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Mechanics of Materials 38 (2006) 119–127
MECHANICS OF MATERIALS
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Relationship between mechanical properties and microstructure of ultra-fine gold bonding wires

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Abstract

The ultra-fine gold bonding wires, having diameter of 24 μm and consisted with nano-sized grains, show much higher strength and modulus than those of wrought and annealed gold. The stress–strain curves of ultra-fine Au wires have been characterized by using the micro-tensile testing technique. The ultimate tensile strength of ultra-fine Au wires was measured from 190 MPa to 407 MPa, and decreased with increasing the annealing temperature. The elastic modulus was measured from 79 GPa to 97 GPa, which was also higher than that of wrought and annealed gold. The grain size of ultra-fine Au bonding wire was characterized using high-resolution scanning electron microscope. The grain size was measured from 230 nm to 1650 nm, and the grain growth was not observed up to an annealing temperature of 500 °C. The texture of ultra-fine Au bonding wire was characterized using X-ray diffractometer to characterize the orientation distribution function. Theoretical elastic moduli of ultra-fine Au wires have been calculated by using the Voigt model. The theoretical elastic moduli show good agreement with the measured elastic moduli using the micro-tensile testing technique. The tensile strength of ultra-fine Au bonding wire can be controlled by controlling the grain size and texture.

Keywords: Gold bonding wires; Tensile strength; Elastic modulus; Texture; Recrystallization

1. Introduction

The gold bonding wire used for semiconductor wire bonding process is one of the important commercial nanocrystalline materials (Busch et al., 1988). The package size for semiconductor is continuously reduced smaller than that of ten years ago (Nguyen, 1988). The pitch of pads becomes less than 60 μm and the diameter of commercial ultra-fine Au wire is about 24 μm. If the diameter of ultra-fine Au wires becomes smaller, the stiffness and the loading capacity will be decreased. If thin

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0167-6636/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mechmat.2005.05.015

Au wires are applied to the same kind of packages, the mechanical properties of Au wires needs to be enhanced (Qi and Zhang, 1997). The numbers of current packaging pins have been increased more than 400. The pitch between contact pads on Si chip is decreased less than 50 μm, so the diameter of ultra-fine Au wire needs to be decreased under 20 μm. As the pitch of pads decreases, the requirement for thinner and harder Au bonding wire has been increased.

The ultra-fine Au wires are fabricated by multiple steps of drawing process and annealing process. The grain size and texture are changed due to severe deformation during the drawing process. The reduction ratio of commercial Au bonding wire is more than 99.6%. The grain size of ultra-fine Au wires was decreased with decreasing the diameter of wires. The grain size and texture of ultra-fine Au wires were characterized by using transmission electron microscope (Noguchi et al., 2000). The grain size measured by transmission electron microscope was about 200 nm and a $\langle 111 \rangle$ texture was observed parallel to the drawing axis. The elastic modulus of ultra-fine Au wire is about 90–110 GPa, which value is higher about 20 GPa than that of pure annealed Au. The yield strength and the ultimate tensile strength of ultra-fine Au bonding wire are also higher than those of pure annealed Au.

It is becoming very important to characterize the mechanical properties and to understand the mechanism to enhance the mechanical properties of ultra-fine Au wires. In this study, the characterization method of mechanical properties and the relationship between the elastic modulus and microstructure of ultra-fine Au wires were investigated for the development of high strength ultra-fine Au bonding wires.

2. Experimental procedure

2.1. Fabrication of ultra-fine Au wires

The ultra-fine Au wires in this study were fabricated by employing multiple drawing processes at room temperature. The ultra-fine Au wires were made from vacuum cast rod with diameter of 7.0 mm. The alloying element for the ultra-fine Au wires was controlled to less than 100 ppm. The investigated specimens were selected with different conditions of annealing temperature. The drawing process was composed with about ten steps and each step of drawing process was composed with five or ten drawing dies. The diameter of ultra-fine Au wire specimens was fixed to investigate the effect of annealing temperature for a specific time of 1–10 s on mechanical properties.

