Printed Circuits from Light

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Most of us have seen printed circuit boards (PCB) because they are prevalent in so many of the electronic products we use in our everyday lives. We are even more familiar with printed materials ranging from newspapers, magazines and decorative markings on packaging. Both these technologies are well established and have similarities as well as major differences.

Printed circuits serve a function. On a PCB for example there are traces needed to conduct electricity form one point to the next. If there are electronic components then they too serve a function; a light emitting diode (LED) may be used for illumination, a switch may act as an interface to provide human control with the system.

On the other hand printed materials have no particular function apart from the requirement of creating an image based on the pattern that is formed. This image may be text or some graphics. Multiple pigmented inks can be used to provide color information to the viewer. They are typically not required to perform functions.

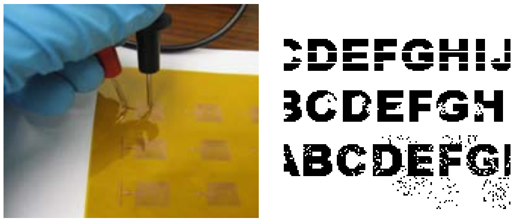
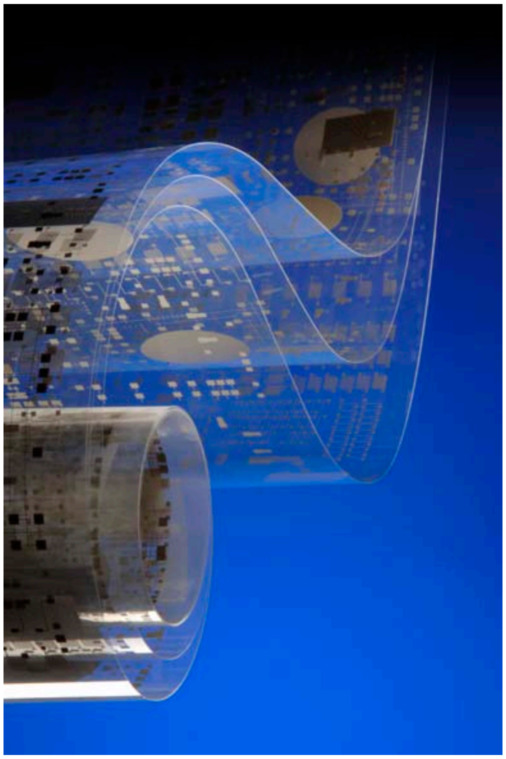


Figure 1: Resistance is important for functional inks and any defects are significant whereas regular printing is more forgiving

A key difference between PCBs and printed materials lies in their basic development process. Standard printing is an additive process where the ink is used only where ink needs to be placed, thus minimizing the use of ink. PCBs on the other hand are typically fabricated in a more complex manner.

First a sheet of copper is bonded to a rigid material like fiberglass. Then the sheet is coated with a layer of photo sensitive material called etch-resist. This is then exposed to a light with a mask which allows selective regions to remain unexposed. Then the treated sheets are etched by immersion in an acid bath. The acid penetrates into the unexposed etch resist and removes the copper. The copper that remains form the traces on the PCB. This process is repeated for multiple layers of the PCB and these layers are bonded together. Holes are then drilled into PCB called vias which allow for connections between various layers. As we start from a complete sheet of copper, this technique is a subtractive process and is wasteful of chemicals and copper. Furthermore the process is quite complicated requiring many specialized steps.



Another key difference is that typically PCBs are based on rigid materials to allow for components to be easily added. Printed material on the other hand enables the use of many different lower cost substrates like paper and plastics. A lot more options are available for printing, for example; ink jet printing, silk-screening or gravure printing. These are relatively simple processes requiring deposition of ink and drying.

