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SOP EMBEDDED THIN FILM RESISTORS ON HIGH AND LOW LOSS THICK FILM DIELECTRICS

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ABSTRACT

This paper describes low-cost materials and processes for embedded thin film resistors that can be integrated into printed wiring board using sequential build-up processes. Realization of embedded resistors on conventional board level high loss epoxy (~0.015 at 1 GHz) and proposed low loss BCB dielectric (~0.0008 at > 40 GHz) has been explored in this study. Foil transfer and electroless plating have been attempted for embedding thin film resistors. Ni-P alloys were plated using conventional electroless plating, and NiCr and NiCrAlSi foils were used for the foil transfer process. A test vehicle consisting of various geometry and values of resistors was designed and fabricated to evaluate electrical and mechanical reliability of embedded thin film resistors. For the first time, Benzocyclobutene (BCB) has been proposed as a board level dielectric for advanced System-on-Package (SOP) module primarily due to its attractive low-loss (for RF application) and thin film (for high density wiring) properties. To realize embedded resistors on multi-layer BCB, a low-cost large format electroless process for deposition of NiP and NiWP thin film resistors using both low- (25^{o}C) and high-temperature (90^{o}C) baths has been developed. The electroless process exhibits uniform resistor thickness in the sub-micron range and offers low profile and excellent adhesion to BCB dielectric. These films also act as a seed layer for the subsequent direct electroplating of copper traces. NiP alloys can also be tailored to variable temperature coefficient of resistance (TCR) with different alloy compositions. The electroless process can be adopted in the PCB manufacturing industries with no additional investment.

INTRODUCTION

Embedded passives provide practical solution in system miniaturization. In a typical mixed-signal circuit, over 70 percent of the electronic components are passives such as resistors, inductors, and capacitors that could take up to 50 percent of the entire printed circuit board area. By integrating passive components within the substrate in contrast to the surface, embedded passives reduce the system volume and mass, eliminate the need for some discrete components and assembly, enhance electrical performance and reliability, and potentially reduce the overall cost.

Current world wide fixed-resistor market is approximately 2 billion USD, and less than 1 percent is embedded. In order to increase the embedded resistor market share, several technical challenges need to be resolved such as tight tolerance, low TCR (thermal coefficient of resistance), and wide range of resistance values for a variety of applications. International Electronic Manufacturing Initiative (iNEMI) projects portable and handheld product tolerance of 5% without trim and maximum resistance of 100k ohm/sq by 2007. Also, the target for TCR is ~100ppm/C. Although several options are being investigated to meet iNEMI projections, thin film resistor technology seems promising due to its low-cost, relatively tighter tolerances, compatibility with PWB, and good adhesion.

Numerous materials and processes [1 and references cited therein] for embedding resistors are summarized in Table 1. Sheet resistance in the range 25 to 250 Ω/sq are commercially available from Ohmega. Intarsia Corporation, Boeing, NTT, and GE have utilized Ta_2N films for thin film resistors with resistivity values in the range of 10 to 125 Ω/sq. AT & T Bell Labs and Singapore Institute of Microelectronics reported TaSi films with resistivity in the range of 8 to 40 Ω/sq. Sheldahl Corporation and the University of Arkansas deposited CrSi films with sheet resistivity ~360 Ω/sq., and TaN and NiCr films with resistivity ~100 Ω/sq. W. L. Gore and Associates deposited TiW films with resistivity in the range 2 to 4 Ω/sq. Deutsche Aerospace utilized NiCr materials with resistivity 35 to 100 Ω/sq.

Although there are a wide variety of materials available, the choice is limited when low temperature processes are desired. Materials requirements for embedded resistors can largely be satisfied by choosing materials systems that will

provide sheet resistance in the range of (i) 5 to 50 Ω/sq, (ii) 500 to 1000 Ω/sq, and (iii) 5K to 40 KΩ/sq with a temperature coefficient of resistance (TCR) on the order of +/- 50 ppm/^{o}C. Several materials systems (Table I) have been explored for integrating resistors. Besides materials, there are also challenges in process integration such as large area fabrication with good reproducibility and yield, materials stability, variations in length, width and thickness of the deposited thin film, contact resistance, smoother substrate to reduce noise, trimming, and development of low cost fabrication processes [2]. Among the many materials and processes referred in the literature [3], electroless plating [4-6] appears to be a good approach to meet the required goal in the low-value resistors.

