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Methods for Testing Wire-Bond Electrical Connections

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Methods for Testing Wire-Bond Electrical Connections

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METHODS FOR TESTING WIRE-BOND ELECTRICAL CONNECTIONS*

Harry A. Schafft

Abstract

A significant fraction of the failures that occur in integrated circuits are due to failures of the wire-bond electrical connections that are used. Therefore, a critical area for reliability improvement is in the methods for testing and evaluating wire bonds. Several of these methods are surveyed. In particular, analyses with regard to the stress that the test imposes on the wire bond in the pull, centrifuge, mechanical shock, vibration, and temperature cycling tests are presented and used in discussing the capabilities and limitations of these methods.

Key Words: Bonding; electrical connection; failure (wire bond); integrated circuits; microelectronics; reliability; semiconductor devices; testing (wire bond); wire bond.

1. Introduction

Many microelectronic devices use wire bonds to electrically connect the semiconductor die and the package terminals. The diameter of the wire is typically 1 mil.† Unless special precautions are taken, a significant fraction of the failures that occur in these devices is due to wire bond failure. Because of the increasingly large number of devices used in many present-day electronic systems, the reliability of the individual devices must be increased, even from present-day levels. Hence there is considerable interest in methods for testing and evaluating wire bonds.

The term wire bond, for the purposes of this paper, includes all the components of the die-to-terminal electrical connection: the wire, the metal bonding surfaces, and the adjacent underlying supportive material. It is customary to speak of the *bond* as that part of the wire bond that is associated with the volume of the wire deformed at the weld or attachment point and to speak of the *heel* of a stitch or wedge bond as that part of the wire at either end of the wire span which is deformed by the edge of the bonding tool.

The purpose of this paper is to review aspects of the following tests: pull, centrifuge, temperature cycle, thermal shock, mechanical shock, variable frequency vibration, and vibration fatigue. In particular, these tests are examined with regard to the stress that

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†The data referenced in this paper that are not given in the International System (SI) of units are followed in parentheses by the values in the appropriate SI unit. General usage dictates that three exceptions be made: (1) acceleration is given in units of gravity (1 g = 9.8 m/s^2), (2) the wire diameter is given in mils (1 mil = 25.4 μm), and (3) the force exerted on the wire or wire bond is given in grams-force (1 gf = 9.8 mN).

the test applies to the wire bond and what that implies about the capabilities and limitations of the test. These and other test procedures, including visual inspection, have been discussed in detail elsewhere [72S2]*.

2. Pull Test

2.1. Destructive, Double-Bond Test†

The destructive, double-bond test consists of pulling on the wire span by some means (usually with a hook) with increasing force until a rupture in the wire bond occurs. The pulling force required to produce rupture is called the pull strength, and it is used as a measure of quality for the wire bond.

In the test, pull strengths of a sample are taken to be representative of the group. Usually, the location of the rupture is recorded as well as the pull strength which is often expressed in grams, although grams-force§ are implied. To facilitate analysis of the data, the distribution of pull strengths can be displayed in a histogram. The magnitude of the pulling force at the peak in the distribution displayed in the histogram gives an indication of the general ruggedness of the wire bond while the spread of the distribution indicates the uniformity of a group.

The actual stress in the wire bond is the tensile force in the wire. If the geometrical variables are defined as in figure 1, wire tensile forces on the terminal side, F_{wd}, and on the die side, F_{wt}, are related to the applied pulling force by

$$F_{wt} = F \times \frac{\cos(\theta_d - \phi)}{\sin(\theta_d + \theta_t)} \tag{1}$$

$$F_{wd} = F \times \frac{\cos(\theta_t + \phi)}{\sin(\theta_t + \theta_d)} \; . \tag{2}$$

It is assumed that the pulling probe is in the plane of the wire loop but inclined at an angle ϕ with respect to a normal to the bonding surface. The angles θ_t and θ_d are the contact angles that the wire makes with the bonding surfaces of the terminal and die, respectively. The ratio F_{wt}/F as a function of θ_t is given in figure 2 for $\phi = 0$ and various fixed ratios of θ_d/θ_t. The ratio of F_{wd}/F as a function of θ_d may be obtained by interchanging the subscripts d and t in figure 2.

Although the geometrical dependence is easily visualized in terms of the contact angles, these angles are difficult to measure. The contact angles depend on the height, h, of the wire span above the terminal contact surface, the height difference, H, between the

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*Alphanumerics in brackets indicate the literature references at the end of this paper.

†[66R1], [67H1], [67S3], [68D2], [69B5], [69K1], [70A1], [71B4].

§See footnote on page 1.

