Study of Au Ball Bond
Mechanism and Reliability
on
Pd/Ni/Cu Substrate

by
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A thesis
presented to the University of Waterloo
in fulfilment of the
thesis requirement for the degree of
Master of Applied Science
in
Mechanical Engineering

Waterloo, Ontario, Canada, 2009

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Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

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Yan Huang
Abstract

Microelectronic wire bonding is a manufacturing process used to electrically connect integrated circuits with circuit boards or other substrates. Conventionally, balls are molten at the end of a Au bonding wire and subsequently bonded on Al metallization of a integrated circuit. However, Pd/Ni metallization has recently been used for its improved mechanical properties.

The bondability, bonding mechanism, and reliability of Au ball bonds on Pd are studied in this thesis. The substrates were produced in this project using three different materials. The base material is polished Cu in the shape of a coupon (1.0 cm × 1.0 cm × 0.5 mm). Cu coupons are plated with Ni (1.0 µm) using an electroless process, followed by electrolytic plating of a layer of Pd (0.3 µm), resulting in an arithmetic mean roughness of the surface of 0.08 µm (baseline sample, sample 0). Higher roughness values of 0.2, 0.4, and 0.5 µm are artificially produced by rolling (sample 1), sanding (sample 2), and sandblasting (sample 3), respectively, on the Cu surface before plating Ni and Pd.

A 25 µm diameter Au wire is used for bonding on the polished and roughened substrates with a process temperature of T = 220 °C, and it was found that ≈ 4 % to ≈ 18 % less ultrasonic amplitude was required for successful bonding on the roughened substrates compared to the polished substrate. Bondability is measured by shear testing the ball bonds. An average ball bond strength achieved on the polished substrate is 130 MPa. This value is lower on the roughened substrate with the exception of the sandblasted substrate.

Long-term thermal aging at 250 °C was performed with ball bonds on samples 0-3 for durations of ≈ 300 h. The reliability of the bonds is characterized by non-destructive contact resistance analysis during aging and destructive cross section analysis after aging. Contact resistance values for
the ball bonds range from 1.6 to 3.5 mΩ at 20 °C before aging, and does not correlate with roughness. For the baseline sample, contact resistance of the ball bonds decreases during aging by -6 % (median value), which indicates electrical integrity of the interconnections at high temperature. This decrease possibly is due to interfacial gap filling by Au or Pd diffusion. In contrast, the contact resistance increases for the roughened samples 1-3 and changes are 0.4, 5, and 14 %, respectively (median values). A conclusive explanation for this increase has not yet been found. After 250 h of aging, a TEM analysis showed Au to Pd diffusion in the baseline sample with a diffusion depth of ≈ 0.1 µm Au. No intermetallics, voids, or contamination is found on the interfaces after aging according to nanohardness, SEM, and TEM analyses. No bond lift-offs or electrical opens were found for the aging temperature and durations chosen. No conclusive evidence for the presence of Au-Pd intermetallics or voids is found.
Acknowledgements

I would like to thank my supervisor Michael Mayer for providing me with guidance and support throughout my time as a graduate student in the University of Waterloo. I was motivated to work hard and learned valuable skills, which will help further reach my career goals.

Special acknowledgement goes out to Michael McCracken and all the members of the CAMJ for helping me transition and adapt to the research environment. I will remember all the laughter we shared over the past two years.

This thesis would not be possible if not for the financial support from Intel Corporation, which deserves an appreciation for also giving me feedback and suggestions in order to keep me on track.

Finally, I want to thank my parents for everything they have done for me.
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1. Introduction
In today’s microelectronic packaging industry, wirebonding and flip chip bonding have led the way in interconnecting semiconductor devices. Wire bonding has accounted for over 70% of the total units of advanced packages of microelectronic devices for the past decade. At the same time, electronic devices are becoming smaller in size, which causes the demand for fine pitch wire bonding to rise. With the high demand, electronic packaging industry leaders are constantly investing time and money to improve the quality of the process, while attempting to reduce cost to maximize profit.

1.1 Motivation
Reliability of interconnect in wirebonding is an essential measure of its overall quality. Wirebonds with lack of reliability are deemed to fail over a short period of time. Even if all the major components in a electronic chip assembly are functional, one dysfunctional wire could cause a complete disaster for the whole system. Not only would there be additional cost incurred, the reputation of the company would be affected depending on the severity of the failure. Therefore, interconnects are required to be of the highest quality. In a typical electronic assembly, a certain amount of power is required to drive its components. Therefore, power dissipation in the form of heat is expected to occur. Reliability tests performed at elevated temperature over long period of time can simulate the actual environment the wirebonds would experience, which makes these tests a vital part of a quality assessment plan. In order to achieve reliability without the high cost of changing electrical and mechanical hardware of the bonding equipment, proper choices of the wire and substrate material are required.
1.1.1 Effect of Wire

The material of the wire used in the wire bonding process remains an interesting research topic in today’s electronic packaging industry. Therefore, the property of wire is an important modulator in analyzing the reliability of the wire bond. The wires discussed in this section are those commonly used in the industry.

Au wire to Al substrate has been the most popular method in the wirebonding industry. Au wire has good electrical, thermal properties and is resistant to oxidation. Au wire is also found to have good adhesion to Al at elevated bonding temperature. However, exposure to high temperature of above 150 °C has promoted intermetallic (IMC) growth between the Au bond and the Al bond pad [1, 2]. The presence of IMC degrades the electrical conductivity, and reduces the quality of the overall electrical assembly. IMC formation can lead to crack propagation, which could result in connection failure [1, 2].

Cu wire has emerged in recent years as an alternative to the standard Au wire to Al bondpad. Even more so than Au, Cu has excellent mechanical, electrical, and thermal properties [3]. Cu is also cheaper and more readily available. Void formation due to IMC does not degrade the electrical conductivity in the Cu-Al system [4]. However, Cu is very prone to oxidation, which can be compensated by adding shielding gas during bonding, and properly storing under dry conditions. Cu-Al does produce brittle IMC, whose growth is accelerated by temperature [3]. Effects of cratering, and Al pad thinning as a result of the relatively high Cu hardness could cause chip cracking, and is a predominant issue on low-k dielectric material [5, 6]. Cu wire on Al has also shown degradation in quality over short periods of time under high humidity environment [7].

Another type of wire material commonly used in wirebonding is Al. In the Al-Al process, both wire and substrate material are the same, which makes the system not prone to IMC formation.
However, the bonding between Al and Al has reliability issues due to the high frequency of bond lift off and cracking failure [8, 9], and is exclusively used for wedge-wedge bonding, a process variation less productive than ball bonding.

1.1.2 Effect of Substrate
Au is chosen in this study on the wire side due to its useful properties in wire bonding. One remaining process modulator that can be investigated is substrate material. Similar to wire material, numerous types of substrate have been explored.

Al is the most widely used material for bonding to Au wire. Being one of the most abundant metals on earth, Al is relatively inexpensive compared to other substrate materials. Al is low in density, which reduces system weight to enhance the portability of electronic devices. The relative resistance to corrosion and oxidation properties improve the life span of the interconnect. As described earlier, Al forms IMC with Au and is prone to underpad damage.

The Au-Ag system is reliable at elevated temperature and resistant to corrosion. However, Ag is prone to contamination, causing bondability issues. The presence of oxide and organic contaminants reduces the interfacial friction and decreases the heat dissipation between bonding materials, leading to bad bond quality [10]. Therefore, Au-Ag system is used primarily in second bond formation, and elevated bonding temperatures are used to remove contaminants.

Similar to the Au-Al system, IMC formation is present in the Au-Cu system. Cleanliness of the bonding surface is imperative to improve the quality of the bonding process. Shielding gas is also required to prevent Cu from oxidation during bonding. The Au-Cu process is used mainly in second bond formation similar to the Au-Ag process. Due to the complexity for the setup of this process, it is often not preferred in the current microelectronic packaging industry.
The Au-Ni system is generally reliable at elevated temperature. Ni is a much harder material than Al, and is less likely to break under high stress, which is why it is used in direct chip bonding applications. However, Ni forms oxide and corrodes rapidly [11]. Therefore, wirebonding must take place in an inert atmosphere after plating of Ni. Alternatively, a thin film of Au can be deposited on top of the Ni layer as an oxidation barrier, but this is an additional process step and an additional cost.

The Au-Au system is deemed reliable over long times at elevated temperature. The bondability of Au-Au system is excellent as no interface corrosion, IMC formation, or other mechanism that degrades bonding are known. Although the Au on Au system shows both excellent bondability and reliability, Au is an expensive material and relatively scarce.

The properties of Pd make it an acceptable candidate for substrate material. Pd is electrically stable, and resistant to tarnish, chemical erosion, and intense heat, which makes it a good candidate for overcoming reliability issues seen in other types of substrate material. It has been reported that Pd material shows good adhesion to Au wire and improves the shelf life of lead frames during the wedge bonding process [12]. However, while the Au-Pd system is already in industrial use, studies of its bondability remain scarce in the thermosonic ball bonding community.

1.2 Objectives
The intention of this research is to form Au ball bonds of size 50 µm to 60 µm on Pd/Ni/Cu substrates and analyze the nature of bonding between Au wire and Pd. The reliability of the Au-Pd process is compared with the standard Au-Al process through aging at 250 °C over 200 h. As a process modulator, roughness is varied on the Pd/Ni/Cu substrate in an attempt to get a better understanding and possibly improve the Au-Pd process.
1.3 **Thesis Outline**
To explain the background of the study, the basic bonding and plating processes, bonding and failure mechanism, and techniques to characterize bondability and reliability are introduced in Chapter 2. Before bonding, the layers of Ni and Pd are plated on top of the base material Cu. The setup, and results of the material deposition process are given in Chapter 3. Bonding optimization of the Au-Pd system to analyze bondability in terms of achieving the desired geometry and shear strength are introduced in Chapter 4. The basic bonding mechanism is explored here. Chapters 5 and 6 investigate the reliability of the Au-Pd system through aging, by destructive (nanohardness, SEM, TEM) and non-destructive (in-situ contact resistance) techniques, respectively. The goal is to analyze any possible IMC and interdiffusion within the system.

The development of Pd/Ni/Cu substrates at different roughnesses, with the corresponding bondability and reliability analyses are discussed in Chapter 7.
2. Literature Review
Among the methods to make interconnections between an integrated circuits (IC) and a printed circuit boards (PCB), wire bonding is considered the most cost effective and flexible technology. The earliest reported wire bonding development was by scientists of Bell Laboratories in the 1955-1958 time period, which led to growing popularity in many semiconductor companies, and paved the way for affordable integrated circuits worldwide.

2.1 Wire Bonding Process
In order for a semiconductor device to operate, it must be electrically connected to an outside assembly. The electrical connections to this external hardware are made by wires of a few microns in diameter. Essentially, the wire bonding process is a method to bond metallic wires between two electrical devices. The ideal connection should show good conductivity and will not degrade over time.

Two variants of wire bonding process are (1) ball bonding and (2) wedge-wedge bonding. In a typical ball bonding process, there are two forms of wire bonds. The ball bond is the first bond and is responsible for connecting the first end of the wire to the bond pad of the chip. A schematic of the wire bonding process is shown in Fig 1. Initially, the tip of the wire is melted by a spark from the electrical flame off (EFO) electrode. Subsequently, a ball shape known as the free air ball (FAB) is formed from rapid solidification and surface tension at the wire tip. The shape and size of the ball formed depends on the EFO current and its duration (time). Impact force (IF) is then applied by the capillary to drive the ball to the substrate. Subsequent bond force (BF) and ultrasound energy (US) by the attached transducer are then applied to deform the ball and create interfacial adhesion between the bottom of the deformed ball and the bond pad on the chip. The
capillary then travels in a predetermined direction, while the wire feeds through. Once the capillary reaches the lead frame (2nd bond position), a wire loop is formed between the substrate and the lead frame. Subsequent IF, BF, and US are applied similarly to the ball bond process to form the second type of wire bond known as the wedge bond, which is responsible for establishing the connection between the remaining end of the wire and lead frame. The wire is cut at the 2nd bond position, leaving a tail at the end of the wire. The capillary moves back to its original position, and the next FAB is formed on the tail extruding from the capillary. The process can be repeated thousands of times per minute. There is no ball formation in the wedge bond stage and the deformation is applied directly to the wire. The shape and the amount of deformation on the ball and wedge bonds are heavily dependent on the bonding parameters, which also include bond time (BT) and temperature (T). The BT parameter defines the duration of the US generation. The ball bonds are generally stronger than the wedge bonds. In this research, the focus is on the ball bond. An example bonding process window is shown in Fig. 2 for Au on Al. The BF and US are dominant parameters during bonding. The non-shaded region indicates area acceptable for bonding, where the strength of the ball bond is above a certain required threshold. Within the shaded region, two
boundaries are known. Beyond the first boundary, excessive US deformation occurs and the strength of the ball bond drops with increase in its diameter. Beyond the second boundary, interfacial sliding is absent and US bonding cannot occur. Optimization of the bonding process is vital for achieving bondability.

2.2 Bond Materials
In typical wire bonding processes, the minimum material requirement include a wire bonding machine, a capillary, a wire spool, and the package to be bonded. In this research, a thermosonic wire bonding machine supplied by ESEC, Cham, Switzerland, is used. The machine is used mainly for bonding of Au wire. The bonding temperature used on the machine generally ranges from 100 °C to 240 °C. The desired capillary chosen in the process is the standard 60 µm pitch alumina model supplied by Small Precision Inc, Boston, USA.

![Figure 2](image.png)

Figure 2 Typical ball bond process window for Au on Al. After [21].
In the joining process under investigation, Au wire is bonded to Pd substrate. The diameter of the wire is 25 µm. Its composition is 99.99% Au and is supplied by MKE, Yongin, Korea. The base material of the substrate is made of 99.99% high conductivity oxygen free (HCOF) Cu supplied by Goodfellow, Inc, Hungtingdon, England. To protect the Cu material from oxidation, thin layers of Pd and Ni are deposited. The goal of the Ni is to ensure the integrity of the Pd finish by preventing diffusion and migration of Cu [13]. Also, Ni is a very hard material with high Young’s Modulus, which overcomes underpad damage problems seen in Al substrates. The Pd layer not only protects the Ni from oxidation, but most importantly, it provides the required wire bondability through surface adhesion and shows excellent reliability at elevated temperature over long periods of time [12, 13]. As one of the Palladium group metals (PGM), Pd is relatively inert, with respect to chemical attack by oxygen or other acids. Figure 3 shows the binary phase diagram between Au and Pd. The Au₃Pd and AuPd₃ phases occur at temperatures above 800°C, which is above the temperature normally experienced by the electronic components. The dotted lines indicate the two phases that cannot be confirmed. The remaining phase at about 100°C is hypothetical and may not exist [14]. In general, Au and Pd form continuous series of solid solutions, which would indicate an improvement in reliability over the Au-Al process [14]. It is of interest to analyze the bonding mechanism between Au and Pd, and to confirm the lack of IMC.

