Gravure Printing of ITO Transparent Electrodes for Applications in Printed Electronics

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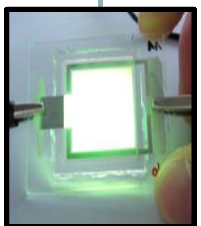
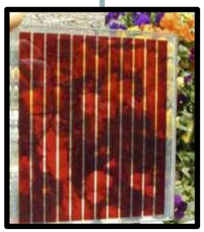
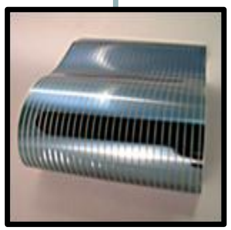
Applications of Transparent Electrodes



OLED



DSSC



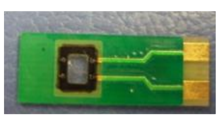
Solar cells Glass

Self-Tinting Smart Windows

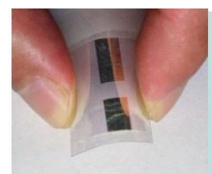
Touch Screen for LCD

E-Paper

EM



Biosensors

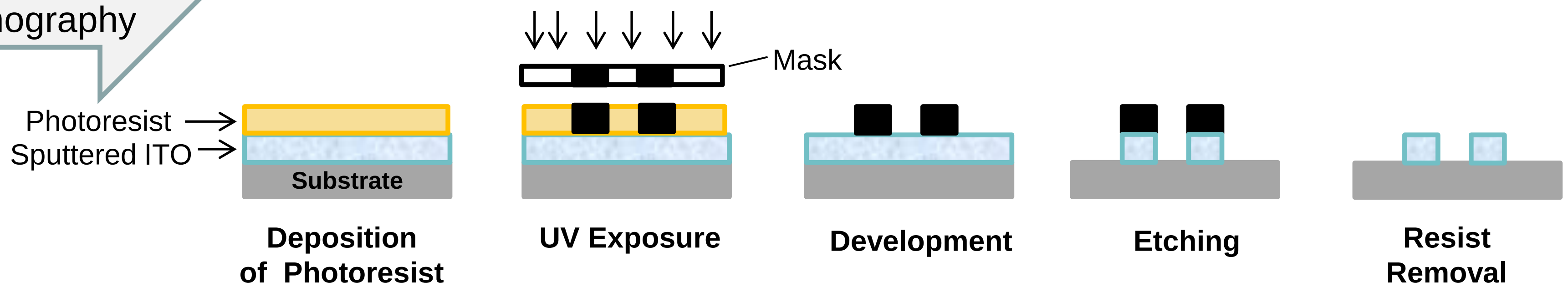


TFT

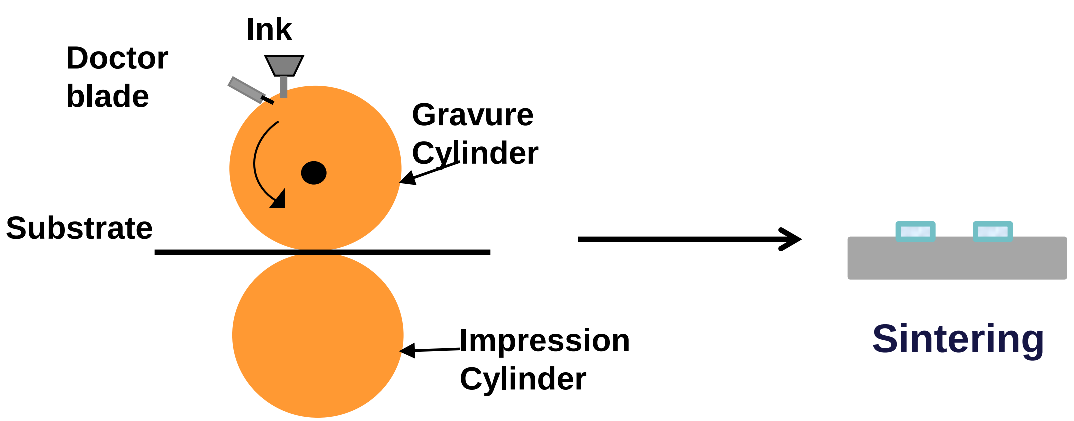
Sourse: Prodi-Schwab, Adam /Creavis, (Takeda, Kato, and Toyoda), Solarmer ,Sage Electronic, Fujifilm, Amazon kindle , Jiahao Sensors and Actuators B: Chemical, 139 (2009)

