

# Roughness Enhanced Au Ball Bonding of Cu Substrates

Narendra J. Noolu, Ivan Lum, and Y. (Norman) Zhou

**Abstract**—Process development studies of Au ball bumping on metallographically polished Cu substrates at ambient temperature were conducted by investigating the effect of process parameters on the ball bond shear force and the extent of bonding. These studies were performed on substrates polished with 0.06- $\mu\text{m}$  or 1- $\mu\text{m}$  abrasive solutions so as to assess the effect of surface roughness on bondability. Response surfaces were generated to illustrate the effects of ultrasonic power, bonding force, and time on bond shear force, and process windows were defined as those parametric combinations that yielded bond shear forces of 25 gf or higher. After dissolving the Cu substrate away, the etched surfaces of the Au bumps were examined for bonded areas. Au–Cu ball bonds of about 65  $\mu\text{m}$  diameter with bond shear force values higher than 25 gf were obtained on 0.06- $\mu\text{m}$  polished substrates, but at an optimum bonding time of 1000 ms. Increase in surface roughness, however, reduced the bonding time considerably, and values as low as 200 ms were sufficient to yield bond shear force values higher than 25 gf on 1.0- $\mu\text{m}$  polished substrates. Bonding on 1.0- $\mu\text{m}$  polished substrates not only reduced the bonding time, but also increased the maximum bond shear force and reduced the localization of bonded areas. These results suggest that a greater number of surface asperities of sufficient height on rougher substrates provide more bonding sites and hence improve the bondability.

**Index Terms**—Au wire, Cu substrates.

## I. INTRODUCTION

COPPER has emerged as a superior material to replace Al not only for microelectronic interconnects but also for ball bond pads. The main advantages of Cu over Al are its lower electrical resistance, higher electromigration resistance and possibly lower processing cost [1]–[3]. Although replacement of Al interconnects is well-underway, the replacement of Al bond pads with Cu is constrained by difficulties with thermosonic ball bonding of Au wire to Cu pads. Most of the studies [4]–[11] attributed this poor bondability to the inherent presence of Cu oxides. Kajiwara *et al.* [4] ion bombarded Cu films and reported improvement of ball bondability of Au wire. Kajiwara *et al.* [5] also reported that the bondability deteriorated in Ar shielding

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gas shroud mixed with moisture, acetone or oxygen, and attributed the loss of bondability to the growth of oxide film. In addition, Batra [6] electropolished Cu substrates to accomplish thermosonic Au ball bonding in a shielding gas envelope and observed degradation of bondability with the buildup of oxide at higher substrate temperatures. Ueno [7] deposited Ti thin films on Cu pads and apparently improved the ball bondability. Similarly, Tran *et al.* [8], Lee *et al.* [9], and Hotchkiss *et al.* [10] deposited Al over Cu bond pads to facilitate thermosonic wire bonding. A barrier layer was used between Al and Cu films in these studies to retard the interdiffusion reactions. Although Harman *et al.* [11] suggested the application of organic solderability preservatives (OSPs) as a possible alternative, it was also mentioned that the deposition solutions used may damage the wafer. Deposition of thin inorganic films represents another methodology to protect Cu films from oxidation. It was suggested that the thin, hard, and brittle inorganic film would breakup and shear away during wire bonding, thereby facilitating metallurgical bonding [11].

The present study focuses on the development of Au ball bonding on Cu substrates at ambient temperatures as a function of surface roughness and is intended to serve as a knowledge source to successfully develop ball bonding of Cu pads.

## II. BACKGROUND

Although most of the studies to improve ball bondability of Cu films have relied on the removal of Cu oxide prior to bonding, high power (in the order of kW) ultrasonic welding of bare Cu substrates was successfully achieved by Mohamed *et al.* [12]. Based on electron microscopy observations of the dislocation structures, Batra [6] concluded that deformation of the substrate surface is key to Au–Cu ball bond formation. Krzanowski *et al.* [13] reported that the wedge bond strength on stainless steel substrates was maximum at a surface roughness of 3  $\mu\text{m}$ . Studies on bulk substrates suggest that factors beyond the formation of oxides, such as roughness, thickness, and hardness, may also play a significant role in ball bondability of Cu.

Despite successful attempts of ball bonding of electropolished Cu substrates in an Ar envelope [6], electropolishing may not be practicable in the microelectronic industry, and in addition, use of Ar increases the cost of manufacturing. Deposition of Al or Ti films on Cu pads also adds a processing step in the packaging process. Successful ball bumping on Cu at ambient temperatures would eliminate the use of Ar shielding and reduce the manufacturing cost. Therefore, studies on the role of other materials variables (roughness, hardness etc.) affecting the ball bondability of Cu are needed to successfully develop Au–Cu ball bonding for electronic packaging.

