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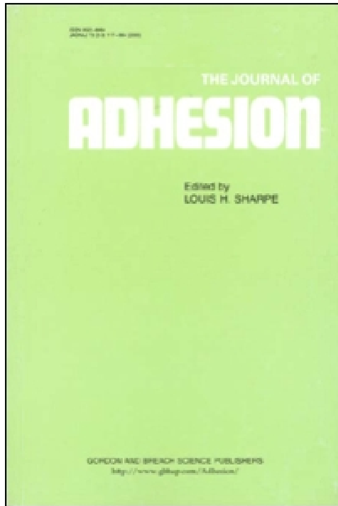

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Ultrasonically-Induced Interfacial Changes

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Ultrasonically-Induced Interfacial Changes*

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The ultrasonic wirebond failure mechanism associated with interfacial changes in a thin-film device was studied. The thin-film device was fabricated on a ferrite substrate and composed of a gold layer on top with titanium, nickel-iron and aluminum oxide underneath. The chemical changes at the nickel-iron/aluminum oxide interface, induced by the transfer of ultrasonic energy through the gold and the titanium layers were investigated by Auger electron spectroscopy. The applied ultrasonic energy promoted preferential migration of iron to the interface resulting in weakening of the bond between the nickel-iron and its adjacent aluminum oxide layer.

KEY WORDS ultrasonic wirebond process; Auger electron spectroscopy; interface; delamination; failure mechanism; iron migration; dissociation of aluminum oxide.

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INTRODUCTION

Ultrasonic wirebonding has always been an important process step used in microelectronic device manufacturing. After the wirebond operation, a large proportion of the microelectronic devices malfunction. Much work has been done to study the cause of wirebond failures. The thermal stress induced in the bond pads by ultrasonic energy has been reported elsewhere.[1] For example, thermal stress occurred when an aluminum wire was bonded to a gold surface at an elevated temperature.[2] The stress developed in the bond pads due to the growth of a gold-aluminum intermetallic created craters within the bond area resulting in bond failures.[3,4] Contamination, impurities or corrosion reactions such as the combined effect of halogens and moisture in the bond pads were other identified failure mechanisms. These latter mechanisms were shown to have lowered the wirebond strength.[5,6,7]

In an ultrasonic wirebonding process, transfer of ultrasonic energy from the wedge of a wirebonder transducer to a wire creates compression and expansion processes in the wire. During the bonding operation, the compressed top part of the wire becomes hot and the expanded lower part remains relatively cold. The induced thermal energy is thus transferred from the hot part to the cold part, melting

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materials in contact with the device. The localized ultrasonic energy is transferred into the materials underneath the bonded pads. The transfer of ultrasonic energy through solid materials not only generates heat but also induces changes in the materials.[8,9]

In this paper, the authors present a wirebond failure mechanism associated with interfacial changes due to the transfer of ultrasonic energy into a thin-film device. Auger electron spectroscopy (AES) was used to analyze the induced chemical changes within the bond pad site. The results led to a model for failure in wirebond pads.

EXPERIMENTAL PROCEDURE

The thin-film system in this study was identical to the one which has been used for fabricating magnetic recording devices throughout the last decade. An aluminum oxide film deposited on ferrite was used as a substrate. A nickel-iron film with 80 wt.% nickel and 20 wt.% iron, and a titanium overcoat, were deposited on this substrate followed by a conductive gold layer (Figure 1a). Aluminum wires were ultrasonically bonded to this gold layer using a wirebonder (K&S model 1470) at specific settings, *i.e.* compression force = 25 grams, ultrasonic power = 10 mwatts and pulse duration of energy = 10 ms. The bond strength was tested by a standard pull test instrument. The aluminum wire broke when the pull strength reached approximately 25 grams. In this instance, however, there was no pad pull-out or delamination. When the energy input of the wirebonder setting was increased to 14 mwatts, bond failures occurred at a pull strength of only 5 grams. This reduction of the bond strength was found to be related to a typical failure which was characterized by local pad pull-out and film delamination. Throughout the rest of the paper the pull-out surface of the pad will be referred to as "the delaminated surface on the pad" and the exposed surface on the substrate will be referred to as "the delaminated surface on the substrate," as illustrated in Figure 1b.

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CONDUCTIVE GOLD LAYER
(1000 nm)

TI (50 nm)

NiFe (100 nm)

Aluminum Oxide (200nm)

FERRITE SUBSTRATE

FIGURE 1a The thin-film device structure showing the order of magnitude of thin film layer thicknesses.