Patterning of Indium Tin Oxide (ITO)

Sputtering & Photolithography



Direct Patterning Gravure Printing



Sintering of ITO Nanoparticles
1. High Temperature Sintering

- Each oxygen vacancy in ITO film contributes two free electrons.
- To form these oxygen vacancies, ITO nanoparticles films are usually sintered with high temperatures.
- A post annealing in a forming gas (N_2/H_2) as a reducing agent improves the electrical performance.
- This limits the sintering to glass substrates

Sintering of ITO Nanoparticles

- The surface to volume ratio of nanoparticles is larger than that in the bulk, altering their thermodynamic properties.

- The melting point of nanoscaled material is much lower than the bulk "melting point depression"

$$T_m(r) = T_m(\infty)\left(1 - \frac{2\sigma_{sl}}{\Delta H_f(\infty)\rho_s r}\right)$$

$T_m(\infty)$	bulk melting temperature
$\Delta H_f(\infty)$	bulk latent heat of fusion
ρ_s	solid phase density
r	radius of a spherical particle
$T_m(r)$	melting point of a particle with radius r
σ_{sl}	solid–liquid interfacial energy

Sintering of ITO Nanoparticles
2. Photonic Sintering

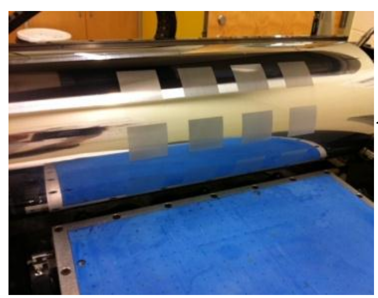
Photonic sintering: Is a high energy delivered in the form of light pulses or “flashes” from a flash lamp system to convert the nanoparticles to a continuous film.

- The energy raises the temperature in less than milliseconds- rapid sintering at room temperature
- Produces **high peak power**, more efficient use of energy and allows for deeper penetration depths in film
- **Is a low temperature process-** use of low cost, flexible substrates like paper and PET.
- System compatible to roll-to-roll process

Experimental

- 30% ITO dispersion from Evonik Industries (VP Disp ITO TC8 DDAA) in diacetone alcohol
- The AccuPress MicroGravure Printing system (120, 160, 200, 250) lpi
- All printed ITO films on glass were first cured in a conventional oven at 120 ° C for 1 hour.
- The films were then sintered by two methods; High temperature sintering @ 500 ° C for 2 hours and Photonic sintering with Sinteron 2000.