Table 1. Embedded Resistors Approaches [1]

Industry/Institution	Materials	Approach	Range of values ohms/sq (TCR ppm/ ^{o}C)
Intarsia Boeing NTT GE	Ta_2N	Sputter	10-100 20 (+/- 100) 25-125 (-75 to -100)
Osaka University Metech Acheson Colloids Electra Ashai Chemical W R Grace DOW Corning Raychem Corporation Ormet Corporation	Conductive Polymer composites	Polymer thick film process Liquid phase sintering	Insulating to conducting
Ohmega Ply	NiP alloy	Electroplate	25-500
Singapore Inst. Microelectronics AT & T Bell Labs	TaSi	DC Sputter	10-40 8-20
University of Arkansas/Sheldahl	CrSi	Sputter	(- 40)
W. L. Gore and Associates	TiW	Sputter	2.4-3.2
Shipley	Doped Pt on Cu foil	PECVD	Up to 1000 (100)
Deutsche Aerospace GOULD Electronics	NiCr NiCr NiCrAlSi	Sputter	35-100 25-100
Georgia Institute of Technology MacDermid	Ni-P/Ni-W-P NiP	Electroless plate	10-50 25-100
DuPont	LaB_6	Screet print and foil transfer	Up to 10K (+/-200)

In this study, two approaches have been investigated for deposition of thin film resistors on low-temperature organic substrates: foil lamination and direct electroless plating. For foil lamination, commercially available resistor materials from GOULD Electronics are utilized. Electroless resistors were formed using NiP, and a combination of NiP and NiWP alloy compositions for low TCR.

NOMENCLATURE

SOP, Embedded Resistor, Electroless Process, TCR

RESULTS AND DISCUSSIONS

Direct Foil Lamination on high loss epoxy dielectrics

The Gould TCR NiCrAlSi and NiCr foil resistors were selected for direct lamination. The Gould resistor layer is a sputtered NiCrAlSi or NiCr thin film layer on the rough, matte surface of a copper foil. The foil is laminated with the resistor surface in contact with the dielectric. Processing of the resistor proceeds with photolithography and etching of the circuit features and resistor widths. Acidic cupric chloride was used as the first etch to remove Cu and the underneath resistor layer. A second photolithography step using ammonical etch was then performed to define the resistor widths by selectively removing the copper from and over the resistor material. Figure 1 shows a general overview of the Gould thin film resistor fabrication process [7]. Figure 2 shows fabricated resistors with resistances in the range of 25 to 1000 ohms.

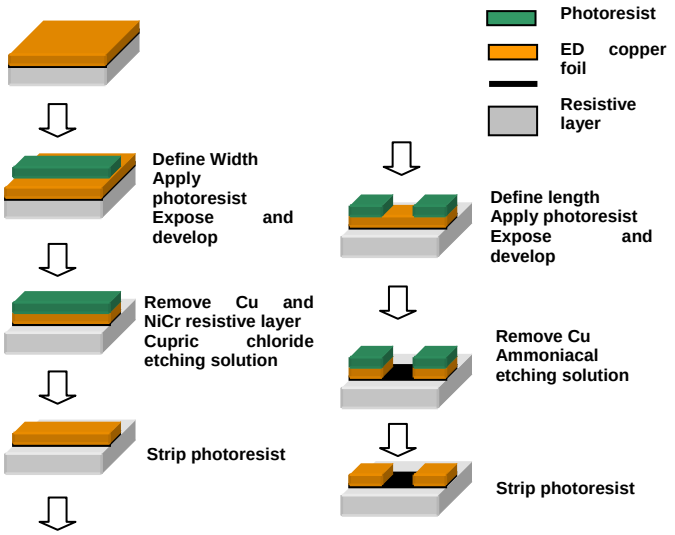

Figure 1. Gould resistor fabrication process [7]

