Developments in Printed Electronics

Processing - Photonic Curing
Materials - Copper Oxide Reduction Inks
Simulation - Numerical Thermal Processing

Stan Farnsworth VP Marketing Oct 2011

NovaCentrix® in the Supply Chain

Printed Electronics Manufacturing

Tool Integrators

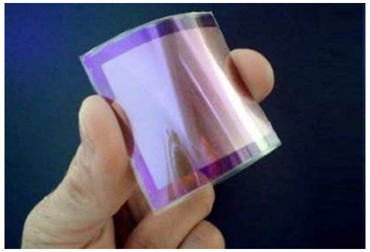
Raw Materials	Mfg Materials	Material Handlers	Printers	Dryers	Curing Tools	Device/ Application
Ink components; Raw substrates	Inks; Substrates	Roll-to-roll; Conveyors	Inkjet; Screen; Aerosol; Flexo; Gravure;	Ovens; Air knives; New Tech	Ovens; UV Lamps; Lasers; Pulsed Thermal Processing; New Tech	Solar; RFID; Batteries; Transistors; Displays; Packaging; Smart cards

Industry product types

	Nanoparticles	Metalon® inks Novele™ substrates	PulseForge® tools SimPulse™ thermal simulator
Commercial Product Release	1999	2006 (inks) 2009 (substrate)	2007 (tools) 2010 (simulation)

Printed Electronics

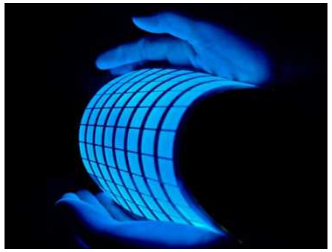
The Next Generation of Energy and Function



Solar cell

Battery

RFID tag



OLED lighting

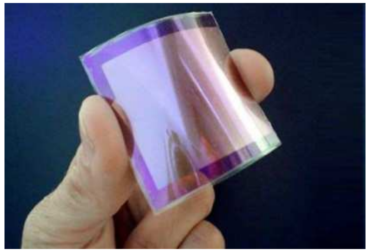
>$50B Projected component value in 2020 across printed electronics*.

> 2500 Number of organizations involved in developing new applications*

* IDTechEx (www.idtechex.com)

Printed Electronics

Advanced Functionality



Solar cell

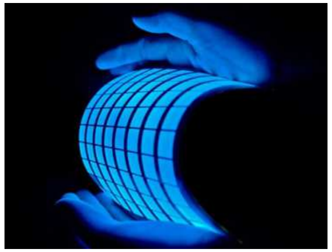
NanoSolar

Battery

Solicore, Inc.

RFID tag

PolyIC



OLED lighting

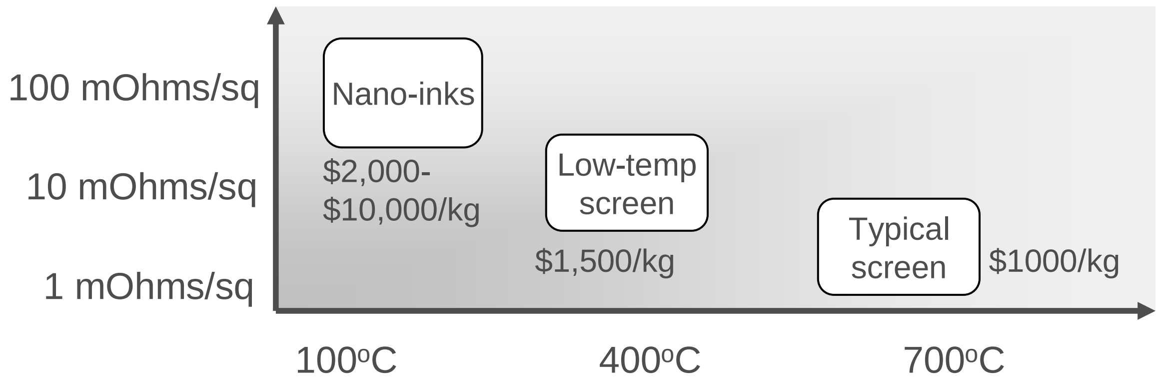
GE

By the m^2:

Clemson's Sonoco Institute

Temperature, Performance, and Price

Achieving high performance from printed materials requires post-processing at elevated temperatures.



Plastic and paper substrates can't accommodate those temperatures and maintain low cost.

