Photonic Curing for Printed Electronics

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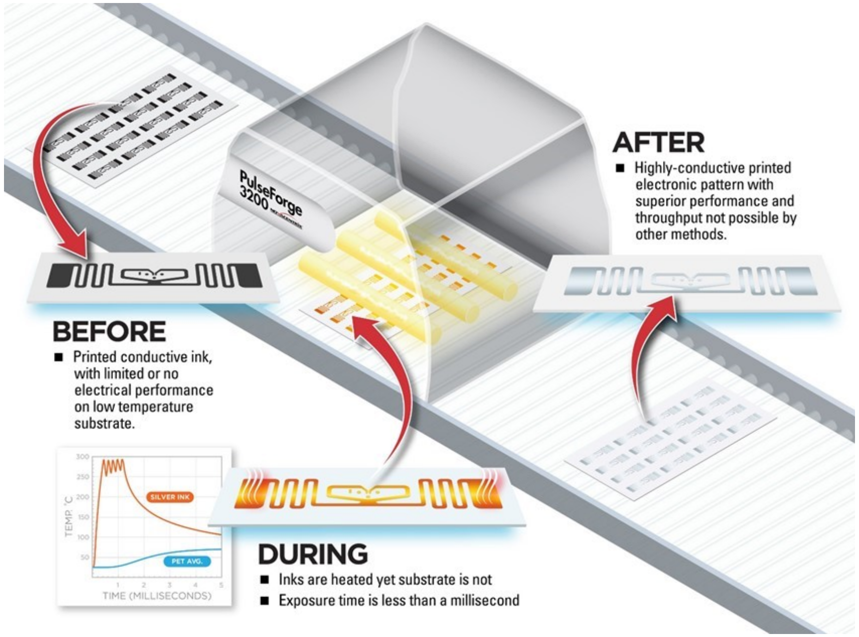
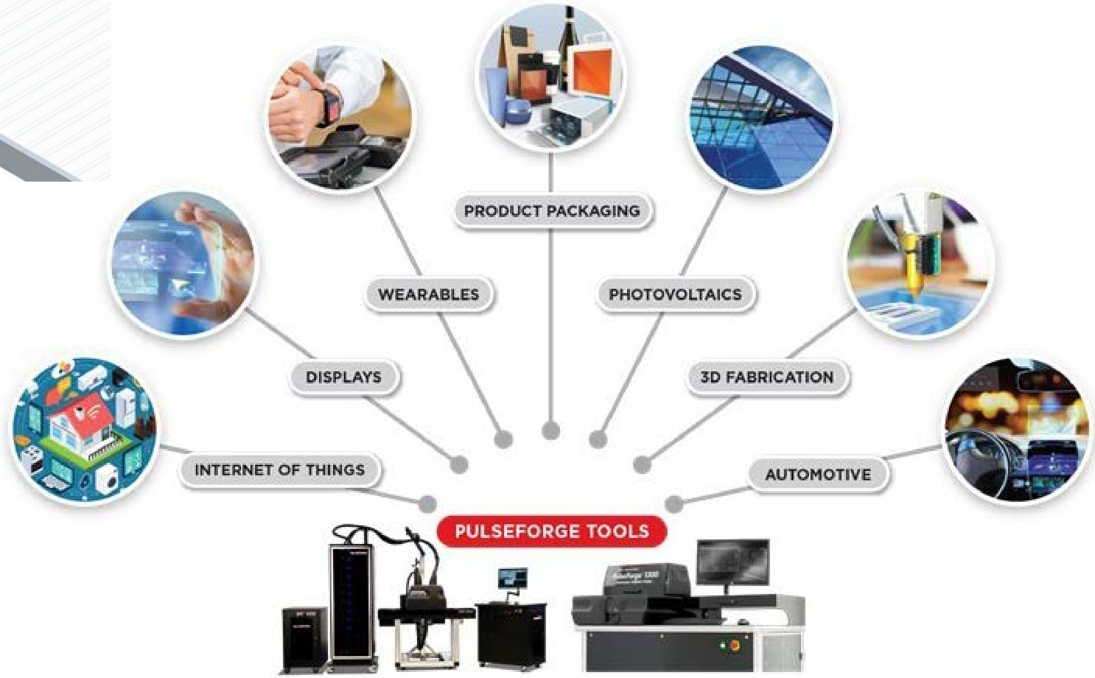
Photonic Curing



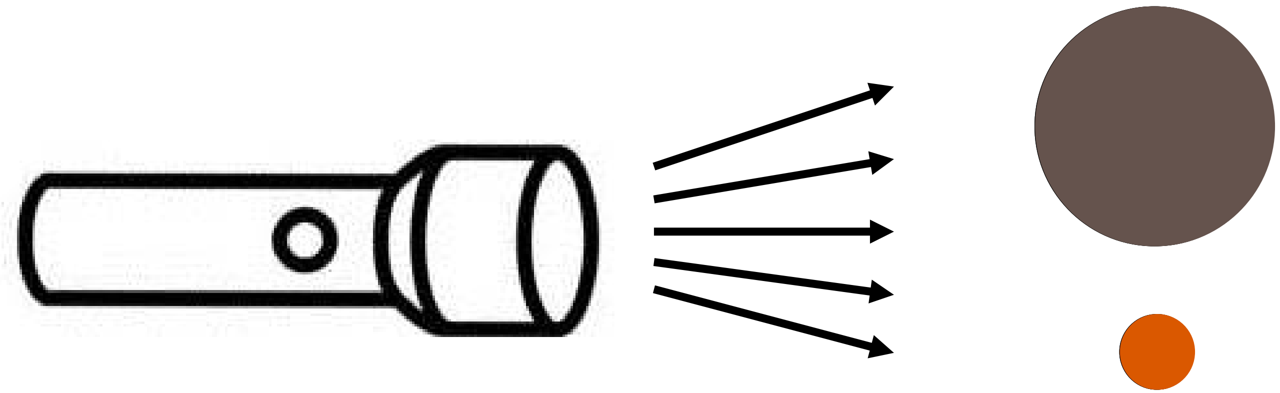


What is Photonic Curing?