2.3 Film Deposition
Various material deposition methods were considered in the process. Some of the less novel techniques include chemical vapor deposition (CVD), physical vapor deposition (sputtering), electroplating and electroless plating. CVD is used to produce high purity and high performance solid material. However, the process is complex and requires a large amount of resources and time to find the most viable precursor for the metallic target [15]. Sputtering is a much more viable option
for metallic layers used in IC packaging as it is relatively easier and less expensive to set up than most of the deposition processes. The quality of the sputtered surface is degraded compared to other deposition processes due to impurity and contamination problems [16]. In most cases, the quality of the material deposition process is directly proportional to cost and complexity of the setup.

2.3.1 General Plating Process

Plating is a process primarily used for depositing metal on a conductive surface. The goal of typical plating processes is to provide corrosion inhibition, radiation shielding, solderability, and con-

![Binary phase diagram of Au-Pd](image)

Figure 3 Binary phase diagram of Au-Pd [14]
ductivity. In general, the plated material shows good uniformity and surface adhesion to the base material [17].

There are two types of plating methods, the first type is called electroplating, which models a standard Galvanic Cell. A negative charge is applied by a constant voltage power source on an object to be plated (cathode). The positive side of the power supply is attached to an anode. Both the cathode and anode are immersed in the solution containing metallic salt. As the object to be plated is negatively charged by the constant voltage, the positive metallic ions are attracted to the surface of the cathode and reduce into metal form. The motion of the metallic ions is also a result of interaction between the electric and magnetic field within the solution medium. At the same time, the anode removes electrons from the metal salt in the solution, oxidizing it to its metallic ion state [17, 18]. Both the oxidation and reduction process occur simultaneously as long as current flows within the plating bath. Typical anode materials are metals with equilibrium potential higher than that of the metallic salt in the solution.

The second type of plating process is electroless plating, which does not require an external power source. The reduction and oxidation processes are purely chemically driven [17, 19, 20]. Similarly to the electrolytic process, metallic salt is dissolved in the plating solution. However, plating is initiated by activating the destination metal with another metal that has a higher equilibrium potential, for about 10 to 20 s. A potential difference results when both the activation and target metals are inserted in the plating bath [19, 20]. The bath types for both electrolytic and electroless plating processes include, alkaline, acidic, and neutral baths [17, 18]. The plating time is heavily dependent on temperature, pH and concentration of the bath [17-20]. Table 1 lists a comparison between the properties of the two plating processes. The step coverage is defined as the ratio of the thickness of a film over a step edge to the thickness in a flat area. For the electroplating pro-
cess, the step coverage depends on the geometry of the substrate to be plated. With a square shape Cu coupon as a substrate, the thickness of the plated layer tends to increase at the edges due to the "edge effect", generated by the interaction of an electric field with a nonuniform (gradient) magnetic field [22]. In this study, the bonding is arranged to take place at locations away from the edges to eliminate the "edge effect".

2.3.2 Plating Process for Ni
Both electroplating and electroless plating of Ni have been developed. Although electroplating of Ni provides a commercially important and versatile surface finishing method, there are a few issues that are critical for the application of interest. In a typical electroplating process, organic agents are added to maintain the pH of the bath. The presence of impurities within the bath could react with the organic agents causing a high internal stress, which reduces the ductility of the plated metal [17]. The stress can be either tensile or compressive resulting in variation in the

<table>
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<th>Table 1: Properties of electrolytic and electroless process</th>
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<td>Driving Force</td>
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<td>External Power</td>
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<td>Additional Requirements</td>
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shape of the metallic target. In the low current density operating range, discoloration in the final plated surface from metallic contamination has been reported [17]. When current is increased above the specified range for bath operation, excessive heat is produced resulting in burning on the metallic target. Most critically, interaction between the electric and magnetic field causes uneven distribution of thickness [17, 18]. Achieving a low roughness surface is critical for consistency of the bonding parameters, therefore it is vital that the first plated layer be as flat as possible.

The electroless Ni process has been around since the mid 1940’s, and has been growing in popularity ever since. The topography of the plated surface is essentially flat with no excessive build up on the edges and projections of the target [19, 20]. The deposits are less porous than if electroplated, hence better corrosion resistance is obtained. In general, the setup time for electroless plating is less due to the absence of power supplies, electrical contacts, and other apparatus necessary for electroplating. The electroless Ni plating process has often been used with great success in the past for electrical packaging purposes, and therefore is chosen as the technique for plating Ni on the Cu layer in this study.

2.3.3 Plating Process for Pd
The quality of electroless plating of Pd is often degraded due to a high degree of solution instability within the process [17]. Development of electroless Pd plating has been ongoing with limited success in plating quality with acidic plating baths [18]. However, mixing of acidic solutions pose health and safety risks, and therefore was not considered in this project.

Unlike the electroless Pd plating process, the electroplating of Pd has a long history dating back to the early 1930’s [17]. The quality of the plated surface is acceptable for electronic packaging purposes. The only known issue with electroplating of Pd is hydrogen embrittlement. If hydrogen is
introduced in the plating solution, the thermodynamic instability causes the PdH_x phase to decompose, which is accompanied by corresponding lattice contractions [17]. Cracking occurs when the tensile stress exceeds the yield point. The hydrogen embrittlement issue in electrodeposited Pd is a great concern when attempting to deposit films of technological use. However, the issue can be compensated by minimizing or maximizing the current ratio of the two simultaneous reactions occurring at the electrode interface [17, 18]. In the study of interest, the current ratio is maximized. Lastly, cleaning methods before and after plating are important in the quality of the film deposited regardless of the type of plating process.

2.4 Bonding Mechanism
The three main impediments to material joining at their faying surfaces are their roughness, lattice mismatch, and contamination. The roughness of the Cu coupon can be compensated by proper grinding and polishing methods. Different techniques in material preparation considered include electropolishing, chemical mechanical polishing (CMP), and mechanical polishing. Electropolishing is essentially the reverse of the electroplating process, where the metal work piece is immersed in a temperature controlled bath, and connected to the anode. Direct current is applied, and oxidation occurs at the anode [23]. For metals with complex geometry, manual polishing requires extensive care during the handling of the material. With electropolishing, areas that are not accessible during the mechanical polishing process are exposed to the polishing solution. However, the typical electropolishing process is very time consuming [23]. In the present case, the Cu material has a basic shape, which can be easily polished mechanically. CMP is the most desirable method for overcoming the roughness of a metallic layer. Both mechanical and chemical components are utilized [24]. The overhead cost for purchasing an automatic system and development of the slurry required for polishing are considerable. Nonwithstanding mechanical polish-
ing, the parameters IF, BF, and US used for ball bonding can reduce surface roughness by plastic flow of the ball and US friction at the interface.

Pd and Au have face centred cubic crystal structures and their lattice constants are 3.89 Å and 4.08 Å [14], respectively, which is considered a small lattice mismatch that will not interfere with adhesion. Figure 4 shows the Au-Pd lattice parameters with change in Pd composition. In the Au-Pd bonding system, the difference in lattice parameters is of no concern.

The effect of contamination is addressed by proper cleaning and storage of the materials. After each stage of grinding and polishing, the samples are cleaned with ethanol in an ultrasound bath, and dried with air blower. Before plating of Ni, the base material is airbrushed to remove the dirt on the surface. The material to be plated is immersed in two separate solutions: “Asset” and “Actimite” to remove grease and oxidation on the target material, respectively. After plating, the

![Figure 4](image)

**Figure 4** Lattice parameter of Au-Pd system [14].
material is cleaned with de-ionized water. To minimize surface oxidation at room temperature, the substrates used in the research are stored in a glovebox filled with N$_2$. The humidity in the glovebox is maintained below 10%. The Au wire is kept inside a sealed box to prevent contamination. During the bonding process, US causes wire-substrate interfacial motion, which removes contamination and oxide at various asperity points on the surface.

Thermosonic ball bonding is carried out on the ESEC 3088 wire bonder. The bonding process can be divided into stages. In a first stage, the FAB is deformed by a high enough IF. In the following stage, the US vibration is started and gradually results in interfacial friction that wears away contaminants and roughness features. In the final stage, the friction coefficient increases, which causes the US amplitude of the capillary relative to the substrate to decrease. This is because an interfacial bond is forming and the US can cause additional ball deformation. The key bonding parameters in the Au-Pd process are assumed to be the same as those of the Au-Al system, which are US, BF, and BT [21].

Wirebonding is known as a solid state process [51]. The studies of electrical conductivity and resistivity, thermal conductivity, mechanical properties, magnetic susceptibility, and optical properties have confirmed the AuPd system to be devoid of transformations in the solid state [25]. In terms of impediments to bonding, The lattice parameter changes practically linearly with the composition in at.%. The effects of contamination and roughness are minimized by the process parameters during bonding, and mechanical grinding and polishing during sample preparation. Therefore, the basic bonding type in the process is believed to be a chemical bond of metallic nature, where an electromagnetic interaction between conduction electrons and nuclei of the metals is taking place.
2.5 Bond Characterization
There are two ways to analyze the bondability of a wire bond. The first is the shear test, which characterizes the strength of the ball bond. The second is called the pull test, which can measure the strength of the wedge bond. Figures 5a and 5b show the general configuration of the shear and pull test, respectively.

2.5.1 Wire Pull
Wire pull is a destructive technique where an upward force is applied on the pull hook to the wire, pulling the wire away from the substrate. The force at which the wire failures is recorded by the machine is usually in units of gram-force. The failure modes include breaking at the wedge bond,

![Diagrams showing shear and pull test configurations](image)

Figure 5  Ball bond quality characterization methods: a) shear and b) pull test (not to scale)
ball bond, heel, ball neck, and midspan of the wire. Typically, failure occurs at the heel of the wire, near the wedge bond side, because the wedge bond tends to be weaker than the ball bond. If failure occurs at the wedge or the ball bond, the bonding parameters can be re-optimized and an improvement might be achieved. The pull hook can be placed at various locations of the bonded wire. The common configurations are pull at the ball, wedge, and midspan, depending on the application. Typical pull tests are performed at the mid-span of the wire.

2.5.2 Ball Shear
The bulk of the bondability characterization in this study is performed using the ball shear test shown in Fig. 5b. Similar to the wire pull, the shear test is a destructive test technique that destroys the wire bond. The chisel shaped shear tool is moved to a starting location a few microns away from the ball bond. The lower end of the tool stands off the substrate surface by about one third of the bonded ball height. During the test, the shear tool moves horizontally and pushes the ball (shears) off the substrate. The shear force (SF) is defined as the force at which the ball is sheared off the substrate, and recorded by the machine in units of gram-force. The SF is directly correlated with the ball diameter. Therefore, the shear strength (SS) of the ball is used as a normalized measure for ball bond quality, and is given by

$$SS = \frac{SF}{A}$$

where $A$ is the area of the deformed ball bond. The failure modes in ball shear include bond lifting, bond shearing, cratering, and bond surface lifting. There is no reported $SS$ in the literature for typical Au-Pd ball bonding processes as the majority of the research has focused on the second bond. The minimum $SS$ required for acceptable ball bond in the Au-Al system is 90 MPa [26], with a typical $SS$ of 110 MPa reported in literature [27]. Therefore the goal in this research is to achieve a $SS$ above that of the standard Au-Al process of 110 MPa [27].
2.6 Ball bond Aging

2.6.1 Intermetallics and Interdiffusion
One common way in industry to analyze the reliability of the ball bonding process is to age the wire bond in air at elevated temperature over a sufficiently long period of time. For the Au-Al system, aging temperatures range from 50 to 250°C. Ratchev [28] performed Au ball bonding on Au/Pd/Ni capped bond pads, and aged the bonds in an oven at 150°C over 120 days. Figures 6a and 6b show SEM images of the ball bonds aged and as bonded. No IMC formation was observed before and after aging. Interdiffusion is another effect, which can occur during the aging process. Interdiffusion usually does not degrade the bond quality, and is preferred in some cases as it could increase the overall bond strength. Figure 7 shows the amount of interdiffusion between thin film

![Figure 6](image)

Figure 6 SEM image of the Au ball bond on Au/Pd/Ni cap a) after aging, and b) as bonded at magnification ×10k [28].
Au and Pd in vacuum and air. For an aging temperature of 250°C, 2 h of aging, and about 0.5 µm from the interface, there is approximately 0.3 at% concentration of Au diffused into Pd, and about 0.4 at% of Pd diffusion into Au [29]. Therefore, interdiffusion between Au and Pd can be a significant phenomenon in this research. In a similar study, Mirakami et al. [30] reported the presence of diffusion in Au-Pd alloy, but the amount of diffusion changes with atomic concentration of Pd.

Figure 7  Interdiffusion between Au and Pd metallic layers at temperatures 200°C, 250°C, 312°C, and 389°C in vacuum and air [29].
in the Au-Pd thin film alloy as shown in Fig. 8. Interdiffusion between Au and Pd decreased with increase in Pd concentration, until at about 50% at. Pd, the diffusion rate saturates. The diffusion rate is consistent with time within 8 hours of aging at 350°C. Compared with the standard Au-Al process, which forms IMC phases including but not limited to AuAl$_2$, Au$_2$Al, Au$_4$Al and Au$_8$Al$_3$ at similar aging temperature and time, the Au-Pd is expected to be a more reliable system.

