Testing of electromigration resistance of copper and silver thick films

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***Abstract*—This paper is focused on the electromigration resistance of copper and silver thick films. Electromigration was tested by water drop test. Four common conductive thick film pastes were used for testing – silver paste with low platinum content, and two silver pastes with different content of palladium and copper paste. Electromigration was tested under voltage of 6 and 12 V and time to shortcut was measured. Results of testing including the comparison of electromigration resistance depending on thick film paste type and different electrode spacing are described in this paper.**

Keywords—electromigration, copper, silver, thick film, water drop test

I. Introduction

Thick film technology is used in hybrid microelectronic applications for decades. This technology is intended for the realization of conductive, dielectric (insulation) or resistive films [1]. Thick films are printed in the form of paste (usually with screen printing) and fired in a belt furnace in an oxidative atmosphere. In general, thick film paste formulation contains functional component (metal particles in the case of conductive pastes), glass binder and organic component [2]. Commonly used conductive thick film pastes are based on silver (pure or in alloys with palladium or platinum), copper or gold [3].

Thick film technology can be also utilized for the realization of power hybrid modules. Special copper pastes have recently been used for these applications, but the use of silver pastes is also possible for whole or parts of circuits [4]. These modules usually integrate a power and control section and are exposed to harsh conditions. Due to the current trend of continuous miniaturization, control parts in particular are made up of high-density circuits. The use of copper and silver conductors in high-density circuits raises the issue of their long-term environmental reliability because mainly silver has a tendency to migrate under DC voltage in the presence of humidity and also in the presence of residues after soldering which is difficult to remove from the porous ceramic surface. Therefore, this paper is focused on testing of electromigration resistance of commonly used copper and silver pastes.

Electromigration is usually tested according to IPC standards or by water drop test when two electrodes (copper or silver) are subjected to droplets of distilled water and DC voltage [5,6]. Electromigration results in dendrite growth between these two electrodes and a causes short circuit.

Electromigration can be reduced by proper circuit design and with using of overglaze films which cover conductive film (mainly pure silver) and protects it against environmental effects. Another option is using silver pastes with palladium content. The addition of palladium reduces the tendency of silver to migrate. In the case of copper films, the tendency to migrate is low.

II. Experiment

Electromigration was firstly measured according to IPC standard 2.6.14.1 Electrochemical Migration Resistance Test [6]. The IPC-B-25A test pattern (Fig. 1) was used for the measurement and the electromigration was measured on part D. This pattern was printed with three commonly used thick film pastes – AgPt 99:1 Heraeus C1076SD, AgPd 3:1 Heraeus C2030 and Cu Heraeus C7403A on 96% Al_2O_3 substrates.

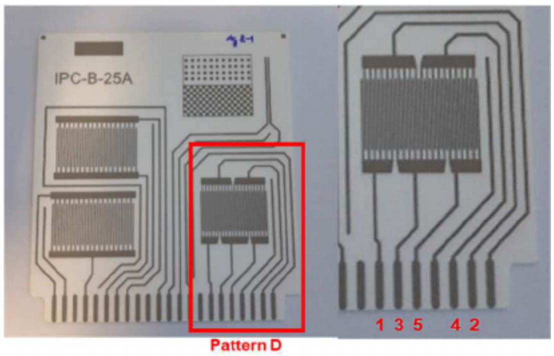

Fig. 1. Realized IPC-B-25A test pattern (left) and detail odf pattern D with marking of terminals (right).

According to the above-mentioned standard, the samples were tested in a climatic chamber at 85 °C and 88.5% RH. The test samples were first stabilized at these conditions for 96 hours. After stabilization, the insulation resistance was measured with an electrometer at 100 V between terminals 1-2, 3-2, 3-4 and 4-5 (Fig. 1). Then the samples were connected to a voltage of 10 V. T Limiting 1 MΩ resistors were connected in series in each measured path (at terminals 1, 3 and 5, to which the positive terminal of the source was connected - Fig. 1). The samples with the connected voltage were tested in the climatic chamber for 500 hours at the same conditions as during stabilization (85 °C and 88.5% RH). After 500 hours, the insulation resistance of the samples was measured again. The average insulation resistance was calculated using the following formula

$$IR_{avg} = 10^{\left[\frac{1}{N}\sum_{1}^{N} logIR_i\right]} \tag{1}$$

where N is the number of test points, IR_i is individual insulation resistance measurements. Samples were observed under a microscope and evaluated for changes and growth of dendrites after the test.

