Investigation of Silver Migration Impacts on Microwave Systems Fabricated on LTCC Substrate Under High-Power RF Excitation and High Temperature and Humidity Conditions.

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Abstract

The demand for cost effective LTCC systems has led to increasing use of silver based thick film conductors for inner layers of RF modules. There exists some level of concern about the reliability of silver as a conducting material for electronic circuit packaging. This arises from the tendency of silver to migrate under the influence of electric fields when subjected to certain favorable environment conditions. However, previous research has shown that if silver is used in a properly designed LTCC system on inner layers, the LTCC dielectric forms a hermetic seal around the circuit pattern, which leads to a highly reliable circuit and a low cost solution. This paper describes the results of an investigation to characterize and quantify the impact of silver migration on real-life microwave systems fabricated with DuPont GreenTape™ 951 LTCC material system with silver metallization. A buried multilayer filter was chosen from an actual production design in a high-reliability application, and was tested at 15W of continuous RF power at 1.5 GHz under 85°C/85% temperature and relative humidity. The chosen test conditions were meant to simulate actual operating conditions encountered by the circuit in real-world, high reliability applications. The focus of this work is to collect useful operational information under environmental stresses encountered in typical applications. To this effect, unlike previously reported work [1], [2], [3] by proponents of silver, the work described in this paper is not forcing silver to migrate, but rather tries to evaluate the performance of an actual application circuit fabricated with silver under high-reliability test conditions and high power, high frequency RF excitation. Material characterization data as well as RF performance data – in terms of S parameters and power delivered – indicates no evidence of detrimental effects or performance impairments due to silver migration or other mechanisms.

Key Words: LTCC, Silver Migration, High Power RF Testing, DuPont GreenTape™ 951

Introduction

Finding low-cost metallization options without compromising electrical performance becomes critical as Low Temperature Co-fired Ceramic (LTCC) technology penetrates further in to cost sensitive consumer electronics and automotive applications. Current metal schemes available for LTCC system design include thick film compositions with Gold, Silver, and Copper metallizations. Given the price and price fluctuations of gold, metal schemes based on it are proving to be prohibitively costly for certain applications.

When considering low cost solutions for highly integrated LTCC modules, the designer primarily has two options: silver based thick film conductor systems or a copper based thick film conductor system. Although copper has excellent electrical conductivity in pure metal form – both bulk and as thin sheets - there really is no advantage of using a copper based thick film conductor compositions due to several factors, such as: the thick film copper has additives which decreases it's conductivity much lower than that of bulk copper [3]; the thick film copper system must be co-fired in a nitrogen environment, which eliminates the possibility of utilizing air fired printed resistors; firing in nitrogen is much more expensive than firing in an air environment; and the options are much more limited for brazing metal parts onto the external surface (which may be required for hermetic sealing). Many applications are demanding the use of buried resistors for beam forming networks and termination resistors, so eliminating them for use with LTCC will restrict designs from exploiting the full range of capabilities provided by the multilayer, 3 dimensional, LTCC packaging technology.

Silver has the highest possible electrical conductivity as a bulk metal, and to a large degree it preserves this quality when made into thick film metal pastes. When used as the inner layer conductor of multilayer LTCC packages, silver can be a low-cost, high conductivity, and highly reliable metal system since the inner layer metallization is hermetically sealed by surrounding glass-ceramic. Thick film gold can be used for surface metallization with suitable transition via metallizations to interconnect the inner silver trances and surface gold traces [4]. However, silver migration through ionic diffusion under electric field and resulting dendritic growth in glass-ceramic systems like LTCC has been a concern in the design community. A general perception in the industry is that silver cannot be reliable due to migration of silver through the glass-ceramic matrix. Expected electrical performance impairments include increase in leakage current between closely spaced conductors leading to unwanted cross-talk and coupling issues, decreased insulation resistance, dielectric breakdown, higher levels of RF loss, and outright shorting of interconnects.

