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Keynote Paper

SENSITIVE MICROWAVE NONDESTRUCTIVE EVALUATION OF MATERIALS

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Abstract Microwave is a tool, which enables us to evaluate materials without bringing a sensor into contact with the surface of inspected material and also without coupling medium between the sensor and the surface. The present paper reviews some microwave techniques developed recently for sensitive evaluation of materials. One is a dual frequency technique which deals with a small crack on the metal surface, where both the extent of crack closure and the crack size are unknown. It is noted that usual microwave techniques have not succeeded to detect a crack on the metal surface due to lack of sensitivity, while they have been able to detect a slit having finite width. It is shown that the crack size is precisely evaluated by using a highly sensitive sensor, which is coaxial line sensor, with two different frequencies. Secondly, microwave imaging of a delamination happened in an IC package is demonstrated. The delamination is known to happen at the interface between the encapsulant resin and the chip pad as a result of the stress due to thermal expansion mismatch between dissimilar materials and the evaporation of the moisture, absorbed in the package, during the solder reflow process. The shape and size of the delamination can easily be recognized by the image obtained through scanning the coaxial line sensor above the package. Finally, quantitative evaluation of the moisture absorbed in IC package is also shown.

Keywords: Nondestructive evaluation, Material, Microwave, Coaxial line sensor

INTRODUCTION

Microwave is an electromagnetic wave having a wavelength of 1 mm to 1 m [Pozar, 1998]. Microwave has an advantage that it can propagate well in the air. Therefore, a coupling medium is not necessary when nondestructive inspection is carried out [Ju *et al*., 1998]. Another advantage of microwave is that the inspection result is independent of density but the intrinsic properties of the materials. That is why microwave inspection has often a higher sensitivity than the other techniques, especially for inspection of dielectric materials. With the development of new materials, microwave inspection has become an important technique in the field of nondestructive testing (NDT). Microwave NDT has been used for testing voids, delamination and porosity etc. in polymers, ceramics, plastics, and composites [Urabe, 1992; Gopalsami *et al*., 1994; Diener, 1995; Qaddoumi *et al*., 1995]. Usually, waveguide or horn antenna has been used as a probe to couple the microwave energy with the materials. However, they have a dimension dependent cutoff frequency below which the propagation of microwave is not possible. Hence, the spatial resolution is limited since the aperture of the probe cannot be made sufficiently small, in order to ensure the operating frequency not to be cut off. In addition, the distribution of electric field is not symmetric to the center of the sensor aperture, so the spatial resolution is different with the change of the scanning direction. Recently, an open-ended coaxial line sensor has been suggested for sensitive nondestructive evaluation of materials [Ju *et al*., 1999a]. Coaxial line sensor can support transverse electromagnetic (TEM) waves with no cutoff frequency for the fundamental TEM mode. Therefore, the operating frequency band can be broad and, for near-field inspection, it would also be possible to decrease the size of the sensor aperture to increase the spatial resolution. Moreover, the electric filed at the sensor aperture is center of symmetry, thus the spatial resolution is independent of the scanning direction. In the present paper, a dual frequency technique for quantitative evaluation of fatigue cracks in metals and a microwave imaging technique for inspection of delaminations in IC packages are demonstrated, and microwave evaluation of moisture absorbed in IC packages is also described.

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EVALUATION OF FATIGUE CRACKS IN METALS

Dual Frequency Technique

A crack is the most dangerous defect in machines and structures. Aircraft fuselage, pressure vessel and piping of chemical and power plants are examples where it sometimes occurs. Fatigue cracking often initiates from the surface, since the stress on the surface is often higher than that of inside when a material is under load. Hence, nondestructive evaluation of the surface connected cracks in practical structures is inevitable for their integrity assessment [Buck and Skillings, 1982; Clark *et al*., 1987; So and Sinclair, 1987]. However, the evaluation of a small surface fatigue crack under a no load condition is a difficult issue because the state of the crack, i.e., the width or the extent of closure of the crack [Elber, 1970], is unknown [Saka *et al*., 1987; Ahmed and Saka, 2000]. Just recently, a novel microwave dual frequency technique was developed and succeeded for quantitative evaluation of fatigue cracks [Saka *et al*., 2001a].

