NEXT-GENERATION, ADVANCED THICK FILM MULTILAYER SYSTEM

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Abstract: A new thick film multilayer material system has been developed to meet the increasingly demanding cost and performance requirements of the marketplace. The key feature of the system is a new two print multilayer dielectric composition that survives -40/+125 °C thermal cycle excursions with soldered components, and has good yield and electrical reliability at 30 μm fired thickness instead of the usual 40 μm. The dielectric has a wide conductor compatibility, the system including solderable silver-bearing and wire bondable Au conductors. The dielectric can be used with mixed metals (Ag, Pd/Ag, Au) without blistering. The surface resistors have ±75 ppm TCR´s and less than 0.5% drift after 1000 hours aging. Cadmium-free versions of all materials are available, for compliance with environmental regulations. The dielectric, via fill, and a solderable Pd/Ag conductor can be cofired together, reducing the number of process steps in the circuit manufacture and so reducing manufacturing cost. The system has already been qualified for use in a high-volume, cost-sensitive automotive application.

Naslednja generacija materialov za večplastna debeloplastna vezja

Ključne besede: materiali za elektroniko, materiali dielektrični, materiali debeloplastni večplastni, elektronika industrijska, elektronika avtomobilska, CG steklo kristalizirajoče, FG steklo polnjeno, vezja elektronike avtomobilske, zanesljivost sistemov elektronskih, cikliranje termično

Povzetek: Razvili smo nov sistem debeloplastnih materialov, s katerim bomo ustregli naraščajočim zahtevam trga po izboljšanih tehničnih latnostih in cenovno ugodnih izdelkih. Ključna lastnost sistema je nova sestava večplastnega dielektrika za dvojno tiskanje. Le-ta vzdrži termične cikle -40/+125°C skupaj s prispajkanimi komponentami. Po žganju je pri debelini 30 μm po izkoristku in električni zanesljivosti enakovreden prejšnjemu sistemu z 40 μm debelino. Dielektrik je kompatibilen z mnogimi debeloplastnimi prevodniki, tako s spajkljivimi na osnovi srebra kakor tudi tistimi na osnovi zlata, predvidenimi za bondiranje. Dielektrik lahko uporabimo za vezja s kombinacijo prevodnikov na osnovi različnih kovinskih sistemov (Ag, Pd/Ag, Au), ne da bi pri žganju prišjo do napihovanja ali luščenja plasti. Upori, izdelani na površini dielektrika, imajo ±75 ppm TCR in manj kot 0.5% spremembe uporovnih vrednosti po 1000 urnem staranju. Na voljo so tudi verzije brez vsebnosti kadmija, ki ustrezajo vsem okoljevarnostnim predpisom. Dielektrik, prevodnik za tiskanje skozi povezovalne odprtine in spajkljivi Pd/Ag prevodnik lahko žgemo hkrati, s čimer zmanjšamo število procesnih korakov in s tem proizvodne stroške. Opisani sistem so že ovrednotili v velikoserijski, stroškovno občutljivi proizvodnji avtoelektronike.

INTRODUCTION

Thick film multilayer materials systems have to be both electrically and mechanically reliable, as well as cost-effective in high volume manufacturing environments. Crystallizing-glass (CG) dielectric compositions have become a technology of choice because of their high electrical reliability associated with their high density and resistance to migration of silver, but have not had the same mechanical reliability as highly filled, traditional filled-glass (FG) dielectrics, particularly during thermal cycling with soldered components /1/. Thermal cycle performance is critical for automotive applications, especially with the trend of moving components under the hood.

In order to obtain the best features of the CG and FG materials, a system was adopted based on a stratified dielectric scheme employing a single layer of QM42, plus two layers of 5707H dielectrics /2/, and has been used successfully to build automotive electronic circuits. However, it was recognized that it would be valuable to have a single dielectric material that would have the functionality of the two, especially if thermal cycle performance and electrical reliability could be obtained with only two prints of dielectric instead of the three. Furthermore, to be the most cost-effective, such a new multilayer system needed to incorporate as much cofiring as possible in order to reduce the number of process steps.

This paper describes a new thick film multilayer dielectric system that was developed to meet the challenging needs of the industry. It has already been qualified for automotive applications in the US /3/. An example of an engine control module made with this system is shown in Fig.1.

