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DEVELOPMENT OF A MODEL FOR THE ULTRASONIC WIRE BOND USED IN MIC--ETC(U)
SEP 76 N00163-76-C-0171

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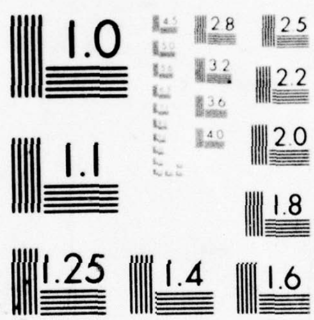

MICROCOPY RESOLUTION TEST CHART
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Development of a Model for the Ultrasonic Wire Bond Used in Microcircuit Fabrication.

1 Sep[redacted] 1976

16p.

Receiving Officer
Naval Avionics Facility
21st Street and Arlington Avenue
Indianapolis, IN 46218

Dear Sir:

This letter is the final report on contract N00163-76-C-0171 and covers the period Feb. 16, 1976 through Aug. 16, 1976. The work reported was done in the Drexel Graduate Microelectronics Laboratory under the supervision of Professor T.J. Matcovich. A graduate student, Mr. Robert Krawchuck, has been working full-time and a second graduate student, Mr. Mike Gale has been working part-time on this contract.

The objective of this program is to develop a model for the ultrasonic wire bond used in microcircuit fabrication. This program is a continuation of the work started under contract N00163-75-0029. Development of a suitable model could lead to methods for fabricating more reliable and stronger wire bonds.

A model for the ultrasonic bonding of bulk materials was developed by Frisch and Chang*. This model has been modified to make it more consistent with the data obtained under contract N00103-75-0029 on the microcircuit bond. The data reported herein suggests that the modified model is generally consistant with the observations of the microcircuit bond but that additional modifications may be required.

The primary objective of this contract has been to develop and improve the experimental techniques needed to evaluate the microcircuit bond model. To this end an alternate technique has been developed for separating the bond so that the interface can be examined; techniques and equipment for fabricating substrates have been improved; methods for measuring substrate properties have been developed; techniques for making several thousands of bonds to each substrate have been developed and methods for controlling ball size and shape have been developed.

The techniques and equipments required for a full scale study of the microcircuit bond model are now available. The initial results indicate that the bond model is reasonably consistant with the test results. A full scale study of the bond model is recommended.

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BOND MODEL

The basic mechanism by which ultrasonic welds are produced is believed to be solid-state bonding.[1-7] Solid-state bonding requires that surface atoms of one metal be placed within the atomic bonding force field of the surface atoms of the other metal. To accomplish this, surface irregularities and contaminants must be removed or displaced from the bonding area. A model for the ultrasonic bonding of bulk materials has been developed by Frisch and Chang.[1] This model was modified, on the basis of work done under contract N00163-75-C-0029, to adapt it to microcircuit bonding. The modified model predicts that bonding will occur in an annular area as shown in Figure 1.

