Broad Implications Arising from Novel Sintering Process and Conductive Inks for Printed Electronics

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Abstract

Photonic curing has been shown to be effective in heating inks and functional films to very high temperatures, in excess of 500C, on low-temperature substrates such as polymers and paper. This paper reviews the basic principles of the technology and expounds on implications to applications and materials, including cost and performance.

1) Objective and Background

For some time, one of the key limiting challenges in flexible printed electronics has been to reconcile the conflicting high-temperature processing requirements of high-performance materials such as inorganic conductive inks with low temperature substrates such as polymers and paper materials. Efforts to resolve this mismatch have historically focused primarily on

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developing nanomaterial-based conducting inks processable at low temperature, or using polymers such as polyimide. Both approaches have cost and/or performance performance penalties. The authors present a photonic curing process designed to heat only the target inks using light energy delivered from flash lamps in micro-second pulses. This flashlamp-based technology dries, sinters, anneals, and even modulates chemical reactions, and has already been developed into a toolset suitable for direct integration for roll-to-roll manufacturing. The photonic sintering tools enable the use of traditional conductive inks on a wide variety of desired flexible substrates which do not have the ability to withstand sustained elevated processing temperatures. These tools also enable the development of new materials based on the unique energy delivery capabilities the tools offer.

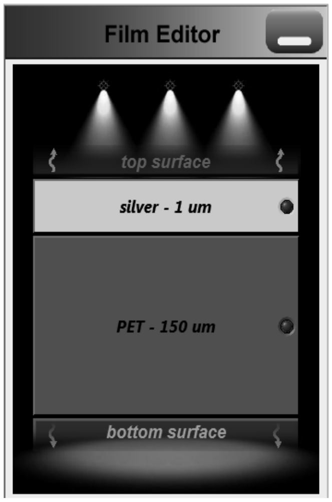
2) Methods

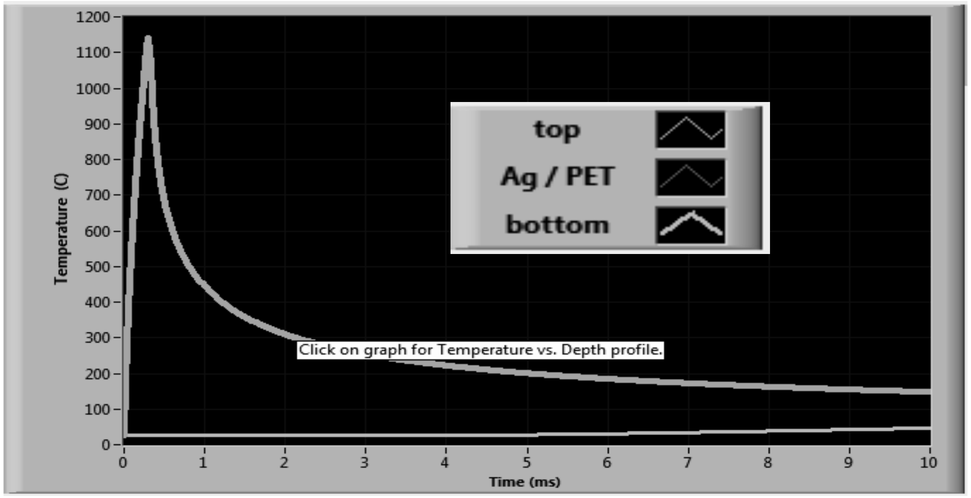
Experimental work demonstrates that conductive inks of very differing particle morphologies and formulations can be effectively processed on a wide range of substrates with this technology when correctly applied. Examples presented include traditional silver inkjet inks composed of nanoparticles in water on coated PET, and off-the-shelf screen print inks composed of silver flakes also on PET. Additionally, an example of a new type of material enabled by this processing is presented. Copper oxide when formulated with a reducing agent can be converted to copper thin film in situ when processed with the photonic curing tool. A new commercially-available ink embodying this principle is presented on paper substrates.

Computational results are also presented demonstrating the thermal gradients created in the target materials during processing with photonic curing, derived from use of code developed in-house specifically to serve as an experimental aid and design tool for users of the photonic curing technology.

3) Results

To model the thermal response of arbitrary user-defined material systems, a proprietary numerical simulation tool was developed. The following graphics are captured from the simulation tool and depict silver on PET (below left) when processed with a broad spectrum light pulse of 300 microsec duration and 1 J/cm^2 of total delivered energy (below right). Note the very high process temperatures indicated as reached by the silver, and the temperatures experienecd by the PET, as well as the very short total process time. Using the model, and defining the material conditions and the pulse exposure conditions, results in a quick presentation of the thermal impact in the materials as a function of time and of depth.





The following table summarizes the processing conditions and results with the photonic curing tool, against the results of processing in a traditional oven.

Print Method	**Ink**	**Print Thickness-Dried (microns)**	**Total Exposure Duration** *milliseconds*	**Total Energy Delivered** *J/cm^2*	**Average Power Delivered** *(kW/cm^2)*	**Final Sheet Resistance (photonic curing)** *mOhms/sq*	**Sheet Resistance (oven @ 30 minutes)**
Inkjet	JS-B25HV (Ag)	0.6	6	5	1	50	100 (125C)
	ICI-003 (CuO/Cu)	<0.5	10	8	1	100	NA
Screen	HPS-021 (Ag)	5	3	5	2	18	13 (150C)
	ICI-020 (CuO/Cu)	4-5	3	8	3	60	NA

The substrate used for the inkjet inks is a commercial PET coated to be especially receptive to water-based inks. For depositing the inkjet inks, a Dimatix DMP-128 was used for the silver and an Epson C88+ Photo Stylus Inkjet Printer was used for the ICI-003.

The substrate used for the silver screen-print inks is PET ST505 produced by DuPont. The substrate used for the screen-printed copper oxide reduction ink is Wausau Paper Exact® Index 110 lbs smooth finish. The screen inks were deposited using a 325 mesh screen. Ink thicknesses were approximately 4-5 microns when dried.

4) Impact

The ability to process high-temperature materials on low-temperature substrates, in both development scale and in production sheet-to-sheet or roll-to-roll configuration, is finding a role in a range of printed electronics applications, including displays, photovoltaics, batteries, medical sensors, and RFID.