probability of surface contamination present in the bonding area. Activation energies of about 0.4 eV are typical of contamination caused by residues deposited on the surface during the curing of epoxies.

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Acoustic-Emission-Monitored Tests for TAB Inner Lead Bond Quality

GEORGE G. HARMAN, FELLOW, IEEE

Abstract—An introduction to acoustic-emission (AE)-based tests applied to quality control in the electronics industry is given. Bond integrity tests for tape automated bonding (TAB) devices using AE monitoring are described. These include a pull tester and a microfatigue tester for off-line evaluation of bond quality and metallurgical system reliability as well as a prototype of an automatic on-line production bond quality tester. The microfatigue tester for TAB leads can apply a small oscillatory (up to 80 Hz) force on top of a constant force bias of a few grams. A major result was that the most common metallurgical system (tin-plated copper leads bonded to gold bumps) results in the formation of brittle intermetallic compounds which crack relatively easily. The cracks propagate under cyclic stress and result in a very low fatigue life, compared to another TAB metallurgical system. The inner lead bond integrity tester and lead-forming system is designed to be used on-line. Precision tools apply a predetermined force to the leads, which nondestructively tests the bonds and forms the leads. The AE monitor can indicate any failures and the device can be rejected.

I. INTRODUCTION TO ACOUSTIC-EMISSION TESTING IN ELECTRONICS

ACOUSTIC EMISSION (AE) is generally defined as being a transient elastic wave or stress wave generated by the rapid release of elastic energy within a material undergoing fracture or deformation. In 1950, Kaiser made the first comprehensive study of the phenomena [1]. His name is associated with the generally irreversible nature of AE, in which little or no acoustic emission occurs until previously applied stress levels are exceeded. The emitted stress waves may have frequencies ranging from the audible to the megahertz region, but the maximum energy is usually concentrated in the mechanical resonance modes of the test specimen. Most AE detection equipment operates at several hundred kilohertz to avoid interference from environmental noise. Detection of AE waves usually takes place with ceramic piezoelectric transducers that are acoustically coupled to the specimen; however, wide band optical [2] and capacitive detection [3] methods have also been used. Publications are available that give theory, equipment, and applications of AE to a variety of nonelectronic applications [4], [5].

The various sources of acoustic emission that have been observed include: crack nucleation and propagation; twinning; grain boundary sliding; multiple dislocation slip; creation of multiple dislocations; solid-solid, solid-liquid, and liquid-solid phase transformations; and the Barkhausen effect (realignment of magnetic domains). Most microelectronic uses of AE are concerned with solid-liquid-solid phase transformations (as during welding or soldering) or with crack propagation (as when a weld or a solder joint breaks).

Recently acoustic emission has been used for real-time evaluation of electronic materials and assembly processes during production. The largest effort in this area took place at the Western Electric Engineering Research Center, Princeton, NJ [6]. Vahaviolos [7] used AE to reveal substrate...
cracking during the thermocompression bonding of beam lead semiconductor devices to gold metallization on ceramic substrates. Saiifi and Vahaviolos [8] have reported the use of AE for real-time nondestructive evaluation of laser spot welding of small polymer insulated wires to electronic terminal posts. Carlos and Jon [9] used AE to detect cracks in the ceramic casings of capacitors that resulted from the thermal shock of soldering. Cracks so generated could not be observed during visual inspection because the crack-susceptible area was covered with solder. Jon et al. [10], [11] have described the use of AE for the nondestructive evaluation of the quality of several types of complex-metallurgy resistance welds such as those used in welding leads to tantalum capacitors. Another evaluation of resistance welding quality by AE monitoring of nickel wire welding in electronic assemblies was carried out by Knollman and Weaver [12].

