

Screen printed RFID antennas on low cost flexible substrates

Kamil Janeczek¹, Małgorzata Jakubowska^{2,3}, Grażyna Koziol¹, Anna Młóżniak², Janusz Sitek¹

¹Tele & Radio Research Institute, Ratuszowa 11 Str., 03-450 Warsaw, Poland
+48 22 619 01 64, +48 22 619 29 47, kamil.janeczek@itr.org.pl

²Institute of Electronic Materials Technology, Wolczynska 133 Str., 01-919 Warsaw, Poland
+48 22 835 30 41, maljakub@itme.edu.pl

³Warsaw University of Technology, Institute of Metrology and Biomedical Engineering, 8 Sankt Andrzej Bobola Street, 02-525 Warsaw, Poland, +48 849 94 47, maljakub@mchtr.pw.edu.pl

Abstract

Recently, more and more studies are carried out in the field of printed RFID tags. It is connected with rapid development of new electronic technology, i.e. printed electronics which utilizes printing techniques, like screen printing, inkjet, flexography or gravure, for production of electronic components. This method is on one hand environmentally friendly because it allows eliminating wastes emerging during etching process used commonly in electronics. On the other hand, components can be printed on low cost flexible substrates, like foil or paper. These two factors cause that such products are cheap and can be competitive with their equivalents used currently.

In this study, investigations of RFID tag antennas working in UHF frequency range made with screen printing technique are described. Conductive polymer pastes containing silver nanopowder, silver flakes or carbon nanotubes were used for antenna fabrication. Each of them was deposited on foil and paper. Properties of printed antennas were investigated by return loss measurements performed in the frequency range $0.5 \div 1.5$ GHz. Achieved results were compared with simulation carried out in CST Microwave Studio. Antenna surface profile was checked using optical profilometer or metallographic microscope. Its mechanical tests were also conducted. The obtained results showed that the best candidate for antenna printing on flexible substrate was the paste with silver nanopowder because it combined high conductivity and high mechanical durability.

1. Introduction

Nowadays, more and more investigations are conducted in the field of printed electronics. It makes possible to fabricate electronic components using printing techniques. Among them the most popular are screen printing [1-3], inkjet [4], flexography [5] and gravure [6].

Use of printing techniques which are additive process leads to decreasing of component's unit

cost. No chemical wastes, like in the case of etching technique, are coming into being. In the effect, this technology contributes to protection of natural environment [7].

Lower unit cost of printed RFID antenna comparing to etched ones contributes to wide-spread of RFID technology. Currently, their high price is the main obstacle to common use of RFID tags [8].

Performance of screen printed RFID antennas was characterized by Shin et al. [9]. The paste with silver nanoparticles was used in their study for antenna screen printing process. Also, its radiation performance was evaluated. It was revealed that silver antennas had comparable parameters with copper etched ones.

Aside from silver nanoparticles other materials for RFID antennas were tested. Syed et al. [10] tested bulk and deposited copper, aluminum, bulk silver and two commercial silver pastes. The results revealed that the antenna printed with silver pastes and made with deposited copper characterized with comparable parameter. These results were confirmed by Nikitin et al. [11].

Another study was conducted by Merilampi et al. [12]. Polymer silver paste deposited on paper with screen printing technique was investigated for production of bow-tie antenna. It was noticed that the substrate absorbed a solvent contained in used paste because of its porous surface. Regardless, the RFID tags with the elaborated antenna worked properly.

Similar investigations were carried out by Rida et al. [13]. Inkjet printing techniques were applied for elaboration of UHF antenna. It was found that paper can be excellent substrate for RFID tags. This conclusion was confirmed by Yang et al. [14] and by Amin et al. [15].

In this paper, investigations of UHF RFID tag antennas carried out with screen printing technique are described. Three type of conductive materials containing silver flakes, silver nanopowder and carbon nanotubes were used. The antennas were screen printed on flexible substrates: foil and paper. Their properties were evaluated by return loss measurements depending on applied

substrate, conductor and also multilayer printing. The achieved results were compared with simulation conducted in CST Microwave Studio. Surface profile of antennas was investigated by an optical profilometer and metallographic microscope. Electromechanical properties of elaborated materials were also investigated.

