

Observation of Copper Ionic Migration in Insulation Layer by Pulsed Electroacoustic Method

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Abstract—We have studied the behavior of ionic impurities in the insulation layer of metal–base PWBs and carried out nondestructive detection of copper ionic migration using the pulsed electroacoustic method for measuring the space charge. Space charge polarization was observed initially and after pre-absorption under high-temperature, high-humidity conditions. It appears to be attributable to the ions present initially in the insulation layer. The space charge measurement detected a conductive region formed in the insulation layer near the anode after bias testing under high-temperature, high-humidity conditions (THB test). Element distribution analysis verified, it as a region of copper ionic migration. Growth of copper ionic migration in the insulation layer was detected nondestructively.

Index Terms—Insulation layer, ionic impurities, ionic migration, metal–base PWB, pulsed electroacoustic method, space charge.

I. INTRODUCTION

POWER electronic equipment and appliances have become smaller, with their parts being mounted more densely on the printed wiring board. In power transistor modules, general purpose inverters and switching power supplies, which use power devices, some form of heat dissipation is required. This has led to the increasing popularity of the metal–base printed wiring board (metal–base PWB) [1], [2]. Fig. 1 shows the basic structure of a metal–base PWB. The metal base consists of an aluminum metal plate of, an insulation layer and a layer of copper foil. The insulation layer is 150–200 μm thick and generally made of a thermally conductive epoxy resin containing an inorganic filler.

The metal–base PWB has been used in 100–400 V power circuits for power transistor modules, general purpose inverters and switching power supplies. In these metal–base PWBs, the insulation layer is exposed to a high electric field stress of 1–3 kV/mm. It is therefore important to evaluate the insulating performance of the insulation layer, particularly the occurrence of copper ionic migration (or simply “migration”) in the insulation layer under the presence of dc voltage. The authors

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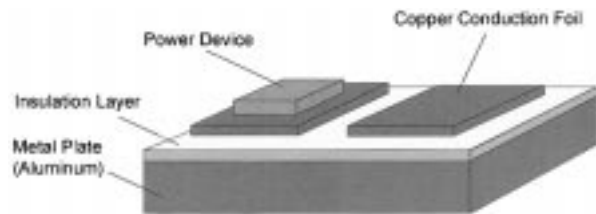


Fig. 1. Application of metal–base PWB.

have previously studied the phenomenon of migration in the insulation layer of a metal–base PWB [3].

Observation of the migration process is indispensable in the study of migration. Due to the structure of the metal–base PWB and the fact that migration occurs in the insulation layer, however, direct visible observation of migration between conductors on the board surface is impossible. The authors initially attempted to identify the migration process via continuous observation of conventional dielectric properties such as insulation resistance R , capacitance C and the dielectric loss tangent $\tan \delta$ in conjunction with bias testing, but with out success: i.e., insulation resistance increased, while both capacitance and $\tan \delta$ decreased. This failure was attributed to the effect of space charge polarization caused by dissociated ions in the insulation layer [4].

Advances in the technique of space charge measurement by the pulsed electroacoustic method now enables the observation of the behavior of ionic impurities in a thin (approximately 100 μm) resin layer [5].

In the next section, we will consider the use of the pulsed electroacoustic method as a nondestructive means of observing the behavior of ionic impurities in the insulation layer of a metal–base PWB under high-temperature, high-humidity conditions, as well as the phenomenon of migration during bias testing under high-temperature, high-humidity conditions.

II. OBSERVATION OF ION BEHAVIOR AND MIGRATION

A. Test Samples

The test samples were two types of metal–base PWBs, A and B, both consisting of an insulation layer of epoxy resin and an inorganic filler, but containing different levels of ionic impurities. Table I shows the concentrations of various ions of these two sample types after immersion in distilled water at 85 $^{\circ}\text{C}$ for 48 h, as determined by ion chromatography. Sample A (metal–base PWB A) contained 509 ppm of SO_4^{2-} , 11.5 ppm of Cl^- , and 27.6 ppm of NH_4^+ . Sample B (metal–base PWB B) had a very low NH_4^+ concentration of 9 ppm, and undetectable levels of SO_4^{2-} and Cl^- .