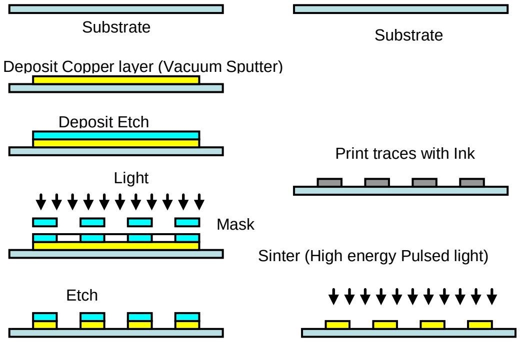


Figure2: Comparison of Standard Printed Circuit Manufacture and Photonic Sintering

In most printing applications repeatability and accuracy is not essential. These defects are typically tolerable and at worst they may produce scrap prints. PCBs on the other hand are a lot less tolerant to defects. These defects can cause short circuits or open circuits and produce non functioning equipment. Precision in PCB manufacturing is vital for defining the feature size (the minimum width of the traces and gaps between adjacent traces). A rigid substrate offers a clearer definition of these tolerances.

As electronic systems become more prevalent and in some cases disposable, the desire to find low cost alternatives to current PCB manufacture has increased. Furthermore, as these systems find inroads into everyday products, requirements such as being foldable or flexible become a significant value for the product. As an example, RFID tags are used as electronic systems that can be applied to track or monitor goods for a short time after which they may be discarded. For these requirements, the use of large scale roll-to-roll printing processes is a very attractive alternative and is often referred to as Printed Electronics (PE).

One of the key hurdles of using the standard printing process for PE is the deposition of conductive traces on a flexible substrate like paper or plastic. The main reason is that these traces need to have a low resistance value to be efficient. In the case of PCBs these are solid sheets of metal and so typically have very low resistance. In the case of PE they need to start in the form of a liquid ink that can be easily deposited on the substrate by the printing process and then converted to a solid uniform layer of conductive material. This requires the ink be sintered to go from its powdered form in the ink to a solid conductive trace. Additionally the liquid carrier medium has to be removed. A conventional sintering process requires heat above 150°C and therefore does not lend itself to printed electronics because of resulting damage to the substrate the ink is deposited on. Metals have a higher melting point than the flexible substrate and so it would seem that it would be impossible to achieve sintering without subsequent damage to the substrate.

One common type of conductive ink is silver flakes. These are microscopic flakes that are suspended in an emulsion. Once the ink is deposited on the substrate the emulsion is evaporated away to leave the flakes thus forming a conductive layer. The flakes are not bonded together and conduction occurs from contact between the flakes. Typically silver flakes are used because metals tend to oxidize and both silver and silver oxide is conductive so oxidation is less of an issue. Removal of the emulsion can be achieved either as a low temperature oven over time or by use of high energy pulsed light.

More interesting is the use of nanotechnology for the formulation of inks. Nanotechnology is based on particles whose size is in the region of 1 to 100 nanometers.

The basic properties of the nano-scale material changes. All materials have basic physical and chemical properties; these include melting point, color and reactive characteristics which are traditionally considered independent of volume. As an example the melting point of one kilogram copper is the same as the melting point of one ounce of copper. The color of gold is the same if it was seen through a microscope as when observed on the roof of a building. However, when materials are converted to nanoparticles these characteristics start to change.

The first important change is the change in their melting point. This is termed melting point depression and is a phenomenon that occurs when the surface area to volume ratio is increased as the particles becomes smaller. In metals the attractive forces of the core of the clusters are too weak to keep the surface atoms from being mobile and so the melting point starts to drop significantly as the particle size is made smaller.

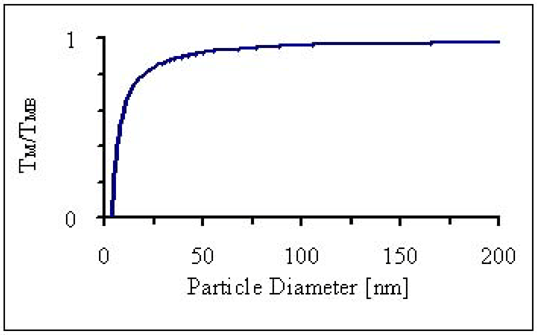


Figure 3: Melting point depression for Gold based on particle size

$$T_M(d) = T_{MB}\left(1 - \frac{4\sigma_{sl}}{H_f \rho_s d}\right)$$

Where: T_{MB}=Bulk Melting temperature
σsl=solid liquid interface energy
H_f=Bulk heat of fusion
ρ_s=density of solid
d=particle diameter

Because of the low temperature melting point of nano materials, low temperature ovens that do not damage the substrate can be used to sinter the nanoparticle into a homogenous conductive layer on the substrate. However, typically for these conductive inks the time required for sintering can be in the order of tens of minutes and therefore this technique is not preferred in high speed roll-to-roll applications.

