Key Engineering Materials
ISSN: 1662-9795, Vol. 926, pp 220-225
doi:10.4028/p-8n7ycr

Submitted: 2022-01-12
Revised: 2022-01-29
Accepted: 2022-02-23
Online: 2022-07-22

Silver Nano-Colloid Characterization for Printing Application

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Keywords: Silver nano-colloid, zeta potential, particle concentration, UV-VIS, DLS, TEM.

Abstract. Silver nano-colloids have been generated *via* Laser Ablation Synthesis in Solution (LASiS) system. Nanoparticle formation with particle size below 50 nm in DI water was confirmed using UV-VIS spectroscopy, Dynamic Light Scattering (DLS) technique, and transmission electron microscopy (TEM). Supercapacitor structure, having dimension 11 mm x 10 mm, was successfully Aerosol Jet printed on an untreated polymer substrate using as produced LASiS silver nano-colloid.

Introduction

Flexible electronics [1, 2], a class of lightweight electronic components and devices on flexible and stretchable substrates (*e.g.*, paper [3], polymer [4], textiles [5] *etc.*), offer opportunities in many novel applications in different sectors such as smart packaging and logistics, consumer electronics, textiles, energy and photovoltaics, healthcare and wellbeing, building and construction, and automotive industry [6]. The most attractive characteristic is the ability to bend or stretch, in contrast to electronic devices or components developed on rigid materials. The global market of flexible electronic and device technology is estimated to rise from \$ 31.7 bn in 2018 to over \$77.3 bn by 2029 [7]. Printed electronic technologies, a novel way to manufacture electronic components, are an important tool in producing flexible electronics. This technique is used to manufacture electronic components and devices by printing them on various flexible or stretchable substrates. The method is one of the fast growing technologies, allowing high throughput, large volume, cost effective fabrication for numerous every-day products. The most common printing methods used for making electronics with solution based inks on the flexible substrates are screen printing, flexographic printing, inkjet printing, Aerosol Jet printing, and roll-to-roll gravure printing [8, 9]. In comparison to traditional electronics, flexible printed electronics are key to manufacture portable, bendable, low cost, and light weight electronics, with parts which can be recycled easily avoiding waste accumulation and reducing the environmental footprint.

Organic materials, for example, 2D materials, polymers, cellulose, *etc*., are used as substrates (to print on) and functional materials (to print with) [8, 9]. Flexible printed electronic technologies rely on the fact that even in a deformed state polymeric materials maintain their structural and electrical properties. Inorganic and metallic materials are also used in this technology [10]. In recent years, functional conductive inks have received much attention due to their popularity and application in flexible printed electronics [11]. To meet the growing demand for large volume, low cost fabrication methods and the challenges faced in producing printed electronics, advancements in innovative materials and methods for conductive ink production are required. Numerous functional inks, for example aluminum [12, 13], nickel [14, 15], copper [16, 17], gold [18, 19], graphene [20], carbon nanotube [21, 22], silver [23, 24] *etc.* for printed electronic application have been synthesized. Among the functional inks, silver nanoparticle based inks exhibit excellent conductivity and stability. The conductive structures based on the silver nanoparticle inks can be sintered relatively at low temperature. These characteristics makes silver ink suitable for producing flexible printed electronic circuits and components including sensors [25], light-emitting devices [26], radio frequency identification device tags (RFID) [27], touch screen panel [28], antenna [29], thin-film transistors [30], and solar cells [31].