Sinteron 2000, Xenon Corporation

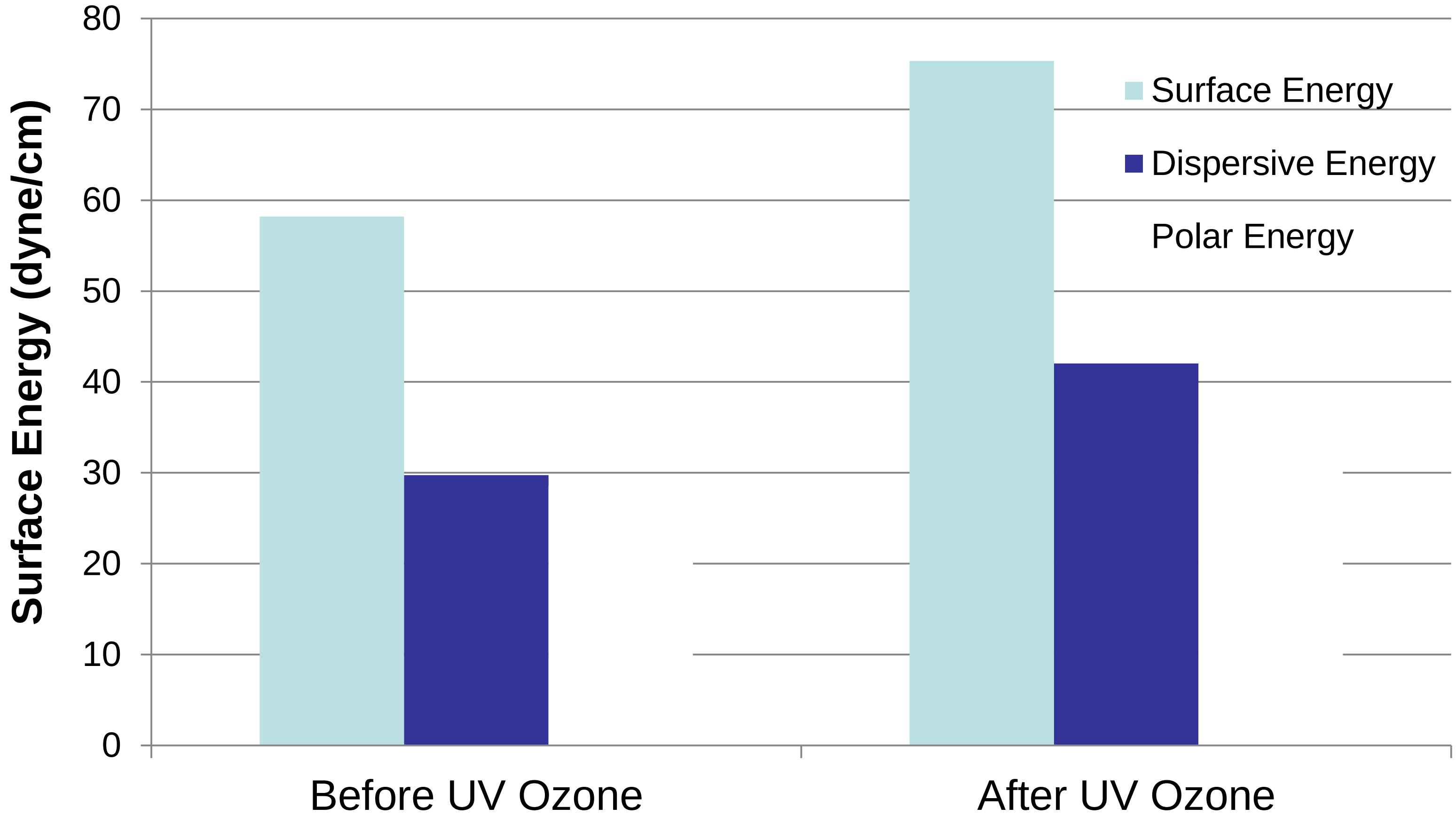


Engraved cylinder with the four solid areas

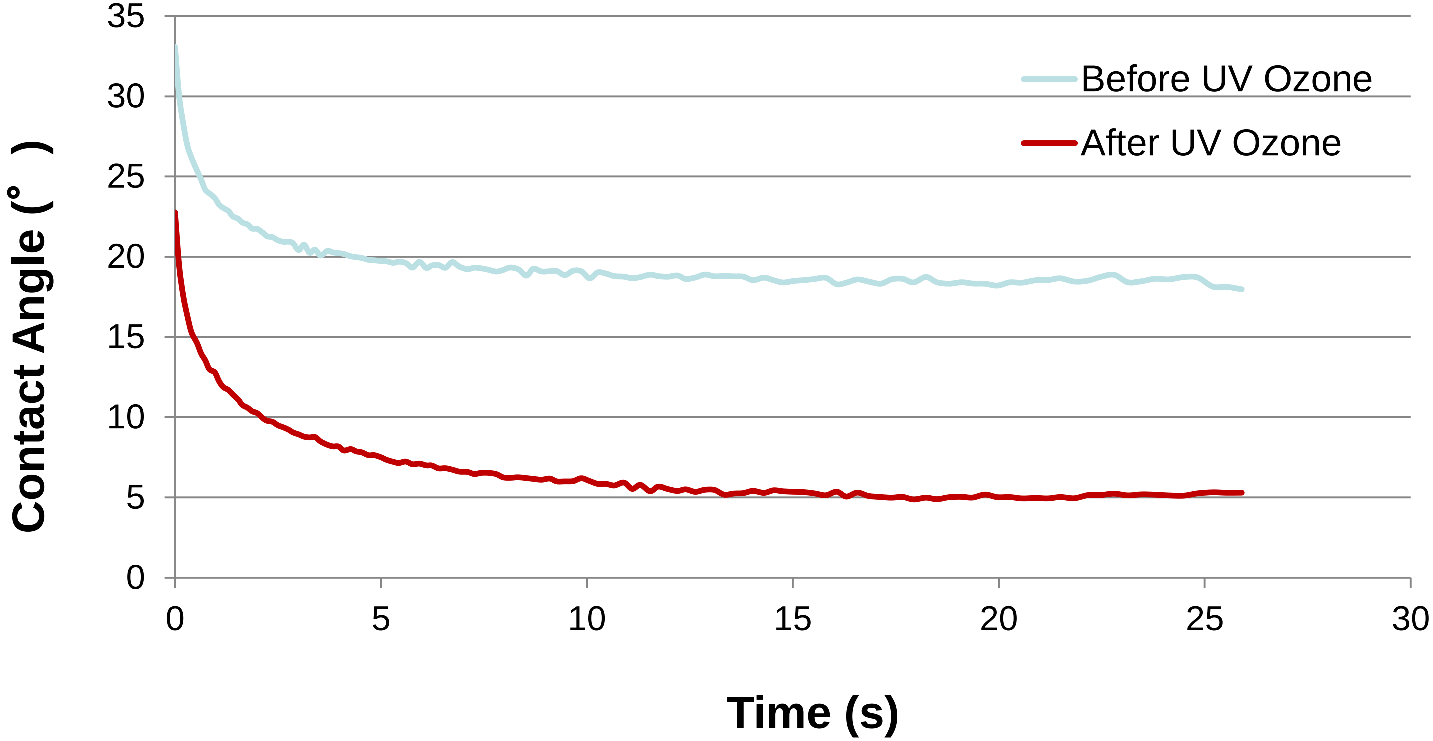
AccuPress MicroGravure Printing system

