The Photonic Curing Process for Printed Electronics with Applications to Printed RFID Tags and Thin Film Transistors

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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 1000C, 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. Specifically, application with thin film transistors and with radio frequency identification tags are presented. Some of this work has been previously presented by the authors.

Author Keywords

Photonic curing; sintering; copper; printed electronics; displays; silicon; RFID; TFT

Objective and Background

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. The authors present a photonic curing process designed to heat only the target inks using pulsed light from flash lamps. The high intensity and short duration of the processing preferentially heats the inks while minimizing energy transfer to the substrate. 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 curing 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. Photonic curing technology shows promise for converting a-Si to micro-crystalline Si on low-temperature substrates, and for enabling new transistor structures. The combination of tools, materials, and processing methods has positive implications in applications such as displays.

Methods

Photonic curing was developed to resolve the fundamental thermal processing challenge common to printed electronics, namely processing high-temperature functional materials such as conductors, semiconductors, and dielectrics on low-cost flexible substrates such as polymers and paper. The photonic curing process uses pulsed broad-spectrum light from specially-designed flashlamps to thermally process almost any thin film. The thin film, printed on a low temperature substrate, is heated by a brief but very intense pulse of light from the flashlamps. If the pulse of light is short enough, the thin film can be heated to a temperature far beyond the normal maximum working temperature of the substrate without damaging the substrate. This technique, which was developed by NovaCentrix®, is embodied in their PulseForge® tools. Figure 1 below depicts a typical PulseForge tool, including the primary module components (left- right) of:

- Heat exchanger
- Power rack
- Lamp Assembly (top)
- Material conveyor (bottom)
- Control module with touch-screen interface.

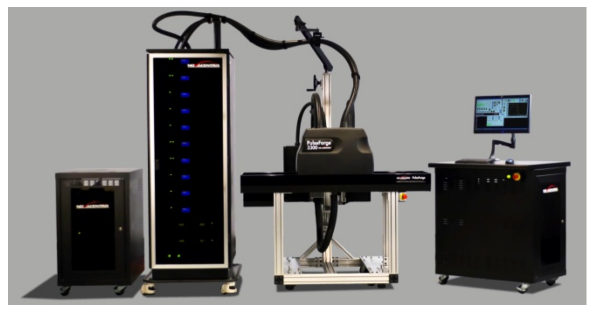

Figure 1. *PulseForge® 3300 photonic curing system*

Using the touch-screen interface, a tool user is able to control parameters such as:

- Pulse duration from 25 to 10,000 microseconds, in 1 microsecond intervals
- Number of pulses delivered
- Spacing between pulses
- Pulse intensity, with peak power delivered as high as 10 megawatts or greater
- Effective pulse shape
- Adjustment of peak wavelengths, from UV to near IR
- Numerous other parameters

The minimum effective curing area per pulse is 6 inches cross-web x 3 inches down-web in the standard configuration. Cross-web width can be configured larger in 3-inch increments. Down-web length options include 3 inches, 6 inches, and 12 inches. The tool is built with an encoder to automatically synchronize the pulses to a moving web and provide the user-configured pulse conditions on each area of the target material. The tool can be placed over a material conveyor for stand-alone operation, as shown in Figure 1, or mounted over a user-provided material handling system such as a roll-to-roll web handler.

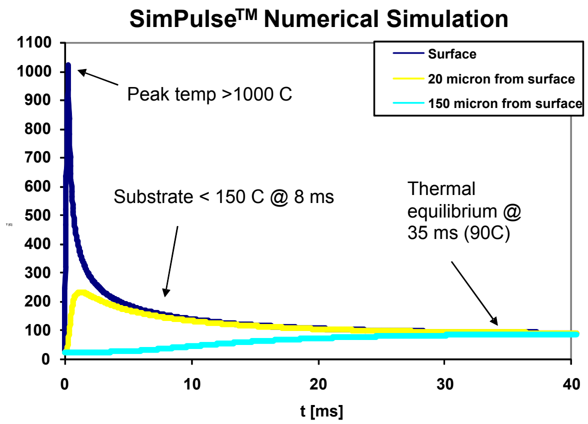

Figure 2. *Thermal simulation of the photonic curing process (300 microseconds, 1 J/cm^2) for a 1 micron thick silver film on 150 micron thick PET. Temperatures beyond 1000 °C can be achieved on PET without damage to the PET.*

