Proceedings of 2008 International Symposium on Electrical Insulating Materials, September 7-11, 2008, Yokkaichi, Mie, Japan

Detection of Ion Migration in Composites for Printed Circuit Boards by the Pulsed Electroacoustic Method

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Abstract: Pulsed electroacoustic (PEA) method is applied as a nondestructive technique to detect ion migration that progresses to the thickness direction in insulation composites for printed circuit boards. In both cases of a paper/phenol-resin composite and a glass/epoxy-resin composite, penetration of Cu migration into the bulk after aging was confirmed. Namely, a shift of the peak location of positive charge, which corresponds to the progress of migration in the aged composite, is observable by the PEA method.

INTRODUCTION

In recent years, electronic devices have become even more compact and more highly functional. This trend requires high-density integration of circuits to minimize printed circuit boards (PCBs) used in the devices, which in turn leads to a decrease in the mutual gap distance between conductors that enhances the electric field intensity applied to the insulation layer of a PCB. This accelerates degradation of insulating property, resulting in ion migration or electrochemical migration and failure of the devices. Ion migration is a kind of electrochemical phenomena, in which conductor materials are ionized and migrated to and through the insulation layer by electric field. Therefore, PCBs for electronic devices must have good resistance to ion migration in order to keep high reliability for a long period.

Most of previous research has paid attention mainly to the surface degradation phenomena such as surface breakdown, tracking, and surface ion migration[1]. On the other hand, to achieve further integration of circuits, a built-up PCB and a PCB in which electronic parts such as passive and semiconductor modules were embedded are at the beginning stage of practical use. Since these PCBs have multi-layered wiring of conductors, their insulating properties are important not only along the surface direction but also along the thickness direction. On this point, a reliable nondestructive method of detecting growth of migration in the thickness direction is required. Therefore, the authors have tried to apply the pulsed electroacoustic (PEA) method, which is a widely used nondestructive method for measuring space charge distributions mainly in insulating polymers[2], to detect growth of migration along the thickness direction in two kinds of composites for PCBs.

EXPERIMENTAL PROCEDURES

Table 1 shows the samples and their details. Sample A is a paper/phenol-resin composite (Sunhayato No. 19), which is a copper clad insulating material commonly used in PCBs for home electric appliances. It consists of a seven-layered paper prepreg impregnated with phenol resin, and was manufactured by pressurized molding. Its thickness is 1.56 mm. Sample B is a glass/epoxy-resin composite (Sunhayato ICB-075), which is a copper clad insulating material for PCBs widely used in various industrial and electronic appliances. It is also made of prepregs consisting of lattice-woven E-glass fibers impregnated with epoxy resin by pressurized molding. It consists of a one-layered prepreg with a thickness of 0.12 mm. The rightmost row in Table 1 shows generally accepted values of water absorption ratios of the two composites, which were measured according to JIS C6481[3].

The two samples have no resist layers on their surfaces, while they have a copper layer on one side. Part of the copper layer was used as an anode for an accelerated aging test of ion migration by etching off the rest in $FeCl_3$. During the test, a dc voltage was applied to the sample in a thermo-hygrostat between the Cu anode and an aluminum earthed cathode under a high temperature and a highly humid environmental test condition shown in Table 2, which had been determined according to the literature[4][5][6]. After a

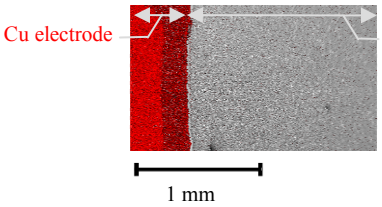
Table 1. Samples.

	Material	Thickness (mm)	Number of layers	ΔW^*
A	Paper/phenol	1.56	7	0.8 %
B	Glass/epoxy	0.12	1	0.07 %

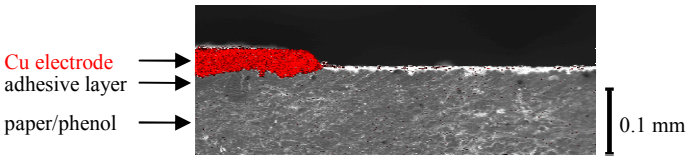
*ΔW: Weight increase after immersion in water at 23 °C for 24 hours[3].

Table 2. Experimental Conditions.

