Modern Microelectronic Technologies in Fabrication of RFID Tags

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Abstract. *This paper presents fabrication of RFID tags, especially antennas for HF band (13.56 MHz), on cheap flexible substrates. The physicochemical, geometrical, DC and AC electrical properties as well as long-term stability (under thermal, moisture-thermal and mechanical exposures) have been characterized for several low-temperature polymer thick-film conductive films made on various paper or foil substrates. Resistance measurement during curing has been used for investigation of polymerization velocity, which is very important for increase of process capacity.*

Keywords

RFID, printed antenna, polymer conductive ink, electrical properties.

1. Introduction

Mixtures consisting of powdered filler/polymer matrix from the materials science point of view can be treated as composites, i.e. macroscopically inhomogeneous materials [1]. The functional phase of polymer thick film conductors consists of about 90 wt% (i.e. 60 to 70 vol.%) of such composites. The electrical conductivity takes place in such films through contacts between neighboring conductive grains (usually this is flaked silver). Therefore their minimal value of sheet resistance is equal to about 20-30 mΩ/sq, i.e. an order of magnitude higher than of one-component high-temperature cermet thick-film conductors or copper foil [2], [3]. The kind of polymer matrix is dependent on substrate, on which the film has to be deposited.

About 25-30 years ago membrane switches became the main source of increased interest of polymer thick films (in particular conductive ones) [4], [5]. In recent years there has been great interest in application of these materials for fabrication of RFID antennas.

This paper presents fabrication of such tags (especially antennas) on cheap, flexible substrates. The physico chemical, geometrical and electrical (both DC and AC) properties as well as long-term stability (under thermal, moisture-thermal and mechanical exposures) have been characterized for polymer thick-film conductors and RFID antennas made of them in dependence of kind of applied substrate and curing conditions. The measurement of resistance during the curing process has been used for evaluation of polymerization velocity of polymer thick-film conductors, which is very important from the maximization point of view of process capacity.

2. RFID System – Basic Information and Technologies

2.1 Basic Information

RFID (*Radio Frequency Identification*) means the wireless identification system based on radio frequencies transmission [6-9]. Such system comprises of a stationary transceiver, called a reader, and a mobile transceiver, commonly referred as an RFID tag or transponder and antenna (integrated with tag or autonomous one). At this very moment RF tags are built of small antenna, directly integrated with microchip. Two kinds of RFID tags can be distinguished - active (which use a battery to power themselves) or passive ones (they use the power induced across its antenna terminals). RFID systems can work with various frequencies – from 125 kHz up to 5.8 GHz. The range of the communication primarily depends on the operation frequency.

Passive RFID communication typically occurs at 135 kHz and 13.56 MHz, where at low power levels the bulk of the energy radiated by the reader is contained in the near-field (in the distance from some cm to about 30 cm; such systems use loop antennas in the readers and the tags). At higher operating frequencies, namely at 860/960 MHz and 2.4-2.5 GHz, the operation range is in the range up to some meters and the RFID tags operating at these frequencies use dipoles.

2.2 Antennas for RFID Tags

The shape of RFID antenna is dependent on frequency. For their fabrication the following technologies can be used:

- winding the wire into loop (for 135 kHz RFID tags),
- etching of copper or aluminum foil (with thickness of 18, 35 or 70 μm) laminated to the polymer foil,
- printing of a conductive ink on any flexible substrate (not only standard screen-printing [10], but also gravure printing [11], ink-jet deposition [12], [13], stamping [14] or rotary screen-printing [15] are used).

2.3 Interconnection between Antenna and Microchip

There are various technologies used for microchip fabrication. In the most conventional approach low-cost silicon RFID tags are used. Various attachment methods are used to connect integrated circuits to a paper or foil substrate with external antenna [16-20]:

- conventional pick-and-place (application of flip chip bonding technology for making the joints),
- I-connect technology,
- vibration assembling,
- Fluidic Self Assembly (FSA),
- adhesive bonding with using of Anisotropically Conductive Adhesives (ACAs),
- adhesive bonding with using of Non Conductive Adhesives (NCAs),
- adhesive bonding with using of snap cured Isotropic Conductive Adhesives (ICAs).

