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Micromechanical Studies of 4n Gold Wire for Fine Pitch Wire-bonding

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Abstract

This study focuses towards typical micromechanical properties such as strength, yield point, Young's Modulus, strain, shapes of fracture end and element analysis, atomic percentage of Ca of 4N gold (Au) wire using microstructures and composition observation, micro-tensile test and depth sensing indentation technique. A series of micro-tensile test were performed with different strain rate values of 10˚-10-4 min-1 on to a 25.4 µm diameter plain gold wire. The nanoindentation with 20 mN maximum load was indented on a near fracture end of a gold wire specimen, for which this test was carried out after the micro-tensile test. The stress-strain curves were used to characterize the 4N purity gold wire. The shapes of fracture end of gold wire after micro tensile test were carried out using Scanning Electron Microscopic (SEM). The finding showed that the mechanical properties of ultra-fine gold wire was in the proportional relationship with the increment of the strain rate value. It is suggested that micromechanical behaviour gave the effect for the wirebonding process in order to characterize the wire loop control and strengthen the wire loop to avoid the wire sweep.

Keywords: Gold wire; Fractured End; Micro-Tensile; Nanoindentation; Strain Rate; Strength

1 INTRODUCTION

The trend in semiconductor industry is moving towards miniaturized footprint, cost reduction and multifunctional components with higher inputs and outputs. It is interesting work to characterize the mechanical properties and understand the mechanism to enhance the mechanical properties of ultra-fine gold wire [1]. The extremely small dimensions of micro-wires impose a tremendous challenge for experimental study of their micromechanical properties and reliability. As the development of integrated circuits (IC) packages move towards higher power, smaller and denser, the IC wire bonding process is still using the bonding interconnection technique in first-level of microelectronic packages [2]. In the semiconductor packaging area, the soft gold type III with the purity of more than 98.7% Au or greater was widely used.

Variation of the results were also been found when correlating the strain rates and the mechanical behavior might caused by the grain size of the 25.4 μm gold wire [3]. In addition, the amount of alloying dopants of gold wire also played a role. Ohno et al. [4] investigated that higher dopant levels generally give higher strength, elastic modulus, and recrystallization temperature. The effects of Be, Cu, Ag, Ca, Pt and Al additions to pure gold in conjunction with a hydrostatic wire-extrusion process [5].When discussing about the wire fracture, this damage normally occurs in a transgullar manner (through the grain) in metal that have a good ductility and toughness. When the material is pulled in a tensile test, necking begins and voids form. As deformation continues at 45º shears lip may form and producing a final cup-and-cone fracture [6].

However mechanical properties of gold micro-wire are still lacking and also not been established [2].The critical issues encountered during wire bonding process design are how to base packaging configuration constraints to characterize the wire loop profile control and how to strengthen the wire loop and maintain loop height as low as possible to avoid wire sweep. Extremely pure gold (99.999%wt Au) is simply too soft and unstable for successful wire drawing or wire bonding. If the diameter of ultra fine gold wires becomes smaller, the stiffness and the loading capacity will be decreased. If the thin wires are applied to the same kind of packages, the mechanical properties of gold wires needs to be characterized [7]. From the previous studied by Liu et. al [8] showed that the load strain rate has a significant effect on the high loop wire type compared to low loop wire.

It is important to study the mechanism of wire breaking and failure under stress condition. Hence, this present work investigates the micromechanical behavior under different tensile testing strain rate and low load depth sensing indentation to characterize the plain Au wire. The findings of this study can lead to the enhancement of the micromechanical properties of the gold wire type used in a semiconductor package.

2 MATERIALS AND METHOD

The microstructures and composition of gold wires were observed using high-resolution scanning electron microscope (SEM) with EDX system. The shape of fractured end of the five specimens of gold wires at different strain rates were observed up to 10 µm magnification.

The Micro-universal Testing Machine was used to carry out the micromechanical properties of 4N gold wire. Figure 1 shows the experimental setup for testing the gold wire under the tensile test. The experiment was conducted at the room temperature i.e. at 27ºC. The load that was initially applied to the specimen before the test was sufficient to keep the wire in the straight position, thus to retain its original strength. Table 1 shows the parameter set up for micro tensile test. A total of three tests were performed at different strain rates, i.e. 100, 10-1, 10-2, 10-3 and 10-4 min-1. The tensile test has been performed until the sample broke. A typical stress-strain curve was automatically plotted using the designed software which incorporates to the Micro-universal Testing machine.