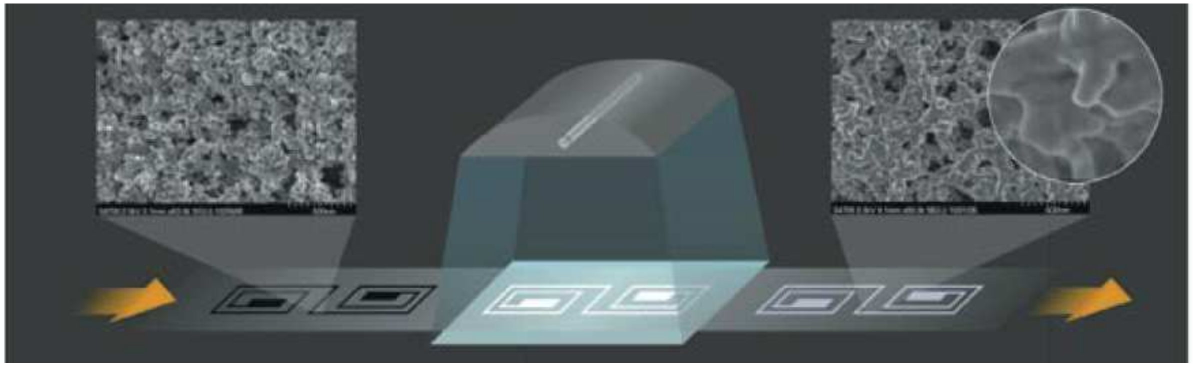
Substrate	Temp	Cost
PET	150°C	$0.10/ft^2
Polyimide	375°C	$1-$20/ft^2

PulseForge® Tools

Designed and built specifically to solve the thermal problem.

The tools use intense pulsed light to heat functional inks and thin films without damaging fragile temperature-sensitive substrates like plastic films and paper.

- Designed for development and production use.
- Developed in cooperation with Oak Ridge National Laboratory.
- **Patented Process: USPTO Patent # 7,820,097.**



Materials processing

Drying

Sintering

Annealing

Reacting

PulseForge®: Simple Beginnings

PulseForge®: Simple Beginnings

Inspired by camera flash which has properties of:

- High power : 2 kW/cm^2
- Low energy: 1 J/cm^2
- Suitable for certain types of nanoparticle processing on low temperature substrates

But camera flash needs improvement for use in printed electronics

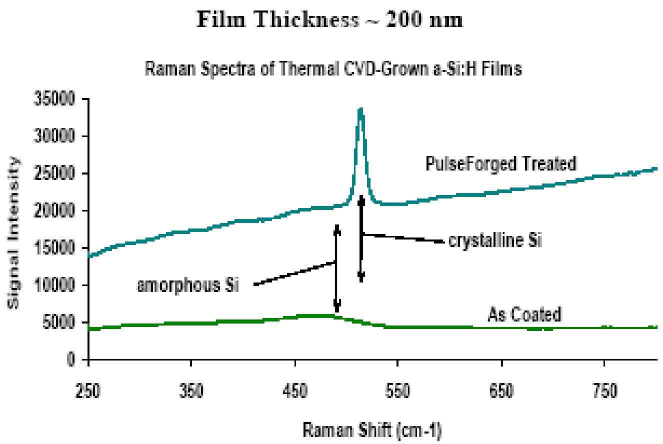
- Poor controllability
- Limited power and energy
- Erratic output
- Not well suited for use in roll-to-roll production

The need was to create a tool based on these principles that could be used for industrial-scale processing as well as for lab-scale development.