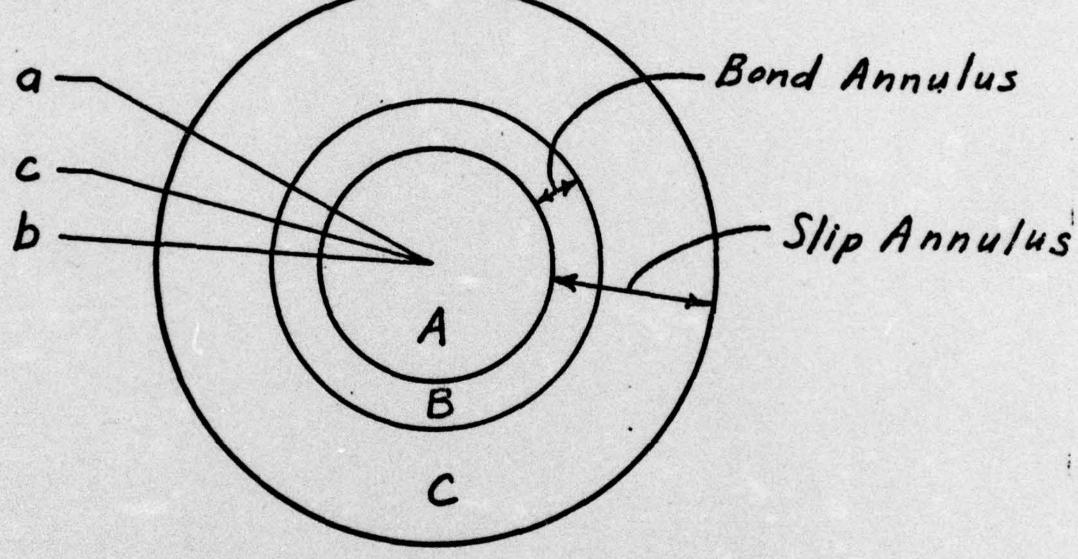

FIGURE 1
BOND PATTERN: MODIFIED MODEL

The areas A and C are contact areas where bonding did not occur; the area B is the bond area. A detailed description of the model is given in Appendix A.

DESCRIPTION OF EQUIPMENT

For this program a large number of bonds were made and separated to determine if the bonding pattern corresponded to the model. The bonds were made with a Kulicke and Soffa Model 472 ultrasonic gold ball bonder equipped with a Uthe Model 20C, 20 watt ultrasonic generator. The wire used was 0.001 inch diameter, 99.99% pure, stress annealed gold wire supplied by Joseph B. Cooper & Sons. A Micro-Swiss Model 472A-10-WC tool was used to fabricate most of the bonds. A Model 4138 B&K capacitor microphone was used to monitor the tool tip vibration. This microphone was fitted with a constricting taper designed in accordance with the description given in NBS Technical Note 573.

The bonds were made to thin films of aluminum which were evaporated onto glass slides. The slides were coated in a VEECO Model VE 775 high vacuum system. The deposition rate was controlled by a system comprising a Sloan quartz crystal oscillator, a Sloan DRC deposition rate control unit, a Sloan DTM-3 deposit thickness monitor and an SCR power control module. The deposition rate was typically 5000 Å/min.

WORK PERFORMED

The primary objective of this program was to improve the techniques, procedures, and equipment developed under the preceding contract (N00163-75-C-0029) for the evaluation of the bond model. The work performed under this contract can be divided into three classifications: substrate preparation, bonding machine and observational techniques. These efforts are described in the following sections.

Substrate Preparation

At the beginning of this program the evaporation chamber was accidently coated with tungsten oxide; consequently, the first effort on this program was to disassemble, clean and reassemble the vacuum system. After reassembly the ultimate pressure attainable was less than 10^{-6} torr and the pressure during a typical evaporation ranged from 5×10^{-6}-to-2×10^{-5} torr. These values are equivalent to the pre-contamination values and are adequate for the preparation of substrates.

A masking system was designed, fabricated and installed in the vacuum system. This system made it possible to deposit the aluminum in desired patterns. A pattern was designed to permit the thickness and quality of the aluminum to be measured. Previously the thickness was inferred from the deposition variables and the quality was not monitored. The pattern used is shown in Figure 2.

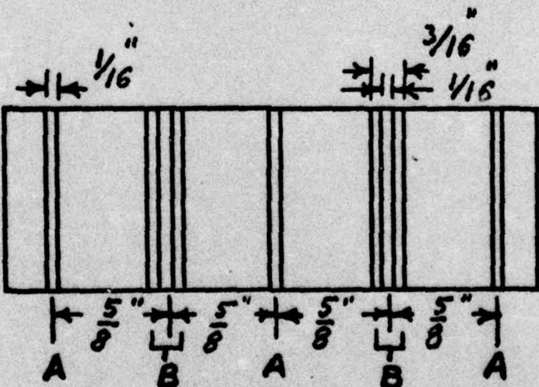

FIGURE 2
SLIDE PATTERN

The slide is coated with the required thickness of aluminum over the entire surface except for the stripes marked A and B. The A areas are coated with a flash of aluminum to make them highly reflective and these areas are used to check thickness by use of a multiple beam interferometer. The B areas are uncoated thereby isolating the thin stripe of aluminum between the adjacent pairs. The resistance of these stripes is measured at room and liquid nitrogen temperatures to help establish the quality of the aluminum coating. When thick coatings are prepared sufficient aluminum deposits in the A regions during the initial evaporation to make them reflective and the flash coating is not used. The thickness measured in these cases will be less than actual, but should be adequately accurate for model evaluation. The thickness profiles across these steps are sufficiently smooth so that fringes can be traced and thicknesses to 60,000A can be measured.

