IOP Conf. Series: Materials Science and Engineering **307** (2018) 012082 doi:10.1088/1757-899X/307/1/012082

Dry aerosol jet printing of conductive silver lines on a heated silicon substrate

A A Efimov[1], P V Arsenov[1], N V Protas[1], K N Minkov[2], M N Urazov[1], V V Ivanov[1]

[1]Department of Physical and Quantum Electronics, Moscow Institute of Physics and Technology, Dolgoprudny 141700, Russia
[2]Moscow Institute of Electronics and Mathematics, National Research University of Higher School of Economics, Moscow, Russia

Abstract. A new method for dry aerosol jet printing conductive lines on a heated substrate is presented. The method is based on the use of a spark discharge generator as a source of dry nanoparticles and a heating plate for their sintering. This method allows creating conductive silver lines on a heated silicon substrate up to 300 °C without an additional sintering step. It was found that for effective sintering lines of silver nanoparticles the temperature of the heated substrate should be about more than 200-250 °C. Average thickness of the sintered silver lines was equal to ~20 µm. Printed lines showed electrical resistivity equal to 35 µΩ·cm, which is 23 times greater than the resistivity of bulk silver.

1. Introduction
In the last decade, aerosol jet printing has been actively investigated to create cheap electronic components and devices. This technology allows creating of printed antennas [1], thin-film transistors [2,3], light-emitting diodes [4,5], solar cells [6], and others. In conventional aerosol jet printing technology, functional ink is used as a source of aerosol particles. The use of ink causes several problems related to their preparation, storage, removal of solvents and etc. In this connection, alternative sources of particles for aerosol jet printing are being investigated. For example, the use of dry silver aerosol particles obtained in a spark discharge for printing conductive lines has recently been reported [7]. As a rule, such deposited lines require sintering to reduce contact resistances between the nanoparticles. The sintering process takes additional time and requires moving the sample from the print zone to the sintering zone, which is not convenient in the production process of a large number of printed samples, for example, the conductive buses of solar cells. Thereby, in this paper, it is proposed to combine the printing process and thermal sintering in order to reduce the time for the formation of functional lines. The proposed approach is realized using dry aerosol printing with silver nanoparticle beam on a heated silicon substrate and described in detail in the paper.

2. Experimental
The scheme of the experiment on the formation of conductive silver lines using dry aerosol printing on a heated silicon substrate is shown in figure 1. Silver nanoparticles in size range from 5 to 150 nm were produced using the multi-spark discharge generator [8] as a result of electrical erosion of silver electrodes. The generator parameters were as follows: energy, repetition rate and flow rate were 3 J, 4 Hz and 2 l/min, respectively. Further, the nanoparticles stream was focused into a narrow beam by means of a coaxial nozzle with an aerosol flow rate and a sheath flow rate of 30 and 90 ml/min, respectively. Nanoparticles beam, after focusing, was deposited on a heated silicon substrate stated on

IOP Conf. Series: Materials Science and Engineering **307** (2018) 012082 doi:10.1088/1757-899X/307/1/012082

a hot-plate. The temperature of the hot plate was regulated in the range from 25 to 300 °C. Lines of silver nanoparticles were printed at a distance from the nozzle to the substrate, the speed of the substrate moving and the number of printing layers equal to: 0.5 mm, 7 mm/min and 5 layers, respectively.

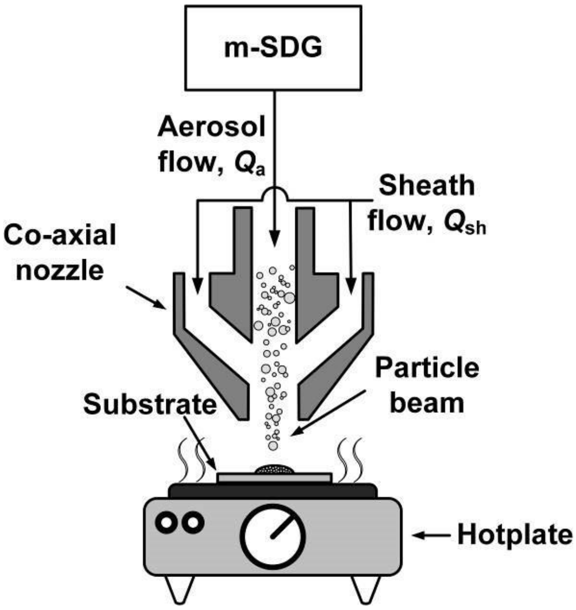

Figure 1. The scheme of the experiment on the formation of conductive silver lines using dry aerosol printing on a heated silicon substrate.

The width and length of the formed lines were measured using an optical and scanning electron microscope. The line profile was measured using an optical profilometer. Electrical resistivity of the printed and sintered lines was measured by four-probe method.

