AN INSTRUMENT FOR LAYER THICKNESS MEASUREMENT USING PSEUDO-SEZAWA WAVES

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ABSTRACT

An instrument for layer thickness measurement has been developed to measure the layer thickness of lead frames for LSI's more rapidly and accurately than the conventional X-ray fluorescence method. The lead frame consists of 42-alloy substrate with gold layer, 2-5 μm in thickness. The measurement is made by means of the excitation of pseudo-Sezawa waves. This paper discusses the performance of the instrument, in respect to the stability, accuracy and temperature-dependence of the measurement. Considering the measurement environment in the mass-production-line, effects of alignment and displacement of a sensor on the measurement are also discussed. Influence of Lamb waves, which are excited when the substrate is thin, is also discussed. The performance of the instrument is achieved as follows: Measurable thickness range; 1-20μm, stability;±0.2%, accuracy; ±1%, measurement time; 1-sec.

I. INTRODUCTION

IC and LSI chips are usually mounted on lead frames. The lead frame is a thin substrate made of either copper or 42%Ni-Fe alloy(42-alloy). Typical thickness of the substrate is 225μm. The substrate is electroplated with gold or silver on a surface. The electroplated layer is 2 to 5 μm in thickness. The production process of the lead frame consists of electroplating, drying and washing, and is continuously conducted in an automated production-line. It is, therefore, desirable to measure the layer thickness immediately after the electroplating process and to feed back to the controller of the electroplating process, in order to keep the layer thickness precisely constant. The X-ray fluorescence method is currently employed for the layer thickness measurement of the lead frames. It requires, however, longer than 10-seconds for the measurement with this method, so that it is not suitablly applied to the production-line.

A novel method of layer thickness measurement was proposed in previous papers(1,2). The method was based on the discovery of dips in the frequency and angular dependence of reflection coefficients for layered surfaces. It was experimentally demonstrated and theoretically explained that the phenomenon is caused by the excitation of pseudo-Sezawa waves. The same phenomenon was also observed by Liang et al(3). The measurement with a high resolution can be accomplished in a short time with no mechanical movement of a sensor.

In this method, however, a knowledge of the dispersion curves of surface waves is required prior to the measurement, in order to set the incident angle of the ultrasonic beam at an appropriate value to excite the pseudo-Sezawa wave.

The method was successfully implemented into an instrument for layer thickness measurement of lead frames. The purpose of the present paper is to describe the instrument and to examine factors which dominantly influence the performance of the measurement. In the following, principle of the measurement is briefly described. The construction of the instrument and its operation are explained. The performance of the instrument such as the stability, accuracy and temperature-dependence of the measurement is then discussed to achieve the satisfactory performance of the instrument. When the instrument is introduced in the production-line, mechanical allowance of sensor positioning becomes a crucial factor. Therefore, effects of sensor positioning on the measurement are discussed. Since Lamb waves as well as pseudo-Sezawa waves are excited if the substrate is thin, their effect on the measurement accuracy is also discussed.

II. Principle of Measurement

Suppose that an infinitely thick substrate occupies a lower half space, and a layer with thickness d covers the surface of the substrate. It is well

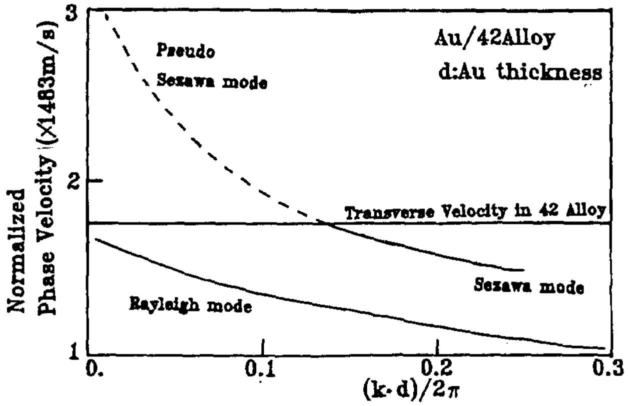

Fig.1 Dispersion curves of surface waves excited on a layered half space, loaded with water.