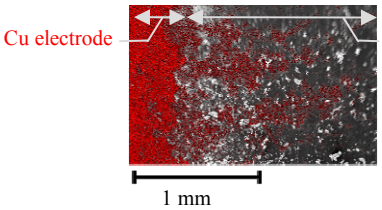
Sample	Material	Temperature	Humidity	DC Electric Field Applied
A	Paper/phenol	85 °C	85 %RH	0 kV/mm
A	Paper/phenol	85 °C	85 %RH	3 kV/mm
B	Glass/epoxy	85 °C	70 %RH	10 kV/mm



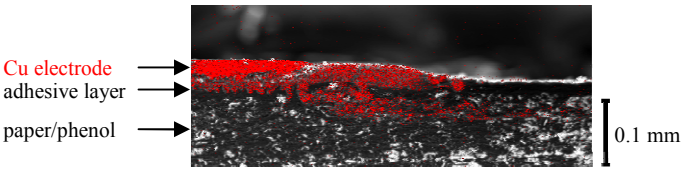
(a1) A surface SEM-EDS image of sample A before aging



(b1) A cross-sectional SEM-EDS image of sample A before aging



(a2) A surface SEM-EDS image of sample A after 98-hour aging



(b2) A cross-sectional SEM-EDS image of sample A after 98-hour aging

Figure 1. SEM-EDS images in the vicinity of an anode edge on the paper/phenol-resin sample A before and after a 98-hour aging under dc electric field application of 3 kV/mm at 85 °C and 85 %RH. Red dots indicate Cu.

certain designated period of accelerated aging, the sample was taken out of the thermo-hygrostat. The PEA measurement was carried out after the sample temperature had dropped to room temperature. Then, the sample was set again in the thermo-hygrostat for the next designated period. This process was repeated until the total designated aging period was over. The presence of Cu was observed by combined scanning electron microscopy and energy dispersive x-ray spectroscopy (SEM-EDS) before and after the test.

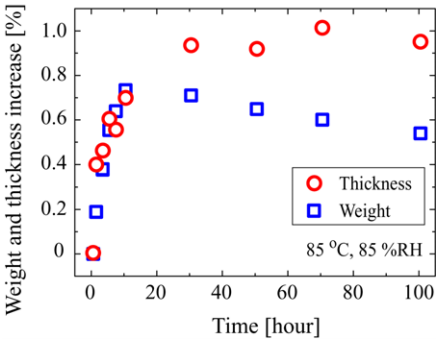


Figure 2. Thickness expansion and weight increase observed for sample A as a function of the total duration time at 85 °C and 85 %RH.

RESULTS AND DISCUSSION

Paper/phenol-resin composite

Figure 1 shows surface and cross-sectional SEM-EDS images in the vicinity of an anode edge in sample A before and after the test, in which the sample had been kept at 85 °C and 85 %RH for 98 hours while a dc electric field of 3 kV/mm had been applied. The red dots indicate the presence of Cu. The migration along the surface direction, shown in Fig. 1(a2), obviously progresses and the presence of Cu extends more than 1 mm from the anode edge. In the thickness direction, penetration of the Cu migration through the adhesive layer and its extension into the bulk is clearly seen in Fig. 1(b2).

Figure 2 shows the thickness expansion ratio and weight increase ratio observed for sample A as a function of the total duration time under 85 °C and 85 %RH atmosphere. As the time passes, the expansion ratio increases and reaches about 1.0 % after 100 hours. The weight increase ratio reaches about 0.8 % after 10 hours. However, it gradually decreases afterward to about 0.6 % in 100 hours. The weight increase indicates the infiltration of water, which decreases the sound velocity in the bulk. Such thickness expansion and decrease in sound velocity would affect the determination of location of PEA signals. Therefore, in the present research, the sampling time of the PEA measurement is plotted on abscissas in Figs. 3, 4, and 6 representing the results of PEA measurements.

Figure 3 shows a typical result of PEA measurements carried out for sample A with and without the Cu electrode and the adhesive. While the Cu electrode causes almost no change in the result, the existence of adhesive produces negative charge in front of the anode. The charge seems to be induced by the discontinuity of the ratio of permittivity and conductivity (ε/σ)[7] between the phenol resin and the adhesive. The repetitive oscillatory signals observable in the sample seem to be induced by similar (ε/σ) discontinuity between the paper and the phenol resin. The effect of this (ε/σ) discontinuity on the PEA signal intensity is not compensated in the present research.