2. Experimental

Three various conductive materials containing silver flakes, silver nanopowder and carbon nanotubes were investigated with regard to their applicability for a production of RFID tag antennas working in UHF frequency range. Semi-automatic screen printer Ami Presco model 465 with a polyester mesh screen 68T was used for their printing on flexible substrate: paper and foils. The first one was a commercially available photo paper Everyday 180 g/m² (Emtec) with a thickness of 150 μm. Two types of foil were applied: polyethylene naphthalate foil PEN (Teonex Q51, DuPont Teijin Films) and polyimide foil Kapton HN500 (DuPont). Their thickness was 125 μm.

Mentioned above conductive materials were prepared according to following procedure. Appropriate filler was added to a polymer resin and grinded in a mortar. In the next step, obtained composition was three-roll-milled in order to break agglomerates.

After screen printing process the obtained layers were cured in an oven in 120°C for 15 min. Moreover, the layer made with the paste with silver nanopowder was cured in 300°C for 60 min.

The silver flakes AX20LC (SF) were bought from Amepox Microelectronics. Their average size varied from 2 to 4 μm and maximum agglomerate size from 6 to 12 μm. Their purity was equal to min. 99.99 % [16]. The silver flakes were added in the proportion of 70/30 wt% to the polymer resin poly(methyl methacrylate)-poly(butyl methacrylate) PMMA-PBMA dissolved in butyl carbitol acetate (10 wt%).

The silver nanopowder (nAg) was produced by authors. Its average size measured on the basis of SEM analysis was 6.5 nm. It was mixed in the proportion of 80/20 wt% with the polymer resin 10 wt% PMMA-PBMA dissolved in butyl carbitol acetate.

The used multi-wall carbon nanotubes (MWCNT) were bought from CheapTubes.com. Combustion chemical vapour deposition (CCVD) was used for their production. Their average length varied from 0.5 to 5 μm and diameter from 10 to 50 nm. MWCNT were added to 10 wt% solution of poly(methyl methacrylate) PMMA in butyl carbitol acetate.

The antenna pattern presented in Figure 1 [17] was used in the conducted investigations. It characterized with the square shape (20 x 20

mm) and input impedance $Z_{in} = 32 + 216 j [\Omega]$ for the frequency 915 MHz.



Fig. 1. Pattern of the antenna used in the performed investigation.

The materials used in the performed investigations were characterized with regard to their electrical parameters measured with four-point method with the digital multimeter Agilent HP34401A. Surface structure of printed antennas was observed on an optical profilometer NT2000 Veeco. Microstructures of printed layers were observed using the scanning electron microscope (SEM) JOEL JSM-7600F. Return loss for investigated antennas was checked using the network analyzer N5242A PNA-X Agilent Technologies. Their mechanical durability was investigated using the Force Testing System Mecmesin Multitest i-1.

3. Results and discussion

3.1. Antenna simulation

Before practical measurements a simulation of the antenna presented in Figure 1 was performed. The simulation software CST Microwave Studio was applied. It made possible to evaluate properties of tested antenna, especially its characteristic of return loss and radiation pattern. Apart from it, conducted simulation accounted for a reference to the measurement results.

During performed reflection coefficient simulation it was revealed that the investigated antenna exhibited its basic resonant frequency near 915 MHz (Fig. 2). It was consistent with the initially taken assumption mentioned in the second paragraph (see Experimental).

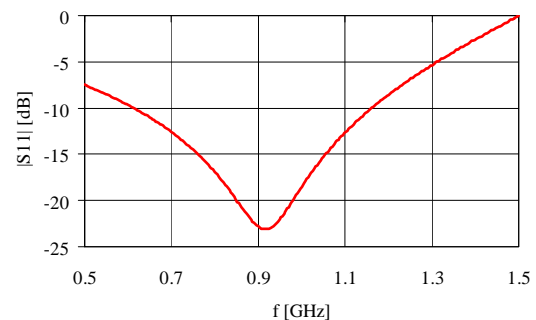


Fig. 2. Characteristic of antenna return loss for the source impedance $Z = 32 - 216 j [\Omega]$.

Radiation pattern was also taken into account (Fig. 3; the scale means the antenna directivity). It was simulated for the frequency 915 MHz.