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known that a number of modes of surface waves exist in such a case, when the transverse sound velocity in the layer is less than that in the substrate(4). The fundamental mode is a Rayleigh wave, and the second mode is a Sezawa wave(5). The dispersion curves of these waves are shown in Fig.1. In the figure, the phase velocity is normalized by the sound velocity in water, and a dimensionless variable $kd/2\pi$ is used in place of the wave number k. The substrate is 42-alloy and the layer is gold. The Sezawa wave has a cut-off wave number, at which the phase velocity is equal to the transverse sound velocity in the substrate. The Sezawa wave is usually defined for the wave number greater than the cut-off wave number, as indicated by a solid line in Fig.1. A dashed line in the figure is a pseudo-Sezawa wave, which is a kind of leaky surface waves. The pseudo-Sezawa wave, when excited by some means, would not propagate freely along the surface, but radiates its energy into the substrate and decreases exponentially(6).

Suppose, then, that the upper half space is filled with water and a plane wave is incident onto the layered surface with an incident angle θ. If the frequency of the wave satisfies the condition of excitation of the pseudo-Sezawa wave, then the majority of the incident energy transmits into the substrate, and therefore, the energy of the reflected wave reduces drastically. The phenomenon is experimentally observed as a dip in the power spectrum of the reflected wave. It was shown in the previous paper(1) that the deepest dip is obtained when the pseudo-Sezawa wave is excited with a wave number just below the cut-off wave number. This condition is practically realized by setting the incident angle at an appropriate value, which was shown to be 31 degree for a lead frame consisting of a 42-alloy substrate with a gold layer.

Once the incident angle and materials of the layer and substrate are determined, then a fd value, or a product of the dip frequency f and the layer thickness d, is uniquely determined, except for the temperature dependence. Therefore, the layer thickness d_0 can be estimated by measuring the dip frequency f_0 and calculating $d_0=(fd)/f_0$.

III. Instrument

A block diagram of instrument is shown in Fig.2. An ultrasonic sensor consists of a pair of transducer rods. An electrical impulse generated by a pulse generator is applied to a piezoelectric transducer of the transducer rod. A reflected wave is received by another transducer and the electrical output-signal is fed into an amplifier. The first pulse in the reflected wave is extracted by using a delay line and a gate circuit. The power spectrum of the extracted signal is obtained by a spectrum analyzer. The frequency of a dip in the power spectrum is evaluated by using a special function of the spectrum analyzer. A controller converts the dip frequency into the layer thickness and calibrates the temperature dependence of the measured value.

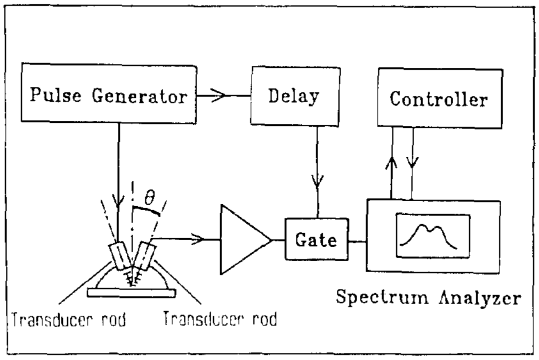

Fig.2 Block diagram of instrument for layer thickness measurement.

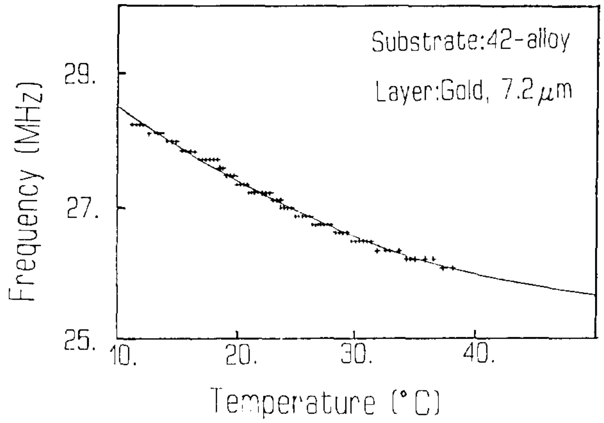

Fig.3 Dependence of dip frequency on temperature. Incident angle:27.4° . Frequency resolution:0.125MHz. Solid line is least-squares-fitted.