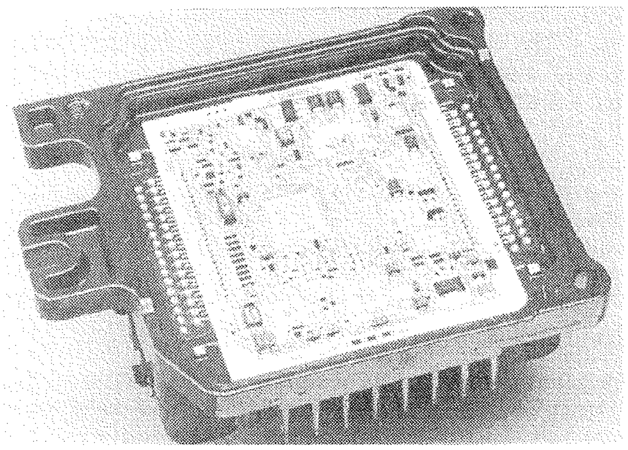

Fig.1. Engine control module made with QM44 dielectric system, Delco Electronics

SYSTEM PERFORMANCE

Build Scheme

There are several ways of introducing cofiring to a two print dielectric multilayer circuit, as listed in Table I. For simplicity, the discussion will assume a two metal layer circuit, though the build scheme concepts apply to circuits that have additional levels of circuitry. Also, only build schemes that employ one via fill print per pair of dielectric prints are listed since a new via fill material was developed that was optimized for filling with a single print.

In Table 1, D1 and D2 refer to the first and second dielectric prints, respectively, C2 refers to the top conductor, and V refers to the via fill. The control build using sequential firing requires four firing steps to create the second metal layer after the first metal layer has been printed and fired. The ultimate approach to cofiring, which involves firing D1,D2,V, and C2 together, requires only one firing, but is not practical because printing large areas of dielectric over unfired dielectric typically leads to print defects in the second layer. Similarly, cofiring D1 and the substrate level conductor C1 is not recommended because of the potential for defects in the dielectric when printing over the dried (unfired) conductor.

Table I. Possible cofire build schemes.

Build Scheme	Number of firings
Fire D1, D2, V and C2 sequentially	4 firings
Fire D1 and D2 sequentially Cofire V and C2	3 firings
Fire D1 and V sequentially Cofire D2 and C2	3 firings
Cofire D1 and V Cofire D2 and C2	2 firings
Fire D1 sequentially Cofire D2, V, and C2 (Preferred build)	**2 firings**
Cofire D1, D2, V and C2	1 firing

Firing the via fill and C2 together but separately from the dielectric is technically feasible, but requires three firings and so is not an aggressive enough approach to removing firing steps. Similar comments apply to firing D1 and V separately and cofiring D2 and C2. The remaining two build schemes, which both employ metals cofired with dielectric, require two firings, and represent the most process savings that can realistically be achieved. Cofiring V and D 1 left a modest via posting before printing D2, complicating the printing of D2. The approach of cofiring V, D2, and C2 is preferred from a printing point of view. This cofire build scheme eliminates two firings for each metal layer beyond the substrate level conductor.

Dielectric

The basis of the new system is a novel dielectric composition, QM44. It is a Pb-free and alkali-free, ceramic filled crystallizing glass composition, where the filler loading and crystallization kinetics are controlled to optimize both fired film density and strength properties. It is dense and hermetic, with good print yields and reliability at 30 μm fired thickness. The dielectric constant is approximately 9, and dissipation factor is 0.1-0.2% at 1 kHz. The dielectric can be fired with mixtures of silver and gold conductors more than 30 times without blistering. Excellent adhesion is obtained with a wide range of conductors.