The evaporation source was modified so that thicker and more uniform coatings could be made. A source comprising four 1/2-inch-diamater-by-2-inch long tungsten filaments was used. The filaments were placed parallel to each other, 3/4-inch apart and 8 inches from the substrate. The filaments were held in copper blocks which contained V grooves to facilitate placement and good electrical contact. Electrically, the filaments were arranged in two isolated sets; each set contained two filaments connected in parallel. Using this arrangement, the maximum film thickness obtainable was increased to 60,000A. Operating the filaments in parallel also increased the useful life of the filaments.

Some of the thicker coatings separated from the substrate when bonds were made at high power. To improve adhesion of the thicker films, a substrate heater was installed in the vacuum system. The heater comprised a copper block 1x1x3 inches in size and a 165 watt cartridge heater. The cartridge was inserted into a hole in the copper block and the assembly was placed on top of the substrate. Use of the heater resulted in an apparent increase in adhesion. Substrates with thicknesses of 20, 24, 25, 30, 38, 40, 41, 50 and 60 KA have been fabricated in this system. These substrates are stored in a dustproof chamber until ready for use.

Thickness is measured using a Sloan M-100 Angstrometer. Measurements are made at the top, middle, and bottom of each of the three reflective steps formed on the substrate. Thickness variation is on the order of 750 to 3000 A°. Slides which have been evaporated from unused tungsten filaments have the best uniformity due to even distribution of the wetted aluminum. Accuracy of the thickness measurements is estimated to be ± 500A.

The narrow isolated stripes on the substrate were provided so that the resistance of the aluminum could be measured.* At room temperature these stripes have resistance of-the-order-of tenths of an ohm. The resistivity may be written in the form[8]

$$P = P_i + P_L$$

where P_i is due to impurity atoms and P_L is due to thermal motion of the atoms. The P_i component is independent of temperature and P_L varies directly with temperature at least down to liquid nitrogen temperatures. Since P_L goes to zero as temperature goes to 0°K the P_i component can be determined by extrapolating

*This technique was suggested by Dr. George Schnable.

the P(T) curve to 0°K. The P_i value should be a measure of the quality of the aluminum coating. The resistence of some of the strips was measured at room and liquid nitrogen temperatures. The anticipated behavior was observed; however, the reproducibility was poor. The approach appears to be practical; however, the experimental techniques must be improved.

The hardness of the aluminum can also be estimated by use of an inpact type microhardness tester. The interpretation of this type of data is hampered by the thinness of the coatings. Arrangements were made with a local industry to use their microhardness tester; however, no tests were made.

The bonds made to the substrate are located and identified by scribing location lines on the substrate. A new scribing technique has been developed which permits maxumum utilization of substrate area. The aluminum coated, 1"x3" glass slides are mounted on the vacuum chuck of a wafer scriber which has had the diamond tool replaced by a razor blade. Sets of three lines are scribed perpendicular to the length of the slide at .005" intervals; a .010" gap is left between sets. This process continues until the entire slide is scribed. The pattern is shown in Figure 3.

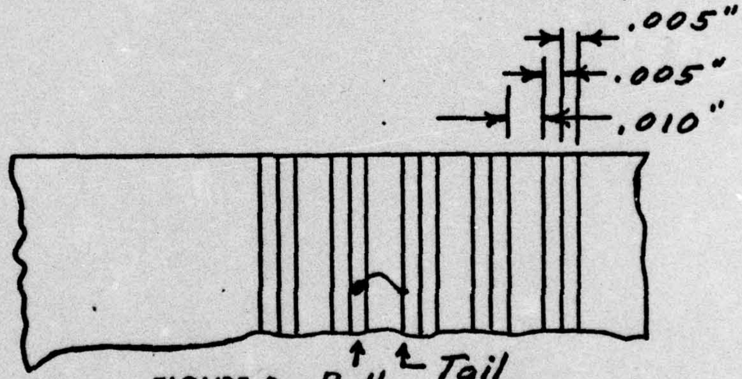

FIGURE 3
SCRIBED LINE PATTERN

In practice, ball bonds are made in the right hand side of the double columns, and the tails are centered on the line .010" to the right. Experience has shown that the 125 useful sets of lines can be scribed on a 3" slide, and 125 bonds can be made per column.

Consequently, 15,000 bonds can be made on a single substrate. An additional advantage of the scribing technique described is that it provides an accurate .005 inch size reference for use in microscopic observation.

Bonding Machine

The K&S Model 472 bonder was returned to the factory for insepction and modification. It was fitted with an improved wire feed and a heated substrate holder and was functionally tested.

