A REVIEW OF PALLADIUM COATED COPPER WIRE BONDING FOR AUTOMOTIVE DEVICE

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ABSTRACT

The semiconductor package manufacturer has vigorously shifted toward the usage of palladium coated copper (PCC) wire as the substitution of gold (Au) and bare copper (Cu) wire. However, the acceptance of the PCC wire in the automotive industry is hindered by the difficulty to fulfill stringent Automotive Electronics Council (AEC) standard requirements for automotive semiconductor packages. Therefore, it is important for this paper to review the past and recent PCC wire bonding studies related to the automotive semiconductor package in order to gain a better perspective on what changes are needed to improve the performance. The review begins with an insight into the current opportunity and challenge of PCC wire bonding. These are followed by the discussion on the reliability challenges of the PCC wire under AEC Q100 and AEC Q106 standards, with special attention is given to the high temperature storage (HTS) reliability test. Lastly, mechanism and solutions to the galvanic corrosion occurred on the PCC wire bond during HTS test are also been presented.

KEYWORDS: Corrosion, Palladium Coated Copper Wire & High Temperature Storage Stress Test

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1. INTRODUCTION

Copper (Cu) wire bonding had been increasingly used in the semiconductor package in the last 10 years, especially in the consumer product due to the cost advantage over gold (Au) wire. However, the application of Cu wire is still not widely used in the automotive industry due to the reliability limitations of Cu wire performance in the humidity stress and oxidation environments. A recent AEC Q006 standard for Cu wire bonding is set as benchmark for the qualification of semiconductor packages for automotive applications. Recent focus of car technologies toward platform-based services, enhanced products for electrification, and increased level of automation have led to a proliferation of studies on reliability of PCC wire bonded semiconductor packages.

This paper will review the previous studies on PCC wire bonding for automotive semiconductor package. The structure of this paper encompasses the PCC wire and automotive package background, wire bonding and high temperature storage (HTS) reliability challenges of PCC wire, AEC standards related to copper wire bonding reliability, the corrosion failure mechanism, and potential solution to corrosion failure at HTS. Reliability challenge of PCC wire focuses on HTS test, which was reported as the worst reliability performance among the stress test stated in AEC standards [1].

2. BACKGROUND OF PALLADIUM COATED COPPER WIRE AND AUTOMOTIVE PACKAGE

Palladium coated copper (PCC) wire was first introduced into the semiconductor packages in 2009 by Nippon Micrometal Corporation (NMC). It gains market share very fast as it's able to resolve the limitation of bare Cu wire, especially on oxidation issue and reduce chloride corrosion risk [2]. According to SEMI 2010, NMC is the world No 1 supplier for PCC wire (~77%) followed by Tanaka (8%), MKE (7%), Heraeus (5%) and other (3%).

According to the SEMI Industry Research and Statistic 2018 report, semiconductor interconnect material market for the PCC wire was increased significantly since 2011 (figure 1). PCC wire shipment increased from 13% in 2011 to 34% in 2016, while bare Cu wire shipment has remained stagnant at 16-18% share since 2013. However, Au wire market share dropped from 77% in 2011 to 38% in 2016. It is projected PCC wire will overtake Au wire in the near future market share.

Figure 1: Bonding Wire Shipment Share of Different Wires Versus Year [3].

Based on a recent market research published by IC Insights in 2018 [4], the automotive semiconductor market demand will grow at a CAGRs of 5.4% from year 2016 to 2021 (see figure 2). It is the highest growth market within the 6 major user system categories. The research report reveals more than 75% of the automotive industry innovation for the past 10 years is driven by the advance electronic systems, the electronics application mainly in infotainment, safety control protection like air bag system, comfort or convenience features, environment friendly (CO₂) control and autonomous driving.

Figure 2: Worldwide Electronics System Forecast Compound Annual Growth Rate (CAGR) from 2016 Through 2021 [4].