But a more aggressive approach aims at elimination of silicon and application of alternative flexible electronics technologies like polysilicon thin film transistors (TFTs) on plastic, vacuum-sublimated small-molecule TFTs on plastic, amorphous silicon TFTs on plastic, and printed organic TFTs on plastic [21]. The final approach leads to fabrication of RFID tags in all-printed organic electronics.

3. Fabrication of Thick-Film and LTCC Fine Lines

In thick-film and LTCC technologies screen-printing is the most reliable and cost-effective process for film deposition on tape or ceramic substrates. The standard screen-printing resolution (line width and line-to-line space) is equal to 100-125 μm [10]. The fine line print resolution is limited by ink rheology and screen properties (mesh size, wire thickness, calendaring and angle of the screen fabric in the frame) and the current achievable print resolution is about 50 μm for curved structures and 30-40 μm for straight lines [22], [23].

There are also other techniques developed for deposition of fine lines – in general they are based on printing processes, like printing through etched solid metal masks, offset printing (for example gravure-offset printing [24] where as narrow as 25 μm wide conductors have been printed), stamping or pad printing.

Next techniques are based on combination of standard screen-printing with photolithography. This attempt is present in photosensitive inks, where pattern is defined after film drying [25], [26] – this method enables to produce fine lines narrower than 20 μm in case of Hibridas-like materials. Also standard screen-printing can be connected with photoetching, where patterns are defined after firing of the layer. There are also tests with diffusion patterning [27] or nanoimprint technologies [28].

There is also a group of methods involving the deposition of thick-films by capillary action from a precious stylus (nozzle) that also serves as the ink reservoir. Three methods are used to deposit inks through the writing orifice:

- hydraulic positive displacement pumping synchronized with substrate stage motion (direct write printing), where standard inks can be applied,
- non-contact electrostatic thick-film printing, where ink is ejected by a high electrostatic field applied between the nozzle and the substrate,
- drop-on-demand ink-jet printing, in which ink droplets are jetted from small aperture directly to a specified position by application of a voltage pulse to a piezo-electric material that is coupled directly or indirectly to the printed fluid; typically drop-on-demand systems are able to produce droplets of diameter between 25 and 100 μm [29]; the ink-jet process made it possible to metalize fine lines with line/space equal to 30/30 μm.

Investigation of author and his PhD and MSc students in this area (please see e.g. [30]) was devoted to preparation of set-ups for exposure and development of miniature photoimageable thick films, self-building of apparatus for deposition of thick-film with the usage of ink-jet technique, elaboration of stamping technology and geometrical characterization of lines obtained in these techniques and set-ups. Our Fodel made lines had minimal width of about 50 μm, ink-jet printed lines – 90 μm and stamped lines – 80 μm.

4. Material and Process Requirements

There are several issues to be taken into account when selecting materials and manufacturing procedures for fabrication of antennas. First of all the substrate material has to be compatible with conductive film and manufacturing process. The cost is also an important issue for mass production. Antennas should be made on cheap and flexible substrates (e.g. polymer foils – like polyester or polyimide (Kapton) or foiled papers). Both substrates and conductive film should tolerate bending, vibration, thermal shocks and stretching. Their linear dimensions should be thermally stable. Conductive inks should be cured at relatively low temperature (from the 60-150°C range). They also should posses good adhesion to applied substrates (measured by so-called Scotch tape pull-off test from scratched film) and high conductivity (which is dependent on polymerization degree of polymer matrix and can be analyzed electrically by resistance measurement of long meander path – for 10-50 mΩ/sq sheet resistance of such inks and 1000 square length meander the resistance of such structure is equal to 10-50 ohms).

Many manufactures of thick-film materials offer special inks for this purpose and the results of comparative test can be found for example in [20]. But still many papers treat about novel low-temperature polymer thick film conductive ink and films [11], [31-34].