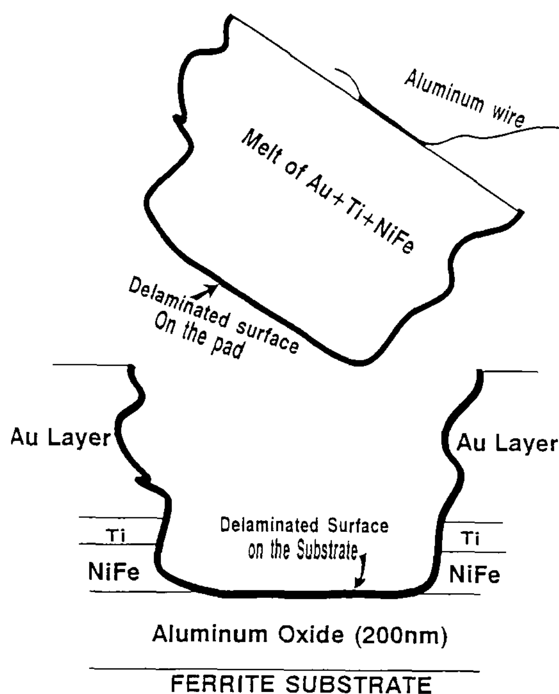

FIGURE 1b A schematic presentation of the pad delamination illustrating the "delaminated surface on the pad" and the "delaminated surface on the substrate," as shown by arrows.

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The depth of the pull-out sites was measured with a profilometer. The measurements indicated that the pad delamination occurred at the nickel-iron/aluminum oxide interface. The delaminated surfaces on the pad and on the substrate were examined by an optical microscope. No cratering-defect pattern was found on the delaminated areas.

AES analysis was carried out with a Perkin-Elmer model 600 Auger electron spectrometer equipped with a single-pass cylindrical mirror analyzer and a sputter gun. General Auger survey spectra were collected from the delaminated surfaces on the pad and on the substrate. The chemical composition of a surface was semi-quantitatively calculated from the relative Auger elemental peak intensities which were corrected for sensitivity factors.[10] The nickel-iron/aluminum oxide interface on an area adjacent to a delaminated location was reached by *in-situ* sputter-etching of the area in the Auger chamber. The sputter time for the required depth was determined by the known etch rates for gold, titanium and nickel-iron alloy under the specified sputter gun settings. The depth in the sputtered area was measured by profilometry for confirmation. The chemical composition of this surface at this location was then determined by the general Auger survey analysis.

The changes induced by the application of ultrasonic energy in the thin-film device were investigated by an ultrasonic wirebonding test performed on a bare gold surface of a device having no aluminum wire. One test was performed under the same settings used for the real bonding process. In this case, the gold surface was found

to have undergone a noticeable color change and limited physical damage, such as partial delamination, at the site where energy was applied. This area, as well as the nickel-iron/aluminum oxide interface underneath it, were analyzed by AES using the procedure described above. Another wirebonding test was performed at a lower energy than that used for the real bonding process except for the compression force and the duration, *i.e.* compression force = 15 grams, ultrasonic energy = 8 mwatts and pulse duration of energy = 30 ms. Under these conditions, there was no visible change or serious damage at the site where energy was applied. The Auger depth-profile analysis was then performed on this sample at the sites where the ultrasonic energy was applied and the sites where there was no ultrasonic application.

RESULTS

The delaminated surface on the pad was composed of nickel, iron, titanium and oxygen with a small amount of carbon, as shown in the Auger survey spectrum of Figure 2a. The relative Auger intensity ratio of Fe : Ni was much less than 1 and was estimated to be 20 wt.% iron and 80 wt.% nickel, which was identical to that of the nickel-iron film composition. The delaminated surface on the substrate was composed of aluminum, titanium, nickel, iron and oxygen with a small amount of carbon, as shown in Figure 2b. The iron content of this surface was greater than