2.6.2 Kirkendall Voids
The effect of interfacial voids can lead to irregular formation of IMC and/or degradation of the ball bond quality. Kirkendall voids can occur between two metals that have different interdiffusion coefficients and sometimes can be attributed to contamination on the surface of the substrate material after bonding [31]. However, Kirkendall voids can usually observed due to stress on the weakened area in the bond during thermal cycling. The voiding was found to develop faster with elevated temperature [50]. Figure 8 shows the diffusion coefficient in pure Pd is two magnitudes less than that in pure Au. The difference in diffusion coefficient between Au and Pd could result in Kirkendall voids in the Au-Pd bonding process. Also, the degree to which possible voids in the Au-Pd process can lead to IMC is not known. Void formation in the Au-Al system leads to the formation of IMC [32-34]. The voids in the Au-Al system are known to be formed by passive regions resulting from contamination by Al oxide, with IMC formation at the bottom of the passive region [32]. Another source of void formation is attributed to improper bonding, where an inhomogenous weld is produced at the interface [34]. As a result, a non welded region is widely spread and is the source of an initial interfacial void before aging.
Figure 8  Change in diffusion coefficient with respect to atomic fraction of Pd for thin Au/Pd alloy film with aging at 350°C over 4 h and 8 h [30].
2.7 Some Process Modulators
In order to get a thorough understanding of the Au-Pd ball bonding process, process parameters can be varied to analyze how the overall system responds. The bonding parameters are optimized for the type of process. A standard Au wire is used and no other wires are tested. The properties of the substrate material including roughness, thickness, hardness, chemistry and contamination have been adjusted in the past [35], and are discussed in more detail in the subsections that follow.

2.7.1 Thickness
Thickness of the substrate can be adjusted by varying the parameters of the deposition process. In this study, the thickness of the deposited layer is directly proportional to the length of the deposition time and the magnitude of the current density. So far, there has been no reported variation of ball bond strength and quality with thickness of the metallization on the ball bond side. The strength of the Au wedge bonding increases with thickness of substrate metallization as the metal impurities migrate and diffuse less to the surface. In the Au-Pd process, the Ni layer is thick enough to minimize any Cu migration into Pd. Therefore, the effect of Ni thickness on the bonding strength is negligible.

2.7.2 Hardness
Metal hardness can be adjusted by presence of hydrogen and other impurities, which introduces hardening on the metallization [35]. However, the degree of change in hardness is hard to control, and the repeatability of the result is difficult. It has been reported [35] that the ball bond strength is inversely proportional to hardness. However, a soft coating is more likely to deform and spread to create more contact area for bonding. As a result, the best bondability occur when the hardness of the wire and metallization are the same. In this study, hardness is inherently varied by aging, which anneals the material over elevated temperatures.
2.7.3 Roughness
Various methods can be employed to change the surface roughness of the substrate. In the past, plasma bombardment has been used in both metallic and non-metallic materials [36]. However, the roughness variation obtained with this method is in the nanometer range, which is too small to have any effect in the wire bonding application. Other ways to vary the roughness includes various degrees of sandblasting, sanding, or rolling. The methods employed determines the orientation of the final roughness. In general, a rough surface provides more contact area for welding, resulting a stronger bond possibly aided by mechanical interlocking. However, a large roughness substrate may require a higher energy or force for successful bonding. Therefore, proper adjustment of the bonding parameters must be made for bonding on rough substrates in order to achieve bonding quality and strength.

2.7.4 Contamination
The possibility of contamination is always present in wire bonding. As one of the impediments in welding, contamination should always be minimized. However, the ability to vary contamination would allow a better understanding of the process behavior. Controlling the amount of impurities in a bonding process in a repeatable way can be difficult as contaminants are usually introduced in a system unintentionally. Depending on applications, impurities have been added in the past [53] during plating to increase the hardness, wearability, brightness and ductility of the final deposited material. However, the amount of impurities vary after repeated use of plating chemical or improper rinsing, handling and storing of the samples. Therefore, the end effects are likely difficult to reproduce. The variation in the amount of Al oxide on standard Al pads was reported [48]. The thicker the oxide, the lower the bond quality. A comparable modulation of the Pd surface is impractical because no Pd oxide can be formed easily in a repeatable way. In any case, contamination always reduces the bond quality, and therefore is not further considered as a modulator in
this study. However, the effect of contamination if any, can be promoted through the aging process, with subsequent discoloration [53] on the surface of the substrate.

2.7.5 Plating Chemistry
In the Au-Pd process, the electroless and electrolytic processes are used for plating Ni and Pd, respectively. The plating chemistry can be changed if other types of bath with different pH levels are considered in the process. Variations in chemistry can cause changes in the plating quality and subsequent bonding quality due to metallic impurities and contamination. Hardness and roughness of the final plated layer can also be altered with plating chemistry. Kim et al. [35] reported an increase in bond strength of 160% by plasma cleaning the Au substrate before plating with Ni due to removal of organic contamination and inorganic compounds on metallic bond pad [35, 47].

Due to the time required and the complexity for the development and optimization of the different plating processes associated with change in chemistry, this modulator is not considered.

2.8 Summary
Based on the literature study, several points can be generalized before conducting the Au-Pd ball bond study. Electrolytic and electroless plating are the preferred option for plating thin metallic layers of Pd on Ni and of Ni on Cu, respectively. The bondability of Au on Pd is expected to be similar to that of Au on Al, where US and IF are expected to be the dominant parameters for bonding. The bonding mechanism of the Au-Pd process is believed to be a chemical bond of metallic nature, and will be confirmed in the analyses of the report. Proper cleaning and storage of the material in the process is required. Ball shear is the most common method for analyzing and optimizing the SS of the ball bond. The reliability of the bonds after aging is expected to be better in the Au-Pd process compared to that of the standard Au-Al process due to lack of IMC formation. However, both voids and interdiffusion could occur in the Au-Pd process. In general, Au and
Pd form continuous series of solid solutions. Parameters which can lead to the improvement of the overall process includes thickness, hardness, roughness, chemistry, and contamination of the substrate material. However, roughness is the modulator of choice in this research as it can be easily reproduced and is expected to have a significant impact on the overall process.
3. Development of Pd/Ni/Cu Coupon
This section describes the production of Pd and Ni layers on Cu coupons as bonding substrates using electrolytic and electroless plating processes. The substrates produced will mimic the actual Pd/Ni/Cu substrate used in the industry, which is a silicon microchip with Pd/Ni pad metallization on the Cu layer for signal and power distribution. Target thicknesses of 1 µm and 0.3 µm were chosen for the Ni and Pd layers, respectively.

3.1 Experimental

3.1.1 Cu Base Material
The base material is an oxygen free high conductivity (OFHC) Cu foil with thickness of 0.5 mm supplied by GoodFellow Corporation, and is cut into coupons with dimension of 1.0 cm×1.0 cm. A WYKO NT1100 Optical Profiler is used to measure the original roughness of the coupon under vertical scanning interferometer (VSI) mode with vertical resolution of 3 nm. The parameter $R_a$ is the arithmetic average of absolute distances to the mean line, and is used to quantify roughness in this work. The $R_a$ of the coupon after cutting is 0.2 µm, which is above that of the chip metallization used in industry. The coupon is grounded with silicon carbide abrasive paper starting with 600, followed by 800, 1200, and 1200 fine grit. Polishing with 0.1 µm, 0.25 µm, and 0.05 µm diamond slurry is performed after grinding. The polished sample are cleaned with ethanol and dried with an air blower. The grinding and polishing are performed on the Fischione Instrument Model 160 Grinder supplied by Fischione Instrument, Pittsburgh, USA. Figures 9a and 9b show the coupon before and after polishing with the corresponding optical profiler measurements, respectively. The magnitude of $R_a$ is reduced by one order, which is comparable to that of the substrate used in industry.
3.1.2 Electroless Plating of Ni

The general principle for electroless Ni plating follows the standard oxidation and reduction reactions, which occur simultaneously. The reduction and oxidation of this process uses Ni\(^{2+}\) ion as salt in the plating solution to be reduced, and the Cu metal is oxidized. The total number of electrons transferred is 2. Steel is used as the activation agent in the plating process. The electrode potential of Fe is -0.447 V, when connected to Cu, which has a electrode potential of -0.257 V, the resulting potential difference activates the plating process [17]. Table 2 lists the recipe [37] and the plating conditions of the electroless Ni process. Before plating, the coupon is airbrushed, and
rinsed with solutions listed in Table 3 in order to minimize grease and oxide on the surface of the Cu coupon [37]. A temperature of 35 °C is recommended for the cleaning process. The Ni plating and cleaning solution are supplied by Cadwell Inc, Kennewick, WA, USA.

Figures 10a and 10b show illustrations of the plating setup. The Cu coupon is held by an alligator clip on one side and has a steel clip on another side. Both the alligator clip and steel are kept as close to the edge of the coupon as possible to reduce any influence on the central area on the Cu

| Table 2: Properties of electroless Ni process [37] |
|----------------------------------|-----------------|
| Target thickness                | 0.3 µm          |
| Substrate size                  | 1cm×1cm×0.5mm   |
| Solution                        | Alkaline bath   |
| Salt                            | Nickel sulphate (NiSO₄.6H₂O) |
| Reducing agent                  | Sodium hypophosphate (NaH₂PO₂.H₂O) |
| Replenishing agent              | Ammonium hydroxide (NH₄OH) |
| Deposition rate                 | 0.42 µm/min     |
| Temperature                     | 90 °C           |
| pH                              | 8-10            |
| Activation                      | Steel           |

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<th>Table 3: Cleaning solution for Ni plating process [37]</th>
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<td>Name</td>
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<td>-------------</td>
</tr>
<tr>
<td>Asset</td>
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<td>Actimite</td>
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coupon. The coupon is kept in a horizontal position in order to achieve uniform plating across its surface. When the coupon is plated vertically, the thickness varies by up to 50\% between measurements in the vertical and horizontal directions, which can be attributed to the change in depth experienced by the coupon across its surface. Once the temperature reaches 90 °C as measured by an immersed thermometer, and the pH is between 8-10 as measured by an immersed pH meter, the coupon is immersed in the plating solution as shown in Fig. 8a. For consistency, the Cu coupon is kept at about the same depth in the beaker during every plating experiment. The time required to plate 1 µm of Ni, is given by

\[ T_{dep}^{Ni} = \frac{t}{R} \]

(2)

where, \( t \) represents the thickness to be deposited, and \( R \) represents the deposition rate. The \( T_{dep}^{Ni} \) in the electroless Ni process is approximately 140 s. Air bubbles can accumulate on the coupon, pre-
venting Ni ion to be deposited. Therefore, when a bubble builds up on the coupon during plating, the coupon is shaken manually to remove the bubble. The Ni credit is defined as

\[ Ni_{\text{credit}} = A \times T_{\text{dep}} \] (3)

and is a measure of Ni concentration in the plating solution. where \( A \) is the area of the coupon. \( Ni_{\text{credit}} \) is in unit of \( \text{in}^2 \text{min} \), both \( A \) and \( T_{\text{dep}} \) are not in their SI unit. The \( Ni_{\text{credit}} \) required to plate one coupon is about 0.37 \( \text{in}^2 \text{min} \). The bath is generally replenished when the amount of Ni credit falls below 1100 \( \text{in}^2 \text{min} \). After replenishing the bath, the \( Ni_{\text{credit}} \) is 1300 in the plating solution. If \( Ni_{\text{credit}} \) is below 1100, the plating quality and deposition rate reduces drastically. After plating, the coupon is rinsed with de-ionized water and dried with an air blower.

3.1.3 Electroplating of Pd
Table 4 shows the properties of the Pd plating solution [38]. The deposition time \( T_{\text{dep}}^{\text{Pd}} \) can be adjusted with current density (\( I \)), and is defined by

\[ T_{\text{dep}}^{\text{Pd}} = \frac{h d}{Z I} \] (4)

\[ Z = \frac{A_{\text{wt}}}{n F} \] (5)

\[ F = N_A e \] (6)

where \( h \) is the thickness of the deposit, \( a \) and \( d \) are the area and density of the cathode, respectively. \( T_{\text{dep}}^{\text{Pd}} \) is inversely proportional to \( I \) and \( Z \). \( A_{\text{wt}} \) is the atomic weight of the cathode, \( n \) is the number of valence electron of the metallic ion in valence state, \( N_A \) is Avagadro’s number, and \( e \) is the charge of an electron. Assuming a cathode efficiency (\( \eta \)) = 95\%, \( T_{\text{dep}}^{\text{Pd}} \) is approximately 70 s for \( I = 1 \text{ A/dm}^2 \). From eqn. (2), \( T_{\text{dep}}^{\text{Pd}} \) for \( I = 1 \text{ A/dm}^2 \) is 0.25 \( \mu \text{m/min} \).
A basic design of experiment (DOE) is setup to analyze the deposition time required for various $I$ in the actual Pd plating experiment. Table 5 lists the calculated deposition time for different $I$, starting with 0.5 A/dm$^2$ in steps of 0.5 A/dm$^2$, up to the maximum allowable [38] 2.0A/dm$^2$. The $T_{dep}^{Pd}$ at different $\eta$ is computed [17] and shown in Table 5.

Before plating, the Ni plated coupons are cleaned. Table 6 shows the ingredient for the cleaning solution. Both the plating and cleaning solutions are supplied by Technic, Inc., Florida, USA. The
Ni/Cu coupon is first cleaned with dish detergent to remove any grease build up on the surface, and then immersed in 20 %v/v sulfuric acid at room temperature for plating activation.

Figures 11a, 11b and 11c show an overview and detailed illustrations of the plating process.