PulseForge® Toolset

PulseForge® Tools: Commercial Implementation

PulseForge 3300

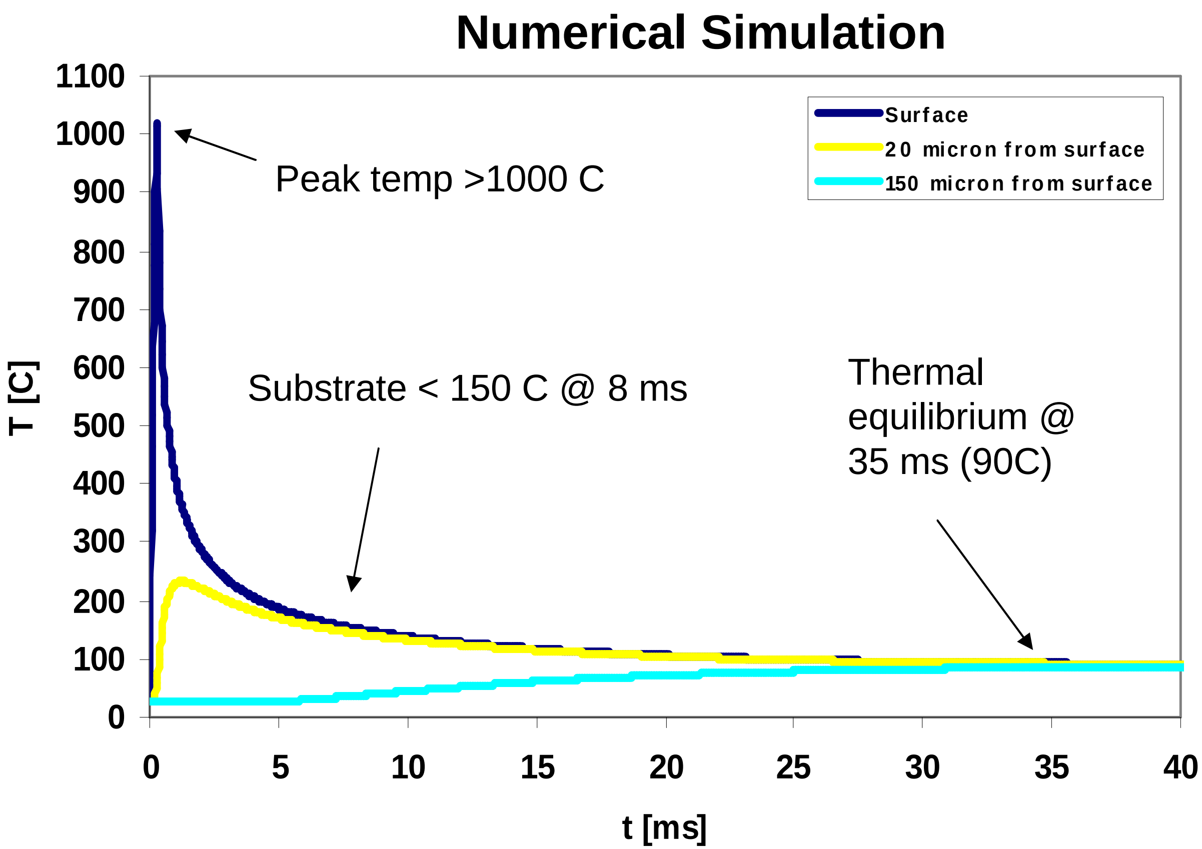


Use
- Development and Manufacturing

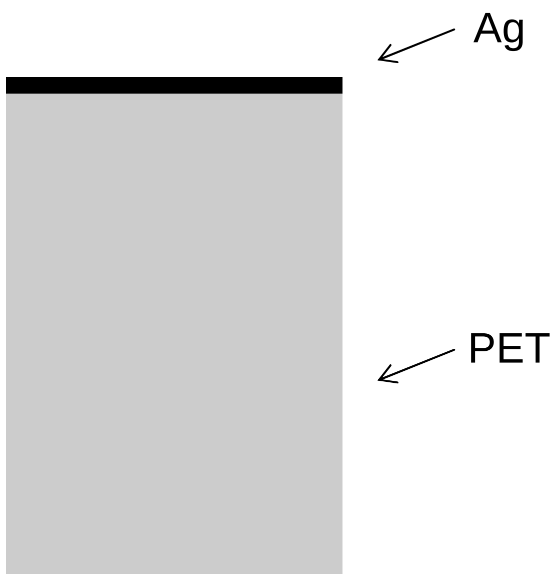
Sample Tool Performance
- Peak Delivered power: 14 Megawatts/pulse
- Minimum Pulse: 25 micro seconds
- Pulse Frequency: kHz
- Cooling: Water-cooled
- Lamps: No tools required
- Pulse Settings: Touch-screen
- Line Speeds: >100 Meters/min

Target Applications
- Energy: PV, batteries, capacitors
- Communications: displays, sensors
- Lighting, flexible circuits
- Broadly applicable to organics, metals, and semiconductors
- Process speeds over 100 meters/min
- Drop-in with existing material handling systems

Typical Single-Pulse Thermal Profile



Conditions:
1 µm Ag on 150 µm(6 mil) PET
Radiant exposure: 1 J/cm^2
Pulse length: 300 µs



- High temperature processing removes excess solvent and enhances sintering.
- Substrate is undamaged.