3. Results and discussions

figure 2 shows the dependence of the resistivity of the silver line on the temperature of the substrate at a dry aerosol printing process. Figure 2 shows that within the limits of measurement error and the reproducibility of the printing process the resistivity of the samples does not change significantly and is about 10^8 μΩ·cm for the substrate temperature range from 25 to 100 °C. This result indicates that temperatures of up to 100 °C are not yet sufficient for efficient sintering of nanoparticles. A significant reduction in the resistivity begins to observe at a substrate temperature above 150 °C. For example, at a substrate temperature of 150, 200 and 250 °C, the resistivity of the samples was $3{\cdot}10^5$, $2{\cdot}10^3$, and 35 μΩ·cm, respectively, see figure 2.

Consequently, from the experimental data in figure 2, it can be concluded that the temperature of the start of sintering of silver nanoparticles, received in a spark discharge, exceeds 100-150 °C. This result agrees with the data of other researchers on the sintering of nanoparticles with printing process. It was also found that at a temperature above 250 °C the resistivity of the printed samples did not change significantly. Consequently, the use of high substrate temperatures above 250 °C is not advisable. The inset of figure 2 shows that the cross-section profile of the line printed on heated substrate at 300 °C has a bell-shaped form with average thickness and width equal to ~20 and ~200 μm, respectively.

Figure 3 shows SEM images of the silver lines formed at different temperatures of the silicon substrate at 25, 150 and 250 °C, respectively. Figure 3a shows that the sample formed at a substrate temperature of 25 °C consists of very small particles with a large number of voids between them. These voids limit the number of percolating paths for electric current, therefore, the specific electric resistance of this sample is very high. When the temperature is raised to 150 and 250 °C, as shown in Figures 3b and c, respectively, the particle sizes have grown and the voids between them are minimized.

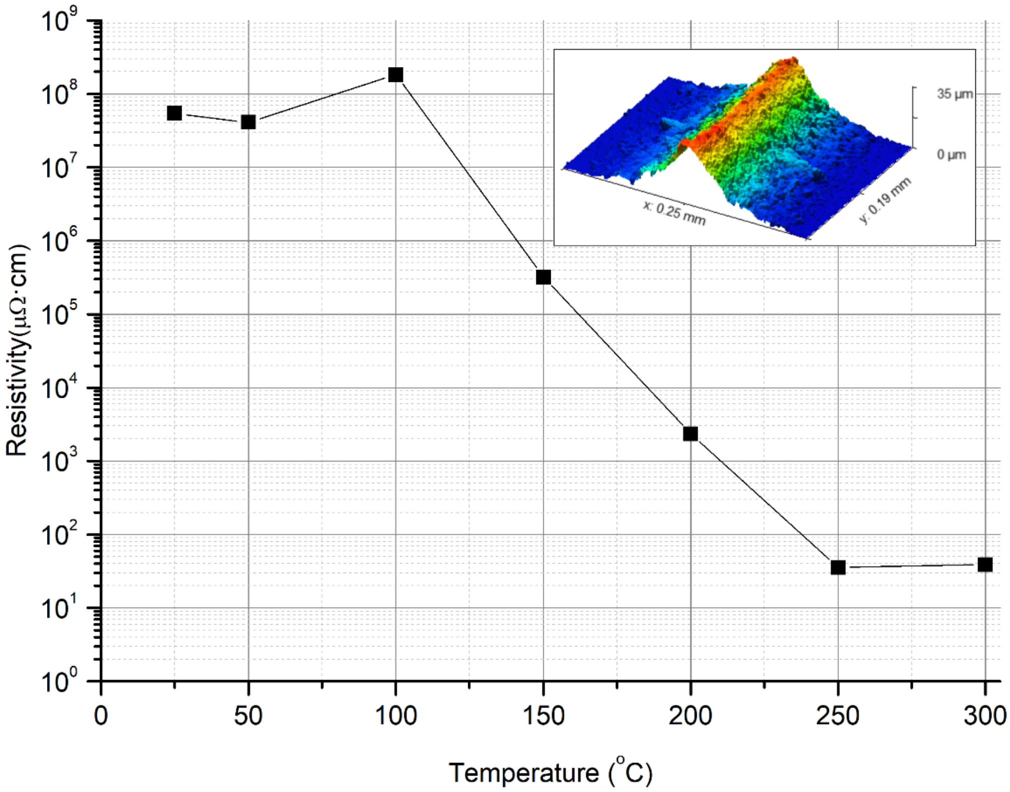

Figure 2. The resistivity of silver lines depending on the silicon substrate temperature at a dry aerosol jet printing. The inset shows a 3D-profile of silver line printed on heated substrate at 300 °C.