Before plating, the one gallon solution is shaken to re-distribute the Pd salt accumulated at the bottom of the container. About 800 ml of the one gallon plating solution is poured into a 1000 ml beaker, which is about 2 g of Pd salt. The mass of Pd required for plating one coupon is defined by

$$m = V \rho$$  \hspace{1cm} (6)

where $V$ is the volume of the cathode and $\rho$ is the density of Pd, which is 58.7 g/cm$^3$. The amount of Pd in the 800 ml beaker can plate about 340 Ni/Cu coupons of size 1cm×1cm×0.5mm. The

<table>
<thead>
<tr>
<th>$I$ [A/dm$^2$]</th>
<th>$\eta$ [%]</th>
<th>85</th>
<th>90</th>
<th>95</th>
<th>100</th>
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<tr>
<td>0.5</td>
<td></td>
<td>100s</td>
<td>110s</td>
<td>120s</td>
<td>130s</td>
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<tr>
<td>1.0</td>
<td></td>
<td>50s</td>
<td>60s</td>
<td>70s</td>
<td>80s</td>
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<tr>
<td>1.5</td>
<td></td>
<td>30s</td>
<td>40s</td>
<td>50s</td>
<td>60s</td>
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<tr>
<td>2.0</td>
<td></td>
<td>20s</td>
<td>30s</td>
<td>40s</td>
<td>50s</td>
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</table>

Table 5: Calculated $T_{dep}^{Pd}$ with change in current density and cathode efficiency

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<tr>
<th>Name</th>
<th>Composition</th>
<th>Purpose</th>
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<tbody>
<tr>
<td>Dawn Detergent</td>
<td>Biodegradable cleaning ingredients (detailed not shared)</td>
<td>remove grease</td>
</tr>
<tr>
<td>Activate</td>
<td>20%v/v Sulphuric acid, sodium flouride</td>
<td>remove oxide</td>
</tr>
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Table 6: Cleaning solution for Pd plating process [38]
anode and the cathode are connected to the positive and negative ends of the constant current power supply, respectively. The stir knob is adjusted to have mild stirring for agitation, which minimizes the porosity during plating [53]. Once the desired temperature, $I$, and pH are reached, both the anode and cathode are placed vertically inside the beaker. The side of the Ni/Cu coupon to be plated must face the anode directly, in order to get the maximum electric field exposure as illustrated in Fig. 12. The other side of the coupon will be plated with an undesired thickness due to...

Figure 11  Electro Pd setup in a) overall view and b) detailed view of Ni/Cu, and c) detailed view of anode.

Figure 12  Electric field line distribution in electroplating process
to the weak strength of electric field line, combined with possible electroless plating taking place. The process is repeated for each current level at the specified plating time.

3.2 Plating Results
The Fischerscope x-ray fluorescence (XRF) machine, Fischer Inc., Windsor, USA, is used to measure the thickness of the plated layers. Five measurements are made across the horizontal and vertical directions for each coupon and plated layer. The lateral tolerance of a single measurement is ≈ 2% of the measured value. The XRF can be programmed to measure specific points on single or double coated layers with tolerance below 10% of the measurement range. The surface quality of the plated layer is analyzed by a JEOL 6480 tungsten filament scanning electron microscope (SEM), JEOL, Tokyo, Japan along with the energy dispersive x-ray (EDX) analysis for measuring the chemical composition of the plated layers. SEM images of cross sections of the plated layers are also used to confirm the thickness measured by the XRF.

3.2.1 Electroless Ni Plating
Figures 13a and 13b show the thickness of the plated Ni layer measured across the horizontal and vertical directions, respectively. The plating times of 130s, 140s and 150s were used. The blue and pink lines in Fig. 13 are the average and +/- standard deviation of the thickness measurements. The difference between the measurements in vertical and horizontal directions are within 25%, and the difference between maximum and minimum thickness measurements in the same direction are within 30% for both horizontal and vertical directions. Therefore, the Ni thickness has no significant directional dependence during the plating process. As expected, an increase in plating time results in an increase in plating thickness. In order to get a Ni plating thickness of about 1 µm, the desired plating time should be between 140s and 150s. Figures 14a and 14b show
SEM micrographs of the Ni plated surface at magnifications of ×5k, and ×100k, respectively. The surface of the plated layer is smooth. Focused ion beam (FIB) is used to cut through the surface of the Ni/Cu layer, and measure the thickness on the cross section of the cut sample for deposition times of 130s, 140s and 150s. Figure 15 shows a sample cross section thickness measurement at deposition time of 140s under the SEM. EDX analysis to confirm the chemical composition of the
plated layer is performed at the cross section shown in Fig. 15. At the Cu and Ni side, the chemical composition is predominately Cu and Ni, respectively. The oxygen and phosphorous components in the Ni region are from the plating solution. The cross section thickness measurements obtained with the SEM are within 10% of the XRF measurement results.

3.2.2 Electrolytic Pd Plating
Figures 16a to 16d show the Pd thickness measurement for values of $I$ varied from 5 mA to 20 mA in steps of 5 mA. For $I$ below 20 mA, $h$ is below the thickness specification by using the calculated deposition time. At $I = 20$ mA and $T_{dep}^{Pd} = 50$ s, $h$ reaches 0.3 µm on average over 5 samples, and remains consistent along the vertical and horizontal directions. As expected, $t$ increases with both $T_{dep}^{Pd}$ and $I$.

Figures 17a and 17b show SEM images of the plated surface. Similar to the Ni plated surface, the Pd plated surface is smooth, with visible corrosion pits of sizes between 20 nm and 200 nm. Corrosion pits have been reported [51] to occur in the Pd electroplating process. Although Pd has excellent corrosion resistance, electrolytic process is more prone to surface pore than the electro-
less process [17]. Cross sections are made on the Pd/Ni/Cu coupons by mounting them in epoxy. Grinding and polishing procedures similar to that of the preparation for lower roughness Cu coupon are carried out, and $h$ is measured to confirm the XRF results. Figure 18 shows an example thickness measurement from a Pd/Ni/Cu coupon cross section with Pd deposition time of 50s and Ni plating time of 140s after a Au ball bond has been made. Both Pd and Ni thicknesses are within 10% of the results measured by XRF. Figure 19 shows an SEM image of the surface with chemical analysis to confirm the composition of the plated layers.
Figure 16  Curve of best polynomial fit for Pd thickness variation at input current of a) 5 mA, b) 10 mA, c) 15 mA, and d) 20 mA in the vertical (i), and horizontal (ii) directions. Fit is polynomial of 2nd degree (parabolic). Dashed lines are standard error
3.3 Summary
Processes to plate thin layers of Ni and Pd have been developed. The electroless Ni deposition time of 140s, and electrolytic Pd deposition time of 50s are required to consistently plate 1 µm and 0.3 µm of Ni and Pd, respectively. The current of the electroplating process used is 20 mA. The thicknesses are measured nondestructively by XRF and confirmed by SEM cross section.

Figure 17 SEM of the Pd plated surface at magnification of a) ×50k and b) ×100k.

Figure 18 SEM thickness measurement of Pd/Ni/Cu coupon for Pd deposition time of 50s, Ni plating time of 140s.
measurements. The surfaces of both Ni and Pd plated layers are smooth with surface pores on the Pd layer with sizes ranging from 20 nm to 200 nm, the degree for which the pores have on the bonding and reliability of the Au ball bonds are to be determined in subsequent sections of the report. Chemical analysis confirms the materials deposited on the bulk Cu.

Figure 19  SEM-EDAX of Pd/Ni/Cu coupon at magnification of ×5k
4. Development of Wire bonding Process
The plating processes for the Cu coupon have been developed with consistent thicknesses. In this section, the bondability of Au on the Pd/Ni/Cu substrate in terms of achieving the specified ball geometry and maximizing shear strength is reported. The specified ball diameter is between 50 µm to 60 µm, and the ball height is between 7 µm to 12 µm. The maximum shear strength (SS) is desired to be comparable to that of a typical Au-Al process, 110 MPa.

4.1 Experimental

4.1.1 Bonding Plan
An ESEC 3088 ball-wedge automatic bonder supplied by Oerlikon ESEC, Cham, Switzerland, is used in this experiment. The US frequency of the bonder is 130kHz. The wire bonder used is capable of bonding 10 wires per second. Cu and Au wire bonding are preferred applications for the bonder. The ESEC 3088 offers a maximum process temperature (T) of 300°C. A 25 µm diameter 4N Au bonding wire is supplied by MKE, Yongin, Korea, with properties shown in Table 7. A ceramic capillary with hole diameter (H) and chamfer diameter (CD) of 35 and 51 µm, respectively, is provided by SPT, Inc., Petaluma, USA. The coupon is placed in the center of the bond area on the heater plate of the wire bonder. Both vacuum and heat are supplied by the machine through the heater plate to fix and heat the coupon, respectively.

<table>
<thead>
<tr>
<th>Content</th>
<th>Breaking load (gf)</th>
<th>Elongation (%)</th>
<th>Vickers hardness (HV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>99.99% Au</td>
<td>10.0</td>
<td>2.8</td>
<td>50.0</td>
</tr>
</tbody>
</table>
Figures 20a and 20b show an overview and a detailed illustration of the bonding diagram. Both the ball and wedge bonds are placed on the coupon. Bonding takes place away from the edges of the coupon to minimize contamination and any other "edge effect" during bonding. Equal spacing between the ball and wedge of the same wire bond, and subsequent ball and wedge bonds are maintained. The wire loops are bonded parallel to the direction of US.

While only the ball bonds are of interest in this study, a consistent bond off on the coupon is required for FAB formation, and is achieved by setting up proper second bond parameters. The FAB diameter for achieving desired ball geometry is optimized by properly adjusting the EFO current and time. To achieve the desired ball geometry, the IF is varied with all other parameters kept constant. Finally, the SS is maximized by increasing the US while maintaining all other parameters fixed. To avoid complexity and time during the optimization process, the BT, T and BF are kept constant throughout the process, as they are factors minor to US and ball bond geometry. The ranges of BT, T and BF parameters are comparable to those used in Au-Al processes [27].
4.1.2 Ball Bond Geometry
Figures 21a and 21b show the definitions of FAB and ball bond geometric features, respectively.

The ball diameter as conveniently measured optically at the capillary imprint and at the ball peripheries are defined as BDC and MBD, respectively. The ball diameter at the interface (BDI) cannot be measured without cross sectioning the ball or otherwise removing it from the substrate. The ball height (BH) is measured by taking the absolute difference in height between the focus at the bottom and the top of the ball bond under the microscope. In general, only one of the three ball diameters and the BH are required to determine the ball dimensions. In this work, the MBD and BH are chosen to classify the ball geometry.

4.1.3 Ball Bond Shear Strength
The Dage 4000 ball shear tester supplied by Days, Buckinghamshire, UK, is used for the shear testing. The ball shear is performed using a shear tool (chisel) placed at a height of about 1/3 of the BH, to ensure the shear height is above any IMC. The travel speed of the chisel is 250 μm/s. The shear direction is parallel to the direction of the US during bonding.

Figure 21 a) Illustration of a) FAB, and b) bonded ball bond.
4.1.4 Summary
Table 8 summarizes the settings for the initial bonding process. The crescent bond parameters used for bond off are derived from the Au-Al process reported in literature [27]. The FAB diameter of about 45 µm is desired for the range of ball shape specified in this process. The parameter on the wire bonder is the nominal FAB diameter (FAB$_{\text{nom}}$), which usually is different from the actual measured FAB diameter.

4.2 Bonding Results

4.2.1 Free-Air Ball
Table 9 lists the actual crescent bond parameters, used for ten consecutive bond offs on the coupon. Between each bond off, a FAB is formed. Figure 22 shows the measured FAB (FAB$_{\text{act}}$)

<table>
<thead>
<tr>
<th>Class</th>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating stage</td>
<td>T</td>
<td>°C</td>
<td>220$^a$</td>
</tr>
<tr>
<td>Crescent bond or</td>
<td>IF</td>
<td>mN</td>
<td>700</td>
</tr>
<tr>
<td>bond off</td>
<td>BF</td>
<td>mN</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>US</td>
<td>%</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>BT</td>
<td>ms</td>
<td>20$^a$</td>
</tr>
<tr>
<td>Ball bond</td>
<td>IF (ball geometry)</td>
<td>mN</td>
<td>500-1100 (steps: 50)</td>
</tr>
<tr>
<td></td>
<td>BF</td>
<td>mN</td>
<td>240$^a$</td>
</tr>
<tr>
<td></td>
<td>NSOP US</td>
<td>%</td>
<td>0 - 10 (steps: 1)</td>
</tr>
<tr>
<td></td>
<td>US for maximum SS</td>
<td>%</td>
<td>NSOP-45 (steps: 2)</td>
</tr>
<tr>
<td></td>
<td>BT</td>
<td>ms</td>
<td>20$^a$</td>
</tr>
<tr>
<td>To get 45 µm FAB</td>
<td>FAB Diameter (ESEC 3088)</td>
<td>µm</td>
<td>47</td>
</tr>
</tbody>
</table>

a. Maintained constant;
diameters for various FAB\text{nom} values. The initial attempt of FAB\text{nom} = 47 µm gives an average of FAB\text{act} = 53.5 µm (ten samples). At FAB\text{nom} = 40 µm, the average FAB\text{act} is approximately 45 µm. An example FAB micrograph is shown in Fig. 22. The US for consistent ball bond sticking is determined to be 10 % after 5 successful ball were bonded on the Pd/Ni/Cu substrate with that value.

Table 9: Bond off/wedge bond parameters

<table>
<thead>
<tr>
<th>IF (mN)</th>
<th>BF (mN)</th>
<th>US (%)</th>
<th>Time (ms)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>300</td>
<td>18</td>
<td>20</td>
<td>220</td>
</tr>
</tbody>
</table>
4.2.2 Ball Geometry
Figures 23a and 23b show the variations in BH and MBD, respectively, with change in IF. The US parameter for consistent ball bond sticking is maintained from the previous step, and all other bonding parameters are fixed. The range of IF for both average MBD and BH to be within the specified ranges is 850 mN to 1000 mN. IF of 950 mN is used arbitrarily in order to achieve the median of the BH range, which is 10 µm. The IF of 950 mN gives a MBD of 58µm, which is within its range. The ball geometry is measured over five ball bonds. The micrograph of an example ball bond is shown in Fig. 23b.

4.2.3 Shear Strength
After determining the ball geometry, the US is varied from the magnitude required to get consistent ball bond sticking to 45%, which is about the same US magnitude to achieve maximum SS in the Au-Al process [27]. All the other parameters are kept constant. The SS is shown in Fig. 24. The corresponding MBD and BH are measured before shearing, and are shown in figures 25a and 25b, respectively. The SS for US above 36% decreases due to the ultrasound enhanced deformation (UED) [27] kicking in and causing an additional rise in the MBD. The US of 36% in this process is defined as the UED limit. The maximized SS is achieved at the UED limit and is approximately 130 MPa, averaged over ten ball bonds. The SS is above the minimum standard for the ball bonds, 65.2 MPa [4] and the typical Au ball bond shear strength of 110 MPa [5]. The shear occurs at the ball, with Au residue remaining on the surface of the coupon as shown in Fig. 24.
Figure 23  Measured ball bond a) BH, and b) MBD for various IF. Pd substrate. BF = 240 mN. $F_{AB_{nom}} = 45 \mu m$. 