Consider microwave irradiating a metal surface where a crack is in the near-field of the sensor. When the electric field is perpendicular to the crack, from Maxwell's equations, a microwave current will occur on the crack surface. This current, $\vec{J}_s$, can be written as

$$\vec{J}_s = \vec{n} \times \vec{H} \tag{1}$$

where $\vec{n}$ is the normal unit vector pointing out of the crack surface and $\vec{H}$ the magnetic field interacting with the crack. The current propagates along the crack surface in the direction of crack depth and recreates a microwave electromagnetic field in a gap between two crack surfaces. Thereby, the crack becomes a waveguide, which propagates the microwave. In the process of the microwave propagation in the crack, conductor loss is induced which is enlarged with the increase of the crack depth. In addition, if the crack is open, as the crack is located in the near-field of the sensor, an attenuation of the microwave in the air occurs in the above gap, which enlarges with the increase of the depth and the width of the crack. On the other hand, if the crack is closed, the conductor loss will be decreased. Hence, the amplitude of the reflection coefficient, a ratio of the reflected wave to the incident wave concerning the interaction of the microwave with the crack, can be expressed as a function of the depth of the crack.

On the other hand, when a crack presents under the sensor and the electric field is parallel to the crack, there is no current generated on the crack surface. Therefore, no microwave propagates in the crack. Thus, the amplitude of the reflection coefficient is same as that in the case of no crack existence.

Fig. 1 shows the mechanism of the sensor scanning a crack [Ju *et al*., 2001a]. Since the electric field in the coaxial line sensor is only in the radial direction between the inner and outer conductors for the fundamental TEM mode and the crack passes two times between the inner and outer conductors under the sensor, a *W*-shaped characteristic signal will be obtained due to the aforementioned reason.

By paying attention to the amplitude of the reflection coefficient obtained by the coaxial line sensor, its difference in decibel, Δ*A*, between the case that no crack exists and the case that a crack is under the sensor has simply been expressed as [Saka *et al*., 2001a]

$$\Delta A = S(f)d + G(f)\Phi(w,\sigma)d \tag{2}$$

where

$$\Phi(w,\sigma) = \begin{cases} \xi(w), & if\ \sigma = 0 \quad (open\ \ crack) \\ \eta(\sigma), & if\ w = 0 \quad (closed\ \ crack) \\ 0, & if\ \ w = 0\ and\ \sigma = 0 \end{cases} . \tag{3}$$

In Eq. (2), $S(f)$ and $G(f)$ are constants depending on the operating frequency, f; d and w denote the depth and the width of a crack respectively and σ the closure stress; $\xi(w)$ is a function of w and $\eta(\sigma)$ a function of σ. The first term on the right hand side of Eq. (2) indicates the conductor loss generated on the crack surface. The second term expresses the attenuation of the microwave in the air in the case of an open crack or the decrease of the conductor loss in the case of a closed crack.

Based on Eq. (2), an equation for evaluating the depth of any crack has been derived as follows by using two arbitrary operating frequencies f_1 and f_2. Two fatigue cracks with known crack depths, d_a and d_b, are prepared in advance, where the width and closure stress of the crack having the depth d_a are zero. First

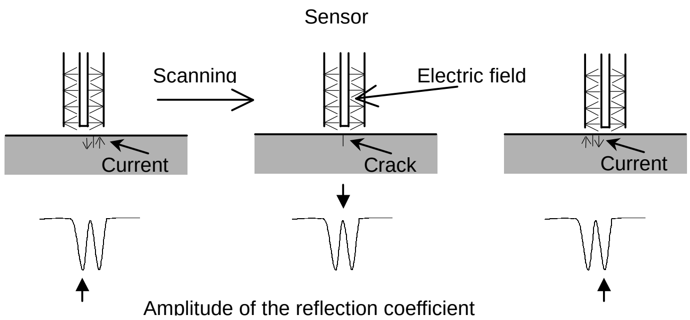

Fig. 1 The Relation of the microwave response with the sensor position for the detected crack