TABLE I
AMOUNT OF IONS EXTRACTED (ppm)

Ion Substance	Cl ⁻	SO ₄ ²⁻	NH ₄ ⁺
Sample A (PWB A)	11.5	509	27.6
Sample B (PWB B)	—	—	9.2

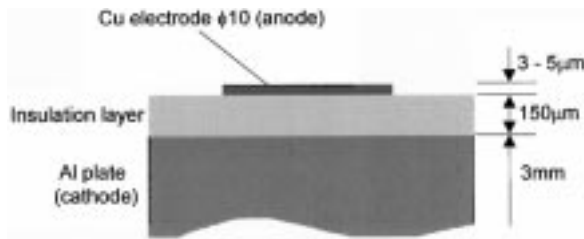


Fig. 2. Test specimen.

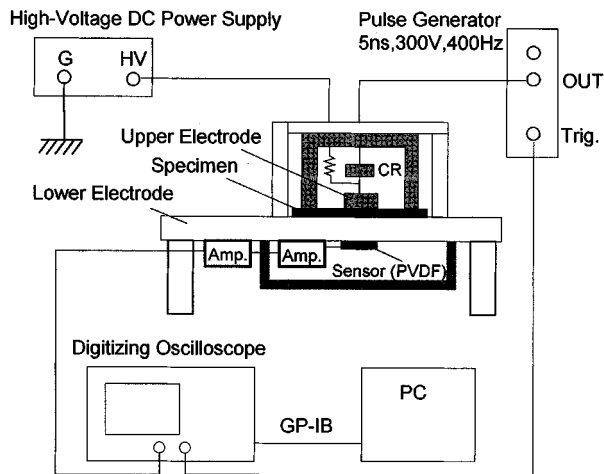


Fig. 3. Space charge measurement system for the pulsed electroacoustic method.

Fig. 2 shows the test specimen used. The copper deposition electrode served as the anode, and the aluminum base electrode as the cathode.

B. Test Procedure

Fig. 3 shows the setup for space charge measurement by the pulsed electroacoustic method. Space charge was measured by applying a dc voltage of 1250 V at room temperature after extracting the specimens at each of the stages given below from the constant-temperature, constant-humidity chamber. The voltage of 1250 V was the same as that used in the thermal humidity bias (THB) test.

- Initial condition
- After pre-absorption for 18 h at 85 °C and 70% RH without bias voltage.
- After THB testing for 20 h at dc 1250 V, 85 °C and 70% RH.
- After THB testing for 50 h at dc 1250 V, 85 °C and 70% RH.

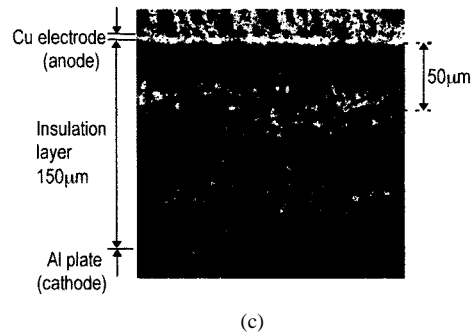
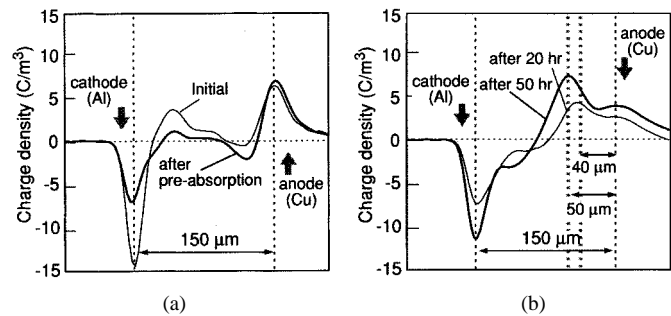


Fig. 4. Sample A (metal base PWB A).