Another important change is the way that these nano-particles interact with light. Light has wavelength and frequency and for visible light the wavelength is in the range of 400 to 650 nm. When particle sizes become smaller than the wavelength of light, the electromagnetic field of light can modulate the electrons of the atom. This changes the absorption characteristics of the material. This absorption characteristic is related to particle size. The energy absorbed from light is sufficient to cause increased mobility of the atoms and can cause sintering.

The combination of melting point depression and absorption characteristics changes mean that ink composed of these nanoparticles can be sintered at a low temperature with light. Once the material has been sintered with light the nanoparticles form large metallic structures and lose their nanoparticle properties. Using nanotechnology, conductive traces can be deposited and then formed on the substrate in a simple two step process that is very similar to a standard printing process. One advantage of using high energy pulsed light is that the sintering process can take fractions of a second to completely sinter the material and this process lends itself to roll-to-roll application.

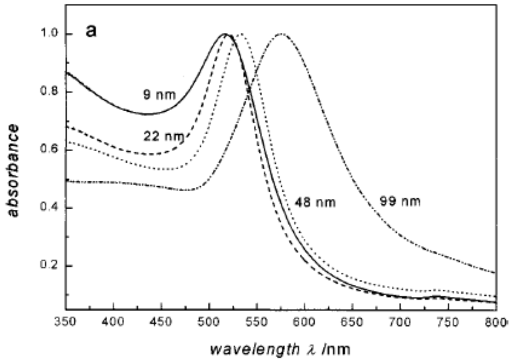


Figure 4: Absorbance characteristic change for Gold based on particle size

A number of nanoparticle conductive inks exist but the two main categories are silver nano-inks and copper nano-inks. Although they seem similar, there are some significant differences between the two inks. As mentioned earlier the oxide of silver is conductive. However, copper oxide is non conductive and copper oxidizes more readily. For this reason copper nanoparticles require some form of coating to prevent them from oxidizing. These coatings can be a protective polymeric or metallic shell which must be removed during the sintering process. Additionally agents can be applied to the emulsion to reduce copper oxide to copper. Though it is currently harder to manufacture suitable copper inks for sintering, the benefit of lower resistivity and lower cost of raw materials make it a viable alternative for PE.

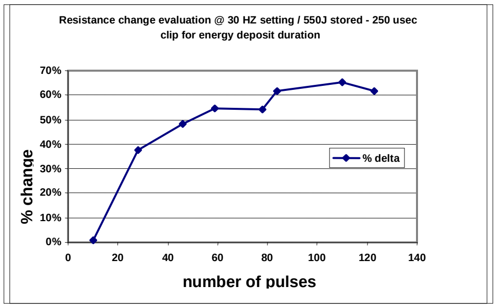


Figure 5: Graph showing how multiple pulses reduces resistance with Silver Nanoparticles

Another important difference between silver and copper is how they sinter with pulsed light. Though not all silver nano-inks are the same, typically, they do lend themselves to multiple flashes that bring the resistivity down. They also have a large operational window which means that there is a large range of pulse energies that can be applied without evaporation of the metal inks and still positively impact resistance. This reduces issues related to stitching as multiple pulses are required over the boundary between sintered areas as the roll passes under the flash lamp source.

Again not all copper inks are the same, and in some cases it is found that the operational window between when sintering takes place and when the material is destroyed is small. This means a tighter control of the optical energies is required and boundary conditions where stitching takes place can be a potential problem. Careful use of masking techniques and control of optical energies can generally mitigate these problems.