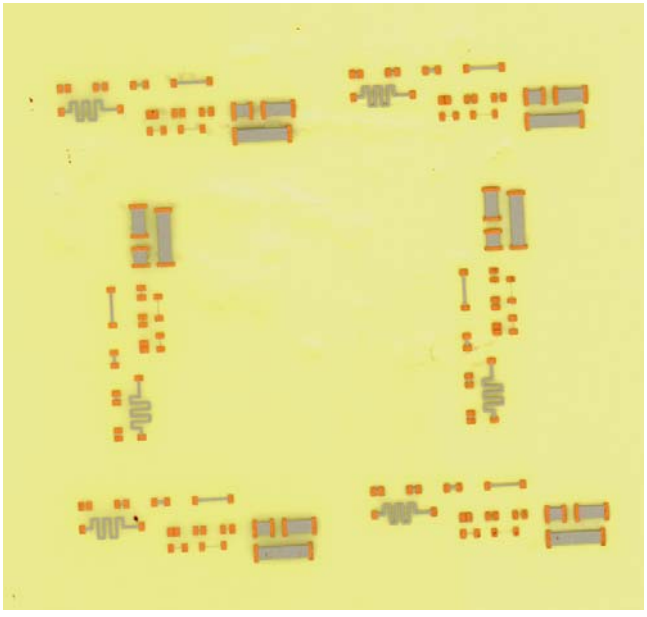

Figure 2. Fabricated resistors using Gould process

After completion of each embedded component layer, thermal shock and temperature humidity tests based on JEDEC standards (No. 22-A104-B and No. 22-A102-C) were performed. For thermal shock test, temperature profiles of -55 to 125 ^{o}C was used with soak time of 20 minutes/cycle for up to 1000 cycles. For constant temperature humidity test, resistors were tested at 85^{o}C and 85% RH for 150 hours. Figure 3 and Figure 4 show initial reliability test results.

