Thin Solid Films 556 (2014) 452–459

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Alternative sintering methods compared to conventional thermal sintering for inkjet printed silver nanoparticle ink

Juha Niittynen [a,*], Robert Abbel [b], Matti Mäntysalo [a], Jolke Perelaer [c,d], Ulrich S. Schubert [c,d], Donald Lupo [a]

[a] Department of Electronics and Communications Engineering, Tampere University of Technology, Korkeakoulunkatu 3, 33720 Tampere, Finland
[b] Holst Centre, High Tech Campus 31, 5656 AE Eindhoven, The Netherlands
[c] Laboratory of Organic and Macromolecular Chemistry (IOMC), Friedrich-Schiller-University Jena, Humboldtstrasse 10, D-07743 Jena, Germany
[d] Jena Center for Soft Matter (JCSM), Friedrich-Schiller-University Jena, Humboldtstrasse 10, D-07743 Jena, Germany

ARTICLE INFO

Article history:
Received 22 January 2013
Received in revised form 5 September 2013
Accepted 3 February 2014
Available online 8 February 2014

Keywords:
Inkjet
Sintering
Plasma
Photonic
Laser
Thermal

ABSTRACT

In this contribution several alternative sintering methods are compared to traditional thermal sintering as high temperature and long process time of thermal sintering are increasing the costs of inkjet-printing and preventing the use of this technology in large scale manufacturing. Alternative sintering techniques are evaluated based on the electrical and mechanical performance they enable on inkjet-printed structures as well as their potential feasibility for large scale manufacturing. Photonic sintering was identified as the most promising alternative to thermal sintering.

1. Introduction

Flexible electronics combine bendable substrates with inorganic materials by means of printing technologies, enabling light-weight and extremely costs-efficient electronic systems [1]. A highly viable and innovative fusion of three technological areas – microelectronics, chemistry and printing – is foreseen in the near future [2].

For example, radiofrequency identification tags [2,3] and various flexible electronic devices, including batteries [2,4], (organic) photovoltaics [5] as well as logic and memory components [6], are among the interesting and possible application areas for inkjet printed electronics. Inkjet printing has been shown to be suitable for electronic miniaturization and rapid research and development prototyping [7,8]. Furthermore, inkjet printing represents a digital "drop-on-demand" manufacturing technique that delivers expensive materials on demand, which reduces the material waste during the manufacturing process. Furthermore, the process efficiency is improved as well as the environmental stress of the manufacturing process is reduced [9].

Inkjet printing is currently moving from the lab-scale to a manufacturing scale, which demands a significantly decreased price as well as increased process output in order to become competitive towards conventional manufacturing methods [10,11].

An important requirement for microelectronic devices is the conductive structures, which makes metals the most obvious choice due to the superior conductivity compared to organic materials. Inkjet printing of metal containing precursor materials has been widely accepted as a suitable processing alternative for the fabrication of contacts and interconnects at relatively high speed that enables roll-to-roll production [9]. The required post-printing sintering step to render the precursor materials conductive, high process temperature is usually required, which means that most of the cost-effective polymer foils, such as polyethylene terephthalate or polycarbonate (PC), which have relatively low glass transition temperature (Tg) are not compatible with traditional thermal sintering [12]. As an alternative, more expensive polymer substrates, such as polyimide or polyarylate, can be used [13]. These expensive materials obviously hamper the cost-efficiency of the production process.

Two different classes of conductive inks are commonly used for inkjet printing, either based on metal-organic decomposition complexes, or metal nanoparticles [7]. The metal nanoparticles in an ink are generally stabilized by an organic layer in order to keep the nanoparticles well-dispersed in solution. In order to gain conductivity, the organic moieties first need to be removed after the printing process. Subsequently, the particles make direct physical contact, followed by neck formation between the particles and larger particles will be formed, triggered by Ostwald ripening and the surface-to-volume reduction [14]. Upon sintering a continuous percolating network is formed throughout the printed features, resulting in electrical conductivity.

The organic stabilizer is typically removed by heat, but this process is not compatible with common polymer foils due to their high thermal

* Corresponding author. Tel.: +358 40 849 0624; fax: +358 3 364 1445.
E-mail address: juha.niittynen@tut.fi (J. Niittynen).

0040-6090/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tsf.2014.02.001

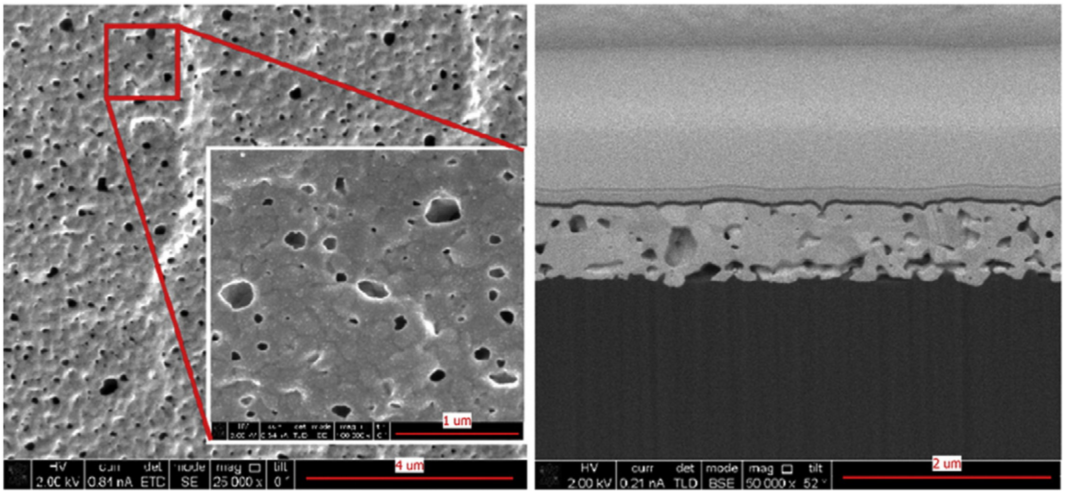

Fig. 1. Top-view and cross-section SEM images from a thermally sintered sample.

sensitivity [15]. Therefore, alternative sintering techniques are required to reduce the manufacturing costs and shorten the processing time.