There are many cases where real-time AE testing during production is neither practical nor desirable. Instead, a screen or test applied at a later time may be necessary to remove production defects. For instance, in cases of simultaneous multiple bonding such as the high-lead-count tape automated bonding (TAB) of integrated circuits, it is not possible to use AE to assure that all leads are well bonded in real time. A stress test must be applied to the leads at a later time. Likewise when multiple devices or leads are simultaneously bonded, such as in wave soldering or in TAB bonding, AE signals are not interpretable. Epoxy-bonded components yield little or no acoustic emission during curing and thus cannot be tested in real time. Also, tests are often required as screens for incoming inspection of individual parts. Thus the ability to test the component at a later time may, in some cases, be the only way to assure bond or package integrity. This rationale has led to the development of tests for bond integrity of TAB devices described in this paper.

The application of appropriate nondestructive stresses necessary for the acoustic-emission testing of microelectronic-sized joints is often difficult. The most obvious stress is some form of pull or shear test similar to those normally required on a sample basis for production line control. An example of this was described by Harman [13] in which AE equipment was used to monitor a nondestructive wire bond pull test. In testing for the quality of flip-chip integrated circuit solder joints [14], reasonable success was achieved by applying a downward orbiting force on the exposed bottom of the silicon chip. AE revealed poorly soldered bumps on small chips with four to six bumps, but too high a force was required for larger chips with more bumps and this caused some chips to crack. However, the same procedure was successful in revealing weak epoxy bonds to structurally stronger hybrid chip capacitors.

A successful test for relatively large microelectronic thermocompression bonds was described by Jon et al. [15] in which an AE-monitored automated pull test apparatus was used to determine the failure modes of sample quantities of integrated circuit lead-frame bonds. An excellent discussion of the AE waveform analysis techniques required to separate the various failure modes was included in this work.

One of the more promising methods of stressing electronic joints for AE monitoring is the use of thermal shock. This may be accomplished as easily as placing the component on a hot plate or cold stage with an AE detector attached. Such a test was recently used to determine hybrid microelectronic package seal integrity [16]. A focused infrared beam may also be used. However fast-pulsed lasers generally cannot be used because the extremely rapid differential heating of a small area, even on a uniform surface, creates a large burst of stress waves (AE) which mask any thermally induced crack propagation. A continuous wave (CW) laser beam moved across a surface can be used to produce differential heating in small areas. Care must be taken, however, not to overheat the surface (melt solder, damage epoxy, etc.), and different optical reflectances can result in less heat on a shiny surface solder joint than on an equally strong but dull surface solder joint. Also, the volatilization of flux or other dark surface coatings can produce extraneous AE signals.

II. THE DEVELOPMENT OF AE TESTS FOR INDIVIDUAL TAB LEADS

A. Apparatus: An AE-Monitored Lead Pull Tester and Microfatigue Tester

The general electronic instrumentation used for most AE testing in the present study is given in Fig. 1. Various portions of the apparatus may not be used in all experiments. The computer is used to control the transient recorder's operation mode and to analyze the AE waveforms captured by the transient recorder in order to perform fast Fourier transforms on the data. A more detailed explanation of the present electronic equipment is given in [14] and [16]. It should be noted that a wide range of AE instrumentation can be obtained off-the-shelf from several AE instrumentation suppliers.

When working with any microelectronic bonding system it is necessary to evaluate the bond quality as well as the bonding machine set-up parameters with some form of stress test. In the present work this is done with an NBS-constructed motorized pull tester, shown in Fig. 2. During a pull test the AE-trigger-controlled switch (Fig. 1) can turn off the pull motor at failure or before failure on a prebreak AE signal.

The pull tester also has a capability of applying a small low frequency oscillatory force (up to ±10 mN) to a lead either during the motorized pull test or separately. The in-line vibration fatigue unit, Fig. 2(c), is expanded and shown in detail in Fig. 3. It consists of a bar magnet (b), which is epoxy-bonded in-line with the force gage (a) and the microtweezer (d). The magnet is surrounded by a low impedance coil (c) which is driven by an audio amplifier at frequencies of from five to about 80 Hz. The amplifier signal for the vibration solenoid is passed through the electronic switch (Fig. 1) and is controlled (turned off) by the acoustic-emission trigger unit when a bond begins to lift, when lead fatigue cracks propagate, or when the lead plating separates. The sample can then be removed and observed in that prebreak condition.