Tables 1 : Parameter for Micro-Universal testing machine

Parameter	Value
Wire diameter	25.4µm
Wire length	5cm
Strain rate	10º-10-4 min-1
Load cell	2.5 N

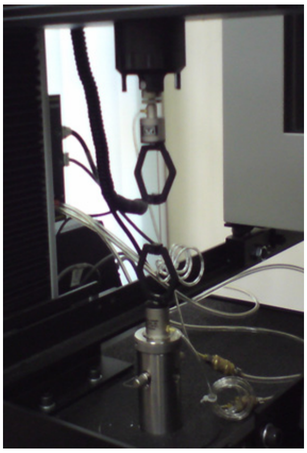


Figure 1 : The setup for the gold wire tensile

The gold wires after tensile test were test by nano-indentation. The specimens for nano-indentation were prepared by the resin mounting and they are subjected to the metallography polishing. The shallower the indentation depth, the smoother the specimen surface is required to be. A nano test of the nanoindenter system was used for this experiment and it involved four steps: approaching the surface, loading to peak load, holding the indenter at peak load and finally unloading completely. The hold period is to avoid the influence of creep on the unloading characterization [1]. After positioning the sample in the indentation equipment a time period of 30 minutes was allowed for a specific temperature of. These parameters were used 25˚C to stabilize the specimens in the enclosure. The indenter tip with a three-sided pyramidal diamond berkovich was used. The parameter and experiment setup was shown in Table 2 and Figure 2.

Table 2 : Parameter set-up used for the nanoindentation technique.

Parameter	**Value**
Maximum load	20 mN
Depth gain (%)	40%
Loading rate	3.3 mN/s
Hold time	2 second at the maximum load
Initial load	0.01 mN/s

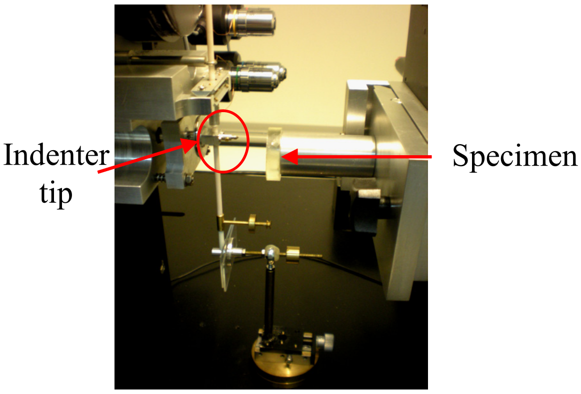


Figure 2 : Nanoindenter machine with the specimen fixed at the sample stub.

3 RESULTS AND DISCUSSIONS

3.1 Effect of alloy elements on mechanical properties

Elemental analysis by EDX detected amounts of Ca and Mg doping element in of gold wire as shown in Table 3. Ca is an effective hardener above 10ppm and has an immediate benefit to a short HAZ by increasing the recrystallization temperature. Element trace of Ca gives higher strength, higher elastic modulus, and higher recrystallization temperature. Recrystallization temperature would result in shorter heat affected zone (HAZ) length and thus, form lower loop height. Chew et al. [9] reported that increasing amounts of Ca raised the yield strength, ultimate tensile strength and the elongation break. According to Wulff and Breach [10], a strengthening mechanism may be due to the microsegregation of specific dopants along grain boundaries, especially larger atoms like Ca. The atomic size of calcium is 30% larger than gold, and so it would be expelled from the lattice and find it's place at grain boundaries. The hardening effect of grain boundary constituents (Ca) is not as quickly apparent, but their grain boundary presence pins these zones and eventually not only increases it strength but more importantly increases the recrystallization temperature.

Table 3 : Atomic percentage for wire A and B

Element	Atomic percentage (%) Wire B
Mg	0.12
Ca	3.62
Au	96.26

3.2 Tensile test of gold wire

Figure 3 showed the stress-strain curve was obtained for those five different strain rates tested under the tensile test. Higher plastic deformations after yielding point of the tested gold wire occur at the strain rate of 100 min-1. From the figure 3, strain rate of 100 min-1 showed 3.27% tensile strain and tensile stress at 148.43 MPa.. For the whole test of this rate, the strain maintained the increment of the applied stress before the necking pattern developed and the stress slightly decreased until it completely failed.