the crack having the depth d_a is measured. From Eqs. (2) and (3), one gets

$$S(f_1) = \frac{\Delta A_a(f_1)}{d_a} \quad (4)$$

and

$$S(f_2) = \frac{\Delta A_a(f_2)}{d_a} \quad (5)$$

where $\Delta A_a(f_1)$ and $\Delta A_a(f_2)$ are amplitude difference of the reflection coefficient measured for the crack on the frequencies f_1 and f_2 respectively.

After the constants $S(f_1)$ and $S(f_2)$ are determined by using the above crack, next, the amplitude differences, $\Delta A_b(f_1)$ and $\Delta A_b(f_2)$, for another crack having the depth d_b are measured. Thus, the ratio of $G(f_1)$ to $G(f_2)$ can be determined from Eq. (2) as

$$\frac{G(f_1)}{G(f_2)} = \frac{\Delta A_b(f_1) - S(f_1)d_b}{\Delta A_b(f_2) - S(f_2)d_b}. \quad (6)$$

For any fatigue crack having the depth *d*, once $\Delta A(f_1)$ and $\Delta A(f_2)$ are measured, the evaluation equation of the crack depth can finally be expressed from Eq. (2) as

$$d = \frac{\Delta A(f_1) - \frac{G(f_1)}{G(f_2)}\Delta A(f_2)}{S(f_1) - \frac{G(f_1)}{G(f_2)}S(f_2)} \quad (7)$$

where the values of $S(f_1)$ and $S(f_2)$ are given by Eqs. (4) and (5), respectively, and the value of $G(f_1)/G(f_2)$ is given by Eq. (6). It is noted that we do not need to know $\xi(w)$ and $\eta(\sigma)$ in Eq. (3), because these functions are not included in Eq. (7). By using Eq. (7), the depth of any crack can be evaluated quantitatively irrespective of the closure stress. Here, one does not need such an analysis of inverse problem as done in Refs. [Saka *et al.*, 1987; Ahmed and Saka, 2000] and also does not need to assume any value of crack width.

In order to obtain the values of $S(f_1)$, $S(f_2)$, and $G(f_1)/G(f_2)$, two specimens made of austenitic stainless steel AISI 304 were subjected to four point cyclic bending under the conditions of the stress ratio 0.1 and the maximum stress intensity factor 22 MPa·m$^{1/2}$, for introducing 2-D fatigue cracks. One of them was laid up for three months after introducing fatigue crack to make the crack satisfying the conditions of w = 0 and σ = 0 by releasing residual stress, then offered for microwave measurement, and finally broken to observe the crack depth d_a on the fractured surface. The value of d_a was 4.0 mm. Another specimen, in which the extent of crack closure was unknown, was also offered for microwave measurement and then broken. The value of its crack depth d_b was 2.8 mm. By using these two fatigue cracks, the values of $S(f_1)$, $S(f_2)$, and $G(f_1)/G(f_2)$ were determined for f_1 = 105 and f_2 = 110 GHz as follows:

$$S(f_1) = 0.0056 \text{ dB/mm}, \quad S(f_2) = 0.0082 \text{ dB/mm},$$
$$\text{and } G(f_1)/G(f_2) = 0.82\,. \quad (8)$$