Linear fit for BH: $BH = -0.0175 \times IF + 26.375 [\mu m]$

Linear fit for MBD: $MBD = 0.02 \times IF + 39 [\mu m]$
4.3 Summary
The optimized process parameters include nominal FAB diameter, ball bonding parameters, geometry and shear strength, all summarized in Table 10. Figures 26a, 26b and 26c show the SEM

Table 10: FAB, ball bond parameters and responses

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAB (µm) IF (mN) BF (mN) US (%) Time (ms) T(°C) MBD (µm) BH (µm) SS (MPa)</td>
<td></td>
</tr>
<tr>
<td>40 500 300 18 20 220</td>
<td>58 10 130</td>
</tr>
</tbody>
</table>
Figure 25    Boxplot of a) MBD, and b) BH for various levels of US.
images of the ball bond overview, detailed top view, and detailed side view, respectively. The geometry of the ball is achieved to be within the specified range. The ball bond shape is similar to that of the standard Au-Al process. However, the bondability of Au-Pd system is better (increase in SS) than that of a typical Au-Al process.
5. Reliability Study Through Destructive Analysis

After successful bonding on the Pd/Ni/Cu coupons, it is of interest to analyze the nature of the bond. The possibility of IMC formation and interdiffusion is studied in detail. A standard aging process is used in an attempt to thermally increase the possible voids and diffusions near the interfaces of Pd/Ni/Cu coupons.

The ball bonds are aged at a temperature of 250°C over 50 h, 100 h and 200 h. Cross section analysis is performed on the ball bonds, and nanohardness, SEM and TEM techniques are used to compare aged and as bonded ball bonds on the Pd/Ni/Cu coupons.

5.1 Shear test

The same shear test setup used previously for ball bonds before aging is used in this study.

Figure 27 shows the SS variation with aging time. Ten ball bonds were sheared for each aging time. The average shear strength of the ball bond for aging of 100 h and 200 h show increase in magnitude compared with the as bonded and 50 h samples. The MBD and BH remain the same during aging. The increase in SS for the aged samples above 100 h over the as bonded samples is significant according to the t-test. Such increase can be attributed to the expansion of effective bonded area through surface diffusion filling interfacial gaps, which promotes the strength of the ball bond. Similar to the as bonded failure type, the shear occurs at the ball in all aged samples.

5.2 Cross-section Analysis

Mechanical grinding and polishing are used to prepare the ball bond cross sections. The coupons before and after aging are held by epoxy hardened in a cup holder for 12 h. The mounted sample is removed from the cup to be ground and polished. The epoxy allows for grip, and minimizes smear during polishing of the coupon. The grinding starts near the second bond. Similar to the
previous grinding process, 300 and 600 grit paper are used to quickly grind away the material remote from the wire bond. Silicon carbide paper of 800 grit is used when the wedge bond has been reached, until the top of the wire loop is exposed, which is near the edge of the ball bond under the microscope. Grit paper of 1200 and 1200 fine are used to grind from there to the ball center.

The same polishing procedure as used for lowering the roughness of the as bonded sample is employed for the cross section of the ball bond. After polishing with diamond slurry, an additional polishing stage is used to minimize smear of Cu. The solution in this final polishing stage is a

![Figure 27](image)

Figure 27  Boxplot of shear force for various aging time.
mixture of colloidal silica, ammonia, and hydrogen peroxide. Figure 28 shows an example micrograph of the ground and polished as bonded ball bond.

5.2.1 Nanohardness
A Hysitron TriboIndenter supplied by Hysitron, Minneapolis, USA, is used for nanoindentation testing to identify possible hardness differences between the as bonded and aged sample. The cross section is placed on an adhesive, and inserted in the machine. No additional modification is performed to address possible surface hardening due to mechanical polishing since the relative hardness of the various metallic layers is sufficient for comparisons. The goal in this stage is to see whether IMC or interdiffusion can be detected by means of change in nanohardness next to the Au/Pd interface.

Figure 29 shows the topography of the cross section at the interfacial layer between the Au ball and Pd/Ni/Cu substrate after indentations are made for a sample aged for 200 h. The process is repeated for an as bonded sample. Table 11 lists descriptions of the fourteen nanohardness points
Figure 29  Topography view of cross section of interfacial layer between center of Au ball and Pd/Ni/Cu substrate after nanoindentation for an aged coupon for 250 °C over 200 h. Image size 8 µm×8 µm.

Note: P13 and P14 are not in figure

Table 11: Description of points in a typical nanohardness measurements

<table>
<thead>
<tr>
<th>Point (P)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Center of Ni layer I</td>
</tr>
<tr>
<td>P2</td>
<td>Center of Ni layer II</td>
</tr>
<tr>
<td>P3</td>
<td>Center of Pd layer I</td>
</tr>
<tr>
<td>P4</td>
<td>Center of Pd layer II</td>
</tr>
<tr>
<td>P5</td>
<td>Au/Pd interfacial layer I</td>
</tr>
<tr>
<td>P6</td>
<td>Au/Pd interfacial layer II</td>
</tr>
<tr>
<td>P7</td>
<td>0.2 µm vertically from Au/Pd I</td>
</tr>
<tr>
<td>P8</td>
<td>0.2 µm vertically from Au/Pd II</td>
</tr>
<tr>
<td>P9</td>
<td>0.4 µm vertically from Au/Pd I</td>
</tr>
<tr>
<td>P10</td>
<td>0.4 µm vertically from Au/Pd II</td>
</tr>
<tr>
<td>P11</td>
<td>1.5 µm vertically from Au/Pd I</td>
</tr>
<tr>
<td>P12</td>
<td>1.5 µm vertically from Au/Pd II</td>
</tr>
<tr>
<td>P13</td>
<td>Cu (3 µm away from Ni/Cu) I</td>
</tr>
<tr>
<td>P14</td>
<td>Cu (3 µm away from Ni/Cu) II</td>
</tr>
</tbody>
</table>
taken. Ideally, the points taken at the same region should be close to each other, but there are indents and scratches from the sample preparation stage, so the locations of the points were carefully chosen to avoid these features.

Figure 30a shows a plot of nanohardness results for the as bonded and aged coupons compared with Vickers hardness [40] of the corresponding metals. Similar to the Vickers, the overall pattern of aged and as bonded nanohardness over separate metal layers shows Ni has the highest nanohardness, followed by Pd, Cu and Au. Compared with nanohardness test of aged coupon, there is an increase in magnitude for the Au/Pd, Ni, and Pd regions in the as bonded coupon, attributed to the effect of aging, which counteracts annealing and softening. The nanohardness for Au is an average of the points P7, P8, P9, P10, P11, P12 taken away from the Pd/Au interfacial region in the Au side. All other data are an average of two sampling points. To verify the possibility of interdiffusion between Au and Pd, nanohardness taken at the Au region in steps of 0.2 µm away from the Pd/Au interfacial is performed for the aged and as bonded samples. Figure 30b shows a comparison of the change in nanohardness with distance from the Pd/Au region. The overall trends of the two curves are the same regardless of aging time. At a distance of 0.4 µm from the Pd/Au interface, the nanohardness saturates to that of bulk Au as measured at 1.5 µm away from the Pd/Au interface. Total of two measurements were made at each position interval for each coupon.

5.2.2 SEM
The LEO FESEM 1530 with ultra high resolution is used with EDAX EDS Sapphire Si(Li) 10mm² detecting unit supplied by Carl Zeiss, Peabody, MA, USA for imaging and chemical analysis of the cross sections.
Figures 31a to 31d show detail SEM views of the ball bond center for the as bonded, aged in 50 h, 100 h and 200 h, respectively. Different metallic layers are discernible by distinct contrast differ-

![Figure 30](image)

**Figure 30** Nano-hardness of a) across interfacial cross section of Au ball on Pd/Ni/Cu substrate for the as bonded and aged compared with Vickers of corresponding metals and b) comparison between as bonded and aged with change in distance from Pd/Au interface to pure Au region.
ences on the images. The thicknesses of the plated layers are consistent with previous measurements. Figure 32 shows a typical EDAX of the aged sample at 200 h confirming the chemical composition of the material. Figures 33a and 33b show the left and right edges of the as bonded ball in comparison to Fig. 33c and 33d, which shows the left and right edges of ball bonds aged for 200 h. Similar to Fig. 31, separate metallic layers are distinguishable. There is no conclusive evidence of diffusion, IMC or voids near the interfaces in the SEM analyses.
5.2.3 TEM
The JEOL 2010 field emission TEM/Spectroscopy TEM (STEM) of the Brockhouse Institute of Material Research at McMaster University in Hamilton, Ontario, is used with maximum magnification in transmission mode of 1.5 million and the information limit of 1.4 Å to further characterize the bond cross section interface. In STEM mode its spot size has been optimized to 1 nm. This allows for high magnification imaging (X 8 million) and energy dispersive analysis of materials. The small spot size enables elemental analysis with special resolution limited by the scattering in the specimen.

Before analyzing the sample under TEM, carbon film deposition is performed perpendicular to the ball bond cross section with SEM micrograph shown in Fig. 34. The sample chosen for TEM analysis has been aged for 200 h at 250 °C. Once the deposition is completed, FIB milling is performed to cut out a thin Au-coupon interface. The milling direction is perpendicular to the ball bond cross section. The milling process is continued for 45 min until the front and back surfaces of the cross section are exposed with SEM micrograph as shown in Fig. 35. Any effect of smear-

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Ni</th>
<th>Cu</th>
<th>Pd</th>
<th>Au</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>7.91</td>
<td>4.01</td>
<td>74.10</td>
<td>13.98</td>
<td>100.00</td>
</tr>
<tr>
<td>B</td>
<td>76.61</td>
<td>2.56</td>
<td>20.01</td>
<td>0.81</td>
<td>100.00</td>
</tr>
<tr>
<td>C</td>
<td>1.26</td>
<td>87.25</td>
<td>-0.62</td>
<td>12.11</td>
<td>100.00</td>
</tr>
<tr>
<td>Mean</td>
<td>28.60</td>
<td>31.27</td>
<td>31.16</td>
<td>8.97</td>
<td>100.00</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>41.72</td>
<td>48.48</td>
<td>38.59</td>
<td>7.12</td>
<td></td>
</tr>
<tr>
<td>Max.</td>
<td>76.61</td>
<td>87.25</td>
<td>74.10</td>
<td>13.98</td>
<td></td>
</tr>
<tr>
<td>Min.</td>
<td>1.26</td>
<td>2.56</td>
<td>-0.62</td>
<td>0.81</td>
<td></td>
</tr>
</tbody>
</table>

All weights in %

Figure 32   EDX of grinded and polished as bonded ball bond.
ing in the mechanical preparation of the sample is removed in the process. Figure 36 shows the area to be analyzed in the TEM after milling the bottom section of the ball bond cross section. The manipulator tip is positioned on top of the carbon film, and lifts the free lamina away from the cross section sample using carbon film deposition shown in Fig. 37. The milled section of the sample is placed on a copper grid by the manipulator tip shown in Fig. 38. After fixing the lamina to the Cu grid holder, the manipulator tip is released by additional FIB milling. The lamina is thinned for 2 h, with the final extracted sample shown in Fig. 39 for TEM analysis. The region near the Au/Pd region, and the Cu/Ni shown in Fig. 39, are of interest in the study.

Figure 33 SEM image of a) left edge of bond as bonded, b) right edge as bonded, c) left edge aged for 100 h, and d) right edge aged for 200 h.
Figures 40a and 40b show detailed representation of the Au/Pd region at different magnifications. The interface between Au and Pd is distinguished from the contrast in the figures. In order to resolve the interface between Ni and Pd, which is of less interest in the study, a different set of
milling process is required. Dislocations and grain boundaries are visible throughout regions near the Au/Pd interface.

Figures 41a, 41b, 41c and 41d show TEM micrographs near the Au/Pd interface at different tilt angle. The Au/Pd boundary can be identified through the contrast of the images in Fig. 41, and is used as reference to identify dislocations near the Au/Pd interface. The presence of dislocation near the Au/Pd interface is confirmed when a change in dislocation plane (change in tilt angle) oc-
curs as shown in Fig. 41. However, The presence of IMC formation and/or interdiffusion in the system is not clear. In an attempt to analyze the microstructure at the Au/Pd interfacial line, TEM micrographs are shown in Figs. 42a and 42b with higher magnification of the regions near the Au/Pd interface. The dark region varies in shape and intensity with change in tilt angle, which indicates the presence of dislocations near the Au/Pd interface. Figures 46a and 46b show an overall
TEM image at the Au region where “oval” shapes in the dislocations are present. For comparison, TEM micrographs near the Cu/Ni side are shown in Fig. 43, away from the bonding region. Figures 43a and 43b show grain boundaries and dislocation to have "flake" patterns on the Ni/Cu interface, which differs from that of Au/Pd interface.

A TEM-EDS analysis was conducted in a similar way to that of the SEM-EDS. Figure 44a shows the Cu, Ni, Pd, and Au metallic layers with Figs. 44b to 44e showing x-ray spectra plots for Au, Ni, Pd, and Cu. The gap between Cu and Ni is due to sample preparation (ion milling) during which all of the Cu was removed in the region. Figure 45a shows the EDX scan over a higher resolution TEM micrograph with focus on the Pd layer. The x-ray energy scans of O, Ni, Pd, Au, and Cu are shown in Figs. 45b to 45f, respectively. Similar to the lower resolution analysis, Cu exists through all metallic layers. With the exception of Au, Ni, Pd, or Cu in the sample, there is no other
material such as oxide, in the system, and the surface is free of impurities. Similar to the previous analysis, there is no observable evidence of IMC formation near the Au/Pd interface. However, At the regions near the Au/Pd interface, there is a visible concentration of about 0.1 µm of Au present on the Pd side.
Figure 42  Detailed TEM image near the Au/Pd region at magnifications shown in a) and b), zoom of a)

Figure 43  TEM image near the Cu region at magnifications various tilt angle (a, b)
Figure 44   EDX line scan across the a) Pd/Ni/Cu/Au metallic layers for x ray spectra of b) Au, c) Ni, d) Pd, and e) Cu.
Figure 45  EDX line scan across the a) Au/Pd/Ni metallic layers for x ray spectra of b) O, c) Ni, d) Pd, e) Au and f) Cu.
5.2.4 Discussion
For the nanohardness results, between 0 to 0.4 µm away from the Pd/Au interface, the variation in the magnitude of the nanohardness is due to the small distance to the interface causing a “proximity effect” in which the adjacent harder material raises the perceived hardness of the adjacent softer material. Therefore, the nanohardness technique is not applicable in determining a correlation between diffusion and/or IMC formation near the interfaces in this process.