For the microfatigue test the TAB lead is gripped with the microtweezer (Fig. 3(d)) and a small bias force (20 to 50 mN) is applied. Then the oscillatory force is superimposed on the
bias force. The vibratory displacement is measured with a 120X binocular microscope having a calibrated eye-piece reticle. The displacement blur of a light reflection point on the vibrating lead is adequate for displacement measurements during tests. However, a stroboscope unit is desirable for initial setup and calibration since any nonvertical displacement of the lead or other potential problems can be observed. Although the AE system can be used to detect prebreak cracks it is usually operated at reduced sensitivity during fatigue tests so that it stops both the solenoid and a counter when the lead breaks. The counter output then gives the exact number of cycles to failure. This is an example of incorporating acoustic-emission-monitoring equipment in an experiment in which AE data as such are not important, but the exact timing of a microevent is essential and can be obtained in no other way.

**D. Pull Tests on TAB Leads**

AE-monitored pull tests on TAB leads have been carried out on devices bonded to both 11-mm and 35-mm tapes. These devices are shown in Fig. 4 and represent two TAB metallurgical bonding systems. The 11-mm tape leads are bare copper and are thermocompression-bonded (TC bonding) to gold-plated bumps. The 35-mm tape leads are tin-plated copper and are melt bonded to solid gold bumps.

The forces actually applied to the TAB-chip bond during a pull test can be calculated from the resolution of forces (1) and (2). The variables are defined in Fig. 5. The tensile
pull force along the lead is

$$F_L = F_{app}(1 - \varepsilon)\left(1 + \frac{e^2d^2}{h^2}\right)^{1/2}. \tag{1}$$

The peel force (vertical component of $F_L$) applied to the bond interface of the bond heel is

$$F_p = F_{app}(1 - \varepsilon). \tag{2}$$

These equations are also appropriate for the nondestructive push-up testing for tape bonds described in Section III. The equations assume that the leads extend out perpendicularly from the edge of the chip. For most effective acoustic-emission testing of TAB bonds, the pull hook (or force probes in Section III) should be positioned to apply a relatively high peel force. This is achieved by pulling or lifting the leads as near as practical to the edge of the chip, as seen in (2).

Examples of simple cumulative AE data from three pull tests of leads are plotted in Fig. 6. Curve A is AE data from a lead that gave three prebreak AE bursts [at 46, 107, and 137 mN] before peel failure at 145 mN. Well-bonded leads from these TAB devices that failed by heel breaks had a mean ($\bar{x}$) pull force of 260 mN and a 52-mN standard deviation ($s_x$). Fig. 7 gives the AE waveform burst from the position of the arrow on curve A. Curve B of Fig. 6 is AE data from an adjacent lead that peeled at approximately the same force as that of curve A, but with no prebreak AE bursts. About 75 percent of the 11-mm tape leads that failed by peel failure without detectable prebreak AE bursts. About 75 percent of the 11-mm tape leads that failed by peel failure without detectable prebreak AE bursts. This may be characteristic of TC bonding. Curve C is the AE data from the pull test of a strong lead-to-bump bond on the 35-mm polyimide tape. Failure occurred when the bump lifted from the chip, and after a long series of small prebreak cracks at 220 mN. For this tape during several hundred pulls, well-bonded leads that failed by heel breaks had an $\bar{x} = 382$ mN and an $s_x = 60$ mN. After observation of data such as in Figs. 6 and 7, it should be possible to automatically determine the failure mode by using data processing techniques described for pull tests on lead frames in [15].

