Multi-Technology Electronic Printing on Ultra-Smooth PowerCoat Paper

Michael Carlisle, Gael Depres, Victor Thenot,
Nadège Reverdy-Bruas, and Denis Curtil

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Abstract

Today, Printing electronics is mainly done on glass and plastic films (PET, PI...) by using printing techniques very close to those used in the graphic industry. Paper is not used, because it has a porous and rough surface and it has not a very good resistance to temperature. That's why Arjowiggins developed a specific paper, made with cellulosic fibers and a special coating. This paper, named PowerCoat, has a very smooth surface, measured with AFM below 10 nm (Ra). This smooth surface is ideal for manufacturing very accurate patterns and prevents the conductive particles to penetrate into the surface.

Another advantage of PowerCoat is its temperature resistance. All the chemicals, in the paper and its coating, which were unstable at high temperature were removed and replaced by temperature resistant chemicals. Thus, the sintering of the ink can be done with an air tunnel at 180 °C during 5 minutes and by using photonic sintering techniques like near-infrared (NIR) or Xe pulsed light.

At these high temperatures, the ink is better sintered and higher conductivity were achieved, especially with silver nano-particles inkjet inks for which the gain was very high.

Different patterning techniques were used during this study: screen printing, flexography, inkjet, laser ablation and conventional graphic ink printing.

For all these techniques, we compared the results of conductivity obtained on plastic and on PowerCoat paper using different conductive inks.

Arjowiggins Creative Papers

We also give some examples of demonstrators we manufactured using multi technology printing, including graphic printing.

Introduction

Printing electronics is a growing science with each year new applications on the market. The purpose of this science is to print electronics devices (resistors, capacitors, inductances, diodes, transistors, memories, screens...) instead of using the standard electronics methods which used thin film deposition and chemical ablation. Thus, an additive process is used instead a subtractive process [1].

Printed electronics has a lot of advantages: low cost investment, large area, small or big production runs depending on the techniques. But the main disadvantage at this time is the resolution, that is to say the smallest line you can print: 5-50 µm depending on the techniques. It is 1000 times lower than the standard electronics process.

That is why, there is currently a race to improve the resolution of printed electronics and paper is almost not used because of its bad surface properties [2].

But when the targeted applications involve graphics or packaging products generally made of recyclable materials, the only solution to marry printed electronics and graphics is to glue or to laminate plastics on paper which consists in adding an extra step in the product integration and is not easily recyclable.

The purpose of this work is to develop a range of recyclable papers with the same smoothness as commonly used plastics films and with a better temperature resistance.

Materials

The characteristics of the papers developed were compared with plastic substrates commonly used in the printed electronics industries.

For the substrate, we used:
- Heat stabilised PET: Polytherm 125 from DuPont,
- PEN: Teonex Q83 from DuPont
- Polyimide named Kapton from DuPont
- PowerCoat HD paper from Arjowiggins Creative Paper
- PowerCoat XD paper from Arjowiggins Creative Paper
- Standard coated paper Chromolux from Zanders

For screen-printing, the following inks were used:
- DuPont 5064 (silver ink)
- DuPont Alloy PE815 (alloy of silver, tin and copper)
- Novacentrix Copper ink ICI-021

For the inkjet inks:

- Sunjet U5603 silver from Sunchemical

For flexographic inks:

- Novencentrix water based silver inks HPS-021LV for screen printing thinned with water to achieved the right viscosity

Methods

Different printing devices were used during this study. For Screen printing, a DEK Horizon 03i machine was used with a 195 (77/48) with 9µm emulsion screen.

For inkjet, a Dimatix DMP 2800 was used for flexographic; a RK roll-to-roll printing pilot machine was used. For laser ablation, a Tamarack YAG laser was used.

The AFM used for roughness evaluation was an INOVA apparatus from Digital Instrument, and the roughness Ra was measured on a 5 µm by 5µm area.

The thickness of ink was evaluated with SEM with cross-section images.

The conductivity and resistance of layers were measured with a 4 probes micro-ohmeter.

The Young Modulus was measured using a DMA RSA3 apparatus from TA Instrument.

For the drying and sintering of the inks, we used a standard oven, a Near Infra-Red lamp from the company ADPHOS and a pulsed Xenon lamp from the company Xenon.