From figure 3, it showed that the tensile stress was decreased from 148.43 MPa to 10 MPa with the reduction of the strain rates from 100 to 10-4 min-1. Thus, it indicated that higher strain rates provide to the better ductility behavior of the gold wire compared to the lower strain rates. According to the research by Boyle and Dilmore [11], they recorded a good result of different of alloys contributed to 3-10% drop in their ductility with the increment of the strain rates.

From the results obtained in figure 3, the Young's modulus, the yield strength and the ultimate strength is proportionally increased with the increment of the strain rates. All of these happened because of the size factor of gold wire is very tiny (25.4μm) which is near to the typical size of one grain size. Kim et al. [1] discussed on the average grain size of ultra-fine gold wires before the annealing process was measured at about 230 nm. This value was found to be contradicting to the typical bulk properties alloys behavior including the gold wire. Most grains are typically slipped and the grain boundary mobility can occur at an earlier stage of the material deformation. Different amounts of Ca and Mg doping element in of gold wire also give an effect for the micromechanical properties of gold wire. Higher element trace of Ca gives higher strength, higher elastic modulus, and higher recrystallization temperature [12].

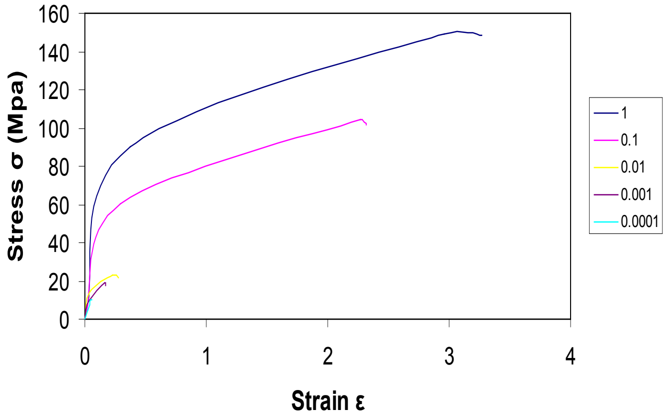


Figure 3 : Stress-strain relationship for 100 to 10-4 m-1 strain rate under tensile test.

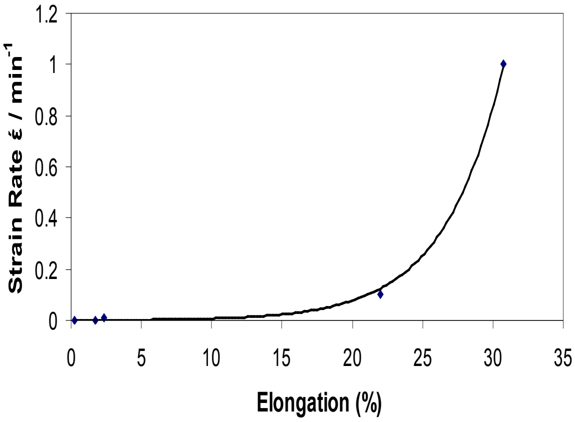


Figure 4 : The elongation trend at different strain rates

The elongation of the gold wire was also affected by the strain rates. The findings in figure 4 showed the addition of the strain rates in the test gave the increment of the wire elongation and the figure also indicated the significant difference of the wire elongation for the strain rates 10-2 to 10-4 min-1. The percentage of elongation for the 100 min-1 of strain rates were recorded higher, which is more than 30%. Higher plastic deformation was observed to be occurred at 100 min-1, and before the necking pattern was developed. For this case, the necking effect will lead to the wire fracture. The elastic modulus, the strength and the elongation were found to be higher with respect to the re-crystallization behavior [1], for which this statement can be suggested as the supporting evidence of our findings.

The Young's Modulus of Au wire which was determined from the stress- strain curves in Figure 5. This modulus values were increased with the increment of the strain rates. The Young's Modulus of the wire with 100 min-1 strain rates was recorded higher than the other values and the modulus values were proportionally decreased when the strain rates decreased from 100 to 10-4 min-1. This finding revealed the Young's Modulus and tensile strength were minimally affected by the tensile test strain rates values. For other materials such as thermoplastic, when it loaded at a low strain rate, the molecular chain have sufficient time to adjust to the imposed stress and the modulus value is lower than would be the case for the same material loaded at a higher strain rate [13]. Higher strain rates also lead to higher yield strength. The yield strength pattern of different strain rate of Au wire was plotted in Figure 5. The yield strength for the 100 min-1 strain rate was recorded 90.45 MPa.

