Room Temperature Micro Adhesional Bonding†

TAKAHASHI Yasuo*, UESUGI Katsuhiro** and MATSUSAKA Souta***

Abstract

The room temperature adhesional bonding of fine Au wires was investigated. Au wires with a diameter of 100 μm were contacted to Au plates and Si substrates after the surfaces had been activated by Ar ion irradiation. It was found that the experimental contact width, 2a, was nearly equal to the theoretical adhesional elastic contact width, $2a_j$, when f was small enough (f < 500 N/m) but the contact 2a gradually became greater than $2a_j$ if f increased (f > 500 N/m), and became nearly equal to the elasto-plastic contact width a_{ep}. It was also found that the experimental bond strength increased with increasing the holding time after bonding (contacting). It was suggested from the experimental results (T / t_r - $1 / T$ plots) that the mechanism of increasing bond strength is due to the stress induced diffusion along the bond interface, where t_r is the time taken to obtain a constant increase in the bond-strength and T is the absolute temperature. Further, the possibility of nano contact joining was suggested.

KEY WORDS: (Room Temperature)(Adhesion)(cohesion)(Micro joining)(Elasto-plastic contact) (Stress induced diffusion)(Bond strength)

1. Introduction

Surfaces of metals exposed in air are usually covered with oxide film or contamination[1] and therefore are not easy to bond without bonding pressure. However, if the surface oxide film is removed, then the metals have an activated surface. Two solids with activated surfaces are able to exhibit an adhesion without any compressive force [2]. This bonding process is hereafter called surface activated adhesional bonding [3].

If the size of wire and sphere is small enough, the effect of the surface energy should be taken into consideration for the elastic contact of non-flat surfaces [3, 4]. The contact area deviates from Hertz's solution [2] as the applied force decreases. However, as the applied force increases, the amount of stress around the contact zone exceeds the yield stress for the plastic deformation and an elasto-plastic contact is produced [5]. The contact area is larger than the adhesional elastic contact. The strength of bond-interface formed by the surface activated adhesional bonding increases with the holding time after bonding [5] and the reason was discussed by Takahashi et al. [5, 6].

The micro-contacting process of fine wires will be very important in the field of electronic packaging technology in the near future. Therefore, the present paper deals with the surface activated adhesional bonding between gold wires and gold electric pads. The purpose of the present study was to investigate the behavior of adhesional bonding of fine gold wires. Further, the time dependence of the adhesional bond strength is examined to infer that stress induced diffusion occurs even at room temperature.

2. Experimental Procedure

Fig. 1 illustrates the adhesional bonding apparatus used in the present study. A gold wire with a diameter of 100 μm and a purity of 99.99 mass % and a gold foil with a thickness of 100~150 μm were used as the bonding specimen. After they were degreased using acetone and ethanol, they were placed one by one in the introduction chamber and moved into the Ar ion irradiation chamber using the transfer rod. After the gold foil was fixed onto the stainless steel substrate, it was irradiated by Ar ions and placed at the specimen-holder position in the main chamber. After that, the gold wire was treated in the same manner. The acceleration voltage of the Ar ion beam