Results and discussions

The PowerCoat range is composed of 2 grades: HD and XD. The formulations are similar but the coating process is different for each grade. The roughness was measured using an AFM apparatus and compared with other substrates like PET, PEN and PI. Figure1 summarizes the results:

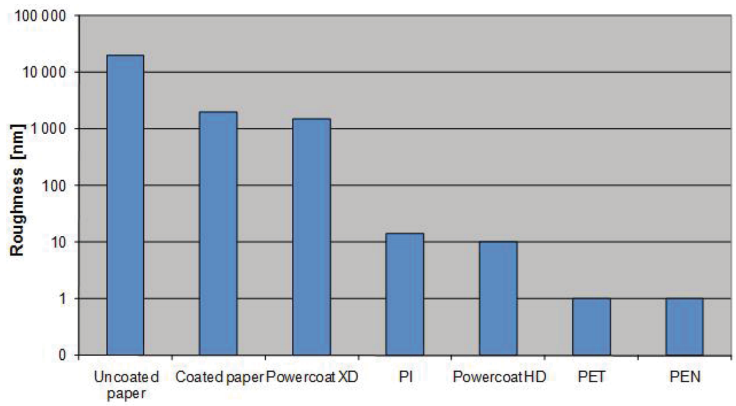

Figure 1: *Roughness of different substrates*

The smoothness of PowerCoat XD paper is similar to a coated paper used in magazine but the smoothness of PowerCoat HD is close to the plastic used in the electronic industry (PET, PI, PEN) with a value of 10 nm. The good result is due to the patented [3] coating process used for this grade. Some authors [4, 5,6,7] reported that smoothness is one of the main properties to achieve good conductivity of the ink film.

Temperature resistance of the substrate was also quantified to determine at which temperature the sintering of the inks could be done without damaging or yellowing the substrate. The Young Modulus was measured on a temperature range from 50 to 250 °C with a 2°C per minutes ramp. Figure 2 shows the results.

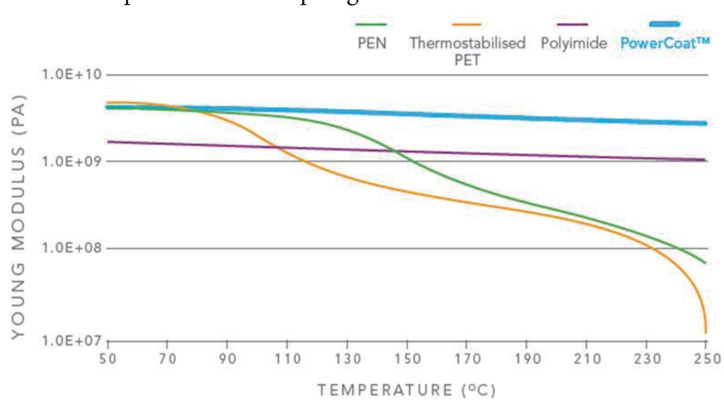

Figure 2: *Young Modulus in Machine direction vs. temperature of different substrates*

For PET, the modulus drops sharply at 90 °C. The value is slightly better with the PEN which drops at 120°C. These temperatures correspond to the polymers glass transition [8] and will limit the sintering step. On the contrary, PowerCoat paper has the same trend as the polyimide, that is to say a very stable modulus even at high temperature, up to 220°C.

These good results with the paper allow to carry out efficient sintering process, even under tension (Roll-to-roll).

After these preliminary tests, several printing tests were carried out using different methods: screen, inkjet, flexography, laser ablation, graphic.

With screen printing, 3 kinds of micro particles inks were used, one made of silver particles, one made of an alloy of silver, tin and copper and the last one made of copper. These inks were printed on different substrates and with different drying conditions (oven, NIR, pulsed Xe). Table 1 summarizes the results for silver ink.

	XD	HD	PET	PI
	Resistivity (μΩ.cm)			
Oven (140°C – 15 min)	49	36	33	34
NIR	31	20	60	40
Pulsed-Xe	44	23	No data	

Table 1: *Resistivity results obtained with silver ink by screen printing on PowerCoat XD and HD and on plastics (15µm of ink thickness).*

With an oven drying at low temperature (140°C), similar results were obtained on PowerCoat HD, PET and PI as their smoothness are very close. For PowerCoat XD, as it is a little rougher, the resistivity is slightly higher. However with NIR sintering, results are very good on PowerCoat papers because of their very good temperature resistance. With Pulsed-Xe light, electrical performances are close to NIR for PowerCoat HD grade

With alloy ink (table 2) resistivity is 3 to 4 times lower with NIR than with an oven sintering at 200°c for 5 minutes. We also demonstrate that this ink is very sensitive to temperature as we can see on figure 3. In this case, a NIR drying is strongly preferable than an oven drying.