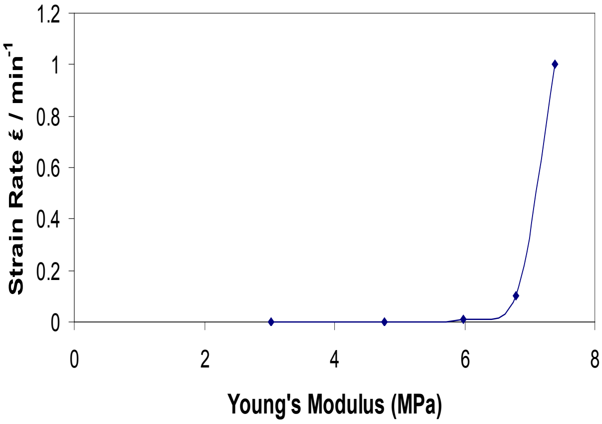


Figure 5 : The Young's modulus trend at different strain rates.

Figure 6 showed the yield strength for 10-4 min-1 strain rate was recorded at 4.98 MPa and this value was found at 90.45 MPa at 100 strain rates. The different yield strength between higher and lower value of strain rates is 85.47 MPa. Under a higher strain rates, the yield strength value shows a significant difference, as it can be explained based on the grain size effect. The hardness and the yield strength were significantly improved as the grain size decreases [3].

Shin et al. [14] reported the different strains rates influence the maximum stress, the Young's modulus and the deformation behaviors. With different strain rates, many different deformation behaviors had appeared which include sliding, multi-sliding, phase transformative, twisting, necking and brittle deformation before breaking. Less details about the trend of all parameters has been discussed by Shin et. al. [14]. However, the findings of this paper lead to a meaningful conclusion that will be explained at the later part of this paper. From the micro-tensile test, the mechanical properties of the 4N Au wire gave the exponential plot. This unique trend can be seen in the plot of strain rate versus the yield strength values (Figure 6). The graph show higher strain rates, which lead to higher strength and this occurrence, might be caused by the behavior of smaller grain size in tiny 25.4 µm gold wire.

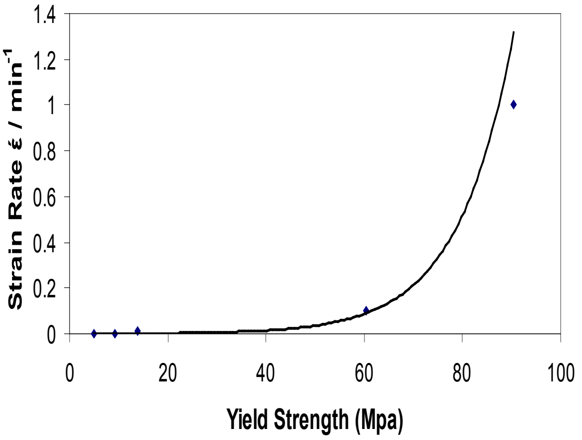
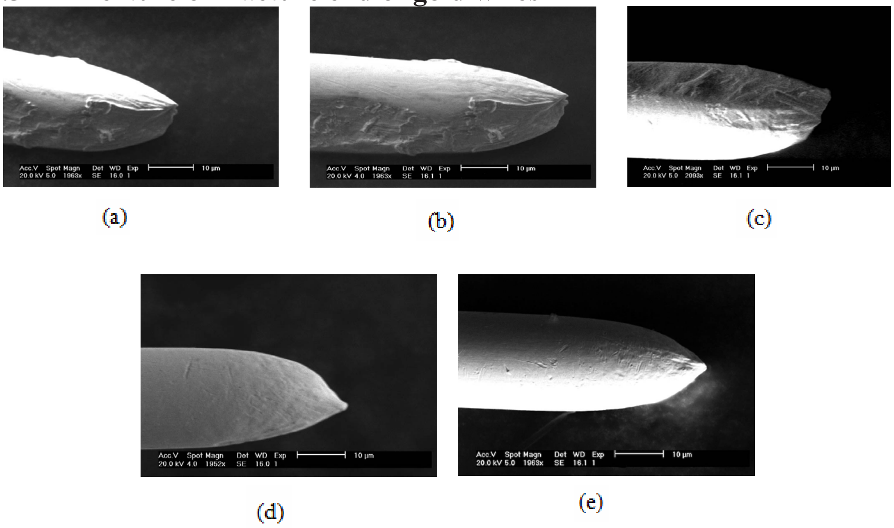


Figure 6 : The yield strength trend at different strain rate

3.3 Texture of fracture end of gold wires



(a) (b) (c)