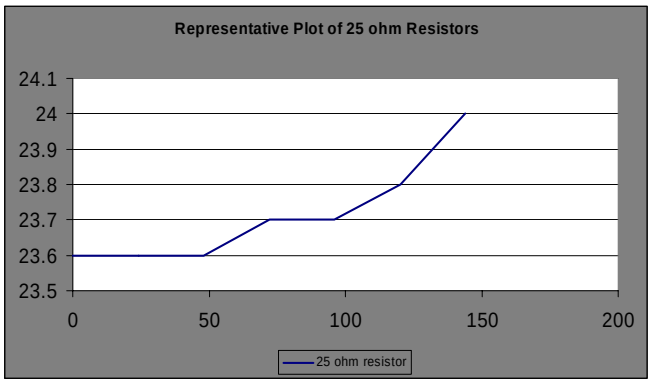

Figure 3. Temperature/Humidity 85^{o}C/85%

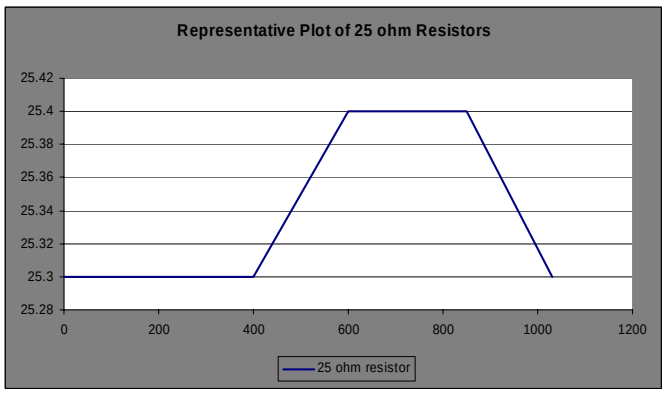

Figure 4. Thermal Cycling -85^{o}C to 125^{o}C

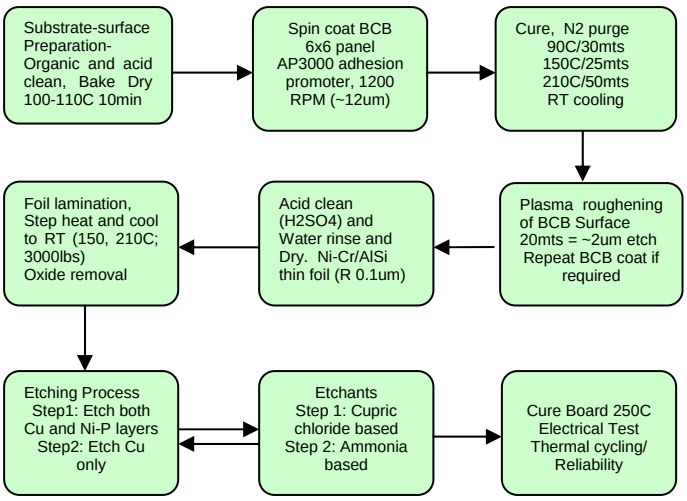

Figure 5. Process flow for resistor foil lamination on BCB

Direct Foil Lamination on low loss BCB dielectric:
Figure 5 exhibit the process flow optimized for resistor foil lamination on liquid Benzocyclobutene (BCB). The inherent brittleness of BCB required design of experiments for proper tunning of lamination time, temperature, and pressure. After successful lamination of NiCrAlSi resistor foils, the resistors were patterned using the two-step etch process described in Figure 5. This is the first report on demonstration of thin film embedded resistors on low loss BCB dielectric and is targeted for the RF application. Figure 6 shows resistors fabricated on a low CTE and high modulus carbon fiber reinforced SiC composite.

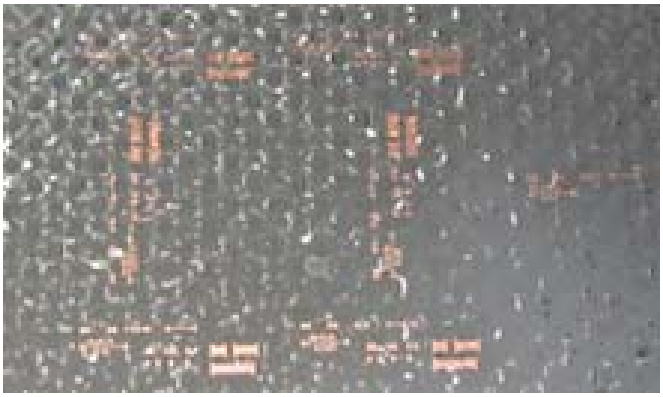

Figure 6. Fabricated resistors on BCB using foil lamination

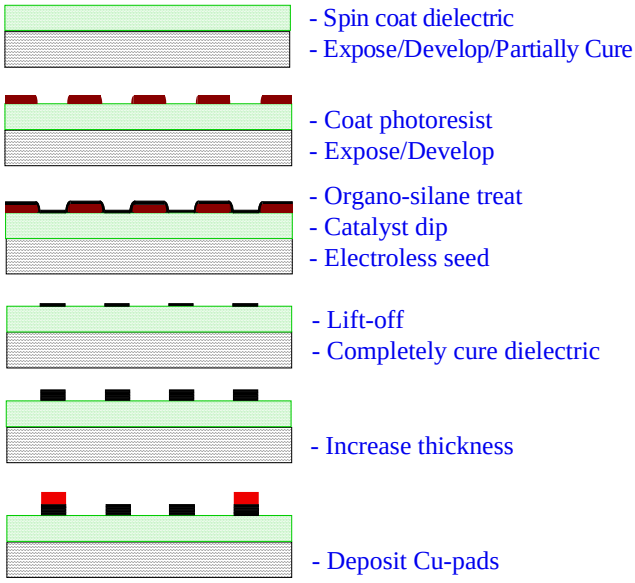

Figure 7. Electroless resistor structure fabrication sequence on epoxy dielectric.

Electroless Plating on EPOXY dielectric
Electroless plating onto a nonconductive substrate requires the surface to be sensitized and then activated. Tin chloride ($SnCl_2$) and palladium chloride ($PdCl_2$) dissolved in diluted hydrochloric acid (HCl) are used as sensitizers and activators respectively. Acid hypophosphite-based baths were used in this work for their low pH (most polymers can withstand low pH

baths). The composition of the electroless plating bath used are the same as for Ni-W-P alloys [4,5] summarized in Table II.