The substrate was polyimide foil. It was assumed that its dielectric constant was 3.5 for the frequency 1 GHz and that antenna was made from silver.

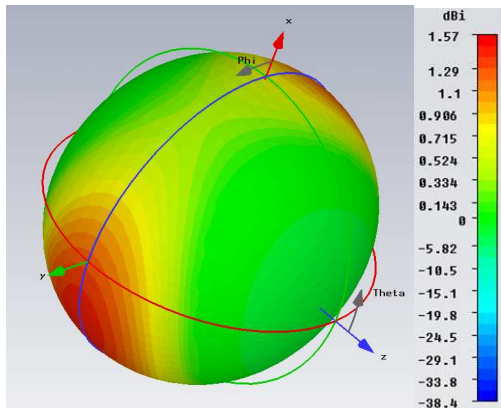


Fig. 3. Radiation pattern of the antenna used in the conducted investigation.

It was revealed that the radiation pattern of simulated antenna had two symmetrical radiation beams.

3.2. Resistance measurements

Resistance measurements were carried out for three investigated conductive materials in order to evaluate their applicability for antenna printing. It was noticed (Tab. 1) that the lowest sheet resistance ($19 \text{ m}\Omega/\square$) was achieved for the layer printed with the paste nAg and the highest one ($6027 \Omega/\square$) with the paste MWCNT.

Tab. 1. Sheet resistance of the layers printed with the investigated pastes.

Substrate	R [Ω/\square]		
	SF	nAg	MWCNT
foil	0.248	0.019	6027
paper	0.031	x	1229

The higher resistance achieved for the layer MWCNT can be probably a result either of higher tunneling resistivity or smallest contact area between filler particles according to the Eq. 1 [18].

$$R_c = \rho_i / d + \rho_t / a \quad (1)$$

where ρ_i means intrinsic filler resistivity, d - diameter of a contact spot, ρ_t - tunneling resistivity and a - contact area.

In order to verify this statement a microstructure of the layers printed with elaborated materials was analyzed (Fig. 4). It was carried out using SEM microscope. The results revealed that silver particles, both in a form of flakes and nanopowder, were distributed uniformly. Another behavior was observed for carbon nanotubes. This filler exhibited a tendency to create cluster which caused that CNTs were distributed chaotically in the printed

layer. However, according to experiments described in the literature it is possible to decrease the CNT layer resistance by CNTs alignment using electric or magnetic field [19-21].

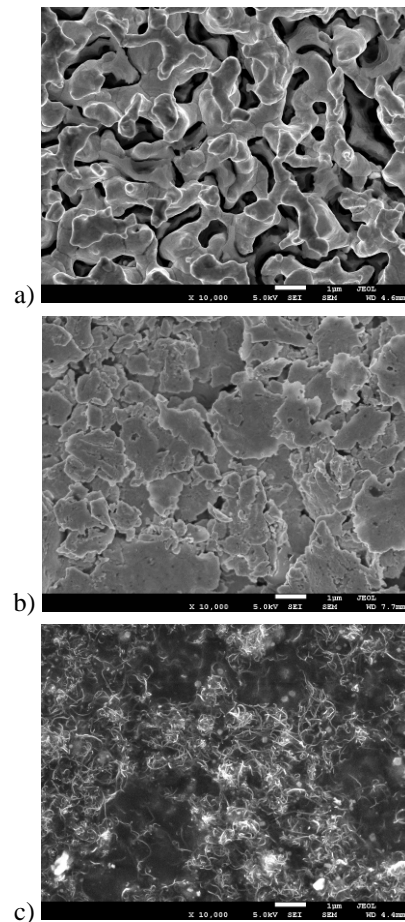


Fig. 4. Microstructure of the layers printed with the pastes: a) nAg, b) SF, c) MWCNT (magnification: 10 000 X).

The resistance depended also from applied substrate type as it can be seen in Table 1. It was revealed that the SF and CNT layers printed on paper characterized with the larger thickness. It was equal to $23.67 \mu\text{m}$ and $8.67 \mu\text{m}$ (paper) comparing to $9.75 \mu\text{m}$ and $3.33 \mu\text{m}$ (foil), relatively (Fig. 5). The achieved results were consistent with theoretical considerations which point that together with an increase of layer thickness its resistance decreases.