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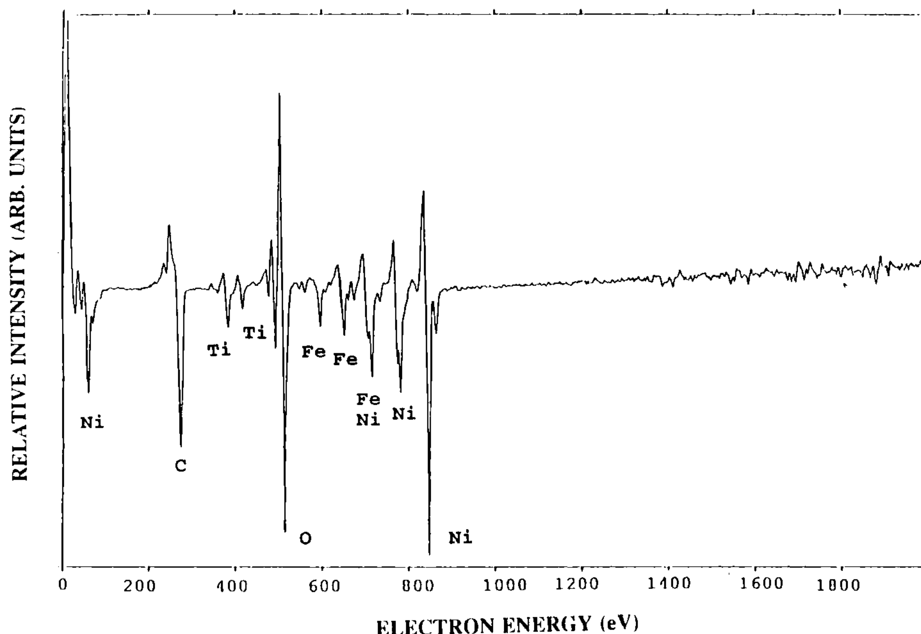

FIGURE 2a Auger survey spectrum from the delaminated surface on the pad showing the surface was composed of nickel, iron, titanium and oxygen with some carbon. The iron content of this surface was less than nickel. The surface did not contain any aluminum.

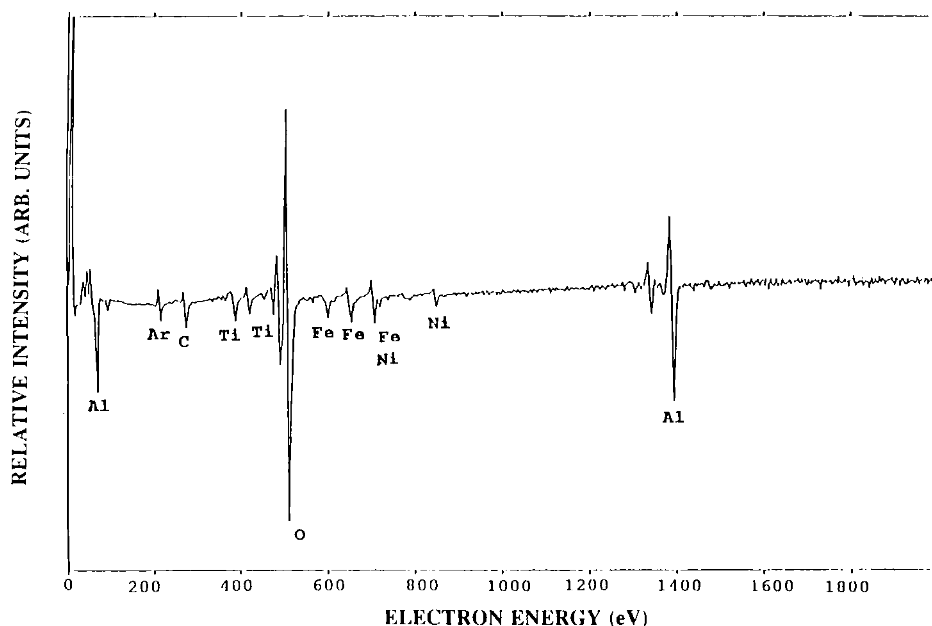

FIGURE 2b Auger survey spectrum from the delaminated surface on the substrate showing the surface was composed of aluminum, titanium, nickel, iron and oxygen with a small amount of carbon. The iron content at this interface was enriched since the relative Auger peak intensity ratio of Fe:Ni was greater than 1.

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that shown in Figure 2a. *In-situ* sputter-etching of this delaminated surface on the substrate indicated that the iron-rich film thickness was approximately 40Å.

Figure 3 is the Auger general survey spectrum from the nickel-iron/aluminum oxide interface on an area adjacent to a delaminated site. The surface was composed of nickel, iron, aluminum and oxygen. No titanium or any other contaminants were identified on this surface. The relative Auger intensity ratio of Fe:Ni was much less than 1 where the concentration ratio of iron to nickel was estimated to be identical to that of the nickel-iron film (i.e. 20:80 wt.%). No iron enrichment was found at this location.