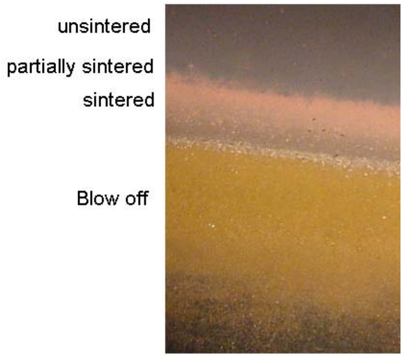


Figure 6: Copper Nanoparticle on Kapton with different intensity of light showing regions that are unsintered, partially sintered, sintered and evaporated

Photonic sintering uses light to sinter material. By using high energy flash lamps high peak power pulses can be generated. They are capable of delivering significantly greater peak energies compared to continuous sources like mercury, fluorescent or halogen lamps by storing energy over time and delivering it as a short duration high intensity pulse. Xenon arc lamps generate light by using high voltage to breakdown the inert gas within the lamp envelope creating a conductive discharge path where the flash exists. These lamps are broadband incoherent sources with spectra ranging from the deep UV to the Infrared. Use of flash lamps includes sources for Lasers, beacons, UV Curing, solar simulators and sterilization. Because typical flash lamp use is with a very short on time compared with off time, they are very effective at delivering high peak photonic power without significantly increasing the surface temperature of the object being illuminated. Typical on times can be in the order of a few microseconds to milliseconds with duty cycle ranging from tens of hertz to a few hertz. In these very short durations peak powers of a few Mega Watts can be generated. By adjusting the voltage and the current delivery through the lamp, they can be tailored for specific application delivering repeatable and uniform intensities over a broad spectrum. These are ideal characteristics for sintering applications. High peak power means that there is a greater penetration depth and also sufficient energy for useful work particularly in the case for sintering. By delivering this energy over a short time means that substrate temperature rise can be very small in the range of a few degrees.

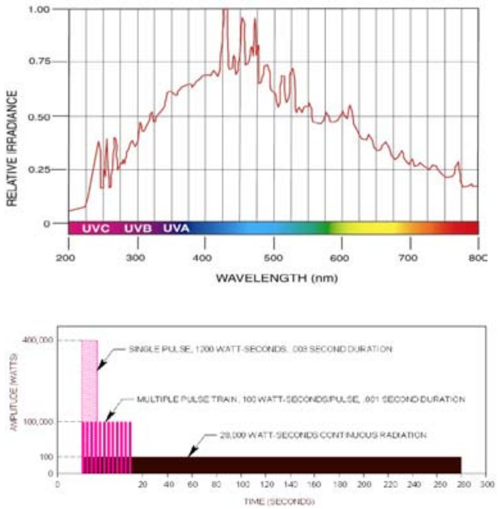


Figure 7: Spectra of Xenon Flash Lamp and image below shows how high energy can be delivered using short pulses

Xenon Flash Lamps are manufactured with a low pressure xenon gas inside a transparent envelope. There are two electrodes typically made of different materials; the cathode is typically barium doped and designed to have a low work function for the generation of electrons whereas the anode is usually made of tungsten to sustain the bombardment of electrons during a flash. These lamps do have a polarity and improper connection of the lamp can cause lamp damage and early lamp failure. During normal use the electrodes are damaged, metal particles get deposited on the glass and other aging effects take place with the result the intensity falls off. This gradual fall off in intensity defines the lamp life time and is usually reported in millions of pulses at typical use and is approximately the number of pulses for the lamp to remain within 20% of the initial intensity. This value would change based on the energy of the pulse and cooling. If the lamps are driven with lower energy, the lifetime of the lamp can be significantly increased.

The lamp envelope defines the physical lamp profile. The material used for the envelope can define the output spectra from the lamp. If deep UV is required, Clear Fuse Quartz (CFQ) is used but high energy flashes from this source can generate significant amounts of ozone which may not be desired. Alternates include Germisil which blocks UVC and therefore does not generate ozone. The envelope thickness, bore diameter, length and gas pressure are important parameters in defining the optical power that can be safely generated by the lamp. A theoretical limit called the explosion energy for the lamp is a function of some of these parameters and is the energy that can catastrophically destroy the lamp. Typical operation of the lamp is set at 10% of this explosion energy.