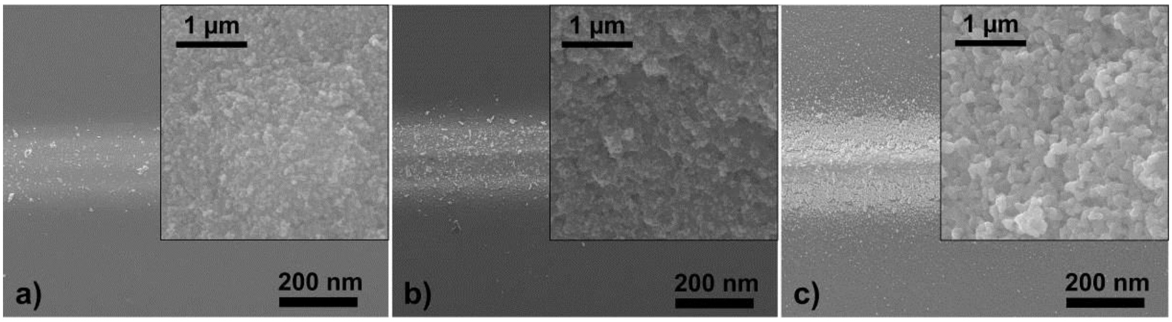

Figure 3 (a, b, c). SEM images of silver lines printed on heated substrate at 25 °C **(a)**, 150 °C **(b)**, and 250 °C **(c)**. The insets show more detail.

Besides, when depositing nanoparticles on a heated substrate, the possibility of their fixing on the surface increases, which means that the resulting particles line is formed from a large number of particles when sintering which forms a more voluminous structure having a low resistance. Based on the results of the experiments, it was also established that the resistivity of the best samples obtained at a substrate temperature of 250 °C is approximately 23 times worse than bulk silver. As we know, from the other works [9] this result is acceptable for some practical applications of e.g. for the production of microheaters, interconnectors, microstrip antennas, gas flow sensors etc. Thus, the considered approach of aerosol printing of conductive lines on heated substrates is quite promising.

4. Conclusion

A new method of dry aerosol printing of conductive silver lines on heated silicon substrates are investigated. This method allows forming conductive lines in one-step without a separate post-sintering operation. It was found that for effective sintering lines of silver nanoparticles the temperature of the heated substrate should be about more than 200-250 °C. Printed silver lines had an average thickness and resistivity equal to ~20 μm and 35 μΩ·cm, respectively. The same microstructures can be used in printed electronics devices.

Acknowledgments

This work was supported by the grant of the President of Russian Federation for young scientists MK-2302.2017.8 and carried out using the equipment of the Center for the collective use of high-precision measuring technologies in the field of photonics (ckp.vniiofi.ru).

References

[1] He Y, Oakley C, Chahal P, Albrecht J and Papapolymerou J 2017 Aerosol Jet printed 24 GHz end-fire quasi-Yagi-Uda antenna on a 3-D printed cavity substrate *2017 International Workshop on Antenna Technology: Small Antennas, Innovative Structures, and Applications (iWAT)* 2017 International Workshop on Antenna Technology: Small Antennas, Innovative Structures, and Applications (iWAT) pp 179–82
[2] Cho J H, Lee J, Xia Y, Kim B, He Y, Renn M J, Lodge T P and Daniel Frisbie C 2008 Printable ion-gel gate dielectrics for low-voltage polymer thin-film transistors on plastic *Nat. Mater.* **7** 900–6
[3] Vaillancourt J et al. 2008 All ink-jet-printed carbon nanotube thin-film transistor on a polyimide substrate with an ultrahigh operating frequency of over 5 GHz *Appl. Phys. Lett.* **93** 243301
[4] Zhou L, Zhuang J Y, Song M S, Su W M and Cui Z 2014 Enhanced performance for organic light-emitting diodes by embedding an aerosol jet printed conductive grid *J. Phys. Appl. Phys.* **47** 115504
[5] Rudorfer A, Tscherner M, Palfinger C, Reil F, Hartmann P, Seferis I E, Zych E and Wenzl F P 2016 A study on Aerosol jet printing technology in LED module manufacturing Fifteenth International Conference on Solid State Lighting and LED-based Illumination Systems vol 9954 (International Society for Optics and Photonics) p 99540E
[6] Yang C, Zhou E, Miyanishi S, Hashimoto K and Tajima K 2011 Preparation of Active Layers in Polymer Solar Cells by Aerosol Jet Printing *Acs Appl. Mater. Interfaces* **3** 4053–8
[7] Efimov A, Potapov G, Nisan A, Urazov M and Ivanov V 2017 Application of the Spark Discharge Generator for Solvent-free Aerosol Jet Printing *Orient. J. Chem.* **33** 1047–50
[8] Efimov A, Lizunova A, Sukharev V and Ivanov V 2016 Synthesis and Characterization of TiO2, Cu2O and Al2O3 Aerosol Nanoparticles Produced by the Multi-Spark Discharge Generator *Korean J. Mater. Res.* **26** 123–9
[9] Perelaer J, Hendriks C E, de Laat A W M and Schubert U S 2009 One-step inkjet printing of conductive silver tracks on polymer substrates *Nanotechnology* **20** 165303