Table II. Electroless plating recipe for Ni-P and Ni-W-P

Materials	Ni-P	Ni-W-P
Nickel sulphate ($NiSO_4$)	57.8 g/l	7 g/l
Sodium hypophosphite	42 g/l	10 g/l
Maleic Acid	35 g/l	---
Sodium Succinate	17.4 g/l	---
Sodium Tungstate	---	10 g/l
Sodium Citrate	---	45* g/l
pH	4.5 - 5.5	
Bath Tempetature (^oC)	90	90

The electroless resistor processing sequence is outlined in Figure 7. Substrate material is spin coated with dielectric, which is subsequently dried, exposed, developed and partially cured. A photoresist is coated and patterned on top of the epoxy layer. The sample is then surface treated with organosilane and followed by immersion in catalyst baths. Rinsing in DI-water is carried out between each step. The substrate is then placed horizontally in a 90^{o}C Ni-P bath to maintain uniform temperature across the board for 1.5 to 3 min. to form a thin seed layer. After annealing the substrate to improve the adhesion of the seed layer (~100^{o}C, air ambient), the Ni-P patterns are formed by lift-off in photoresist.. This is followed by annealing the resistor pattern at 150^{o}C for 30min (to improve adhesion) and deposition and patterning of Cu-pads through electroless plating to form the final resistor structure [8].

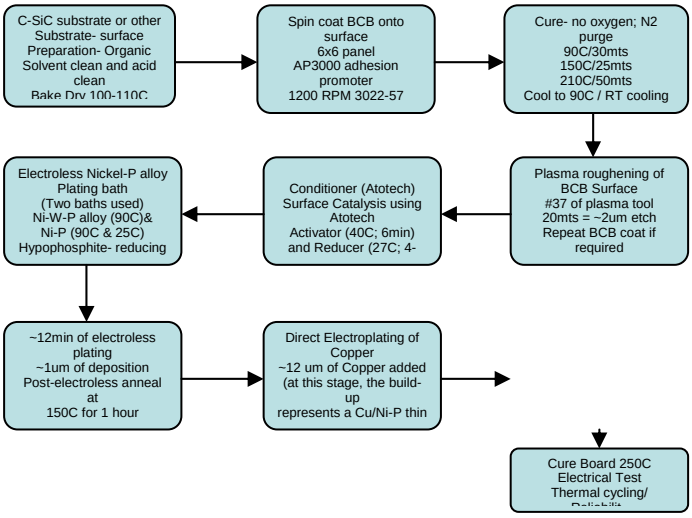

Figure 8. Process sequence for electroless plating on low-loss BCB dielectric surfaces

Electroless Plating on low loss BCB

Since BCB surface is relatively inert, it was difficult to deposit NiP resistors by electroless plating method described for the epoxy dielectric. BCB surface treatment and process modifications were required for successful deposition of NiP and NiWP alloys by electroless plating [9]. The NiP alloys were subsequently plated with Cu and then patterned to define resistors. Excellent adhesion of NiP alloy on BCB has also been observed. The measured sheet resistance values are in the range of 250-400 ohms which can cover the niche applications in telecommunications, low-cost handheld electronic products and computing products. The thickness of the Ni-alloy deposit is of the order of 2000-5000 A (angstrom). A brief flow chart for the electroless plating on BCB is given in Figures 8 and 9.