- The high temperature processing of a thin film on a low temperature substrate using pulsed light from a flashlamp.
- A family of thermally driven processes including sintering, drying, initiating and modulating chemical reactions, annealing, and others.
- “High temperature processing on low temperature materials”

- The marriage of four separate effects:
  1. Surface area/mass ratio
  2. Heat accumulation
  3. Arrhenius relation
  4. Thermal damage phase lag

1. Surface Area/Mass Ratio: Small Objects are Heated Faster by Radiation



- The smaller sphere is heated more rapidly by the light.
  - → Because it is heated through the surface, and it has more surface area per amount of mass than the larger sphere.

2. Heat Accumulation

- If you wait long enough, shining a flashlight on a two similar balls of differing diameters, such as a golf ball and a baseball should result in different temperatures for each ball.
  - → But it doesn’t
  - → Why?
  - → The energy leaks off due to natural convection and conduction to the surroundings.
- Need high power: the rate that the target gets heated by the light needs to be greater than the bleed off rate or no difference will be observed.
- High power generally insures that we don’t need to expose the target for very long.
  - → Hence a pulse!
  - → Uses very little energy!

Photonic Initiation: 1+2

3. Arrhenius Relation for Thermal Curing

- In 1899 Swedish physicist Svante Arrhenius in 1899 realized that the progression of a thermal process increased exponentially with the temperature at which it was held.
- This means that even a small increase in processing temperature greatly reduces the processing time.
- So in order to maximize throughput, one should run an industrial thermal process at the highest temperature possible.
  - → There are limitations, however …
- For thin film processing, this temperature is usually limited by one of the layers in the stack.
  - → It is usually the substrate.
- Unfortunately, inexpensive substrates are generally thermally fragile.

4. Thermal Damage Phase Lag

- It takes time to cause thermal damage to many materials –especially polymers!
- If we can heat up a thin film on a thermally fragile substrate really quickly and cool it down really quickly, then we can reach a temperature MUCH higher than what is generally accepted as common knowledge – without damaging the substrate!!!
- We can heat the film up very quickly by exposing it to an intense pulse of light.
  - →But how do you cool it down quickly?