Due to the limitation in the resolution of the SEM, no conclusive results for the presence of IMC, voids, or interdiffusion can be drawn.

Diffusion from Au to Pd observed in the TEM-EDS analysis has been reported previously [29]. However, The depth of diffusion from Pd to Au is expected to be about 10-15 % higher than that of from Au to Pd. Diffusion from Pd to Au is not observed in this study. The overall chemical analysis indicates lack of impurities across all interfaces, which could attribute to the increase in bondability of the ball bonds post aging.

![TEM image near the Au region at magnifications various tilt angle (a, b)](image)

Figure 46 TEM image near the Au region at magnifications various tilt angle (a, b)
The lack of IMC formation from the SEM and TEM analysis is confirmed by the TEM-EDS analysis.

The difference of the dislocation shape between the Au/Pd and the Ni/Cu interface is likely due to the bonding process parameters affecting area near the Au/Pd interface, where repeated cycles of US motion result in dislocations shape subjected to repeated bending. The decrease in the amount of grain boundaries observed near the Pd/Au interface compared with the Ni/Cu interface indicates lack of Cu migration at the Au/Pd interface, which would degrade the bondability [54, 56].

The presence of Cu in the Ni and Pd region in the TEM-EDS analysis can be attributed to noise from the sample holder, which is made of Cu. The high Cu concentration in the Au wire is possibly due to a combination of noise, and error in the calculation of the x-ray spectra as Au and Cu have lattice parameters 4.08 Å, and 3.62 Å, respectively.

5.3 Summary
Based on shear testing results, the SS are higher for ball bonds aged for 200 h at 250 °C compared with that of the as bonded and aged for 50 h. No evidence of IMC formation and oxide were observed with the SEM, TEM, and nano-hardness techniques in the study. There is an indication of Au diffusion into Pd, which can correlate to the increase in bondability for ball bonds after aging. The nature of the chemical bond between Au and Pd is confirmed to be metallic.
6. Reliability Study Through Contact Resistance Monitoring
The contact resistance of the ball bonds is monitored for reliability analysis to confirm the previous results from the cross section analysis. A better understanding of the Au/Pd interface during aging is obtained. If formation of IMC or interdiffusion occurs during aging, a rise of the contact resistance is expected.

6.1 Experimental
The contact resistance \( R_c \) is measured by the standard 4-wire resistance measurement method illustrated in Figs. 47a and 47b in top view and side view, respectively. A second wire is attached to the ball bond using a modified bonding process with an US parameter reduced by at least 90 \% resulting in a cold weld between the two Au balls, produced mainly by plastic deformation. Constant current \( I_c \) is fed via the second wire through the ball bond. At the same time, the voltage difference \( (V_L - V_H) \) is measured between the ball bond and substrate, where \( V_L \) and \( V_H \) are explained in Fig. 47b. \( R_c \) is calculated using Ohm’s law by dividing the voltage difference by the applied current. The four wire configuration eliminates the wire loop resistance from the measurement.

Figure 47    a) Top view and b) side view of the 4-wire contact resistance measurement method.
The same method has been used previously [42] for a similar experiment with an Au ball bond to a standard Al metallization.

The baseline substrate sample used in the contact resistance measurement during aging is denoted as sample 0. Sample 0 was plated with the optimum parameters and cut using a precision cutter to dimensions that fit on the diepad of the 28 pin chip package. The mounting of the Pd/Ni/Cu substrate on the package was performed using a thermally conductive silver epoxy cured at room temperature for 24 h. Figure 48 shows a photo of the assembly after mounting. The bonding diagram for the resistance measurement process is illustrated in Fig. 49. In total, 38 wire bonds are made. The pin configuration and its corresponding functionality are shown in Fig. 49. Pin 4 and pin 19 are used for I_L and V_L, respectively. Additional wires are bonded for the two pins as a precaution against premature failure. The remaining 26 pins are used to bond 13 sets of double bonds, with each set corresponding to V_H (bottom bond) and I_H (top bond). A maximum of 13
sample resistance measurements can be generated from the 13 double bonds. The sample ball bond number is given in parentheses in Fig. 49. Below the ball bond number, there is the actual contact resistance measured at ambient temperature. The number given inside the package terminals in blue color indicates the sequence in which the bond is made on the wire bonder. The bottom ball bond parameter and the crescent bond parameters were taken from previous optimization processes for the baseline sample. Table 12 lists the top ball bond parameters. The IF and US for
the top ball bond are much lower than those used for the bottom ball bond to prevent the bottom ball bond from lift off by e.g. ultrasonically induced fatigue. A negative value for the "neck angle correction" parameter is used to obtain the desired loop shapes. Figures 50a and 50b show the actual chip during and after the wire bonding process.

High temperature solder consisting Pb and Ag, supplied by Kester Solder, Neuensalz, Germany, is used to join the leads of the package to a high temperature flat band cable supplied by Tyco Electronics, Berwyn, USA, and thereby to the multiplexer unit and the multimeter, supplied by Keithley Instrument, Cleveland, USA. The multiplexer is used to sequentially measure the 4-wire

<table>
<thead>
<tr>
<th>IF (mN)</th>
<th>BF (mN)</th>
<th>US (%)</th>
<th>BT (ms)</th>
<th>T (°C)</th>
<th>Loop Height (µm)</th>
<th>Neck Angle Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>240</td>
<td>3</td>
<td>20</td>
<td>220</td>
<td>200</td>
<td>-0.826</td>
</tr>
</tbody>
</table>

Figure 50 Photo of Au ball bonding process a) during and b) after bonding on Pd/Ni/Cu for contact resistance measurement.
resistance of each of the 13 available bonds via the multimeter. The computer, controlled by a custom made program (programming language is Matlab\textsuperscript{TM}) given in Appendix A (INSERT PROGRAM), switches the multiplexer and records the readings from the multimeter. The multimeter is used in the 4-wire resistance measurement mode, supplying a test current of $I_c = 0.1$ mA. The process is repeated for all 13 contact resistance measurements. Before starting the measurements, the chip is placed inside an oven (Omegalux, NJ, USA) where it remains at room temperature for 1 h to obtain reference measurements. The temperature next to the chip is measured by a Pt100 resistive temperature detector with a standard accuracy of $\approx \pm 4$ K at 250 °C. Along with the contact resistance samples, the Pt100 unit is placed inside the oven, and the resistance is recorded using a DAQ unit and the same custom made program. The overall wiring diagram of the setup is illustrated in Fig. 51.

![Figure 51 Wiring diagram for contact resistance measurement process of Au ball bonds to Pd/Ni/Cu substrate while in oven.](image)
6.2 Results
The three process phases discussed are (I) heat-up, (II) aging, and (III) cool-down. The contact resistance rises with change in temperature in the heat-up phase until the target temperature of 250 °C is reached. The contact resistance saturating to a steady state value is observed in phase II. In the third phase, the oven is turned off and temperature drops to room temperature. The oven is turned on shortly again to obtain data for post aging temperature coefficient (TC) calculation.

Before phase (I), initial resistance measurements are made for reference at room temperature outside the oven by directly connecting each sample to the multimeter (bypassing the multiplexer) with results shown in Table 13. These measurements are then repeated with the samples connected to the multiplexer. Both results are identical, which indicates that the multiplexer does not add any offset to the $R_c$ measurements. The actual temperature at the time for which the $R_c$ was taken is also recorded in terms of resistance by the Pt100. The Pt100 resistance is converted back to temperature by

$$ R = R_0 \cdot (1 + a \cdot T + b \cdot T^2) $$

(1)

where $R_0 = 100 \, \Omega$ is the resistance at 0 °C, $a = 3.9083 \cdot 10^{-3} \, K^{-1}$ and $b = -5.775 \cdot 10^{-7} \, K^{-2}$ are constants [57].

After 1 h of measurements at room temperature, the oven is reprogrammed to 50 °C and 100 °C, each for 30 min. Results from these additional temperature levels are used to calculate the TC of the $R_c$. 


where $T$ is the temperature and $R(T)$ is the resistance as a function of $T$ [43]. The average $TC$ at 20°C is 0.0022 K$^{-1}$ with a standard deviation of 0.0001 K$^{-1}$, which is exactly the same as the $TC$ post aging. The measured $TC$ of $R_c$ is lower compared to that of standard Au (0.003715K$^{-1}$) and Pd (0.0038K$^{-1}$). The value $R_{ref} = R(T_{ref})$ serves as comparison value between the magnitude of the contact resistance before and after aging. It is defined by

$$TC(T) = \frac{dR}{dT} \frac{1}{R(T)} \quad (2)$$
\[ R_{ref} = \frac{R_x(T)}{1 + TC_{ref}(T_x - T_{ref})} \]

where \( R_x(T) \) is the contact resistance with respect to temperature \( T_x \), \( TC_{ref} \) is the temperature coefficient at \( T_{ref} \) and \( T_x \) and \( T_{ref} = 20 \, ^\circ C \) are the actual and reference temperature, respectively [43]. The reference resistance before \( (R_{ref}^{pre}) \) and after \( (R_{ref}^{post}) \) aging, and the average and standard deviation of the contact resistance during aging are shown in Table 14. The median change is -6%. As seen in Table 14, \( R_{ref}^{pre} > R_{ref}^{post} \) for all 13 bonds after 287 h at 250°C.

<table>
<thead>
<tr>
<th>Ball Bond</th>
<th>Before aging ( R_{ref}^{pre} ) (mΩ)</th>
<th>During Aging Average ( R_c ) (mΩ)</th>
<th>During Aging Resistance STDEV (mΩ)</th>
<th>After aging ( R_{ref}^{post} ) (mΩ)</th>
<th>Difference before and after (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.00</td>
<td>2.7</td>
<td>0.01080</td>
<td>1.78</td>
<td>-11.04</td>
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<tr>
<td>2</td>
<td>2.15</td>
<td>2.9</td>
<td>0.02113</td>
<td>1.90</td>
<td>-11.62</td>
</tr>
<tr>
<td>3</td>
<td>1.70</td>
<td>2.4</td>
<td>0.00321</td>
<td>1.60</td>
<td>-5.92</td>
</tr>
<tr>
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<td>0.00320</td>
<td>1.67</td>
<td>-1.76</td>
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<td>5</td>
<td>1.83</td>
<td>2.6</td>
<td>0.03198</td>
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<td>6</td>
<td>2.40</td>
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</tr>
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<td>0.02162</td>
<td>1.66</td>
<td>-2.35</td>
</tr>
<tr>
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<td>2.5</td>
<td>0.00571</td>
<td>1.63</td>
<td>-5.78</td>
</tr>
<tr>
<td>10</td>
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<td>2.4</td>
<td>0.02524</td>
<td>1.75</td>
<td>-1.13</td>
</tr>
<tr>
<td>11</td>
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<td>0.01098</td>
<td>1.72</td>
<td>-6.52</td>
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<tr>
<td>12</td>
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<td>0.04480</td>
<td>2.14</td>
<td>-31.41</td>
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<td>13</td>
<td>1.57</td>
<td>2.2</td>
<td>0.00244</td>
<td>1.48</td>
<td>-5.73</td>
</tr>
</tbody>
</table>
Figure 52 represents in situ measurements of $R_c(t)$ of the bond with least change (bond #10), most change (bond #12) and typical change (bond #9) during aging. The thermal noise observed in Fig. 52 could be due to random variations in the measured voltage caused by random movement of the electrons jolted around by thermal energy during the aging process. Figures 53a, 53b and 53c show SEM images of the double ball bonds #9, #10 and #12, respectively in top and side views. The shape of the ball bonds and the wire loops are similar to those observed on standard Al sample experiencing largest change (#12)

sample experiencing typical change (#9)

sample experiencing least change (#10)

Figure 52  Contact resistance measurement test for largest change and least change in resistance for coupon with $R_a$ of 0.08 µm. $T = 250$ °C during phase II.
chips. The $R_c$ measurements of the remaining samples are shown in Fig. 54. For these bonds, $R_c$ does not rise during aging. On the contrary, $R_c$ drops as observed for all 13 samples. The drop is strongest in the first 100 h of aging. The subsequent 100 h of aging shows a slower drop before $R_c$ reaches a steady state value in some cases.

Figure 53    SEM images of double ball bond for a) largest $R_c$ change (bond #12), b) the typical change (bond #9) and c) least change (bond #10) in i) top and ii) side view for coupon with $R_a$ of 0.08 µm.
Figure 54  Contact resistance measurements for ball bond numbers 1-8, 11, and 13 through the 287 h aging at 250 °C for coupon with $R_a = 0.08 \mu$m.
6.3 Discussion

Logie et al. [44] reported an increase in resistivity that occurs from pure Au or Pd to AuPd alloys at liquid nitrogen point (77.2 K) as shown in Fig. 55. To correlate the results with the experiment conducted, if IMC formation was to occur, $R_c$ is expected to increase similarly to that repeated in [44]. As $R_c$ does not rise during aging, this indicates little or no IMC formation. The negligible variation between pre and post aging $TC$ also reconfirms the lack of substantial IMC.

Figure 55 Resistivity of undeformed Au-Pd alloys at liquid nitrogen temperature (77.2 K) [44].
The findings here directly correlate with those of the destructive analysis where no IMC formation was observed.

The amount by which \( R_c \) decreases varies between ball bonds. The ball bonds with higher initial \( R_c \) show a greater drop during aging. \( R_c \) is affected by interfacial gaps (unbonded area) that are nanoscopic in size and located at different locations of the bonded interface. The amount of such gaps varies between the ball bonds. During aging, the gaps possibly experience a gradual filling by Pd or Au atoms diffusing into them as shown in the TEM-EDS analysis in chapter 5. Bonds starting with a relatively large amount of interfacial gaps (higher contact resistance) would experience substantial gap filling and therefore a relatively large decrease in \( R_c \). Over time, the rate of decreases declines as less gap and dislocations are available near the contact zone to be filled.