2.2. Micro-tensile test

The mechanical properties of ultra-fine Au wires were measured using micro-tensile test (Brotzen, 1994). The mechanical properties were elastic modulus, yield strength, ultimate tensile strength and elongation that were possible to be characterized in the micro-tensile test. Instron 8848 model was used for micro-tensile test using a static load cell with maximum load capacity of 5 N (Tsai, 1999). Specific low pass filter was applied to reduce the noise of load and 1500 data points were measured to characterize the elastic modulus of ultra-fine Au wires (Kim et al., 2003). The gage length of specimen was 100 mm and the strain rate was changed from 10^{-4} to 10^{-2}. The yield strength was measured at 0.2% offset strain. The elastic modulus was measured by using partial-unloading method. The stress was partially unloaded at an interval of 0.5% strain, and the elastic modulus was characterized from the slope of stress–strain curve during partial unloading.

2.3. Microstructure analysis

The microstructure of ultra-fine Au wires was characterized by employing high-resolution scanning electron microscope from Philips XL 30S FEG. The preparation process of specimens were improved as follows. The ultra-fine Au wires was mounted in acrylic resin. The mounted Au specimen was polished up to 0.3 μm diamond paste. The grain shape and size of specimens were investigated after etching the specimen. The specimen was etched for 5–10 s using aqua regia solution. The average grain size was measured using the image analysis software, AnalySIS 3.1 from Soft Imaging System GmbH.

The texture of ultra-fine Au wire was characterized by employing Rigaku D/max-RC X-ray diffraction equipment. The pole figure was measured with reflection method under a condition of 30 kV and 60 mA. The specimen for texture analysis was prepared as follows. A glass plate was cut to 18mm square plate. The ultra-fine Au wire was also cut to 18 mm long wires. The bundle of 18 mm long Au wires was bonded to single layer on the glass plate by using adhesive tape. The orientation distribution function was calculated from the (1 1 1), (2 0 0) and (2 2 0) pole figures obtained from the ultra-fine Au bonding wires. The elastic moduli are calculated from the orientation distribution function by using the Voigt model.

3. Results and discussion

3.1. Mechanical properties of ultra-fine Au wires

The mechanical properties of ultra-fine Au wires with various annealing conditions were characterized by the micro-tensile test. The stress–strain curves of ultra-fine Au wires were shown in Fig. 1. The hard ultra-fine Au wire, which was as-drawn wire before annealing, showed brittle fracture with limited elongation. The hard ultra-fine Au wire showed limited plastic deformation after yield and high tensile strength over 470 MPa. The annealed ultra-fine Au wires showed extended plastic deformation as shown in Fig. 1. The yield strength decreased from 325 MPa to 112 MPa and, at the same time, the tensile strength decreased from 357 MPa to 191 MPa with increasing the annealing temperature from 400 °C to 580 °C as shown in Fig. 2. The elongation increased from 0.8% to 12.2% with increasing the annealing temperature as shown in Fig. 3. The elastic modulus was measured by using partial unloading technique during the tensile test. The stress–strain curve to measure the elastic modulus of ultra-fine Au wire was shown in Fig. 4. The partial unloading was executed at an interval of 0.5% strain. The amount of partial unloading was about 100–120 MPa, which is about 50% of the load during tensile elongation, and the elastic modulus was calculated from the slope of unloading curve. The elastic modulus of as-drawn ultra-fine Au wire before annealing was 95 GPa, which was higher than that of annealed Au known as 79 GPa (Hannula et al., 1983). The elastic modulus of as-drawn ultra-fine Au wires increased about 15% compared

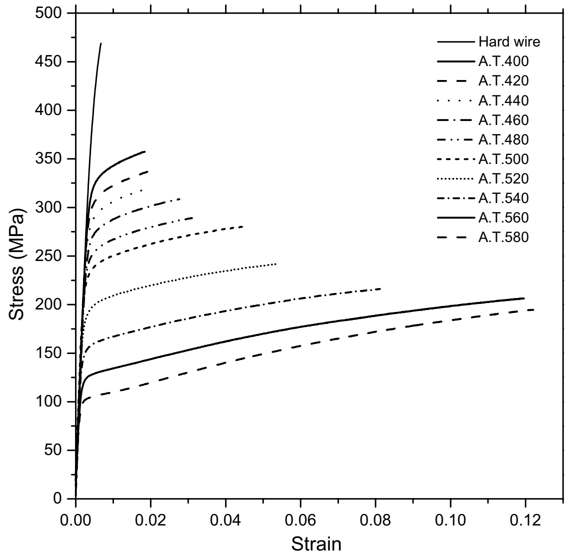

Fig. 1. Stress–strain curves of ultra-fine Au bonding wires obtained by micro-tensile tests.