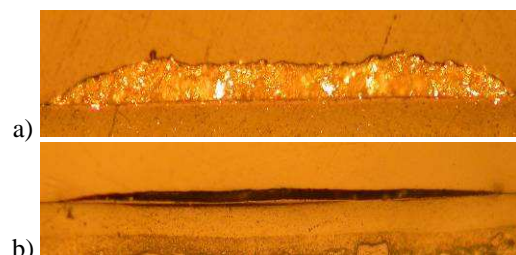


Fig. 5. Cross sections of the layers printed on paper with the paste a) SF and b) MWCNT (mag. 200 X).

3.3. Surface structure observation

Apart from layer sheet resistance also its surface structure (Fig. 6) can play an important role. Average surface roughness has an influence on a layer AC resistance. It changes per unit length according to Eq. 2 [22].

$$c = \left[1 + \frac{2}{\pi} \tan^{-1} \left\{ 1.4 \left(\frac{\Delta}{\delta} \right)^2 \right\} \right] \quad (2)$$

$$R = \frac{c}{w} \sqrt{\frac{\pi \mu f}{\sigma}} \quad (3)$$

where w means track width and Δ - average surface roughness.

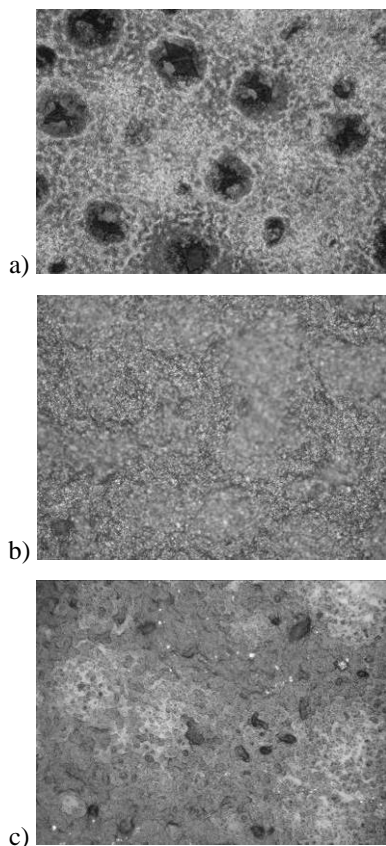


Fig. 6. Surface structure of the layers printed with the paste: a) SF, b) nAg, c) MWCNT (mag. 200 X).

The average surface roughness measured with a contact profilometer was 2.9, 0.4 and 0.5 for the layer printed with the pastes SF, nAg and MWCNT, relatively. In the consequence, the AC resistance increased by approximately 13, 7 and 0 % for the mentioned above layers, relatively.

In order to investigate surface structure of the printed layers more accurately optical profilometer was applied. The achieved results confirmed that a mapping of screen eyes took place like it was observed on Figure 6. It was especially seen for the SF antenna (Fig. 9).

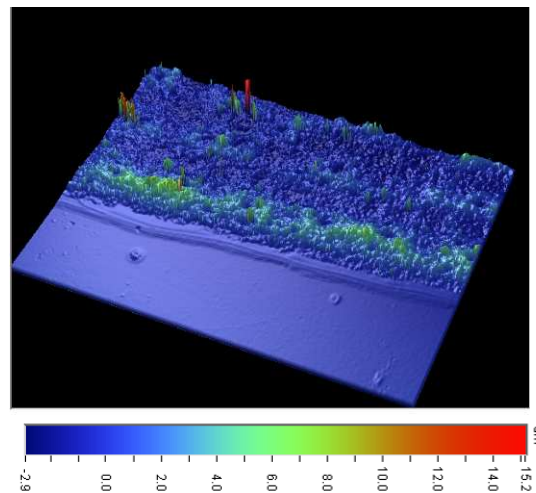


Fig. 7. 3D surface profile of the MWCNT antenna printed on PEN foil.