Results

The effect of UVO treatment on the surface energy of glass



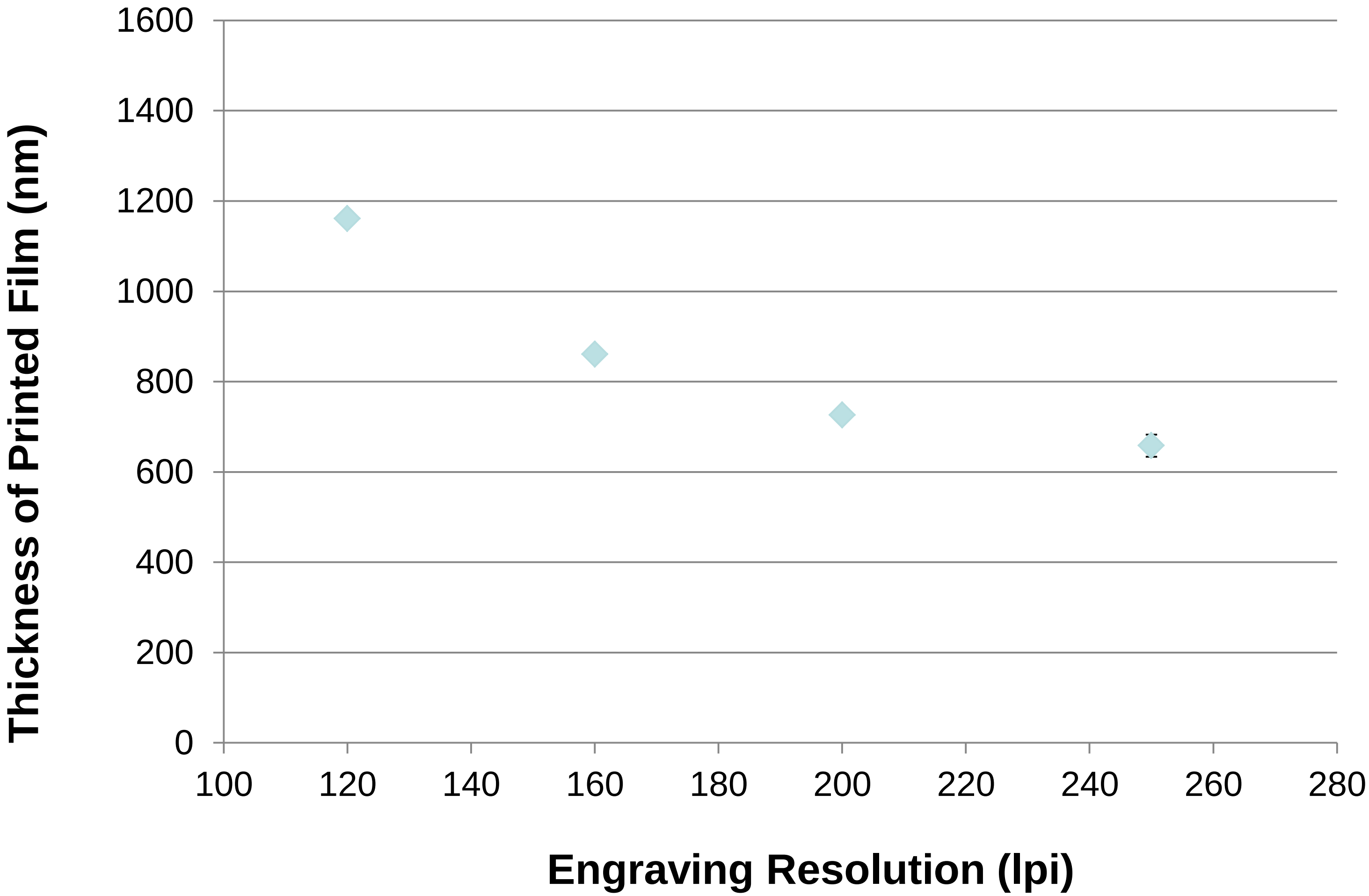
The Effect of UVO Treatment on The Contact Angle of ITO on Glass