The surface exposed to an ultrasonic bonding operation at the same settings as used for the real bonding process was composed of gold, titanium, nickel, iron and oxygen, as shown in Figure 4a. The nickel-iron/aluminum oxide interface underneath this surface was composed of a mixture of aluminum, gold, titanium, nickel, iron and oxygen, as shown in Figure 4b. The iron content at this interface was high.

Figures 5a and 5b show the depth profiles at the site where ultrasonic energy was not applied and at the site where the ultrasonic energy was applied at lower settings, respectively. After *in-situ* sputtering of the sample for 55 minutes, the concentration depth profiles showed the presence of titanium in the nickel-iron region only at the site where the ultrasonic energy was applied. This is shown in Figure 5b, indicating that the titanium diffusion into the nickel-iron film was induced by the application of the ultrasonic energy. The nickel-iron/aluminum oxide interface

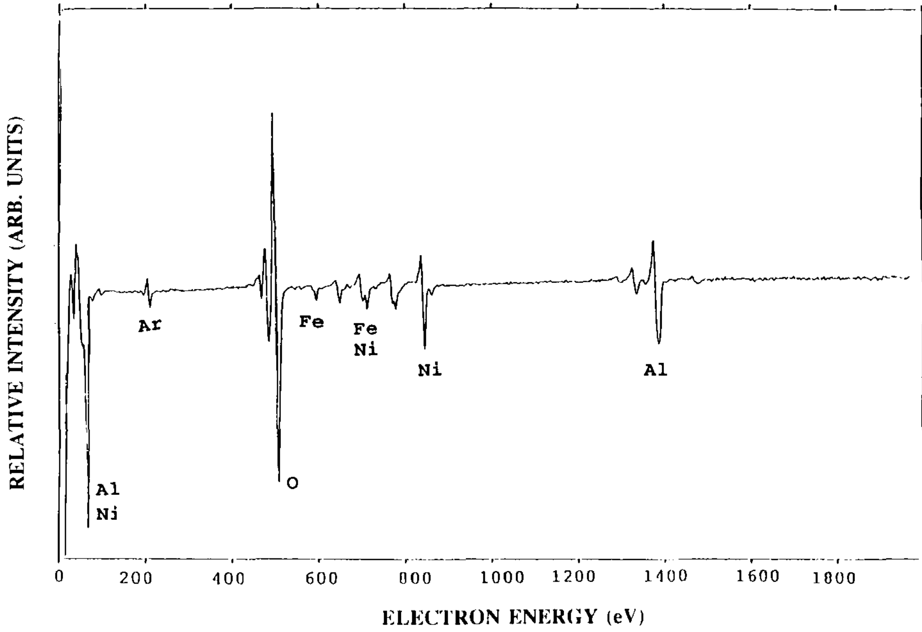

FIGURE 3 Auger survey spectrum from the nickel-iron/aluminum oxide interface on an area adjacent to a delaminated site. The surface was composed of nickel, iron, aluminum and oxygen. No titanium or any other contaminants were identified on this surface. The relative Auger peak intensity ratio of Fe:Ni was less than 1.

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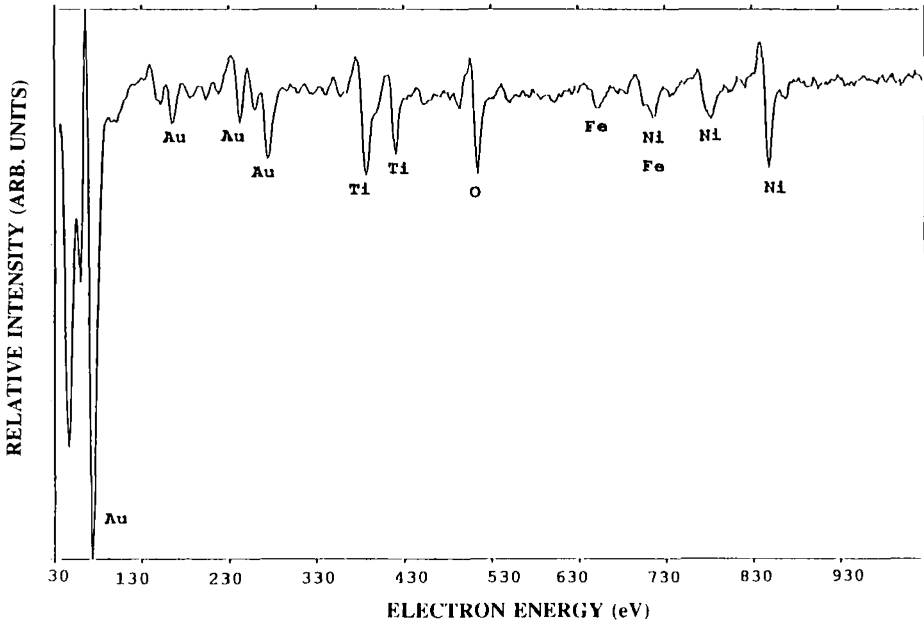