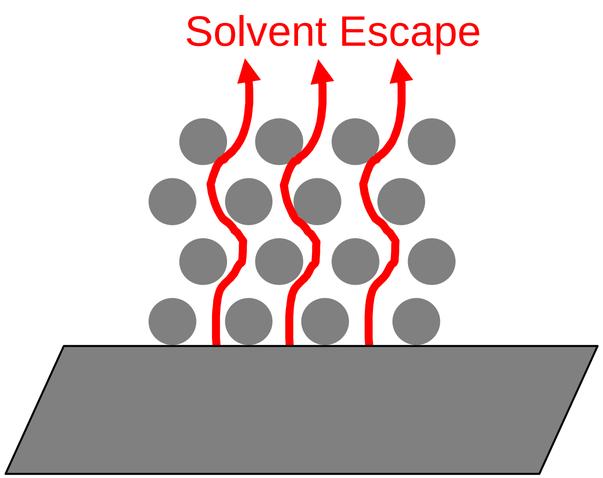
Key Processing Parameters

Material Characteristics

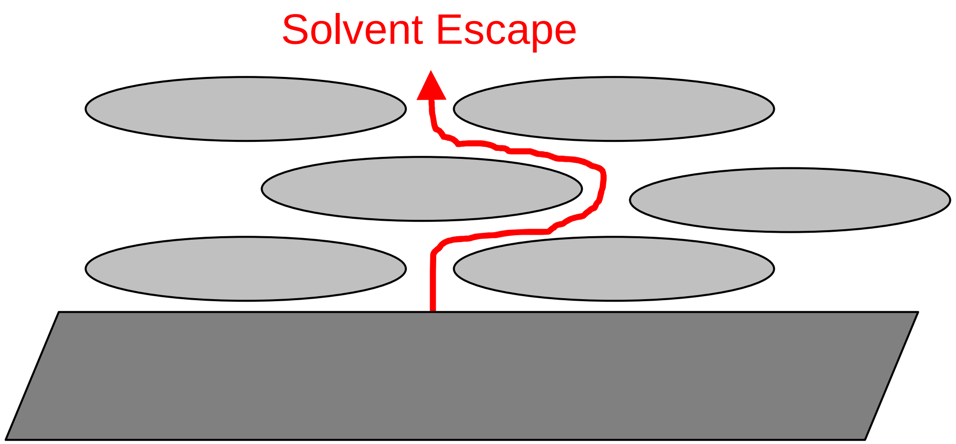
- Thermal / physical properties of ink and substrate
- Film/ ink thickness
- Particle morphology
- Substrate composition and thickness
- Barrier or intermediate layers

Tool Adjustability Requirements

- Pulse energy/ amplitude
- Pulse duration
- Impinging wavelengths
- Number of pulses
- Speed of pulses
- Other parameters



Nanoparticle inkjet
- ~500 nm thick



Micron flake screen print
- ~5-30 microns thick

Metalon® Inks: Low Cost and Available

- Water-based, low VOC, with nanoparticle and flake materials
- Priced as low as 1/20 vs. competing inks
- Next-day delivery in most cases
- Can be used with low-cost consumer printers
- Options for any print method
  - Inkjet, screen, flexo, gravure
- Silver and copper are standard, can be customized

Case Study: Screen Ag on PET

Material System

Ink material:	Metalon® HPS-021 Ag screen print
Substrate:	PET w/ 150 ºC max working temp
Print method:	Drawdown, #10 bar
Coating weight:	~0.003 g Ag/cm^2 (~ 3 micron thick assuming 100% dense)

Cure Condition	Oven	PulseForge
Temperature	150 C	NA
Time	30 minutes	4 millisec
Resulting sheet resistance	18 mΩ/sq	18 mΩ/sq
Comments:	• Much faster curing with PulseForge tools • Cure speed 30 fpm	

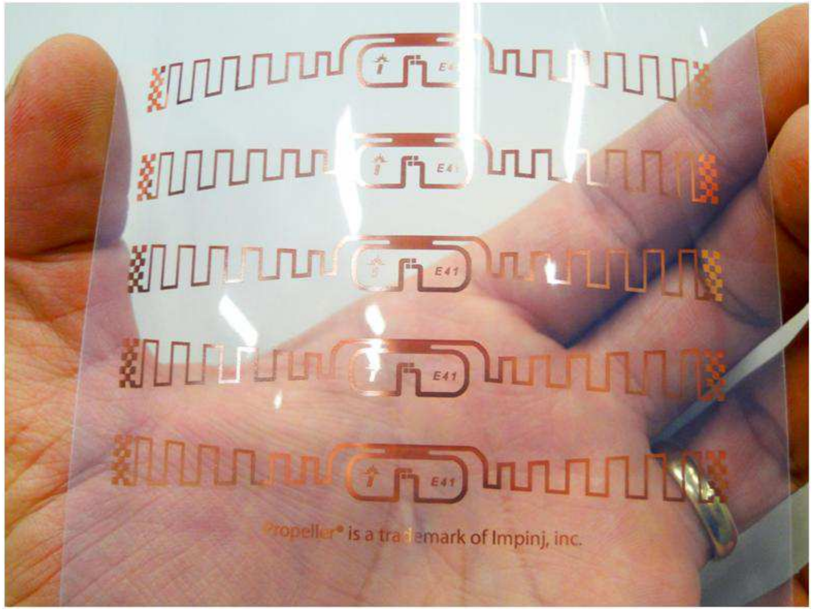
Qualitative Tool Exposure Assessment: Screen Ink Processing

Material Set-up

- Ink: Dupont 5025
- Substrates
  - Melinex 329 (white)
  - STS 505 PET (clear with black background for contrast)
- Ink thickness when properly cured: ~10 microns
- Ink conductivity when properly cured: <10milliOhms/sq
- Cure Conditions:
  - Conventional: ~140C, 10-30 minutes
  - PulseForge tool process: ~500C, ~1 millisecond