Electromigration was further tested using a water drop test. Samples (Fig. 2 and Fig 3) were also manufactured from aluminium oxide (96% Al_2O_3) 0.635 mm thick. Similar conductive thick film pastes were used (AgPt 99:1 Heraeus C1076SD, Cu Heraeus C7403A, AgPd 3:1 Heraeus C2030) and in addition AgPd 6:1 Heraeus C2060. The electrode width was 1.5 mm. Spacing was chosen between 0.2 and 1.2 mm. Except for the testing area and contacts, samples were covered with a thick film overglaze to prevent water drops from spilling onto the surface. The description of materials used for each type of sample is mentioned in Table 1.

Fig. 2. CAD design of test samples.

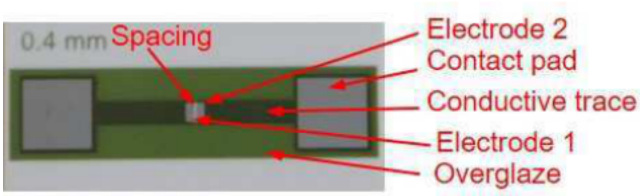

Fig. 3. Realized test samples.

A drop of distilled water was applied to the test area. Samples were attached to the power source, the current was limited to 100 mA, the voltage was set from 6 V to 12 V and the time to 100 mA shortcut was measured. Dendrite growth was observed under a confocal microscope.

TABLE I. DESCRIPTION OF MATERIALS

Paste	Alloy	Overglaze
C1076SD	AgPt 99:1	IP9025ST
C2060	AgPd 6:1	IP9025ST
C2030	AgPd 3:1	IP9025ST
C7403A	Cu	IP7098

The third test was a water drop test with 5% NaCl solution which was proven only for samples with Cu films with spacing 0.4 mm under voltage of 20 V.

III. RESULTS

A. Test according to IPC standard 2.6.14.1

The results of insulation resistance measurement for all sample variants are summarized in Table 2. Samples were also observed under a microscope with bottom light for verification of dendrite growth and an example of the sample with AgPt 99:1 film is shown in Fig. 4.

TABLE II. RESULTS OF INSULATION RESISTANCE MEASUREMENT

Sample (paste)	Insulation resistance – IR_{avg} (MΩ)	
	After stabilization (96 h, 88.5 °C, 85 % RH)	After test (500 h, 10 V, 88.5 °C, 85 % RH)
AgPt 99:1	470,0	1,06
AgPd 3:1	558.6	2,73
Cu	541.6	2,48

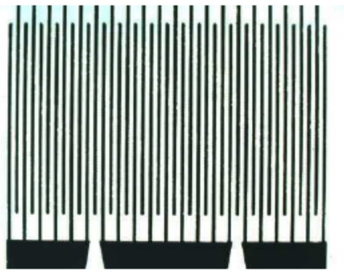

Fig. 4. Microscopic image of the sample with AgPt 99:1 film after the test.

It was verified that electromigration did not occur in the tested samples after testing according to IPC standard 2.6.14.1. No dendrite growth was observed in any type of sample. However, the insulation resistance decreased from values of ~500 MΩ to values of 1-3 MΩ.

B. Water drop test – distilled water

Considering that no electromigration occurred during the test according to the IPC standard, an additional test was chosen in which the samples are exposed to more harsh conditions – a water drop test.

The first measurement was performed under voltage 6 V. Results of electromigration testing under this voltage for different electrode spacing are shown in Fig. 5-8. Results of AgPt and AgPd films are described in graphs, Cu films shown current close to 0 mA.

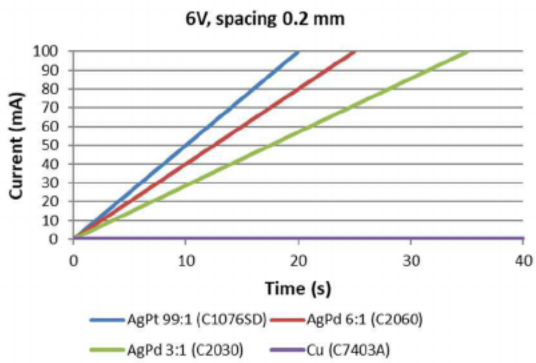

Fig. 5. Result of electromigration testing – test voltage 6 V, electrode spacing 0.2 mm.