THERMAL CONDUCTION

Photonic Curing: 1+2+3+4

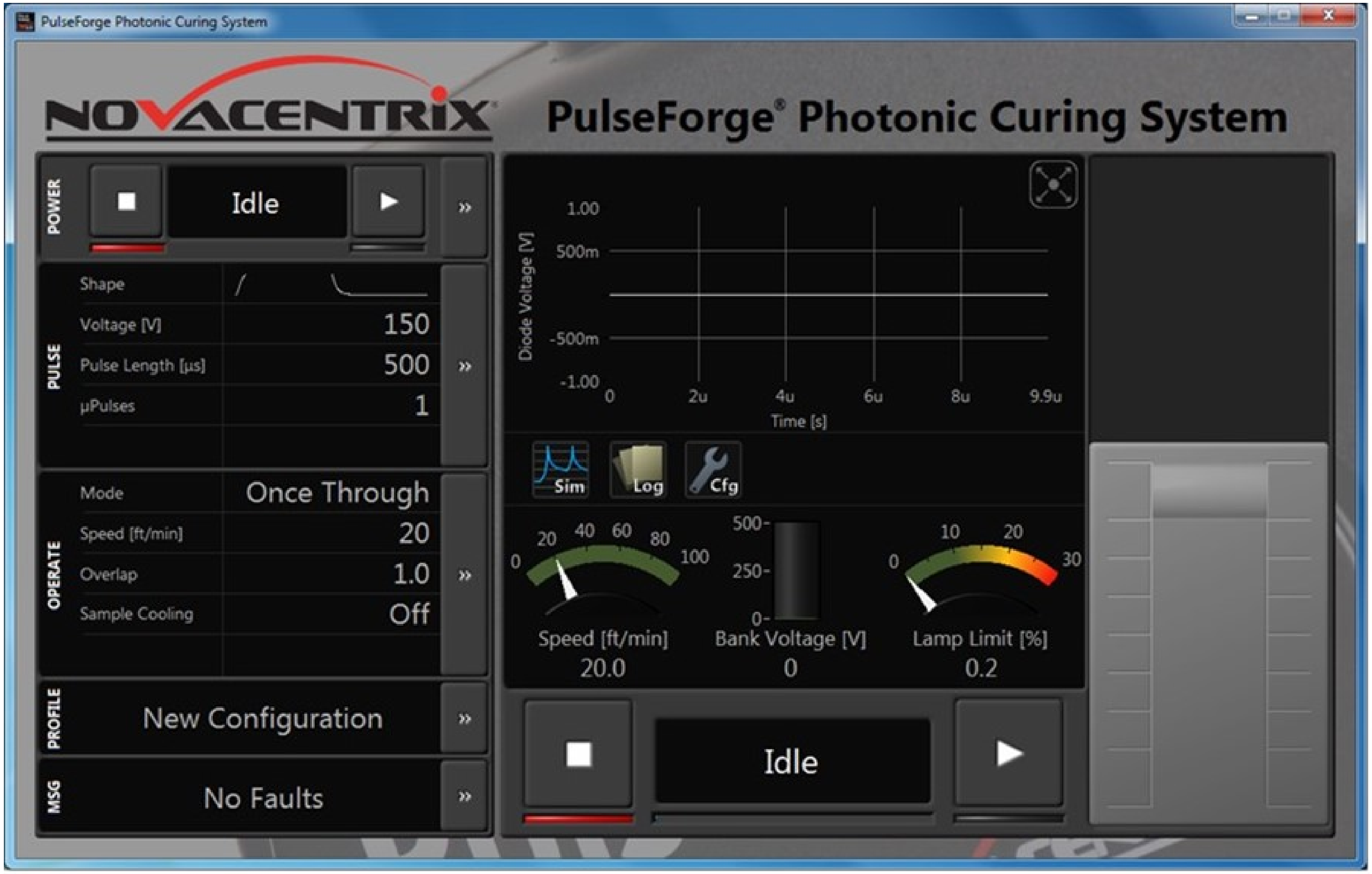
Advantages of Photonic Curing

- Much smaller footprint compared to conventional thermal processing equipment, e.g. an oven!
  - →Important when space is at a premium, such as in clean rooms.
- It's faster!
  - → Contributes to reducing the overall time to make a product.
- Less energy needed!
  - → We only heat the film versus conventional thermal processing which heats the film, the substrate, the air around it, the oven, and the building!
- Higher performance!
  - → Since we can reach a higher temperature, we can often out perform thermal processing. This is more pronounced when the film is thin and the substrate is thermally fragile.
- Other effects
  - → We can often achieve effects that are not possible with conventional thermal processing such as high-temperature chemical reaction modulation on a low temperature substrate.

Curing System: Parameter Processing Control

Graphical User Interface

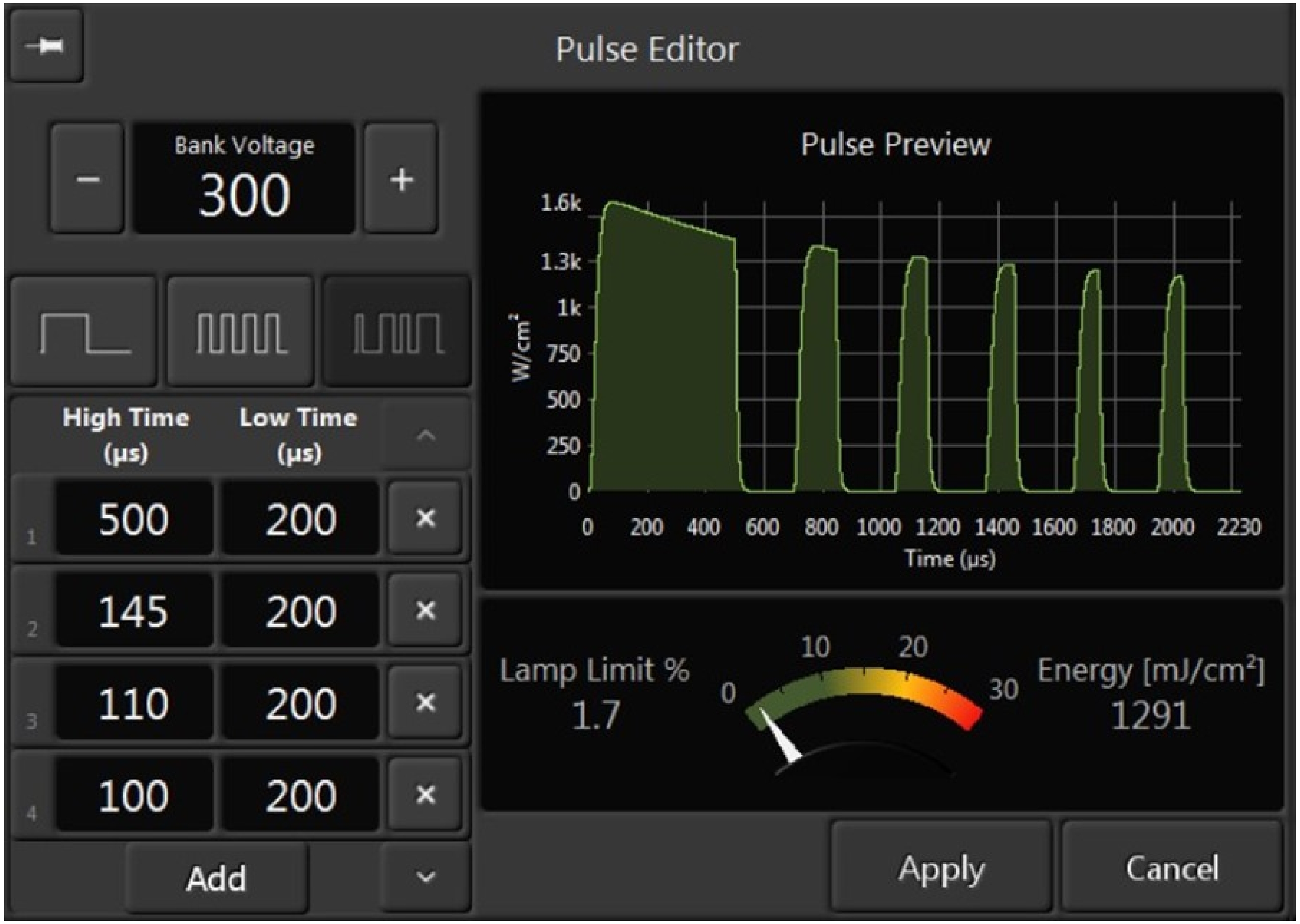
- Full system control: pulse modulation, sample cooling, web speed etc.