The investigations presented in this paper are related with films deposited by standard screen printing or rotary one. Typically the rotary screen-printing is used for printing on flexible substrates (foils, textiles or papers). It permits for larger automation than planar screen printing and makes possible larger deposition speed – typical linear production velocities are from the range 10-30 m/min.

5. Test Structures of Antennas

The radiated structures (inductors) for 13.56 MHz frequency are made from high-conductive inks (for this frequency the conductivity requirement is larger in comparison with antennas for higher frequency). The curing temperature should be as low as possible and the curing time should be as short as possible. Based on data sheets we have investigated four commercial silver-loaded inks, provided by different manufacturers, namely Du Pont (DP 5029, DP 5064), ESL (ESL 1901-S) and Amepox (Amepox ER 53A) and four experimental inks prepared and delivered by Amepox - Amepox 55, Amepox 59, Amepox 63 and Amepox 70.

Before fabrication of test structures we have analyzed which substrates preserve their shape and dimensions in typical curing conditions for polymer thick-film conductive inks. We have investigated 7 kinds of paper and 6 kinds of polymer foil. After curing of substrates (without deposition of inks) we made visual estimation of shape and dimensions and we chose 2 kinds of paper and 3 various polymer foils for further tests. Next selection took place after analysis of interactions between substrates and polymer conductive films – some combinations of materials disclosed considerable changes of substrate shape and planarity as well as lack of adhesion between cured polymer conductive films and substrate. As a result of the above described investigations polyimide (Kapton) and polyester foils and PE Gloss Clear paper has been used for further complex characterization of polymer conductive ink/substrate system. Moreover, for comparison, test structures have been made on alumina substrates.

The spiral coil pattern has been prepared based on the following preliminary assumption – substrate area – 70 mm×50 mm, path width – from the 0.5-1 mm range, distance between lines – 0.1–1 mm, number of turns – between 5 and 9. Using SONNET simulator [35] the coil shown in Fig. 1 (overall dimensions – 66.2 mm×44.0 mm, 1 mm path width and distance between paths) has been designed, fabricated and tested. Tested inductors have been printed on mentioned substrates through 325 mesh stainless screen and next cured in MR-10 reflow solder furnace (temperature profile shown in Fig. 2) with 100ºC or 120ºC maximal temperature, SML-32/250 dryer (profiles 80ºC, 100ºC or 120ºC) or BTU tunnel furnace.

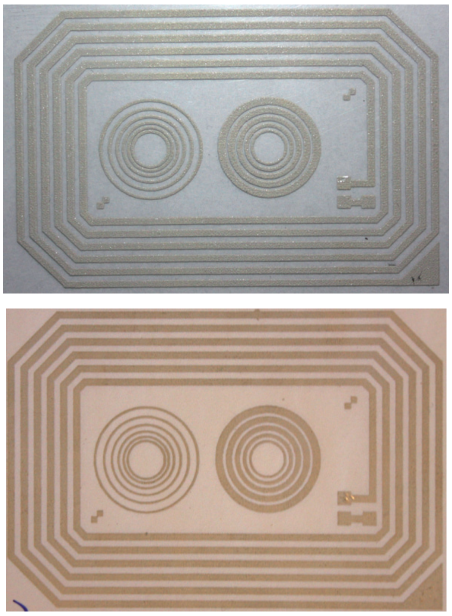

Fig. 1. Examples of tested coils – Amepox ER53A on polyester foil (top) or PE Gloss Clear paper (bottom).

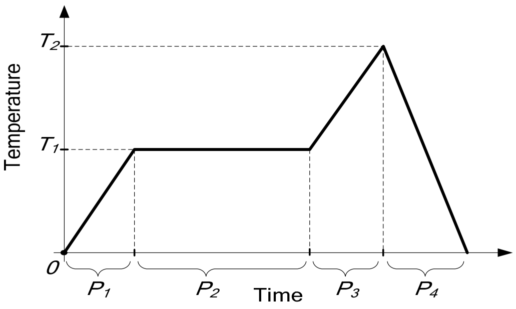

Fig. 2. Temperature profile of MR-10 reflow solder furnace.