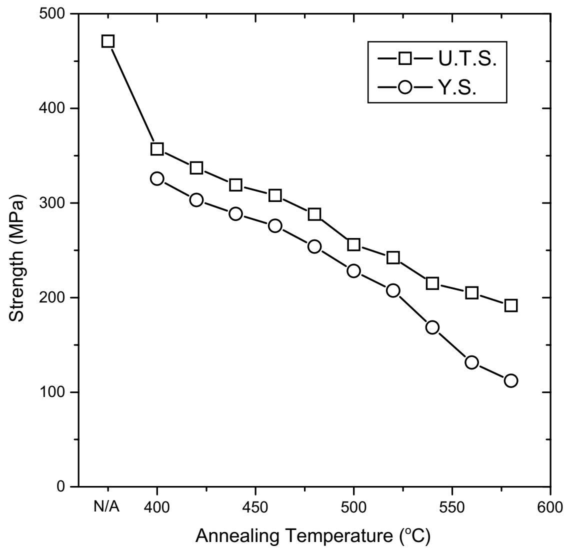

Fig. 2. The variation of yield strength and U.T.S. of ultra-fine Au bonding wires with varying the annealing temperature.

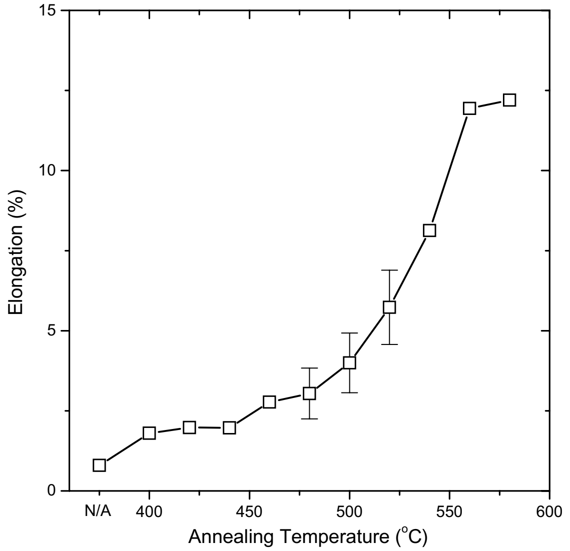

Fig. 3. The variation of elongation of ultra-fine Au bonding wires with varying the annealing temperature.

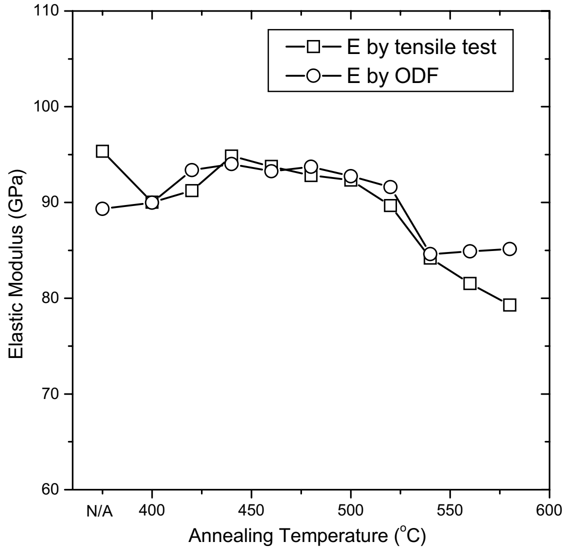

Fig. 5. The variation of measured elastic modulus and predicted elastic modulus with varying the annealing temperature.