In recent years, researchers have reported various methods to reduce the sintering temperatures of metal precursor inks by tailoring the organic content in the ink [16,17]. Instead of heating the complete sample, more selective sintering techniques were used by various groups, including laser sintering [18], low pressure argon plasma exposure [19], microwave radiation [20], electrical [21] and photonic sintering [22]. These techniques converted metal precursor inks into conductive features and excellent conductivity values up to 60% were obtained in short processing times [23].

The electrical performance of the printed and sintered features is essential for the final electronic applications; a low conductivity causes unnecessary power losses throughout the device due to increased resistances, resulting in excess heating and possibly reliability issues. Furthermore, a low conductivity can disturb high frequency conductor lines and time-critical signal lines [24–27]. A conductivity of one tenth of bulk silver material can be considered to be adequate for some low-performance applications.

Secondly, the mechanical performance of printed and sintered features is important to evaluate, since it directly relates to the reliability of the printed structures. Poor mechanical properties lead to a decreased reliability and a shortened lifetime, in particular in the dynamic and flexible applications where mechanical stresses are more prominent than in rigid printed circuit boards [28]. The ability to endure mechanical stresses caused by the flexible action is very important as flexible devices are considered as one of the most promising applications for printable electronics [29].

It is therefore extremely important to achieve good sintering and a homogeneous microstructure as a porous microstructure means that the local conductivities may vary greatly even inside a single sample. Local differences in conductivity may cause “hot spots” where the current density is higher which, in turn, may cause local heating and therefore reliability issues within the structure. Non-uniform sintering is undesirable as the large-scale electronic manufacturing demands highly repeatable and reproducible fabrication processes in order to achieve the desired levels of long-term reliability.

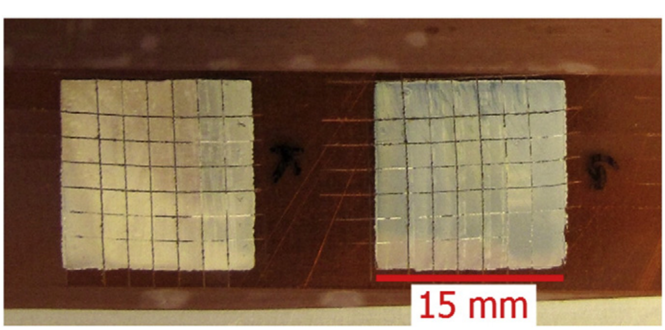

Fig. 2. Peel-off adhesion test sample for thermal sintering on polyimide. The size of the peel-off adhesion test squares is 15 mm by 15 mm.

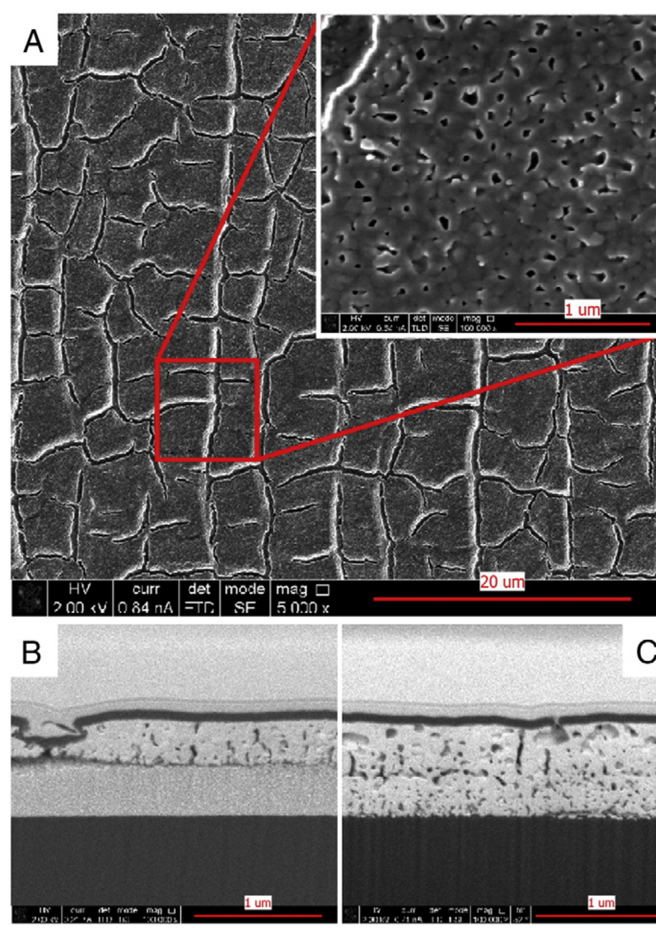

Fig. 3. Top-view (after 4 h) and cross-section (after 30 min (A) and after 4 h (B)) of plasma sintering.