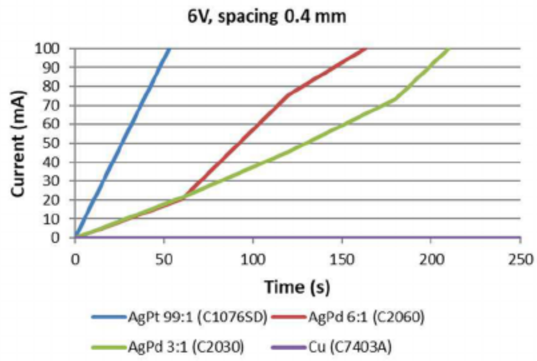

Fig. 6. Result of electromigration testing – test voltage 6 V, electrode spacing 0.4 mm.

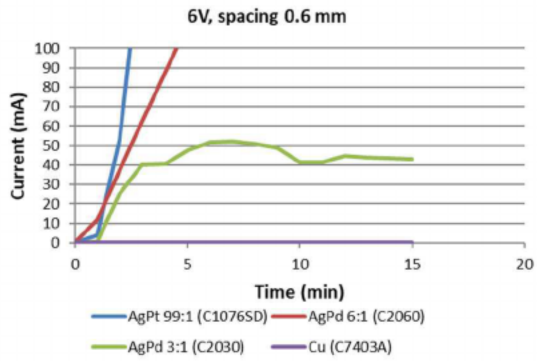

Fig. 7. Result of electromigration testing – test voltage 6 V, electrode spacing 0.6 mm.

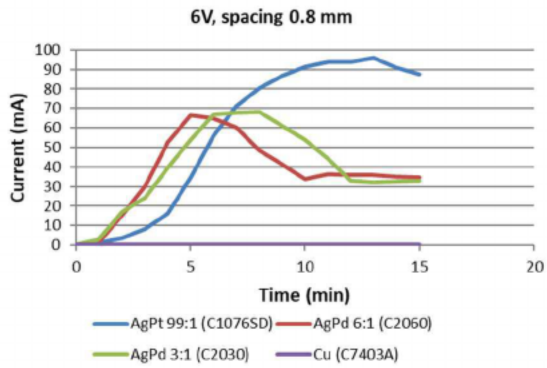

Fig. 8. Result of electromigration testing – test voltage 6 V, electrode spacing 0.8 mm.

It is obvious, that spacing (distance) between electrodes and also the material of thick film has a significant influence on the rate of electromigration. In the case of spacing 0.2 mm, all samples get a shortcut (shortcut current 100 mA) within 20-35 seconds. At two times higher spacing of 0.4 mm, a short circuit occurred at 50-210 s for all samples. For samples with a 0.6 mm spacing, a shortcut occurred only in the case of AgPt 99:1 and AgPd 6:1 films (within 2-5 minutes). For samples with 0.8 mm spacing, no shortcut was observed, however, the current was approaching 100 mA in the case of AgPt 99:1 film. In terms of the used thick film materials, AgPt 99:1 paste has the highest tendency to migrate compared to AgPd pastes. The tendency to migrate decreases with increasing palladium content. The neither high amount of palladium in the silver paste will not prevent electromigration completely.

The second measurement was performed under voltage 12 V. Results of electromigration testing under this voltage for different electrode spacing are shown in Fig. 9-13.

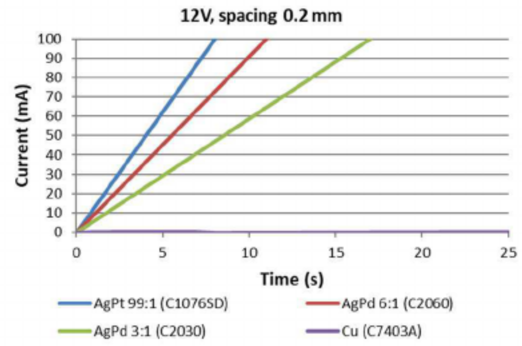

Fig. 9. Result of electromigration testing – test voltage 12 V, electrode spacing 0.2 mm.