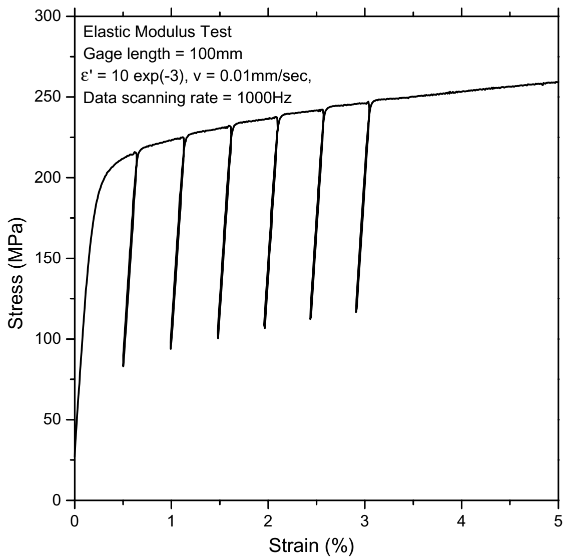

Fig. 4. A series of partial unloading curve during the micro-tensile test of ultra-fine Au bonding wire.

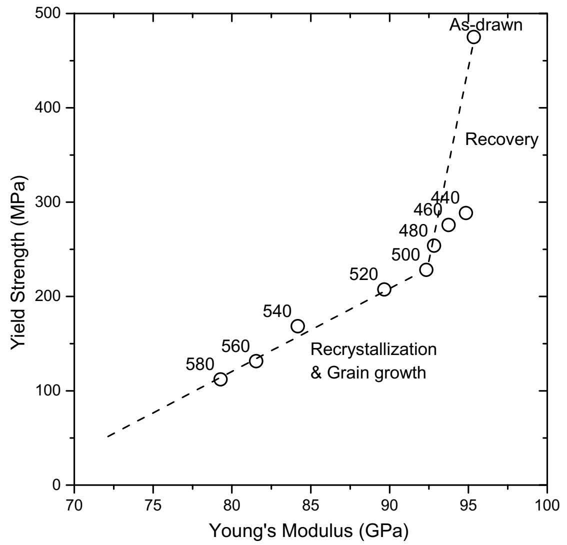

Fig. 6. Plot of yield strength vs. elastic modulus of ultra-fine Au bonding wires.

to that of wrought and annealed Au as shown at Fig. 5. The elastic modulus slightly decreased after annealing at 400 °C, but the elastic modulus was recovered after annealing at 440 °C. Then, the elastic modulus decreased to 80 GPa with increasing annealing temperature from 520 °C. The strength and the elastic modulus of ultra-fine Au wires were decreased after annealing at 520 °C.

The decrease of strength and elastic modulus above 520 °C were due to the recrystallization of ultra-fine Au wires. The yield strengths and the elastic moduli of ultra-fine Au wires were plotted in Fig. 6. The elastic modulus of ultra-fine Au wire decreased more rapidly than the yield strength by recrystallization and grain growth behavior after annealing at 500 °C as shown in Fig. 6. The yield strength of ultra-fine Au wires decreased, while the elastic modulus did not decrease before annealing at 500 °C. The recovery of ultra-fine Au wire during annealing below 500 °C decreased the yield strength but did not change the elastic modulus.

3.2. Microstructure of ultra-fine Au wires

The recrystallization behavior of ultra-fine Au wires was investigated by using microstructure analysis. The microstructures of ultra-fine Au wires were characterized by high-resolution SEM as shown in Fig. 7. The grain size of ultra-fine Au wires increased due to grain growth with increasing the annealing temperature. The average grain size of as-drawn ultra-fine Au wires before annealing was measured about 230 nm. The grain size of ultra-fine Au wire slightly increased up to 410 nm after annealing at temperature ranged from 400 °C to 500 °C. The grain size of annealed