Introduction of Fatigue cracks

To conduct the experiment, three fatigue cracks were introduced in different specimens respectively. Specimens were prepared as plates having the initial dimensions of 330×35×25 mm as shown in Fig. 2, from the same materials of austenitic stainless steel, AISI 304. To introduce a fatigue crack, an initial notch was situated in the *L-S* orientation of the plate, where the direction of crack growth is considered perpendicular to the longitudinal rolling direction, *L*, and parallel to the short transverse direction, *S*, of the material (ASTM code for crack plane orientation). The fatigue crack in each specimen was grown from the tip of the initial notch by cyclically loading the plate in four points bending of tension and tension on the dynamic testing machine. During the process of fatigue, crack growth was monitored from both sides of the specimen and the maximum value of the stress intensity factor, $K_{\mathrm{Im}ax}$, was determined with the average value of the crack depths measured on both sides of the specimen. The stress ratio, *R*, defined as a ratio of the minimum to the maximum value of the stress intensity factor, was maintained during the crack growth. After the desired depth of the crack was reached, the plate was machined and polished to remove the initial notch, leaving a true

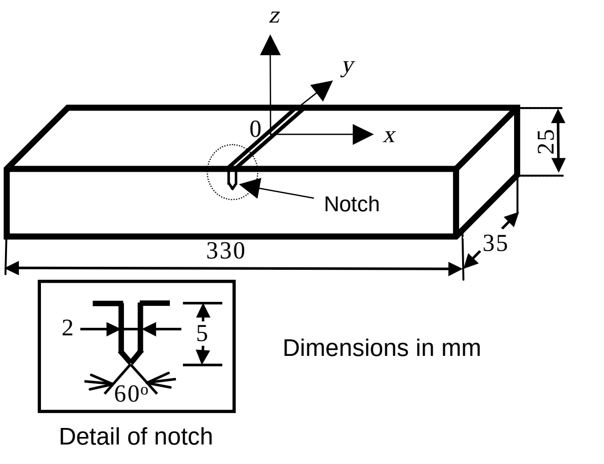

Fig. 2 Descriptive geometry of the specimen

fatigue crack in the remaining material. The conditions used for introducing fatigue cracks in the specimens are listed in Table 1. The value of the crack depth, *d*, indicated in Table 1 is an average of the measurements performed at the three locations in the direction of the

Table 1 Conditions used for introducing fatigue cracks

Specimen	Maximum stress intensity factor K_{Imax} (MPa·m$^{1/2}$)	Frequency (Hz)	Stress ratio *R*	Crack depth *d* (mm)
S1	22	6	0.1	0.1
S2	22	6	0.1	0.9
S3	22	6	0.1	3.6

specimen width on the fractured surface after the microwave inspection was carried out.

Microwave Measurement System

The configuration of the microwave measurement system is shown in Fig. 3. A network analyzer was used to generate a continuous wave signal that was fed to an open-ended coaxial line sensor and to measure the amplitude of the reflection coefficient, *A*, at the sensor aperture. Fig. 4 shows the photograph of the microwave measurement system. The operating frequencies were $f_1 = 105$ and $f_2 = 110$ GHz and the standoff distance between the sensor and the specimen was 0.06 mm. Cracks were scanned by the sensor under a no load condition with a pitch of 0.04 mm in a direction perpendicular to the crack at the center of the specimen width. The amplitude *A* was continuously recorded corresponding to the measurement position. A computer was employed to synchronize the stage and to create a one-dimensional graph. The used open-ended coaxial line sensor is shown in Fig. 5. The sensor has an inner and outer conductor with a radius of 0.1 and 0.5 mm,