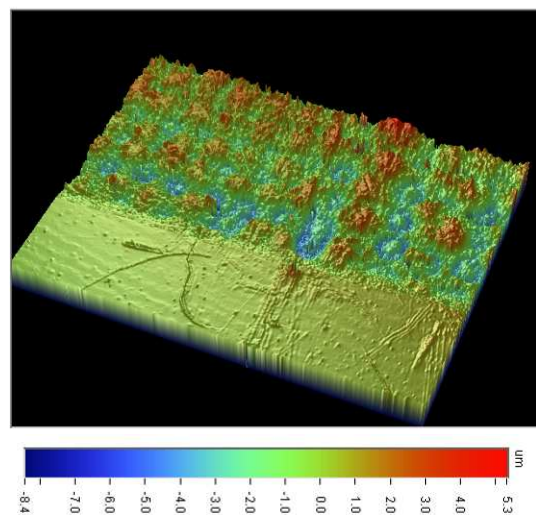


Fig. 8. 3D surface profile of the nAg layer antenna printed on Kapton.

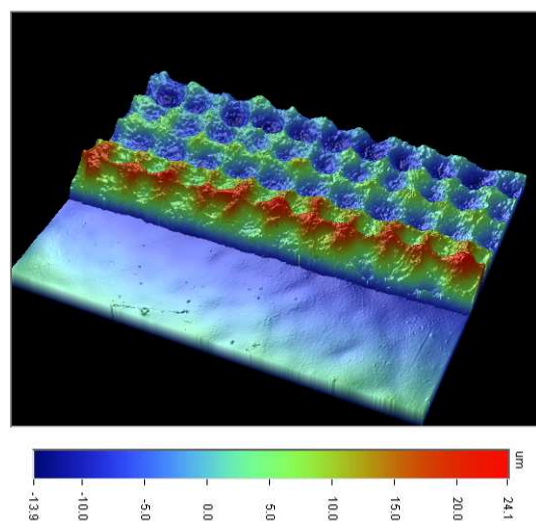


Fig. 9. 3D surface profile of the SF layer printed on paper.

3.4. Return loss measurements

Return loss measurements were carried out in order to verify properties of elaborated antennas. The biggest challenge in these measurements was a construction of measurement probe. Syed et al. [10] constructed a circuit board. It consisted of a balun and balanced output terminals and it is driven with a coaxial cable.

Similar circuit board was constructed in the performed investigation (Fig. 7). It consisted of a waveguide in the form of a 50 Ω non-symmetrical strip line, SMA connector, output produced as a pad connected to the ground and the end of the strip line. A calibration was done using a short section of conductor (short), 51 Ω SMD resistor (load) and "free" output (open). The probe provided limited accuracy however it was sufficient for preliminary tests to verify if the printed antennas worked properly in UHF frequency range.



Fig. 7. A probe used in performed return loss measurements.

In the performed investigations an influence of substrate, conductor and applied number of printed layers were taken into consideration.

Characteristics of return loss for the antennas printed on foil or paper with the paste SF are presented in Figure 8. For comparison copper antenna was measured.

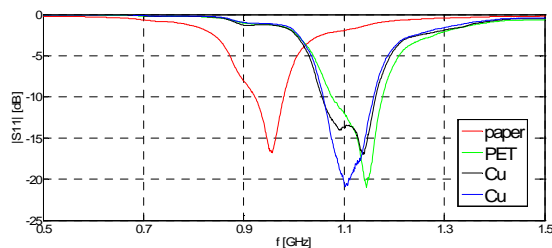


Fig. 8. Characteristics of return loss for the antennas printed with the paste SF.

The basic resonant frequency was 957 and 1145 MHz for the antennas printed on paper and foil, relatively. The shift of 188 MHz was noticed. It can be a result of different dielectric constant between paper and PEN foil. It is higher for paper comparing to foil. According to theoretical consideration [23] an increase of dielectric constant results in a shift of reflection coefficient characteristic to the left side like it was observed in the conducted investigations.

The second factor influenced on printed antenna properties which was taken into consideration was used conductive material (Fig. 9).

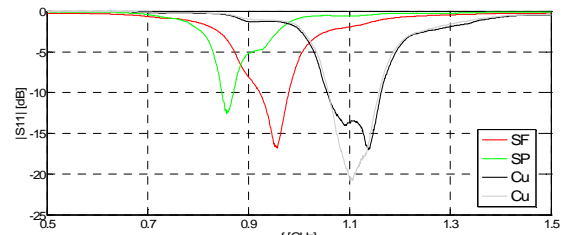


Fig. 9. Characteristics of reflection coefficient depending on used paste.