Curing System: Pulse Modulation

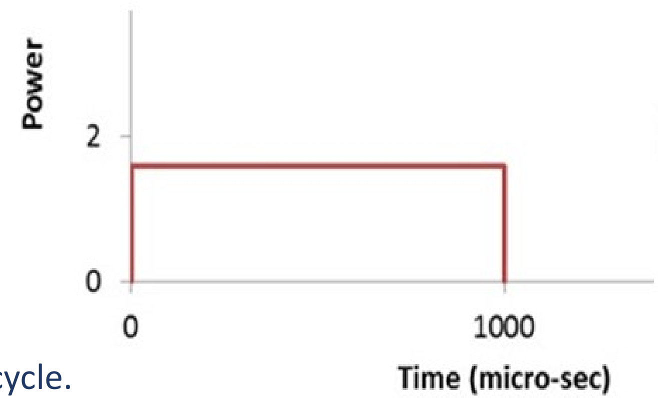
Pulse modulation

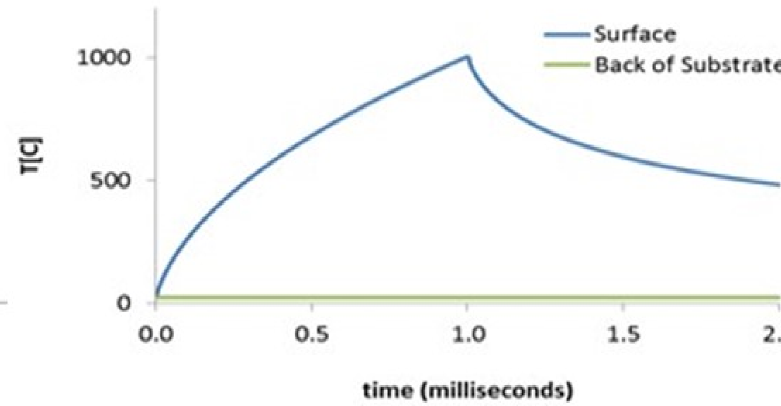
- The flash lamp can be switched on and off at a microsecond resolution

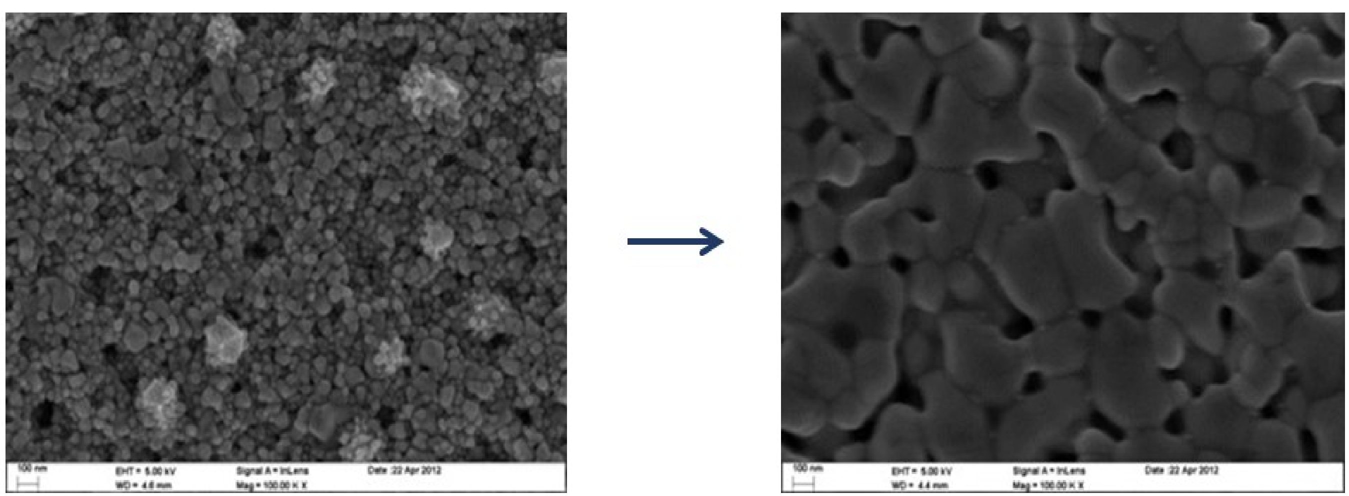


Curing System: Basic Pulse

- Basic pulse shape:
  - Simple ON-OFF cycle.
  - Can be repeated
- Basic pulse suitable for depositions <10 um:

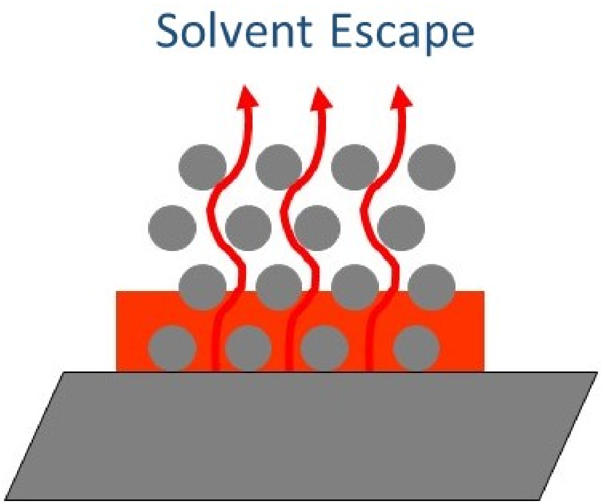






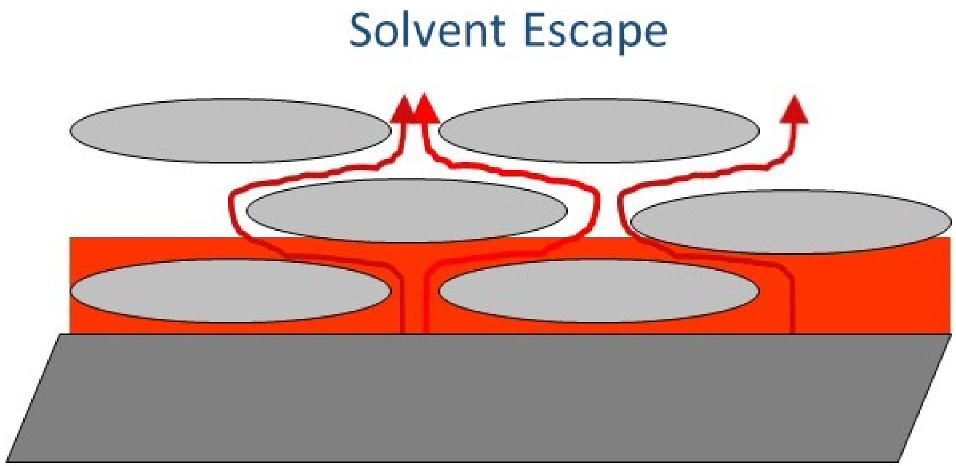
Curing System: Basic Pulse vs. Thick film