C. Test Results

1) *Initial and After Pre-Absorption: Sample A (Metal-Base PWB A)*: Fig. 4(a) shows the space charge distribution of sample A with the application of dc 1250 V both initially (before) and after pre-absorption for 18 h at 85 °C and 70% RH. Measurements were made approximately 2 min after applying voltage, so that the change in distribution would be adequately converged. In the initial stage, the specimen exhibited a heterocharge distribution [thin line in Fig. 4(a)], which tended to be negative in the vicinity of the anode and positive in the vicinity of the cathode. It is assumed that dissociated ions accumulated in the insulation layer. The ionic impurity distribution shows that the positive heterocharge is NH₄⁺ and the negative heterocharges are SO₄²⁻ and Cl⁻.

After pre-absorption for 18 h at 85 °C and 70% RH [thick line in Fig. 4(a)], the negative heterocharge at the anode rose significantly while the positive heterocharge at the cathode fell. It is thought that the rise of dissociated negative heterocharge is accelerated by pre-absorption.

Sample B (Metal-Base PWB B): Fig. 5(a) shows, in the same way as for sample A, the space charge distribution under dc 1250 V both initially (before) and after 18 h of pre-absorption at 85 °C and 70% RH. In the initial stage (thin line), sample B exhibited a similar heterocharge distribution to sample A, which tended to be negative in the vicinity of the anode and positive in the vicinity of the cathode. After pre-absorption for 18 h at 85 °C and 70% RH (thick line), the negative heterocharge at the anode fell significantly (an outcome opposite to that of sample A), while the positive heterocharge at the cathode fell to a virtually negligible level (same as for sample A).

2) *Space Charge Distribution After THB Test: Sample A (Metal-Base PWB A)*: Fig. 4(b) shows the space charge distribution for sample A after THB testing for 20 and 50 h (dc 1250 V at 85 °C and 70% RH). After 20 h [thin line in Fig. 4(b)], a positive charge distribution appeared near the

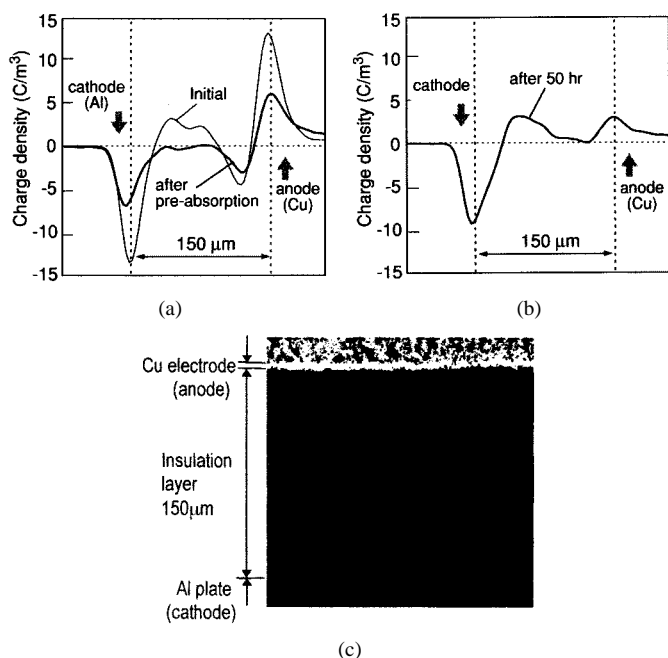


Fig. 5. Sample B (metal base PWB B).

anode. The peak of positive charge is approximately $40 \mu\text{m}$ from the anode; the anode has appeared to extend toward the insulation layer away from the position indicated in Fig. 4(a). Similarly, after THB testing for 50 h (thick line), a positive charge peak situates at approximately $50 \mu\text{m}$ from the anode, and the positive charge distribution indicates further extension of the anode. This distribution suggests that a conductive region for migration was formed upon applying a dc voltage of 1250 V.