Presented above characteristics exhibited different basic resonant frequency. It can be probably connected with various structures of printed antennas. Moreover, the minimum of return loss was different. For antennas fabricated with the paste SF it was -17 dB and with the paste SP -12 dB.

Observed differences can be combined with skin depth effect. It can be calculated from the following equation [24]:

$$\delta = \frac{1}{\sqrt{\pi\mu_0}} \sqrt{\frac{\rho}{\mu_r f}} \approx 503 \sqrt{\frac{\rho}{\mu_r f}} \quad (4)$$

For silver conductor μ_r equals 1 and ρ is $3.4 \cdot 10^{-7}$ $\Omega \cdot m$. When basic resonant frequency is 15 MHz the skin depth equals $\delta = 9.7$ μm . The highest antenna efficiency is achieved when its thickness is two times bigger than skin depth so it should equal 19.4 μm . If the antenna has another thickness its efficiency decreases [24].

In the conducted measurements the antenna printed with the paste SF exhibited a thickness which was comparable with an optimal value resulting from skin depth. In the consequence, the SF antenna characterized with the lower minimum of S_{11} characteristic comparing to its equivalent printed with the paste SP. The last one provided a several times to low (than optimal) thickness of ca. 1 μm .

It was also found that a number of printed layers played a significant role (Fig. 10). The experiment was performed for the paste SP printed on Kapton. The characteristics of return loss for one- and two-layer printing revealed that the second layer caused a change of properties of investigated antenna. Its basic resonant frequency was shifted from 859 to 1082 MHz. Observed differences could result from different layer structure (Fig. 11). After printing of second layer the surface of antenna was more even. It was noticed a decrease in the average roughness from 6.1 μm to 5.5 μm .

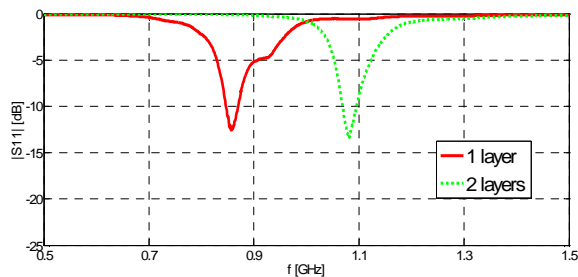


Fig. 10. Characteristics of return loss for the paste SP for one- and two-layer printing.

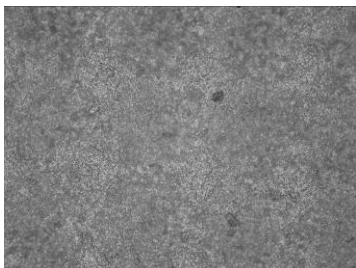


Fig. 11. Surface profile for two-layer printing.

Furthermore, no significant difference in the minimum of return loss characteristic was noticed. For a single layer it was -12 dB and for double one -14 dB. This might be a result of larger thickness ($3\ \mu\text{m}$ for two-layer printing) which was closer to the optimal one ($19.4\ \mu\text{m}$).

3.5. Mechanical durability

One of the most important advantages of printed RFID antennas is their flexibility. This causes that RFID tags can be applied even on corrugated surface and this does not lead to their damage. Mechanical durability of investigated screen printed antennas on low cost flexible substrate was analyzed during bending exposure.

It was assumed that bending distance was 10 mm and speed of head 200 mm/min. Antennas were exposed up to 1000 bending cycles.

Tab. 2. Increase of resistance after 1000 bending cycles.

Number of cycles	ΔR [%]			
	SF		nAg	MWCNT
	foil	paper	foil	foil
0	0.00	0.00	0.00	0.00
100	15.93	3.61	1.25	2.11
500	24.35	9.01	2.03	2.87
1000	39.65	31.99	2.65	2.86

The highest durability to bending cycle exhibited the antenna printed with the paste with silver nanopowder (nAg). It was even higher than for the layer made with the paste with carbon nanotubes (MWCNT) which characterize with excellent mechanical properties [25]. Several times lower durability was noticed for the SF antenna. It exhibited above twelve times larger increase

of its resistance after 1000 bending cycles. The results revealed that the form of silver particles played an essential role. Silver nanopowder characterized with significantly smaller size comparing to silver flakes. It could cause that stresses emerging during bending cycles resulted in larger damages in the layer structure.