Sample Inkjet Deposition



Nanoparticle inkjet
- ~500 nm thick

Sample Screen-print Deposition

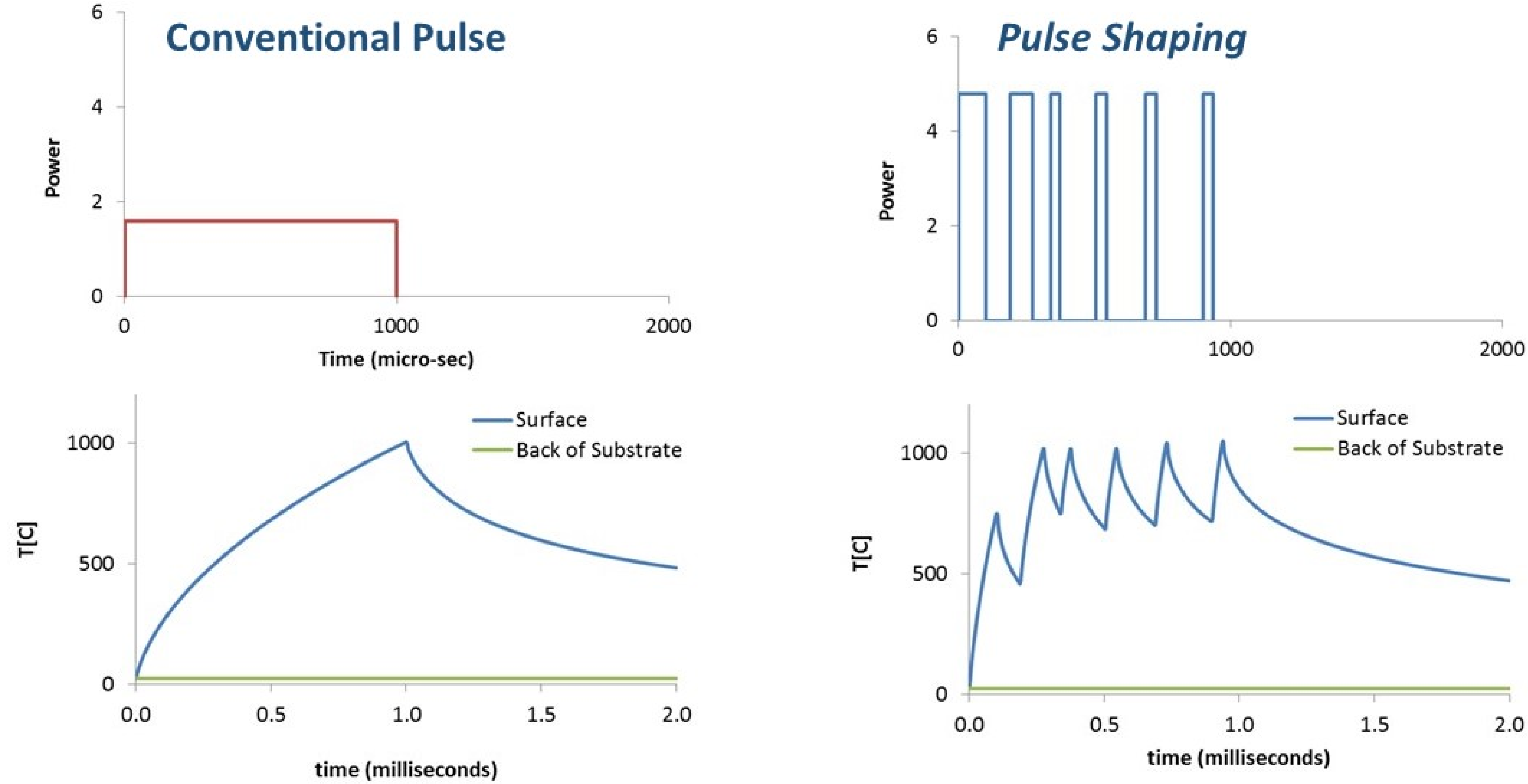


Micron flake screen print
- ~5-30 microns thick

For thick films:

- Thermal mass is greater, so need more processing energy to reach required temperatures.
- Diffusion escape of volatilized solvents takes longer due to tortuous path.
- The exposure conditions for inkjet/thin-film processing are probably not the same as optimized conditions for thick films.

Curing System: Pulse Shaping



Pulse Shaping: Multiple pulses acting within the thermal equilibrium time of the material.

- Equivalent energy but composite pulse allows better control of temperature profile.
- Preferred pulse structure for many thicker depositions as well as for drying.

