

Evaluation of Tool for Processing Metallic Conductive Inks on Low Temperature Substrates

S. Farnsworth; I. Rawson; K. Martin, Ph.D.; K. A. Schroder, Ph.D.; D. Pope, Ph.D.
NovaCentrixTM
200-B Parker Dr Suite 580, Austin, TX 78758
phone: (512) 491-9500, stan.farnsworth@novacentrix.com

Abstract

To grow as a market technology segment, Printed Electronics technology components such as advanced displays, RFID tags, batteries, and flexible solar cells must be able to be manufactured at commercial scale and cost, and in novel form factors. The PulseForgeTM tools (patented and patent pending) from NovaCentrix are proposed to address these needs by providing the ability to dry, sinter, or anneal inks and thin-film materials in only milliseconds, and to be able to do so on a wide variety of substrates, including low temperature, flexible materials. A PulseForge 3100 in 12-inch width configuration is used to process nanosilver and nanocopper formulated inks, and a silver screen ink, on PET. The conductivity results are significantly improved from oven processing, to within 3x bulk silver conductivity. Additionally, it is seen that the PulseForge tools are applicable to direct application in volume manufacturing. PulseForge tools can reduce product material costs, reduce manufacturing cycle times, and enable new innovative form factors.

Keywords: printed electronics, rfid, battery, display, photovoltaic, conductive, silver, copper, curing

Introduction

For some time the appeal of additive print-based manufacturing of electrical devices has been strong. Printing methods to deposit the functional electronic materials only where needed can allow the use of non-traditional material substrates such as polymers and even paper. These substrate materials are attractive because of their low-cost and because of their ability to flex and conform to non-rigid structures. When considered in application of technology devices such as displays, RFID, batteries, and photovoltaics, the value potential of current and future products produced by printed electronics methods is in the hundreds of billions of dollars.

Yet, use of these substrates presents a specific difficulty. These substrates are also generally not capable of surviving the temperatures required to process traditional conductive inks. Researchers have worked to develop inks with lower processing temperatures, but use of these inks introduces additional challenges such as the ability to deposit enough thickness to achieve high absolute conductivity. A solution is needed therefore to be

able to process the inks at higher temperatures while not damaging the low-temperature substrates. The PulseForge tools from NovaCentrix are designed for such a purpose.

Principle of Function

The PulseForge tools are designed to create a transient non-equilibrium thermal condition in the ink-substrate system wherein the ink is heated to temperatures required for effective processing, but without heating the substrate and causing damage. A gradient is created between the temperature of the ink and the temperature at the base of the substrate. The time-scales for this transient condition are milliseconds, or fractions of milliseconds depending on the thermal properties of the system. PulseForge tools create this thermal transient by the use of proprietary lamps which are cycled on and off in fractions of a millisecond to deliver the energy to the target material. Inks are seen to have a higher absorbance of the lamp radiant energy than the substrate^[1]. The absorbed energy becomes increased temperature, proportional to the mass and the specific

heat of the ink material, and by delivering enough energy to the inks the required processing temperature can be reached. Yet, by careful control of the duty cycle of the lamps, the energy delivery to the inks can be stopped before enough energy is delivered to the inks to transfer to the substrate causing damage, or before the substrate is able to absorb enough direct radiant energy to result in damage.^[2]

Method Comparison

Ovens, which are the traditional processing method, offer the primary disadvantage in that they operate in an equilibrium mode. The inks and the substrates reach the same temperature. Therefore the maximum allowable temperature of the system is limited by the allowable temperature of the substrate, preventing the ink from reaching optimized cure. Ovens also have longer processing times, typically in terms of minutes. Ovens do have positive attributes, such as area of coverage, and uniformity of temperature. These positive attributes are also carried forward in the PulseForge tools.

Lasers are often used for certain types of materials processing, including CO₂ and excimer lasers. Lasers have the advantage of delivering high specific power to achieve a non-equilibrium condition, but are limited in scalability. Additionally, lasers emit very narrow wavelengths. Unless the target material is optimized to absorb that wavelength, the result is an un-optimized coupling of energy to the ink.