### III. OBJECTIVES

In order to develop Au ball bonding of Cu substrates, the objectives were as follows:

- 1) develop Au ball bumping procedures at ambient temperatures on 0.06 and 1.0  $\mu\text{m}$  Cu polished substrates;
- 2) qualitatively assess the effect of surface roughness on bondability.

### IV. EXPERIMENTAL METHODS

A 25- $\mu\text{m}$  diameter Au (AFW-AW8) wire was used to ball bump on 1-mm thick oxygen free high conductivity (OFHC) copper substrates. Substrates, instead of thin film bond pads, were selected for this study so as to produce surfaces with desired roughness. The effect of surface roughness was studied by a comparison of the results of 0.06 and 1.0  $\mu\text{m}$  polished substrates. The substrates were metallographically polished with  $\text{Al}_2\text{O}_3$  solutions up to a nominal particle size of 1.0  $\mu\text{m}$  or 0.06  $\mu\text{m}$  to attain the required substrate surface roughness and ball bumping of the Cu substrates was completed within a few days after polishing. 25  $\times$  25 mm coupons were used to make as many ball bonds as possible for the generation of response surfaces, while 12.5  $\times$  12.5 mm coupons were used for etching studies of bumps with limited parametric combinations.

Au ball bumping was performed on a Kulicke & Soffa 4524D manual ball bonder with the Cu substrate at ambient temperature. Response surfaces were generated starting with the minimum parametric values possible in the bonder and increasing up to values that resulted in severely inconsistent bonding. The minimum values in the ball bonder used for bonding force and power were 30 gf and 0.07 W, respectively. The ball bonds were evaluated quantitatively by shear testing on a DAGE 4000 shear tester at a tool height of 3  $\mu\text{m}$  and the shear forces reported here are averages of about 10 values.

The extent of bonding was judged qualitatively by examining the Au-Cu interdiffusion zones (IDZs) on the etched surfaces of Au bumps after dissolving the Cu substrate away. To reveal the IDZs, bumped Cu substrates were dissolved in 50%  $\text{HNO}_3$  solution leaving the bumps embedded in a cold mount. The growth of the IDZs between a Au bump and the Cu substrate was minimal in the as-bonded condition and difficult to be identified in scanning electron microscope (SEM) images. Therefore, the ball bumped substrates were thermally exposed for 5 h at 200  $^\circ\text{C}$  prior to dissolving the Cu substrate, and the etched surfaces of the bumps were then examined in a LEO field emission scanning electron microscope (FESEM). The presence of Cu in the IDZs on the bonded surface of the Au bumps was quantitatively analyzed by energy dispersive spectroscopy (EDS). The extent of bonding was assessed by qualitative examination of the uniformity and the growth of the IDZs.

### V. RESULTS AND DISCUSSION

#### A. Studies on 0.06- $\mu\text{m}$ Polished Substrate

1) *Response Surfaces:* Response surfaces developed for Au ball bumping on 0.06- $\mu\text{m}$  substrates at ambient temperatures are shown at the bonding times of 200, 600, and 1000 ms in Fig. 1(a), (b), and (c), respectively. The process window for each