Curing System: SimPulse

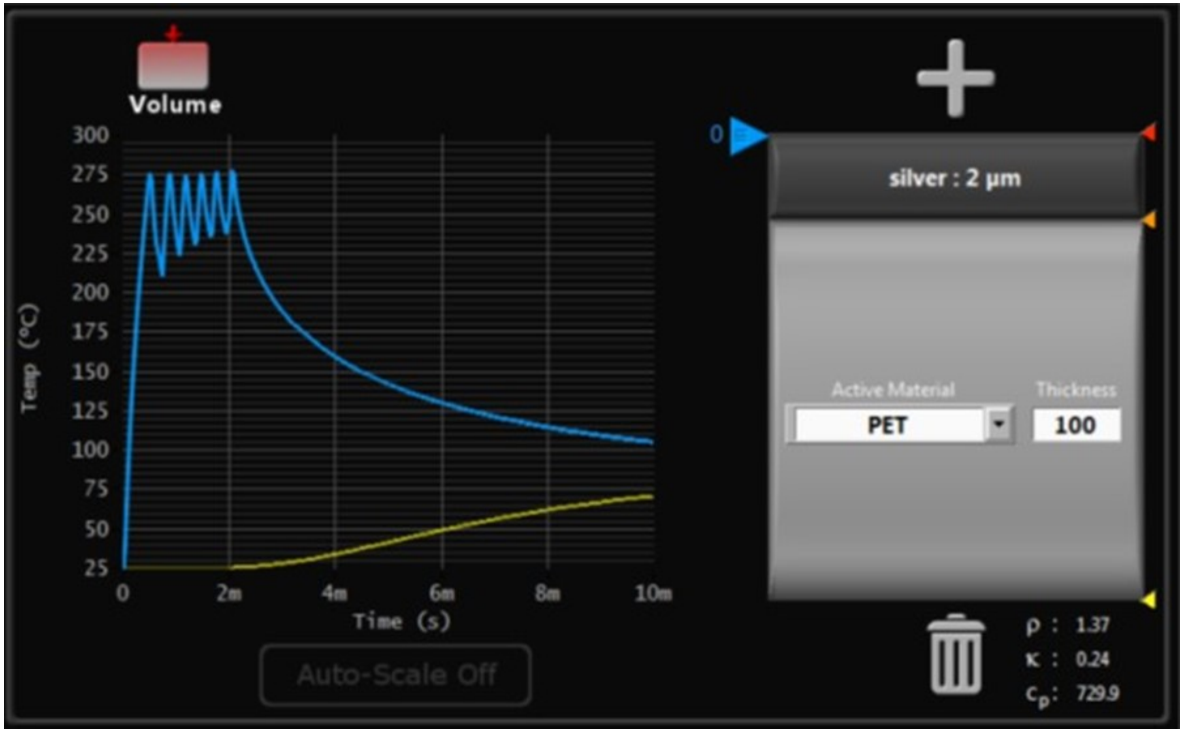
- **SimPulse:** Temperature profile simulation
  - Design your stack → Shape the pulse → Desired temperature profile
  - Very fast for optimizing process conditions
- Revealing the effectiveness of Simpluse for prediction of output for known stacks and parameters.

Stack design
-Add up to 7 layers
-Define thickness

Materials
-Database
-Physical properties
-Add your own

Boundary conditions
-Convection, heat sink

Simulation time:
-Fraction of a second

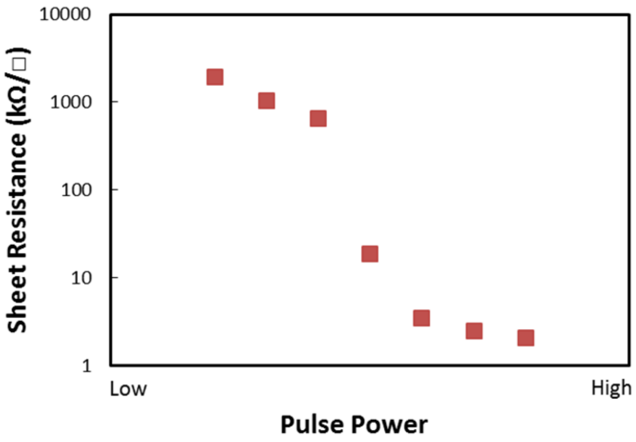


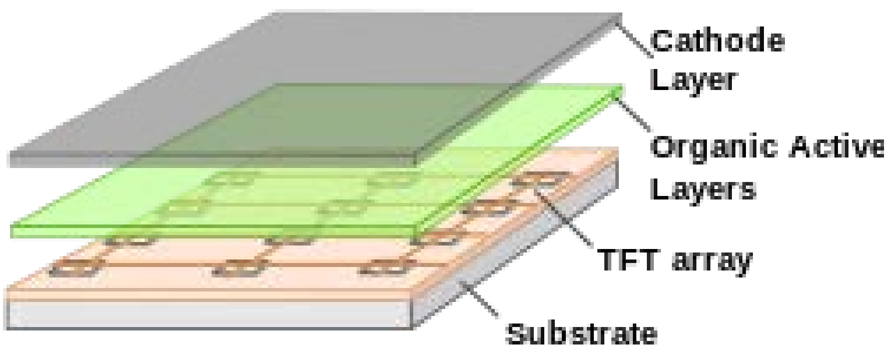
Leading Applications for Photonic Curing

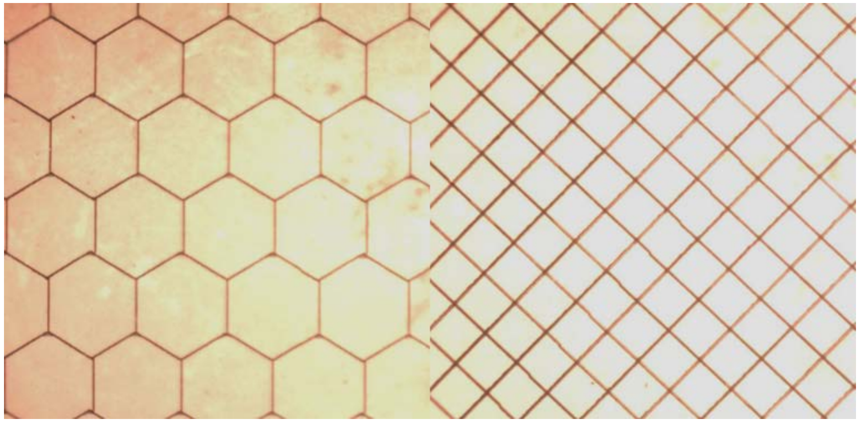
- Processing for displays, optical coatings
- RFID/ Antenna development
- Automotive
- Wearables/ Textiles
- Smart product packaging
- Smart card development
- New materials development
  - Conductive inks
  - Coatings such as for displays
  - Processing of Inorganic Semiconductors
- Ongoing PV development
  - CIGS/CIS such as at University of Texas

