ORNL Manufacturing Demonstration Facility
Technical Collaboration **Final Report**

Photonic Curing of Metal Films for Direct-Write Sensor Development[1]

NovaCentrix

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Company Size: Small business, with <50 employees

Summary
The collaboration between NovaCentrix and ORNL focused on the photonic curing of metal interconnects inkjet-printed on low temperature substrates. The combination of additive inkjet printing and photonic curing was explored for flexible electronic applications. High conductivity Ag and Cu interconnects were demonstrated exploiting photonic curing pulses as short as 250µs in duration. An all-printed electronic circuit was developed to demonstrate the potential of innovative photonic curing technique and additive digital printing to meet the demands of high volume and low-cost roll-to-roll manufacturing technology. The demonstrated performances of metal interconnects and printed circuit and component show promise for the realization of a fully printed multifunctional sensor platform exploiting roll-to-roll manufacturing technology.

Background
Printed electronics is an emerging processing technology for a new generation of large-area multifunctional devices. Recent advances in low cost and all-printed flexible devices could impact diverse technology sectors such as healthcare, automotive, consumer electronics, and defense. Printed and flexible devices offer distinct advantages of light-weight, conformal profile, and hybrid integration to realize diverse sensor platforms. A key obstacle to achieving high performance flexible electronics is the temperature limitation imposed by low cost polymer substrates (~200°C). The combination of the inkjet printing and photonic curing technology was explored to develop highly conductive digital traces on temperature sensitive and flexible substrates.

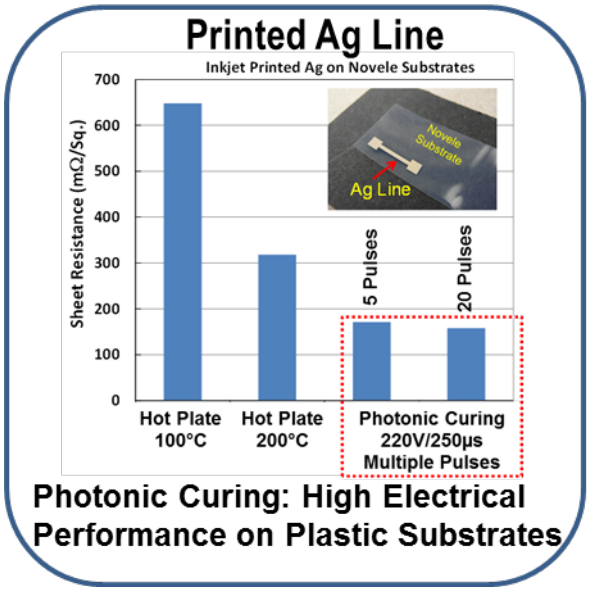
NovaCentrix is a leading manufacturer of the state-of-the-art photonic curing tools and functional materials. PulseForge® line of photonic curing tools are engineered by NovaCentrix to meet the demands of the next generation of low-cost flexible electronics

[1] Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

and sensor technologies. PulseForge® tools use the photonic curing process to heat thin films using novel flash lamp and power supply technologies to deliver continuously adjustable, megawatt intensity, microsecond resolution pulses of broad-spectrum light. The high intensity, short duration broadband light generates very high processing temperatures required for thin film densification, recrystallization and annealing, but without damaging the underlying low-temperature substrate material or co-integrated electronics. NovaCentrix's Metalon® conductive inks are formulated to provide high conductivity traces for additive manufacturing of printed electronics like photovoltaic devices, RFID, smart cards/labels, displays, and advanced packaging. Low thermal budget sintering of functional inks is critical to realize low-cost, flexible electronics on paper and plastic substrates. The present development activity aimed at bringing together the elements of photonic curing and inexpensive, high performance metal nanoparticle inks to realize multi-functional direct-write sensor technology.

Technical Results

Photonic curing technology was explored to develop high performance electrical interconnects using Ag and Cu inks received from NovaCentrix. Metal nanoparticle inks have the potential to meet the low processing temperature and high electrical conductivity demands of flexible printed circuits. PulseForge 3300 system was used to cure metal lines inkjet printed on low-temperature polyethylene terephthalate (PET) substrates. Electrical conductivity of the metal lines was measured to analyze the impact of photonic curing conditions and establish the process window for practical applications. The main findings are highlighted in the following sections.