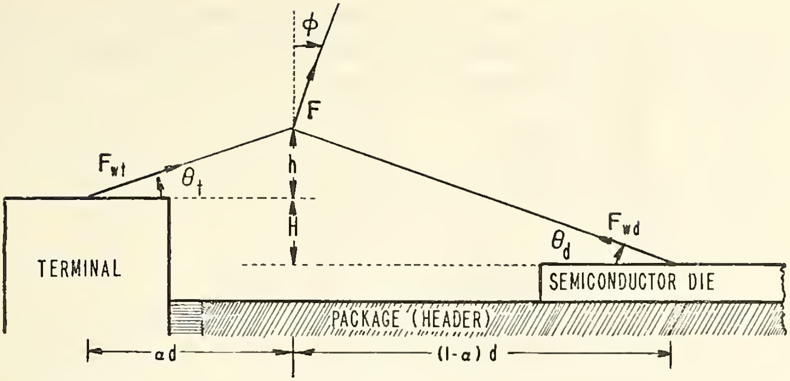

Figure 1. Geometric variables for the double-bond pull test.

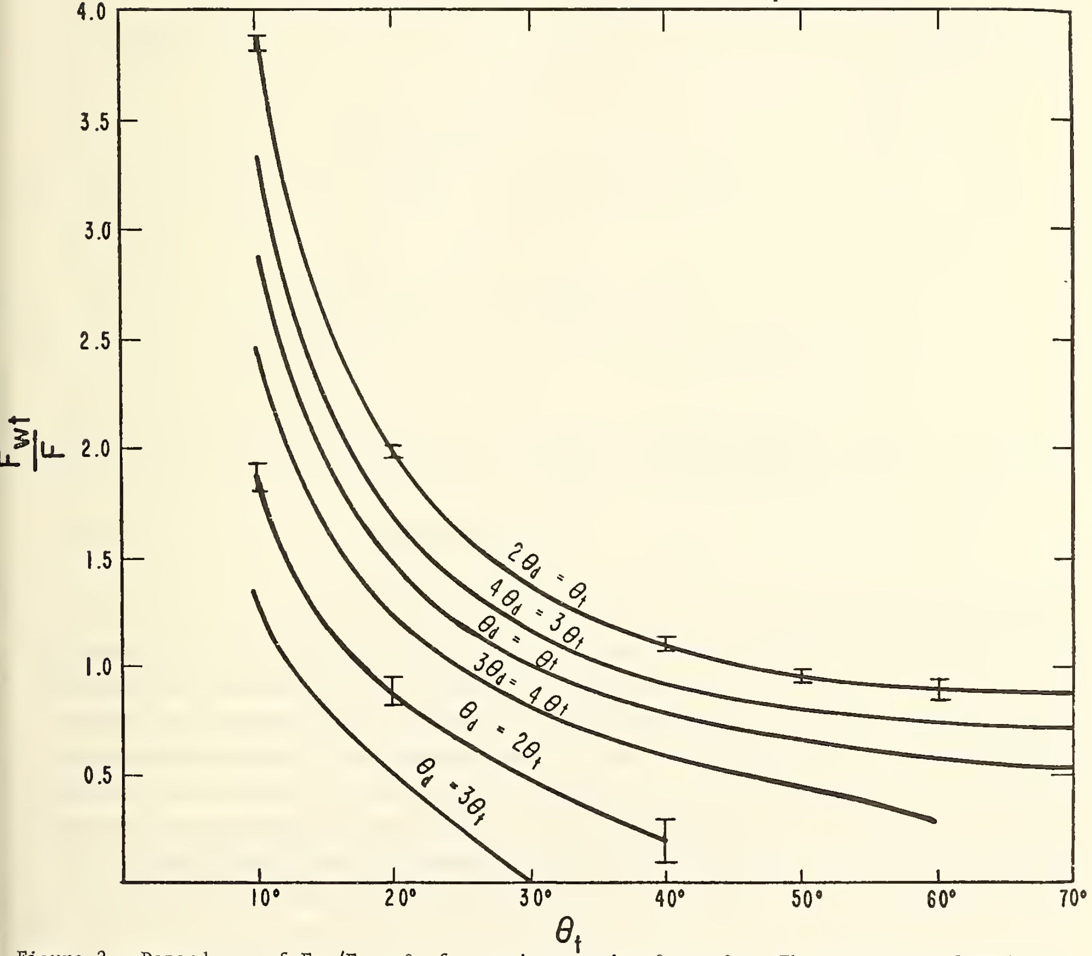

Figure 2. Dependence of F_{wt}/F on θ_t for various ratios θ_d to θ_t. The curves are for the case $\phi = 0$. Horizontal bars above and below the curves for $2\theta_d = \theta_t$ and $\theta_d = 2\theta_t$ show the effect of changing ϕ to plus and minus 5 deg, respectively. To obtain the dependence of F_{wt}/F, interchange everywhere the subscripts d and t and change the sign of ϕ.