Figure 2 illustrates the main thermal effect utilized by the process. A high power, short pulse of light is used to heat a thin film of material, such as printed silver or copper nanoparticles or flakes, to a high temperature for a brief amount of time. This can be done on a low-temperature substrate, such as polyethylene terephthalate (PET). Normally, PET has a maximum working temperature of 150 °C. In contrast, photonic curing can heat a thin film to temperatures beyond 1000 °C on the surface of a PET substrate without damaging it. This is due to the extremely rapid heating and subsequent cooling of the thin film. Temperatures can be achieved suitable for sintering many materials including silver and copper. The pulse of light is very rapid and short, and suitably configured by the operator such that the back side of the substrate is not heated appreciably during the pulse. After the pulse is over, the thermal mass of the substrate rapidly cools the film via conduction. The pulse is usually less than a millisecond in duration, and the time spent at elevated temperature is only a few milliseconds. Although the substrate at the interface with the thin film reaches a temperature far beyond its maximum working temperature, there is not enough time for its mechanical properties to be significantly changed. This effect is highly desirable as the thin film has now been processed at a temperature which would severely damage the substrate if processed with an ordinary oven. Photonic curing often allows the replacement of high-temperature substrates with lower-temperature (e.g. cheaper) alternatives.

Since most thermal processes are Arrhenius in nature, i.e., the curing rate is related to the exponential of the temperature, this short process can, in many cases, replace minutes of processing in a 150 °C oven. This further means that if the light is pulsed rapidly and synchronized to a moving web, it can replace a large festooning oven in a space of only a few feet. In addition to curing materials quickly, higher temperature materials such as semiconductors or ceramics that cannot ordinarily be cured on a low-temperature substrate can now be cured using this technology. Because typical processing times are about 1 millisecond, photonic curing systems can cure near-instantly, and are currently available for high-speed roll-to-roll processing. In addition to sintering, photonic curing is being used to dry films as well as anneal and modulate chemical reactions to make new types of materials.

Computational Model:

There was a need to model the thermal response of arbitrary user-defined material systems, so a proprietary numerical simulation tool (SimPulse™) was developed by NovaCentrix. The model allows the user to arbitrarily define a material system, composed of film layers using user-provided thicknesses and library or user-provided thermo-physical property values. The user interface for the simulation is similar to the user interface for the PulseForge photonic curing tools, and contains all of the internal settings of the PulseForge 3200/3300 platforms. SimPulse ships as a standard option with these systems. Figure 2 (above) depicts data generated from the model as described. 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 model dramatically reduces development time as over 10 discrete exposure conditions can be adjusted.

Applications and Results

Enabled Material- Copper Oxide Conductive Inks:

Copper has long been the desired material as a conductor for printed electronics. Currently, copper is over 100 times cheaper than silver yet has over 90% of silver's electrical conductivity. Still, silver remains the dominant conductor in printed electronics. The reason a precious metal is still used over copper is almost exclusively related to the oxidation behavior of copper. Since copper oxide does not appreciably conduct electricity, protection from oxidation is needed at all stages. Since the sintering stage is high in temperature, it is the most critical. If there is any oxygen present when attempting to sinter using traditional thermal processes, the particles will oxidize before they sinter.

Alternatively, instead of fighting the oxidation of copper, one can begin with pure copper oxide and formulate it with a high temperature reducing agent. The copper oxide particles are then converted to copper by modulating the redox reaction with the beam from the photonic curing tool.

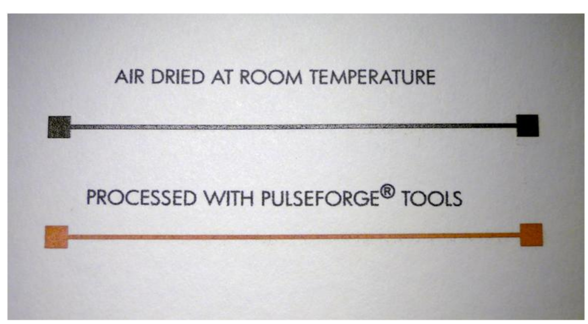

Figure 3: *Image of screen-printed copper oxide reduction ink before and after conversion to copper in open air on Paper. Note the pronounced color change after processing.*

Figure 3 shows a screen print version of a copper oxide reduction ink (Metalon® ICI-021) on ordinary paper before and after processing with a photonic curing tool (PulseForge® 3200). The sheet resistance before curing is of order 1 GΩ/sq, and after curing the sheet resistance is approximately 60 mΩ/sq. That is, photonic curing increases the conductivity by approximately 8 orders of magnitude in about 1 millisecond. As expected, the trace turns from the black color of copper oxide to the familiar shiny hue of pure copper. Since, the reduction relies upon a transient effect; the inks cannot be cured in an ordinary oven. They are available commercially from NovaCentrix.