It is known from previously published research that if silver is exposed to certain environmental conditions, dendrites can grow and cause shorting between metal traces, if placed close enough, and also cause impedance changes in RF lines or shorting of interconnects. Previous work [2**]** has been done at DC showing that silver can be reliable for DC interconnects, and used in high volume automotive applications for many years. Designers were not convinced that the successful work performed at DC would be indicative for high power RF applications, so a test method needed to be developed, and designs needed to be tested, to prove that silver is a viable and cost effect solution.

Materials and Test Methods

The purpose of testing described in this paper is to check whether there are any detrimental effects in performance of a component fabricated with silver metallization on the interior layers of DuPont GreenTape™ 951 LTCC system, due to ionic migration of silver. A filter in a high power transceiver application is selected and is subjected to 85^0C / 85% temperature and humidity in an environmental chamber. S parameters (frequency range 0.9 to 2.2 GHz) and RF power (at a fixed frequency of 1.332 GHz) delivered to the filter were measured in situ for 1026 hours. Silver concentration at predetermined locations within the multilayer LTCC structure was measured after the environmental testing and results compared to control samples which did not undergo such testing.

Test Circuit

A filter in the transmitter block of a transceiver used in a real-world high reliability application operating at a rated 12 W is selected as the functional test circuit. This filter is in the transmit path, and will see 12 watts of RF power for short periods of time (milliseconds) when the radio is transmitting. However, the test condition was designed to be 15 W of continuous power to ensure enough margins are built in. The filter uses a lumped element design implemented on internal LTCC layers using the DuPont Green Tape™ 951 and silver conductor system. A full wave electromagnetic analysis was performed to determine the locations within the circuit that would have the highest concentration of electric field, where if silver migration were to occur, would affect the performance of the circuit. This information was used to identify test locations for material characterization to quantify silver concentration changes if migration of silver occurs.

Figure 1 A and 1 B shows measured reflection and transmission spectra respectively; of the test filter circuit.

Material Characterization

SEM cross-sectioning and EDX are used as the main material characterization techniques to detect concentration of silver within the circuit layers. Three distinct locations within the multilayer structure were selected where the electric field is highly concentrated.

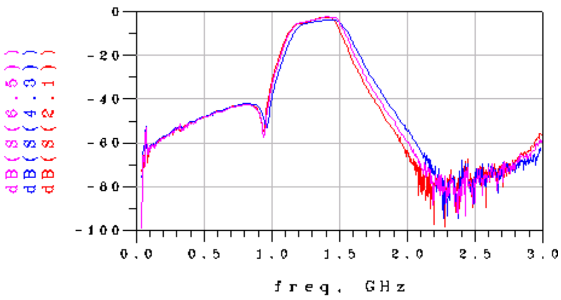

Figure 1 A: Measured Reflection spectrum of the test filter.

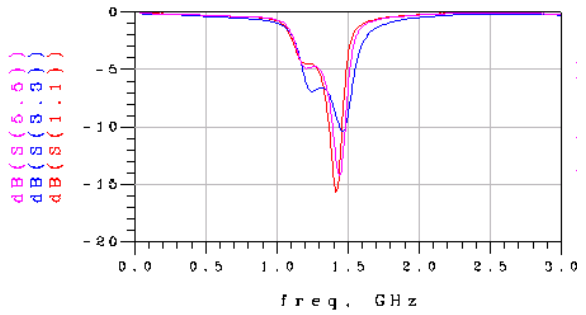

Figure 1 B: Measured Transmission spectrum of the test filter.

Location A is sufficiently far away from any silver metallization and hence serves as a control location where silver migration is expected to have no effect. Location B is between two silver metal structures – a via wall with a very high concentration of silver and an inner layer signal line - in the horizontal plane. Test site C is located between two capacitor plates and hence will be subjected very high electric fields. It is expected that if there is any silver migration under operating conditions, we will see a significant increase in silver concentration at test locations B and C while minimal changes expected at location A. These locations are shown in figure 2.