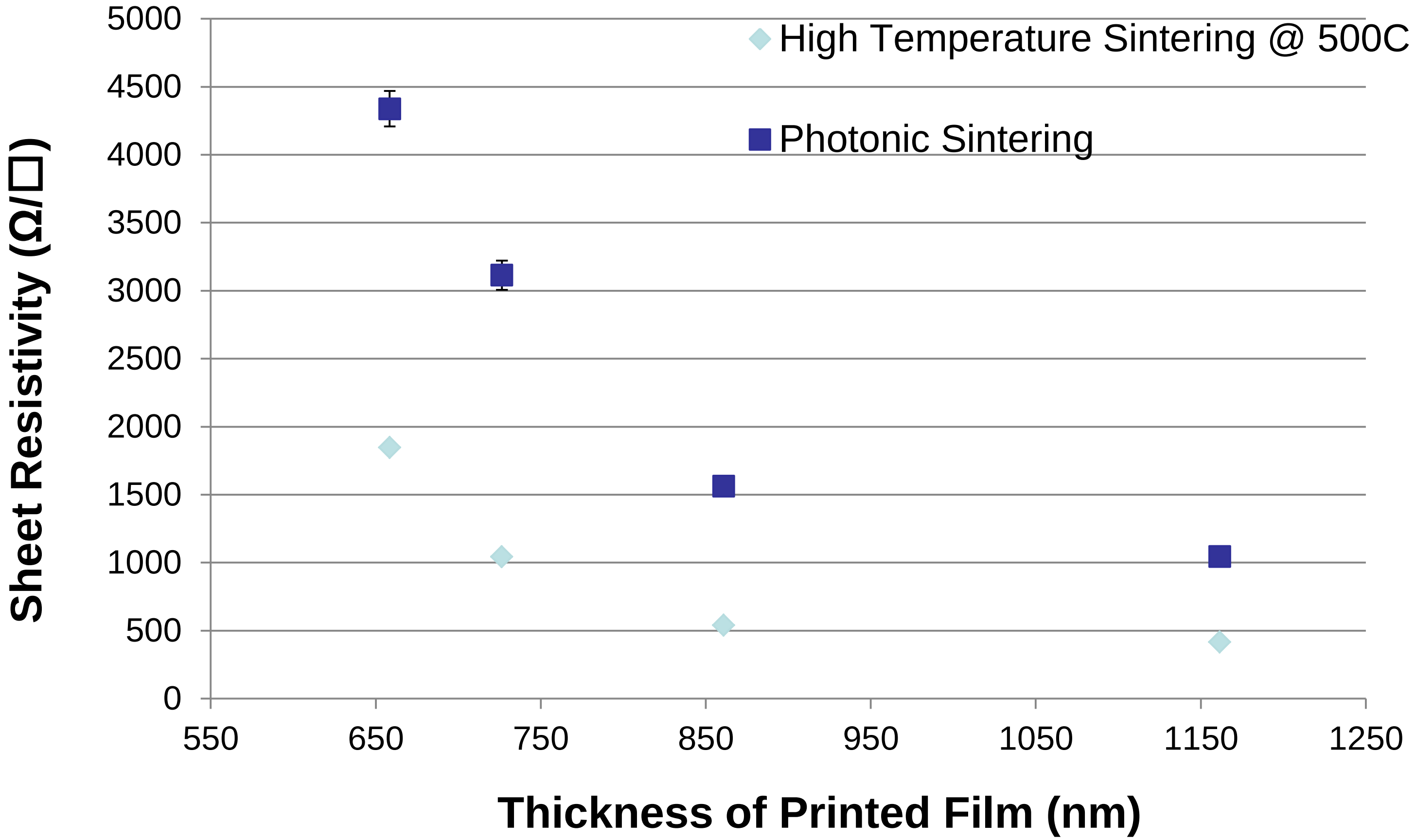
Before UVO

After UVO

Thickness of Printed ITO Films on Glass at Different Engraving Resolutions



Sheet Resistivity of Printed ITO Films on Glass



* Photonic sintering at 80 pulses for 100 seconds, 2000 J/pulse

Energy balances in photonic sintering

- Based on the “first law of thermodynamics”, the thermal energy causes enthalpy changes (ΔH) in the nanoparticles.
- The energy *first* raises the temperature of the nanoparticles to the melting point
- The energy is *then* consumed to melt the nanoparticles - depends on the latent heat of fusion
