

Digital Printing of Electronics: Mass-Production Technologies & Applications

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PV Nano Cell

April 20th, 2021



pvnanocell



Founded 2009



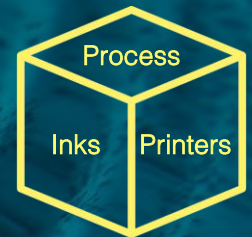
Migdal HaEmek



20 People



Conductive Inks



Complete Solution

Current Massive Wave: Electronics Everywhere

PV Nano Cell's Digital Printing Solution Enables Electronics Everywhere



Smart
Automotive



Solar
Cells



IoT
Applications



Wearable
Technologies



Flexible
Electronics



Medical
Devices

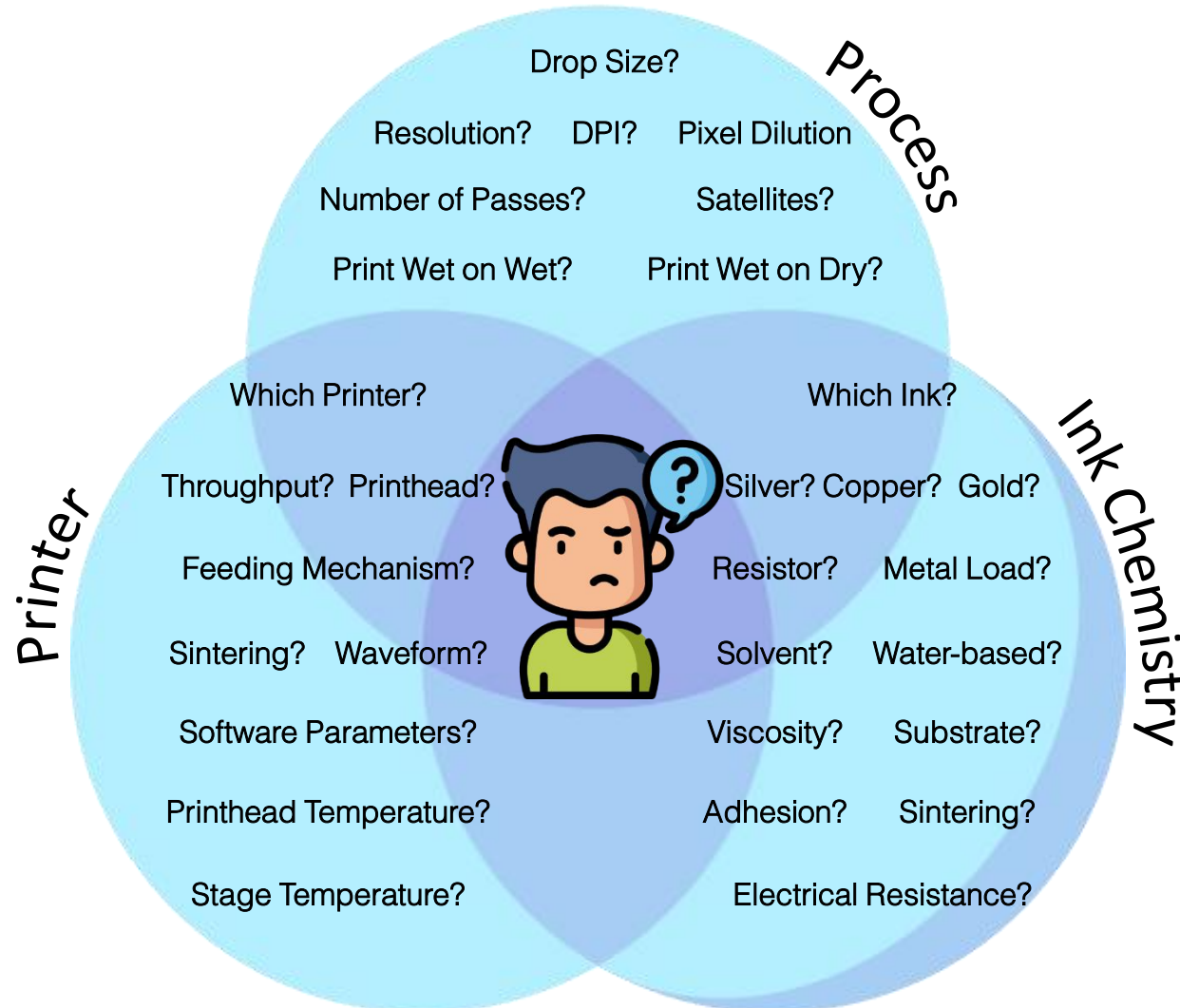


Smart
Packaging

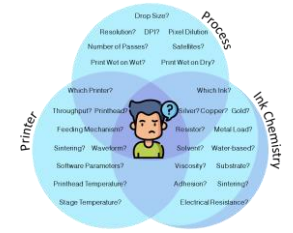


Self-Driving
Cars


Customer Needs a PhD in Printed Electronics




PVN's Complete Solution Makes it as Easy as Driving




Driving Essentials:



Car



Gas



Know how to Drive

PVN's Solution:



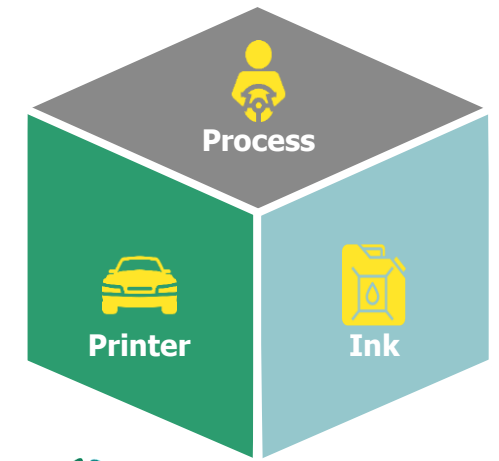
Printer



Ink



5D Printing Process



PV Nano Cell's Offering: 5D Technology



Printers



Conductive Inks for Mass Production



pvnanocell
Sicrys™ Digital Inks
Single Crystal Nano Inks



Silver



Copper



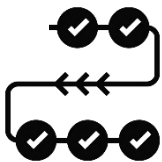
Gold



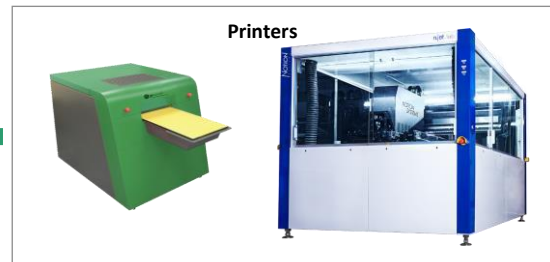
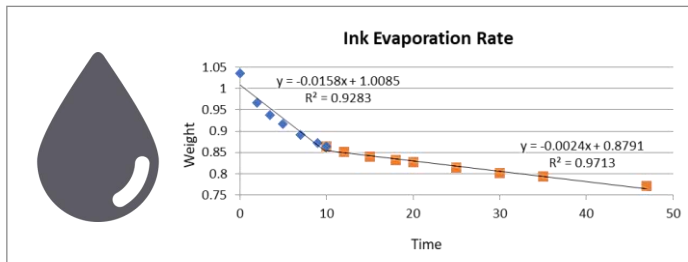
Dielectric



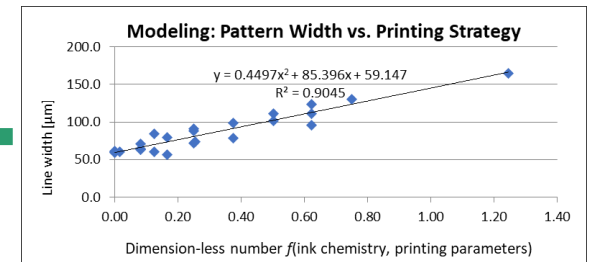
Resistor



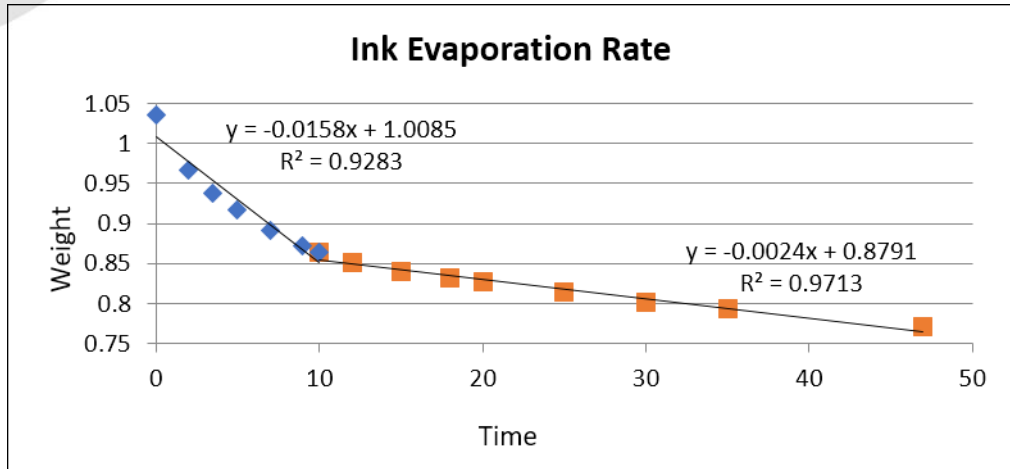
5D Printing Process



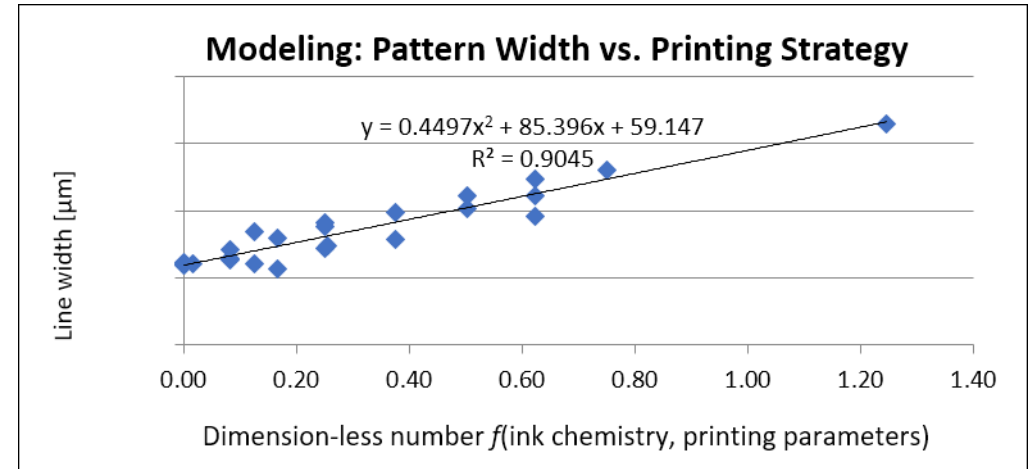
Printers



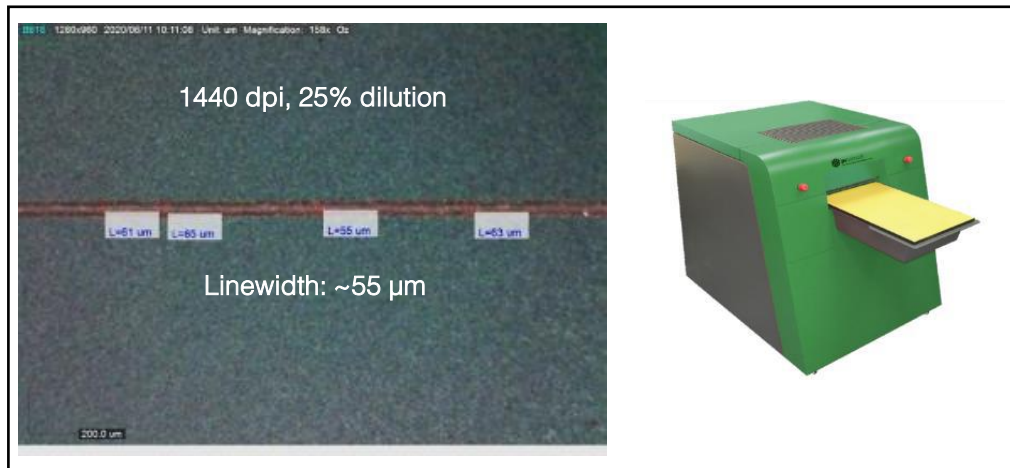
Complete Solution Linking: Chemistry, Printers & Process