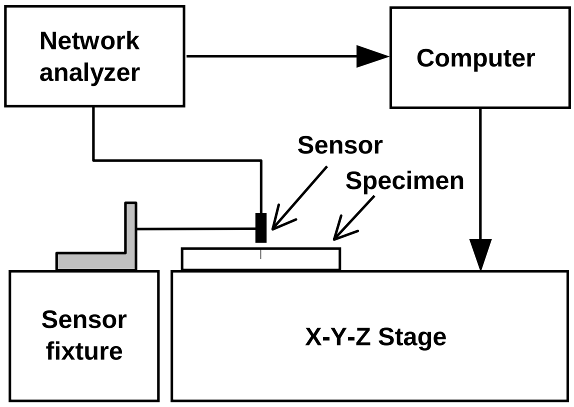

Fig.3 Configuration of the microwave measurement system

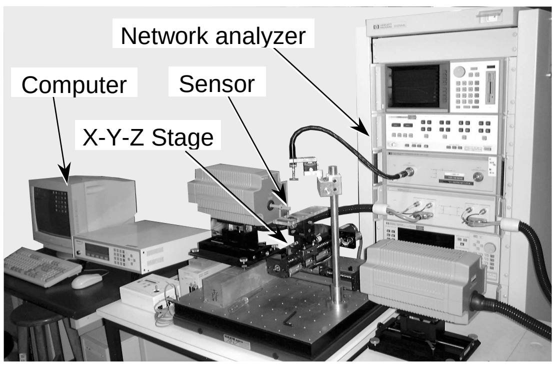

Fig. 4 Photograph of the microwave measurement system

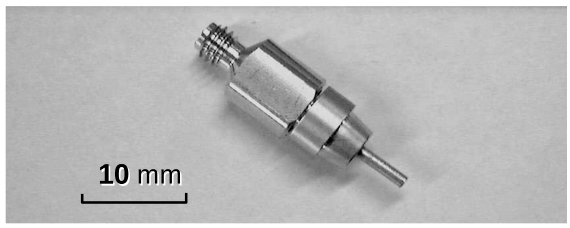

Fig. 5 Photograph of the open-ended coaxial line sensor

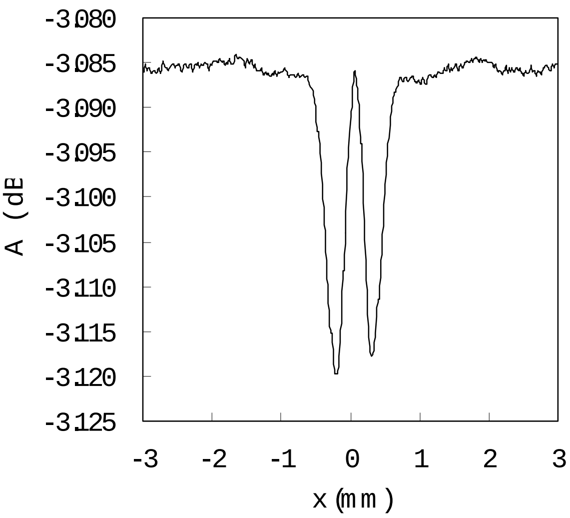

Fig.6 Amplitude of the reflection coefficient obtained by scanning the fatigue crack at the frequency 110 GHz

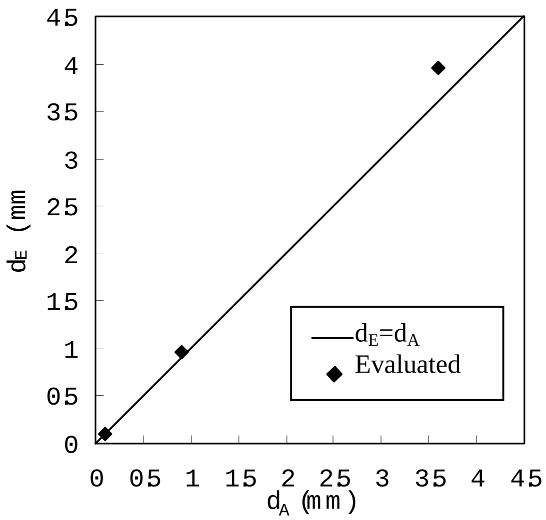

Fig. 7 Comparison of the evaluated crack depths with their actual values

respectively. The spatial resolution of the sensor was evaluated to be 0.125 mm when the standoff distance was 0.5 mm at the operating frequency of 110 GHz [Ju *et al*., 2001b].