C. Microfatigue Tests on TAB Leads

Over half of the 35-mm tape leads that were pull tested gave AE bursts at low force levels (~30 to 40 mN) but failed (broke) within the normal pull force range of well-bonded leads ($\bar{x} = 382$ mN). This bond system consists of gold bumps on the chip and tin-plated copper leads on the tape. During the bonding process the tin melts and forms various intermetallic compounds with the gold bump, as is evident in Fig. 8(a). These compounds are relatively brittle, especially any AuSn$_4$ that forms, and if the lead is stressed they will crack at comparatively low forces. Such cracks are shown in Fig. 8(b). The upper lead cracked at 50 mN accompanied by an AE burst. It was further stressed to 100 mN with no additional AE. The lower lead was stressed at 40 mN and cracked, as shown in the figure. An acoustic-emission burst was recorded at that point. It was further stressed to 70 mN with no additional AE. Fig. 8(c) is a closeup of the lower lead. The AE burst is associated with the small double crack. Upon pull testing these two leads required 370 and 440 mN to break, respectively, and were within one standard deviation of all 35-mm tape pulls, with or without intermetallic cracking, that failed by heel breaks. Thus for this metallurgical system the low-stress AE, while indicative of brittle intermetallic compound formation, was not observed to degrade the bond strength obtained in a pull test.

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4 The difference in pull force between the two tape sizes, indicated in this paragraph, is attributed to differences in the lead cross section as well as metallurgical properties, such as hardness and elongation, but the leads were typical of their 1977-1979 manufacturing period.
Fig. 8. (a) Scanning electron micrograph of original unstressed tape-bonded leads. Arrow on upper lead points to large gold-tin intermetallic compound lump. Only minimal intermetallic compound is observable on lower lead. (b) Same two leads in (a) after stressing upper lead to 100 mN and lower one to 70 mN. Cracks at heel of bond in both are obvious. (c) Closeup of lower cracked lead and bump of (b). Small amount of intermetallic compound is evident filling area as lead leaves bump, indicated by arrow. Double acoustic-emission burst that occurred when lead was stressed to 40 mN is shown below. Horizontal scale is 130 μs/div.

Since the intermetallic cracks did not affect the pull strength it was postulated that they might propagate under a low amplitude repeated flexing type of stress, such as is encountered in thermal cycling. Some fatigue studies on small bonding wires had indicated rapid failure if they were thinned or notched [17]; therefore, 35-mm TAB leads with gold-tin intermetallic compound formation, similar to that in Fig. 8, were tested in the microfatigue apparatus of Fig. 3. These tests were made to compare the effects of the brittle intermetallic against the unplated copper TC-bonded leads of the 11-mm tape. Such tests were carried out with a constant upward force (bias force) of from 0 up to 50 mN. Tests have been run with constant displacement (±0.017 and 0.034 mm) and at a constant vibration force ±5 and 10 mN at a frequency of 40 Hz. The microtweezer-hook clamped the lead approximately 0.18 mm out from the edge of the bump. For leads so tested (38 leads from eight devices widely spaced along the length of the tape, vibrated at a displacement of ±0.017 mm and a bias force of 20 mN), the tin-plated leads on the 35-mm format on average broke within 140 vibration cycles at the edge of the bump.
Unfortunately the standard deviation of the cycles-to-failure was as large as the mean so it was not possible to plot the data as strain versus cycles-to-failure. Metal fatigue is statistical in nature, but tests on individual microleads introduce additional uncertainties resulting from the difficulty of precise tweezer placement along the lead, as well as varying lead shapes and dimensions. By comparison, the 32 unplated TC-bonded leads of the 11-mm tape that were tested withstood an order of magnitude more vibration cycles (X = 1605) before breaking at the edge of the bump.

The combination of tin plating and melt-type bonding resulted in a more fatigue-prone bond heel than the TC-bonded unplated copper leads. This was additionally verified by fatiguing the tin-plated leads at the tape interface where no gold-tin alloy was present. The fatigue strength of this end of the lead (using constant displacement comparisons to account for increased lead width) was as high as that of the unplated TC-bonded leads. The implication is that if TAB devices are to be used in thermal-cycle-type environments (e.g., in an automobile) which can result in lead flexing then the unplated copper leads should be more reliable. Only TAB devices in each tape size and from one manufacturer's lot were available for testing although for experimental purposes each manufacturer had changed some bonding parameters along the length of the tape. The purity and hardness of the leads were not known so it is possible that other similar TAB leads may show better fatigue strength. However, considering the factor-of-ten difference in microfatigue strength, it appears desirable to conduct fatigue tests when determining both the lead-bonding parameters (time, temperature, and force) and the device suitability for use in thermal-cycle-type environments.