1) Inks: Chemistry



2) Process: Software Algorithms



3) Printing

PVN is designing an Optimization Software



for Mass-Production Conductive Printing

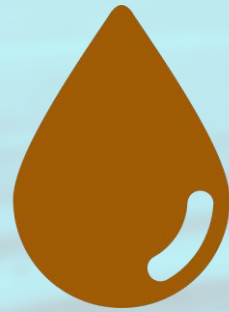


4) Application: very narrow & dense conductive patterns

Families of Sicrycs™ – Single Crystal Nano Inks



Silver



Copper



Gold



Dielectric



Resistor

- ❖ High metal load, over 60%
- ❖ Stability: Shelf life – over 12 months
- ❖ Low sintering temperature (< 130 °C).
- ❖ Low resistivity: $\rho < 2.5 \times \text{bulk}$.

- ❖ Narrow pattern printing as narrow as 50 μm .
- ❖ Lower viscosity at high metal loading (50%+).
- ❖ Green & clean process, no hazardous material.
- ❖ SMT/soldering-capable.

Sicrys™ Digital Silver Inks: Technical Characteristics

Ink properties	I20DM-206	I40DM-106	I50DM-106	I50TM-115	I50TM-119	I50T-13	I30EG-1	I60PM-116
Metal Loading (% w/w)	20%	40%	50%	50%	50%	50%	30%	60%
Main Solvent ¹	DGME	DGME	DGME	TGME	TGME	TPM	EG	PM/DGME
Typical Viscosity @ 25°C (cP)	5	11	20	37	34	26	28	26
Surface Tension (dyn/cm) (Pendant Drop method)	34	34	34	36	29	26	47	23
Open Time ² (jetting temperature, °C)	15 min (25°C)	10 min (30°C)	10 min (30°C)	30 min (40°C)	10 min (35°C)	60 min (35°C)	5 min (35°C)	
Resistivity (μΩcm) (thermal sintering, °C, min)	≤ 10 (150,30) ≤ 12 (130,30)	≤ 10 (150,30) ≤ 12 (130,30)	≤ 10 (150,30) ≤ 12 (130,30)	≤ 10 (150,30) ≤ 12 (130,30)	≤ 10 (150,30) ≤ 12 (130,30)	≤ 10 (200,30) ≤ 24 (150,30)	≤ 10 (180,30) ≤ 14 (150,30)	≤ 10 (130,60)
Sheet Resistance (mΩ/□) (thickness, μm)	10 (10 μm)	10 (10 μm)	10 (10 μm)	100 (1 μm) 20 (4 μm)	30 (3.5 μm) 15 (8 μm)	100 (1 μm) 25 (4 μm)	100 (1 μm) 25 (4 μm)	
Substrate Adhesion ³ (tested) ⁴	ITO, Glass	ITO, Glass	ITO, Glass	ITO, Glass, PET, PC	Kapton®, FR4, PET, PC, ITO, Glass, CTO	PC, PEN, PET	Kapton®, PC, PEN, LCP, Glass	Kapton®, PC, PA, PC/ABS, Glass
Compatible Printing Technologies	Inkjet	Inkjet	Inkjet	Inkjet	Inkjet	Inkjet	Inkjet, Aerosol	Aerosol
Compatible Printheads (tested) ⁴	Epson DemonJet Desktop printers	KM1024 KM1024i Ricoh E3 DMC-11610 Samba	KM1024 KM1024i Ricoh E3 DMC-11610 SapphireQS-10pl	KM1024 KM1024i KM512 Ricoh E3 SapphireQS-10pl	KM1024 KM1024i Ricoh E3	KM1024 KM1024i Ricoh E3 DMC-11610 SapphireQS-10pl	KM1024 KM1024i Ricoh E3 DMC-11610 Aerosol	Aerosol (pneumatic) atomizer)
Shelf life: 12 months. Storage at room temperature. No need to stir the inks.								
¹ - Solvents: DGME - diethylene glycol methyl ether, TGME - triethylene glycol methyl ether, PM - propylene glycol methyl ether, EG - ethylene glycol, TPM - tripropylene glycol methyl ether								
² - Ricoh E3 printhead								
³ - Adhesion depends on substrate, sintering conditions, substrate pretreatment and pattern thickness (tested according to ASTM-3359-09 or ISO-2409)								
⁴ - Substrates and printheads listed here were tested and perform well. Other substrates and compatible printheads may also be applicable.								

Sicrys™ Digital Silver Inks: Technical Characteristics

Ink properties	I50TM-119
Metal Loading (% w/w)	50%
Main Solvent ¹	TGME
Typical Viscosity @ 25°C (cP)	34

Sicrys™ Digital Silver Inks: Technical Characteristics

Ink properties	I50TM-119
Resistivity ($\mu\Omega\text{cm}$) (thermal sintering, °C, min)	≤ 10 (150,30) ≤ 12 (130,30)
Substrate Adhesion ³ (tested) ⁴	Kapton [®] , FR4, PET, PC, ITO, Glass, CTO
Compatible Printing Technologies	Inkjet
Compatible Printheads (tested) ⁴	KM1024 KM1024i Ricoh E3

Sicrys™ Digital Copper Inks: Technical Characteristics

Ink properties	IC25EG-1	IC40DM-7	IC50DM-7	IC50TM-8
Metal Loading (% w/w)	20%	40%	50%	50%
Main Solvent ¹	EG	DGME	DGME	TGME
Cu oxide in Cu nano-particles	< 10%	< 5%	< 5%	< 5%
Typical Viscosity @ 25°C (cP)	32	16	20	32
Surface Tension (dyn/cm) (Pendant Drop method)	47	28	28	30
Open Time ² (jetting temperature, °C)	5 min (35°C)	1.5 min (35°C)	1.5 min (35°C)	20 min (40°C)
Resistivity (μΩcm) - Laser sintering (Photonic sintering)	≤ 5 (≤ 32)	≤ 5	≤ 5	≤ 5
Resistivity (μΩcm) - Thermal sintering (°C, min, Argon)	≤ 90 (300, 30, Ar)	≤ 120 (300, 30, Ar)	≤ 120 (300, 30, Ar)	≤ 120 (300, 30, Ar)
Substrate Adhesion ³ (tested) ⁴	Kapton®, PA, LCP, Glass	Kapton®, FR4, ITO, Glass	Kapton®, FR4, ITO, Glass	Kapton®, FR4, ITO, Glass
Compatible Printing Technologies	Inkjet Aerosol	Inkjet	Inkjet Aerosol	Inkjet
Compatible Printheads ⁴	KM1024 KM1024i Ricoh E3 Aerosol	KM1024 KM1024i Ricoh E3 DMC-11610	KM1024 KM1024i Ricoh E3 Aerosol	KM1024 KM1024i Ricoh E3

Shelf life: 12 months. Storage at room temperature under Argon. No need to stir the ink. Copper ink can be exposed to air for short periods of time (minutes), refill the bottle with Argon every time the bottle is opened.

