Investigation of sintering of silver lines on a heated plastic substrate in the dry aerosol jet printing

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Abstract. The study on dry aerosol jet printing with simultaneous sintering of deposited Ag nanoparticles 20-80 nm in size on a heated plastic substrate is presented. It is established that to achieve minimal electrical resistivity of microstructures produced of ~200 μΩ·cm, the recommended temperature of the heated substrate is to be ~200 °C. It is also found that when increasing the heated substrate temperature above 225 °C, formed microstructure electrical resistivity rises abruptly due to plastic substrate deformation. The result obtained is of interest in developing a one-step technology for producing electronic components on a plastic substrate.

1. Introduction
In recent years, new technologies for the creation of electronic circuits with printing equipment are actively developing [1]. In conventional aerosol jet printing technology, functional ink is used as a source of aerosol particles [2]. The use of ink causes several problems related to its preparation, storage, removal of solvents, etc. Dry aerosol jet printing (AJP) is a recently developed additive technology for producing functional microstructures [3]. This technology does not use ink, unlike conventional aerosol jet, inkjet, and screen printing methods. In dry AJP technology, solid aerosol nanoparticles with the size of a few tens of nanometers are produced by a multi-spark discharge generator [4]. Then aerosol nanoparticles are directed into the printing head for focusing and deposition on a substrate [5]. After deposition, the structures printed are thermally sintered to improve conductive properties [6]. The sintering process may take a long time. Thus producing electronic components may require a prolonged period of time. In this study, it is proposed to combine the deposition and sintering processes to shorten the time to produce the printed lines. This approach is realized by using a hotplate and a commercial aerosol jet printer together with a custom-build multi-spark discharge generator.

2. Experimental
Silver nanoparticles in the size range from 20 to 80 nm were produced using the multi-spark discharge generator as a result of electrical erosion of silver electrodes [7]. The generator parameters were as follows: energy, repetition rate and flow rate were 3 J, 4 Hz and 2 l/min, respectively. The scheme of the experiment on the formation of conductive silver lines using dry aerosol printing on a heated plastic substrate is shown in figure 1.
Figure 1. Experimental scheme of the formation of conductive silver lines on a heated plastic substrate, where $Q_a$ – aerosol flow rate, $Q_{sh}$ – sheath flow rate, $d$ – distance from nozzle to substrate and $V$ – substrate moving speed.

Further, the nanoparticles stream was focused into a narrow beam by means of a coaxial nozzle with an aerosol flow rate $Q_a$ and a sheath flow rate $Q_{sh}$ of 30 and 90 sccm, respectively. Nanoparticles beam, after focusing, was deposited on a heated plastic substrate from polyethylene terephthalate stated on a hot plate. The temperature of the hot plate was regulated in the range from 25 to 250 °C. Lines of silver nanoparticles were printed at a distance from the nozzle to the substrate $S$, the speed of the substrate moving $V$ and the number of printing layers equal to: 0.5 mm, 7 mm/min and 5 layers, respectively. The electrical resistivity $\rho$ of printed lines was calculated according to formula (1).

$$\rho = \frac{RS}{l}$$  \hspace{1cm} (1)

where $R$ – resistance; 
$S$ – cross-sectional area from the line 3D-profile; 
$l$ – length.

The width and length of the formed lines were measured using an optical and scanning electron microscope (SEM). The line 3D-profile $S$ was measured using an optical profilometer Leica DCM 3D. The resistance $R$ of the printed and sintered lines was measured by the multimeter Agilent U1253B.

3. Results and discussions

As a result of Ag nanoparticles deposition on a heated plastic substrate, it is found that with the substrate temperature $T_s$ increasing from 50 to 200 °C, there is a monotonous decrease in the printed line electrical resistivity $\rho$ by more than 6 orders of magnitude from $6 \times 10^8$ to $2 \times 10^2 \, \mu\Omega\cdot\text{cm}$, see Figure 1a. This decrease in electrical resistivity is probably caused by an increase in the number of conducting bonds between particles, formed as a result of diffusion process at the increased temperature of the heated substrate. Increase in the number of conducting bonds between Ag particles also results in reduced porosity of the microstructure formed, as observed with a SEM, see Figure 3 (a, b, c, d).
Figure 2. The dependency of the silver line resistivity on the heated plastic substrate temperature, insertions: 3D-profiles of the sintered lines.

Figure 3 (a, b, c, d). SEM-images of the silver line microstructure depending on the heated substrate temperature $T_s$ of 25°C (a), 175°C (b), 200°C (c) and 250°C (d), in the dry aerosol jet printing process.
It is also found that when the heated substrate temperature $T_s$ is increased above 225°C, an increase of the line resistivity to $4 \times 10^3 \mu \Omega \cdot \text{cm}$ is observed, which is probably related to the process of microstructure destruction as a result of different thermal expansion coefficients for silver and the plastic substrate. Therefore, from the results of the experiment conducted it is established that the heated plastic substrate recommended temperature is to be $\sim 200$ °C to form silver lines of minimal resistivity.

4. Conclusion
A method is investigated of producing conducting microstructures of silver on a heated plastic substrate by dry aerosol jet printing method. The method allows forming conductive lines in one step without a separate post-deposition sintering operation. It is found that the heated plastic substrate recommended temperature is to be $\sim 200$ °C to provide for minimal resistivity of the microstructures produced.

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