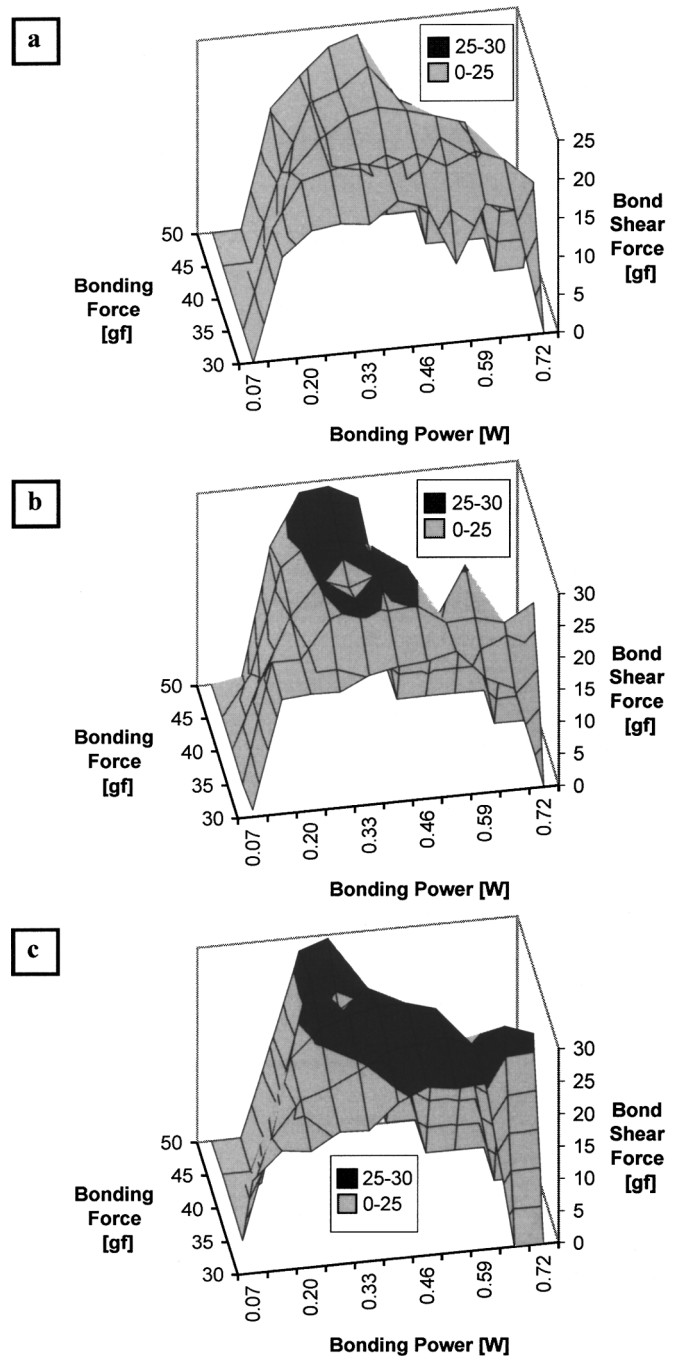


Fig. 1. Response surfaces developed on 0.06- $\mu\text{m}$  polished substrates at bonding times of (a) 200, (b) 600, and (c) 1000 ms. Process windows are shown in regions of dark contrast.

response surface is defined as those parametric combinations that yield a bond shear force of 25 gf or higher and are shown accordingly in Fig. 1. Irrespective of the bonding force and power values, it can be observed that a bonding time of 200 ms was insufficient to achieve bond shear force values higher than 25 gf. However, an increase of bonding time to 600 ms was adequate to yield bond shear forces higher than 25 gf. With increasing bonding time the process window enlarged and reached a maximum size at 1000 ms. Batra's [6] studies of Au bumping on electropolished Cu substrates showed that a lower temperature results in a smaller process window. From the present study, it

TABLE I  
LOW, OPTIMUM, AND HIGH BONDING PARAMETERS  
ON 0.06- $\mu\text{m}$  POLISHED SUBSTRATE

	Optimum Values	Low, Excessive Values
Power	0.33 W	0.13, 0.59 W
Force	35 g	30, 50 g
Time	1000 ms	200, 600 ms (low)

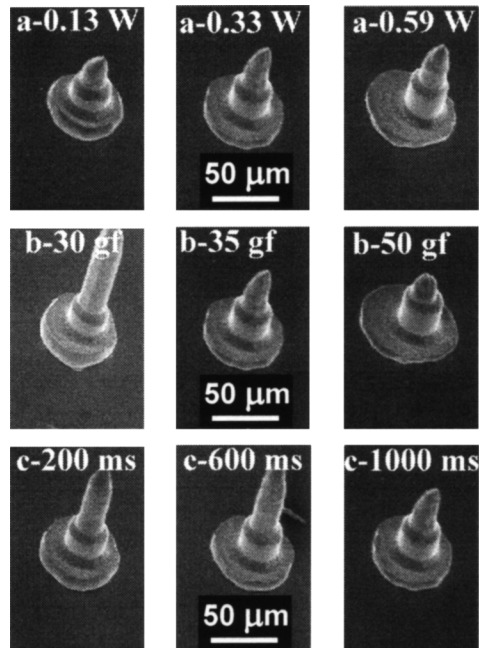


Fig. 2. Morphology of Au bumps on 0.06- $\mu\text{m}$  polished substrate as a function of (a) power, (b) force and, (c) time.

is evident that an increase in bonding time enlarges the process window and it is quite possible that a reduction in the bonding temperature can be adequately compensated by an increase in bonding time. In comparison to the typical thermosonic bonding times of 10 ms for Au–Al ball bonding [14], the bonding time required to yield bond shear force values higher than 25 gf on 0.06  $\mu\text{m}$  polished Cu substrates, however is much higher.

The application of minimum ultrasonic power (0.07 W) resulted only in mere deformation of the free-air-ball without any observable bonding. At this power, the bumps lifted-off from the substrate at the end of the bonding cycle, and a shear force value of zero was reported on the response surface for parametric combinations that produced lift-offs. Further increase of ultrasonic power, however, initiated bonding between the Au bump and the Cu substrate. As can be observed in the response surfaces (Fig. 1), the bond shear force increased with ultrasonic power, reached a peak at a certain value and gradually decreased when ultrasonic power was further increased. The power values that resulted in the highest shear force varied with bonding force, and also varied to a lesser extent with bonding time. Although bonding force also influenced shear force, the variation in bond shear force with bonding force was not as pronounced as that of power.