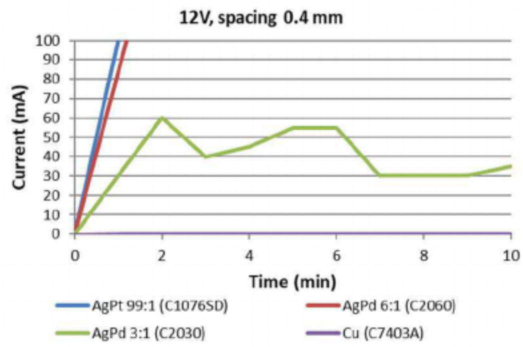

Fig. 10. Result of electromigration testing – test voltage 12 V, electrode spacing 0.4 mm.

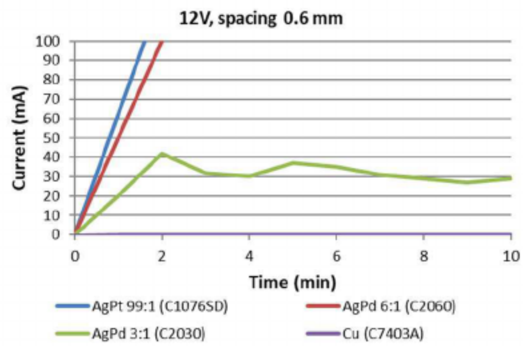

Fig. 11. Result of electromigration testing – test voltage 12 V, electrode spacing 0.6 mm.

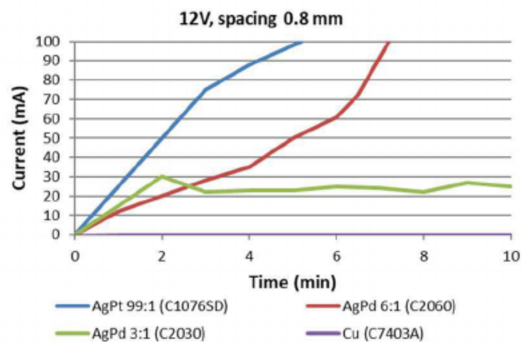

Fig. 12. Result of electromigration testing – test voltage 12 V, electrode spacing 0.8 mm.

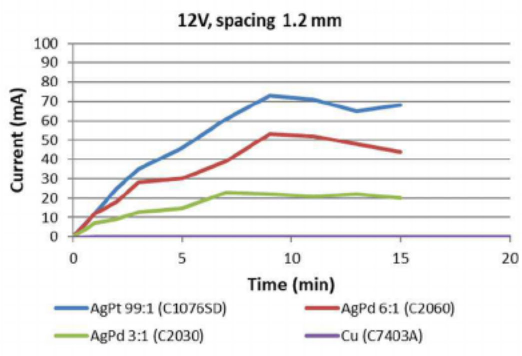

Fig. 13. Result of electromigration testing – test voltage 12 V, electrode spacing 1.2 mm.

The results show that migration is accelerated at the higher voltage. The behaviour of the tested materials is similar to that at lower voltages, only the shortcuts occurred in a shorter time – 7-17 s in the case of spacing 0.2 mm, around 1 minute in the case of spacing 0.4 mm for AgPt 99:1 and AgPd 6:1 films. For samples with 0.6 mm and 0.8 spacing, a shortcut occurred only in the case of AgPt 99:1 and AgPd 6:1 films (within 2 minutes for spacing 0.6 mm and within 7 minutes for spacing 0.8 mm). For samples with 1.2 mm spacing, no shortcut was observed. The copper film showed high resistance against electromigration, shortcut current was up to 1 mA for all variants of spacing.

In Fig. 14 are shown microscopic images of samples with spacing 0.4 mm after the electromigration test under voltage 12 V. There is visible dendrite growth for AgPt and AgPd films between electrodes, while copper dissolution on the anode electrode surface is apparent but no dendrite growth was observed for Cu film.