In searching for a suitable standard specification or other industry method that could be utilized to test the design at high RF power and determine the accelerated lifetime of the design, we determined that we would have to develop our own method. To this effect we modified some of the test standards such as IPC-TM-650-2-6-6-Test Condition 5.1 Class A and MIL-STD-883 Method 1004**.**

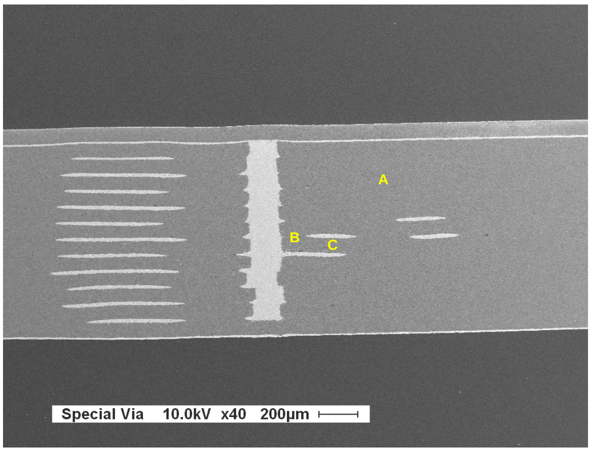

Figure 2: SEM with locations A,B, and C identified.

Test Conditions and Setup

Figure 3 shows the layout and figure 4 shows a photograph of RF test setup that was developed specifically for the testing the filters under conditions of 85°C/ 85% relative humidity, for 1026 hrs, while operating at 15W of continuous RF power at 1.5GHz. The test setup is capable of collecting S parameter data simultaneously.

While the filter in real time use sees only 12W of power for milliseconds at any given time during transmit, we feel the chosen test conditions simulate an extreme application scenario with enough built-in reliability margins. The filters were connectorized and placed inside temperature/humidity chamber. Connector to device interface was potted with a suitable epoxy to prevent degradation and resulting impact on measured parameters. Two thermocouples were mounted on the top surface of test circuits to monitor temperature as seen by the devices under test.

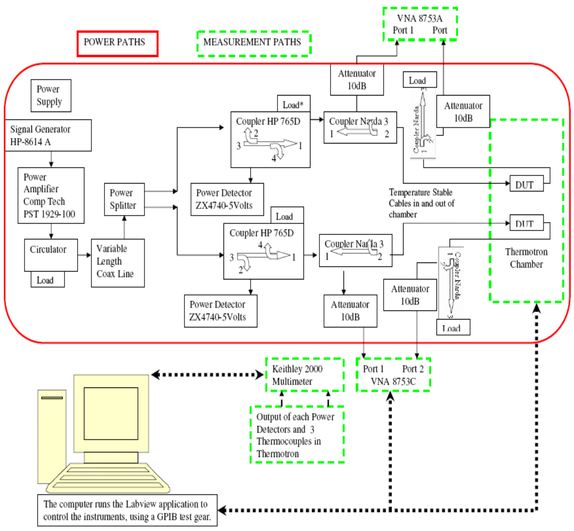

Figure 3: Layout of the RF test setup

S parameters and RF power were monitored in situ in intervals of 15 minutes at the environmental conditions specified above. Automated data acquisition was used with suitable LabView routines.

Results and Discussion

Figure 5 shows typical EDX analysis result. Table 1 shows the results of elemental analysis using EDX for the control sample and Table 2 shows the same for a filter that underwent 1026 hours of environmental testing under high power RF excitation (15 W).