The voltage of the applied impulse is -200 volt with a duration of 5 nsec. The material of the piezoelectric transducer is ZnO film, which is placed on one side of the transducer rod made of fuzed quartz. The diameter and the length of the transducer rod are 8mm and 10mm, respectively. The effective frequency range of the transducer is 30-150 MHz. The half angle, denoted by θ in Fig.2, is set at a specific value between 27 and 31 degree.

The operation of the instrument is as follows: Prior to the measurement, the frequency response of the measurement system should be estimated by measuring the power spectrum of waves reflected by the substrate with no layer on it. The spectrum should be stored in a memory as a reference spectrum. Only the effects due to the layer deposition can be obtained by dividing the power spectrum for a layered substrate with the reference spectrum, to cancel the effect of the frequency response of the measurement system. Before the measurement of test specimens, a calibration should be carried out to ascertain the fd value by measuring the dip frequency for a specimen with known layer thickness.

The minimum time necessary to accomplish the measurement, after the test specimen is set on the stage, is less than one second. The time necessary to set the specimen is not taken into account, because it varies according to the volume and shape of the specimen, and the present paper is not intended to demonstrate the performance of the mechanical handling of the specimen.

IV. Experiments on Performance of Instrument

In order to attain the performance of the instrument required for the thickness measurement of lead frames in the production process, the following problems were investigated; (A) the temperature dependence of the dip frequency, (B) the stability and accuracy of the measurement, (C) the effects of sensor positioning on the measurement, (D) the influence of Lamb waves. In all experiments, substrates were 42-alloy and layers were gold.

(A) Dependence of Dip Frequency on Temperature.

The dip frequency depends on temperature, mainly because the sound velocity in water changes with temperature. In order to obtain the calibration curves of dip frequency as a function of temperature, the following experiment was made using two specimens. The substrates were 2mm in thickness. The layers were 5.2 μm and 7.2 μm in thickness. The thickness was measured with the conventional X-ray fluorescence method. The incident angle was 27.4 degree. The frequency resolution of the spectral analysis was 0.125 MHz. Temperature was changed from 10°C to 40°C. The rate of change was maintained within 3° C/hour to keep homogenity of temperature within water and specimens. The dependence of the dip frequency on temperature is plotted in Fig.3 for the specimen with a 7.2 μm-thick layer. Dotted are measured data, while a solid line is a quadratic curve, fitted to the data by the method of least squares. The measured data are well represented by the least-squares-curve, therefore it is obvious that the calibration of temperature dependence can be accomplished by refering to such calibration curves.

(B) Stability and Accuracy of Measurement

In Fig.3, measured dip frequencies do not fluctuate but lie stably within the minimum resolution of the frequency analysis(0.125 MHz). Therefore, it was estimated that the stability of the measurement was at least within ±0.2%. In general, the frequency analysis with higher resolution requires longer duration of measurement time. In the present instrument, the spectrum analyzer sweeps in the slower rate for higher resolution, and furthermore, such noise reduction techniques as averaging or maximum holding are required to achieve the precise measurement. As a result, the minimum resolution and the measurement time trade off each other.

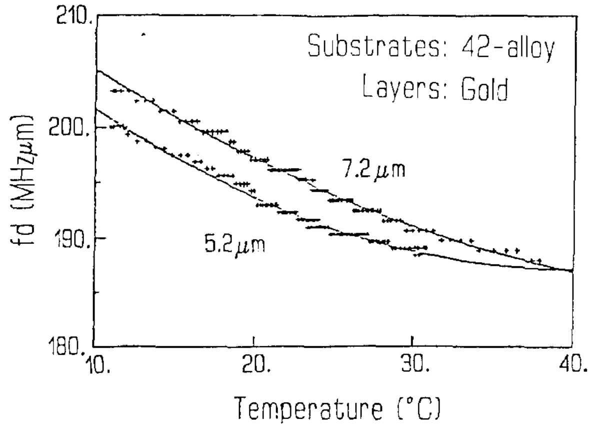

Fig.4 Dependence of fd values on temperature. Incident angle:27.4°. Solid lines are least-square-fitted.