### 6.4 Summary
The in-situ contact resistances of ball bonds are measured while they are aged at 250 °C over 250 h. No evidence of IMC formation has been found. For the baseline sample, \( R_c \) does not increase during aging period. In contrast, it tends to drop. This indicates the electrical integrity of the interconnections is maintained. In general, the reliability of the baseline sample show signs of improvement over the standard Au-Al process, where IMC formation and \( R_c \) rise are known at lower temperature and time used in this process.
7. **Roughness Modulation**

The roughness of the metallization is modulated to investigate the overall process quality and to analyze possible correlations between this adhesion modulator and the Au/Pd ball bond process.

7.1 **Experiment**

Excessive roughness has been found to influence the quality of the wirebond [35]. A typical bonding substrate has a roughness $R_a$ much smaller than the diameter of the bond [52]. For too large $R_a$, the bondability is degraded as the asperities on the surface are too large to be broken down during the process. An upper limit for $R_a$ of 0.5 µm is chosen in this study, which is at the upper end of the values used in typical wire bonding processes.

Three coupons are produced with roughness types and values different from those of the polished baseline sample. The roughness is introduced on the Cu before plating and the plated Ni and Pd roughnesses are within 5% of that of Cu. The electroless Ni and electrolytic Pd processes developed previously were used for the roughened samples. The plating parameters remain the same for regardless of the coupon roughness.

Three different processes are used to vary the roughness of the coupons. The first coupon (sample 1) used in the process is directly used after shipping. The $R_a$ is about 0.2 µm and is directional due to the pre-rolling process of the Cu foil before shipment. The second coupon (sample 2) is mechanically scratched by 600 grit sand paper in one direction for five minutes. The $R_a$ of the scratched coupon is about 0.4 µm and is conformal to the direction of the scratches. Figure 56a shows the photo of samples 1 and 2 with increase in $R_a$ compared with Fig. 56b and 56c for the baseline and standard Ag substrate used in the laboratory. The coupons are mounted on a 90° stub with carbon tape for handling purposes.
The last coupon is sandblasted with glass beads between 170 μm to 325 μm, supplied by Flex-O-Lite, St. Louis, USA. Sandblasting is performed with the minimum recommended allowable pressure of 15 psi over 5 s with the sandblast machine supplied by Ritchey Supply Ltd, Vancouver, Canada, shown in Fig. 57a. A sandblasted sample (sample 3) is shown in Fig. 57c. The $R_a$ of sample 3 is 0.5 μm. During sandblasting, the sandblast gun is held at a 45° angle, and about 5 cm away from the coupon. The coupon is fixed to the stub by carbon tape similar to the two previous

Figure 56 Roughness measurement samples of a) Cu after sanding with 500 grid sand paper, b) Cu after standard grinding and polishing, and c) standard Ag bondpad.
coupons. The operation ensures consistent results if repeated under the same conditions. Both pressure and time are directly correlated to $R_a$ and ensure uniform distribution of the bead across the surface of the coupon in the process. Lower pressure or time values cannot ensure an uniform bead distribution with this machine, and therefore, lower values of $R_a$ cannot reliably be achieved with the existing setup. The sandblast process introduces random roughness in contrast to the previous two samples. The abrasive used in the process is shown in Fig. 57c. The sandblast machine is replenished periodically when the bead are used up or after long storage.

Figure 57  Overview of sandblasting a) machine, b) sample, and c) fine bead.
Before and after adding roughness to the Cu coupons, the samples are cleaned and stored in the same manner as the baseline samples.

The optical profiler is used to measure and analyze the magnitude and direction of the roughness, respectively. Figure 58a and 58b show the optical image and $R_a$ measurement of the original baseline sample. Figures 59a, 59b, and 59c show optical images for sample 1, 2 and 3, respectively. Figures 59d, 59e and 59f show the corresponding optical profiler $R_a$ measurements.

7.2 Wire Bonding Process Adjustments

The same ball bond optimization procedure used previously for the baseline sample was applied on the different roughness substrates. The optimized ball bonding factors are shown in Table 15. The optimized US parameter is reduced in the range of 4% to 18% for depending on the roughness of the samples, while the remaining parameters are mostly the same. The average FAB diameters measured for the rough samples were lower than those of the baseline sample as shown in Fig. 60a. The other responses include average MBD and BH values shown in Figs. 60b and 60c,
Figure 59     Optical microscope image and corresponding optical profiler measurement of a), d) sandblasted, b), e) sandpaper, and c), f) as shipped Pd/Ni/Cu coupon
Table 15: Ball bonding parameters with various roughness substrate

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ra (µm)</th>
<th>IF (mN)</th>
<th>BF (mN)</th>
<th>US (%)</th>
<th>BT (ms)</th>
<th>T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.08</td>
<td>950</td>
<td>240</td>
<td>36</td>
<td>20</td>
<td>220</td>
</tr>
<tr>
<td>1</td>
<td>0.2</td>
<td>850</td>
<td>240</td>
<td>28</td>
<td>20</td>
<td>220</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>650</td>
<td>240</td>
<td>22</td>
<td>20</td>
<td>220</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>950</td>
<td>240</td>
<td>18</td>
<td>20</td>
<td>220</td>
</tr>
</tbody>
</table>

Figure 60  Variation in a) FAB, b) MBD, and c) BH with respect to change in roughness of Pd/Ni/Cu
respectively. The baseline sample has the largest MBD and BH, resulting MBD and BH vary from 55 to 58 µm and 8 to 10 µm, respectively, and are within the specified ranges. The maximum SS obtained with the roughened samples increases with Ra, but is not higher than that obtained with the baseline sample. Similar to the baseline sample, the shear occurs at the ball for all roughened samples. The optimized SS for various roughness values are shown in Fig. 61. The SS increases with roughness for Ra above 0.08 µm. The average SS of Au ball bonds on the sandblasted specimen is comparable with that of polished baseline sample, while the other specimens have a relatively lower SS.

7.3 Non-Destructive Analysis
For comparison with the in situ $R_c$ measurements of the baseline sample, sample 2 was aged over 200 h at 250 °C. The $TC$ at the reference temperature of 20 °C is about 5.8% higher after aging. Figure 62a shows $R_c$ of ball bonds #13, #8 and #6 with the most, typical and least change, respec-
tively. The cool down phase results are not shown. The heat up phase is similar to the baseline sample and shown in Fig. 65b, where an increase in $R_c$ from increase in temperature occurs. During the aging phase, the $R_c$ can increase as indicated clearly for ball bonds #13, This trend is opposite to that of the ball bonds on the baseline sample. Figure 63 shows the $R_c$ of the remaining ball bonds. $R_c$ increases for all thirteen ball bonds. Table 16 lists the comparison between $R_c$ at different stages of the aging process. The $R_{ref}^{pre}$ is below that of the $R_{ref}^{post}$ for all thirteen ball bonds shown in Table 16. The median change is 5 %.

![Graph showing contact resistance measurements for coupons with Ra of 0.4 µm. $T = 250 ^\circ C$ during phase II.](image)
Figure 63  Contact resistance measurements for ball bonds 1-7, and 7-12 through 287 h aging at 250 °C for coupon with $R_a$ of 0.4 µm.
Same contact resistance measurement is repeated for the two remaining roughened samples. In order to measure the $R_c$ for both samples during aging simultaneously using one multiplexer, six ball bonds were made for each of the two remaining roughened samples. Figure 64 shows the variation in $R_c$ for the six ball bonds on sample 3. The six ball bonds shown in Fig. 64 contain the largest change (ball bond #3), typical (ball bond #5) and least change (ball bond #4) in $R_c$ for sample 3. All six ball bonds shows the same trend, where $R_c$ increases during aging. Similar to

<table>
<thead>
<tr>
<th>Ball Bond</th>
<th>Before aging $R_{\text{ref}}^{\text{pre}}$ (mΩ)</th>
<th>During Aging Average Resistance (mΩ)</th>
<th>During Aging STDEV Resistance (mΩ)</th>
<th>After aging $R_{\text{ref}}^{\text{post}}$ (mΩ)</th>
<th>Difference before and after (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.73</td>
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<td>7.32</td>
<td>323</td>
</tr>
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<td>2.04</td>
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<td>1.88</td>
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<td>146.1</td>
<td>32.63</td>
<td>1690</td>
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Figure 64  Contact resistance measurements for 6 ball bond through 287 h aging at 250 °C for coupon with R_a of 0.5 µm.
sample 2, an increase in $R_c$ with increase in temperature is observed in the first stage. During the second stage, the peak temperature of 250 °C is reached, and $R_c$ continue to rise for all six ball bonds. Table 17 shows the $R_{ref}^{pre}$ and $R_{ref}^{post}$ for the six ball bonds on sample 3. The median change is 14%. As expected, the increase in reference resistance is observed for all six ball bonds. The during aging average and standard deviation of the contact resistance are shown in Table 17.

Figure 65 shows the $R_c$ trend for the six ball bonds on Pd/Ni/Cu on sample 6. The $R_c$ for half the ball bonds (#6, #1 and #3) do show increase with aging time. Ball bond #6, #4 and #1 represents the largest, typical and least change in $R_c$, respectively. The slope of $R_c$ during aging is less than those of sample 2 and 3. The other half (#2, #4 and #5) of the ball bonds indicate $R_c$ trend similar to that of the baseline sample, where $R_c$ does decreases after aging. The Table 18 shows the $R_{ref}^{pre}$ and $R_{ref}^{post}$ before and after aging, and the average and standard deviation of $R_c$ during aging. The

<table>
<thead>
<tr>
<th>Ball Bond</th>
<th>Before aging $R_{ref}^{pre}$ (mΩ)</th>
<th>During Aging Average Resistance (mΩ)</th>
<th>During Aging STDEV Resistance (mΩ)</th>
<th>After aging $R_{ref}^{post}$ (mΩ)</th>
<th>Difference before and after (%)</th>
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<td>0.11</td>
<td>1.86</td>
<td>31.0</td>
</tr>
<tr>
<td>3</td>
<td>2.62</td>
<td>2.5</td>
<td>0.25</td>
<td>3.08</td>
<td>17.6</td>
</tr>
<tr>
<td>4</td>
<td>2.33</td>
<td>2.5</td>
<td>0.14</td>
<td>2.71</td>
<td>16.3</td>
</tr>
<tr>
<td>5</td>
<td>2.14</td>
<td>2.5</td>
<td>0.051</td>
<td>2.26</td>
<td>5.61</td>
</tr>
<tr>
<td>6</td>
<td>1.58</td>
<td>1.5</td>
<td>0.065</td>
<td>1.73</td>
<td>9.49</td>
</tr>
</tbody>
</table>

Table 17: Comparison between contact resistance at different stages of aging for $R_a$ = 0.5 μm sample (sample 3).
Figure 65  Contact resistance measurements for 6 ball bond through 287 h aging at 250 °C, for coupon with Ra of 0.2 µm.
median change is 0.4 %. Form the analysis observed so far, a direct correlation between the substrate roughness and percentage of ball bonds with increase in $R_c$ can be drawn.

7.4 Destructive Analysis
The same sample preparation of the baseline sample is used for the roughened samples. Figures 66a and 66b show the optical micrographs of cross sections of ball bonds on the as received and the sandblasted samples, respectively, before aging. The different metallic layers are characterized by the difference in contrast in the figures. The asperities from the increase in roughness are visible on the sandblasted sample, and can be seen more clearly in regions away from the bonded area.

7.5 Discussion
A possible reason for the difference in FAB diameters between the roughened and baseline samples is that the wire tail produced by the wedge bond on the samples can have a different shape resulting in a different amount of material pick-up [45] than that produced on the baseline sample.

Table 18: Comparison between contact resistance at different stages of aging for $R_a = 0.2 \, \mu m$ sample (sample 1).

<table>
<thead>
<tr>
<th>Ball Bond</th>
<th>Before aging $R_{ref}^{pre}$ (mΩ)</th>
<th>During Aging Average Resistance (mΩ)</th>
<th>During Aging STDEV Resistance (mΩ)</th>
<th>After aging $R_{ref}^{post}$ (mΩ)</th>
<th>Difference before and after (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.23</td>
<td>3.0</td>
<td>0.082</td>
<td>3.34</td>
<td>3.40</td>
</tr>
<tr>
<td>2</td>
<td>3.96</td>
<td>4.5</td>
<td>0.13</td>
<td>3.86</td>
<td>-2.52</td>
</tr>
<tr>
<td>3</td>
<td>3.44</td>
<td>3.9</td>
<td>0.14</td>
<td>3.58</td>
<td>4.07</td>
</tr>
<tr>
<td>4</td>
<td>2.70</td>
<td>3.0</td>
<td>0.069</td>
<td>2.63</td>
<td>-2.59</td>
</tr>
<tr>
<td>5</td>
<td>2.38</td>
<td>3.0</td>
<td>0.082</td>
<td>2.31</td>
<td>-2.94</td>
</tr>
<tr>
<td>6</td>
<td>2.83</td>
<td>3.3</td>
<td>0.11</td>
<td>3.04</td>
<td>7.42</td>
</tr>
</tbody>
</table>
The amount of material pick-up on the wire tail has an effect on the diameter of the FAB subsequently formed.

With regard to $SS$ variation in the bonding process, no reliable value for standard deviation derived from such low sample sizes, the t-test shows the increase in $SS$ from ball bonds on the baseline sample to that of sample 8 is not significant. The maximized $SS$ of all roughened coupons are comparable to the standard Au ball bond $SS$ of 110 MPa.

Figure 66 Cross section of ball bonds on Pd/Ni/Cu with roughness of a) 0.2 µm and b) 0.5 µm before aging i) at the ball bond and ii) away from ball bond.
The increase in $R_c$ and $R_{ref}$ from pre to post aging for the roughened samples can be correlate to possible voids, IMC formation at the interfaces and/or impurities from the roughness particles, which grow with increase in temperature, reducing the contact area between the Au ball and Pd/Ni/Cu surface, but further cross section analysis is required to give more conclusive details supporting the claim.

The reliability of the Au/Pd process with increase in $R_a$ in this study remains an improvement over the Au/Al process, where $R_c$ grows linearly at 250 °C, and does not saturate with time [55]. However, compared to the baseline sample, the reliability of the roughened sample is degraded.

### 7.6 Summary
The roughness of the Pd/Ni/Cu substrate as shipped from manufacturer are varied by scratching, sandblasting and mechanically polishing. The sandblast sample has a random roughness of 0.5 µm, while the as received and scratched sample have directional roughness of 0.2 µm and 0.4 µm, respectively.