die and terminal contact surfaces, and the horizontal distances, αd and $(1 - \alpha)d$, from the bonds to the point at which the wire span is contacted by the pulling probe. Expressing eqs (1) and (2) in terms of these quantities we have

$$F_{wt} = F \left\{ \frac{\sqrt{1 + \left(\frac{\alpha d}{h}\right)^2} \left[(1 - \alpha) \cos \phi + \left(\frac{h + H}{d}\right) \sin \phi \right]}{1 + \frac{\alpha H}{h}} \right\} \text{ and} \tag{3}$$

$$F_{wd} = F \left\{ \frac{\sqrt{1 + \frac{(1 - \alpha)^2 d^2}{(h + H)^2}} \left(1 + \frac{H}{h}\right) \left[\alpha \cos \phi - \frac{h}{d} \sin \phi \right]}{1 + \frac{\alpha H}{h}} \right\} . \tag{4}$$

For a normal pulling force ($\phi = 0$), these equations simplify to:

$$F_{wt} = F \left\{ \frac{(1 - \alpha)}{1 + \frac{\alpha H}{h}} \times \sqrt{1 + \left(\frac{\alpha d}{h}\right)^2} \right\} \text{ and;} \tag{5}$$

$$F_{wd} = F \left\{ \frac{\alpha \left[1 + \frac{H}{h}\right]}{1 + \frac{\alpha H}{h}} \sqrt{1 + \frac{(1 - \alpha)^2 d^2}{(h + H)^2}} \right\} . \tag{6}$$

For a normal pulling force applied at mid-span to a single-level wire bond ($\phi = 0$, $H = 0$, $\alpha = 1/2$) these equations simplify further to:

$$F_w = F_{wt} = F_{wd} = \frac{F}{2} \sqrt{1 + (d/2h)^2}. \tag{7}$$

The dependence of F/F_w and F_w/F on d/h in eq (7) is graphed in figure 3.

The experimentally determined dependence of pull strength of ultrasonic aluminum wire bonds on the geometrical variables has been compared with the predictions of eqs (3) and (4), where it is assumed that the tensile force to rupture the wire bond remains constant as the variables are changed.* In general the experimental results on unannealed single-level wire bonds agreed with the theory. However, differences were observed in the dependence of pull strength on loop height, h, for wire bonds with loop height greater than 1/3 the interbond spacing, d. It is felt that this is caused by a weakening of the wire bond because of bond peeling as a result of the relatively high loop heights. Because of the

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*[71B1], [71B4], [72B1], [72B2], [72B3], [72B4], [73B1], [73B2] — A summary of this work by A. Sher will be published as an NBS Technical Note.

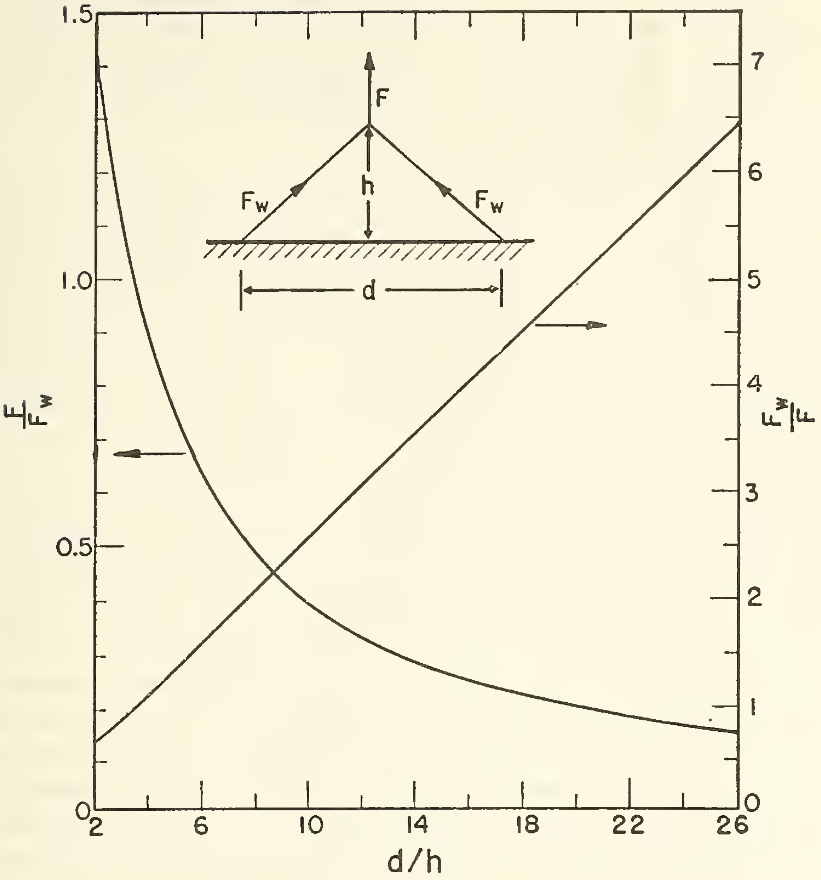

Figure 3. F/F_W and F_W/F as functions of d/h for a single-level, double-bond pull test.

elongation of the wire during the test, all annealed wire bonds studied had loop heights greater than 1/3 the interbond spacing at the time of failure, and hence the experimentally obtained values for pull strength differed from the predicted values.