Peak shear force values, stability of the process window, and a reasonable morphology of the ball bumps, were taken as the cri-

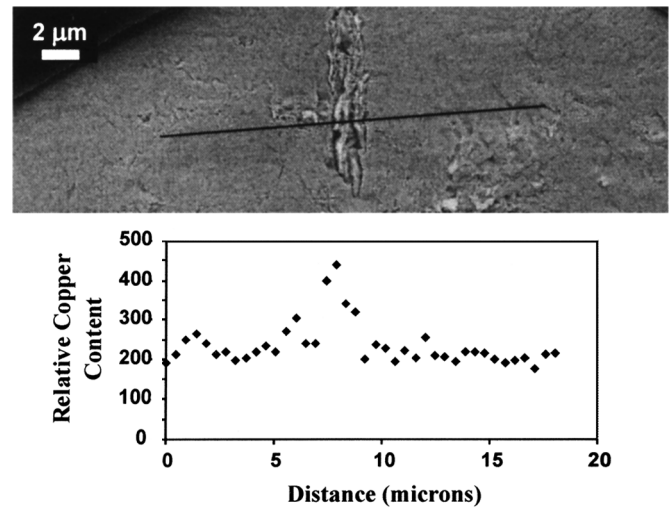


Fig. 3. EDAX line scan on the etched Au bump surface showing the presence of Cu across the bonded areas.

teria to select low, optimum and high parametric values and are listed for 0.06- $\mu\text{m}$  polished substrate in Table I. Fig. 2 shows the morphological changes in the ball bumps at low, optimum, and excessive values of each parameter. Although the bumps were of proper morphology at low values of each parameter, they did not develop the minimum required shear force. The optimum values of each parameter were selected based on those that limit excessive deformation of the bump while generating bond shear force values higher than 25 gf. Furthermore, excessive values of each parameter, as shown in Fig. 2, resulted in massive deformation of the bump, i.e., squashing of the bump periphery and extrusion of most of its volume up into the capillary.

2) *Interdiffusion Zones*: Initial attempts to assess the extent of bonding from the sheared surfaces of bumps did not yield satisfactory correlations, since the chunks of Au left on the substrate may not truly represent the bonded areas. SEM examinations showed that the features of the etched surfaces of the bumps could provide a good method to qualitatively analyze the bonded areas. An EDAX line scan across an IDZ, as shown in Fig. 3, detected Cu in excess of 25 atomic% and these areas were considered as the bonded areas. A comparison of the extent of bonding on sheared and etched surfaces of the same bump is shown in Fig. 4. It is very clear from Fig. 4 that the etched surfaces can reveal the bonded areas much more accurately than the sheared surfaces.

Fig. 5 shows the etched surfaces of Au bumps at low, optimum, and excessive values of each parameter. Fig. 5(a) shows the effect of power on the extent of bonding. At low ultrasonic power (0.13 W), the minimal bonding at the interfaces was sufficient to result in the sticking of the bumps to the substrate. An increase of ultrasonic power resulted in an increase in the extent of bonding. However, within the range of values studied (30–50 gf), an increase in the bonding force did not result in any significant change in the extent of bonding and is shown in Fig. 5(b). From Fig. 5, it is also evident that the application of excessive power or force results in nonbonded regions in the middle of the bond that appear as depressions in the bump. Fig. 5(c) shows that change in bonding time beyond 600 ms,

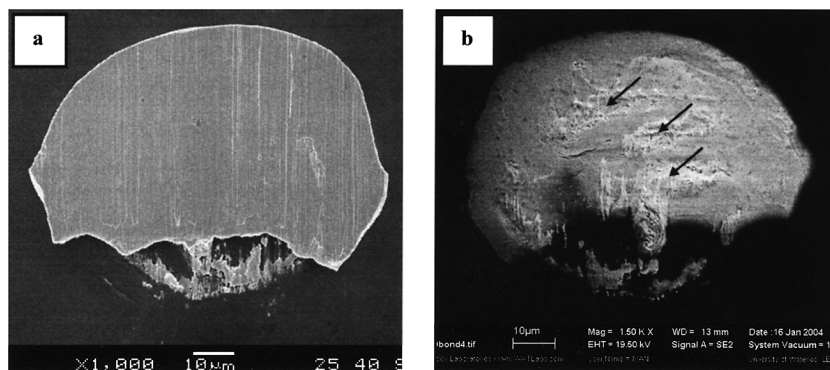


Fig. 4. Extent of bonding shown in (a) sheared and (b) etched surfaces. Arrows show the IDZs.