Figure 4 shows results of PEA measurements obtained for sample A with the Cu electrode and the adhesive before and after the aging at 85 °C and 85 %RH with and without the application of dc electric field of 3 kV/mm. As the aging time passes, regardless of the voltage application, the location of the positive charge peak on and near the anode and the repetitive

oscillations of charge in the sample shift toward the right. As mentioned above, this is caused by the actual thickness expansion and the decrease in sound velocity resulting in a superficial shift of PEA signals, both of which were caused by the aging. In the case of aging without the voltage application, a clear negative peak is seen in front of the anode before and after 100 hours of aging. However, in the case of aging with the voltage application, the negative peak disappears and the repetitive oscillations of charge in the sample become evident after the aging of almost the same duration of 98 hours. The positive peak corresponding to the anode, indicating the interface between the bulk and the Cu electrode, is seen at 675 ns after the aging for 100 hours if no voltage was applied, while it is seen at 646 ns after the aging for 98 hours with the dc voltage. The difference of 29 ns (=675–646) corresponds to the movement of the peak into the bulk by about 75 μm. A similar peak shift was also reported for migration of copper in epoxy resin with silica fillers[6]. These shifts in peak location indicate that the copper of the anode had migrated beyond the adhesive layer, which is in agreement with the result shown in Fig. 1(b2).

To conclude, the ion migration in the paper/phenol-resin sample A progresses both on the surface and along the thickness direction. The above-mentioned results show that the PEA method can detect the progress of migration in the thickness direction.

Glass/epoxy-resin composite

Figure 5 shows surface EDS images and cross-sectional SEM-EDS images observed for sample B before and after aging of 100 hours carried out at 85 °C and 70 %RH with application of dc electric field of 10 kV/mm. The red and green dots indicate the presence of Cu and Si, respectively. Unlike the paper/phenol-resin sample A, red dots are scattered on the surface as shown in Fig. 5(a2), indicating that the Cu ions are migrated in such a form. In the thickness direction, the regions of epoxy resin, glass fiber, and Cu electrode are clearly distinguishable before the aging as shown in Fig. 5(b1). Moreover, the expansion of the region where abundant Cu atoms are seen toward the thickness direction is clearly observed in Fig. 5(b2).

Figure 6 shows the result of PEA measurement obtained for sample B with the Cu electrode at 85 °C and 70 %RH with the application of dc electric field of 10 kV/mm. Since the water absorption rate of the glass/epoxy-resin composite is about one tenth of that of the paper/phenol-resin composite as shown in Table 1, the thickness expansion and decrease in sound velocity caused by the aging are negligibly small in the result of PEA measurement. The acoustic impedance of a glass is 1.4×10^7 kg/m^2/s[8], although it is not a value for the present E-glass but for a general slide glass, while that of epoxy resin is 3.3×10^6 kg/m^2/s[9]. Therefore, the reflection ratio of pressure wave propagating from epoxy to glass turns out to be 0.62 by

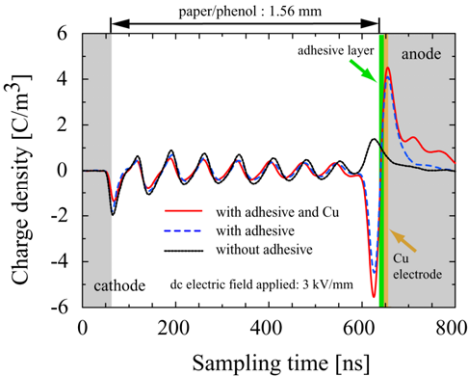


Figure 3. Result of PEA measurement in sample A with and without the Cu electrode and adhesive.

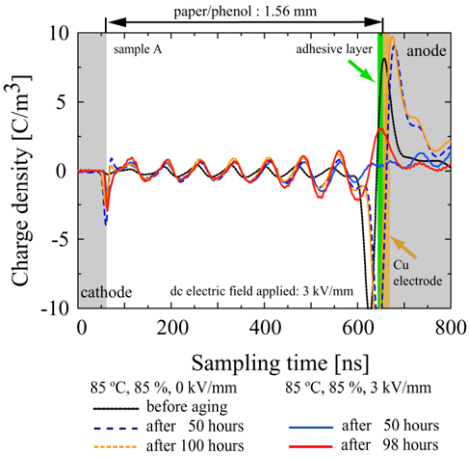


Figure 4. Result of PEA measurement in sample A before and after the aging at 85 °C and 85 %RH with and without the application of dc electric field of 3 kV/mm.