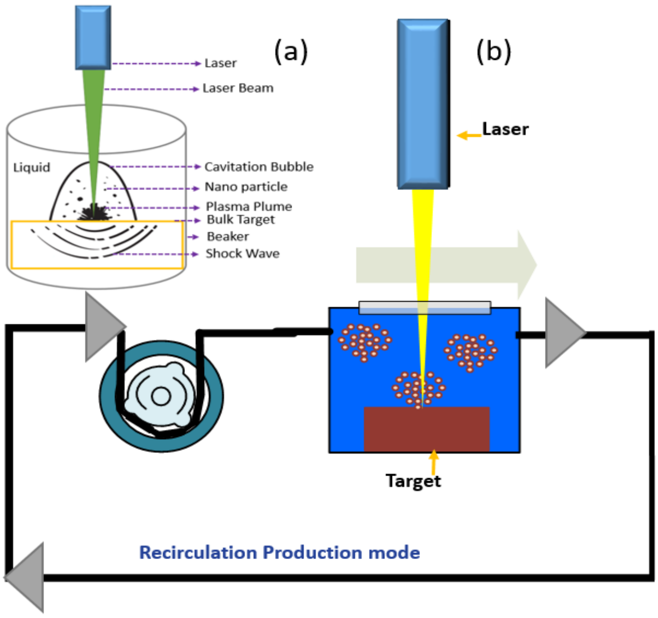


Figure 1. Schematic of (a) nanoparticle generation in aqueous media, and (b) LASiS system in recirculation production mode.

Laser Ablation Synthesis in Solution (LASIS) is a physical approach of producing nanomaterials in a liquid environment (Fig. 1a). In this method, a pulsed laser irradiates a metal target immersed in solvent, where its absoprtion by the target material produces plasma plumes, which generate nanomaterials in the aqueous medium. The production rate and nanomaterial properties strongly depends on the laser parameters (*i.e.* repetition rate, pulse duration, wavelength, and laser fluence) and the target material. The LASiS technique is capable of producing additive free non-toxic stable colloidal dispersions of nanostructures (*e.g.*, aluminium [32], carbon [33], gold 34], nickel [35], copper [36], carbon nanotube [37], and silver [38]) in both organic and aqueous media. Therefore, the eco-friendly, cost effective LASiS technique has received much attention for the industrial production of conductive functional nanomaterials. This work reports the generation of silver nano-colloids in DI water using dynamic LASiS technique and their Aerosol Jet printing on a polymer sheet.

Materials

Silver targets sourced from Goodfellow Cambridge Ltd. were used in this study. The DI water for LASiS nano-colloid formation was purchased from Merck (LC-MS Grade LiChrosolv).

Results and Discussions

Silver nano-colloids have been generated in 10 mL DI water using a dynamic LASiS set-up (Fig. 1b) in a recirculation production mode. The produced colloids were characterized using UV-VIS Spectrophotometer (Biochrom Inc., USA, scan range 200–1200 nm with scan rate 600 nm min^{-1}) (Fig. 2) to confirm nanoparticle formation. The absorption peaks in the 400 nm wavelength region confirm silver nanoparticle formation under the experimental conditions: pulse repletion rate, f_{PRF} = 20 kHz, process duration, t=30 min, and laser bean scan speed, v =2.2 mm s^{-1} in DI water [39]. The inset of Fig. 2 shows a picture of LASiS silver nanocolloids produced for the corresponding UV-VIS spectra. In order to check the reproducibility, the experiments were repeated six times with the same parameters under study. The particle size distribution and shape of the particles in the as-produced silver nanocolloids were then analyzed using dynamic light scattering (DLS, Microtrac Ltd.), and transmission electron microscope, TEM, FEI Titan (S)TEM (FEI, USA) with beam energy of 300 keV. In DLS, the scattering intensity of laser beam in a colloidal solution fluctuates with time due to the Brownian motion of particles leading to the constructive or destructive interference by the surrounding particles in the colloid. Figure 3 shows the average particle size distribution of the six colloidal samples produced corresponding to the UV-VIS spectra, and they were all found to be below 50 nm.