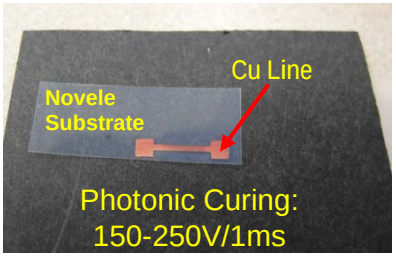


Inkjet Printing of Ag Metal Lines for Flexible Electronics

- High Ag line-definition on Novele substrates
- 20µm drop spacing results in good printing profile and adhesion characteristics
- Photonic curing results in superior electrical conductivity characteristics using photonic pulses as short as 250µs in duration

Copper nanoparticle inks are being developed to replace Ag to meet the cost and performance demands of printed electronics. However, the inherent tendency of Cu nanoparticles to oxidize is a major technological challenge for electronic applications. To realize Cu based interconnects for printed electronics, an efficient photonic curing technology is required to prevent Cu surface oxidation and achieve high electrical conductivity at low temperatures. Photonic curing technique was explored for low-temperature curing of Metalon® ICI series of copper oxide inks under ambient conditions. The sintering process window was established in terms of electrical conductivity of printed Cu structures. A brief summary of the main findings follows.

Inkjet Printed Copper Interconnects



High Cu line definition

Low Sheet Resistance (304 mΩ/Sq) (using photonic pulses as short as 1ms in duration)

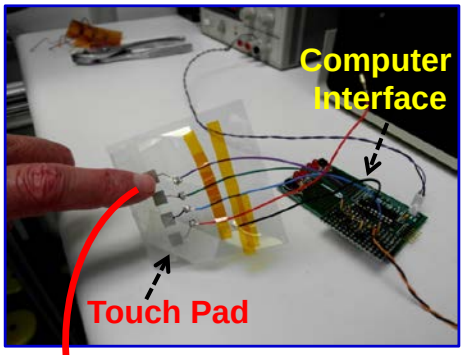
Cu Interconnects for Low-Cost Electronics

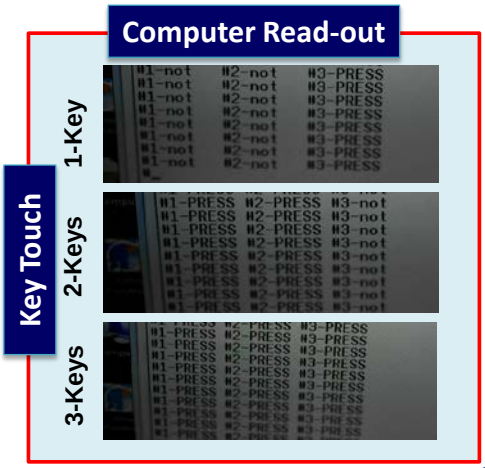
- Copper-oxide reduction inks convert to copper thin-film upon processing with a PulseForge® tool in open air
- Sheet resistance of 304 mΩ/Sq measured after single pass printing
- Electrical performance opens up new possibilities for printed electronics

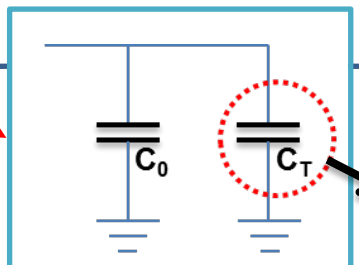
Capacitive touch pads were integrated on plastic substrates to demonstrate path towards disposable, flexible electronics exploiting inkjet printing and photonic curing techniques. Capacitive sensing technology is capable of high resolution sensing of both metallic and non-metallic materials making it attractive for diverse industries. The inkjet printed capacitive elements and associated electronics were designed to detect human touch. The printed touch sensor along with a human interface successfully demonstrates path towards hybrid printed electronics (printed interconnects + surface mount device (SMD) integration) to achieve high functionality at a low cost.