	PowerCoat HD
Oven (200°C – 5 min)	405
NIR Sintering	100 - 125

Table 2: *Resistivity [µΩ.cm] results obtained with alloy ink by screen printing on PowerCoat HD only (20µm of ink thickness).*

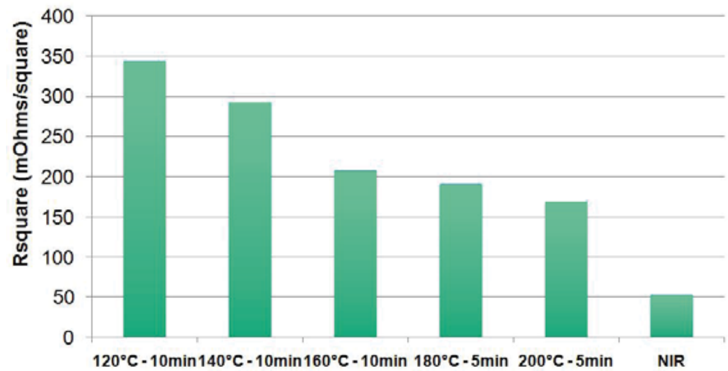

Figure 3: *Resistance of the printed silver alloy inks on PowerCoat HD vs. Sintering conditions (20µm of ink thickness).*

Some trials were conducted also with copper inks on PowerCoat HD and XD with Xe pulsed light sintering. Good preliminary results in terms of adhesion were achieved on XD and rather good conductivity (60-120 µΩ.cm).

For inkjet, we compared the resistance of silver nano particles on different substrates. On PET, as the sintering cannot be made above 120°C because of the temperature resistance of this plastic a value of 10 ohm/sq was obtained.

On PEN, the temperature of sintering can be a little higher and a resistance of 1 ohm/sq was reached for a 140°C sintering.

For standard coated paper, a high resistance was obtained and a yellowing of the paper was observed from 150140 °C.

With PowerCoat paper sintering could be made at higher temperature (above 200°C) and a square resistance below 0.1 ohm/sq was reached that is to say a resistivity down to 10-12 µΩ..cm (about 6 time more than silver bulk).

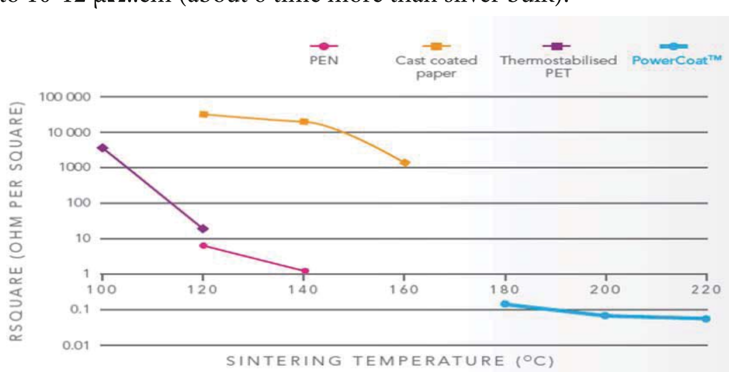

Figure 4: *Resistance of silver inkjet inks on different substrates sintered at different temperatures (depending on the temperature resistance of the substrate).*

The trials carried out with the flexographic press were done using a flexographic head on a RK coater pilot machine (figure 5).

Figure 5: *view of the graphic print head*

Table 3 shows the results of the inks printed by flexographic on PowerCoat. On PowerCoat HD, the resistivity is better by 20% vs. XD because of the smoothness of the paper. On PowerCoat XD, resistivity is twice better than oven sintering at 180°C. In general, resistivity is quite low and similar to screen printing and excellent results were achieved in roll to roll printing at high speed using NIR sintering on PowerCoat papers.