It was observed that used substrate influenced on mechanical durability of tested screen printed antennas. In the case of the paste with carbon nanotubes (MWCNT) cracks were appeared after 2 ÷ 3 bending cycles. This resulted in creating of open in the antenna layer (Fig. 12).

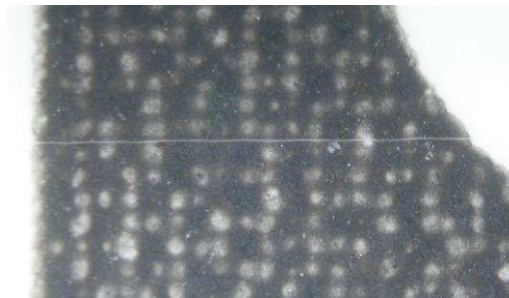


Fig. 12. Cracks appeared in the MWCNT antenna after a few bending cycles (mag. 30 X).

The same phenomenon was occurred for the SF antenna. Also cracks were appeared (Fig. 13). However, in this case the electrical connection in the antenna layer did not break. Only above 30 % increase in its DC resistance was noticed after 1000 cycles.



Fig. 13. Cracks appeared in the SF antenna after 1000 bending cycles (mag. 100 X).

Observed cracks, both in the antenna printed with the paste MWCNT and SF, were a result of cracking of polymer coating a paper. These phenomena were not noticed for the layers printed on foil, either on Kapton or PEN.

4. Summary

In this paper, investigations of screen printed antennas on flexible substrates (foil and photo paper) were described. Three types of conductive materials containing carbon nanotubes, silver nanopowder or silver flakes were used for antenna printing. Electrical properties, surface profile, return loss and mechanical durability on bending stresses were measured for conducted layers.

The electrical measurements revealed that the lowest sheet resistance was achieved for the layer printed with the paste with silver

nanopowder. The paste with carbon nanotubes provided its highest value what resulted in poor performance of MWCNT antenna. Such a big value of sheet resistance for CNT layers can be caused by chaotic dispersion of carbon nanotubes. These particles created clusters and in the consequence, the probability of electron transmission between them decreased and resistance increased. However, silver particles were distributed uniformly.

Surface profile observations exhibited that a mapping of screen eyes took place. It was especially seen for the layers made with silver. The surface roughness could be decreased when two-layers printing was applied.

It was revealed that the paste with carbon nanotubes was not suitable material for antenna printing because of too high MWCNT antenna loss resistance. Two other tested materials allowed to produce antennas characterized with comparable performance. It was found that multilayer printing can contribute to a shift of antenna basic resonant frequency. However, further investigations are necessary to be conducted in order to explain this phenomenon.

The highest mechanical durability on bending stresses was achieved for the layers printed with the paste nAg. It was even higher than for the MWCNT layers. After bending stresses the cracks were appeared in the SF and MWCNT antennas printed on paper. These damages were caused by a cracking of polymer coating a paper.