While the pull test is the most widely used test for wire bonds it is also perhaps the most under-specified. To maximize the usefulness of pull test data, especially when used to evaluate and compare wire bonds, it is important to specify fully the wire bonds tested and the test conditions as well as the failure mode.

It is necessary to have information about the average shape of the wire span* because it can significantly affect the pull strength measured. To indicate the magnitude of the dependence of the pull strength on the shape of the wire span in a double-bond pull test,

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*In cases where the elongation of the wire during the test is large, such as in annealed wire, it is necessary to take this into account when providing information about the shape of the wire span.

consider two single-level wire bonds for which the same tensile force in the wire is requires to produce rupture. Let the contact angles that the wire makes with each bonding surface be 10 degrees for one wire bond and 30 degrees for the other. The pull strength measured for the one with contact angles of 30 degrees will be about three times as large as for the other (see figure 2).*

If information about the wire tensile strength is not provided the pull strength data of different wire bonds cannot usually be used to compare wire bond quality. This is because failure is usually in the wire and in this case the pull strength is dependent on the tensile strength of the wire. Wire tensile strengths may vary significantly. For example, aluminum ultrasonic wire bonds may be made from wire with an initial tensile strength of from 12 to 20 gf; depending on the thermal history of the wire the final tensile strength of the wire may be as little as 20 percent of its initial value [70P1]. A useful way of normalizing the data from pull tests of different wire bonds with wires having different tensile strengths is to employ a bond efficiency [67R1] defined as the ratio of the tensile force in the wire at rupture to the tensile strength of the wire.

There has been some concern about two aspects of the pull test procedure which possibly can affect the pull strength measured. One is the speed of the pulling stress applied. Therefore, the rate of pull is occasionally specified for the pull test. It is given either in terms of the speed of the pulling element [66R1], [67S3], [69K1], or the rate of increase of the force, as measured at the pulling element [70B8]. In some pull tests, the only specification is that the force must be applied "slowly" [67H1]. Leedy and Main [71B4] reported no dependence of pull strength on pull rates in the range of 1 to 77 gf/s (equivalent to a range of from about 0.4 to 30 mm/min) for single-level, unannealed wire bonds with 1-mil diameter aluminum wire bonded ultrasonically to an aluminum film on silicon. The higher rate may be comparable with the speed of some pull test machines used in the industry where the pull may be likened to a jerk. It should be noted that the wire bonds used by Leedy and Main were constructed so that rupture occurred in the heel of the bond; the independence of the pull strength on pull speed in the range reported may not hold for wire bonds where the failure mode is rupture or peel at the bond interface or where the two bonds are on different levels [71B4].

The other aspect of concern arises if the applied pulling force is directed at some angle, α, out of the plane of the wire loop because of possible tearing of the bond heels. Studies by Leedy, Sher, and Main [72B4] on 1-mil diameter aluminum ultrasonic wire bonds have been shown that the measured pull strength decreases only slightly as α increases; the decrease is more pronounced for wire bonds with greater bond deformation. If α is maintained at less than about 10 deg the pull strength will not be affected significantly by variations in α, except when testing bonds with bond deformations† of about three wire diameters or more.

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*For wire bonds made on the same plane, 10 degrees and 30 degrees correspond to values for the ratio of the bond separation to loop height (d/h) of about 11 and 3.5, respectively.

†Bond deformation refers to the width, as viewed from above, of the wire deformed at the weld or attachment point.

2.2. Destructive, Single-Bond Test

The destructive, single-bond test consists of pulling on a wire at some angle with respect to the bonding surface with increasing force until rupture occurs. For the test, either the wire bond is cut somewhere along its span or only one bond is made. The purpose of a single-bond pull test is usually to afford better control of the angle of pull (with respect to the bond and contact surface) and also thereby minimize flexing and hence weakening the heel of the bond.

A means of gripping the wire is required in this test. Wasson [65W1] has described the use of special tweezers to grip the wire. Methods to reduce the grip-stress on the wire have been described by Adams and Anderson [68A1] and by Harman [69B5]. The former described the use of a black wax and a separate heating element to liquify the wax at the end of a probe which engulfs the wire by capillary action. The ability to apply a tensile force of 150 gf was reported. The latter described the use of a high-tensile-strength, hot-melt glue with a discrete melting point, at the tip of a nichrome wire-loop probe. The glue is melted by passing current through the wire loop which was electrolytically thinned so that most of the joule heating occurs at the tip. The tensile strength and adherence of such glues are sufficient to test 1-mil diameter aluminum wire if a length of about 0.13 mm is bonded with the glue. The glues do not adhere as well to gold wire so that a longer length of wire must be bonded.

2.3. Nondestructive, Double-Bond Test

The nondestructive test consists of pulling on the wire span until a predetermined force is applied. The test is meant to be nondegrading as well as nondestructive to satisfactory wire bonds but destructive to those bonds that are unsatisfactory. Such a test has been suggested as a 100 percent screen test by Slemmons [69S1] and Ang *et al.* [69A1]. To substantiate the claim that the test is nondegrading to those that pass, both papers show that after a group of wire bonds has been so tested and then pulled to destruction, the bond strength frequency distribution is merely truncated at the preselected stress level.