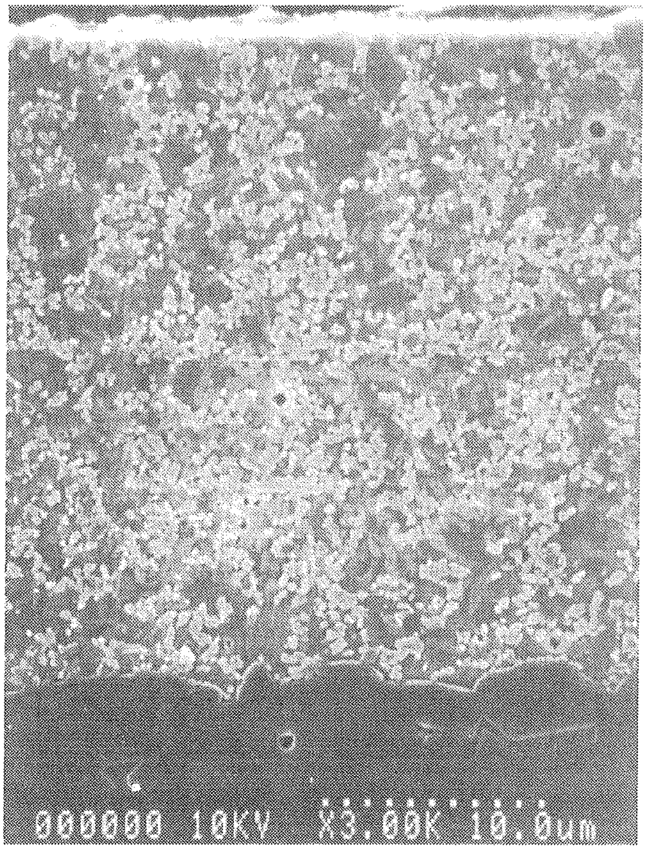

Fig. 2. Cross-section of the QM44 dielectric.

The glass viscosity and starting particle size are the critical factors in determining the maximum fired density a dielectric can achieve, and the filler loading that it can accommodate. Furthermore, to obtain high density films, crystallization must be delayed until after densification. Since glass crystallization often nucleates heterogeneously /4/, premature glass crystallization can occur with small particle size glass powders, especially through interaction with the ceramic fillers. By maintaining a wide difference between the softening point and the crystallization point in the dielectric, dense fired microstructures were obtained, as shown in Fig. 2.

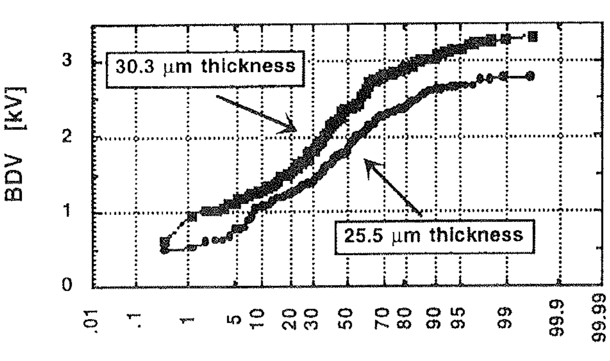

Fig. 3. QM44 breakdown voltage using 7484 3:1 Ag-Pd conductor.

The breakdown voltage (BDV) of the dielectric is shown in Fig. 3. The data is presented as a probability plot, showing the percentage of BDV data less than the Y-axis values. Data is plotted for two different dielectric thicknesses. Excellent BDV results were obtained even at approximately 25 μm thickness, though the distribution of low breakdown voltage values was better at 30 μm. The electrode was a 3:1 Ag-Pd sequential fire conductor printed to 17 μm squares. Only minor differences in QM44 BDV have been observed when using Ag-Pd, Ag-Pt, and pure Ag conductors, and between cofired and sequentially fired builds. The average BDV in Fig. 3 is 2.2 kV normalized to 30 μm.

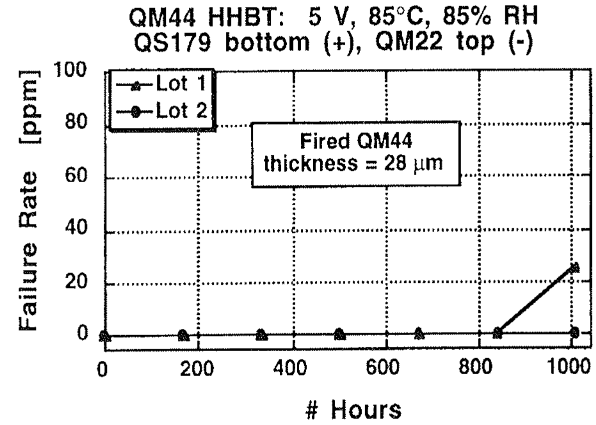

Fig. 4. High humidity biased test results with QM44 (unencapsulated).

High humidity biased test (HHBT) data is presented in Fig. 4. The bottom electrode selected was QS179 Ag-Pt, and the top conductor was QM22 cofired Ag-Pd. Test conditions were 5 V DC, 85°C and 85% relative humidity (RH). A total of 40,000 crossovers were evaluated in the test for each dielectric lot. The line widths were 250 μm, and the dielectric was tested at 28 μm fired thickness. No surface encapsulation was employed. Only one short was detected, at the 1000 hour mark.