¹ - Solvents: EG - ethylene glycol, DGME - diethylene glycol methyl ether, TGME - triethylene glycol methyl ether

² - Ricoh E3 printhead

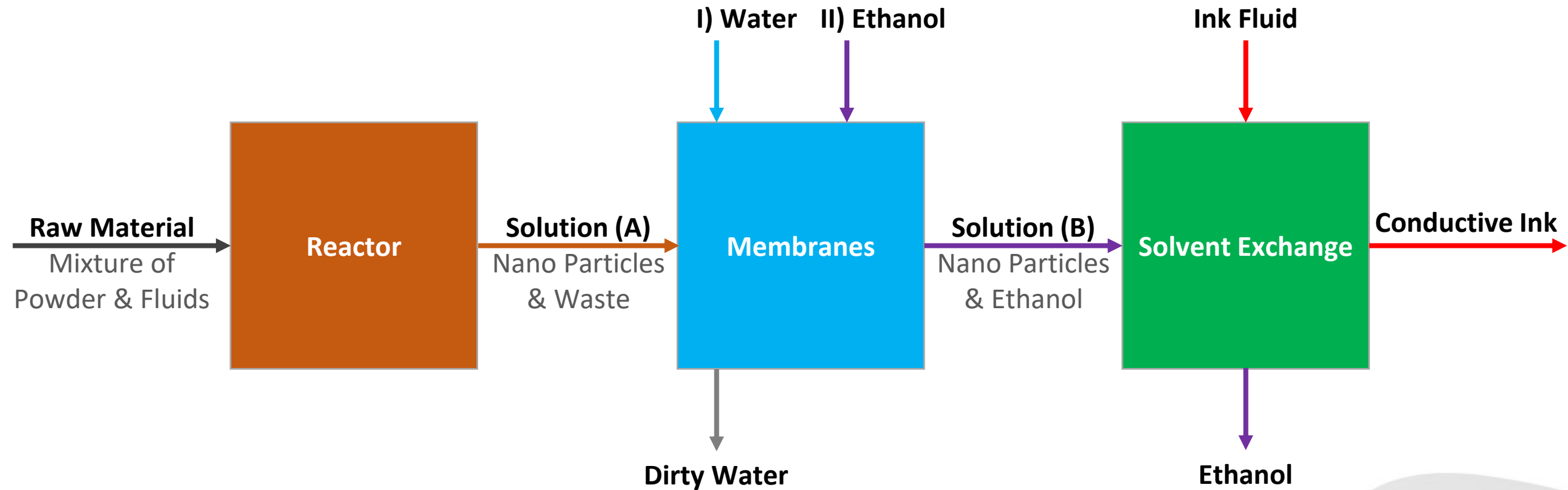
³ - Adhesion depends on substrate, sintering conditions, substrate pretreatment and pattern thickness
(tested according to ASTM-3359-09 or ISO-2409)

⁴ - Substrates and printheads listed here were tested and perform well. Other substrates and compatible printheads may also be applicable

Sicrys™ Digital Copper Inks: Technical Characteristics

Ink properties	IC25EG-1
Resistivity ($\mu\Omega\text{cm}$) - Laser sintering (Photonic sintering)	≤ 5 (≤ 32)
Resistivity ($\mu\Omega\text{cm}$) - Thermal sintering ($^{\circ}\text{C}$, min, Argon)	≤ 90 (300, 30, Ar)
Substrate Adhesion ³ (tested) ⁴	Kapton [®] , PA, LCP, Glass
Compatible Printing Technologies	Inkjet Aerosol
Compatible Printheads ⁴	KM1024 KM1024i Ricoh E3 Aerosol

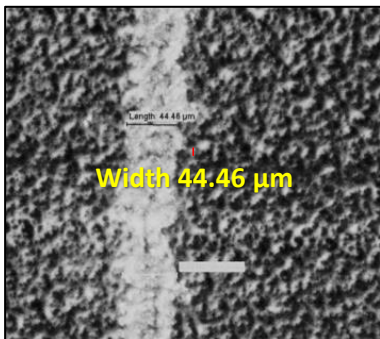
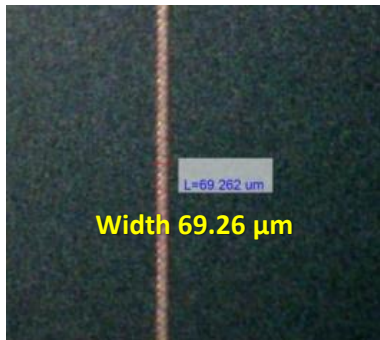
Ink Production Process



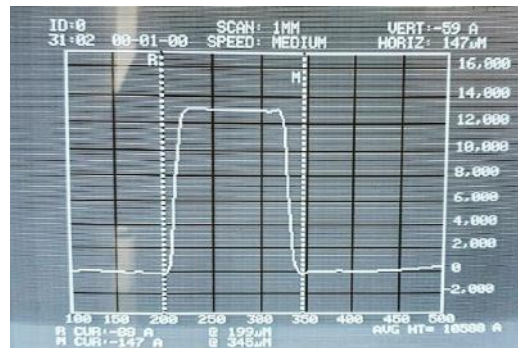
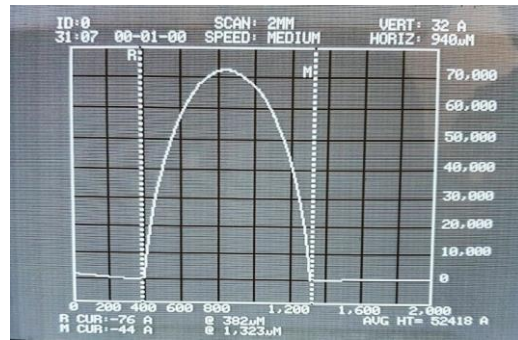
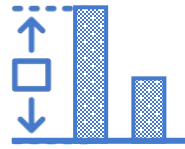
Clean Technology, No Hazardous Material