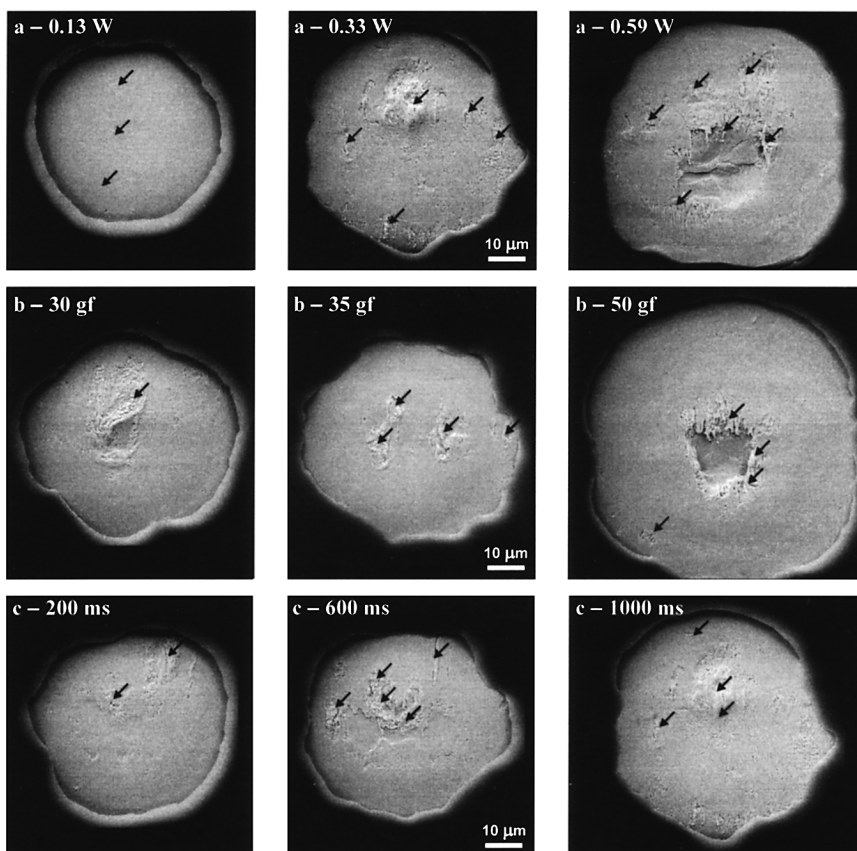


Fig. 5. Etched surfaces of Au bumps on  $0.06\text{-}\mu\text{m}$  polished substrate showing the extent of bonding as a function of bonding parameters: (a) power, (b) force, and (c) time. Arrows show the location of some of the bonded areas.

does not significantly influence the extent of bonding. Amongst the three variables studied, power had the highest influence on the extent of bonding. Although the extent of bonding was not reduced at higher power, excessive deformation of the bump may not be acceptable for fine pitch bonding.

Preliminary results from the present study showed that Au–Cu ball bonds of about  $65\text{-}\mu\text{m}$  diameter with shear force values higher than 25 gf could be obtained on Cu substrates at ambient temperatures. To achieve bonding on  $0.06\text{-}\mu\text{m}$  polished Cu substrates however, excessive bonding times of the order of 1000 ms were required. To reduce the bonding time, the above studies were repeated on  $1.0\text{-}\mu\text{m}$  polished substrates.

### B. Studies on $1.0\text{-}\mu\text{m}$ Polished Substrates

1) *Response Surfaces*: Similar to the studies on  $0.06\text{-}\mu\text{m}$  polished Cu substrates, response surfaces were generated for  $1.0\text{-}\mu\text{m}$  polished substrates. Fig. 6 shows the response surfaces developed for 200, 600, and 1000 ms on  $1.0\text{-}\mu\text{m}$  polished substrate. Similar to the trend on  $0.06\text{-}\mu\text{m}$  polished substrates, the bond shear force reached a maximum value at an optimum power and then decreased with a further increase of ultrasonic power. Within a narrow range of bonding parameter combinations, 200 ms bonding time was sufficient to produce bond shear force values higher than 25 gf. With increase in the bonding time, the process window widened and 25 gf bond