Shortly after its return erratic bonding results were obtained for both ball and tail bonds. The power supply was replaced with a newer model and, when this provided only partial improvement, the transducer was replaced. Prior to changing the transducer, capacitor microphone measurements indicated occasional loading of the tool such that the output dropped by a factor of 5-to-10 from no load to bonding condition. This change is much larger than normal. Normal bonding was resumed with replacement of the transducer. In an attempt to eliminate external vibrations, four commercial vibration mounts (rubber foam mounted between plywood boards) were placed under the table supporting the bonder. The results of this experiment were inconclusive.

Considerable variations of pre-bond ball size and shape was noted in the experiments. In an attempt to circumvent the problem of erratic shape and size, a K&S 479 bonder equipped with electronic flame-off was tested at the factory; however, lack of familiarity with the machine made it preferable to continue work with the 472. A slight improvement in the ball shape and uniformity was obtained after reduction and fine tuning of the hydrogen flame gas flow.

In order to control the ball size and uniformity during the course of making test bonds, a micro projection system was set up to provide an enlarged(100 x) image on a screen of the ball, wire, and tool tip prior to making a bond. By use of calibrated lines on the screen the size of the ball could be determined within a range of 2.5-to-3 mils and visually judged for spherical quality. After development of the projection system, the procedure for making test bonds was as follows: Referring to the scribing diagram (Figure 3), two double columns were used per set of bonding conditions. The right side of one double column was used for bonding properly sized, shaped, and seated balls and the column to the right was used for bonding reject balls.

Work was started on a laser interferometer to be used to check the tool tip vibration during the bonding operation. Since equivalant systems were already in use a literature search was made and Mr. George Harman of the National Bureau of Standards was consulted. A detector of the type used in the NBS unit(SGD-100A) was obtained from EGG. Equipment was set up to measure the motion of analuminized mirror mounted on a loudspeaker in a manner similar to that described by Clunie and Rock[9]. The interference patterns have been observed and accurate measurements of the speaker motion have been made. The old laser used in this experiment operates intermitantly and consequently a new and physically smaller laser has been ordered. The equipment must be made portable and improvements must be made in the noise level before use of the interferometer will be practical.

Observational Technique

A new technique for observing the bond interface was developed.* After the bonds are

*This technique was suggested by Dr. George Schnable.

made they are heated to 300° C for a few hours to promote the formation of intermetallics. Presumably the intermetallics will grow preferentially in the bond areas. After the heat treatment, the bonded wires are potted to hold the gold wires in place. The bonds are then placed in sodium hydroxide which chemically etches the aluminum from the interface. The patterns on the gold wires are then observed by using interferance contrast on the metallographic microscope.

Initially, Dow Corning 6104 Semiconductor Junction Coating was used to pot the bonds. After separation one sample was mounted on a glass cover slide and the bonds observed; a second sample was not mounted and the bonds were observed directly. More detail could be seen in the second sample and the process was simpler than mounting to the cover slide; however, the wires in the second sample were not held firmly and tended to cock making microscopic observation difficult. To minimize these problems a third sample was prepared with Emerson & Cumings Stycast 1266 clear, rigid epoxy resin. When this material was used an ultrasonic bath was used to accelerate the chemical etching of the aluminum. The bonds potted in the material were quite immobile and most of the bonds were able to be photographed, although these were still some focusing problems.

DATA

Bonds were made to three substrates to test the various procedures and techniques which had been developed. The first set comprised 250 bonds made to a 15KA thick substrate.

After bonding, the substrate was heated in air to 300°C and then held at that temperature for 2 hours to induce formation of intermetallics. The bonded slide was then potted in Dow Corning 6104 compound and cured for 2 hours at 150°C. The potted substrate was soaked in NaOH for 24 hours by which time the glass substrate had separated from the bonds and potting compound, and the aluminum had been dissolved. The gold half of the bonds, held firmly in the potting compound, were mounted on glass slides and observed on the microscope.

A photograph of one of the bonds is shown in Figure 4.

FIGURE 4
PHOTOGRAPH OF BOND PATTERN

Many of the bonds showed the ring pattern observed previously for pulled bonds. In general there was less detail to be seen on the potted bonds and determination of ring boundaries was easier. Uniformity of the ring patterns was also increased.