Polcari and Bowe [71P3] have reported the results of some preliminary evaluations of a nondestructive pull test. They concluded that while the nondestructive test could be a valuable reliability tool the proper use and adjustment of the tester would be of critical importance. Furthermore, if the nondestructive pull test were to be implemented, they recommended that the manufacturer control loop heights to minimize variations in the stress imposed by the test.

There has been skepticism that the test is actually nondegrading. The idea of using devices whose wire spans have been pulled and, in the process, altered in shape is new and disturbing to some. On the other hand, there does not seem to be a similar reluctance to use devices stressed in the centrifuge test described in the next section.

3. Centrifuge Test*

In the centrifuge test a constant centrifugal force stresses the wire bonds. Poorly adhering wires are expected to rupture while wires which have a large loop or which have been improperly placed are expected to shift so that they will make electrical contact with adjacent parts of the device. The resultant open or short circuits are detected by subsequent electrical tests.

The stress applied to the wire bond is dependent on the maximum acceleration (expressed in gravity units, g's†), the shape of the wire loop, and the direction of the centrifugal force relative to the wire loop. The typical range of centrifugal forces used is from 30,000 to 50,000 g's. The typical duration at the maximum stress level is one minute in any one direction of applied centrifugal force. The directions are chosen so that the force is directed either away from, toward, or parallel to the bonding surfaces. The test is often preceded by other tests intended to weaken unreliable wire bonds and thereby promote their failure in the centrifuge test.

For the case where the centrifugal force is directed away from the bonding surfaces, the tensile stress in the wire at the heel of the bond on the terminal, F_{wt}, and on the die, F_{wd}, are given in grams-force by the following relations where it is assumed that the centrifugal force is sufficiently large so that the wire loop takes the shape of a catenary:

$$F_{wt} = \rho \pi r^2 G(\alpha + h) \tag{8}$$

$$F_{wd} = \rho \pi r^2 G(\alpha + h + H) \tag{9}$$

where ρ = density of the wire (g/cm^3),

r = radius of the wire (cm),

h = vertical distance between the terminal contact surface and the peak of the wire loop *after* the centrifugal forces have deformed the loop to describe the catenary curve (cm),

H = vertical distance between the terminal and die contact surface (cm),

d = horizontal distance between bonds (cm),

G = centrifugal acceleration (in units of gravity),

and where α is given by the relation $h + H + \alpha = \alpha \cosh (D/2\alpha)$ in which $D/2$ is the lateral distance between the bond at the die and the apex of the wire loop. For $d \gtrsim 2(H + h)$, a good approximation for α is given by

$$\alpha \simeq \frac{d^2}{4h(1 + \sqrt{1 + (H/h)}) + 2H} .$$

A graphical representation of eq (8) is shown in figure 4. Here, the tensile force in the wire at the heel of the bond of a single-level, 1-mil diameter wire bond subjected to a centrifugal force of 10,000 g's is shown as a function of d for different values of d/h.

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*[64U1], [65C5], [65R1], [66G1], [66L4], [66P1], [67G1], [68B1], [68D2], [68I1], [68R2], [69B2], [69O1], [69S4], [70D3].

†See footnote on page 1.