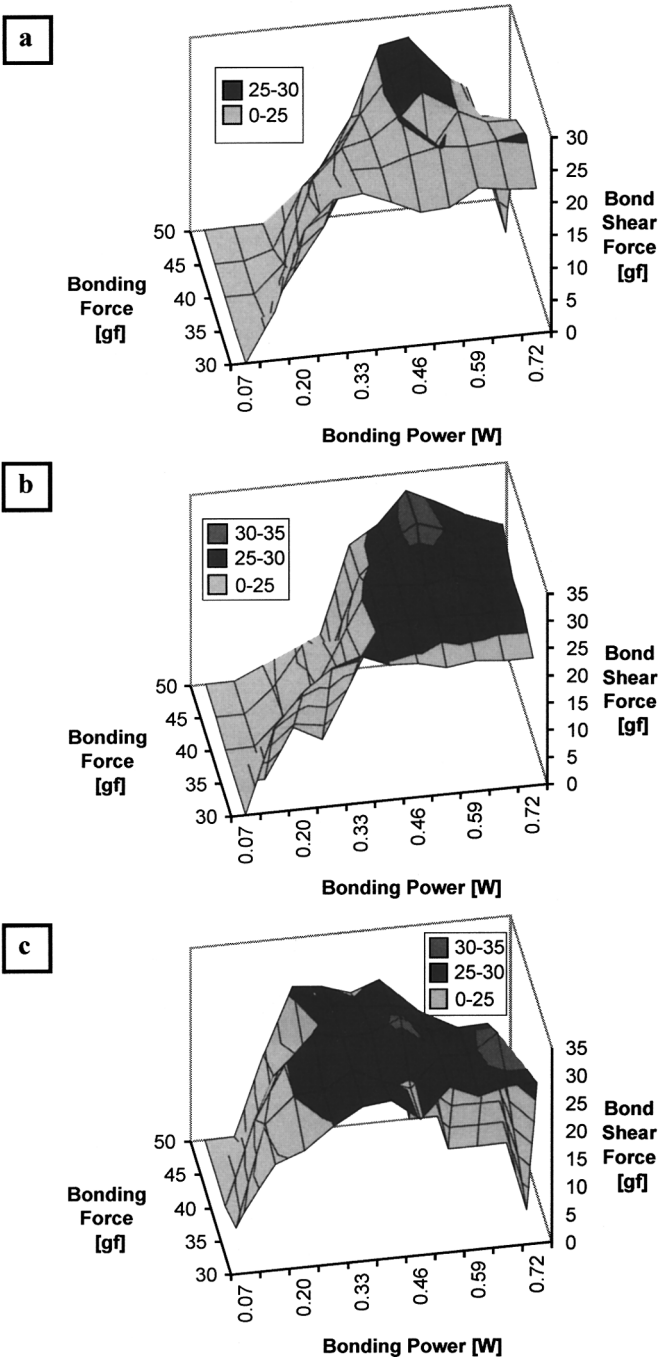


Fig. 6. Response surfaces developed on 1.0- $\mu\text{m}$  polished substrate at bonding times of (a) 200, (b) 600, and (c) 1000 ms.

shear force values were achieved at lower bonding power and force values than at 200 ms bonding time. Based on the same criteria for 0.06- $\mu\text{m}$  polished substrates, the low, optimum, and excessive values for 1.0- $\mu\text{m}$  polished substrate are presented in Table II. Although bond shear force values higher than 25 gf could be achieved on both substrates at the optimum values established for 0.06- $\mu\text{m}$  polished substrates, the optimum values determined with 1.0- $\mu\text{m}$  polished substrates resulted in higher bond shear force values. Comparing the response surfaces of 0.06 and 1.0- $\mu\text{m}$  polished substrates at 200 and 1000 ms, it can be observed that 200 ms was sufficient to achieve the minimum shear force of 25 gf on 1.0- $\mu\text{m}$  polished substrate, which was

TABLE II  
LOW, OPTIMUM, AND HIGH BONDING PARAMETERS  
ON 1.0  $\mu\text{m}$  POLISHED SUBSTRATE

	Optimum Values	Low, Excessive Values
Power	0.45 W	0.13, 0.59 W
Force	40 g	30, 50 g
Time	1000 ms	200, 600 ms (low)

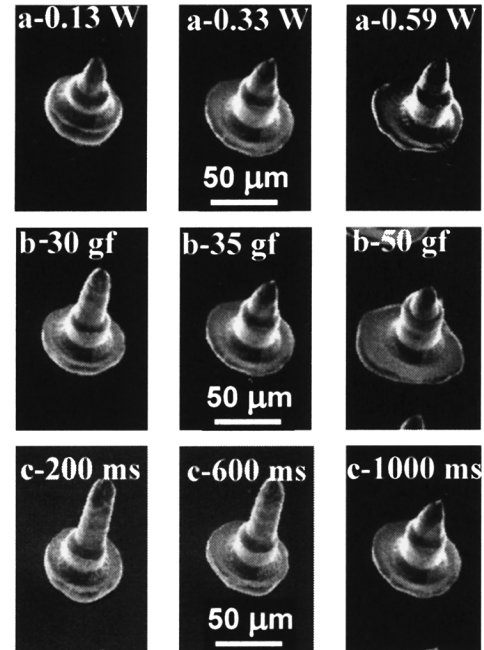


Fig. 7. Morphology of Au bumps on 1.0- $\mu\text{m}$  polished substrate as a function of (a) power, (b) force, and (c) time.