Printed Touch Sensor and Electronic Interface

Capacitive Touch Sensor Development





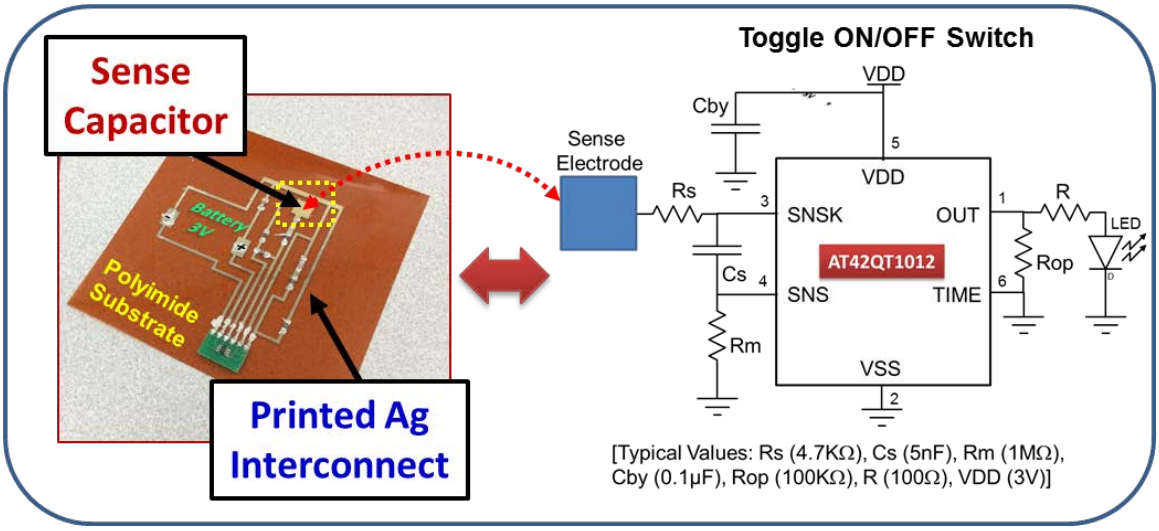


Capacitor Integration for Touch Sensor Development

- Rapid prototyping employing inkjet printing and photonic curing technology
- >10 pF increase in capacitance by finger touch suitable for touch sensor applications (Target: >1pF)

The ultimate goal of 2D and 3D additive printing technologies is to fully print electronic components and systems. An all-printed electronic circuit was developed to demonstrate the potential of innovative photonic curing technique and additive digital printing to meet the demands of high volume and low-cost roll-to-roll manufacturing technology.

Printed Capacitive Touchpad with Interconnects for SMD Integration



Fully Printed Capacitive Touchpad + Circuit

- Additive Integration: Inkjet-printed capacitive touchpad element and Ag interconnects for surface mount device (SMD) Integration
- SMD integration demonstrated using conductive silver epoxy. Commercial SMD pick-and-place machines are available for industrial scale integration.

Impacts

The emerging industry of large area roll-to-roll manufacturing and flexible electronics has the potential to revolutionize diverse technology platforms and create new markets. Printed electronics is bringing new opportunities for low-cost, additive-integration of advanced sensors on 2D/3D structures. The printed and thin film electronics market has been projected to be worth $44.25 Billion by 2021.[2] These systems promise to be a key example of how low cost electronics can be manufactured in high volumes and open new market opportunities. The NovaCentrix-ORNL collaboration aimed at bringing together the elements of photonic curing and inexpensive, high performance metal nanoparticle inks to realize multi-functional direct-write sensor technology. Photonic curing technology was successfully exploited for the low temperature integration of Ag and Cu interconnects on flexible plastic substrates. The demonstration of capacitive touch pad elements and fully printed circuit for sensor-SMD co-integration establishes the suitability of PulseForge® platform for advanced printed electronic applications. The established photonic curing process space for metal ink curing will enable NovaCentrix

[2] Das, Raghu and Peter Harrop. " Printed, Organic & Flexible Electronics Forecasts, Players & Opportunities 2011-2021." *idtechex.com*. IDTechEx, Aug. 2011. Web. 1 Aug 2012.

to capitalize on advanced materials and formulations to provide conductivity options for additive manufacturing of printed electronics. In addition, the scalable PulseForge® technology further establishes its ability for a wide range of applications not available with traditional electronics manufacturing, and also opens the door for high volume printing of electronic components and circuits meeting the cost and performance demands of roll-to-roll manufacturing technology.

Conclusions

ORNL and NovaCentrix collaborated to successfully demonstrate all additive integration of electrical interconnections and passive elements for flexible electronic applications. The combination of additive inkjet printing, high conductivity metal inks, and low thermal budget photonic curing technology demonstrated a clear path towards roll-to-roll manufacturing of electronic components and devices. The present investigation is an important foundational work in development of light-weight, flexible, and conformal printed sensors. Roll-to-roll production processes involving low temperature photonic curing systems and multisensor integration exploiting inkjet printing technology show promise for the realization of a fully printed multifunctional sensor platform for advanced defense, security, industrial, and environmental applications.

About the Company

NovaCentrix, based in Austin, Texas, develops, patents, and commercializes new technologies in printed electronics, nanoparticle manufacturing, pulsed power equipment, and related fields. To enable development and manufacturing of the next generation of electronics devices, NovaCentrix offers state-of-the-art photonic curing tools, materials, and expertise. The portfolio of products enables innovation and development of next generation electronics. NovaCentrix routinely works with global organizations as well as start-ups and institutes to support projects from the initial concept exploration to full production platform.

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