		OVEN (180°C – 5 min)	NIR
HD 230	Rsquare (mΩ/sq)	0,5	0,4
	Thickness (µm)	0,6	0,6
	Resistivity (µΩ.cm)	30	24
XD 125	Rsquare (mΩ/sq)	1	0,46
	Thickness (µm)	1	1
	Resistivity (µΩ.cm)	100	46

Table 3: *Square resistance and resistivity of flexographic inks on PowerCoat paper sintered in oven or with a NIR apparatus.*

Some trials were also carried out by covering the whole paper with a thin layer of gold metal by sputtering (30 nm in thickness). Then, some areas of metal were removed using a laser. This technique, used in the electronic industry allow very sharp pattern, as low as 5-10 µm.

This technique was combined with spin coating and screen printing to manufacture tiny capacitors (figure 6).

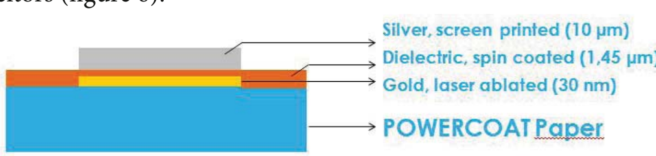

Figure 6: *structure of the capacitors realized.*

Capacitance and leakage resistance of the capacitors (figure 7) were measured. The obtained results were very similar to capacitors manufactured on PEN, which proves that PowerCoat HD paper can replace preferably plastics to manufacture greener electronic devices.

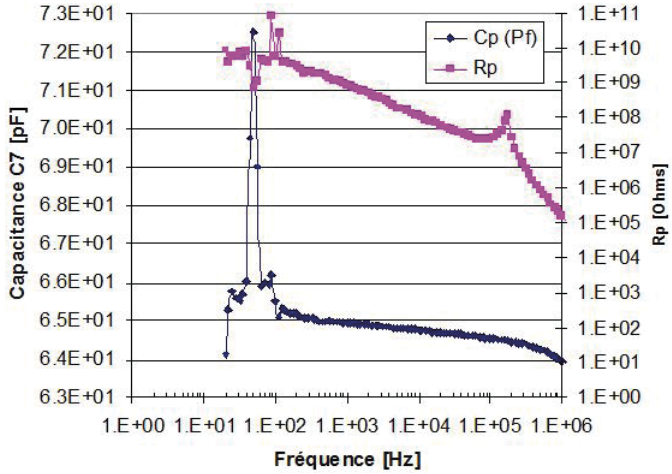

Figure 7: *capacitance and the leakage resistance of the capacitors printed on PowerCoat HD.*

Because PowerCoat paper has an excellent printability with graphic inks, it makes possible to integrate visual content onto flexible Electronics products and Printed Intelligent Features onto Graphics & Packaging Products. It lowers the cost and makes the product recyclable.

Graphic printing can be done on standard laser printer, on HP indigo, on offset machine and screen printing as well. An example of graphic and electronic printing is shown on figure 8. A PowerCoat HD paper was printed by screen with a silver ink to realize the circuitry. Then graphic and thermochromic inks were printed on top. When a 9V battery is apply on the two plots of the circuitry, it warm up the silver circuit at 40 °C and, as some parts of the letters are printed with graphic and thermochromic blue (same color), the heat makes some parts of the letters to disappear.

Before the use of the Battery ***After the use of the Battery***

Figure 8: *PowerCoat HD screen printed with silver, graphic and thermochromic. A 9 V battery makes disappear some part of the letters to let the sentence "paper is alive" appears.*

Conclusions

A specific paper was developed, named POWERCOAT, which provides the ideal substrate for even the most demanding printed electronics applications.

It can be printed with all the different techniques, screen printing, flexographic, gravure, and laser ablation and also with the standard graphic techniques and inks.

This excellent result is performed thanks to the very high smoothness, high thermal resistance and stability of POWERCOAT paper which makes possible to sinter it at high temperature even with a roll to roll technique.

Demonstrators were developed using multi-technology printing to realise working devices, like the "paper is alive" demonstrators.PowerCoat's ability to couple electronic and graphic printing, opens up a world of possibilities:

- Integrating intelligent functionality in disposable labelling and packaging,
- More efficient production of RFID antennae with significant ink savings,
- Manufacturing of passive components: resistors, capacitors, self-inductance... Lighting and display circuitry compatible with large area flexible products
- Battery electrodes, sensing technology

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