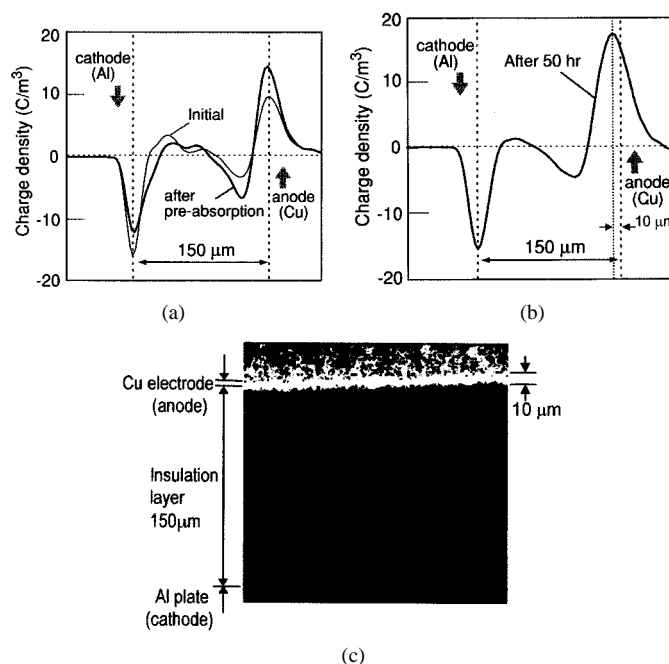
In order to verify whether the extension of the anode toward the insulation layer is caused by migration, the copper element distribution in the cross section of the sample after THB testing for 50 h is observed using an electron probe microanalyzer (EPMA). Fig. 4(c) reveals strong evidence of migration, with elemental copper clearly forming a band in the vicinity of $50 \mu\text{m}$ from the anode. The dense area of the band corresponds roughly to the peak of the charge distribution.

Migration also appears to be occurring in a plane and moving steadily toward the cathode.

The above results confirm that space charge distribution measurement is a valid nondestructive method for detecting migration in the insulation layer.

Sample B (Metal-Base PWB B): Fig. 5(b) shows the space charge distribution for sample B subjected to the same 50 h THB test as sample A. For sample B, a positive charge distribution did not appear near the anode; the negative heterocharge in the vicinity of the anode after the pre-absorption was eliminated by the THB test, and positive heterocharge in the vicinity of the cathode appeared, which seemed to be NH_4^+ . Thus, this distribution suggests that a conductive region was not formed near the anode.

Fig. 5(c) shows an EPMA map of elemental copper in the cross section of the sample after THB testing for 50 h. No evidence of copper was found in the insulation layer, so migration had not occurred.

Fig. 6. Pre-absorption at 60°C , 90% RH atmosphere.

In sample A, three kinds of ionic impurities (SO_4^{2-} , Cl^- , NH_4^+) were detected, where the SO_4^{2-} ion concentration was particularly high, 509 ppm. However, in sample B, SO_4^{2-} and Cl^- ions were not detected and the detected NH_4^+ ion concentration was only 9.2 ppm.

Since a large quantity of ionic impurities were included in the insulation layer of sample A, it is thought that migration may depend on the amount of ionic impurities in the insulation layer.

III. EFFECT OF ENVIRONMENTAL CONDITIONS

THB tests are normally conducted under environmental conditions such as 60°C and 90% RH or 40°C and 90% RH. We investigated the space charge distribution behavior and migration under these low-acceleration environmental conditions and compared the results with those obtained under 85°C and 70% RH.

1) **Test Samples:** Test sample A (metal-base PWB A) was used because it showed evidence of migration after the THB test (dc 1250 V, 85°C and 70% RH).

2) **Test Procedure:** Two sets of environmental conditions (60°C and 90% RH, 40°C and 90% RH) were used for the pre-absorption and THB test. The bias voltage in the THB test was dc 1250 V, the same as above. The space charge distribution was measured in the same manner as described above.

3) **Test Results:** Initial and after pre-absorption: Fig. 6(a) shows the initial space charge distribution and that after pre-absorption at 60°C and 90% RH, while Fig. 7(a) shows the initial space charge distribution and that after pre-absorption at 40°C and 90% RH. The thin lines indicate space charge distribution in the initial stage; these distributions are identical for both sets of conditions.