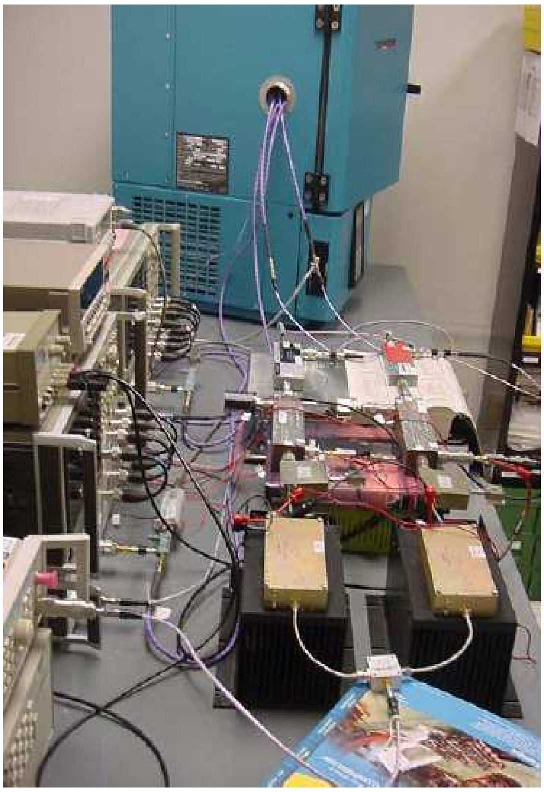

Figure 4: High Power, High Frequency environmental test set up

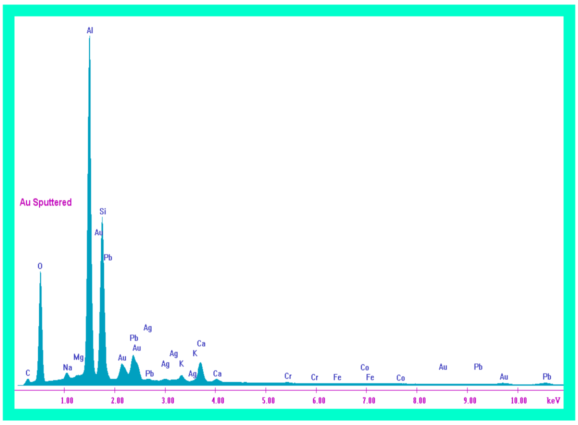

Figure 5: Typical EDX spectrum

It is evident from the presented data that there is no significant difference between silver concentrations for test locations A, B, and C before and after environmental testing. Test sites B and C show slightly higher concentrations of silver compared to location A due to silver migration during the firing process itself.

However, after firing, there is no evidence of further migration of silver under operating conditions encountered in real applications and slight variations in its concentrations are remnants of silver particles contaminating the test sites during the sawing and polishing process for sample preparation for material characterization.

Element	Site A	Site B	Site C
C	10.45	7.81	7.73
O	37.62	38.29	38.21
Na	0.94	1.01	1.18
Mg	0.37	0.35	0.33
Al	25.44	25.86	27.34
Si	19.23	20.46	19.41
Ag	**0.43**	**0.66**	**0.79**
K	0.45	0.49	0.46
Ca	1.42	1.42	1.34
Cr	0.07	0.07	0.07
Fe	0.03	0.00	0.00
Co	0.08	0.07	0.07
Pb	3.47	3.51	3.07
Total	100%	100%	100%

Table 1: Silver Concentration at test sites A, B, and C for the control device.

Element	Site A	Site B	Site C
C	11.52	12.27	18.30
O	32.84	33.35	32.54
Na	1.01	1.28	1.02
Mg	0.34	0.29	0.22
Al	27.82	28.18	27.42
Si	20.32	19.36	16.44
Ag	**0.20**	**0.55**	**0.42**
K	0.44	0.42	0.32
Ca	1.46	1.22	0.96
Cr	0.08	0.05	0.06
Fe	0.05	0.05	0.03
Co	0.10	0.07	0.07
Pb	3.82	2.91	2.20
Total	100%	100%	100%

Table 2: Silver Concentration at test sites A, B, and C for the device after 1026 hours 85^0C and 85% humidity testing

The key point is that the change of silver concentration before testing and after testing is the same and there is no difference observed between location A - which is far away from any silver traces - and locations B, and C, which are very close to silver trances and under significant electric stresses.

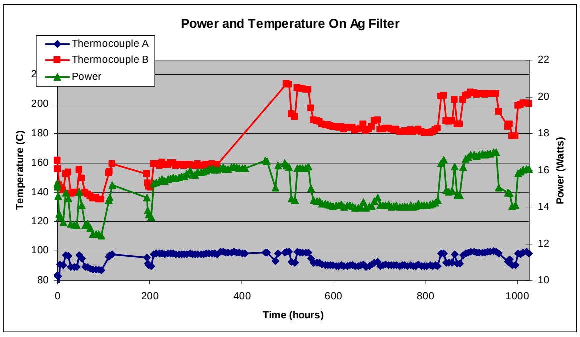

Figure 6: RF Power and Temperature as a function of time.