Cost Reduction Using Copper Inks

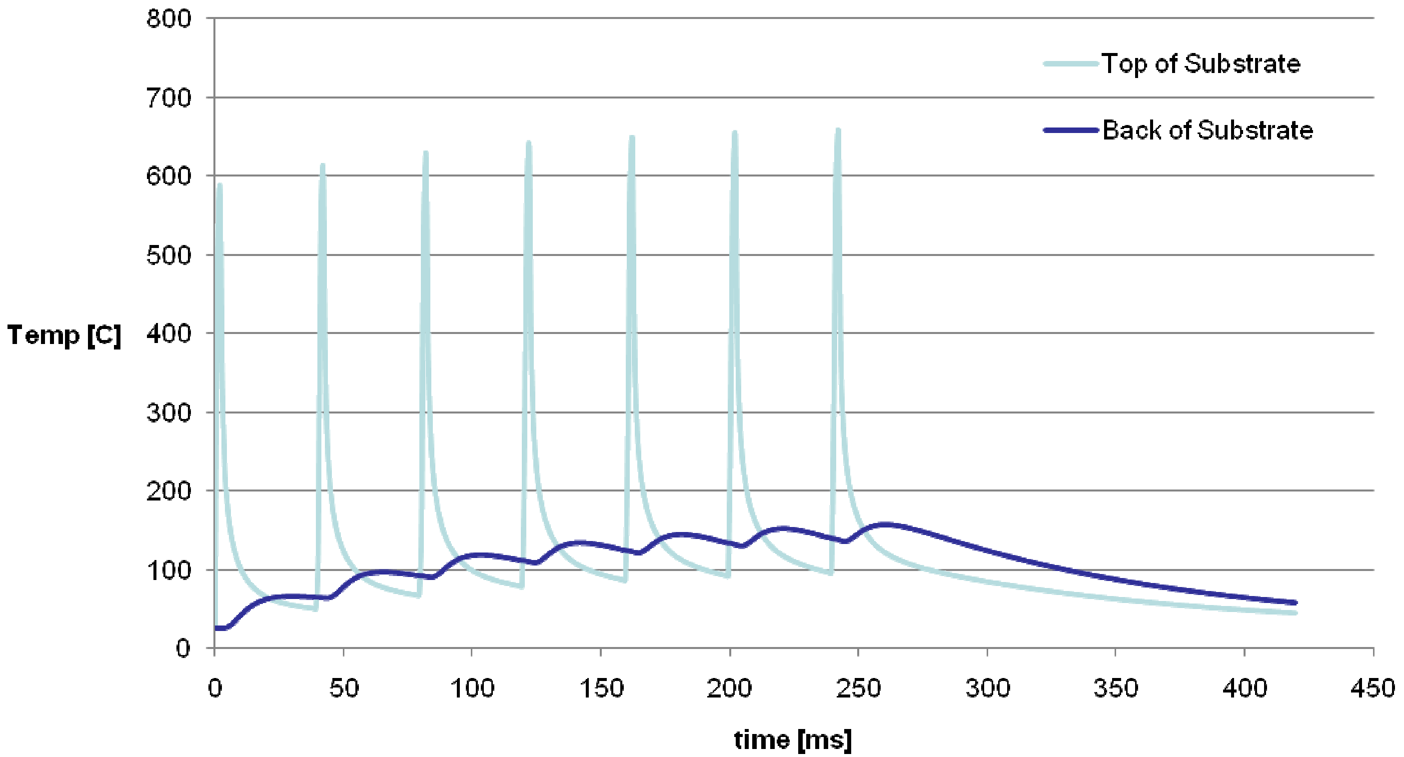
- Good
  - Cu costs 60X less than Ag
  - Cu has 90% of the conductivity of Ag
- Bad
  - True Cu inks want to oxidize, especially nanoparticle inks
  - Stable Cu inks are expensive, outweighing cost benefits



Metalon ICI ink processed on PET with PulseForge tools

- New Approach
  - Instead of fighting oxidation, begin with particles in their terminal state: fully oxidized.
  - CuO ink formulation:
    - Nano CuO
    - Reduction agent
    - Water and ethylene glycol
  - No conductivity when printed
  - Converts to Cu during PulseForge processing.

PulseForge Processing of CuO on PET
(Simulation)



- Peak temperature is high enough to rapidly reduce CuO while reducers are in the gaseous phase.
- The short time scale of processing combined with solvent and reducer evaporation prevent substrate from getting too hot.

Converting the CuO into Cu

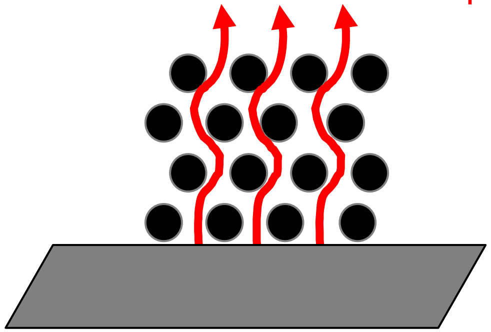
- The reducers in the copper oxide ink don’t work at temperatures below the decomposition temperature of PET (150 C).

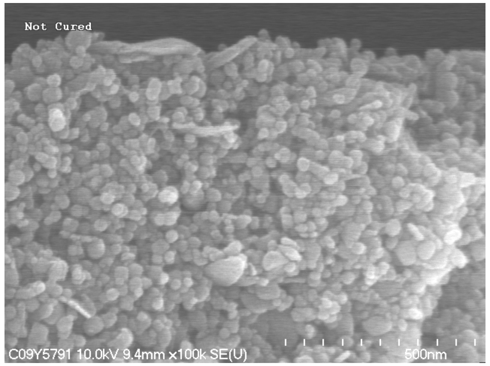
  → An oven doesn’t work.

- An intense pulse from a PulseForge tool is able to heat the printed trace to a high enough temperature to gasify the reducers making them much more active and thereby modulating the redox reaction.