unobtainable on 0.06- $\mu\text{m}$  polished substrates. Fig. 7 shows the morphology of the bumps on 1.0- $\mu\text{m}$  polished substrates using the optimum process parameters established for 0.06- $\mu\text{m}$  polished substrates. Comparing the morphology of bumps on 0.06- and 1.0- $\mu\text{m}$  polished substrates of Figs. 2 and 7, it is evident that rougher surfaces increase the extent of deformation of the bump.

Although bonding on Cu substrates at ambient temperatures takes much longer than on Al substrates, increase in surface roughness drastically reduces the time required to achieve acceptable bond shear force values. At the same bonding time, a higher surface roughness reduces the ultrasonic power required to produce equivalent bond shear forces. Surface roughness not only increases the maximum bond shear force but also enlarges the process window at equivalent bonding times.

2) *Interdiffusion Zones*: Similar to that on 0.06- $\mu\text{m}$  polished substrates, increase of ultrasonic power up to 0.59 W on 1.0- $\mu\text{m}$  polished substrates, as shown in Fig. 8(a), also resulted in an increase in the extent of bonding. Fig. 8(b) shows that bonding force did not have significant influence on the extent of bonding and Fig. 8(c) shows similar behavior as a function of bonding time. Comparison of the etched surfaces of Au bumps of 1.0- $\mu\text{m}$  polished substrates with those of 0.06- $\mu\text{m}$  polished substrates, showed that the extent of bonding was higher and the bonded areas are more uniformly distributed on 1.0- $\mu\text{m}$  substrates. One

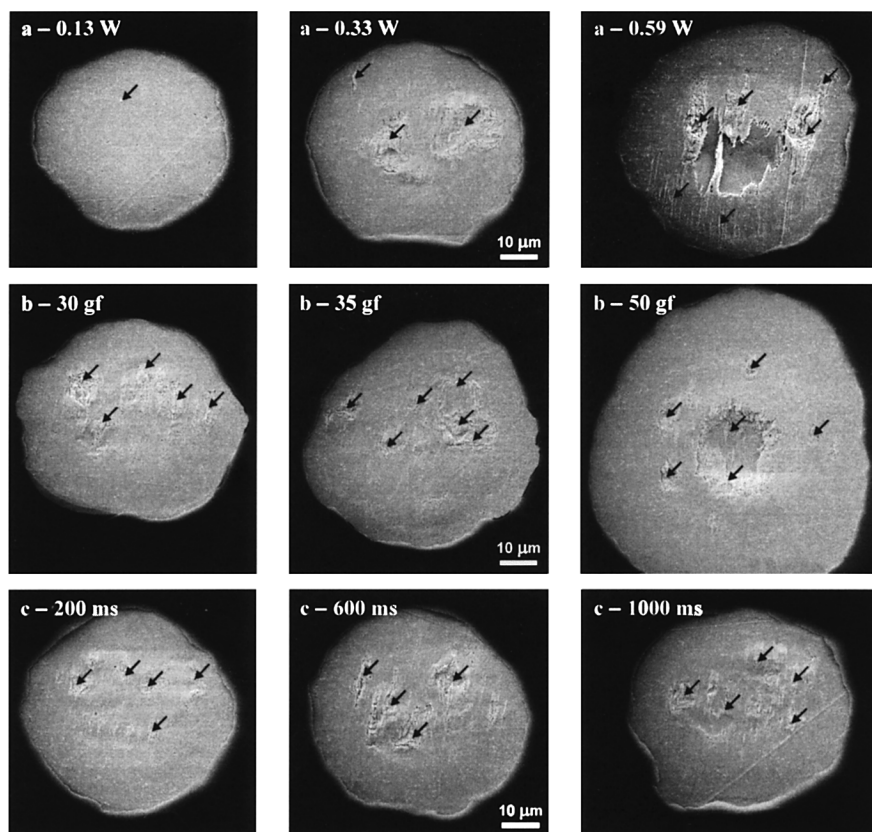


Fig. 8. Etched surfaces of Au bumps on  $1.0\text{-}\mu\text{m}$  polished substrate showing the extent of bonding as a function of bonding parameters: (a) power, (b) force, and (c) time. Arrows show the location of some of the bonded areas.