The thick lines indicate space charge distribution after pre-absorption for 18 h for each set of conditions. In both cases, the

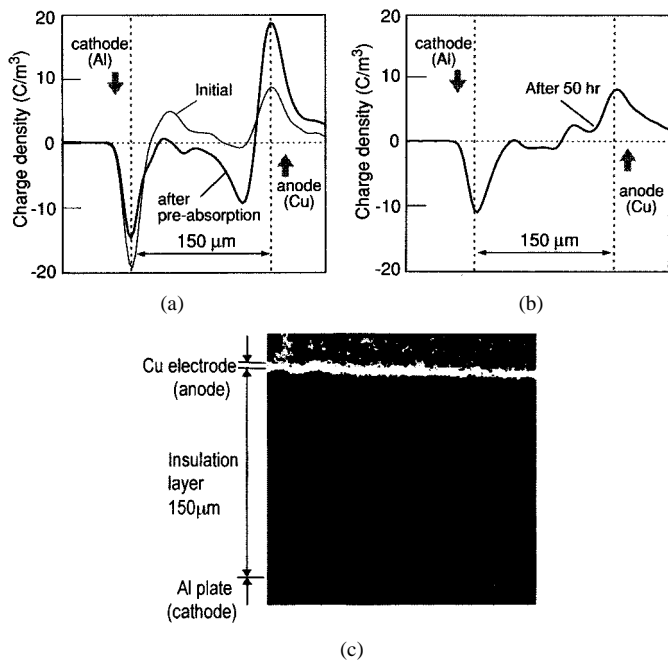


Fig. 7. Pre-absorption at 40 °C, 90% RH atmosphere.

level of positive heterocharge accumulating in the vicinity of the cathode has fallen, while the level of negative heterocharge in the vicinity of the anode has risen. This is thought to be because pre-absorption renders negative ions SO_4^{2-} and Cl^- dissociative. The 40 °C and 90% RH test produced a greater increase in negative heterocharge density than that in the 60 °C and 90% RH test.

Compared all tests including the above-described test at 85 °C and 70% RH shown in Fig. 4(a), the level of negative heterocharge in the vicinity of the anode after pre-absorption is greatest at 40 °C and 90% RH, followed by 60 °C and 90% RH and then 85 °C and 70% RH. These results indicate that lower temperatures increase the amount of accumulating negative heterocharge in the vicinity of the anode.

This is thought to occur for the following reasons. Heating by pre-absorption at 40 °C, 60 °C, and 85 °C promoted curing of the resin which led to the consumption of Cl^- and SO_4^{2-} ions. Therefore, negative heterocharge at the anode fell with increasing temperature.

After THB test: Figs. 6(b) and 7(b) show space charge distribution after applying dc 1250 V for 50 h. In the 60 °C and 90% RH THB test, the anode extended approximately 10 μm toward the insulation layer from the pretest position; this seemed to indicate the occurrence of some degree of migration. In the 40 °C and 90% RH THB test, the anode did not extend. Thus, it is seemed to migration did not occur.

In order to verify whether migration occurred in the insulation layer, the copper element distribution in the cross section of the after THB testing for 50 h samples are observed. Figs. 6(c) and 7(c) show copper element mappings in the cross sections, as determined by EPMA analyses. In the 60 °C and 90% RH THB test and the 40 °C and 90% RH THB test, there was no evidence of copper in the insulation layer. In the 60 °C and 90% RH THB test, extension of the anode shown in the space charge

distribution suggests the occurrence of migration; however, the extended distance is only approximately 10 μm. We suggest that either the anode is linked to the migration products or the copper element distribution at the anode and migration occur in an area smaller than the resolution of EPMA mapping (1 μm/pixel).

The above results indicate that the migration phenomenon is effected by environmental conditions.

IV. CONCLUSION

We used the pulsed electroacoustic method for measuring space charge distribution to study the behavior of ionic impurities in the insulation layer of metal–base PWBs and carried out nondestructive detection of migration. The experiments revealed that the pulsed electroacoustic method is a valid, nondestructive technique for observing the behavior of ionic impurities in the insulation layer, and also for continuously observing the occurrence and progress of migration.

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