Following the cost-saving and superior properties of PCC wire, the application of PCC wire in automotive microelectronics is getting more attention. Although PCC wire cost is estimated about two or three times higher than bare

Cu wire, it is believed that the total assembly cost for PCC wire is still lower than bare Cu wire because of the following reasons:

- It only requires nitrogen gas environment as compared to more expensive nitrogen-hydrogen gas for Cu wire [5].
- It has longer shop floor lifetime ~30 days, as compared to 7 days for bare Cu wire [5].
- It also has a better/wider wire bond process window.
- It reduces wire bond assembly yield lost due to non-stick on pad (NSOP) reject, and
- It had demonstrated a reliability level above the AEC standards, especially for 1st bond on Al pad due to slow intermetallic compound (IMC) formation [6]. More details of the PCC wire advantages are tabulated in Table 1.

Nevertheless, the application of PCC wire in automotive semiconductor packages is consider new and the acceptance is still low mainly due to:

- The insufficient historical data to verify the PCC wire's robustness in automotive harsh environment. For example, a typical automotive package requires a minimum of 15 years' warranty lifespan under harsh environment (with typical working temperature ~150°C), and
- Automotive manufacturers are following the stringent reliability requirement of AEC Q100 and Q006 standards related to the automotive semiconductor packages [1], [7].

Table1: Advantages of PCC Wire as Compared to Bare Cu and Au Wires

Advantage	Reference
PCC wire has better thermal and electrical properties than Au wire; PCC is estimated to be ~25% more conductive than Au.	12,13,14,15,16,17
PCC wire is harder and less ductile than Au wire. Thus, PCC wire loop profile is more rigid and able to minimize wire sweep issue during molding for thin and long wire.	12,13,15,18
PCC wire shows a significant cost saving than Au wire especially for high pin count device.	15,16,17
PCC wire only requires N ₂ purging during FAB formation while bare Cu wire bonding uses gas mixture of 95%N ₂ and 5% H ₂ to prevent FAB oxidation issue. Thus, PCC working cost is lower than bare Cu wire.	19
PCC wire's floor work life is longer than bare Cu wire (estimated 60 days for PCC and 7 days for bare Cu wire). The Pd coating on PCC wire acts as a protective layer to prevent surface oxidation of Cu wire at room temperature.	20,21,22
PCC wire provides a better oxidation resistance than bare Cu wire during FAB formation before 1 st bonding. This leads to a more robust bonding interface as oxidation is negated. PCC with Au flash enhances the bonding stability, make high volume production more stable without many reject.	19,20,23,24,25
PCC wire shows a higher 1 st bond pull strength (~ 11%) than bare Cu wire, indicating higher PCC wire tensile strength.	19,23,25
PCC wire has 50% higher 2 nd bond's pull strength than bare Cu wire, as PCC wire increase the adhesion between the wire and lead frame. Consequently, PCC wire bonding produces a more robust 2 nd bond and less short tails error during bonding.	19,20,25
PCC wire show a slower IMC growth on Al pad than Au and bare Cu wires under HTS stress test. Pd coating act as diffusion barrier between Cu and Al to retard the Cu-Al formation.	16,26,27

3. DESIGN OF COMMONLY USED PALLADIUM COATED COPPER WIRE

PCC wire is a copper wire (with typical diameter about 25-30 μm) coated with palladium (Pd) with a typical thickness range from 100 to 120 nm thickness [8]. Being a stable noble metal, the main role of the palladium coating is to protect the core copper material from interacting with the surrounding environment to form oxidation or corrosion. Table 2 shows

comparison of materials properties between the PCC with other wire types.

Newer version of PCC wire is coated with a thin Au flash (with thickness less than 20 nm). The additional Au flash layer can broaden the WB parameter window [9] and also improving the 2nd bonder ability by enhances the adhesion and promote the diffusion rate of 2nd bonding, particularly on newly introduced rough NiPdAuAg preplated lead frame [9][10][11].

Table 2: Materials Properties of Commonly used Bonding Wire Types [Xu 2010], Excluding * from [8]

Wire Type	Gold (Au)	Copper (Cu)	Palladium Coated Copper (PCC)	Aluminium (Al)
Composition and Purity*	4N Au 99.99 wt%	5N Cu 99.999 wt%	4N Cu 99.99 wt% Pd 1.3-2.3 wt%	5N Al 99.999 wt%
Atomic Number	79	29	46 (Pd)	13
Atomic Weight	196.97	63.55	106.42 (Pd)	26.98
Crystal Structure	FCC	FCC	FCC (Pd)	FCC
Melting Point (°C)	1063	1083	1552 (Pd)	660
Density (g/cm ³)	19.32	8.93	8.99	2.70
Tensile strength (MPa)	230	240	290	100
Young's Modulus (GPa)	88	136	95	70
Vickers Hardness (HV)	60-90	60-100	60-100	20-50
Electrical Resistivity (10 ⁻⁸ Ohm.m)	2.3	1.9*	1.9*	2.7
Thermal Conductivity (W/mK)	293	394	401	241