In addition to using TC-bonded bare copper leads, there are two possible metallurgical solutions to restrict gold-tin intermetallic compound formation and thus improve the fatigue characteristics. One is to severely limit the thickness of the tin plating on the lead, and the other is to use nonmoble bumps having, at most, only a thin strike plating of gold. Also, a limited number of tests (25) of bumped tape leads (gold plated copper), TC bonded to aluminum metallization, have shown fatigue life comparable to that of 11-mm copper tape leads.

III. AN AE-MONITORED NONDESTRUCTIVE BOND QUALITY TESTER AND LEAD FORMING SYSTEM FOR TAPE-BONDED INTEGRATED CIRCUITS

The pull tester and microfatigue tester described in Section II, which tests individual leads, is useful for evaluating lead and bond metallurgy and bond weld schedules, but it is not intended for production monitoring of TAB bond quality. For this purpose a prototype automatic tester has been designed to both nondestructively test as well as to form the leads on TAB inner lead bonds. Bond failure is indicated by AE monitoring. This tester is shown in Fig. 9 with closeups of the test stage, without the TAB device, in Fig. 10 and of the adjustable force wedges in Fig. 10(e). In operation, the 35-mm tape is advanced until the chip is centered in the fixture. A tool clamps the chip by pressing down on top of the bond on one opposite side of the chip, leaving the leads on the other side free to be tested. Another tool consisting of two adjustable wedges (Fig. 10(e)) rises from below, exerts a vertical testing and lifting force against the unplated leads, and bends them upward. (This force is determined for each device type or lead design6 based upon destructive pull tests and the amount of lead-forming desired, but is on the order of 100 mN per lead.) Both the AE trigger and the totalizer of Fig. 1 are used to assist in the interpretation of failures. The AE amplifier may be time-gated (or force-gated) to be sensitive only after approximately 10 mN per lead is applied, in order to avoid any interference noise from contact or scraping of the wedges against the leads. The gate window would be closed after maximum force is applied. With the present equipment, gating was found unnecessary for the slow application of force. However, it was essential when the rate of force application was increased by a factor of ten, which would be required for practical production testing.

Approximately 40 of the 35-mm TAB devices have been tested on the apparatus of Fig. 9. Representative data were selected from four of these tests and are given in Fig. 11. The data are plotted as simple cumulative AE counts with no other data processing involved in order to show the actual AE data obtained from each test. Curves A and B represent cases

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6 Many tapes have complex (zig-zag) lead designs and the force in each lead should be determined. If there is a significant variation in \( F_L \) and \( F_P \) (in (1) and (2)) from lead to lead when using a straight (horizontal) push tool to stress the leads (in Fig. 10(e)) then that tool should be shaped to compensate for unusual lead configuration.
where the lead-to-bump-to-chip interfaces were strong. Points on curve A are the result of cumulative AE noise. This is the ideal case where no intermetallic cracks occurred. Curve B results from leads having strong bond interfaces, but reveals Au-Sn intermetallic cracking during the test. Curves C and D are the result of bumps separating from the chip (the lead-to-bump interface was strong).

It is apparent from curves C and D that the same type and number of lead failures can produce widely different cumulative AE counts (in this case, 4000 and 9000 counts). Such differences may result from the particular form and velocity of crack propagation as well as some nonuniformity of the AE coupling to the detector. However, the separation of weak bonds (curves C and D) from strong bonds (curves A and B) could be improved if signal processing methods described in [15], such as multiple amplitude thresholds, squaring the signal amplitude, etc., were implemented. Examination of the AE waveforms (from the transient recorder output in Fig. 1) indicate far higher peak amplitudes occurred during interface failures (curves C and D) than during intermetallic microcracking in curve B, making clear separation relatively easy.