- The change in enthalpy associated with the temperature rise

$$\Delta T = T - T_0 = (E/ \rho C_p t)$$

E energy density (J/cm^2)= Q/cross section of radiating area
ρ density of material
t film thickness

The temperature rise in films with photonic sintering

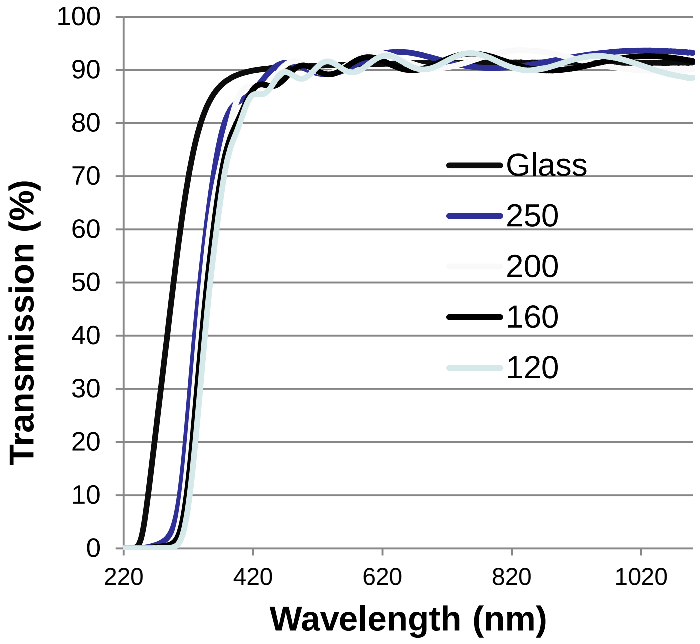
Basis: 1 J/cm^2 radiated into the films

$$\Delta T = T - T_0 = \left(\frac{E}{\rho C_p t}\right)$$

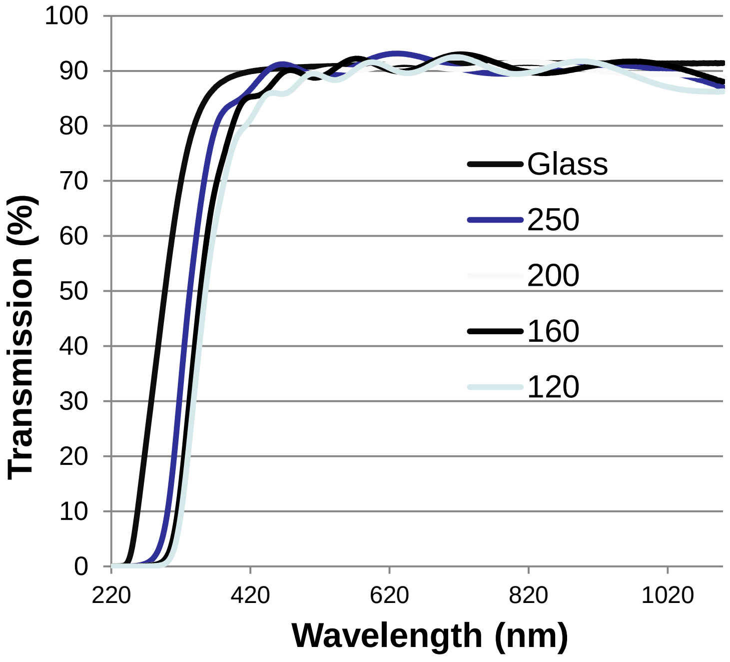
Assumptions: 90 % transmission, 4.5 % of the light energy is absorbed