Figure 6 shows the temperature at two locations on the top surface and the RF power delivered to the device under test for the duration of testing.

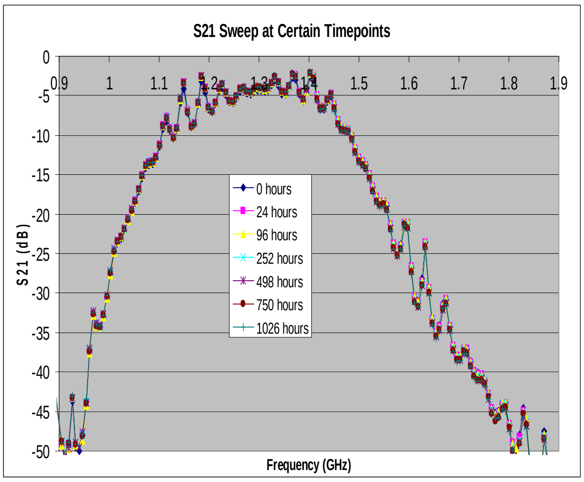

Figure 7: Transmission spectra of the filter at various time points.

Test parameters were selected to ensure an average of 15 W RF power passed through the filter, which is rated only up to 12 W in the application. The transmission spectrum of the filter as measured by S_{21} as a function of frequency (in the range 0.9 to 2.2 GHz) is shown in figure 7. S21 response for is shown for the same filter at the beginning of the test (time 0) and at 24, 96, 252, 498, 750, and 1026 hours.

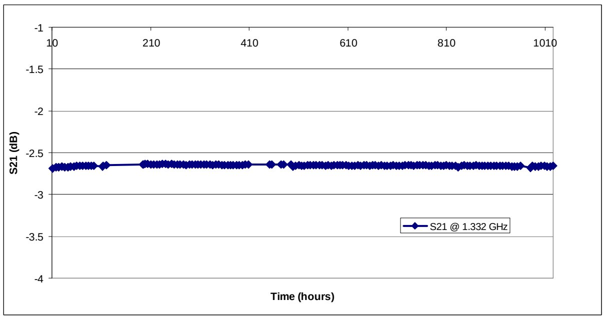

Figure 8: Insertion loss of the filter at 1.332 GHz over time.

It is clear that there is absolutely no difference in the transmission response indicating that there are no detrimental changes that occur for the physical circuit due to silver migration or any other effect. Filter transmission response as a function of time at a specific frequency (1.332 GHz) is shown in figure 8. The insertion loss is found to be extremely stable over the entire duration of the test under the specified conditions; clearly indicating no deterioration in performance due to silver migration or any other phenomena.

Conclusion

We have conducted accelerated testing to verify the viability of using silver as internal conductor metallization for industry standard LTCC materials under high power, high frequency excitation. The testing included continuous, in situ monitoring of RF power and S parameters of typical high power filters fabricated in LTCC. Detailed material characterization was carried out before and after subjecting test circuits to 85^0 C/ 85% temperature and humidity; using SEM and EDX. Results from the testing clearly indicate that there is no detrimental effect on the RF/electrical performance of test devices. Material characterization data do not indicate any evidence of silver migration for the internal layer metallizations under test conditions.

Acknowledgements

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Reference

[1] Robert E. Doty and John J. Vajo, “A Study of Field-Assisted Silver Migration in a Low Temperature Co-firable Ceramic”, ISHM Proceedings, 1995, pp. 468-474.

[2] C.R.S. Needs, “Environmental Durability of Silver Multilayer Circuits”, ISHM Proceedings, 1994, pp. 173-8.

[3] Yi-Ting Shih and Jau-HO Jean, “Failure Mechanism of a Low-Temperature-Cofired Ceramic Capacitor with an Inner Ag Electrode”, Journal of American Ceramic Society, 2010, pp. 1-6.

[4] K.M. Nair, MF McCombs, K.E. Souders, SE Gordon, “New Mixed Metal Transition Via-Fill Conductors for Cost Effective DuPont GreenTape ™951 & 9K7 LTCC Circuits, IMAPS 2010 Proceedings, Raleigh, NC USA (to be published).