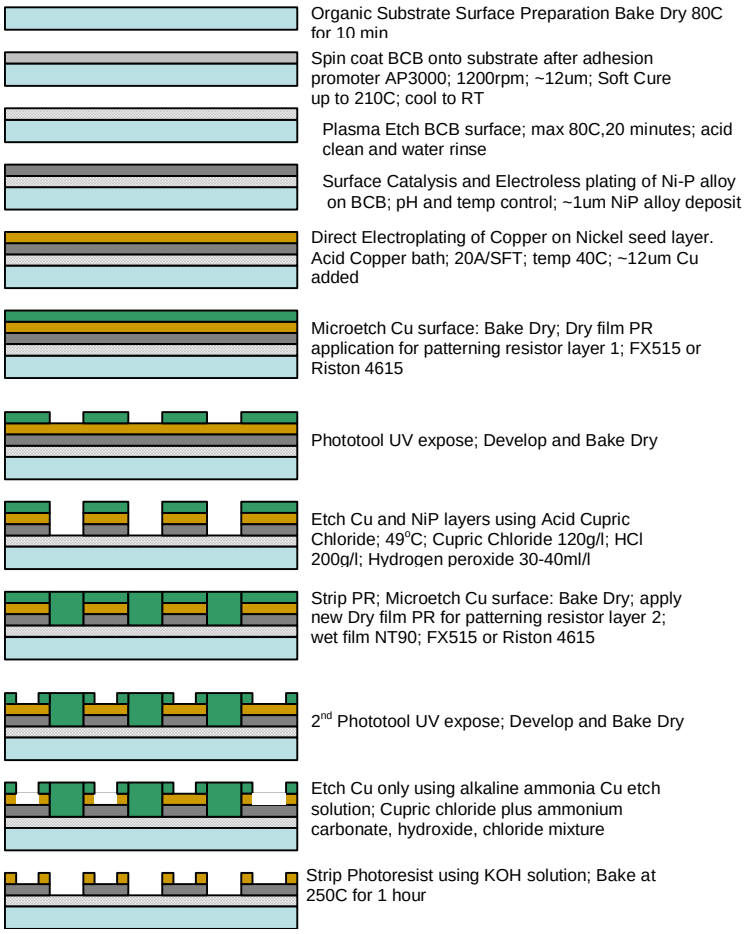

Figure 9. Schematics of electroless plating on BCB

In addition, a low-temperature Ni-P alloy electroless plating bath has been used in our studies. High-temperature electroless plating baths need consistent maintenance of bath temperatures and pH by the addition of buffer solutions. The low-temperature bath has been found to maintain steady plating with no appreciable change in bath pH. The recipe for the low-temperature electroless bath (25 ^{o}C) is given in Table III [10].

Table III: Low-temperature electroless plating bath for Ni-P

Nickel Sulfate hexahydrate	50g/litre
Sodium pyrophosphate	100g/litre
Ammonium hydroxide	200ml/litre
Sodium hypophosphite	50g/litre
Operating temperature	25C

High Frequency Characterization of Integrated Resistors Fabricated on Epoxy Dielectric

A test vehicle, Figure 10, consisting of various thin-film structures to evaluate electrical and mechanical properties, processing conditions, and reliability was designed and fabricated. In order to evaluate the frequency dependent performance of thin-film resistors made from Ni-P/Ni-W-P, several resistor structures were included on the test vehicle. In this paper, the coplanar G-S-G resistor structures, without the ground plane, were used for high frequency measurements. Figure 11 shows the photomicrograph of the resistor structures. Large Cu-pads on these structures were used to minimize contact resistance.

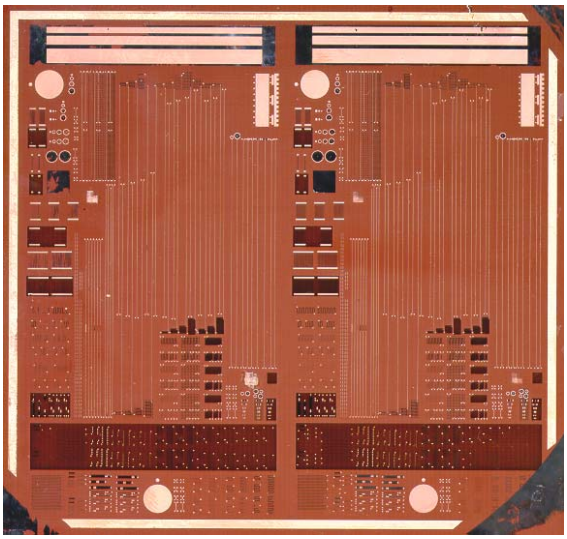

Figure 10. Photomicrograph of a resistor material/structures test vehicle on PWB substrate (approx. 95 cm^2 area).