- High temperature reduction is both transient and adiabatic, so Cu films can be formed on low temperature substrates at roll to roll processing speeds.

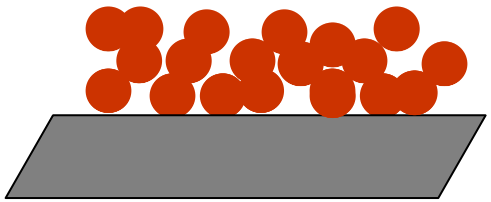
Solvent and reducers escape

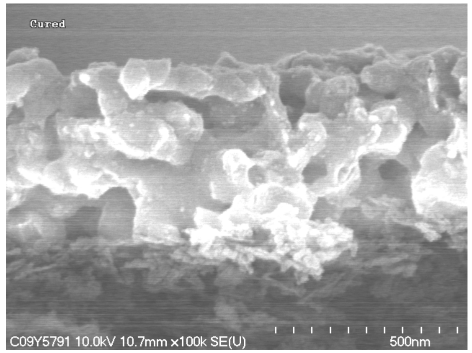




CuO and reducer - ~500 nm thick

Densification and reduction



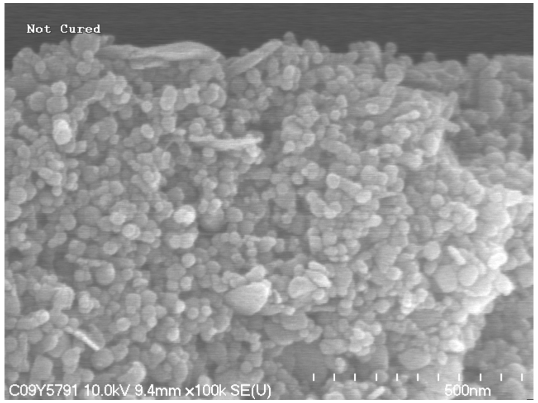
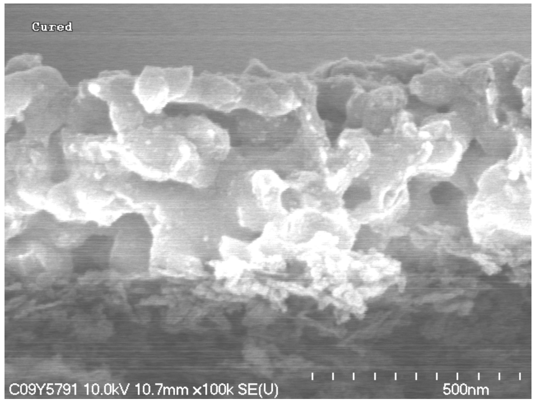


Final trace is highly conductive copper

Case Study: Inkjet CuO on PET

Material System

Ink material:	Metalon ICI-003 CuO inkjet
Substrate:	Coated PET w/ 150 ºC max working temp
Print method:	Epson C88+ Photo Stylus
Print passes:	1 @~0.5 micron total thickness

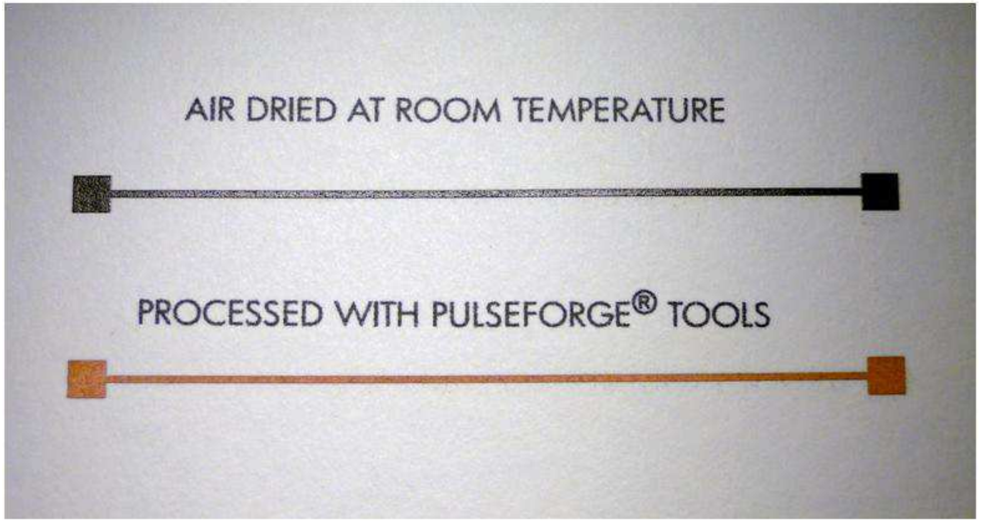
Cure Condition	PulseForge	SEM - Uncured	SEM - Cured
Temperature	NA		
Time	7 millisec		
Resulting sheet resistance	110 mΩ/sq		
Comments:	• Copper inkjet! • 4x bulk Cu resistivity • Processed Cu ink in ambient air conditions		