4. WIRE BONDING CHALLENGES OF PALLADIUM COATED COPPER WIRE

PCC and bare Cu wires have almost similar mechanical properties, both are facing similar challenges when substituting Au wire for wire bonding process in electronic packages [5].

During 1st bonding of PCC wire, FAB of PCC wire is formed by electrical flame off (EFO) and is then applied on the Al bond pad by thermosonic bonding process. PCC wire's free air ball (FAB) hardness is higher than the Au wire [28], give rise to a higher bonding stress on Al bond pad during 1st bonding. The risk of pad damage could appear mainly in form of pad cratering or squeeze out. Pad cratering could result in pad peeling and dielectric cracking (see figure 4), and soft Al can smear off along ultrasonic direction, causing Al splash (figure 5). The Al splash causes short circuit to the adjacent pad, especially for fine pitch device, and reduces Al thickness remain for CuAl IMC formation under stress [29].

FAB hardness of PCC wire could be reduced by increasing the electric flame off (EFO) current. Studied by Lim et al. showed the EFO current optimization prevents the Pd concentrated at FAB tip. Furthermore, the control of bonding parameters maintains the Pd element at peripheral of the PCC FAB. Thus, these reduce contact of PCC FAB hardness with bond pad during 1st bonding [28]. However, the tendency of Pd atoms to congregate at FAB neck area may reduce the neck strength, causing a higher risk of wire break during bonding [23]. This problem is supposedly being negated by using PCC wire applied with Au flash.

Figure 4: Cratering Damage Results in Bond Pad.

Figure 5: Al Pad's Squeeze out and the Remained Pad Thickness after Cu Wire Bonding.

Optimization of bonding force and ultrasonic energy had been proposed to negate the damage risk on bond pad and the underneath easily fractured silicon chip [30]. Nevertheless, the pad damage risk still persists on the PCC 1st bonding on Al pad, because of hardness of PCC FAB is still relatively larger than the Al pad [28].

Pad metallization has been explored to increase the pad hardness against bonding damage issue. Different multi-plating pad have been reported such Ni/Pd/Au, Al/Si/Cu pads [23][31][32]. For example, Ni/Pd/Au pad demonstrates a higher ball shear distribution, with lower cratering risk [23]. Although it is a very robust pad, it does not gain market share due to high foundry cost. Recently, Cu wire bonding to

Cu pad had been heavily discussed as it is believed that mono metallic bonding shall be a more stable and robust system if compare to IMC system and Cu pad is a very low cost solution [32].

Nano voids were observed in unmolded 1st bond samples at HTS time-zero, which is believed due to the volume shrinkage of the solidified FAB. The overlapped of the nano voids position with the Pd elemental concentration suggest the Pd role in the nano voids formation during FAB stage [33],[34],[35]. However, risk of nano void to the wire bond reliability need further investigation due to insufficient data.

Several challenges in term of operating cost as compared to bare Cu or Au wire bonding are not elaborated, but instead tabulated in Table 3.

Table 3: Cost Challenges of PCC Wire Bonding

Challenge	Reference
PCC wire also has a tighter bonding process window as bare Cu wire due to high hardness property, thus PCC with Au flash wire was introduced to overcome this challenges.	11,12,23
PCC wire requires only nitrogen environment during FAB formation to prevent oxidation if compared to Au wire (higher operation cost).	19
PCC wire has lower units per hour (UPH) than Au wire bonding (typical is ~5 to 8% slower in UPH).	12,16
PCC wire is more expensive than bare Cu wire, the PCC with Au flash is ~2 to 3 times more expensive than bare Cu wire (higher material cost).	20
Plasma cleaning before wire bonding is recommended for PCC and bare Cu wire if compare to Au bonding, additional process and operation cost.	36

5. AEC Q100 STANDARDS FOR AUTOMOTIVE SEMICINDUCTOR PACKAGE

PCC wire application in the automotive package is still not widely accepted by many car makers, due to the reliability challenges of the PCC wire bond under HTS test. Thus, it is critical to understand the ramification of AEC Q100 standard for automotive package qualification [1].