The high frequency measurements were performed with an HP 8510C vector network analyzer and ground-signal-ground (G-S-G) coplanar waveguide 200μm-pitch probes. Calibration to the probe tip was carried out using a standard LRM calibration kit. To reduce random errors, the process of calibrating the system and measuring the device characteristics was repeated ten times and the measured S-parameters averaged before any data analysis. RF measurement of the resistor structures was performed by directly probing the CPW pads of Figure 11. No further corrections were carried out to the measured data.

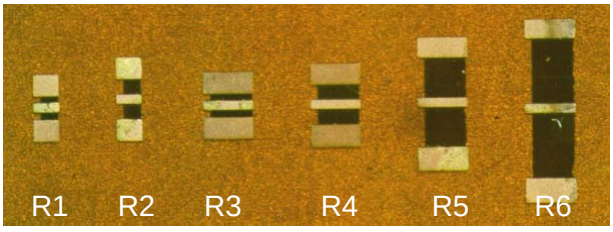

Figure 11. Photomicrograph of G-S-G resistor structures, NiP/NiWP resistor film in dark, used in the high frequency measurements. The middle probe pad width is 50 μm wide for all structures.

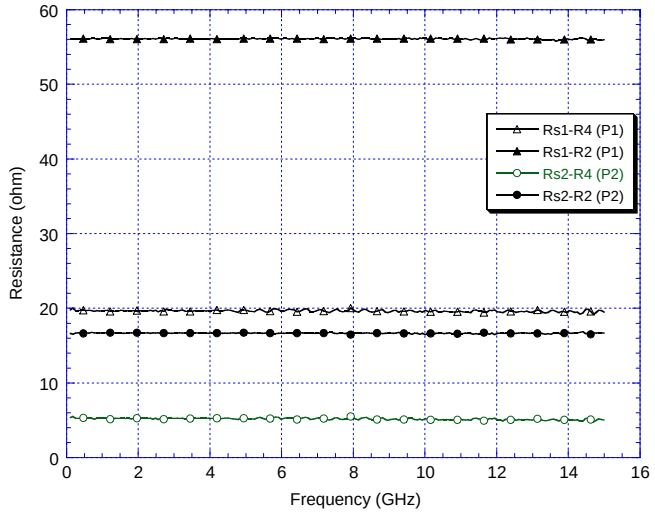

Figure 12. Real component of the input impedance (Z11) for resistor structures (R2 and R4 in Figure 8) with different sheet resistivities (Rs1 ~ 100 ohm/square, Rs2 ~ 35 ohm/square).

The measured results of structures without a ground plane with different sheet resistivities and resistance values are presented in Figure 12. The figure shows the real component of the input impedance of the measured coplanar resistor structures (Ni-P/Ni-W-P based) on the test vehicle (R2 and R4 in Figure 11). No parasitic effects (capacitive or inductive) were observed within the measured frequency range. The intrinsic resistance of the NiP/NiWP thin film can be considered not to vary with frequency from DC to 15 GHz. This indicates that Ni-P/Ni-W-P resistors can be used in mixed-signal applications (high frequency applications).

CONCLUSIONS

In this study, two approaches have been investigated for the integration of thin film resistors on low-temperature organic substrates: foil lamination and direct electroless plating. For foil lamination, commercially available resistor materials from GOULD Electronics are utilized. Electroless resistors were formed using NiP, and a combination of NiP and NiWP alloy compositions for low TCR.

Using electroless plating, fine line structures (< 50 μm range) can be fabricated using the NiP seeding and lift-off technique. The resultant films produce film resistivity in the range of 5 - 100 ohm/square with good uniformity across the substrate (<10% variation), satisfying the lower resistivity value requirements for mixed-signal applications.

For the first time, the electroless deposition of NiP alloys was demonstrated on low loss BCB dielectric. This totally electroless technique allows for use of low cost equipment, tailoring of sheet resistivity, and the need of trimming of resistor structure after processing.

Also for the first time, NiP and NiCrAlSi resistors were laminated on liquid BCB films to define embedded thin film resistors. The lamination process was optimized by varying temperature/time/lamination pressure to yield foils with good adhesion and subsequent process qualification for patterning.

ACKNOWLEDGMENTS

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