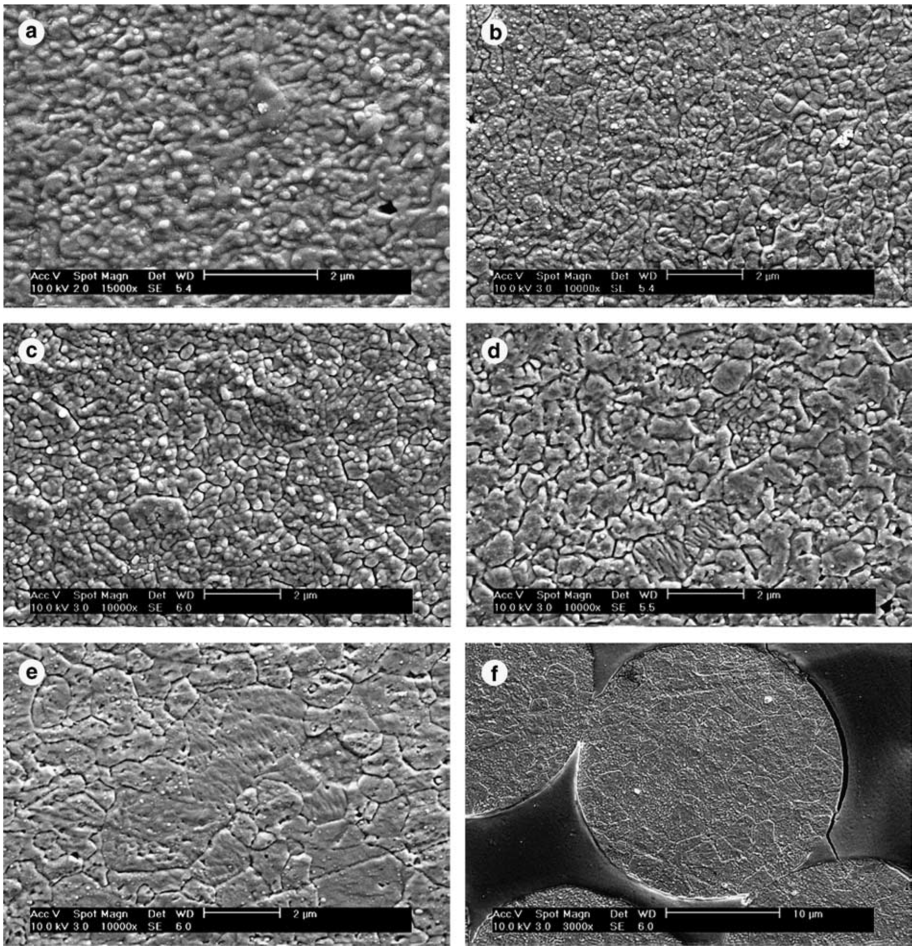

Fig. 7. Microstructure of ultra-fine Au bonding wires (a) as-drawn, (b) annealed at 460 °C, (c) annealed at 500 °C, (d) annealed at 520 °C, (e) annealed at 540 °C and (f) annealed at 580 °C.

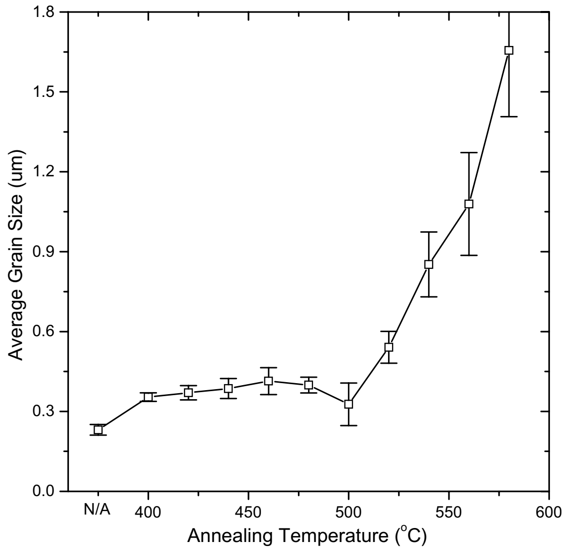

Fig. 8. The variation of average grain size of ultra-fine Au bonding wires with varying the annealing temperature.

ultra-fine Au wires kept very small and the distribution of grain size was normal up to annealing temperature of 500 °C. The grain size of annealed ultra-fine Au wires increased rapidly due to the grain growth after annealing at temperature above 520 °C as shown at Fig. 8. The grain size of ultra-fine Au wire annealed at 500 °C was slightly decreased due to the recrystallization behavior. The distribution of grain size was abnormal at annealing temperature of 520 °C. So the recrystallization was probably occurred at annealing temperature around 500 °C, which temperature was same as the recrystallization temperature measured by the decrease of the elastic modulus and the yield strength.