AEC Q100 - Failure Mechanism Based Stress Test Qualification for Integrated Circuits is an automotive industry standard specification that provides details for a new product qualification and a major change requalification requirement and procedures for integrated circuits (ICs) [1]. It covers the stress test methods based on the potential failure mechanism, but not the reliability requirement for the specific product application. A component passes the specified stress test can be considered 'suitable' to be used in the harsh automotive environment, or the supplier can claim the component is "AEC-Q100 qualified" [1]. The actual component reliability requirements shall be aligned and confirmed with the automotive manufacturers based on their

mission profile requirements. However, the automotive manufacturers can demand reliability requirements more stringent than the AEC Q100 definition based on the actual operation conditions of the package.

During the early introduction of Cu wire bonding in automotive semiconductor packages, the qualification conditions and release criteria of AEC Q100 standard are based on the Au wire bonding. However, several field failures on Cu wire bonded packages reported by automotive manufacturers triggered AEC to review the Cu wire qualification standard. Consequently, first revision of Cu wire interconnects qualification standard known as AEC Q006 entitled 'Qualification Requirements For Components Using Copper (Cu) Wire Interconnections' was released by the AEC in 2015 [7].

AEC Q006 standard defines a set of tests and the minimum qualification requirements for copper (Cu) wire interconnections device to be used in any automotive electronics application. The Q006 standard requires extended stress tests and additional physical analyses on the Cu wire bonding. These Q006 standard requires more stringent requirements to qualify automotive semiconductor packages against set of qualification stresses, test conditions and test durations.

One of important test for high temperature applications is High Temperature Storage Life (HTSL), also known as High Temperature Storage (HTS) test. The additional requirements are established because of the following reasons: (i) the technical properties between the Au wire and Cu wire are difference, (ii) lack of experience to qualify Cu wire bonding, and (iii) limited proven reliable field application data on Cu wire packages.

Essentially the new AEC Q006 standard requirement will provide a safety margin and confidence level to the automotive customer. Thus, there is an urgency for the automotive package manufacturers to find solutions to the

reliability challenge of PCC wire bond resulted from the new AEC requirements.

6. RELIABILITY CHALLENGE OF PALLADIUM COATED COPPER WIRE BOND UNDER HTS STRESS

More recent studies reveal PCC wire fails the HTS test, especially at temperature of 175°C [35][38]. Corrosion was observed on 1st and 2nd bonds, causing severe degradations in the respective ball shear and stitch pull values after HTS stress (see figure 6). PCC wire appears to perform worst under HTS, as compared to other types of stress tests, such as Unbiased Humidity Accelerated Stress Test (UHAST) and Temperature Cycling Test [38], able to produces a more robust stitch bond [19][20].

Figure 6: Pull Strength of Mold Encapsulated PCC's 2nd Bond under: • HTS Test at 150°C@2000hrs, ■ Temperature Cycling test at 1000 hrs from -50°C to 150°C, ♦ Unbiased Highly Accelerated Stress Test at 110°C@96hrs and 85% Humidity [38].

An early HTS failure study on PCC wire was reported by Krinke et al. from Robert Bosch, a leading automotive OEM in 2014 [38]. They reported significant increase of broken 2nd bonds when PCC wire was subjected to HTS stress beyond 150°C@1000 hours [38]. Failure was related to void formation underneath hillock on the 2nd bond surface (see figure 7).

Figure 7: Cross Section of 2nd Bond after HTS at 175°C@2200hrs, Arrow Marks Show a Hillock Covers Cu void [38].

Krinke et al. concluded PCC wire has an intrinsic weakness driven by the thermodynamic mechanism (sensitive to high temperature) [38]. Their experiment showed when PCC wire was subjected to HTS stress without mold encapsulation, hillock or dimple appeared on the PCC wire surface. Furthermore, the hillock growth is sensitive to temperature and duration (refer figure 8).