FIGURE 4a Auger survey spectrum from the site treated with ultrasonic energy having the same wirebonder settings as used for the real bonding process. The surface was composed of gold, titanium, nickel, iron and oxygen.

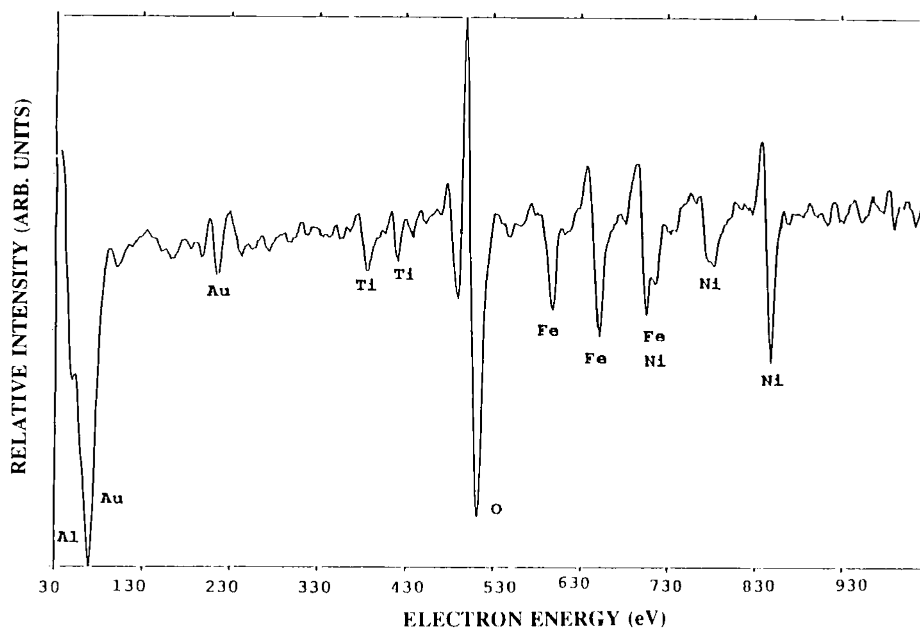

FIGURE 4b Auger survey spectrum from the nickel-iron/aluminum oxide interface of the test site as described in Figure 4a. The surface was composed of a mixture of aluminum, gold, titanium, nickel, iron and oxygen. The iron content at this interface was high, with the Auger peak intensity ratio of Fe:Ni at ≈1.

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boundaries could be referenced by the variations of the aluminum intensity. This boundary started at 84 minutes sputter time for the untreated site, whereas it started at 70 minutes sputter time for the treated site. The relative Auger iron signal and the nickel signal decreased within the interface region for the treated site. However, in Figure 5b the ratio of the Auger signal of iron to nickel increased within this region. In order to intensify the variation in the iron concentration across the nickel-iron/aluminum oxide interface, the intensity of the Auger iron signal relative to that of the nickel was calculated by the ratio of the square of the iron intensity to the nickel intensity, *i.e.* $I_{Fe}*I_{Fe}/I_{Ni}$.

Based on the data in Figures 5a and 5b, the relative intensity of the Auger iron signal to nickel and the intensity of the Auger aluminum signal were plotted in Figures 6a and 6b. Comparison of Figure 6a with Figure 6b shows that the Auger iron signal remained higher and wider within the interface for the treated site.