Case Study: Screen CuO on Paper

Material System

Ink material:	Metalon ICI-021 CuO screen print
Substrate:	Standard 110 lb. cardstock
Print method:	165 mesh screen

Cure Condition	PulseForge
Temperature	NA
Time	5.5 millisec
Resulting sheet resistance	20 mΩ/sq
Comments:	• Cure speed 30 fpm in ambient air conditions • Cannot be cured in ordinary oven



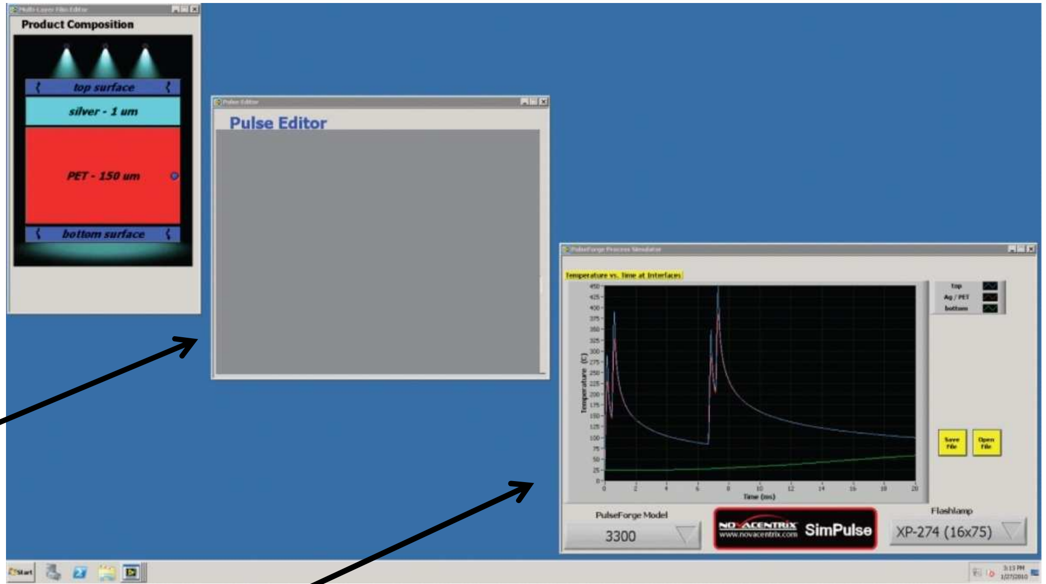
PulseForge® Simulation: SimPulse™

- SimPulse was developed to simulate and predict the results of PulseForge tool processing.
  - It acts as a quantitative visualization tool
  - Accelerates process development
- Inputs:
  - The interface is nearly identical to an actual PulseForge tool
  - Graphically build a thin film stack of any number of layers and materials
  - Enter the desired PulseForge conditions
  - Then hit “Simulate” for near-instant results
- Output:
  - Graphical display of the stack Temperature versus Time
  - Can provide temperature at any location in the stack, at any time during or after the exposure
- Availability
  - Ships installed on standard-configuration PulseForge tools
  - Will soon be available through a portal on our website.

SimPulse™ User Interface

The SimPulse User Interface has 3 panels:

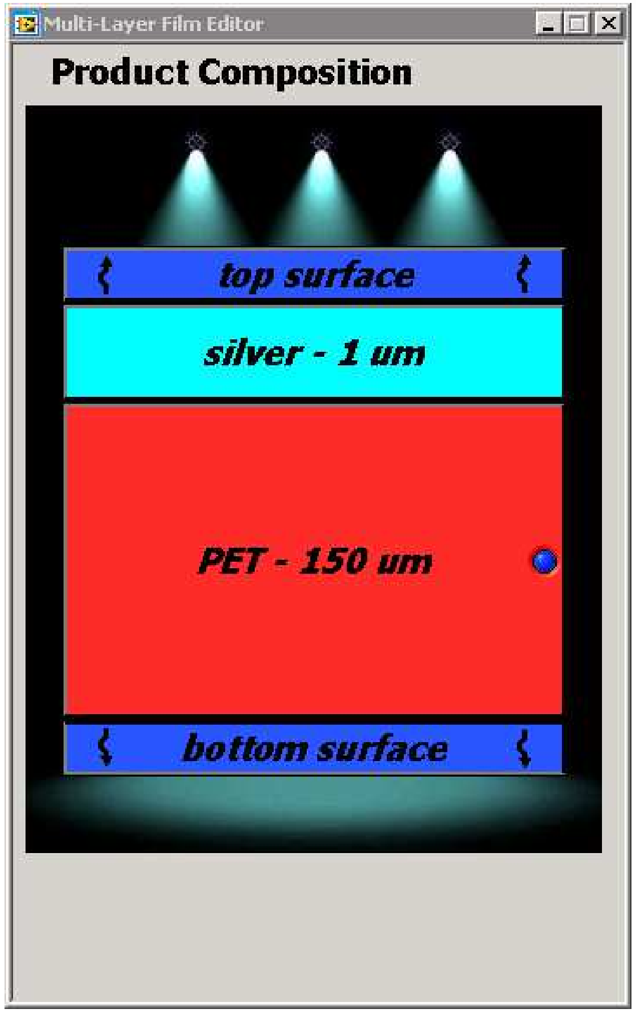
- The Film Editor
- The Pulse Editor
- The Process Simulator



