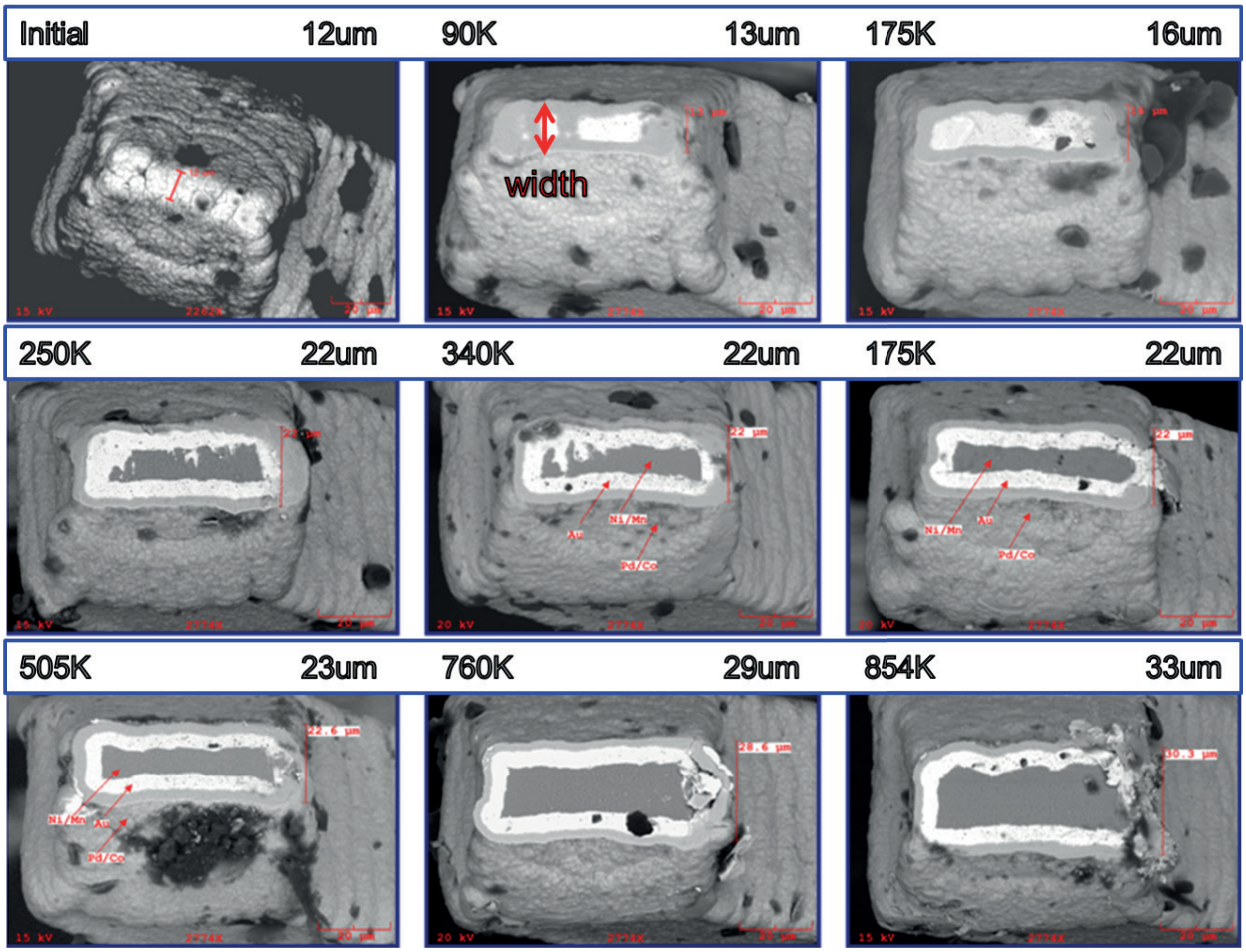


Figure 16: SEM photos showing progression of tip wear in lifetest. The bars above images show number of cycles (from initial to 854K) and measured probe tip with in µm.

alloy is susceptible to oxidation above 100 °C and if used without any coatings as probes, contact pressures need to be increased to achieve stable contact resistance. Also, PdCo (600 HV) [12, 33] is much harder than both NiMn-alloys (300 HV) [9] and BeCu (350 HV) [34]. HV refers to average Vickers hardness values for the electrodeposits. Therefore, probes of these alloys must be coated on the tips for reliable contact resistance.

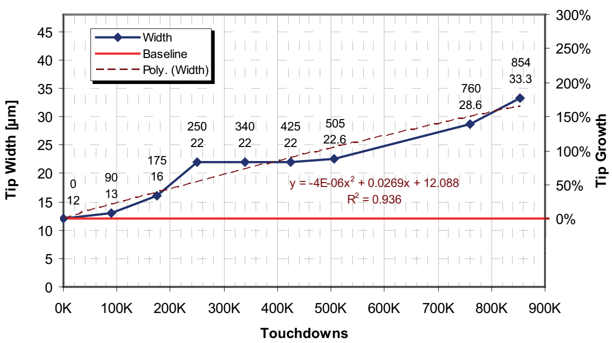


Figure 17: Measurements of the tip width of probes based on SEM photos.

4 Conclusion

A new plating process was developed to plate-up hard PdCo coating in the tip section of NiMn probes used in wafer testing. During testing, PdCo-plating at the probe tip kept Cres low and stable throughout the test even with the excessive wear rate caused by the aggressive cleaning recipe. PdCo thickness could be further optimized to minimize tip wear. Overall Cres performance after cleaning was very satisfactory. The results show the mean value of <0.2 ohms, and a standard deviation of <0.16 ohms. Average tip width grew 200% after 844K touchdowns. Contact force was consistent between initial and after 844K touchdowns.

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