Bonding optimization made on the various roughened samples shows an increase in the US for successful bonding on roughened substrates. The final SS increases with $R_a$ for the roughened sample, and remains comparable to that of the standard Au-Al process.

The $R_c$ of the roughened samples shows increase with aging time, which is the opposite trend to that of the baseline samples. The median and percentage of ball bonds for the $R_c$ increase directly correlate with substrate roughness.

No conclusive evidence is available to justify the increase in $R_c$ for the roughened samples as additional destructive analysis to investigate voids and/or IMC formation at the cross section is planned.
8. Conclusions
The Ni and Pd plating processes developed in this project can be used to coat Cu base material to produce substrates for bonding process studies. Methods to produce roughness variations of the substrates are developed using sandblasting or sandpaper processes, and produce surface modulation suitable for the bonding process studies. The standard ball bonding optimization procedure described was applicable for all produced Pd/Ni/Cu substrates, resulting in mostly uniform bond strength and geometry. The shear strength and shape of the ball bonds are comparable to those typically obtained for Au ball bonds on Al metallization.

Ball bonds were made and aged by high temperature storage. For the aging temperature and duration chosen, TEM analysis indicates some Au diffusion into the Pd layer. SEM, TEM, nanohardness, and contact resistance measurements showed no evidence of intermetallics and void formation at the Au/Pd interface. However, intermetallics and voids may occur when aging at higher temperature or for longer durations. With a low enough roughness, lack of interfacial impurities, and the similarity in lattice structure and constant between Au and Pd, the nature of the bond is determined to be a chemical bond of metallic type.

This study confirms that the bondability and reliability of the Au to Pd system are superior to those of the standard Au to Al system, i.e., the overall electrical integrity of the interconnection is enhanced. Increasing the roughness does not improve the Au to Pd reliability. However, the amount of ultrasound required for successful bonding is reduced.
References


[22] "Method and apparatus for adjusting plating solution flow characteristics at substrate cathode periphery to minimize edge effect", U.S. Patent 5000827

[23] Shigolev, P. V., "Electrolytic and chemical polishing", Tel-Aviv, 1974


[37] Electroless Ni plating kit datasheet, Cadwell Inc.

[38] Electro Pd plating, "Pallaspeed technical datasheet", Technic Inc.


[56] Lin *et al.*. “The evaluation of copper migration during the die attach curing and second wire bondign process”, Proceedings of the IEEE ECTC, 2002

[57] Pt100 Platinum Resistance Thermometers datasheet, Pico Technology.
Appendix A

Matlab program “Rc Resistance Measurement_YH.m” for measuring contact resistances of the samples in the study.

Desired_Alpha_Temps = [20 50 100 200 250];
cutoff = 4*3600; %time then data goes unreliable
cutoff_post = 293.7*3600; %after ageing when data becomes reliable again
cutoff_post2 = 301*3600;
POSTCOMPLETED = 0;

%DELETE-------------
a1 = 295*3600; a2 = 296.5*3600; %50 deg post ageing
b1 = 298*3600; b2 = 299.5 * 3600; %100 deg post ageing
c1 = 302*3600; c2 = 304.5*3600; %250 deg post ageing
d1 = 0.5; d2 = 1.5*3600; dd1=1; %20 deg pre ageing
e1 = 2.6*3600; e2 = 3.7*3600; %50 deg pre ageing
f1 = 4.4*3600; f2 = 6*3600; %100 deg pre ageing
g1 = 10*3600; g2 = 300*3600; %250 deg pre ageing
s=[];
spre=[];
% END DELETE

open('sandpaper_ambient_temp__20090209T160045.mat');

%1 - Find Average Slope between temp and res
slopes = [];%avg slope for each sample
for j = 1:13;%cycle thru all bond pairs
    num_meas = length(y((1:1:end),1,j)/3600); %how many measurements taken
    %cycle thru and get slope at each increment
    Slope = [];%add each incremental slope to array and take mean after
    for i = 1:num_meas-1
        %DELETE -------------
        if y(i,1,j)<d1; dd1 = i; end
        if y(i,1,j)<d2; dd2 = i; end
        if y(i,1,j)<e1; ee1 = i; end
        if y(i,1,j)<e2; ee2 = i; end
        if y(i,1,j)<f1; ff1 = i; end
        % END DELETE

        % END DELETE
    end
end
if y(i,1,j)<f2; ff2 = i; end
if y(i,1,j)<g1; gg1 = i; end
if y(i,1,j)<g2; gg2 = i; end
%END DELETE
if y(i,1,j)<cutoff; %only take readings from before PT breaks
    DR = y(i+1,3,j)-y(i,3,j);
    DT = y(i+1,2,j)-y(i,2,j);
    if DT > 0 || DT< 0; %To avoid dividing by 0
        Slope = [Slope abs(DR/DT)]; %Add to collection of slopes
    end;
end
end
%DELETE
T20 = mean(y(dd1:dd2,2,j)); R20 = mean(y(dd1:dd2,3,j));
T50 = mean(y(ee1:ee2,2,j)); R50 = mean(y(ee1:ee2,3,j));
T100 = mean(y(ff1:ff2,2,j)); R100 = mean(y(ff1:ff2,3,j));
T250 = mean(y(gg1:gg2,2,j)); R250 = mean(y(gg1:gg2,3,j));
s11 = (R100-R50)/(T100-T50); s22 = (R250-R50)/(T250-T50); %s33 = (R50-
    R20)/(T50-T20);
    %spre = [spre (s11+s22+s33)/3]; s_cur = (s11+s22+s33)/3;
    %spre = [spre (s11+s22)/2]; s_cur = (s11+s22)/2;
    spre = [spre s11]; s_cur = s11; % Changed to get rid of s12 because
drift occurs
    %DELETE
    slopes = [slopes mean(Slope)]; %mean slope for each sample
end
slopes = spre;
m = mean(slopes)

%2. Given Average Slope, Find Average Intercept
inters = []; %avg Intercept for each sample
for j = 1:13; %cycle thru all bond pairs
    num_meas = length(y((1:1:end),1,j)/3600); %how many measurements taken
    %cycle thru and get slope at each increment
    Intercept = []; %add each incremental slope to array and take mean after
    for i = 1:num_meas-1;
        if y(i,1,j)<cutoff; %only take readings from before PT breaks
            b = y(i,3,j)-slopes(j)*y(i,2,j);
            Intercept = [Intercept abs(b)];
        end
    end
end
inters = [inters mean(Intercept)];
end

b = mean(inters) %mean intercept for each sample

%3. Calculate Coefficient for desired temperatures
ALPHAS = []; %Individual Alpha for each sample at each desired temp
ALPHAS_dev = [];
Avg_ALPHAS = []; %Avg Alpha for each desired temp
Alpha_STD = [];% stddev for each group of ALPHAS per temperature

for i = 1:length(Desired_Alpha_Temps);
    for j = 1:13
        ALPHAS (i,j) = slopes(j)/(slopes(j)*Desired_Alpha_Temps(i)+inters(j));
        %ALPHAS_dev (i,j) = 
    end
    Avg_ALPHAS = [Avg_ALPHAS m/(m*Desired_Alpha_Temps(i) + b)];
    Alpha_STD = [Alpha_STD std(ALPHAS(i,:))];
end

% GET avg resistance and std res of resistance
Avg_RES_250 = [];
STD_PER_SAMPLE_250=[];

for j = 1:num_meas
    if y(j,1,1)< (30*3600); t_30 = j; end
    if y(j,1,1)< (250*3600); t_250 = j; end
end

for i = 1:13
    Avg_RES_250 = [Avg_RES_250 mean(y((t_30:end),3,i))];
    STD_PER_SAMPLE_250=[STD_PER_SAMPLE_250 std(y((t_30:end),3,i))];
end

    Avg_RES_250_std = std(Avg_RES_250)

%REPEAT FOR POST AGEING: -----------------------------
if POSTCOMPLETED == 1
s=[];
slopes_post = [];%avg slope for each sample
for j = 1:13;%cycle thru all bond pairs
    num_meas = length(y((1:1:end),1,j)/3600); %how many measurements taken
    %cycle thru and get slope at each increment
    Slope_post = [];%add each incremental slope to array and take mean after
    for i = 1:num_meas-1
        %DELETE ------------
        if y(i,1,j)<a1; aa1 = i; end
        if y(i,1,j)<a2; aa2 = i; end
        if y(i,1,j)<b1; bb1 = i; end
        if y(i,1,j)<b2; bb2 = i; end
        if y(i,1,j)<c1; cc1 = i; end
        if y(i,1,j)<c2; cc2 = i; end
        %END DELETE
        if y(i,1,j)>cutoff_post && y(i,1,j)<cutoff_post2; %only take readings
            from before PT breaks
            DR_post = y(i+1,3,j)-y(i,3,j);
            DT_post = y(i+1,2,j)-y(i,2,j);
            if DT_post > 0 || DT_post< 0; %To avoid dividing by 0
                Slope_post = [Slope_post abs(DR_post/DT_post)]; %Add to
            collection of slopes
            end;
        end
    end
    %DELETE---------
    T50 = mean(y(aa1:aa2,2,j)); R50 = mean(y(aa1:aa2,3,j));
    T100 = mean(y(bb1:bb2,2,j)); R100 = mean(y(bb1:bb2,3,j));
    T250 = mean(y(cc1:cc2,2,j)); R250 = mean(y(cc1:cc2,3,j));
    s1 = (R100-R50)/(T100-T50); s2 = (R250-R50)/(T250-T50); s = [s
    (s1+s2)/2]; s_cur = (s1+s2)/2;
    %END DELETE
    slopes_post = [slopes_post mean(Slope_post)]; %mean slope for each sample
end
slopes_post = s;
m_post = mean(slopes_post)

%2. Given Average Slope, Find Average Intercept
inters_post = [];%avg Intercept for each sample
for j = 1:13;%cycle thru all bond pairs
num_meas = length(y((1:1:end),1,j)/3600); %how many measurements taken
%cycle thru and get slope at each increment
Intercept_post = []; %add each incremental slope to array and take mean after
for i = 1:num_meas-1;
    if y(i,1,j)>cutoff_post && y(i,1,j)<cutoff_post2; %only take readings from before PT breaks
        b_post = y(i,3,j)-slopes_post(j)*y(i,2,j);
        Intercept_post = [Intercept_post abs(b_post)];
    end
end
inters_post = [inters_post mean(Intercept_post)];
end

b_post = mean(inters_post) %mean intercept for each sample

%3. Calculate Coefficient for desired temperatures
ALPHAS_post = []; %Individual Alpha for each sample at each desired temp
ALPHAS_dev_post = [];
Avg_ALPHAS_post = []; %Avg Alpha for each desired temp
Alpha_STD_post = []; %stdev for each group of ALPHAS per temperature

for i = 1:length(Desired_Alpha_Temps);
    for j = 1:13
        ALPHAS_post (i,j) = slopes_post(j)/(slopes_post(j)*Desired_Alpha_Temps(i)+inters_post(j));
        %ALPHAS_dev_post (i,j) = [
    end
    Avg_ALPHAS_post = [Avg_ALPHAS_post m_post/(m_post*Desired_Alpha_Temps(i) + b_post)];
    Alpha_STD_post = [Alpha_STD_post std(ALPHAS_post(i,:))];
end
end

%OUTput Data
%ALPHAS
%ALPHAS_post
%Avg_ALPHAS
%Avg_ALPHAS_post
%Alpha_STD
%Alpha_STD_post

%Calculate Reference Resistances
Rref_pre_20 = []; Rref_post_20 = []; Rref_pre_50 = []; Rref_post_50 = []; Rref_pre_100 = []; Rref_post_100 = [];

for j = 1:13
    for i = 1:num_meas-1
        if y(i,1,j)<d1; dd1 = i; end
        if y(i,1,j)<d2; dd2 = i; end
        if y(i,1,j)<e1; ee1 = i; end
        if y(i,1,j)<e2; ee2 = i; end
        if y(i,1,j)<f1; ff1 = i; end
        if y(i,1,j)<f2; ff2 = i; end
        if y(i,1,j)<g1; gg1 = i; end
        if y(i,1,j)<g2; gg2 = i; end
        if y(i,1,j)<a1; aa1 = i; end
        if y(i,1,j)<a2; aa2 = i; end
        if y(i,1,j)<b1; bb1 = i; end
        if y(i,1,j)<b2; bb2 = i; end
        if y(i,1,j)<c1; cc1 = i; end
        if y(i,1,j)<c2; cc2 = i; end
    end
    T20 = mean(y(dd1:dd2,2,j)); R20 = mean(y(dd1:dd2,3,j));
    T50 = mean(y(ee1:ee2,2,j)); R50 = mean(y(ee1:ee2,3,j));
    T100 = mean(y(ff1:ff2,2,j)); R100 = mean(y(ff1:ff2,3,j));
    T250 = mean(y(gg1:gg2,2,j)); R250 = mean(y(gg1:gg2,3,j));

    Rref_pre_20 = [Rref_pre_20 R50/(1+ALPHAS(1,j)*(T50-20))];
    Rref_pre_50 = [Rref_pre_50 R100/(1+ALPHAS(2,j)*(T100-50))];
    Rref_pre_100 = [Rref_pre_100 R250/(1+ALPHAS(3,j)*(T250-100))];

    if POSTCOMPLETED == 1
        T50post = mean(y(aa1:aa2,2,j)); R50post = mean(y(aa1:aa2,3,j));
        T100post = mean(y(bb1:bb2,2,j)); R100post = mean(y(bb1:bb2,3,j));
    end
end
T250post = mean(y(cc1:cc2,2,j)); R250post = mean(y(cc1:cc2,3,j));

Rref_post_20 = [Rref_post_20 R50post/(1+ALPHAS_post(1,j)*(T50-20))];
Rref_post_50 = [Rref_post_50 R100post/(1+ALPHAS_post(2,j)*(T100post-50))];
Rref_post_100 = [Rref_post_100 R250post/(1+ALPHAS_post(3,j)*(T250post-100))];

if POSTCOMPLETED == 1
    AvgRref_post = mean(Rref_post_50)
    StdRref_post = std(Rref_post_50)
end
AvgRref_pre = mean(Rref_pre_50)
StdRref_pre = std(Rref_pre_50)

save(['Statistics.mat'])