In Fig.4, the dip frequencies are normalized to fd values by multiplying with thickness d. The fd values for the two specimens with different layer thickness, plotted in Fig.4, show a discrepancy of ±1%, which bounds the upper limit of the absolute accuracy in this case. The absolute accuracy was, however, difficult to estimate more precisely in this experiment, because the accuracy of the X-ray fluorescence method, which was used to obtain the reference values of the layer thickness, was limited to within a few percent.

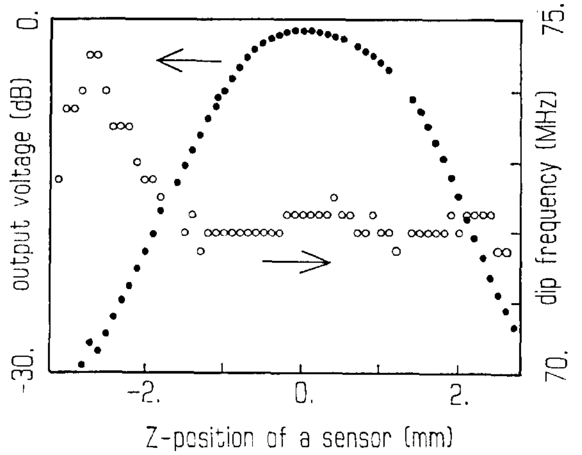

Fig.5 Dependence of output voltage and dip frequency on sensor displacement. Layer thickness:3.1 μm.

(C) Effect of Sensor Positioning on Measurement

Displacement of a sensor along the normal to the surface of the specimen, as well as inclination of a sensor around the proper incident angle, result in a poor accuracy of thickness measurement. Because the instrument is aimed at applications in the factory environment, it is desirable to have a large amount of allowance in the sensor positioning for rapid and stable measurement.

The following experiments were made to estimate the allowance. Layer thickness of a test specimen was 3.1 μm. Incident angle was 29.7 degree. In the experiments, output voltage of transducer and dip frequencies in spectra were recorded, while the sensor was displaced along the direction normal to the surface of the specimen. Measured data are shown in Fig.5. In the figure, ○ is for dip frequency and ● is for output voltage. Allowance in the displacement was estimated to be ±2mm. An experiment on the effect of sensor inclination was also made. Observed allowance in the inclination was estimated to be ±0.2 degree. Measured allowances in sensor positioning were large enough to easily adjust the sensor position in practical applications.

(D) Effect of Lamb Waves in Thin Substrates

Lead frames have thinner substrates than the specimens studied in the above experiments. Thickness of a substrate of a typical lead frame is 225 μm. In this case, Lamb waves(4,6) as well as pseudo-Sezawa waves are excited by the incident waves. A typical example of dispersion curves is shown in Fig.6. The excitation of Lamb waves raises a major problem in the layer thickness measurement, because the absolute minimum as well as local minima in the power spectrum do not correspond, any more, to the frequencies with which the pseudo-Ssezawa wave is excited. Therefore, when the substrate is thin, the layer thickness cannot be accurately estimated by simply measuring the dip frequencies in the power spectrum of the reflected wave.

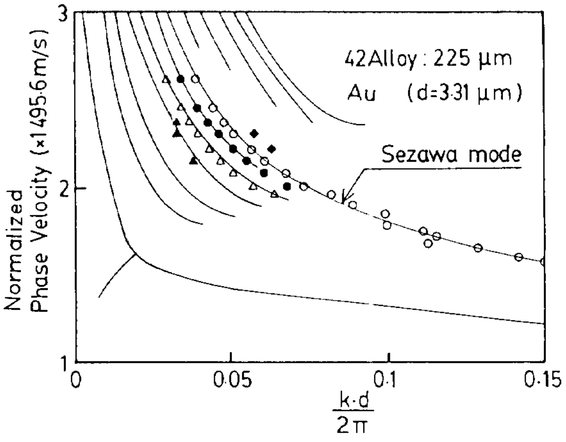

Fig.6 Dispersion curves of waves excited on a layered plate, immersed in water. Solid lines:theoretical curves, ▲ ,△, ● ○ ■:measured values.