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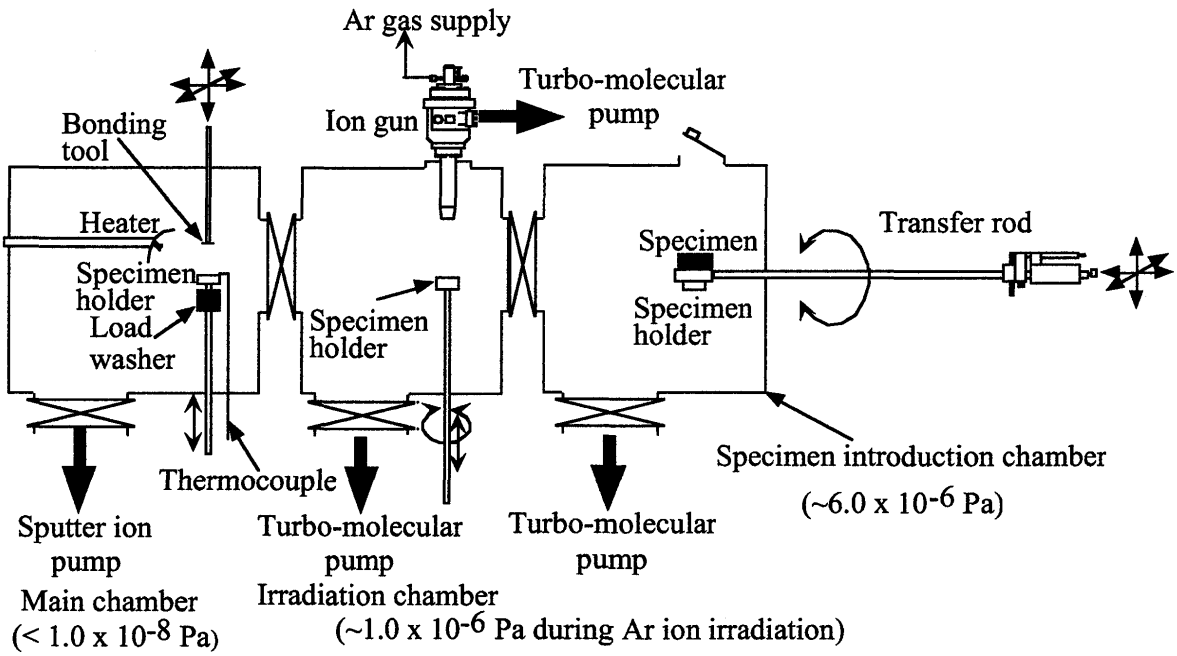

Fig. 1 Schematic illustration of adhesional bonding apparatus.

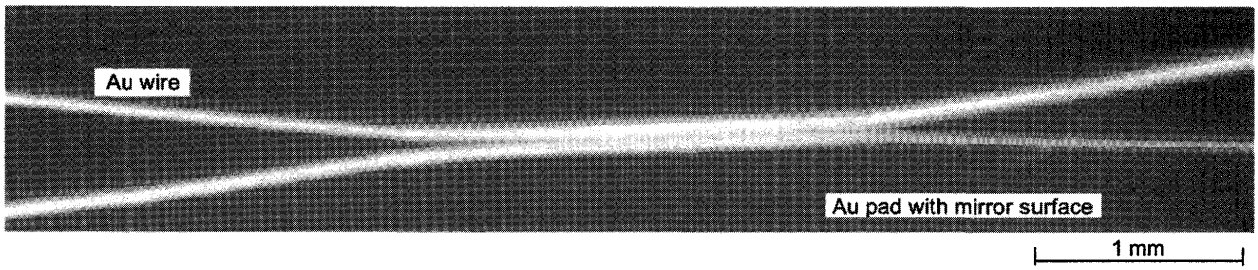

Fig. 2 Photograph of Au wire bonded to Au pad. $R = 50$ μm, $P = 5$ MPa (500 N/m), $a \approx 1.8$~2 μm, $F_p \approx 28$ mN, where R is the radius of wire, P is the mean pressure applied to the wire, a is the half contact width, and F_p is the pull strength.

was in the range of 1 ~ 2 kV. The adhesional bonding was carried out under an atmospheric pressure of < 1×10^{-8} Pa. The bonding temperature was kept at 298 ± 3 K by controlling the room temperature. The bonding load was provided by a bonding tool connected to a manipulator, i.e., the bonding load was controlled by moving the bonding tool along the z axis of the manipulator. The length of each wire used as a bonding specimen was about 20 mm but only the central zone of 1 mm (or 2 mm) length was pressed by the bonding jig.

After bonding, a peel test was performed to measure the bond strength. As the end (length of ~10 mm) of the wire was not bonded, the end of the wire was bent normal to the substrate and fastened to the peeling jig using an adhesive. The peel test was done by pulling the end of the wire perpendicularly to the substrate. But, when the pull force F_p reached a certain value, fracture was suddenly produced without peeling [5]. Therefore, F_p was assumed to express the mean bond strength of the total bonded area.

3. Results and Discussion

Figure 2 shows the photograph of an adhesional contact bond between Au wire and Au pad. The bonding pressure P was 5 MPa ($f = 500$ N/m, $P = f/2R$, where f is the applied force and R is radius of wire). It was difficult to carry out the bonding test well under $P = 1$ ~ 1.5 MPa because of surface roughness due to Ar ion irradiation.

Figure 3 shows a comparison between the experimental half bond width a and the calculated results of half the theoretical adhesional contact width a_j, half the elasto-plastic adhesional contact width a_{ep} and half the plastic contact width a_p.