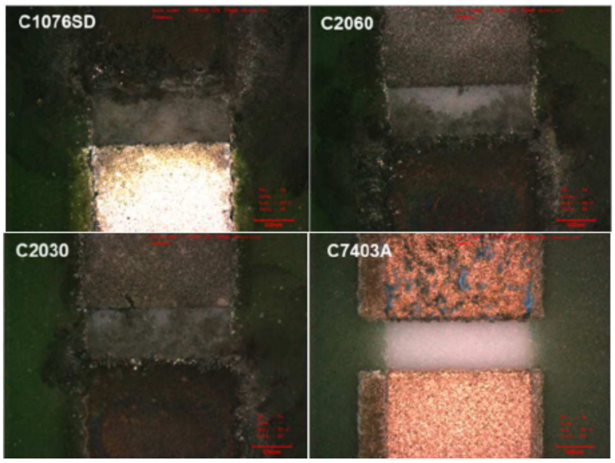

Fig. 14. Example of samples after testing of electromigration – voltage 12 V, spacing 0.4 mm.

C. *Water drop test – 5% NaCl solution*

No electromigration was observed in the samples with copper films during the water drop test. Therefore, in the case of these samples, the water drop test was performed with a 5% NaCl solution in distilled water. Samples with spacing 0.4 mm were tested under a voltage of 20 V. NaCl solution and higher voltage were chosen to promote the conditions for electromigration.

Results are shown in Fig. 15. There was no significant increase of the current between the electrodes even with the NaCl solution and higher voltage. The current was below 0.2 mA after 30 minutes of the test. Samples were also observed under the microscope before and after the test (Fig. 16). Similarly to the previous test at a lower voltage (12 V) and with distilled water, copper dissolution on the anode electrode surface is obvious but no dendrite growth was observed after the test.

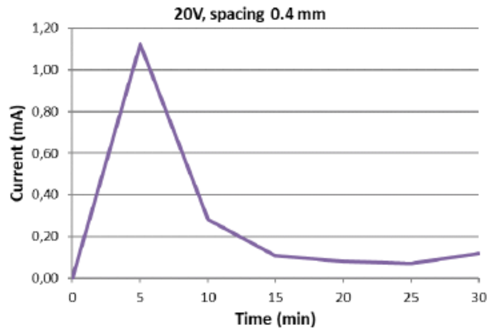

Fig. 15. Result of electromigration testing of sample with Cu film – test voltage 20 V, electrode spacing 0.4 mm, 5% NaCl solution.

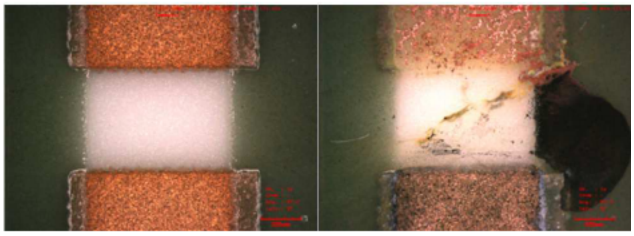

Fig. 16. Sample with Cu film before (left) and after water drop test in 5% NaCl solution (right).

IV. Conclusion

Experiments were carried out to verify electromigration in copper and silver thick films. Tests according to IPC standard 2.6.14.1 and water drop test with distilled water and 5% solution of NaCl in distilled water (only for samples with Cu films) were used.

Testing according to IPC standard 2.6.14.1. did not result in electromigration in samples with Ag and Cu films. Testing using water drop test under 6 V, 12 V and 20 V voltage showed far higher resistance of copper to migration compared to silver alloys. Copper dissolution on anode electrode surface is apparent but no dendrite growth was observed. Comparison between silver and silver-palladium alloys show detectable retardation of migration with increasing palladium content. While 6:1 alloy seems to be closer to pure silver, with 3:1 alloy retardation is quite apparent. Interestingly, with longer times of voltage applied, shortcut currents even decreased. The effect was most evident with 3:1 alloy. This is probably due to heavy oxidation/passivation by silver-palladium oxides limiting the availability of fresh metallic surfaces. Spacing is also important but a significant delay in shortcut time was observed only with spacing 0.8 and 1.2 mm.

From an economical point of view, given two times higher prices for AgPd 6:1 alloy and four times for AgPd 3:1 compared to silver, it is questionable where these alloys offer justifiable improvement. It seems more effective to use silver wherever possible (covered with low-cost overglaze) and apply AgPd 3:1 (or even 2:1) on most critical areas as soldering pads and contacts.

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