Inkjet Printing Capabilities

Width > 50µm



0.7 µm < Thickness < 10 µm



2 µΩcm < Resistivity ≤ 10 µΩcm



$$R = \rho \frac{l}{wt}$$

R: resistance, ρ: resistivity, l: length, w: width, t: thickness

Thermal Sintering (example)

150°C, 30 minutes, ρ ≤ 10 µΩcm

450°C, 15 minutes, ρ ≤ 3 µΩcm

Laser Sintering (example)

200 J/cm², 1,000 mW, 5 mm/s, ρ=5.2 µΩcm

8 J/cm², 5,000 mW, 200 mm/s, ρ=4.8 µΩcm

Adhesion



ISO 2409 STD

FR4

PET

Polyimide

Glass

Ceramics

ITO

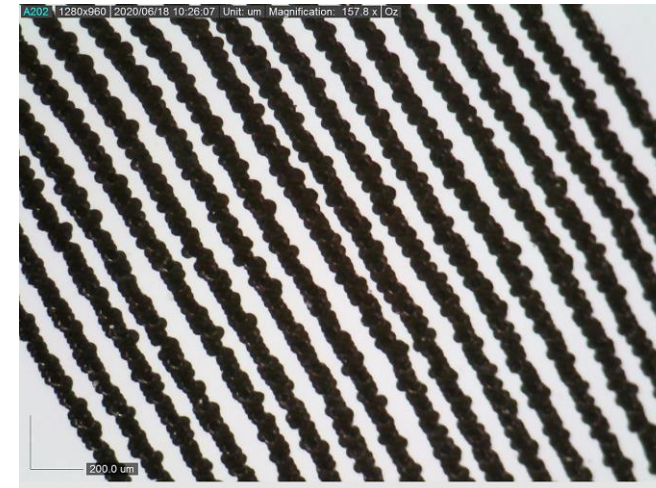
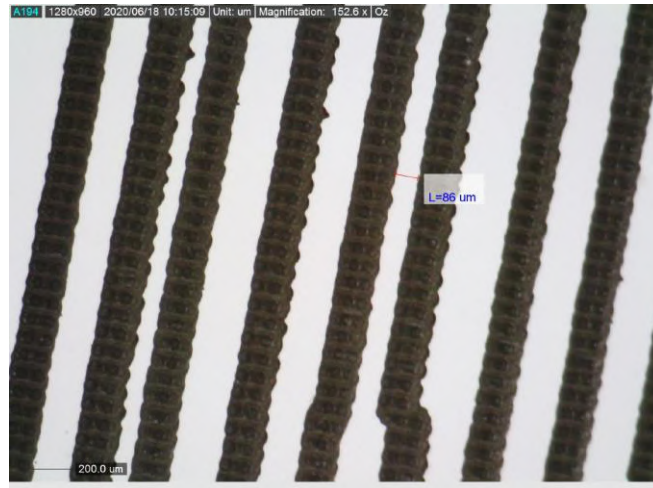
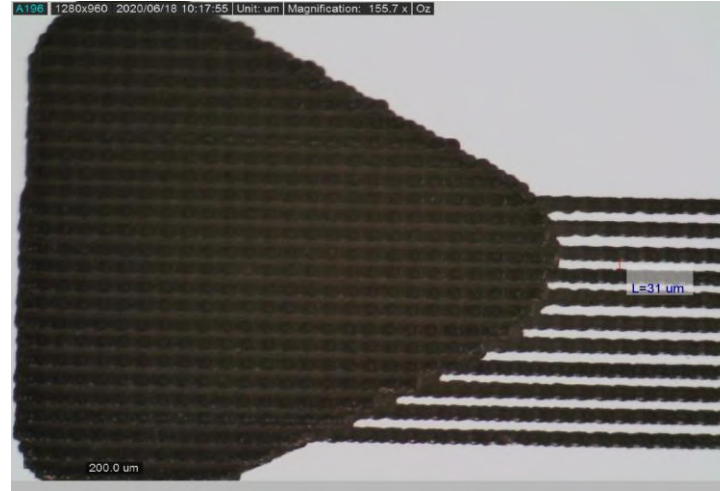
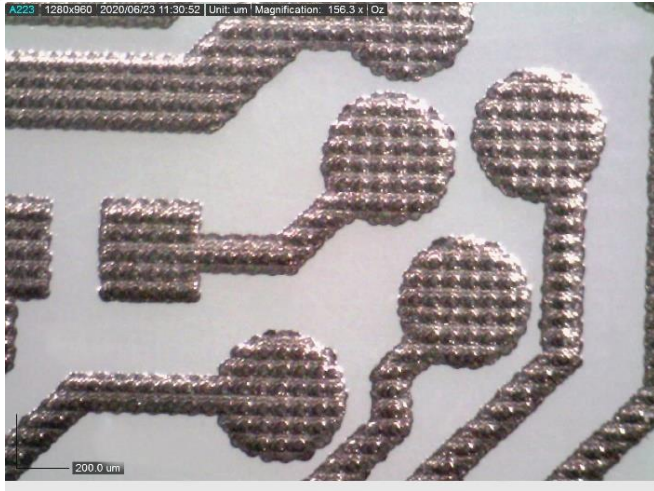
CTO

Polycarbonate

Paper

Etc.