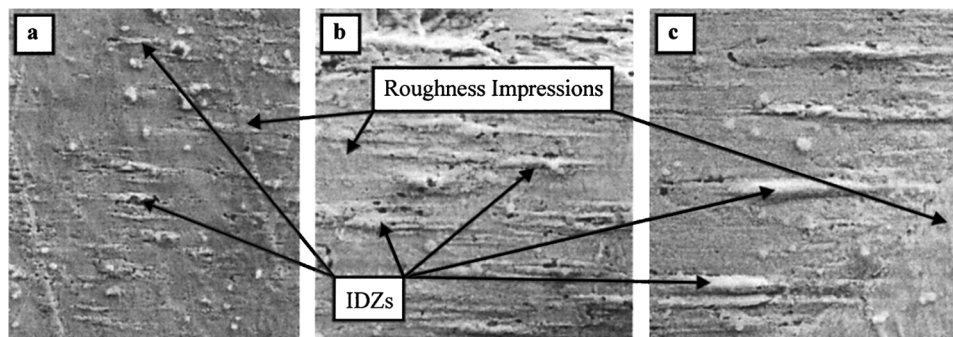


Fig. 9. Comparison of etched surfaces of Au bumps on  $1.0\text{-}\mu\text{m}$  polished substrate at (a) 0.13, (b) 0.33, and (c) 0.59 W showing the difference in the length of the elongated bonded areas.

feature common to these etched surfaces and conspicuous on  $1.0\text{-}\mu\text{m}$  polished substrate is that the bonded areas are elongated in the direction of ultrasonic vibrations. Increases in bonding power, led to corresponding increases in the lengths of bonded areas and a comparison of Fig. 9(a), (b), and (c) at a power of 0.13, 0.33, and 0.59 W, respectively, illustrates this effect. However an increase in bonding force localized the bonded areas and is evident in Fig. 8(b). The length of the bonded areas could be misconstrued to be along the direction of the roughness asperities, but as shown in Fig. 9(a), the impressions left on Au bumps by the roughness asperities were perpendicular to the elongated bonded areas. These observations give credence to the proposed theories [6], [13] that bonding is achieved by relative interfacial movement. The localization of bonded areas on the  $0.06\text{-}\mu\text{m}$  polished substrate [Fig. 5(b)] as well as on the  $1.0\text{-}\mu\text{m}$

polished substrate [Fig. 8(b)] suggests that the application of force higher than the optimum values reduces the effect of ultrasonic power. Although higher surface roughness increases the extent of bonding, variation in bonding force and time seem to have similar effects on the extent of bonding irrespective of the roughness of the substrate.

In Figs. 5 and 8, it is evident that ultrasonic power has the maximum influence on the extent of bonding. The elongated bonded areas suggest that the ultrasonic vibrations in wire bonding cause relative interfacial movements. Murdeshwar *et al.* [13] observed contamination trapped at an asperity well and proposed that rougher surfaces provide a greater number of asperity wells thereby promoting bonding. The increase in the extent of bonding, elongated, and more uniformly bonded areas on  $1.0\text{-}\mu\text{m}$  polished substrates compared to  $0.06\text{-}\mu\text{m}$  polished

substrates shows that the roughness improves bondability. Hence, it is very likely that 1.0- $\mu\text{m}$  polished substrates provide more asperities of sufficient height that act as bonding sites and improve the extent of bonding. Investigations on 0.3- $\mu\text{m}$  polished substrates showed shear force values intermediate between 0.06- and 1.0- $\mu\text{m}$  polished substrates [15], and future studies at higher surface roughness could help to reveal an optimum value of surface roughness for best bondability.

## VI. CONCLUSION

From the present study it is evident that Au bumping on Cu substrates can be achieved at ambient temperatures with ball bond shear forces higher than 25 gf. Based on the response surfaces developed, longer bonding times are required to achieve bond shear force values of 25 gf on 0.06- $\mu\text{m}$  polished substrates. Among the three bonding parameters studied, ultrasonic power had the highest influence on the bond shear force and the extent of bonding. The optimum values of bonding power, force, and time for stable ball bumping on 0.06- $\mu\text{m}$  substrate were 0.33 W, 35 gf, and 1000 ms, respectively. Although a high bonding time of 1000 ms was required for achieving industrial shear forces higher than 25 gf on 0.06- $\mu\text{m}$  polished substrates, the time required to produce equivalent bond shear forces, could be reduced considerably by bonding to 1.0- $\mu\text{m}$  polished substrates. Higher surface roughness not only increased the extent of bonding but also promoted the development of uniformly bonded areas. At equivalent parameters, it appears that higher surface roughness of the substrate provides more number of asperities of sufficient height as bonding sites thereby improving bondability.

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