The shape of fractured end of ultra-fine Au wires after micro-tensile test were showed at Fig. 9. The shape of fractured specimens showed pattern of cup-and-corn fracture. The specimen annealed at temperature above 540 °C showed a needle like shape as shown at Fig. 9(c). 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.

3.3. Texture of ultra-fine Au wires

The texture of ultra-fine Au wires was investigated by employing XRD pole figure analysis

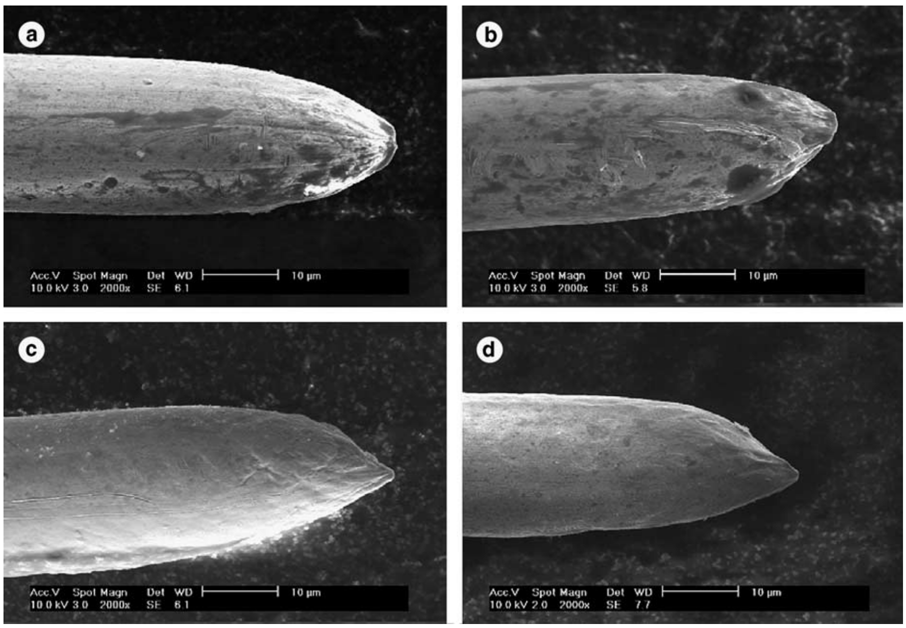

Fig. 9. The shape of fractured end of ultra-fine Au bonding wires after micro-tensile test (a) as-drawn, (b) annealed at 520 °C, (c) annealed at 540 °C and (d) annealed at 580 °C.

method. The texture of ultra-fine Au wires showed very strong ⟨1 1 1⟩ fiber texture parallel to the drawn direction of wire. The ⟨1 1 1⟩ fiber texture decreased, while the ⟨0 0 1⟩ fiber texture increased after annealing at 540 °C as shown in Fig. 10. The decrease of elastic modulus was considered due to the recrystallization behavior. The ⟨0 0 1⟩ fiber texture increases the elastic modulus, while the ⟨0 0 1⟩ fiber texture decreases the elastic modulus of Au wires. As the ⟨0 0 1⟩ fiber texture increased with increasing the annealing temperature, the elastic modulus decreased after annealing at 540 °C (Fig. 11).