Material	Density (g/cm3)	Cp (J/g.°C)	Thickness of film (µm)	ΔT (°C)
ITO	7.2	0.387	1.20	**134.55**
Glass	2.38	0.768	700	**0.35**
PET	1.38	1^{25}	125	**2.61**

Transmission Spectra of Printed ITO Films on Glass



High temperature sintering

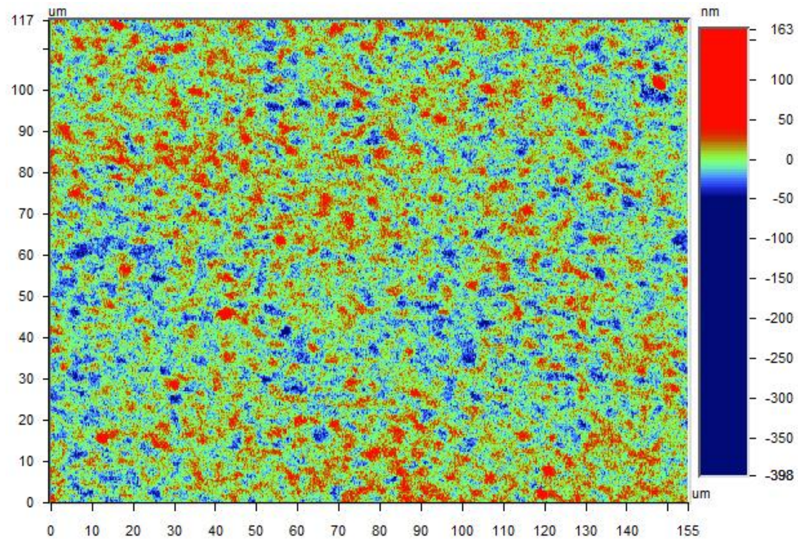


Photonic sintering

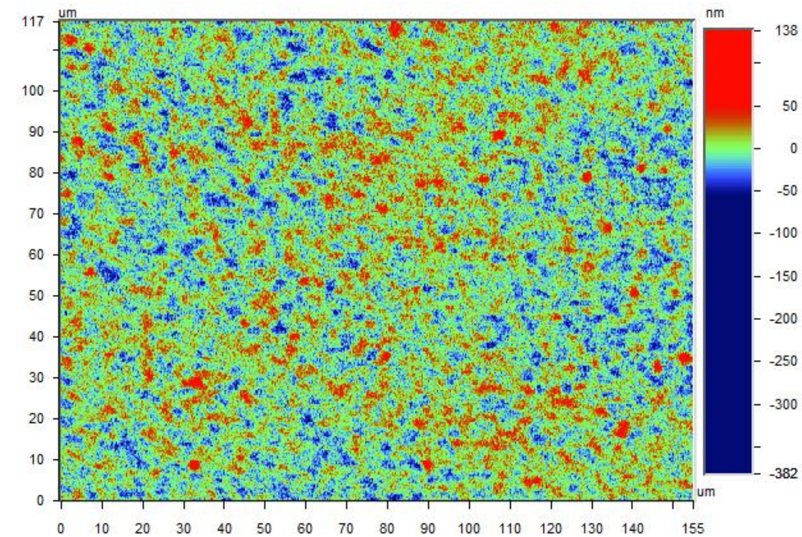
* Numbers in legend are cell engraving in lpi

Surface Topography of Printed ITO films
White Light Interferometer

Roughness of glass (nm)		Roughness of ITO films (nm)	
R_{avg}	R_{rms}	R_{avg}	R_{rms}
5.75	7.86	12 -18	16 -20