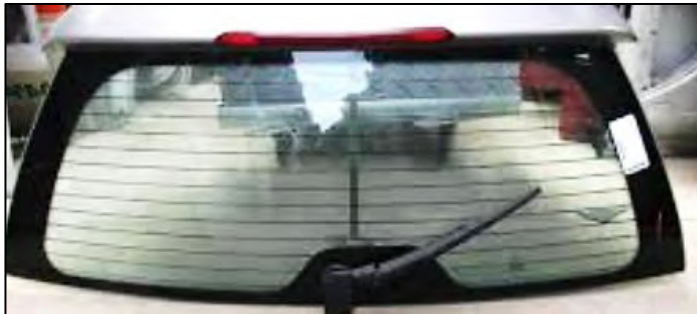
Inkjet Printing: $>50 \mu\text{m}$ Width & Pitch, $>1 \mu\text{m}$ Thickness



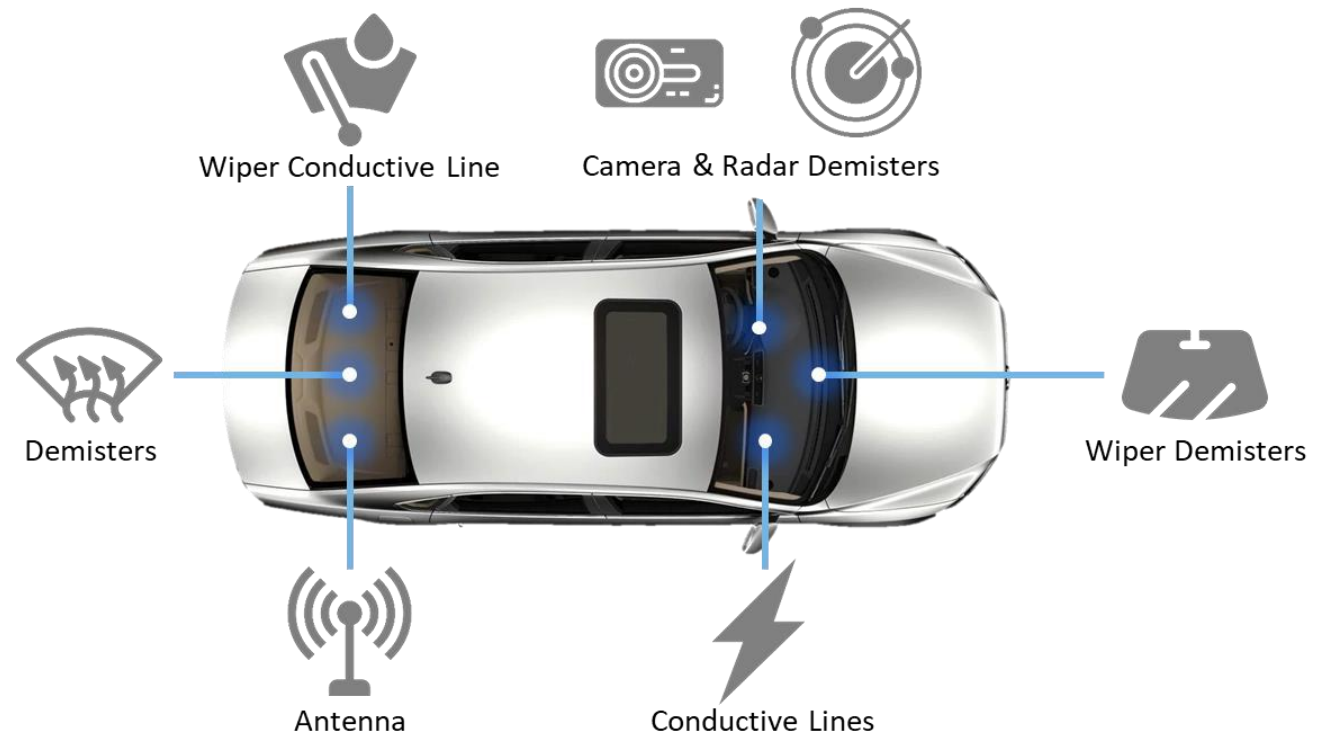
Commercial Applications: Automotive Market

Windshields are filled with Electronics

- Multi inks printed using one printer.
- Narrow & dense electronics.
- Large format
- Each windshield is different.



- Bus Bars Resistivity: $1.5 \text{ m}\Omega/\square$
- Fine Lines Width $< 0.6 \text{ mm}$
- Fine Lines Resistivity: $2.0 \text{ m}\Omega/\square$



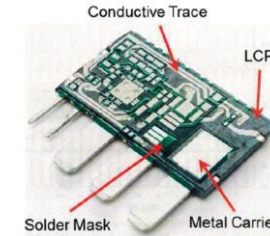
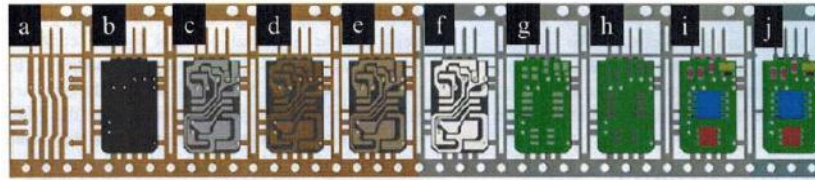
Electronics Everywhere: Automotive Market Future Technologies

“Smart” Connectors by Molex

- Narrow & thin patterns.
- Low resistances at low sintering temperatures.
- 2.5D and 3D printing.
- Usage: light bulbs, power charging, etc.

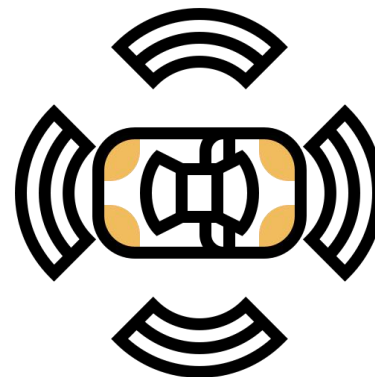
molex ASEP Solutions

pvnanocell Inkjet Inside



Project Tinker

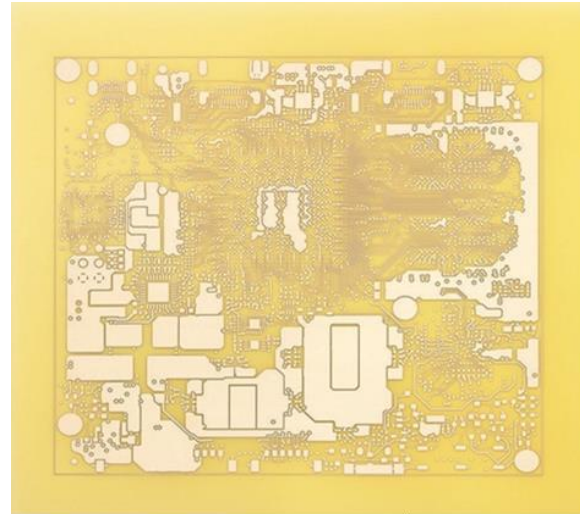
- Radar and LiDAR sensor package fabrication.
- High throughput of up to 250 units/min.
- PVN is sole provider of conductive ink for next generation of automotive electronics.
- \$12M EU funded project.