The elastic modulus of materials can be predicted by using texture information (Bunge et al., 2000). The elastic constants of a material can be found as a tensor value. The tensor data can be changed to the elastic modulus of desired direction. The elastic constants of single crystalline Au were obtained from reference book (Landolt-Börnstein, 1979). The elastic modulus of a single crystal of a cubic metal can be obtained with equations shown as follows:

$$\frac{1}{E} = S_{11} - 2\left[(S_{11} - S_{12}) - \frac{1}{2}S_{44}\right](h_1^2h_2^2 + h_2^2h_3^2 + h_3^2h_1^2), \tag{1}$$

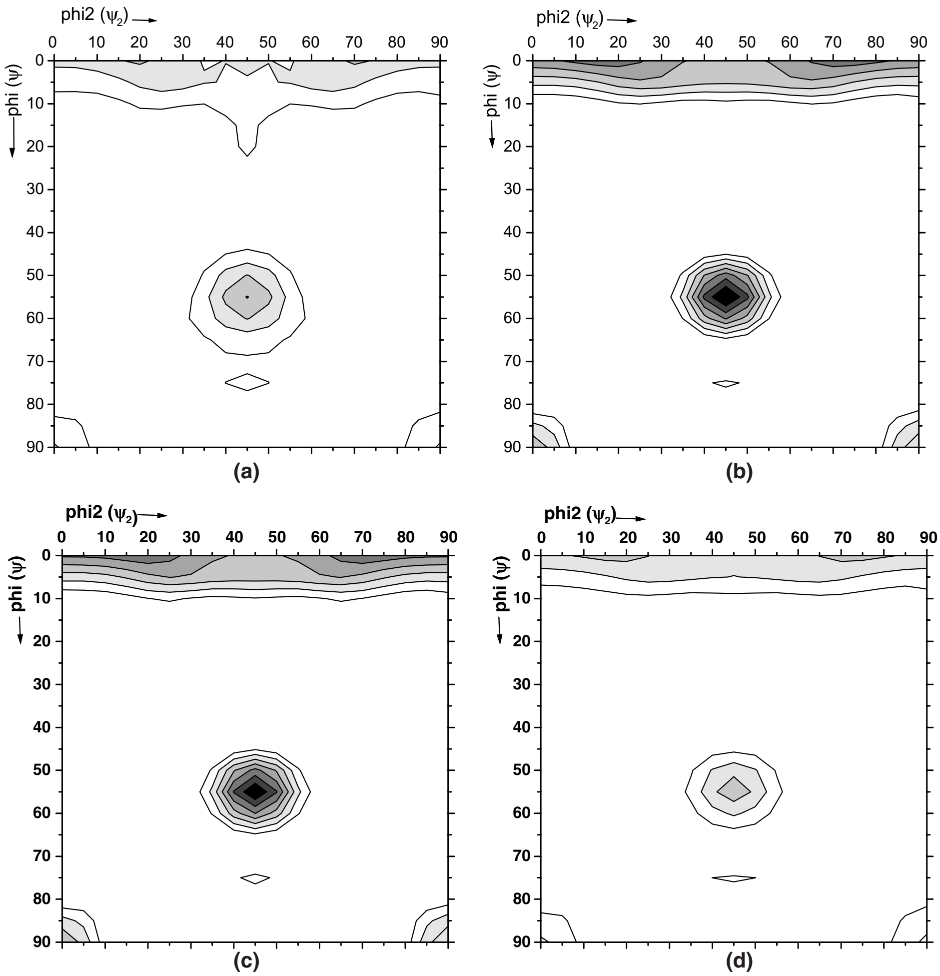

Fig. 10. Orientation distribution function characterized from X-ray diffraction of ultra-fine Au bonding wires (a) as-drawn, (b) annealed at 500 °C, (c) annealed at 520 °C and (d) annealed at 540 °C.

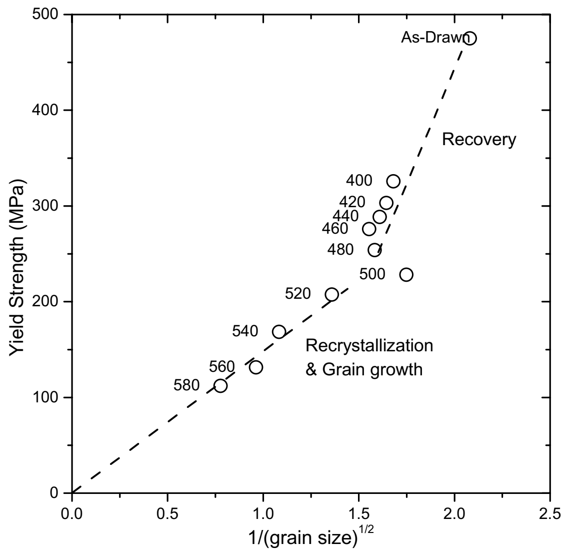

Fig. 11. The variation of yield strength with varying the grain size showing the Hall–Petch type relationship in ultra-fine Au bonding wires.