Evaluation of Fatigue Cracks

Fig. 6 shows an example of the characteristic signal, a distribution of the amplitude of reflection coefficient, *A*, along the *x*-axis, measured by using 110 GHz at the center of the specimen width, $y = 0$. As shown in Fig. 6, the shape of the graph indicates the result of the interaction of the microwave with the crack. Here, the difference in the two peaks of the *W*-shaped characteristic signal is due to an imperfect symmetry of the used sensor. Hence, the average of the two peaks, P_1 and P_2 shown in Fig. 6, was used to calculate the amplitude difference ΔA:

$$\Delta A = \frac{P_1 + P_2}{2} . \quad (9)$$

It should be noted that the intensity of the microwave transmitted into the crack is significantly small. Therefore, the characteristic signal is very difficult to be measured if the spatial resolution and S/N are not high enough.

By using Eqs. (7) and (8) the depths of the cracks in *S1* to *S3* were evaluated as shown in Fig. 7, where d_E and d_A denote the evaluated and actual values of the crack depth, respectively. As shown in Fig. 7, the evaluated crack depths agree well with their actual values.

Here, only 2-D fatigue cracks were demonstrated. Since the spatial resolution of the sensor is high enough, a 3-D fatigue crack has also been evaluated successfully by using the proposed method [Saka *et al*., 2001b].

INSPECTION OF DELAMINATION IN IC PACKAGES

Delamination in IC Packages

The delamination that may occur in IC packages has become more and more an important factor regarding the reliability of the package, because the plastic encapsulant is required to be made as thin and small as possible in order to raise the density of surface mount. The delamination is often created during the solder reflow process, where the package is exposed to the temperature more than 473 K. The stress due to thermal expansion mismatch and the pressure induced by the moisture evaporation may lead to a delamination at the interface between the chip pad and the encapsulant resin [Kawamura *et al*., 1993; Tay *et al*., 1994; Lee and Earmme, 1996]. The inspection of such delamination is a very important issue for either the design of IC packages or the development of encapsulant materials. Scanning acoustic tomography (SAT) has been used to detect the delamination in IC packages. However, a liquid coupling is essentially used since the acoustic signal cannot propagate in air. Recently, we have developed a new microwave imaging technique by which the delamination can be detected effectively without any coupling medium [Ju *et al*., 2001b].

Imaging System and Sample Description

The microwave imaging system is same as the microwave measurement system described before, as shown in Figs. 3 and 4. Here, a package sample was scanned in the *x* and *y*-directions at the frequency of 110 GHz. The standoff distance was 0.7 mm. The amplitude of the reflection coefficient was measured to create a two-dimensional image. A package sample was prepared by encapsulating the chip and lead frame with the epoxy resin filled silica powder. The dimensions of the package are 14×20×2 mm. The size of chip pad is 9.5×9.5 mm with the resin of 0.7 mm thickness above it. The size of IC chip is 9×9×0.35 mm. The package resin is assumed to be homogeneous, isotropic, and nonmagnetic. The sample was hardened for 2 hours in 448 K and exposed to the post cure for 8 hours in 448 K. To introduce delamination, it was treated by moisture absorption in the environmental conditions of 358 K/85% RH, with the exposed time of 96 hours. Then, it was treated by infrared reflow for 30 seconds in 533 K.

Delamination Inspection

The image of the package obtained by SAT is shown in Fig. 8. The part delamination, which is shown in white color located at the top of the chip pad, can be observed clearly. Fig. 9 shows the amplitude image of the package obtained by microwave imaging. The region in white color at the top of the chip pad indicates a delamination between the chip pad and the encapsulant resin, whereas, at the bottom of the chip pad, the grey color shows a good binding of the interface between the chip pad and the encapsulant resin [Ju *et al*., 2001c].