Photonic Curing for RFID Antenna:

The authors used the ICI-021 screen ink to produce the RFID antenna shown in Figure 4 below, on 110lb paper as the substrate.

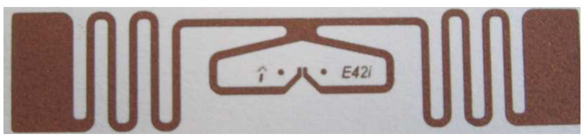

***Figure 4.** Screen-printed RFID antenna on paper after conversion to copper.*

The tag is an Impinj® E42i and is produced under license. The tag has a printed area of 422 mm^2. The ink was deposited with a 165 mesh screen with emulsion thickness of 0.6 thousandths of an inch. The measured dried ink thickness was approximately 10 microns. With these dimensions, and with a volume ink price of $75/kg, the ink cost per tag is determined to be approximately $0.003.

This tag was completed by a customer with the addition of a Monza 4 tag applied via anisotropic conductive adhesive Delo AC 268. Read-ranges were as high as 5.5 meters (See Figure 5 below), which compares favorably to the read-ranges of 7 meters achieved in the same testing using traditional aluminum-etch tags. There is much optimization to do at every step of the process, but these results are encouraging and, to our customers, merit moving forward with specific development efforts.

Applications for Displays:

The use of photonic curing to thermally process thin films in display applications offers several benefits. One major benefit is that one can now focus on the thermal processing requirements of the thin film, unconstrained by the thermal limitations of the substrate. Another benefit is speed of thermal processing. Using photonic curing, temperatures beyond 1000 °C can be achieved in silicon film on glass or plastic, with the substrate base remaining relatively near room temperature. Even traditionally rapid processing still requires seconds to heat the materials, with the resulting thermal equilibrium between the target film and the substrate being undesirable for use in many flexible applications. A third benefit is that the time-temperature profile in a thin film stack be micro-engineered by tuning the energy delivery on a sub-millisecond time scale to achieve an optimized condition for both the thin film and the substrate on which it adheres. This would be especially true for advanced displays fabricated on low cost plastic substrates. These benefits taken together offer the display industry the opportunity to improve performance, rapidly manufacture and lower the cost of future displays. Some example materials that may be of use in current or future displays that have been processed with photonic curing in our labs include silver, copper, silicon, organo-silanes, and a variety of other materials on plastic substrates.

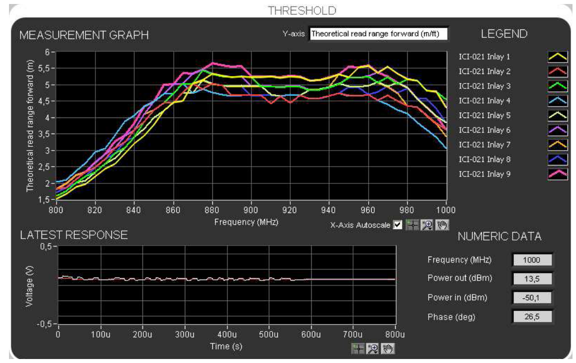

***Figure 5:** Screen shot of the performance measurement oif processed ICI ink show all antennae at the same level on read range*

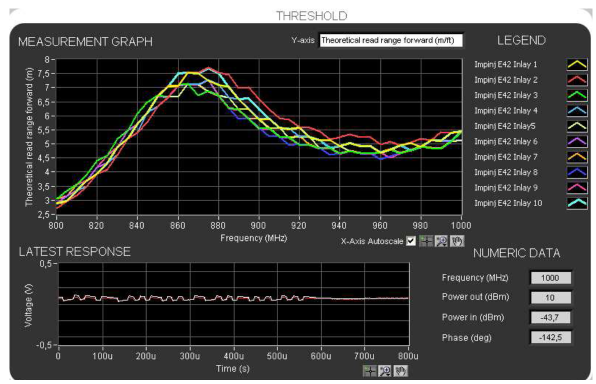

***Figure 6:** Screen shot of the performance measurement of aluminum etched inlays*

Photonic Curing for Annealing Si:

A thin 200nm film of amorphous silicon (a-Si)was vacuum deposited onto a 500 microns thick borosilica (BS) glass wafer by e-beam (EB) thermal evaporation. Annealing experiments with a PulseForge 3300 showed that the a-Si film can be converted from a-Si to a microcrystalline form of silicon (ux-Si) only when a threshold total pulse dose (data withheld) is achieved.