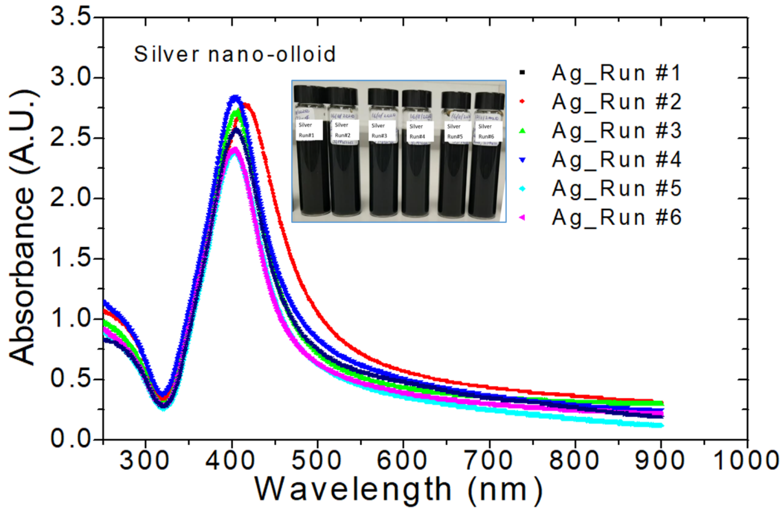


Figure 2. UV-VIS absorption spectra with the corresponding picture of (inset) LASiS silver colloids.

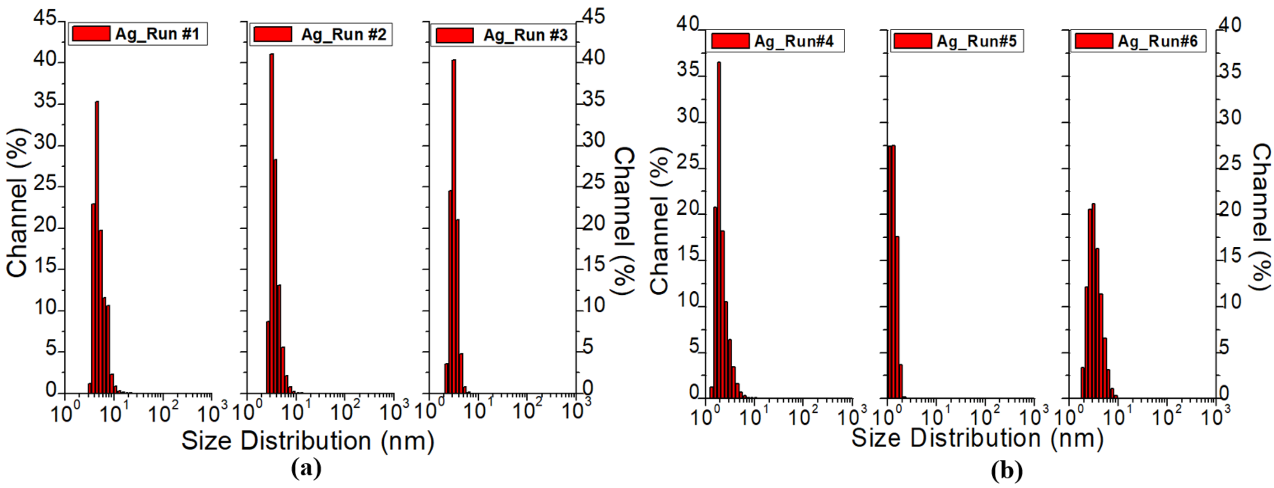
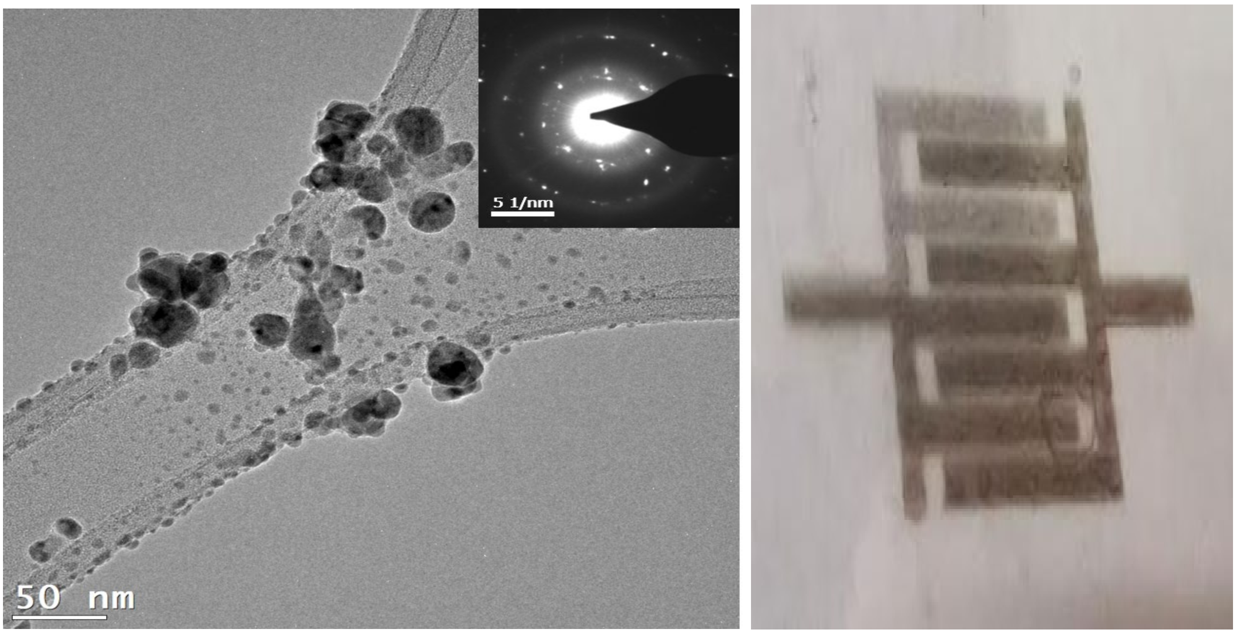