Conductors

Excellent conductor adhesion is a key feature of this system. High aged adhesion with the new dielectric is obtained with a variety of standard conductors, as depicted in Fig. 5. The solder employed in Fig. 5 was 62/36/2 Sn/Pb/Ag.

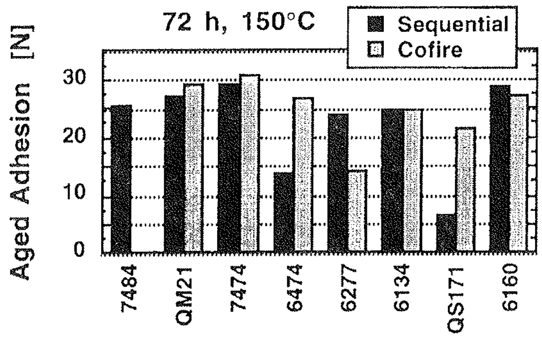

Fig. 5. Soldered aged adhesion of a range of standard conductors over QM44 dielectric. The conductors are 3:1 Ag-Pd (7484, QM21, 7474, 6474), 6:1 Ag-Pd (6277, 6134), Ag-Pt (QS171), and pure Ag (6160). The 7484 was not cofired in this test.

The soldered aged adhesion over QM44 of QM22, a new cofired, 3:1 Ag-Pd composition, is shown in Fig. 6. The adhesion failure mode was solder/conductor separation, indicating superior adhesion of the conductor to the dielectric. The failure rate of this conductor after thermal cycling is shown in Fig. 7. In this test, the standard wire peel geometry was used, but the test was modified to measure electrical continuity instead of adhesion. Three pads were soldered together in a row with a single wire, and each part employed three rows of wires connected together electrically in a daisy chain pattern. Furthermore, the edges of the pads were covered with an organic solder stop in a so-called window-frame geometry /1,5/. Failure was defined as an electrical open. Ten parts were tested, employing a total of 90 pads (30 wires). No failures were observed through approximately 800 thermal cycles.

Thermal cycle data with wire peel geometries can sometimes lead to difficulties in data interpretation if the failure modes don't match those with actual components /6,7/. The failure mode of most concern with multilayer constructions is cracking or divoting into the dielectric layer, a brittle type of failure mode often associated with failure at low numbers of thermal cycles /1,3,5,8/. To be certain that early thermal cycle failures

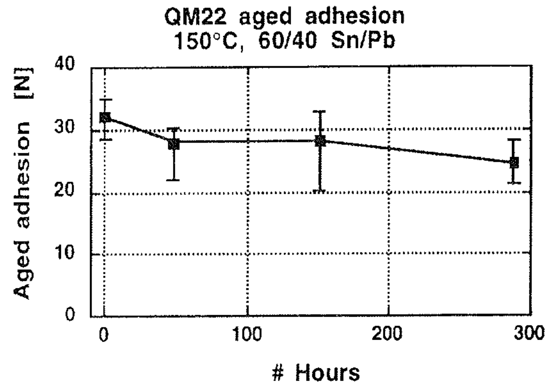

Fig. 6. Aged adhesion (min/max) of QM22 cofired 3:1 Ag-Pd conductor over QM44 dielectric.

associated with dielectric cracking won't occur, the most unambiguous thermal cycle data is obtained with actual soldered components. The reliability after thermal cycling of several electronic components soldered to the QM22 cofire Ag-Pd conductor over the QM44 dielectric was previously published /3/, showing good reliability through 1000 cycles of -40/125°C. Similar thermal cycle data with components soldered to the 7484 sequential fire Ag-Pd conductor over QM44 was also presented previously /1,3/, again showing good performance through 1000 cycles.

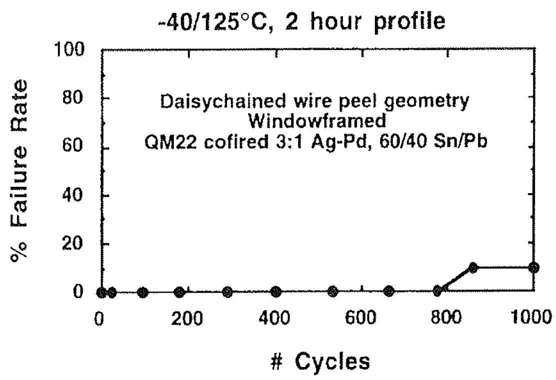

Fig. 7. Thermal cycled reliability of QM22/QM44, using a 3-pad wire peel orientation.