Figure 8: Hillock Growth on PCC Wire Under different HTS Conditions.
Top Shows Time-Dependence at 175°C and: (a) 500 hrs (b) 1500 hrs, and (c) 3000 hrs.
Bottom Shows Temperature-Dependence at 1000 hrs and: (d) 150°C, (e) 175°C and (f) 200°C [38].

FIB cut and EDX study on the hillock revealed only Cu, oxide and Pd elements [33]. One important finding was the hillock only formed when Pd layer was cracked open. The research work also showed bare Cu wire did not show such degradation after HTS stress like the PCC wire. The study emphasizes the need for automotive package manufacturers using PCC wire to consider customer mission profile and AEC Q100 Grade 0 requirement where junction temperatures on interconnects in automotive package could exceed beyond 150°C [33].

Eto et al. in the later study explained hillock formation on PCC was formed during high HTS environment, where corrosive species like O, S, Cl were actively attacking the Cu wire core [39]. Consequently, action of the corrosive species degraded the stitch bond reliability performance [39]. As Eto et al.'s experiment showed hillock formation on PCC did not occur when HTS was conducted in vacuum environment, this proved PCC wire does not have an intrinsic weakness of Cu diffuses out from Pd coating.

Eto et al.'s work showed the PCC wire is sensitive to degradation at temperature above 150°C [39]. Cu void formation only observed on PCC wire at 200°C@1000hrs, but not at 150°C@1000hrs (see figure 9). Furthermore, cross section SEM and EDX mapping showed that S element appeared at the Cu void region [39] [40].

Figure 9: 2nd Bond of PCC after HTS at 150°C@1000 hrs and 200°C@1000 hrs [39].

In 2016, Han et al. had published a work discussed the PCC wire failure after underwent HTS test in QFP platform, the device pass AEC Q100 Grade 1 requirement but cannot pass the “2× stress requirement” defined by AEC Q006 [41]. It was reported ~30% failure rate with lifted ball bond during ball pull and the failure analysis report shown the root cause was due to IMC layer crack [41]. EDX analysis also found corrosive S element at the Cu void region and IMC region (see figure 10).

Figure 10: S Element was Detected near Cu Voids and in IMC Interface between 1st Bond and Pad [41].

It is suspected sulfur is the root cause of the void formation. The experiment also showed the Cu void severity is different with a different type of mold compound even the Sulfur content level given by mold compound supplier is similar, ~16 ppm [41]. Han concludes the sulfur content level in the mold compound plays a significant role in the Cu void formation under HTS stress.

It is concluded that PCC wire is facing challenge of Cu void formation in 1st bond and 2nd bond during HTS stress test. Below are summary of findings on Cu voids in PCC wire under HTS:

- Cu void only found when the PCC was encapsulated with the mold compound, purely PCC wire under HTS only observed hillock formation, hillock formation will not lead to failure [33].
- Cu void only occurs on PCC wire, but not bare Cu wire under the same bill of material and HTS stress condition [39].
- One common finding on Cu void area based on EDX analysis is there is corrosive element “sulfur” detected at the void region [39][41].
- Different mold compound from a different supplier can give different severity of Cu void formation, it is believed related to the sulfur content level in the mold compound [41].
- The Cu void formation is sensitive to temperature, the experiment shown Cu void is dominant when the temperature is >150°C [39].
- Cu void formation is always at the location where the Pd is missing, mean when Cu is exposed to mold compound [39].

7. CORROSION MECHANISM OF PCC WIRE BOND UNDER HTS STRESS

Lim et al. showed that PCC wire is capable of withstanding corrosion when it was not encapsulated with mold compound [33]. This hinted mold encapsulation plays an important role in the corrosion mechanism. Feedback by mold compound supplier had confirmed usage of sulfur (S) in compound formulation to enhance the adhesion between mold compounds to the lead frame surface [41].

PCC wire corrosion based on galvanic corrosion mechanism have been proposed by several studies [40] [41]. According to this mechanism, Pd coating acts as the cathode, while the underneath Cu performs as the anode of a full electrochemical cell (see Figure 11). This is due to the fact that Cu is less noble than Pd, thus more likely to lose electron and oxidize into Cu-based compound. Eto et al. reported sulfate anion (SO_4^{2-}) was released as outgassing from mold compound at 150-200°C [41]. It was argued that S species diffuse to the PCC wire bond surface and functions as electrolyte to enable the anodic corrosion of Cu core [40]. With the continuous supply of S species from mold compound, the corrosion creates voids in Cu core [40]. The voids at wire bond area weakens the wire bond pull strength, thus affect tremendously the wire bond reliability at HTS.