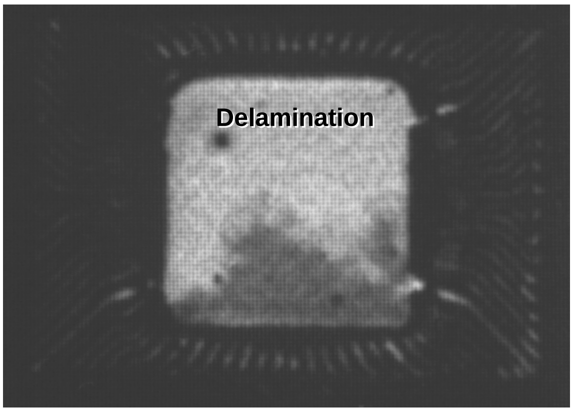

Fig.8 Image of the package with part delamination obtained by SAT

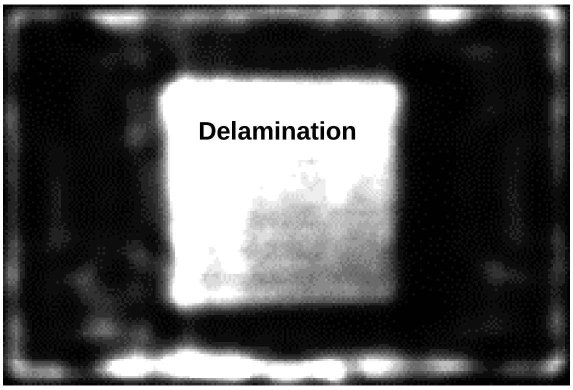

Fig. 9 Amplitude image of the package with part delamination obtained by microwave imaging

EVALUATION OF MOISTURE ABSORBED IN IC PACKAGES

Basic Definition and Approach

It has been reported that the evaporation of the moisture absorbed from the ambient by the encapsulant resin causes a pressure between the resin and the chip pad, which is a factor sometimes causes delamination in IC packages [Kawamura et al., 1993; Tay et al., 1994; Lee and Earmme, 1996]. In addition, moisture diffusion in IC packages can lead to catastrophic failures due to electromigration and corrosion. Therefore, it is important to understand the diffusion behavior of moisture in the encapsulant resin and, the contribution of moisture content to the delamination of IC packages [Puig and Poustan, 1998; Yi and Neo, 1998]. Concerning the study of moisture that affects the reliability of IC packages, the basic issue is the measurement of the moisture content in encapsulant resin. However, most standard methods of moisture content determination require weighing a sample, in some cases drying it for several days (up to several weeks), and reweighing. Recently, a method by using microwave to determine moisture in IC packages has been proposed [Ju *et al*., 1999b]. The primary advantage of microwave methods is that the moisture content can be determined directly from a wet package without drying and weighing it.

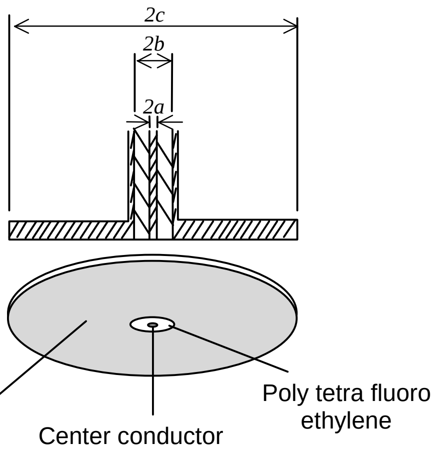

Fig. 10 Configuration of the open-ended coaxial line sensor

The moisture content of encapsulant resin, *M*, expressed in percentage, is defined as

$$M = \frac{m_w}{m_w + m_d} \times 100 \qquad (10)$$

that is, as the ratio of the weight of the contained water per unit volume, m_w, to the total weight of wet material, where m_d is the weight of dry material per unit volume.

The microwave signals interacting with IC packages depend upon the relative permittivity (dielectric properties) of encapsulant resin, standoff distance and operating frequency. Because the relative permittivity of water differs significantly from that of the encapsulant resin, it is possible to separate the effects of water and the dry material in the moist resin. Therefore, when the standoff distance and operating frequency are fixed, the changes in amplitude and phase of the reflection coefficient, which are insertion loss and phase shift respectively, between the cases of with and without a test layer of resin are only due to the dry basis weight and the moisture of the encapsulant resin. Therefore, The moisture content can be determined experimentally from only the microwave parameters independent of the material density.