Twelve columns of bonds were made at clamping force of 28 grams. The power was varied from 0.6-to 1.7 (meter settings) in increments of 0.1. The first two columns (power settings 0.6 and 0.7) showed few rings and indications of incomplete bonds. Columns 3-through-12 averaged 15 ring patterns per column(75%). In columns 3-through-8 the ring patterns were circular. As the power increased (columns 9-through-12) the ring patterns became elliptical.

The second set comprised 3000 bonds made to a 24KA thick substrate. After bonding, the substrate was heated in air to 300°C and held at that temperature for 2 hours. The bonded slide was then potted in Dow Corning 6104 compound and cured for 2 hours at 150°C. The potted wires were separated from the substrate by etching in sodium hydroxide. The gold half of the bonds were observed directly on the microscope. The wires were not held firmly and tilted in the potting material making observation at high power difficult. Those wires which were not tilted showed more detail than the glass-mounted, first-set wires. Consequently, a more rigid potting epoxy was obtained so the wires could be held firmly without the use a glass cover slide. The wires that could be observed showed a greater degree of variation in ring sizes than the first sample. Since the pre-bond ball size and shape is known to vary, and the degree of variation appeared to change from time-to-time, the reduced uniformity was associated with that cause. Consequently, the ball sorting technique described in the previous section was developed.

The third set comprised 1500 bonds made to a 24KA thick substrate. This set was made using the ball sorting technique previously described. After bonding, the substrate was heated in air to 300°C and held at that temperature for 2 hours. The bonded slide was then potted in Emerson & Cumings Stycast 1266 epoxy resin. The potted wires were separated from the substrate by etching in sodium hydroxide and observed on the microscope. Approximately 90% of the bonds showed some ring pattern. Most of the bonds were made at 68 grams clamping force. A new type of pattern comprising four areas was observed in bonds made at this higher clamping force. These can be clearly seen in Figure 5.

FIGURE 5
PHOTOGRAPH OF BOND PATTE

The bond shown was made at 68 gram clamping force and 1.3 power setting. A few bonds in this set were made at lower clamping force and did not show four distinct areas. As this data did not become available until the end of the program a definite identification of the areas could not be made. An electron microbe analysis of this type of bond interface is being made.

ANALYSIS OF DATA AND CONCLUSIONS

Model

Most bonds observed in this and the preceding program show a substantial degree of structure. In most cases the structure appears as a ring pattern although the rings are sometimes not circular or less than complete. Many bonds have structures consistant with the model outlined in the previous section.

These observations suggest that the existing model represents a good starting point for the study of the bond. The model will probably have to be modified to account for the elliptical rings consistently observed at high bonding power, the four region bond recently observed at high clamping force and the large ball deformation which occurs at high power or high clamping force.

Experimental Technique

The newly developed etching technique has several advantages compared to the bond pulling technique used in the previous contract. These include: no distortion of the interface due to pulling, no residual metal from the substrate, applicability to strong bonds (strong bonds cannot be pulled without damaging the interface), and the relative simplicity of the process. The latter advantage is significant when several thousands of bonds are made to a single substrate. The disadvantages of the etching technique include: identification of bond area by inference, unavailability of bond strength data, and relatively complicated process if only a few bonds are involved. Both techniques should be used in future studies to realize the advantages of each.

The technique developed for producing and evaluating substrates appear to be adequate for a continued study. The range of thicknesses available should be adequate unless a major change in the model is required. The resistance test for aluminum quality requires more work; it should be used in conjunction with an impact type microhardness test. The ability developed to make and locate several thousand bonds on a single substrate should make a study of the bond model practical.

The control of the bonder appears to be adequate for further studies of the model. The problem associated with varying ball size and shape is not solved but is circumvented by the use of the projection system developed under this program. The laser interferometer requires more work, but the operation of the bench model has been demonstrated and the development of a practical unit is assured.

RECOMMENDATIONS

The data obtained to date is reasonably consistant with the present bond model. The techniques for fabricating, controlling and observing the bond have been adequately developed. Therefore, we recommend a 12 month program to evaluate and modify, as necessary, the present bond model. A proposal for such a program will be submitted.

APPENDIX A

BOND MODEL

The basic mechanism by which ultrasonic welds are produced is believed to be solid-state bonding.[1-7] Solid-state bonding requires that surface atoms of one metal be placed within the atomic bonding force field of the surface atoms of the other metal. To accomplish this the oxides and other contaminants on the surfaces must be displaced.