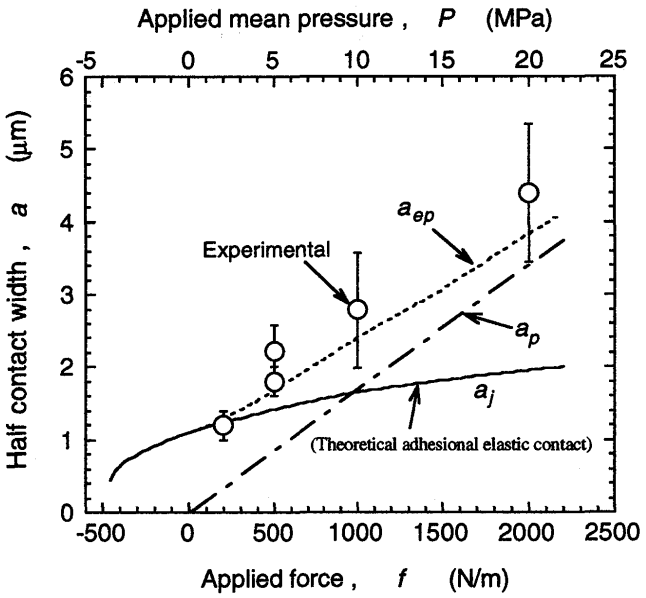

Fig. 3 Comparison between calculated results (a_j , a_{ep} , and a_p) and experimental results (circles) for Au wire (R = 50 μm) - Au foil (thickness of 130 μm). Bonding temperature T = 298 K, Bonding time t_B = 60 s.

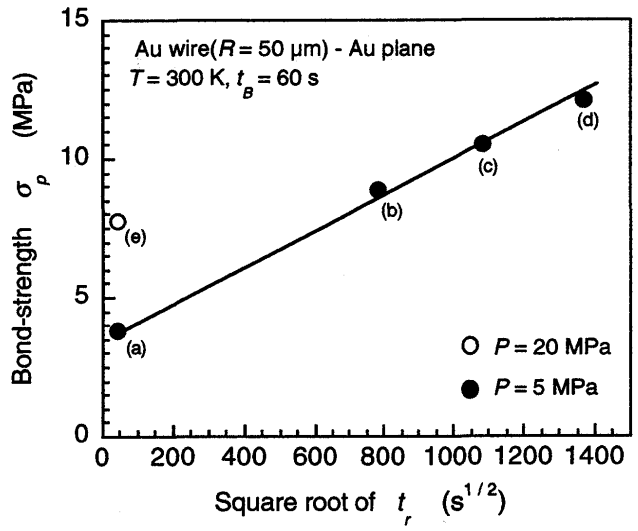

Fig. 4 Change in bond-strength with holding time after bonding. The bond-strength σ_p is obtained by the pull strength Fp divided by the bonded area (Contour area) A_c.

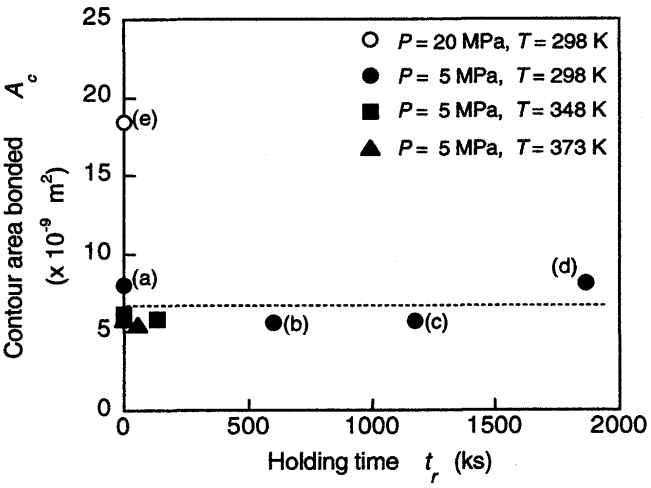

Fig. 5 T/t_r - $1/T$ plots. The holding time t_r is the time taken to obtain F_p = 45 mN. The experimental points (a-e) corresponds to those of Fig. 4.