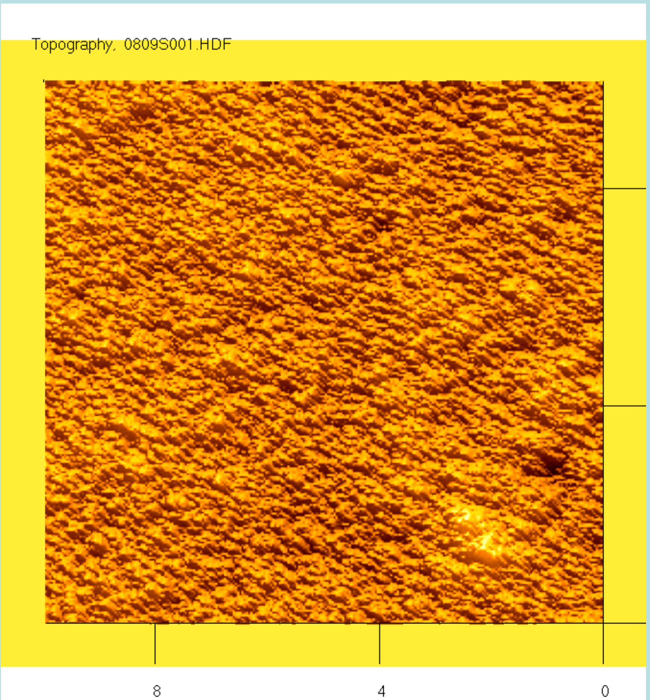
High temperature sintering



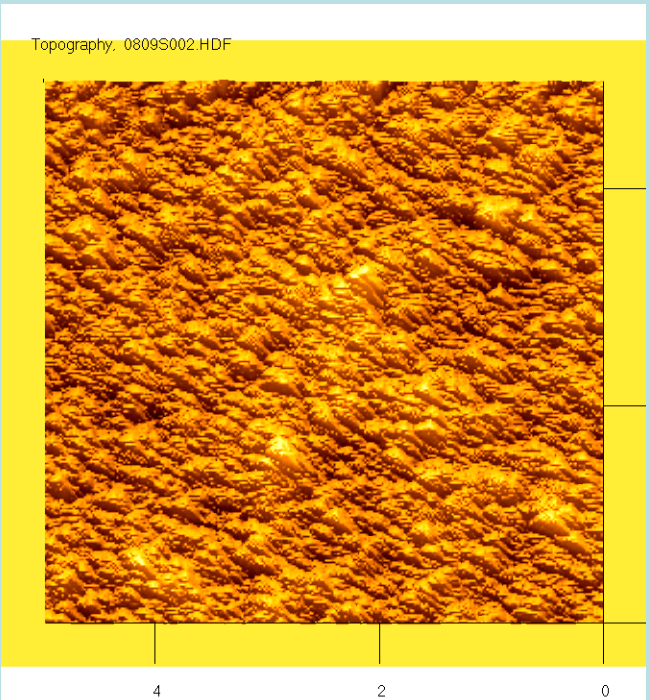
Photonic sintering

Roughness in 0.99 X 1.3 mm^2 scale

Surface Topography of Printed ITO films with High Temperature Sintering
Atomic Force Microscopy (AFM)



(10X10) μm^2



(5X5) μm^2

R_{rms} = 111Å	R_{rms} = 81.3Å

Conclusions

- ITO nanoparticles were successfully printed on glass with the AccuPress Gravure System
- A wide range of sheet resistivity values was achieved with different engraving resolutions of the gravure cells.
- A sheet resistivity as low as 415 Ω/☐ was achieved through the use of high temperature sintering and 1000 Ω/☐ was achieved through the photonic sintering.
- Visible Light transmission above 88% was obtained, regardless of the sintering method of ITO films.

Conclusions

- The sintering method didn’t have a significant effect on surface roughness or transmission.
- The photonic sintering process will add a lot to the field of printed electronic (energy and time savings/ ability to be installed in series with a roll-to-roll printing)
- Gravure printing, as an additive process, offers the advantage of direct patterning of ITO films to significantly reduce material waste, cost and high energy consumption in comparison to sputtering and the photolithography processes.

Acknowledgment

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Thank You