Ultraviolet (UV) systems are used to process many types of materials, but with regard to application for creating a non-equilibrium thermal condition, suffer from the problem of un-optimized energy coupling, as well as insufficient power.

Equipment Description

While using simple flashes has been referenced in the literature^[3-5], developing this technique into reliable industrial equipment is non-trivial. Because of the wide variety of inks and substrate combinations in development commercially, any embodiment of this technology must be very versatile, including with the ability to change the energy and power output characteristics. NovaCentrix' first commercial tool designed for industry use, the PulseForge 1100, was released in 2007. While this tool has proven very versatile for processing many types of materials on many types of substrates, the manual-pulse design of the tool makes it impractical for use in volume production. Accordingly, in 2008 the PulseForge 3100 toolset

was released, designed for high-speed production of printed electronic devices.



Figure 1: PulseForge 3100 in 12" width configuration (from left):

- **Lamp housing mounted over conveyor for stand-alone operation**
- **Cooling system module**
- **Power cabinet**
- **Control module and operator station with touch-screen interface**

PulseForge tools in contrast emit in broad spectrum as per the table below.

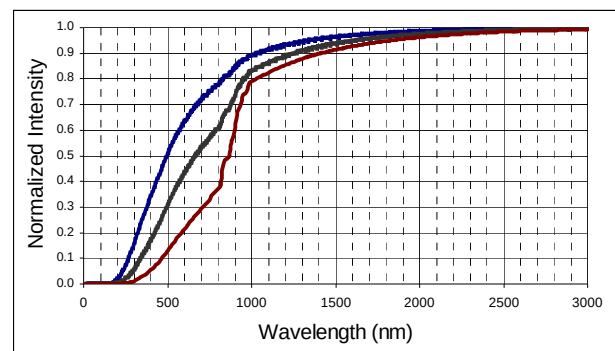


Figure 2: Normalized Cumulative Spectrum from PulseForge, showing three power cases (l-r) of high, med, and low settings.

Note that by adjusting the pulse configuration the tool can provide from up to 35% of the total energy at below 400 nm (left-most curve) to only 5% of the total energy (right-most curve). If the tool is delivering 25 J/cm², this corresponds to as much as 8 J/cm² or as little as 1.25 J/cm² delivered in the UV range.

Key specifications for PulseForge 3100 in 12" width configuration include:

Pulse Energy 0-5 J/cm²

Pulse Duration	100 μ s – 5 ms
Pulse Rate	Up to 30 Hz
Typical processing speed	10 meters/min
Max speed (single-tool)	~100 meters/min
Lamp lifetime	>>1 x 10 ⁶ cycles
Processing cost	~\$0.01/ft ²

[Note: The PulseForge 3300, the next tool in the PulseForge family, is scheduled to be released mid-Sept 2009, with pulse energies as high as 40 J/cm² - 100 J/cm² and pulse lengths as short as 20 μ s. In addition to processing metallic inks and UV materials, this tool is designed to process other materials such as semiconductor films.]

Test Materials

For this evaluation, three inks were selected. Metalon™ JS-015 silver-based inkjet ink
Metalon™ ICI-001 copper-based inkjet ink
Metalon™ HPS-020 silver-based screen ink

All three of these inks are water-based, and are produced by NovaCentrix. Detailed data sheets can be found at www.novacentrix.com. The following table summarizes key properties of the inks.

Table 1: Properties of Metalon inks used in evaluation. * ICI-001 is not curable thermally and requires the use of PulseForge technology to reach conductive performance.

Ink Name	Material	Avg Dispersion Cluster Size	Full Cure Temp
JS-015	Ag	200 nm	375°C
ICI-001	Cu	143 nm	NA*
HPS-020	Ag	1.8 micron	400°C

The substrate used for these evaluations is a commercial PET coated to be receptive to inkjet inks. The same substrate material is used for evaluation of all three inks.

For depositing the inkjet inks, a commercial Epson C88+ Photo Stylus Inkjet Printer was used. This printer is readily available at low cost (~\$100 USD) and is a good platform for basic printing of Metalon inkjet inks. The specific printer settings are beyond the scope of this evaluation, but are readily available from the authors. The Metalon HPS-020 was deposited using a drawdown system with a #20 drawdown bar, resulting in ink thickness of ~15 microns.