The quality of printing (planar accuracy and resolution as well as film thickness) are very important because the inductance of aerial coil depends mainly on its geometry whereas the sheet resistance of conductive ink i.e. the coil resistance is dependent on film thickness. Surface roughness also affects strongly structure resistance i.e. its losses. It is proved that antennas from films with comparable conductivity have different coil quality factor $Q_L = \omega L_s/R_s$ (L_s, R_s – coil serial inductance and resistance, respectively), depending of quality of structure geometry. Therefore such a quality has been tested using optical and/or mechanical profilometer (Fig. 3).

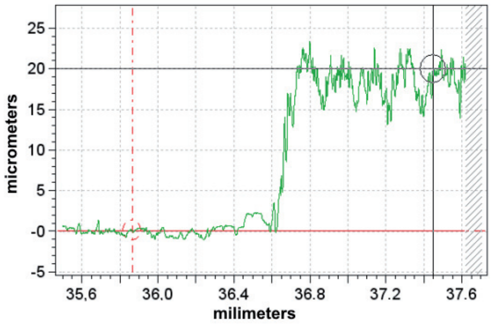

Fig. 3. Cross-section profile of film made of Amepox ER 53A ink.

6. DC and AC Electrical Properties of Antennas

Both serial inductance and resistance of the coil (loop antenna) are important parameters because they affect the antenna ability for absorption of magnetic field, described by quality factor Q_L. Therefore test structures have been cured at various profiles with maximal temperature from the range between 80°C and 120°C. The results of such investigations have shown that structures made of Amepox inks are the most sensitive for curing parameters [36] - in case of these inks curing at 80°C is insufficient. Moreover, when the curing temperature is from the range 110-120°C the resistance of samples made of Amepox inks is dependent significantly on substrate kind (Tab. 1). The remaining used inks can be cured in wider temperature range and on larger numbers of substrate materials.

In general, the resistance of polymer conductive films is decreased both for higher curing temperature as well as for longer curing time; but curing temperature has greater meaning.

The measurements of resistance in the course of curing process at constant temperature have been used to investigate polymerization process of such composites. Such method had been used earlier for analysis of curing kinetics of carbon-filled polyesterimide films [37] and isotropically conductive adhesives [38]. The resistance has been measured for 80 square length alumina-printed conductive paths from various polymer thick-film conductive inks. The sample has been placed onto the table heated by Peltier elements to 90°C or 120°C. The comparison of 2 experimental Amepox inks with DP 5029 and ESL 1901-S ones are shown in Fig. 4. It is visible that polymerization of ESL and Du Pont inks took place even at 90°C; it reaches rather significant level relatively quickly – the resistance stabilization is observed on the level of a few ohms (this is related with sheet resistance of about 30 mΩ/sq) approximately after 60 seconds. Inks from Amepox demand higher curing temperature (about 120°C) and longer curing time (about 300 seconds). For this curing temperature the final resistance level is similar for all used inks.

Profile: T_1/T_2 [°C] $P_1/P_2/P_3/P_4$[s]	Substrate	Ink			
		A 55	A 59	A 63	A 70
		Sheet resistance, R_{sq} [mΩ/sq]			
90/110 150/300/300/10	Kapton	56.8	91.5	30.3	90.5
	Polyester	201	47.9	39.0	21.6
	PE paper	801	445	443	302
100/120 90/180/180/90	Kapton	123	36.0	74.4	53.6
	Polyester	48.9	39.0	32.4	64.9
	PE paper	385	343	446	313
100/120 150/300/300/150	Kapton	47.2	33.8	29.6	21.3
	Polyester	44.1	33.9	28.8	20.5
	PE paper	75.4	129	208	252
100/120 240/480/480/240	Kapton	43.1	33.8	29.0	20.0
	Polyester	40.8	32.9	28.6	20.1
	PE paper	42.2	24.8	153	92.8

Tab. 1. Sheet resistance of experimental Amepox inks versus substrate and curing profile.