Several mechanisms have been proposed for the process by which the oxide is displaced in the fabrication of an ultrasonic, microcircuit wire-bond.[5-7] A quantitative model has been used by Frisch and Chang[1] to describe ultrasonic, spot-welding of bulk materials. This theory relates to bonding spheres to flat surfaces and predicts that the weld will be made around the periphery of the contact area and that it will be accomplished in two stages. Significantly, Harman and Leedy[6-9] have experimentally demonstrated that microcircuit wire bonds sometimes form about the periphery of the contact area and that the bonding process comprises two stages. This correspondence suggests that the bulk model might be applicable to microcircuit bonding. A brief outline of the model used by Frisch and Chang is given below.

If an elastic sphere is pressed against an elastic flat with a normal load, N, the sphere will be distorted and brought into contact with the flat over an area of radius "a" as shown in Figure 6. Note that the formal force, N', at the interface will be a function of position and will vary from a maximum at the center to zero at a distance "a" from the center. If a shear force, S, is applied to the sphere, in the direction shown in Figure 6, one of two conditions will result. If the shear force exceeds the interface friction force $\mu N'$ (μ is the coefficient of friction) over the entire contact area the sphere will slide along the surface of the flat and no permanent bond will be made. If the shear force does not exceed the friction force over an area of radius "b" (Figure 6), there will be no relative motion between sphere and flat over that area, and the sphere will slip with respect to the surface over an annular area of inner radius "b" and outer radius "a". Slip is defined as a localized tangential displacement at the contact surface.

In the slip area, oxides and other contaminants will be displaced and localized areas will come into contact and form solid-state bonds. The ultrasonic energy applied to the ball will be transmitted through these localized bonds to the substrate. When enough bond area is formed and sufficient energy is applied, the flat in the slip area will plastically deform. This deformation will result in additional dispersion of the contaminants and a joining of the two surfaces over most of the slip area. The result will be a large solid-state bond over most of the slip area.

To produce a bond of optimum strength the normal and shear forces must be such that:

1. Sliding does not occur
2. The slip area is maximized; the radius "b" should approach zero. (Note that if b = 0, sliding will occur.)
3. The shear forces transmitted to the plate should be sufficient to cause plastic deformation of the substrate but not large enough to distort the weld.

The theory shows that the optimum displacement of the ball is given by:

$$A_{op} = X_s + X_p$$

where X_s, the displacement associated with slip, is given by:

$$X_s = 1.88\mu\left(\frac{N^2}{E^2 d}\right)^{1/3}$$

and X_p, the displacement associated with plastic deformation, is given by:

$$X_p = 0.44\gamma\left(\frac{Nd}{E}\right)^{1/3}$$

Where μ is the coefficient of friction

N is the normal force

E is Young's modulus

d is the diameter of the ball

γ is the maximum allowable shear strain

The values for μ and γ are not necessarily those associated with the bulk materials, but can be found experimentally.

The optimum value of X_s, can be found experimentally without knowing μ or γ. To find the optimum value, X_{so}, a bond is made at a displacement amplitude X such that $X<X_{so}$. The bond is broken and the radii a and b are measured. The optimum value can be found from the expression:

$$X_{so} = \frac{X}{1-(b/a)^2}$$

Frisch and Chang verified this model using 3/4-inch-diameter spheres and one-inch-diameter discs. The normal forces were as high as 30 pounds and the ultrasonic power input 140 watts. In a typical wire bond the sphere diameter is 0.002 inch, the normal force 50 grams and the power less than 2 watts.

Although the power is less, the energy density is greater and is sufficient to cause acoustic softening.[5] This softening could significantly affect the stress constant, γ, and may, therefore, change the relative importance of the bonding parameters.

The theory also predicts that the plastically deformed layer under the bond extends 0.4 times the bond radius into the plate. A typical ball bond to an integrated circuit would have a 25 micron radius and a plate thickness of one micron. According to the theory the deformed area will extend 10 microns into the plate or ten-times the plate thickness. The thinness of the plate clearly represents a boundary condition not included in the bulk model.

The experimental data obtained in contract N00163-75-0029 showed the bonds do comprise concentric areas as predicted by the model; however, in general two "ring regions" surround the central area rather than the one predicted by the model. These observations can be accounted for by modifying the model as shown in Figure 1. The outer ring predicted by the original model is divided into two rings. Slip occurs in both ring area; however, in the outer ring area, C, the normal force is not sufficient to cause bonding while in the inner ring area, B, it is. The modified model predicts an inner and outer unbonded area (A and C) surrounding a bonded ring area (B). Under some bonding conditions the inner radius "b" of the inner ring, B, will go to zero and the bond will comprise a central bonded region surrounded by an unbonded ring, C. The outer ring may be due in part to ball material which flowed under the influence of the bonding forces and the outer radius may not be directly related to the radius "a" defined in the theory.