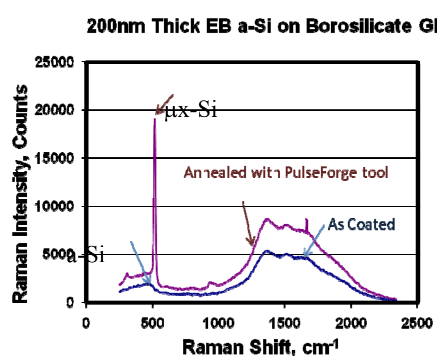

***Figure 7.** Raman results comparing a-Si deposition before and after suitable photonic curing, with resulting microcrystal structure.*

Transverse Thermal Processing: Photonic curing is also being used to develop novel TFT structures enabled by the creation of controlled strong thermal gradients in the target materials and substrates. By applying materials which are more or less absorbing of the PulseForge energy and which have the appropriate thermal properties of the target and adjacent materials, it is possible to use lateral, or transverse, thermal heating to selectively process materials to achieve a change in material properties.

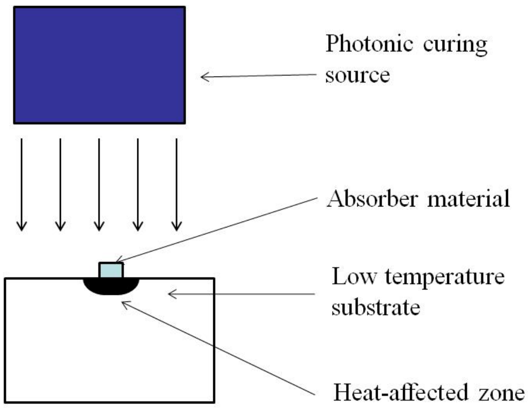

Figure 8. *Simple depiction of creation of heat-affected zone adjacent to absorbing material, created by conduction of thermal energy from the absorbing material.*

By utilizing the lateral heat spreading effect, a small region between two photonic-energy-absorbing materials for example can be thermally processed. The resulting laterally-conducted thermal energy can be used for very selective annealing or doping.

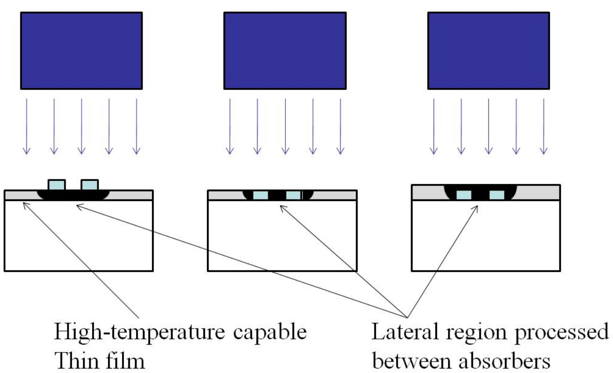

Figure 9. *Extension of Figure 8, depicting possible arrangements of absorber materials with the addition of a high-temperature-capable layer.*

This concept is called transverse thermal processing (TTP) and is currently an area of significant internal development using the photonic curing tools. Using TTP the authors have successfully created functional TFT's. This work will be presented in a dedicated paper soon.

Discussion

Photonic curing is seen to have a myriad of implications. Materials design and engineering is impacted, as exemplified with the copper oxide reduction inks. Materials in turn affect applications such as RFID. The processing technique is also seen to have implications on component design, such as TFT's. It is rare that a well-developed new processing method becomes available with such wide-ranging impact. The displays application sector is certainly one of the areas which may be greatly influenced by photonic curing, with significant application opportunities in flexible and/or organic display application development efforts. Along with these technology implications come opportunities for creating new intellectual property, and ultimately new economic value and advantage in the market. Timing is critical though, and fast-movers are often rewarded with early key patent filings and first-to-market advantages.

Related Work

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