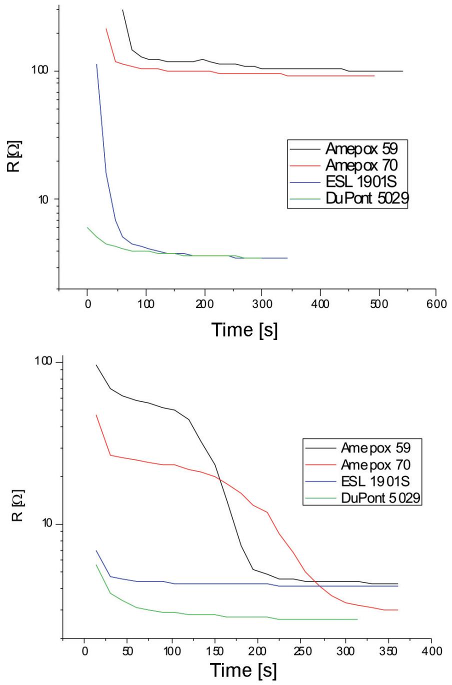

Fig. 4. Comparison of polymerization velocity of polymer conductive films during curing at 90°C (top) or 120°C (bottom).

But it is worth to add that for the best Amepox composition (from the conductivity point of view) cured in the same conditions as DP 5029 ink (radiative curing in MR-10 reflow solder furnace with 100/120°C profile or convective curing in six zones BTU furnace at 15.5 cm/min tape speed i.e. with 15 minutes total process duration and 110/150/150/150/150/110°C firing profile, which gives maximal temperature very close to the above mentioned profile in MR-10 furnace) the resistance of Amepox structures has been somewhat smaller than Du Pont ones (Fig. 5).

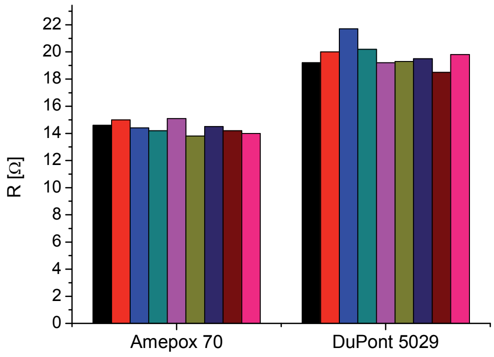

Fig. 5. Resistance of coils from Amepox 70 and Du Pont 5029 inks.

Impedance spectroscopy has been applied for the analysis of the antenna versus frequency behavior [39], especially near designed operation frequency. The measurements have been made in the 1-100 MHz frequency range by means of Agilent (HP) 4294 impedance analyzer. This analyzer measured impedance module and phase and next, using ZView 2 software, it has been possible to calculate many other parameters of investigated coils. For the needs of presented investigations we simulated serial inductance L_s and quality factor Q_L of the loop antennas near operation frequency in dependence of kind of ink and substrate, curing conditions, and environmental exposures (examples of obtained characteristics are shown in Fig. 6).

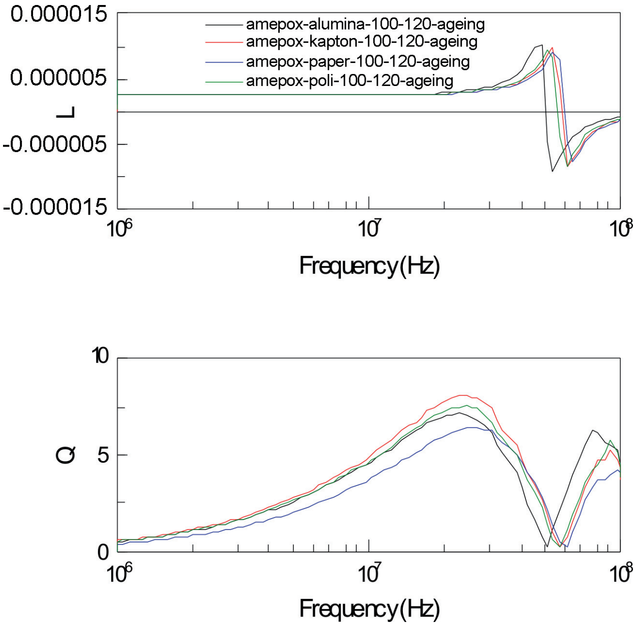

Fig. 6. Frequency behavior of antenna inductance and quality factor (structures made of Amepox ER 53A ink on various substrates).