Processing and Results

The following table summarizes the cure conditions used for the inks. The processing pulses

were delivered in a configuration to best manage the unwanted build-up of thermal energy. The total pulse duration and the total energy delivered are indicated in the table. All of the samples were processed in open ambient air, including the copper ink. The advance rate of the conveyor used to move the samples under the lamp housing was 10 meters/minute for each of the samples. At this speed, the PulseForge tool could process approximately 14.4 km of material in one day. Because the PulseForge 3100 used was in a 12 inch width configuration, this corresponds to approximately 47,000 ft²/day. Energy delivery was measured using a calibrated in-house bolometer.

Table 2: Summary of processing and results

Ink	Print Passes	Total Pulse Duration milliseconds	Total Energy Delivered J/cm ²	Resistivity mOhms/sq
JS-015	3	6.4	5	50
ICI-001	1	9.8	7.6	100
HPS-020	1	1.75	7.5	7

Because of the uniqueness of the copper ink, it is worth noting the following cross-sectional SEM images, which indicate the significant transformation of the copper material following processing.

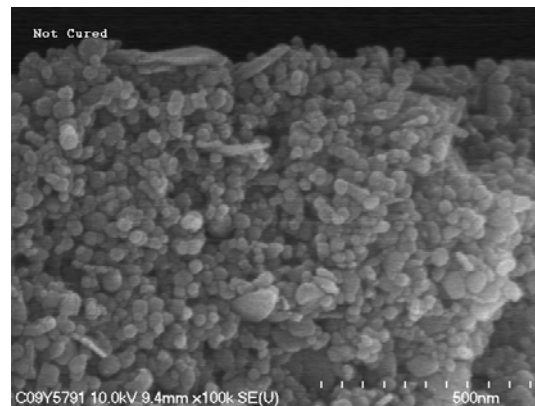


Figure 3: SEM of Metalon ICI-001 copper-based ink printed, but prior to processing to achieve conductivity.

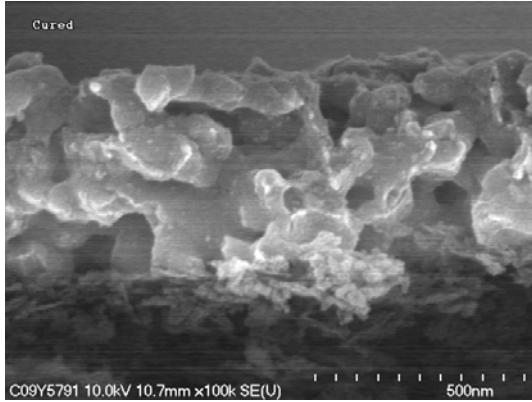


Figure 4: SEM of Metalon ICI-001 copper-based ink printed and processed with PulseForge technology. Note the dramatic change from the pre-cured condition (Fig. 3)

Table 3: Comparison of oven curing and PulseForge processing on PE: Conductivity

Ink	Resistivity after oven at 150C mOhms/sq	Resistivity after PulseForge mOhms/sq	Improvement vs Oven: conductivity
JS-015	450,000	50	9000x
ICI-001	NA	100	inf
HPS-020	72	7	~10x

Table 4: Comparison of oven curing and PulseForge processing on PET: Processing time

Ink	Processing time in oven at 150C seconds	Processing time with PulseForge milliseconds	Improvement vs Oven
JS-015	60	6.4	9375x
ICI-001	NA	9.8	inf
HPS-020	1800	1.75	1,000,000x

Conclusions

The PulseForge 3100 has been demonstrated to significantly improve the conductive performance of three types of conductive inks on PET without damaging the PET, at a processing speed suitable for volume manufacturing. The PulseForge 3100 demonstrated the capability to process high-temperature materials on inexpensive low-temperature materials. This, and the demonstrated potential for high-volume production of printed electronics devices, makes the PulseForge technology an enabler for applications in advanced displays, RFID tags, batteries, and flexible solar cell device design and manufacturing.

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