Experimental Procedure

The microwave measurement system is the same as shown in Fig. 3 and 4. For increasing sensitivity, a coaxial line sensor shown in Fig. 10 was used. The sensor has an inner and outer radii, $a = 0.46$ and $b = 1.50$ mm, respectively. It was terminated into a flat

Table 2 Package samples absorbed moisture in the same environmental conditions for different time

Sample pair number	1	2	3	4
Environmental conditions		303K/ 60% RH	303K/ 60% RH	303K/ 60% RH
Exposed time, hours	0	48	96	144
Dry weight, mN	67.5788	67.5534	67.3348	67.5269
Wet weight, mN		67.5730	67.3603	67.5622
Moisture content, %	0	0.0290	0.0379	0.0522

Table 3 Package samples absorbed moisture in different environmental conditions for the same time

Sample pair number	5	6	7
Environmental conditions	303K/ 60% RH	358K/ 60% RH	358K/ 85% RH
Exposed time, hours	168	168	168
Dry weight, mN	67.5592	67.3799	67.4750
Wet weight, mN	67.5867	67.4485	67.5955
Moisture content, %	0.0407	0.1017	0.1783

metallic flange with radius $c = 14.50$ mm. The operating frequency was 20 GHz. The standoff distance, from the sensor to the surface of the sample, was 0.2 mm. Here, all the samples were considered having the same thickness of resin above the chip pad. For calculating the insertion loss and phase shift, the measurement in the case of the absence of the encapsulate resin layer was carried out in advance by placing a lead frame (without encapsulant) with a standoff distance 0.9 mm.

To conduct the experimental study, 14 IC packages (7 pairs) were prepared. They were formed by epoxy resin filled with silica powder of 79.9 wt%. For introducing moisture, 6 pairs of the packages were treated by moisture absorption in different conditions as shown in Tables 2 and 3, respectively. Table 2 shows the samples absorbed moisture in the same environmental conditions for different time and Table 3 the same time with different environmental conditions. The moisture contents were tested in advance using the standard weighing method. Another pair of packages was free from moisture.

Moisture Determination

The moisture contents determined by microwave and the weighing method are shown in Fig. 11 for different samples, where pairs 1 to 5 experienced different moisture absorption time with the same environmental conditions and pairs 5 to 7 the same time with different environmental conditions. The moisture content determined by microwave method agrees with that based on standard weighing method.

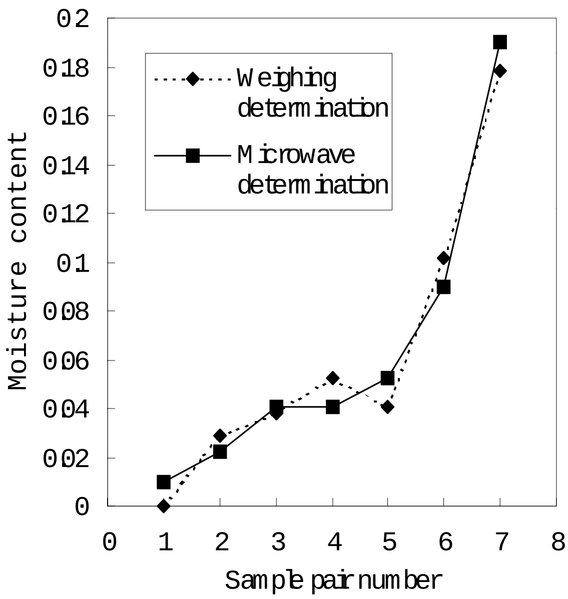

Fig. 11 Measured moisture content for different samples

CONCLUSIONS

Several methods for sensitive evaluation of materials by using microwave have been demonstrated. The novel microwave dual frequency technique for the quantitative nondestructive evaluation of small fatigue cracks has a great significance for the integrity assessment of metallic structures. The small area delamination in IC packages has been detected effectively by microwave imaging technique without any coupling medium. The advanced technique offers a new approach for integrity assessment of IC packages. The method to determine the moisture content in IC packages by using microwaves offers a possibility to measure the moisture content directly without drying and weighing IC packages.

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