The experimental half bond width a was estimated from the pressed or dimple mark after the peel (pull) tests. The bond width a is always larger than the value of a_j and is in good agreement with a_{ep} . The ductile separation of the junction was observed for P > 2 MPa. The range of P = 2~ 20 MPa corresponds to the transition region from elastic to plastic contact (elasto-plastic contact), and P > 20 MPa represents the fully plastic contact region.

The adhesional bond strength gradually increases with the holding time after bonding [4-6]. This phenomena was observed in the present study. **Figure 4** shows the change in the bond strength per unit bonded area ($\sigma_p = F_p / A_c$, where F_p is the pull strength and A_c is the contour area bonded. The plots of σ_p - $\sqrt{t}$ (or F_p - $\sqrt{t}$) exhibit a linear relationship as seen in **Fig. 4**, which was predicted by the numerical analysis [5, 6]. As shown in **Fig. 5**, the bonded area scarcely increases with the holding time t_r after bonding. Also, the temperature dependence of the change in the bond strength with time was investigated. As a result, the increase in the bond strength becomes striking with increasing the temperature T [6].

Because of the elastic contact, a local residual stress exists at the bonded interface [6,7]. The increase in the bond strength is, therefore, due to the stress relaxation on the bond interface [4, 6, 7]. The stress relaxation can be produced by stress induced vacancy diffusion. The volume self-diffusion can be ignored, because of low temperatures (T = 298 ~ 373 K) and the vacancy diffusion along the bonded interface can govern the stress relaxation process [8].

According to ref. [6, 7], the holding time t_r required to obtain certain increase in the bond strength can be examined by the plots of T/t_r - $1/T$, i.e., T/t_r is proportional to D_{bo} exp ($-Q_b$ /RT) if the increase in the bond-strength is governed by the interface (grain boundary) self-diffusion, where D_{bo} is the frequency factor of grain boundary self-diffusion, Q_b is the activation energy for the grain boundary (bond-interface) self-diffusion, and R is the gas constant.

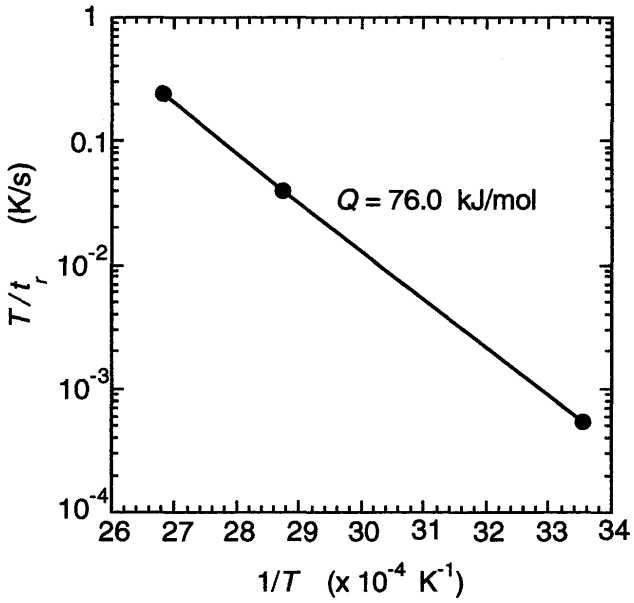

Fig. 6 T/t_r - $1/T$ plots. The holding time t_r is the time taken to obtain F_p = 45 mN.

Figure 6 shows such plots of T/t_r - $1/T$. The activation energy Q is obtained by the slope. The value of Q is 76.0 kJ/mol which is somewhat less than that of the grain boundary self-diffusion of Au (87 kJ/mol). This suggests that stress relaxation by interface self-diffusion increases the bond strength. The activation energy of vacancy diffusion consists of Q_f and Q_m, where Q_f is the formation energy of vacancy and Q_m is the migration energy [8]. The reason why Q is somewhat less than Q_b is that the increase in vacancy concentration around the gold surface due to Ar ion irradiation causes a decrease in Q_f. Even if the vacancy concentration does not increase, the value of Q_f can decrese when a lot of edge-dislocations exist (or are generated) and the compressive stress remains [9, 10].

4. Conclusion

The contacting or bonding behavior in the surface activated adhesional bonding of gold wires to metal substrates has been discussed. The experimental bonded width is in good agreement with the elasto-plastic adhesional bonded width (calculated results). The fracture (bond) strength increases with the holding time after bonding. It is suggested that the stress relaxation due to the stress induced diffusion along the bonded interface increases the bond strength with time.

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