Photonic Curing for Displays

- A combination of Active and Passive layers
  - Each layer requires processing such that underlying layers are not damaged
- Direct fabrication of electronic devices, especially TFTs on flexible substrates
- Processing of some/all these layers using photonic curing technology

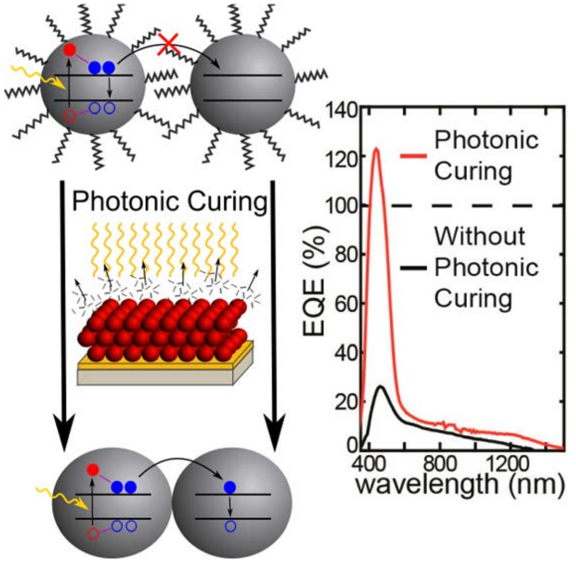


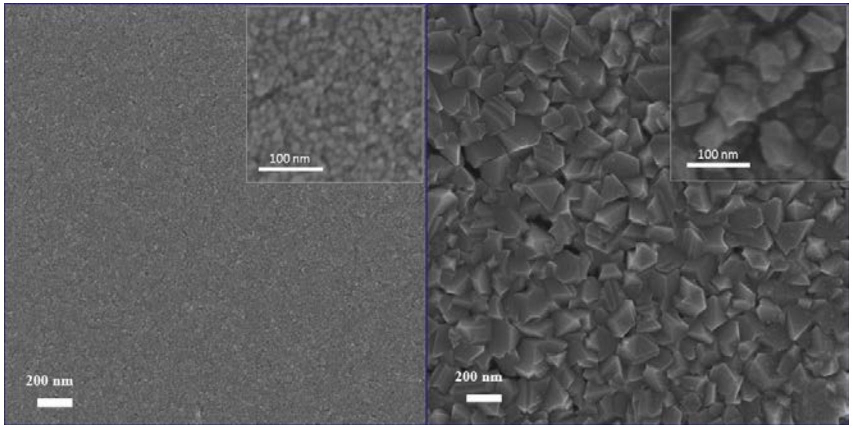




Photonic Curing for Energy

- Semiconductor material for thin film technology in solar cells and PVs
- Deposition on flexible substrate producing lightweight solar panels
- Improve efficiency by processing with photonic curing
  - Peak EQE (>120%)observed in CIS nanocrystal device prepared with photonic curing
- Photonic curing brings nanocrystals into better electrical contact and enables multiexciton extraction





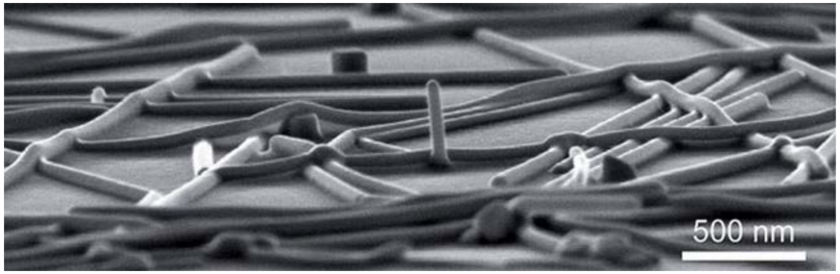
J. Phys. Chem. Lett. 2014, 5, 304−309

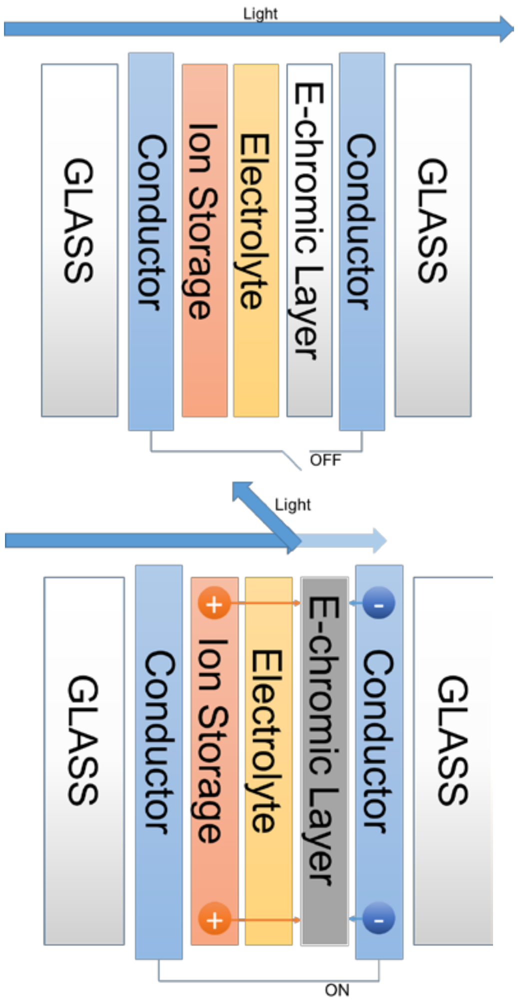
Photonic Curing for RFID Antenna

- Electromagnetic fields to identify and track tags attached to objects
  - Reader sends out waves → antenna draws power for microchip circuit → sends wave back to reader with new waves, converted to digital data
- Innovative concept of “green" antennas
  - Paper substrate - biodegradable
- Metallic inks primarily water-based for ease of handling, clean-up, and for environmental consideration