where E is Young's modulus of specific direction. S_{11}, S_{12} and S_{14} are the elastic compliances of materials. S_{11}(=21.52 GPa), S_{12}(=22.06 GPa) and S_{44}(=−9.83 GPa) were used to predict the elastic modulus of ultra-fine Au wires (Landolt-Börnstein, 1979). The character h_1, h_2 and h_3 are the direction cosines of specific axis with respect to the crystallographic axis. The direction cosines can be obtained from inverse pole figure and can be calculated from the Euler angle value for given specimen axis. The equation of relationship between Euler angle and direction cosine are shown as follows:

$$h_1 = \sin\phi \sin\psi_2, \quad (2)$$

$$h_2 = \sin\phi \cos\psi_2, \quad (3)$$

$$h_3 = \cos\phi, \quad (4)$$

where ϕ and ψ_2 are Euler angle. The h_1, h_2 and h_3 values can be obtained from given Euler angle values. So the elastic modulus can be obtained with given Euler angle. The Young's modulus of ultra-fine Au wires was predicted by Voigt model. The Voigt model is strain constraint model. The microstructure of ultra-fine Au wires had shape of elongated grain according to drawing direction of wire. All the grains may have same strain when they are compressed or elongated to transverse direction of drawing direction. So the Voigt model is one of approvable model to predict the elastic modulus for ultra-fine Au wires. The equation was expressed as follows:

$$\begin{aligned} E &= \frac{1}{8\pi^2}\int E(g)F_g\,\mathrm{d}g \\ &= \frac{1}{8\pi^2}\int E(\psi_1,\phi,\psi_2)F_g \sin\phi\,\mathrm{d}\phi\,\mathrm{d}\psi_2\,\mathrm{d}\psi_1. \end{aligned} \quad (5)$$

The Young's modulus according to drawing direction of wires can be predicted by using Voigt model but the elastic modulus of no other direction can be predicted by this model. The Voigt model is applied only to the elongated direction of grains.

As shown in Fig. 5, the measured elastic modulus by micro-tensile test showed good agreement with the predicted elastic modulus by orientation distribution function analysis. It means that the elastic modulus of ultra-fine Au wires was changed due to the change of texture and the decrease of elastic modulus was mainly due to the recrystallization of ultra-fine Au wires. The grain size increased after annealing at 520 °C, however, elastic modulus decreased due to increase of ⟨001⟩ fiber texture, after annealing at 540 °C. It means that the recrystallization behavior of ultra-fine Au wire do not occur instantaneously at a critical annealing temperature. The recrystallization process of ultra-fine Au wire is time dependent to transform the grain structure and the dislocation structure. The elastic modulus of ultra-fine Au wires was controlled by the formation of texture during wire drawing and annealing process (Table 1).

Table 1
Composition of ultra-fine Au bonding wire

Composition	Au	Be	Ca	Ce	Ge	Pd	Pt
Amount (ppm)	Balance	<10	10–50	<50	10–40	<40	<40

4. Conclusions

The investigation of relationship between mechanical properties and microstructure of ultra-fine Au bonding wires is important to develop ultra-fine Au bonding wires with high strength and high elastic modulus.

1. The mechanical properties were characterized by employing micro-tensile tester and the microstructure was characterized by employing high-resolution SEM equipment and X-ray diffraction pole figure equipment.
2. The elastic modulus, the strength and the elongation were highly related to the recrystallization behavior. The grain size was increased rapidly above an annealing temperature of 520 °C. The elastic modulus decreased after annealing above 520 °C due to recrystallization.
3. The elastic modulus of Au bonding wire, predicted by texture analysis, agrees well with the measured value by micro-tensile test. This indicate that the elastic modulus of Au bonding wire can be controlled by controlling the texture during wire drawing and annealing process.

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