Printed Inorganic Light Emitting Diodes for Solid State Lighting

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Abstract
In this paper we present a new form of inorganic printed electronics (PE) that overcomes many of the problems associated with the act of printing electronics. The technique allows for very high speed, inexpensive production of PE products. To illustrate this approach we will describe a solid state lighting (SSL) device based upon a standard InGaN heteroepitaxy and fabricated as micro LEDs dispersed into an ink binder. We believe that this approach will act as a template for further development of inks and techniques that employ fabricated silicon or III-V semiconductors.

Author Keywords
printed electronics; inorganic LEDs; solid state lighting

1. Introduction
Printing electronics (PE) has been both a laboratory and industrial goal since, at least, Page and Brody inadvertently invented the paper tellurium thin film transistor at Westinghouse in 1967. Research in printed electronics has evolved significantly, particularly in the area of organic electronics. Layer by layer built organic PE has yet to reach any significant industrial fruition largely due to the problems associated with organic semiconducting devices such as low mobility, short lifetime and difficulty in achieving the required feature size. Knuesel notes, for example, that for pentacene to replace a silicon transistor of similar performance something greater than 100 times the silicon area will be required.

Several approaches have also been proposed using inorganic semiconductors by using the direct layer by layer approach, using directed self assembly of fabricated devices and through pad printing of fabricated devices. For the most part, these techniques suffer from both cost and manufacturability problems even though the performance of, particularly, printed, fabricated devices is effectively equivalent to current discrete electronics.

Here we present a new form of inorganic PE that overcomes the great majority of the problems associated with act of printing electronics and allows for very high speed, inexpensive production of PE products. To illustrate this approach we will describe a solid state lighting (SSL) device based upon a standard InGaN heteroepitaxy and fabricated as micro LEDs dispersed into an ink binder. We believe that this approach will act as a template for further development of inks and techniques that employ fabricated silicon or III-V semiconductors.

2. Methods
Silicon or sapphire wafers were used as a base for InGaN epitaxial deposition via MOCVD. The 450 nm emitting micro LED die structures were then fabricated using a mask set developed for this purpose. As illustrated in Figure 1, the 27µm die were released into a proprietary ink binder developed for this purpose.

The subsequent random diode ink (RDI) was then printed onto a 125µm polyester substrate previously patterned with a micro silver metallic conductive developed for this purpose. As illustrated in Figure 2, two transparent dielectric layers and a transparent conductive layer were added to make a vertically connected, randomly spaced diode array.

The nano fiber transparent conductor was developed internally for this device due to the poor quality of existing printed transparent conductors and the lack of robust mechanical flexibility of indium-tin-oxide on flexible substrates.

The phosphor layer of Figure 2 is a doped yttrium-aluminum-garnet (YAG) phosphor that is commercially available from numerous sources. The YAG phosphor acts to convert the blue light produced by high bright LEDs into white light (e.g. a Stokes shift).

The environmental barrier layer is added to prevent mechanical damage to the YAG phosphor. No water or oxygen barrier is needed for typical applications or lifetimes.
3. Results
Figure 4 photographically illustrates two sections of a printed light panel. This panel section is less than 150 μm thick, is 7cm X 14 cm and weighs about 3.75 grams, not including the electrical leads. The panel section operates in the mid 40°C range without a heat sink.

The panel sections are flexible and can spindle to less than a centimeter without damage. With proper electrical lead protection, these devices can operate in extremely harsh environments and under water.

Existing devices include florescent replacements. The florescent replacement produces about 5,000 L from a panel area of 31.75cm X 50.8cm. In order to build a florescent light fixture replacement the lighting panels are laminated onto an aluminum sheet for rigidity with heat conductive double-sided tape. As a result, the surface operating temperature of the completed fixture is considerably lower.

4. Discussion and Impact
We have demonstrated that printing is a new inorganic electronics packaging technology. Axial lead micro devices can accurately and rapidly be printed yielding both very significant cost savings and new, lightweight, flexible form factors. Very large production gains, which yield economies of scale, are possible with this approach. As an example, printing at only 75 meters per minute with a single 60cm wide flexographic press for 20 hours per day for 300 days per year yields about 250,000,000 A-19 light bulb equivalents. Such A-19 bulb replacements should have a retail cost that is similar to existing CFL bulbs.

5. References