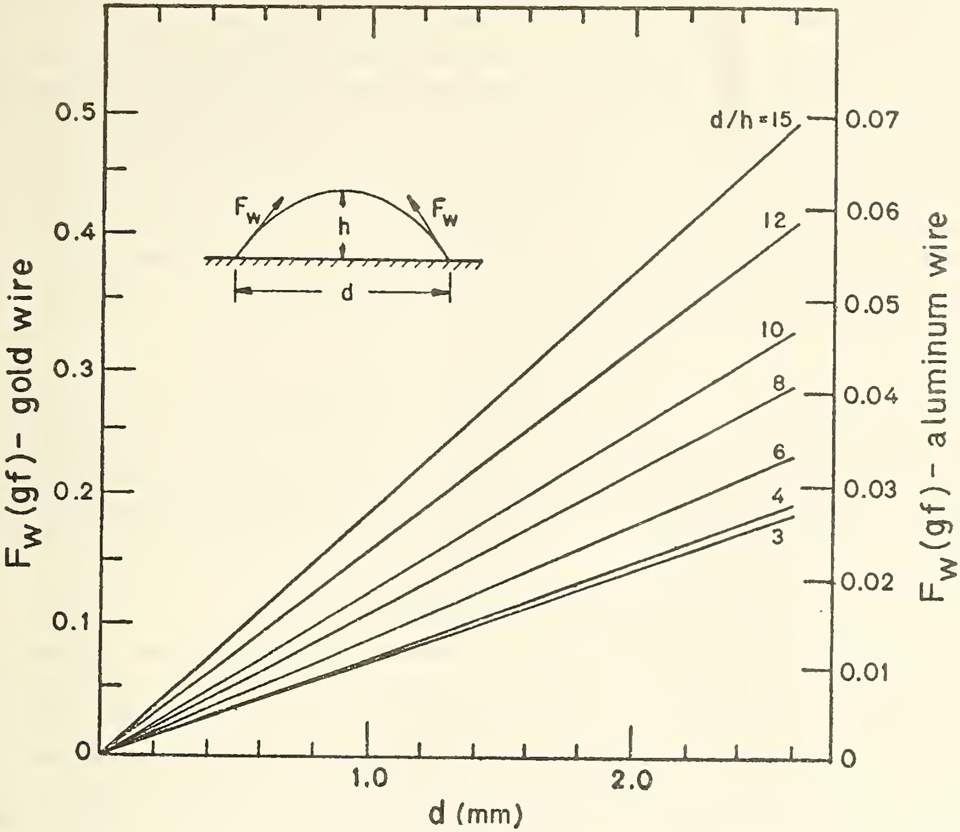

Figure 4. Tensile force, F_W, in the wire at the heel of the bond of a single-level, 1-mil diameter wire bond subjected to a centrifugal force of 10,000 g's for different values of d/h. The left- and right-hand vertical scales are for gold and aluminum wire bonds, respectively.

The tensile force for gold wire is shown on the left vertical axis and for aluminum wire on the right vertical axis. As can be seen, F_W increases as d is increased but F_W decreases as h is increased. F_W begins to increase with h for h $\gtrsim$ d/3.

To use the centrifuge test for accelerations much greater than about 50,000 g's requires that special fixturing be used to hold each device and incurs the risk of damaging other satisfactory components of the device. Therefore, there are practical limitations on the maximum acceleration that can be used. Because of this and the low density of aluminum, only gold wire bonds can be screened satisfactorily with centrifuge tests. While the centrifuge test is widely used for this purpose there are some who believe that even for gold wire the centrifuge test is only acceptable for culling out grossly defective wire bonds [67A1]. For example, using figure 4 and considering a gold wire bond with a separation of 0.15 cm and a loop height of 0.015 cm the tensile force in the gold wire for an acceleration of 30,000 g's will only be about 0.55 gf. As a basis of comparison, such a tensile stress would be produced in a pull test if the hook, placed at mid-span, were pulled with a force of 0.25 gf.

Judging whether a centrifuge test may be useful, as with many of the other tests, is dependent on the values of d and h of the wire bonds to be tested. When d is sufficiently large and h sufficiently small the test may stress the wire bonds sufficiently in those cases when the centrifugal force is directed away from the bonding surfaces. For tests where the centrifugal force is directed either into or parallel with the bonding surfaces no calculations on the stresses imposed have been found in the literature. Again, however, it would be expected that the larger is d the greater will be the stress applied to the wire bond simply because of the greater mass of the wire involved.

4. Mechanical Shock Test*

In a typical test the device is first accelerated either by free-fall or by pneumatic means and then brought to a sudden halt on striking an impact pad. The test conditions that may be specified are the maximum deceleration (usually a few thousand g's), the duration of the impact or shock pulse width (between 0.1 and 1.0 ms), the direction of the stress (usually along one or more of the principal axes of the device package), and the number of shocks per direction (usually less than ten).

In essence, the basic stresses imposed by a mechanical test to a wire bond result from the amplitude and the number of vibrations induced in the wire loop by the mechanical pulse. The number of vibrations depends on the damping of the wire loop. Thus, if the wire has been softened, through earlier exposure to high temperatures, fewer oscillations with smaller amplitudes occur and the resulting flexure stress may be less. However, irreversible changes occur in annealed wire at smaller bending and torsional stress than in unannealed wire.

To discuss the test in terms of the magnitude of the induced deflection and stress, it is useful to define a dynamic-to-static deflection or stress ratio, K:

$$K = \frac{\text{maximum wire deflection or stress by a mechanical pulse}}{\begin{array}{l}\text{wire deflection or stress induced if peak acceleration}\\ \text{of mechanical pulse were applied statically}\end{array}}$$

As a rule of thumb, the upper bound for K is 2 [48F1], [65R3, p. 368], [67I1]. How much less than 2 K is depends on the shape and duration of the pulse and on the lowest resonant frequency of the wire loop. However unless the product of the shock duration and the resonant frequency of the wire bond is less than about 0.4, K is not less than 1 [67I1]. The results of estimates made of the lowest frequency of wire bonds [72S2] indicate that this might occur for 1-mil diameter gold wire bonds with a bond separation, d, greater than about 2 mm and for 1-mil diameter aluminum wire bonds with d greater than about 3 mm.

Changes in the shape of the excitation pulse will produce differences in K. Consequently the International Electrotechnical Commission (IEC) in its recommended test method

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*[67I1], [68D2], [69B2], [69S4], [70D3].