References

- [1] Marcin Słoma et al., „Investigations on printed elastic resistors containing carbon nanotubes”, *Journal of Material Science: Materials in Electronics*, published on line 9.02 2011-04-01
- [2] Kamil Janeczek et al., "Screen printed UHF antennas on flexible substrates", *Proc. of SPIE*, vol. 7745, 77451B, 2010
- [3] Małgorzata Jakubowska et al., “Printed transparent electrodes containing carbon nanotubes for elastic circuits applications with enhanced electrical durability under severe conditions”, *Materials Science and Engineering: B*, vol. 176, no. 4, pp. 358-362, 2011
- [4] Konrad Futera et al., „Printed electronic on flexible and glass substrates”, *Proc. of SPIE*, vol. 7745, 77451B, 2010
- [5] Anne Blayo, Bernard Pineaux, “Printing processes and their potential for RFID printing”, *Proc. of the 2005 Joint Conference on Smart Objects and Ambient Intelligence: Innovative Context-Aware Services: Usages and Technologies*, Grenoble, pp. 27–30, 2005
- [6] Marko Pudas et al., „Gravure printing of conductive particulate polymer inks on flexible substrates”, *Progress in Organic Coatings*, vol. 54, no. 4, pp. 310–316, 2005
- [7] Tamer Elsherbeni et al., “Laboratory scale fabrication techniques for passive UHF RFID tags”, *Proc. of IEEE Antennas and Propagation Society International Symposium (APSURSI)*, Toronto, 11-17 July 2010, pp. 1-4
- [8] Kamil Janeczek, „Technologia identyfikacji radiowej RFID”, *Electronics*, no. 7, pp. 19-22, 2009
- [9] Dong-Youn Shin et al., “Performance characterization of screen printed radio frequency identification antennas with silver nanopaste”, *Thin Solid Films*, vol. 517, issue 21, pp. 6112-6118, 2009
- [10] Afzal Syed et al., “Effects of Antenna Material on the Performance of UHF RFID Tags”, *Proc. of IEEE International Conference on RFID*, Grapevine, 26-28 March 2007, pp. 57 – 62
- [11] Pavel. V. Nikitin et al., “Low cost silver ink RFID tag antennas”, *Proc. of IEEE Antennas and Propagation Society International Symposium*, vol. 2B, 3-8 July 2005, pp. 353 - 356
- [12] Sari Merilampi et al., “Analysis of Silver Ink Bow-Tie RFID Tag Antennas Printed on Paper Substrates”, *International Journal of Antennas and Propagation*, vol. 2007, article ID 90762, 9 pages
- [13] Amin Rida et al., “Design and Integration of Inkjet-printed Paper-Based UHF Components for RFID and Ubiquitous Sensing Applications”, *Proc. of 37th European Microwave Conference*, 2007, (<http://users.ece.gatech.edu/~etentze/EuMC07.pdf>)
- [14] Li Yang, Manos M. Tentzeris, “Design and Characterization of Novel Paper-based Inkjet-Printed RFID and Microwave Structures for Telecommunication and Sensing Applications”, *Proc. of IEEE/MTT-S International Microwave Symposium*, 3-8 June 2007, pp. 1633 - 1636
- [15] Yasir Amin et al., « Inkjet printed paper based quadrate bowtie antennas for UHF RFID tags”, *Proc. of 11th International Conference on Advanced Communication Technology*, vol. 01, 15-18 Feb. 2009, pp. 109 – 112
- [16] Datasheet of silver flakes AX20LC, Amepox Microelectronics (http://www.amepox-mc.com/files/SILVER_FLAKE_20LC.pdf)
- [17] http://www.rfid.averydennison.com/online_sep ec.php?id=41
- [18] Lu Daoqiang et al., „Conductivity mechanisms of isotropic conductive adhesives (ICAs)”, *IEEE Transactions on Electronics Packaging Manufacturing*, vol. 22, issue 3, pp.: 223 – 227, 1999
- [19] Yue-Feng Zhu et al., “Alignment of multiwalled carbon nanotubes in bulk epoxy composites via electric field”, *Journal of Applied Physics*, vol. 105, no. 5, 2009
- [20] C. A. Martin et al., “Electric field-induced aligned multi-wall carbon nanotube networks

in epoxy composites”, *Polymer*, vol. 46, issue 3, pp. 877-886, 2005

[21] Xu-Ming Xie et al., “Polymer assisted dispersion and alignment of carbon nanotubes”, *Proc. of 9th IEEE Conference on Nanotechnology*, pp. 123 – 125, 2009

[22] Li Yang et al., “RFID tag and RF structures on paper substrates using inkjet-printing technology,” *IEEE Transaction on Microwave Theory Tech.*, vol. 55, no. 12, pp. 2894–2901, 2007

[23] Juha Virtanen et al., “Printed humidity sensor for UHF RFID systems”, *Proc. of IEEE Sensors Applications Symposium (SAS)*, pp. 269 – 272, 2010

[24] Bo Gao et al, “Optimization of Silver Paste Printed passive UHF RFID Tags”, *Electronic Packaging Technology & High Density Packaging*, pp. 512 – 515, 2009

[25] Philip. G. Collins, Phaedon Avouris, “Nanotubes for Electronics”, *Scientific American*, vol. 12, pp. 62 – 69, 2005