Figure 11: Illustration of Galvanic Corrosion Reaction on 1st Bond [40].

Studies by Krinkle et al. [38] and Han et al. [41] show corrosion happened on 1st bond (ball area) and 2nd bond (stich area) on particular isolated areas. It is believed that wire bonding process cause missing Pd plating on some area of the bond surface, enable the corrosion attack on the exposed Cu core. Missing Pd on 1st bond might be caused by wire deformation due to initial ball formation by electric flame off [33] and subsequent thermosonic bonding process. Whereas, missing Pd on 2nd bond might be solely created by deformation due to thermosonic process.

The above studies presented thus far provide evidence that PCC wire bonds experiences galvanic corrosion during HTS test. However, much uncertainty still exists about the galvanic corrosion mechanism due to the following reasons:

- Galvanic corrosion requires the presence of an electrolyte. It is not clear in what molecular form that S species participates in the galvanic corrosion and whether water moisture is involved. Until now, the literatures offer contradictory hypothesis or findings on chemical reactions involved in the corrosion.
- ii. These studies have reported that corrosion only happened on PCC wire but not on bare copper wire. Thus, the Pd's role in the corrosion mechanism needs a further study.
- Only 1st bond corrosion was reported. Technically, 2nd bond is more critical than the 1st bond as the former is presumably has lower pull strength than latter due to a smaller bonding area

8. POTENTIAL SOLUTION TO NEGATE CORROSION ON PCC WIRE UNDER HTS STRESS

Han et al. reported that PCC wire passed HTSL test without 1st bond lifted issue when high IMC coverage at wire-pad interface and low sulfur mold compound was used [41]. His study shows higher bond failure counts was produced in samples utilized mold compound with a standard sulfur ppm content as compared to a relatively lower sulfur ppm content compound. Unfortunately, the study does not reveal the actual sulfur ppm content in these mold compounds. Furthermore, the study claims a lower IMC coverage on 1st bond can result in higher failure counts after HTS175°C@1008hrs. The lower IMC coverage was generated by lower bonding parameters in his experiments.

In the same year, Lee et al. reported the void in PCC bond could be prevented when sulfur (S) content (in form of sulfate) in the mold compound was controlled at 8.8 ppm level [40]. Voids were observed when S content is in 34.5-47.5 ppm range. Furthermore, the study also showed voids were formed after HTS175°C@504hrs but not after HTS150°C@2016hrs [40]. This indicates void formation is strongly depended on HTS temperature.

Lee et al. also mention in his study that a new alloyed Cu wire that capable of preventing void formation after HTS200°C@2000hrs, though not much details was disclosed [40]. However, Eto et al. from Nippon Micrometal Co. had published a technical paper in 2017, demonstrating a new version of PCC wire named as New-APC [39]. The New-APC wire had a higher stability under HTS stress than PCC and bare Cu wire, with a higher alloying element concentration to mitigate corrosion risk during HTS test. It was found that the new wire exhibits slower deterioration in pull strength against HTS aging time, in comparison with existing PCC wire (figure 13).

Figure 13: Stitch Pull Results of Different Bonding Wires after HTS Test at 200°C (Courtesy from NMC). Note: APC is EX1R Wire, Existing PCC is EX1P Wire.

9. CONCLUSIONS

PCC wire has numerous advantages to address the limitation of bare Cu wire bonding in semiconductor packages, thus seems to be a good replacement for the Au wire. However, new AEC Q006 standard requirements imposes new challenges for the qualification of Cu and PCC wire bonds for automotive applications under high temperature storage (HTS) test and other stress test. The PCC wire bond experiences galvanic corrosion which deteriorates the wire bond strength at the increasing aging time and temperature.

Nevertheless, it is hope that the understanding of the galvanic corrosion mechanism able to facilitate the development of new materials and design of bond wire, pad and mold compound to mitigate the corrosion risk to automotive semiconductor packages. Affordable and robust semiconductor package for car performance and safety will path way to a new car driving experience and contributes to a sustainable transportation system.

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