To prevent the excitation of Lamb waves, a method is proposed as follows. Fig.7 shows a cross-sectional view of a thin substrate with a layer on it. Thickness of the substrate is D. An arrow ① represents an incident wave. The incident angle is θ. An arrow ② represents a directly reflected wave, while ③ represents a wave which is reflected at the bottom surface of the substrate. In the present case, incident angle is about 30 degree, therefore, the wave ③ propagating in the substrate can be regarded as a transverse wave. From the Snell's law,

$$\sin\theta/Vw = \sin\psi/Vt,$$

where Vt is the transverse sound velocity in the substrate and Vw is the sound velocity in water. The excitation of Lamb waves can be regarded, to the first order of approximation, as a resonance of the waves ② and ③. The condition of the resonance is easily derived,

$$f = m\cdot Vt/(2\cdot D\cdot\cos\psi),$$

where f is the frequency, and m is an integer. The distance W in Fig.7 is subject to the condition,

$$W = 2\cdot D\ \tan\psi .$$

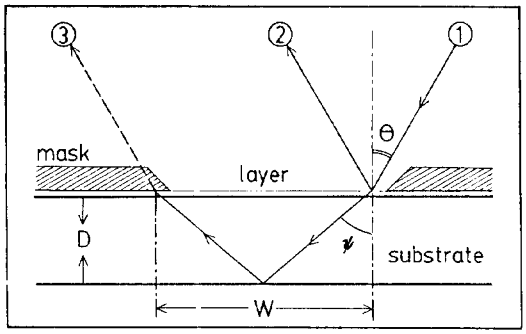

Fig.7 Schematic description of mask. Arrow 1 :Incident wave, Arrow 2 :Wave reflected at upper surface, Arrow 3 :Wave reflected at bottom surface. Mask, with slit-width less than W, prevents interference of waves 2 and 3 .

To prevent the excitation of Lamb waves, a mask having a slit was placed on the layered surface, as shown in Fig.7. The mask should be made of sound insulating materials, silicon rubber for example, and the width of the slit must be less that W. The physical phenomena belonging to the pseudo-Sezawa wave are essentially confined within the vicinity of the layered surface, therefore the mask does not seriously affect the spectral components corresponding to the pseudo-Sezawa wave.

In order to testify the performance of this method, the following experiment was made. A test specimen was a lead frame, 225 μm in thickness. The layer was 3.72μm in thickness. The incident angle was 29.7 degree. The width of a slit in the mask was 1mm. A comparison of spectra measured with and without the mask is made in Fig.8. A power spectrum measured without the mask is shown on the bottom, while a power spectrum measured with the mask is shown on the top. From the figure, it is clear that, by using the mask, dips by Lamb waves can be removed but only a dip by the pseudo-Sezawa wave can be recovered.

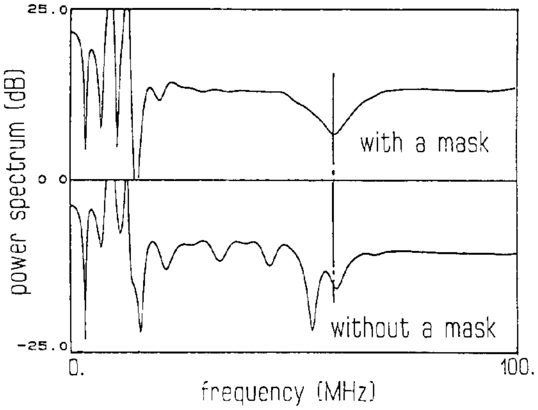

Fig.8 Effect of mask on measured spectra. Width of slit:1 mm. Substrate:225 μm-thick, layer:3.72 μm-thick. Incident angle: 30.5°.

V. Conclusion

This paper described an instrument for layer thickness measurement using pseudo-Sezawa waves. The instrument was constructed, based on the phenomenon that a frequency of a dip observed in the power spectrum of the reflected wave was inversely proportional to the layer thickness. The excitation of the pseudo-Sezawa wave is responsible for the occurrence of the dip. Such items as the temperatue dependence of the dip frequency, the stability and accuracy of the measurement, the effects of sensor positioning, and the excitation of Lamb waves in case of thin substrates were discussed. The performance was achieved as follows: Measurable thickness range; 1-20μm, stability ; ±0.2%, accuracy; ±1%, measurement time; 1-sec.

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