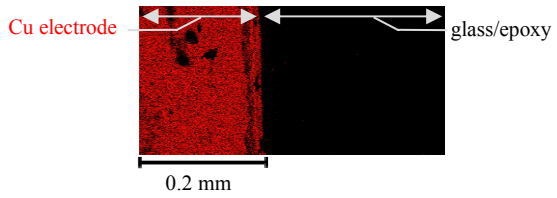
the following equation[10],

$$\frac{P_r}{P_{in}} = \frac{Z_2 - Z_1}{(Z_1 + Z_2)} . \qquad (1)$$

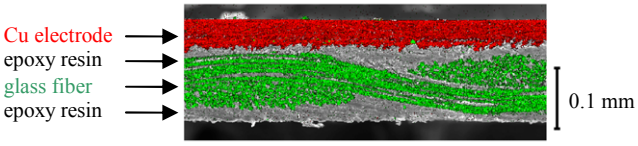
This indicates that the reflection wave exerts a certain influence on the results of PEA measurements in sample B. Therefore, the positive and negative peaks in the bulk shown in Fig. 6 are combined effects of the charges induced by the (ε/σ) discontinuity and of the reflection at glass/epoxy-resin interfaces[7].

Like paper/phenol-resin sample A, the shift in the peak location of positive charge on and near the anode is also observed in Fig. 6. The peak before the aging seen at 101 ns moves to 96 ns by the aging for 100 hours. The difference of 5 ns (=101–96) corresponds to the movement of the peak into the bulk by about 16 μm, which is in agreement with the result shown in Fig. 5(b2). Therefore, the PEA method can detect progress of migration toward the thickness direction in glass/epoxy-resin sample B.

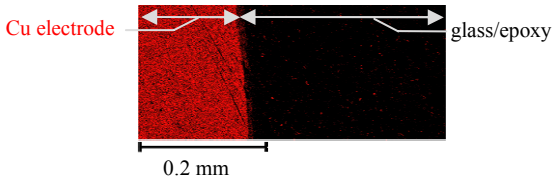
While the location of the positive charge peak corresponding to the anode edge is unchanged between 50 hours and 100 hours of aging as shown in Fig. 6, the intensities of the positive and negative charge peaks in the bulk decrease after the 100-hour aging.



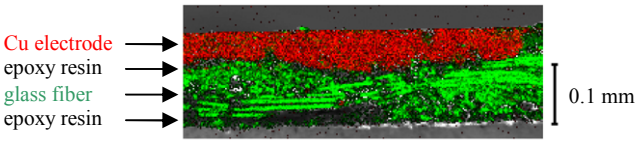
(a1) A surface EDS image of Cu in sample B before aging



(b1) A cross-sectional SEM-EDS image in sample B before aging



(a2) A surface EDS image of Cu in sample B after 100-hour aging



(b2) A cross-sectional SEM-EDS image in sample B after 100-hour aging

Figure 5. EDS and SEM-EDS images in the glass/epoxy-resin sample B before and after a 100-hour aging under dc electric field application of 10 kV/mm at 85 °C and 70 %RH. Red and green dots indicate Cu and Si, respectively.

Furthermore, an upper convex shoulder indicating the presence of local positive charge appears in the vicinity of the cathode (around 69 ns). The appearance of this shoulder may indicate that the Cu migration progressed locally, forming a filamentary growth as in the case of conductive anodic filaments[11], after it had grown rather uniformly until it had reached the glass fiber. However, such local presence of Cu atoms is not observable in Fig. 5(b2), and the possibility cannot be discarded that the red dots scattered in the glass fibers are due to Cu particles spread during the polishing process.

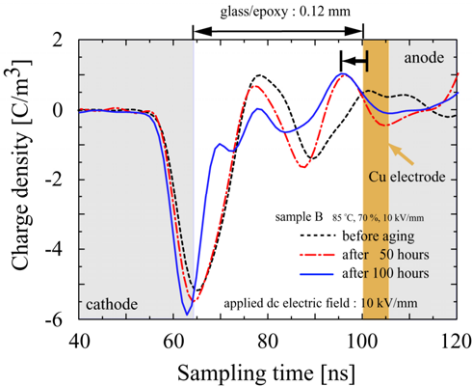


Figure 6. Result of PEA measurement in sample B before and after the aging at 85 °C and 70 %RH with the application of dc electric field of 10 kV/mm.

CONCLUSION

The progress of ion migration along the thickness direction in a paper/phenol-resin composite and a glass/epoxy-resin composite for PCBs can be detected by the PEA method as the shift of positive charge peak on and near the anode.

ACKNOWLEDGMENTS

A part of this research was carried out in the 2nd Stage Knowledge Cluster Initiative No. 23, supported by the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

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