Figure 8: Xenon Flash Lamp

Electronics to drive flash lamps can be quite simple comprising of a high voltage supply, a storage capacitor, a pulse forming inductor and a trigger circuit. However, due to the high power requirements of the system special design requirements need to be met in terms of safety, noise immunity and power management.

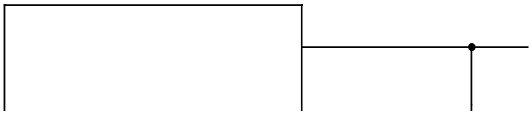


Figure 9: High Voltage Flash lamp circuit

As mentioned earlier lamp cooling is a very significant component of the optical system and sets the operational limits of the lamp and affects lamp life. Air cooled lamps use forced air for cooling offers the simplest solution for most applications. Water cooled Flash lamps also exist. They have the advantage of offering higher power solutions but they tend to be more costly and complex. Maintenance of a water cooled system is also more complicated to mitigate risks associated with the close proximity of water and high voltage.

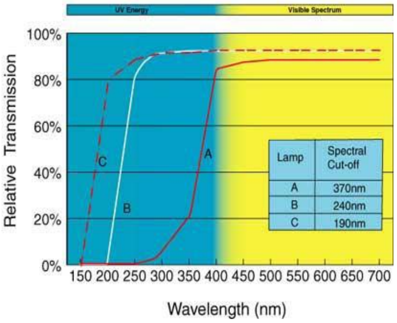


Figure 10: Transmission characteristics of different envelope types

For roll-to-roll systems, simplicity is the key to successful deployment of the process. The solution offered by photonic sintering from this perspective looks very attractive. First we have an ink deposition phase which lends itself to standard printing processes. Then an ink drying phase which is also standard can take place. The only additional step is the photonic sintering phase which can be as easy as a retro fit of a Xenon flash lamp over the web. There are no additional process requirements like pressure, special gas or chemicals. Dwell time in the photonics sintering is not an issue as the reaction is instantaneous as opposed to thermal sintering which can take minutes. What does need to be considered however is the pulse rate, to control the overlap of the photo-sintered regions avoiding overexposure or banding if there is a gap between the two adjacent regions.

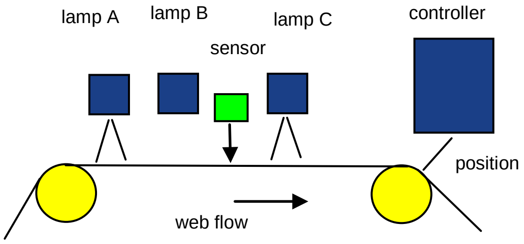


Figure 11: A Roll to roll sintering system with sensor to control intensity

Another consideration in photonic sintering in a roll-to-roll application is the monitoring of the process to ensure that the desired functional characteristics of the process are being met. If for example, regions are not sintered due to banding, then these regions can create non-conductive traces and non functional circuits. This can be achieved by rolling resistivity measuring devices and markers that can be used to control the process flow. Dynamic monitoring can quickly identify faults and stop the process from generating wasted material if desired.

The flexibility of the technology can be illustrated by considering the range of different materials and substrates that have been successfully processed with low temperature photonic sintering.

The successful adoption of photonic sintering depends on a structured development plan. Firstly, the formulators of conductive inks require low cost tools for evaluation and testing of their formulations. The print process manufacturer needs tools for small scale testing of the process and process manufacturer needs to have confidence that this technology will be robust enough for a wide range of current applications and that a suitable solution is available that can be tailored to their own process requirements. This synergy needs to be established without individual groups feeling that their proprietary contributions are not compromised. What ultimately will drive this technology are lower costs. Photonic sintering using Xenon flash lamps realizes these challenges adequately.

Figure 12: Xenon Electronic tool for evaluating Photonic Sintering

For more information please visit
www.xenoncorp.com/sintering