Commercial Applications & Markets Served



Automotive Windshield



PCB on FR4
Resistivity $< 10 \mu\Omega\text{cm}$, Thickness $< 10 \mu\text{m}$.

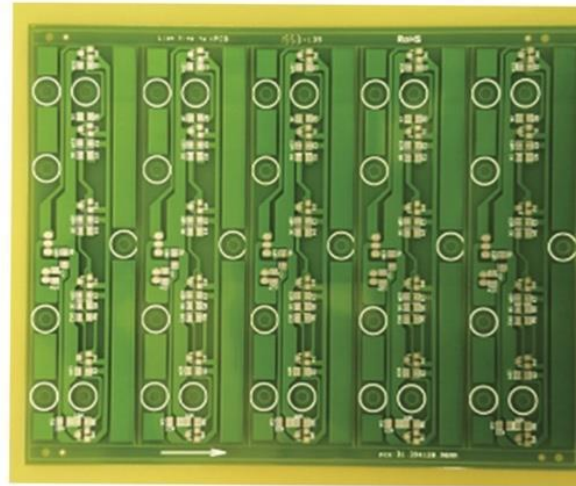


Special Heater on FR4,
Inkjet printed $600 \mu\text{m}$ vias

Commercial Applications & Markets Served



4-Layer PCB
Resistivity $< 6 \mu\Omega\text{cm}$, Thickness $20 \mu\text{m}$

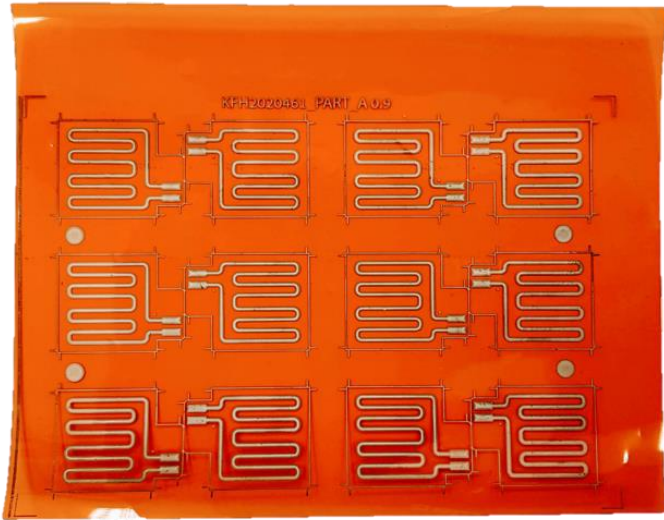


1-Layer PCB Inkjet Printed
Conductive, Solder Mask & Legends

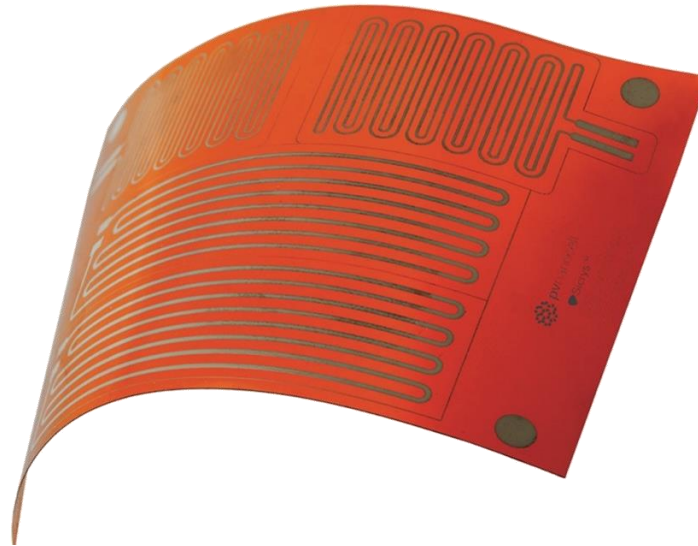


Coil with 18 Turns
Linewidth $70 \mu\text{m}$. Pitch $70 \mu\text{m}$.

Commercial Applications & Markets Served



Commercial 11W Heater on Kapton®
Linewidth 150 μm . Thickness 2 μm .