Du Pont structures exhibit the largest quality factor. But ESL ink has this parameter only slightly smaller and stable for all used substrates and curing conditions. Coils from commercially available Amepox ER 53A ink posses smaller quality factor; this is connected with its higher sheet resistance. But structures from ESL ink exhibit larger changeability of f_{Qmax} - frequency, at which the quality factor has maximal value – in comparison with coils from other investigated inks. Moreover it has been shown, that inductors (antennas) made of polymer conductive inks had maximal quality factor in the range of 21-25 MHz although they have been designed for 13.56 MHz. This indicates for the necessity of the simulation process improvement.

7. Long-Term Stability

Long-term stability is one of key factors defining the usability of various materials and technologies for particular applications. It is well know that RFID tags should operate at different environment. Therefore it is necessary to characterize their behavior at various exposures (e.g. long-term ageing, mechanical bending cycles).

In most cases stability of polymer thick conductive films is analyzed based on changes of DC electrical properties. But investigations of AC properties' changes give wider and deeper view on mechanisms of ageing processes. The investigated inductors have been subjected to the following environmental stresses: durability to long-term thermal exposure (250 hours, 60ºC), durability to long-term moisture exposure at elevated temperature (250 h, 60ºC, 95% RH), resistance to mechanical bending cycles (up to 0.5 million bending cycles by about 45º angle).

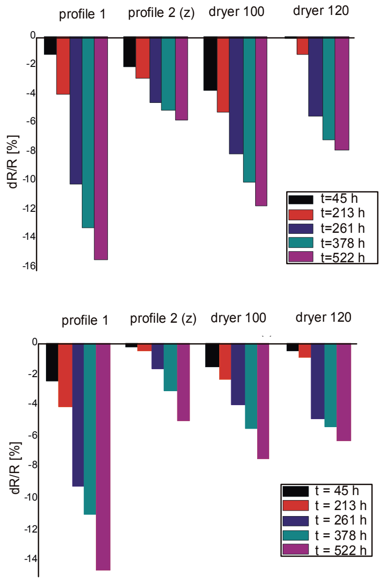

Fig. 7. Relative resistance changes of structures made of Du Pont Ink on PE Gloss Clear paper (top) or polyester foil (bottom) vs. curing profile (measurements after 45 h and 213 h – measurement after thermal exposure, measurements after 261 h, 378 h and 522 h – measurement after temperature-humidity exposure).

We calculated the relative resistance and inductance changes of coils made of various materials and cured in various temperatures. For majority of substrate/polymer conductive film combinations, cured in "optimal" temperatures the resistance is somewhat decreased during thermal or moisture-thermal exposures (Fig. 7). This is very interesting feature because during long-term operation of RFID tags and for almost stable inductance (it is dependent only on geometrical factors) the quality factor of antennas is improved, which results in better microchip powering and larger tag's response signal. Also bending cycles cause rather small changes in serial resistance and inductance of the antennas (Tab. 2).

Ink/substrate/curing profile (T_1 and T_2 [°C])	Number of bending cycles [million]	ΔR/R [%]	ΔL/L [%]
Amepox/Kapton/100/120	0.5	+3.8	+1.0
DuPont/Kapton/100/120	0.5	+1.3	+5.9
ESL/Kapton/100/120	0.5	+1.6	+6.4

Tab. 2. Relative resistance and inductance changes after mechanical exposures.

8. Conclusions

We present wide electrical and long-term stability characterization of materials used for fabrication of RFID antennas. New experimental compositions with electrical parameters similar to offered by world-leading manufacturers of thick-film inks have been presented. It has been shown that the measurement of resistance during the curing process can be used for evaluation the polymer thick-film conductors' polymerization process. Also processes characteristic for integration of microchip and antenna have been described.

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