[67I1] has required the specification of the shape of the shock pulse. For the purpose of reproducibility, the use of a saw-tooth shaped pulse is suggested because it produces the least variation in vibration amplitude with changes in pulse duration and resonant frequency. The IEC method also stresses the need to minimize any ripples on the shock pulse in order to maximize the reproducibility of the method; ripple is considered to be the most significant distortion of the shock-pulse shape.

Because K is no greater than 2, the stress imposed by a mechanical shock test will be less than twice the stress imposed by a centrifuge test at a constant acceleration equal to the peak shock-induced deceleration and directed in the same direction, neglecting the uncertain effect of the number of vibrations that are generated. Because the largest peak acceleration used is generally no more than several thousand g's and considering the small stress that a centrifuge test at twice such an acceleration would impose, the mechanical shock test does not greatly stress most wire bonds.

To make the test more severe by increasing the amplitude of the shock can result in deformation of the package at impact unless special supporting structures are used. In some cases, use of the method is hampered by the fact that some package designs do not readily allow means for support along one or more axes.

5. Variable Frequency Vibration Test*

In a typical test the device is vibrated sinusoidally through a range of frequencies for one or more cycles to excite and rupture any wire bonds which have a resonant frequency within the range swept. The selection of the frequency range is based on an estimate of the frequency components of the kinds of shock and vibrations the device may encounter in its life, subject to the constraints of test equipment available. The test conditions usually specified are the frequency range (typically from about 10 to 2000 Hz); the sweep rate (order of minutes per octave); the duration or number of cycles (from a fraction to tens of hours or less than five cycles); the direction of the vibration (along each of the principal axes of the device); and the maximum acceleration (less than 100 g's), sometimes with a limitation on the maximum amplitude at the lowest vibration frequencies thus reducing the peak acceleration there.

The maximum vibration frequency used in most tests is 2 kHz. Except for gold wire bonds with a bond separation greater than about 3 mm, the lowest resonant frequency of wire bonds is greater than 2 kHz [72S2]. Hence, the dynamic deflection of the wire and the induced stress is at most twice as large as that induced if a constant acceleration equal to the peak acceleration were applied [65R3, pp. 368 and 370]. The maximum acceleration used is usually less than 100 g's which produces vibrations in the wire with a negligible amplitude; hence the test does not stress wire bonds greatly. However if the maximum vibration frequency is increased to 6 kHz [66I1] wire bonds with bond separations smaller than about 3 mm may also be stressed significantly.

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*[66L4], [66I1], [68D2], [69S4], [70D3].

6. Vibration Fatigue Test*

The test involves vibrating the device at a fixed frequency, for many hours, along each of the three principal axes of the device package to determine if the wire bonds can withstand relatively long periods of low-frequency sinusoidal oscillations without metal fatigue. The test conditions usually specified are the frequency (less than 100 Hz), the duration (between about 30 to 100 h), the direction of the vibration (along each of the principal axes of the device), and the peak acceleration (less than 100 g's).

Because the vibration frequency is very much lower than the lowest resonant frequency of any practical wire bond and the peak acceleration is essentially negligible, the vibration fatigue test is an ineffective way to cull out weak wire bonds.

7. Thermally-Induced Stress Tests†

There is a variety of tests that involve heating the device and using the difference in the coefficients of expansion in the component parts of the device to stress the wire bond. Temperature cycling and thermal shock are two such tests which involve exposing the device alternately between two temperature extremes. The test is referred to as a thermal shock or a temperature cycling test depending on the transfer time between these two extremes. A transfer time for shock tests is of the order of seconds; for temperature cycling tests it is of the order of minutes. The low- and high-temperature extremes of the range that is used in such tests vary, but the range usually extends at least as low as -65°C and as high as 125°C.

A power cycling test can also be used. In this test there is sufficient time during the on- and off-power periods for the wire bond to approach thermal equilibrium. The stresses induced are less than in the first two tests because only the part of the wire nearest the semiconductor die, where the power is dissipated, is heated appreciably. Phillips [72B1] [72B3] has shown that the temperature gradient is linear along the wire between the die and the terminal of an unencapsulated device if joule heating in the wire is negligible.

Thermally-induced stresses can dislodge or shift poorly adhering bonds. To detect such defective bonds an electrical continuity monitoring test is combined with a thermal stress test, usually a temperature cycling test. Such tests are effective in detecting intermittent open circuits in plastic encapsulated devices [71H2] [72F1]. In these devices, open circuits may appear when the device temperature is above or below a certain temperature or in one or more ranges of temperature [71H2].

The usual practice when using an electrical continuity test is to limit the peak test voltage to less than about 0.5 V. The reason for this is to avoid arcing, which would heal some kinds of micro-openings in the wire bond. Such openings can occur, for example, in an annular ring of Kirkendall voids [70P2] [70R1] around a gold ball bond made on an expanded-contact aluminum metallized pad.

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*[65C5], [68D2], [69S4], [70D3].

†[68D2], [70D3].