Figure 3 (a) and (b) DLS size distribution plots of silver nano-colloid in 10 mL DI water for repeated six different experiments, all carried out under the same parameters (f_{PRF} = 20 kHz, t=30 min, and v =2.2 mm s^{-1}) and experimental conditions.

The silver colloidal sample was characterized using TEM. Figure 4(a) shows the Bright Field TEM picture of an as-produced silver nano-colloid, with the inset Selected Area Electron Diffraction picture showing polycrystallinity of the sample studied. The TEM imaging observation was in agreement with the DLS studies. The manual calculation, by taking silver target weight measurements before and after the ablation process in DI water, shows ~0.9 mg mL^{-1} productivity for the parameters f_{PRF} = 20 kHz, t=30 min, and v =2.2 mm s^{-1}. The as-produced LASiS silver colloid was successfully Aerosol Jet printed on a polymer substrate. Figure 4(b) shows the single layer super capacitor structure on an acetate sheet printed using an AJP 300 Aerosol Jet Printer. A print nozzle of 300 µm was used for printing alongside nitrogen carrier gas. Gas pressures was adjusted to maintain consistent mass flow. The dimension of the supercapacitor structure shown in Fig. 4(b) is 11 mm x 10 mm (not including the two lines out from either side).

Summary

In this work, colloidal silver nanoparticles were prepared by dynamic flow based LASiS system in a recirculation production mode and successfully Aerosol Jet printed single layer supercapacitor structure on an acetate sheet for the first time using the as-produced LASiS silver colloid with ~0.9 mg mL^{-1} productivity, which was achieved with the parameters, f_{PRF} = 20 kHz, t=30 min, and v =2.2 mm s^{-1}. The UV-VIS, TEM, and DLS studies confirm silver nanoparticle formation, with the average particle size below 50 nm. The reproducibility of the LASiS nano-colloids was studied and confirmed with six repeated experiments for the same parameters under study. This work reports the high yield LASiS silver nano-colloid production and its Aerosol Jet printing application on the flexible polymer substrate.



(a) (b)

Figure 4. (a) TEM picture of as produced silver nano-colloid. Inset Selected area electron diffraction showing polycrystallinity. (b) Aerosol Jet printed supercapacitor structure on a polymer sheet (dimension: 11 mm x 10 mm (not including the two lines out from either side)).

Acknowledgments

This work is supported in part by a research grant from Science Foundation Ireland (SFI) under Grant Numbers 16/RC/3872 and 19/US-C2C/3579.; and is co-funded under the European Regional Development Fund and by I-Form industry partners. The authors acknowledge the Advanced Microscopy Laboratory for the provision of their facilities. Microscopy characterization and analysis has been performed at the CRANN Advanced Microscopy Laboratory (AML) (www.tcd.ie/crann/aml/).

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