At the present time this prototype TAB innerlead test system has only been used on chips bonded to 35-mm wide tape that was available from one supplier. These tape bonds, while intentionally made with some variations of bonding parameters, were not designed to fail at low forces. Although in testing some turned out to be weak and were detected by AE, it was not possible to set up systematic tests on bonds with a known range of strength and failure modes, which is necessary when qualifying a new test method. Efforts are being made to obtain other TAB devices with a range of bond strengths. Certain problems relating to AE-quiet, wear-resistant organic surface coatings for the chip and lead-contacting tools have not been completely solved. A polyester film coating has been used for this purpose but it would be desirable to use a hard, molded plastic such as nylon. The present prototype only tests half the leads on a device. Assuming that 100-percent testing and lead forming are required, a second test stage that applies force to the other leads could be used.

**IV DESIGNING MICROELECTRONIC WELDS FOR AE TESTABILITY**

In developing tests to reveal poor microelectronic (or other) welds one must understand the failure modes, and to do this it is also necessary to understand the nature of poor welds. A poor weld is here defined as having only a small percentage of its interface welded, either due to an underbond weld
When placed in stress, the edge of a poor weld between ductile metals serves as a notch or crack for stress buildup and the interface serves as a channel through which the extending crack must propagate. This has been observed to occur rapidly in many poor welds and without major deformation or yielding of the weldments. This type of break between ductile weldments, therefore, has some similarities to the Griffith break. However, since the density of the microwelds in a poor weld may vary from point to point, a propagating crack could meet increased resistance and stop until a higher force is applied, as in the brittle cleavage of polycrystalline materials when a crack encounters a grain boundary.

Thermocompression welds made between contaminated gold interfaces using normal bonding parameters have been found to contain numerous isolated microwelds with dimensions of a few micrometers as shown in Fig. 12. Underwelding (too low a temperature or force) also produces similar isolated microwelds (Fig. 13), where broken microwelds can be seen on the surface of gold-plated bumps from 11-mm TAB devices in which the copper leads had peeled off at low forces. As a weld between clean interfaces matures, the microwelds increase in size and join together, resulting in a high percentage of the interface (≥ 50 percent) being welded.

Most weldments used in electronic assembly involve copper, gold, aluminum, and other ductile materials. Normally, cracks in the bulk of such polycrystalline ductile materials can be expected to propagate erratically with considerable yielding of the metal. However, surface cracks in brittle materials such as glass propagate in relatively straight lines with velocities about 0.3 times the velocity of sound in that material. This is known as Griffith crack propagation [18], [19]. Once started by the application of a given stress in a brittle material complete fracture usually ensues.

Assuming that the microweld density is reasonably uniform it is likely that many poor welds would fail quickly with a single AE burst or with series of bursts within a few milliseconds before failure and not be preceded by detectable prebreak cracks at significantly lower stress levels. This has been observed on some bonds in Section II as well as in large numbers of nondestructive microelectronic wire bond pull tests. However, perhaps half or so of the welds do fail by two or more partial "lifts." In these cases it is assumed that there is a large change in the density of microwelds across the weld interface.

Obviously it would be desirable to have all poor welds fail by a series of small cracks as the stress level is increased, thus giving a warning AE burst at a low nondestructive test stress level that could be related to premature failure if the stress were increased somewhat. Considering the unpredictable nature of typical poor welds and their frequent rapid break without AE warning, it is apparent that it would be desirable to design the weld interface to optimize it for AE testing. The most likely method applicable to electronic leads would be to shape the welding tool to apply lower force to the bond heel region. In a normal strong weld, this would result in the heel region weld being slightly weaker than the bulk of the weld. Then any underbonded or contaminated weld made with the same tool would have a heel region weld significantly weaker than the bulk of the weld and would begin to peel, emitting AE at a low test force and allowing low-stress detection of weak welds. If the concept of designing welds and other joints for testability is accepted, then the reliability of AE testing as a post-production screen can be further improved.

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