The electrically monitored tests are usually performed for only one cycle while the unmonitored tests often are continued for many cycles to determine if the wire at the heel of the bond, where flexure is greatest, can sustain the flexing stress. The magnitude of this flexing which is produced by changes in ambient temperature is dependent on the wire shape and on the differences in the thermal coefficients of expansion of the wire and the package. The contact angle for the case where the wire loop is in the shape of a circular arc is given by

$$\frac{\sin\theta}{\theta} = \frac{\sin\theta_0}{\theta_0}\left[1 - (\beta_W - \beta_S)(T - T_0)\right], \tag{10}$$

where θ, θ_0 = the final and initial contact angles, respectively,

β_W, β_S = the thermal coefficient of expansion of the wire and bonding surface material, respectively, ($°C^{-1}$), and

T, T_0 = the final and initial ambient temperature, respectively (°C).

The extent of the wire span for a given contact angle can be characterized by the loop height, h, and bond separation, d, with the use of the relation $\theta = 2\tan^{-1}(2h/d)$. The dependence, described in eq (10), of the change in contact angle $\theta - \theta_0$, on the ratio of the initial loop height to initial bond separation, h_0/d_0, is graphed in figure 5. As

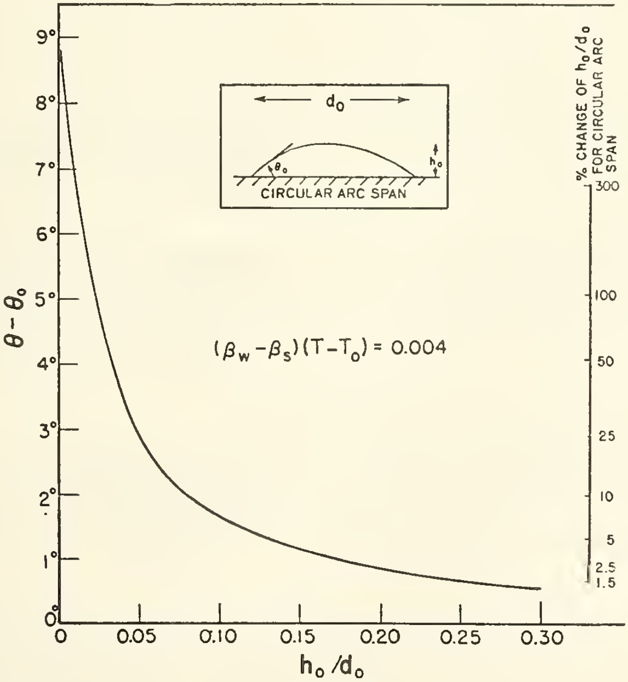

Figure 5. Change in contact angle, $\theta - \theta_0$, versus initial value of the ratio of the loop height to bond separation, h_0/d_0, for a differential expansion between the wire and the bonding surface, $(\beta_W - \beta_S)(T - T_0)$, of .004. A scale parallel to the $\theta - \theta_0$ is provided to show the percentage change in h_0/d_0 for the change in contact angle.

may be seen, flexing increases for smaller values of h_0/d_0 for a given change in temperature. Thus one may expect the wire bonds with relatively large values of h_0/d_0 will not be stressed significantly by these tests. This observation extended to the design of the wire bonds suggests that for devices intended for applications where the device must sustain a great many on-off power or temperature cycles the ratio h_0/d_0 should be as large as practical.

8. Summary

The test stress to which the wire bond is subjected and hence the effectiveness of the test is dependent on the dimensions of the wire loop as well as on a number of other factors. All too often the wire bond tested is insufficiently described to estimate the stress applied and hence to judge adequately the quality of the wire bond. This is particularly true of the pull test which is the most widely used destructive test. The method is fast and easy to perform and it provides a number, the pull strength, for use as a measure of quality. However, the temptation is to use only this number without specifying other data required to interpret the results of the test.

In the centrifuge test the stress is significant only for gold wire bonds and even then it is relatively small for the acceleration levels typically used unless the bond separation is large.

Because of practical limitations on the peak decelerations, the mechanical shock test is generally not an effective screen test for wire bonds. The stress to wire bonds in a vibration fatigue test for any practical wire bond is insignificant because of the very small accelerations involved. The variable frequency vibration test, on the other hand, may stress wire bonds significantly if their lowest resonant frequency is within the frequency range of the test. This may occur for gold wire bonds with large bond separations and loop heights.

Thermally-induced stress tests may apply a significant stress to wire bonds with small loop heights and where the differences in the thermal coefficients-of-expansion of the constituent parts of the device are significant. This is especially true for tests involving many cycles.

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A significant fraction of the failures that occur in integrared circuits are due to failures of the wire-bond electrical connections that are used. Therefore, a critical area for reliability improvement is in the methods for testing and evaluating wire bonds. Several of these methods are surveyed. In particular, analyses with regard to the stress that the test imposes on the wire bond in the pull, centrifuge, mechanical shock, vibration, and temperature cycling tests are presented and used in discussing the capabilities and limitations of these methods.

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