Photonic Curing for Smart Glass

- Light transmission properties are altered by voltage
- Several layers including transparent conductors, semi-conductors and electrolyte
- TCO replacement with Ag nanowires or graphene
- Processing of some/all these layers using photonic curing technology
- Improvement in transparency, line width and cost are still needed for some applications





Wearables

Image source: L'oreal via www.designboom.com

Image source: Biolinq via www.psfk.com/

Image source: http://faculty.ims.uconn.edu/~sotzing_grp/

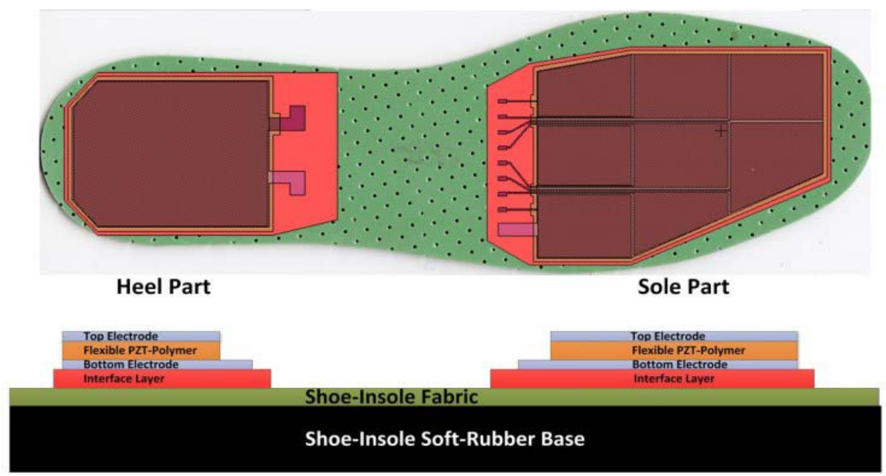
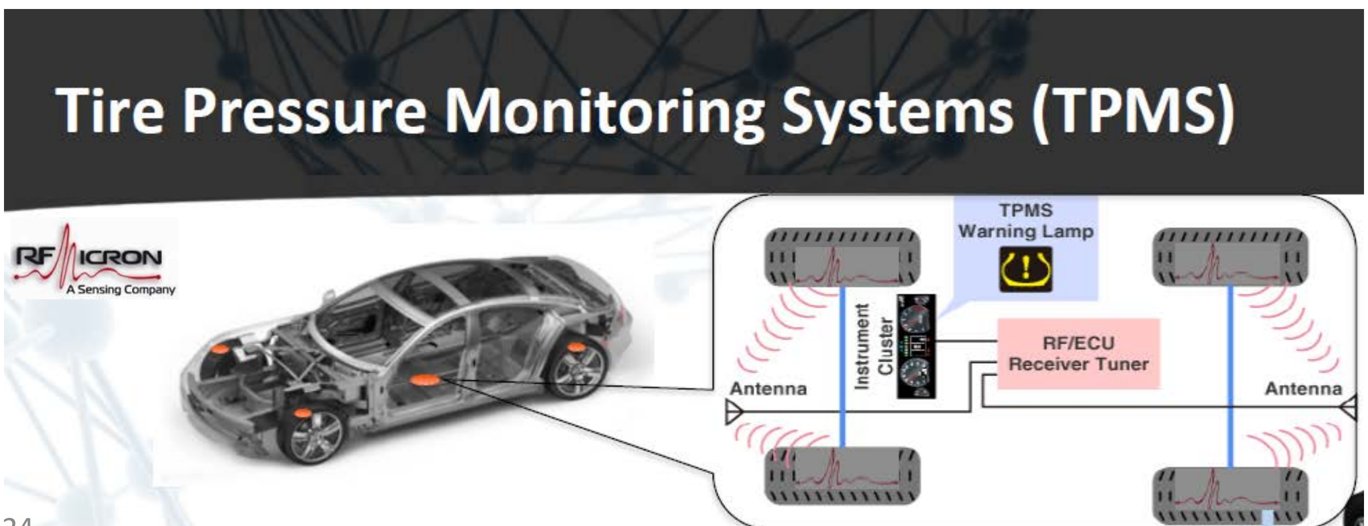


Image source: Journal of Physics: Conference Series **476** (2013) 012108

Home Automation

Automotive


Image source: Boeing via www.airlinereporter.com



Summary

- Photonic curing allows high temperature processes on inexpensive low-temp. substrates
- Low power, short pulse time, fast processing – up to 1000 ft/min
- Suitable for wide variety of printing techniques as well as materials
- Applications can encompass anything requiring a flexible (or not) conducting pathway

Application	Materials	Deposition	Substrates	Value Propositions
Displays	Ag	screen	glass	thinner display stack
	AgNW/cNT	inkjet	flexible glass	less expensive materials
	TCO	slot-die	polymers	faster production time
	Semiconductor	sputter		
	PI Alignment guides, spacers			
Photovoltaics	CIGS	screen	glass	flexible module
	CdTe	slot die	flexible glass	lower-cost materials
	Ag		polymers	novel form factors
Antennas / RFID	CuO	screen	paper	less expensive consumables
	Cu	inkjet	flexible polymers	sustainable materials
	Ag	aerosol jet	ABS	reduced product cost
	dielectrics	pad printing		greater production flexibility
				novel form factor
Circuits	Ag	flexographic	polymers	greater production flexibility
	dielectrics	inkjet		reduced cost
		screen		
Wearables: textiles	Ag	screen	polymers	novel form factors
	various carbon			expanded functionality
3D fabrication	TBD	extrusion	metals	novel form factors
		inkjet	ceramics	integrated functionality
			polymers	

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