SimPulse™ Film Editor

The SimPulse Film Editor allows a user to graphically build a thin film stack of materials

- Any number of layers may be specified.
- Any number of materials may be specified.
  - Standard materials
  - From other databases
  - User defined
- Cooling at the top and bottom surfaces is specified.
  - Natural convection
  - Forced convection
  - Liquid



SimPulse™ Pulse Editor

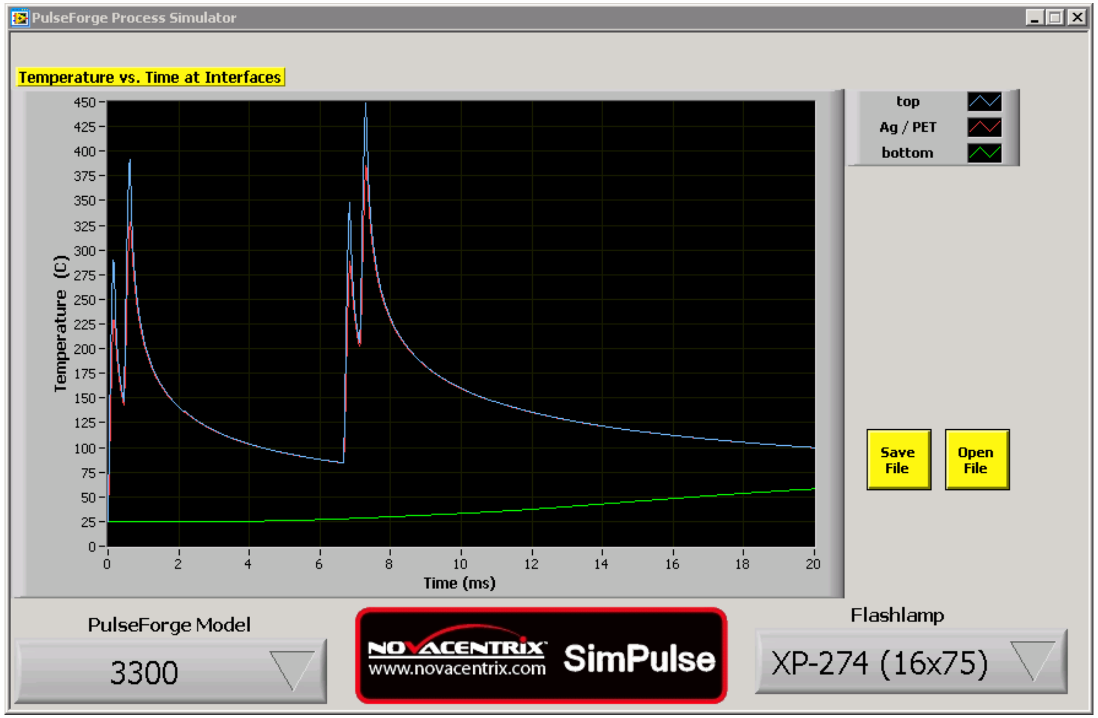
The SimPulse Pulse Editor allows a user to customize the input power delivery to the stack on a microsecond timescale including:

- Radiant power
- Pulse duration
- Advanced multipulse and ramp heating profiles
- Allows user to control the temperature in each portion of the thin film stack.

SimPulse™ Process Simulator

The SimPulse Process Simulator displays the temperature at each layer interface versus time both during and after heating.

- Predicts the actual PulseForge performance system under the conditions provided by the Film and Pulse Editors.



Summary

- Photonic curing is the high-temperature thermal processing of a thin film using pulsed light from a flashlamp.
- We have established three transient curing conditions for optimal high-temperature processing of a thin film on a low-temperature substrate using this process.
- A high speed commercial photonic curing system, called PulseForge, has been developed with 10 process variables to exploit this effect.
- The basis of PulseForge tools is the use of intense pulsed light to briefly heat the film without affecting the substrate.
  - Reduces or even eliminates the need for an oven to cure many materials
  - The process is able to cure materials that cannot ordinarily be thermally processed in air such as sintering a copper particle film
  - The process is broadcast by nature and maskless, with no need for registration
- The system contains an integrated thin film stack thermal simulator with predictive capability.
- PulseForge tools often outperform ovens and are much more scalable than laser processing. Low temperature materials such as PET and paper are now feasible substrates for high-performance printed electronics applications.
- The transient nature of the process allows for the high temperature modulation of chemical reactions on low temperature substrates. An example of this is the formation of very low cost copper film using CuO and reducers in the ink.

Special thanks to Showa Denko K.K. for cooperation

Shoko Co., LTD is official PulseForge tool representative

Contact our partners or us directly with questions
or for samples processing

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