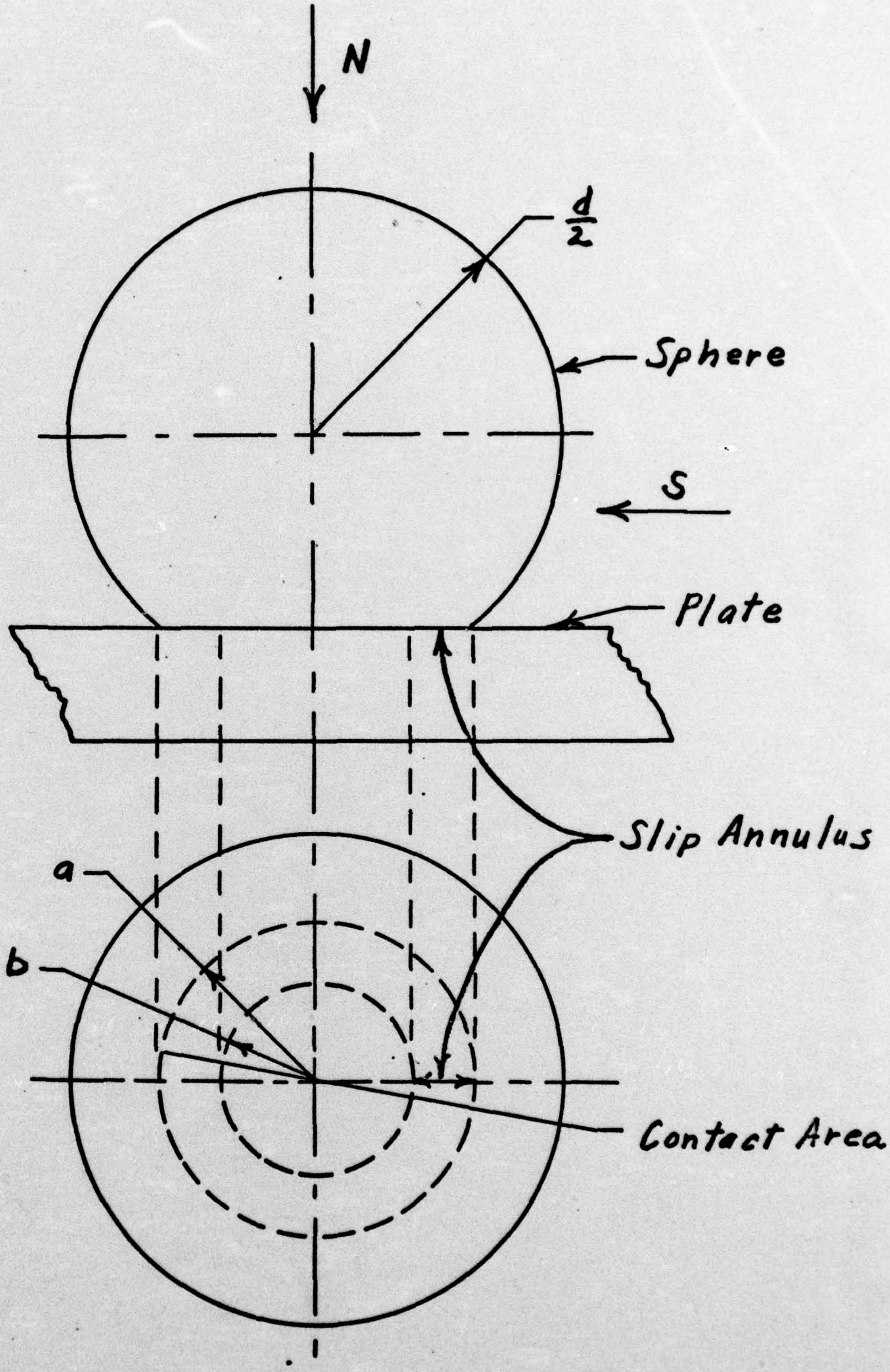

FIGURE 6
Bond Model

APPENDIX B

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