Flexible Antenna



RFID Tag

Commercial Applications & Markets Served



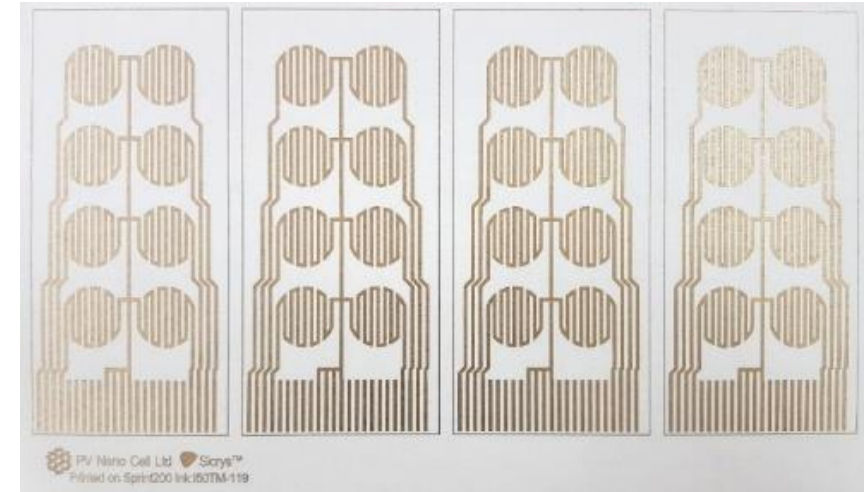
Phone Antenna

Aerosol Printing, Resistivity <math>< 12 \mu\Omega\text{cm}</math>



Silicon Crystalline Solar Sell

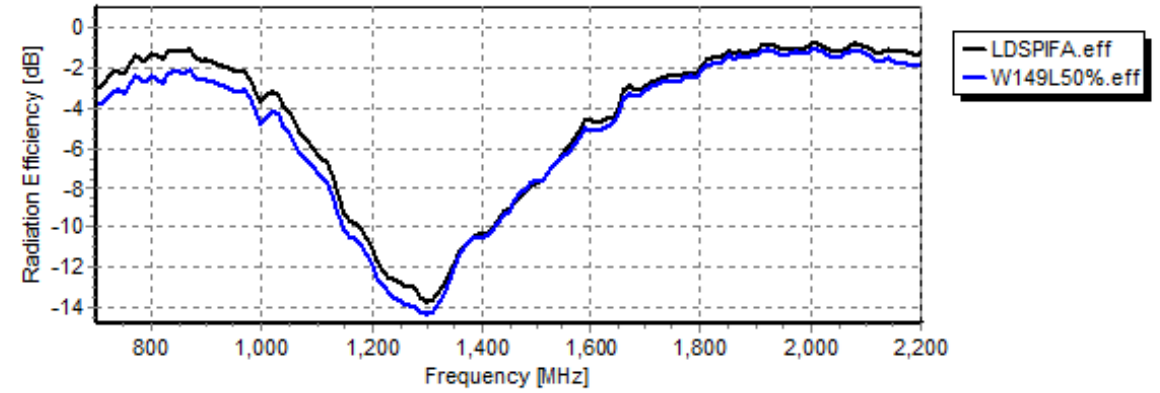
Linewidth 50 μm , Resistivity <math>< 3 \mu\Omega\text{cm}</math>.



Medical Sensor on Paper

Resistance <math>< 20\Omega / 100\text{mm}</math>

Printed Antennas



LDS vs Printed



Wearable Frame

Wi-Fi / Bluetooth

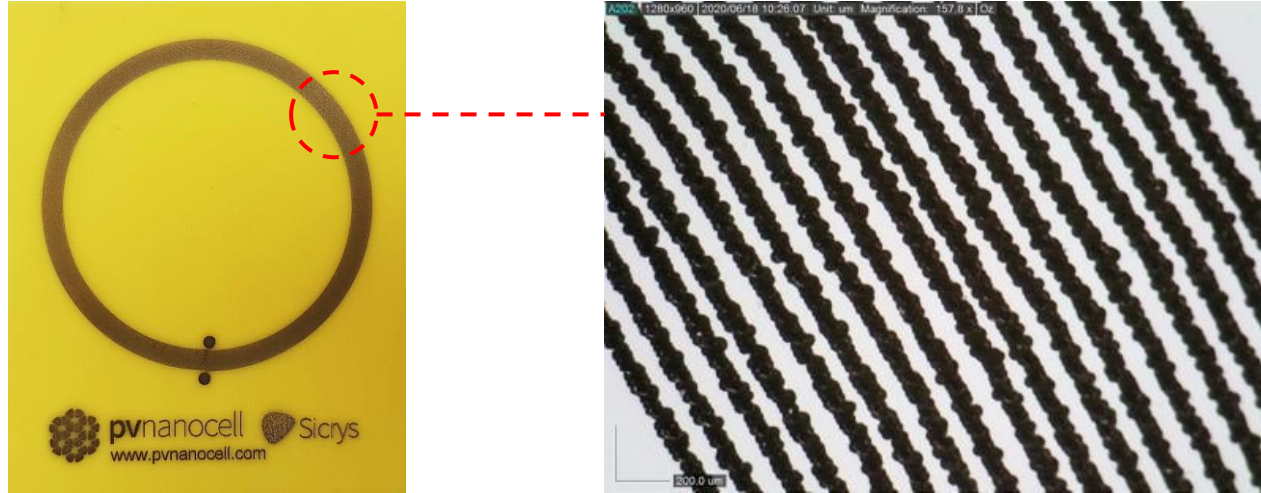
Battery Cover

NFC on Flex

Electronic Housing

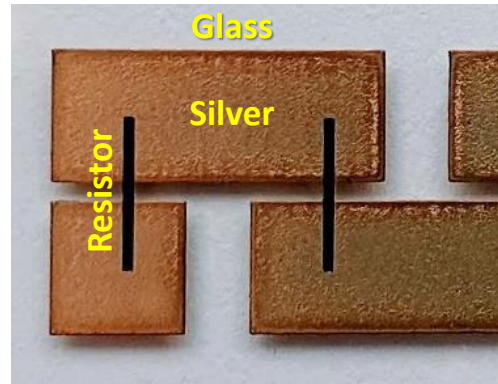
4 Antennas on Cover

Embedded Passive Components

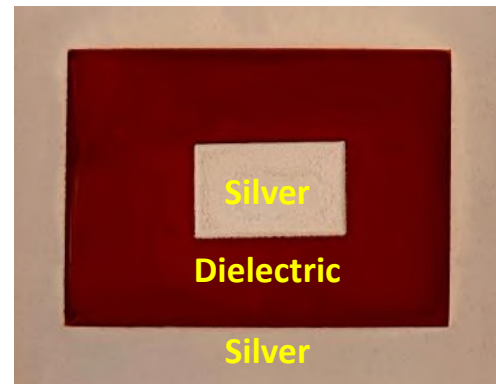


Coil with 18 Turns. 70 μm Width & Pitch. Resistivity: 10 $\mu\Omega\text{cm}$. Printed on FR4.

Selected Resistance Results on Glass					
Sample #	width [μm]	Thickness [μm]	Resistance [Ω]	SR [Ω/sq]	Width [μm]
1	70	0.7	1795	4.2	71.56
2	90	0.8	1291	3.9	90.71




Embedded Printed Resistor



Embedded Printed Capacitor

Selected Capacitance Results & Dielectric Constant Calculation					
Area = pad size	Meas. point #	Thickness [μm]	Average* [pF]	Standard Deviation*	Relative Dielectric constant ϵ_r
1.5x1.5mm	1	13.6	7.7	5.3%	4.84
	3	9	11.4	5.9%	
	5	11.75	8.3	5.2%	
	10	11.25	7.7	5.9%	
	12	7.35	11.6	4.9%	

*Over frequency capacitance



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