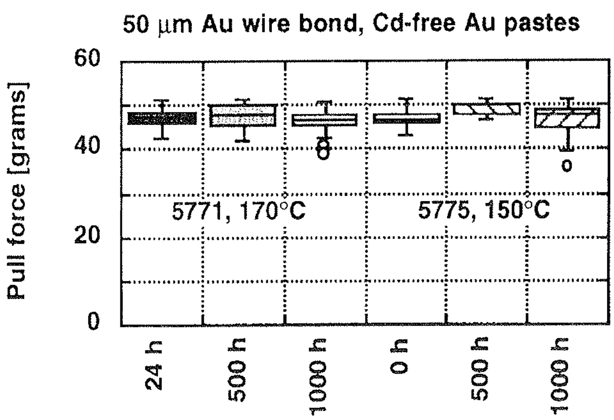

Fig. 8 Wire bond aged adhesion of Au conductors with 50 micron Au wire.

The new dielectric is also compatible with wire bondable gold compositions, including newer Cd-free materials. Wire bond aged adhesion with 50 μm Au and 250 μm Al wire is shown in Figs. 8 and 9, respectively. The data is presented as boxplots, with each box typically representing approximately 30 data points. The median adhesion values are shown at the center of the boxes, with the 25% and 75% points in the distributions at the bottom and top of the boxes, and the extremes of the data shown by the lines from the boxes (open circles are also part of the distributions, but are statistical outliers, and fall outside of the lines. The pull test failure mode after ageing in all cases was 100% wire breaks - failures were either within the wire, or at the heel of the first or second bond sites. No metallization lifts or bond lifts were observed, indicating superior adhesion of the Au pastes to the dielectric, and of the wire to the Au pastes. The reduction in pull strength in Fig. 9 with the 250 μm Al wire is believed to be due to annealing of the Al wire.

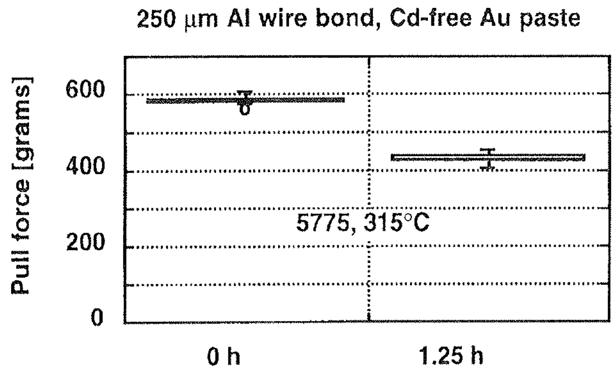

Fig. 9 Wire bond aged adhesion of Au conductor with 250 micron Al wire.

Via Fill

A new via fill material, QM35, was developed to facilitate cofiring in this system. Control of the metal particle size for reduced shrinkage was essential in order to allow cofiring without cracking around the vias. However, since this material must connect Ag-Pt substrate conductor and Ag-Pd top conductor, the via fill must fire sufficiently densely to prevent electrical opens on refiring that can occur due to Kirkendall-type void formation.

The circuit yield in a manufacturing setting with this material was described previously /3/, indicating no opens after a total of 10 firings when connecting Ag-Pt and Ag-Pd materials. Furthermore, preliminary data shows this via fill material to be useful in connecting pure silver and gold conductors, as depicted in Fig.10. The conductors, dielectric, and via fill in Fig.10 were all fired sequentially. The dielectric was printed to a total of 30 μm fired, with 10 μm vias. No opens were obtained through three top Au conductor refirings (four total firings), with approximately 4 ppm opens occurring after 5 refires, and larger amounts of opens occurring only from 10-15 refirings. For circuits that employ wire bondable top Au traces, there might also be resistors and solderable Ag-Pd conductor pads at the top surface, so that the Au prints might be subject to a limited amount of refiring. The expected refiring is within the ability of the QM35 via fill to connect the Ag and Au lines without electrical opens.

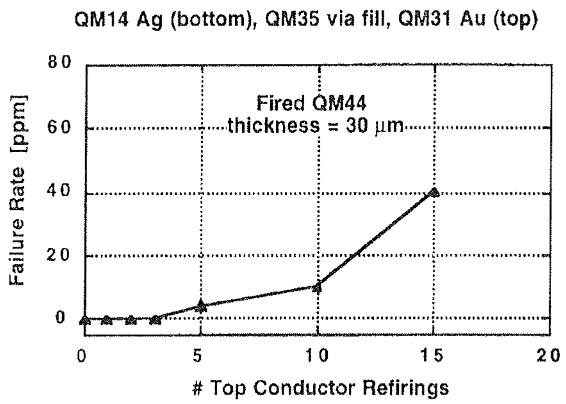

Fig.10 Via fill failure rate (ppm open circuits) connecting Ag and Au conductors.