DISCUSSION

AES analysis revealed that the aluminum was present on the delaminated surface on the substrate but not on the delaminated surface on the pad. This result was consistent with the result obtained from the profilometric measurement, *i.e.* that

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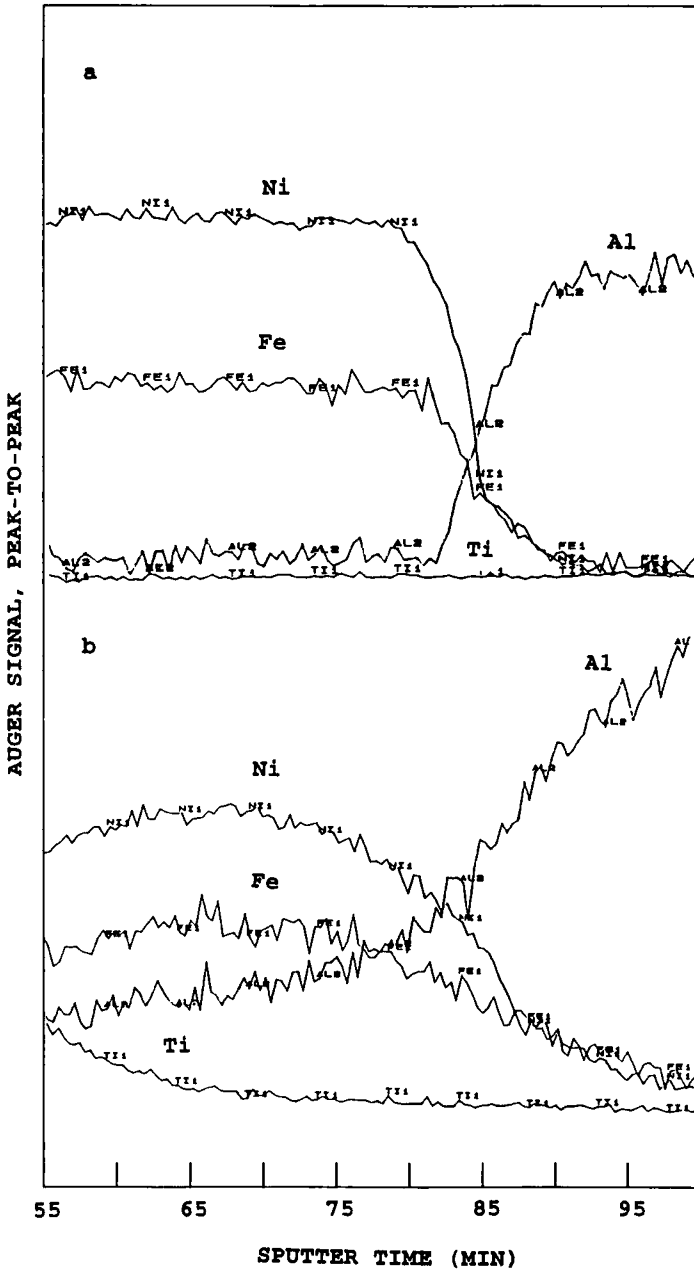

FIGURE 5 (a) Auger depth profile from the site with no ultrasonic application. Note that there was no titanium detected at the sputter time of 55 minutes. The Auger aluminum signal was detected at the sputter time of 84 minutes. (b) Auger depth profile from the site where the low energy ultrasonic was applied for a longer duration. The Auger titanium signal was identified at the sputter time of 55 minutes. The appearance of the Auger aluminum signal at 70 minutes sputter time indicated an interdiffusion between the nickel-iron film and the adjacent aluminum oxide film took place.

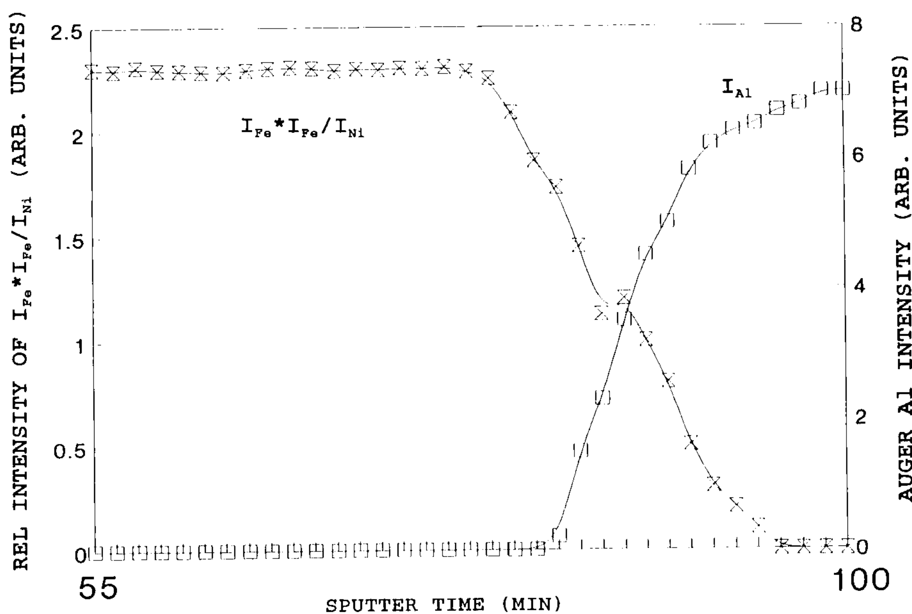

FIGURE 6a The intensity of the Auger iron signal relative to that of the nickel, and the aluminum signal at the site where ultrasonic energy was not applied. Note that there was a speedy rate of decrease of the relative iron signal within the nickel-iron/aluminum oxide interface.