(d) (e)

Figure 7 : The shape of fractured end of gold wires after micro-tensile test (a) strain rate at 10-4 min-1, (b) strain rate at 10-3 min-1, (c) strain rate at 10-2 min-1, (d) strain rate at 10-1 min-1, (e) strain rate at 100 min-1

Figure 7 showed the shape of fracture end of 4N gold wires after the micro-tensile test. The necking occurs near the fractured portion for all of specimens and showed pattern of cup-and-corn fracture. The specimens with a higher strain rates at 10-1 min-1 and 100 min-1 showed a sharp fracture end with a formation like a needle shape as shown at Figure 7(d) and 7(e). The shape fractured end is related to the value tensile strength, tensile stress, elongation, Young's modulus and yield strength (refer to Figure 3 to Figure 6). The specimens that used a lower strain value ie.10-2 min-1,10-3 min-1 and10-4 min-1 produced a lower tensile strength, tensile stress, elongation, Young's modulus and yield strength values, in addiction the fractured end to be seen as a dimples shape as shown at Figure 7(a) to 7(c). These results suggested that the specimens with higher strain rates seem to be more ductility compared to the lower strain rate values. Kim et al [1] reported that the reason for the sharp needle like shape could be consisted due to the ultra-fine grain size and extra cause, which could lead to a ductile fracture of specimen.

3.4 Hardness test of gold wire

This result supported by distribution of different hardness value as showed in Figure 8. From the graph, strain rates have direct proportional relationship to hardness value. Higher hardness which is at 0.45 GPa was presented by gold wire having higher strain rate. This value is still lower when compared to previous studied by Shah et. al [15] that found under 20 mN maximum loads, the hardness value is about 1.35 GPa. This occurrence might be caused by the behavior of smaller grain size in tiny 25.4 μm gold wire. There is significant difference among hardness value presented by 100 and 10-1 with steeply increasing of hardness value, up to 22% differences. On the other hand, smaller differences showed by gold wire having strain rate 10-2–10-4 mm-1 , with 0.5% value.

Indentations of the substrate penetration of the tip into the gold wire surface exhibiting transitions from elastic to plastic deformation and formation of extended atomically thin crystalline connective wires [16]. In this study, less plastic deformation occurs during indentation loaded to wire having higher strain rate value. Different strain rate also contribute different wire break location.

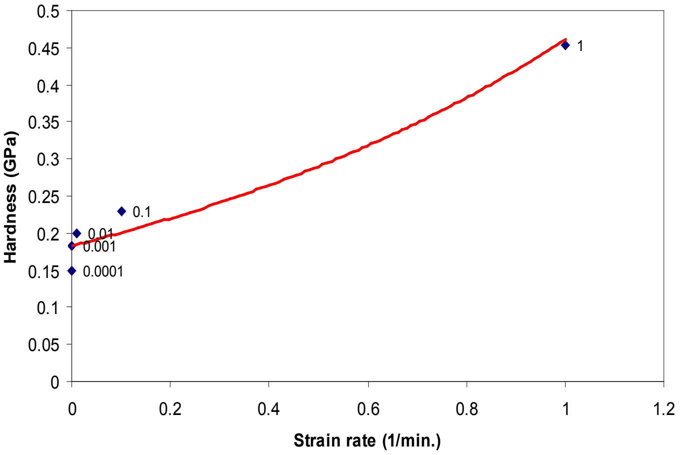


Figure 8 : Exponential graph of Hardness versus variable strain rate after indentation

4 CONCLUSION

The micromechanical properties are significant for producing the gold wire with better behavior of their mechanical properties. The amount of a Ca raised the yield strength and elongation break of gold wire. The results of the tensile test showed that gold wire with the strain rate of 10 μmin-1 gave better micromechanical properties compared to the other test at different strain rate. From the experimental procedure, the strength and ductility of Au wire were influenced by the strain rate values. It can be concluded that the variable strain rates in the tensile test are proportional to the tensile strength, yield strength and Young's modulus values. Based on the fracture end observation for all specimens, the pattern of cup-and-corn fracture can be observed. The specimens that have a higher tensile strength and stress showed a sharp fracture end like a needle shape and the lower tensile strength and stress had dimples from the fracture surface. The hardness of the gold wire increase when the high strain rates were use in tensile test. Finally, it is suggest that this study was able to address the reader about micromechanical behavior gave the effects for wire bonding process design in order to characterize the wire loop control and strengthen the wire loop to avoid the wire sweep.

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