A second via fill material is available for the system when larger number of metal layers are employed. The QM34 is especially suitable in the inner layers when stacked vias are designed in the circuit, with no cracks and flat via fill topologies obtained through three sets of dielectric/stacked via fill/ conductor prints, which is equivalent to a four metal layer circuit (including the substrate level conductor). The QM34 can also connect Ag-Pd and Ag-Pt (or pure Ag) conductors, but is not suitable for connecting Ag and Au conductors, with opens occurring after the first refire.

Resistors

A new resistor series S100 was developed for the dielectric system. The technology is based on a new hybrid series that features improved power handling and process insensitivity, tighter temperature coefficients of resistivity (TCR), and reduced noise vs. older hybrid resistor series /9/. The resistor series spans 10 Ω/sq to 1 MΩ/sq.

The resistance and hot and cold TCR's for the members are plotted in Fig. 11. The TCR's fall within ± 75 ppm/°C, except for the 10 Ω/sq member which is within 100 ppm/°C. Laser trim stability data of unencapsulated resistors are plotted in Fig.12 after 1000 hours aging at 150°C, 1000 hours at 85°C/85% RH, and after 1000 hours at room temperature (see also /3/ for -50/150°C stability data). Excellent trim stability of less than ± 0.5% average drift was obtained under all ageing conditions.

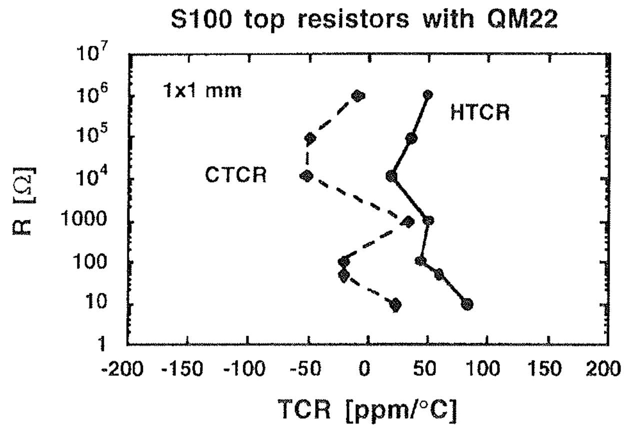

Fig.11. Resistance and TCR values of S100 resistor members over QM44 dielectric.

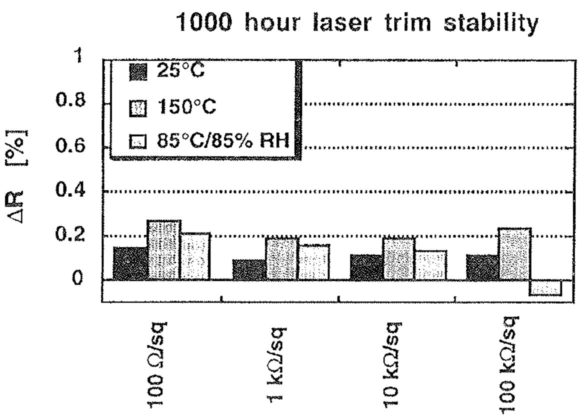

Fig.12. Laser trim stability of S100 resistor series.

SUMMARY AND FUTURE PLANS

A new thick film multilayer system has been developed for applications that require thermal cycle reliability with soldered components. The key feature is a new dielectric material that is tuned for good conductor compatibility, yet has high density for good circuit yield and reliability with only two prints. The dielectric can be cofired with the system via fill and top conductor, which further reduces manufacturing costs. Upcoming enhancements for the system include a set of buried capacitor and resistor materials that will become available (see also ref. /10/). The buried resistors are expected to span a range of 100 Ω to 100 kΩ, with 300 ppm TCR's and ±10% tolerance. A buried capacitor member will be based on barium titanate and will have a dielectric constant of approximately K1300 with X7R temperature characteristics. A pair of relaxor-based capacitor compositions are already commercially available and span a range of K1600-K3900; however, their Y5U temperature characteristics are not suitable for under-the-hood automotive applications.

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