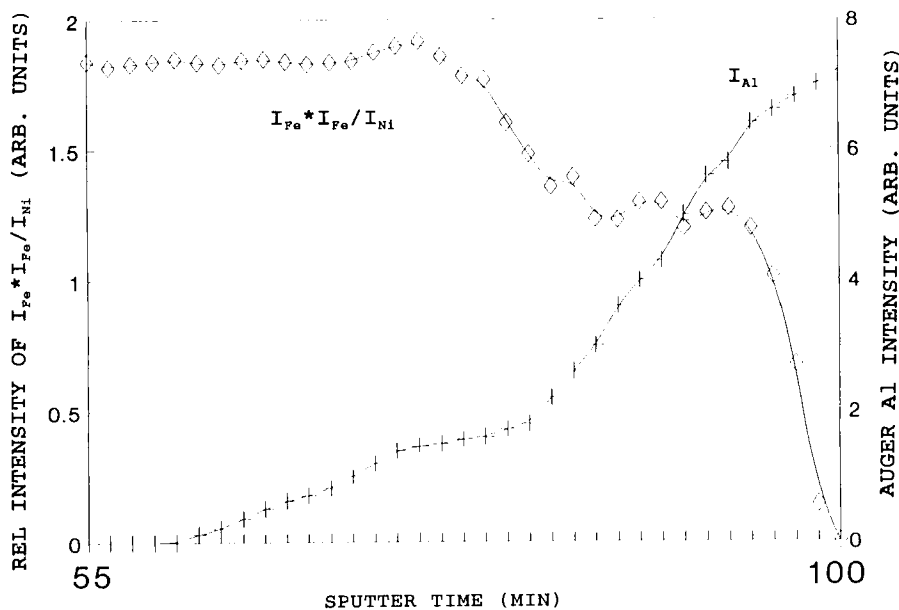

FIGURE 6b The intensity of the Auger iron signal relative to that of the nickel, and the aluminum signal at the site where ultrasonic energy was applied at lower settings for a longer duration. Note that there was a very slow rate of decrease of the relative iron signal within the nickel-iron/aluminum oxide interface, indicating preferential iron migration toward the interface.

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the pad delamination took place at the nickel-iron/aluminum oxide interface. The presence of a small amount of carbon of approximately 50–60Å thickness at the delaminated interface was due to the exposure of the interface to the atmosphere during pull-out. No other impurities were identified on the delaminated surface. The nickel-iron/aluminum oxide interface of the area adjacent to the delaminated location did not contain carbon or any other impurities.

The simulated ultrasonic test site surface was composed of gold, titanium, nickel, iron and oxygen. The presence of all of these elements on the surface indicated that the localized heat induced by the application of ultrasonic energy melted the gold layer as well as the underlying titanium and nickel-iron layers. This melting created a mixture of all of these elements. The iron content at the nickel-iron/aluminum oxide interface on this test site was enriched to such an extent that it was approximately equal to that observed on the delaminated surface on the substrate. It was apparent that the applied ultrasonic energy produced an increased iron content at the nickel-iron/aluminum oxide interface.

In the ultrasonic wirebonding process during the device manufacturing, heat was conducted to the gold and to the underlying titanium layer through the aluminum wire. A portion of this heat was transferred deep inside the underlying layers and increased the local temperature. The high energy promoted melting of local materials and induced diffusion between layers. The appearance of titanium at the nickel-iron/aluminum oxide interface at the ultrasonic test site, as well as on the delaminated surfaces on the substrate and on the pad, was as a result of a diffusion mechanism induced by the heat generated by the application of ultrasonic energy. The local temperature was expected to be greater than 250°C as it was reported that the titanium diffused into the nickel-iron film at this temperature.[11]

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The ultrasonic energy transferred from the transducer to the underlying aluminum oxide surface through the metal layers induced chemical changes in the aluminum oxide. It was reported[12] that aluminum oxide could be dissociated by ultrasonic energy. This dissociation results in the formation of reactive oxygen in the aluminum oxide. When the energy input of the ultrasonic wirebonding was slightly increased, the transfer of excessive energy to the aluminum oxide layer during the bonding process produced chemically-reactive oxygen. Iron has a greater affinity for oxygen to form iron oxide, ($\Delta H_{298}(FeO) = -63.2 \pm 0.3$ kcal/mole) than nickel to form nickel oxide, ($\Delta H_{298}(NiO) = -57.5 \pm 0.5$ kcal/mole). It was, therefore, expected that iron would preferentially migrate from the nickel-iron film toward the nickel-iron/aluminum oxide interface due to chemically-induced surface segregation.[13] Results obtained from the site where a low ultrasonic energy was applied for a longer duration showed that the Auger iron signal remained higher and wider within the interface, confirming the effects due to this chemically-induced surface segregation. In this study a wider diffusion layer was observed at the interface ($\approx$120Å). This widening was undoubtedly due to the application of the low energy ultrasonic pulse (8 mwatts) for a longer duration of time ($\approx$30ms).

The iron that migrated to the interface reacted with the available oxygen and formed iron oxide. Since both aluminum oxide and iron oxide were present at the nickel-iron/aluminum oxide interface, it was not possible to identify the chemical state of iron by using a surface analytical method. X-ray Photoelectron Spectros-

copy (XPS) analysis is an effective method to identify the chemical state. In order to reach the interface sputter-etch was required. Due to the preferential sputtering of oxygen in an oxide material and the complexity of the XPS iron spectrum, it was not possible to characterize the chemical state of iron at the interface. *In-situ* sputter-etching of the delaminated surface on the substrate in the AES chamber indicated that the iron signal persisted for a depth of approximately 40Å. From this study it was suggested that the iron oxide layer thickness at the interface was approximately 40Å under the conditions used for the real bonding process.

CONCLUSIONS

An ultrasonic wirebonding process required an optimum amount of energy transfer from the wedge of a wirebonder transducer to an aluminum wire to bond successfully to a gold layer. If there was an excessive energy transfer, it stimulated the dissociation of the aluminum oxide layer, producing reactive oxygen. The mechanism also promoted preferential iron migration from the nickel-iron film to the nickel-iron/aluminum oxide interface. The free oxygen then formed oxidic iron. The formation of iron oxide at the interface increased the volume of the space occupied by iron and induced local stresses, which ultimately lowered the bond strength at the local area and caused pad delamination. This oxide formation created localized stresses and weakened the adhesion between the nickel-iron film and the adjacent aluminum oxide film, causing interfacial delamination.

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References

1. J. M. Barsom and S. T. Rolfe, *Fracture and Fatigue Control in Structure,* 2nd ed. (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1987).
2. G. G. Harman, *Wire Bonding in Microelectronics* (International Society for Hybrid Microelectronics, 1991).
3. M. Kashiwabara, S. Hattori, *Review of the Electrical Communication Laboratory* **17,** 1001 (1969).
4. W. Gerling, 34th Proc. IEEE Electronic Components Conference, New Orleans, Louisiana, USA, May 14–16, 1984, p. 13.
5. H. K. Charles, B. M. Romenesko, G. D. Wagner, R. C. Benson and O. M. Uy, 20th Annual Proc. Reliability Physics Symposium, San Diego, CA, March 30–31, 1982, p. 128.
6. J. F. Graves and W. Gurany, 32nd Proc. IEEE Electronic Components Conference, San Diego, CA, May 10–12, 1982, p. 266.
7. J. K. Nesheim, Proc. 1984 Intl. Symposium on Microelectronics (ISHM), Dallas, Texas, Sept. 17–19, 1984, p. 70.
8. K. S. Suslick, *Science* **247,** 1439 (1990).
9. K. S. Suslick, *Adv. Organomet. Chem.* **25,** 73 (1986).
10. D. B. Briggs and M. P. Seah, *Practical Surface Analysis,* 2nd ed. (John Wiley & Sons, New York, 1988).
11. M. Kitada, *Thin Solid Films* **131,** 21 (1985).
12. R. Roy, D. Agrawal and V. Srikanth, *J. Mater. Res.* **6,** 2412 (1991).
13. D. Tömnek, S. Mukherjee, V. Kumar and Kitt Bennemann, *Surface Sci.* **114,** 11 (1982).