Roll-to-Roll Manufacturing of Electronic Skins with Print-Like Color

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Abstract

A new roll-to-roll manufacturing platform has been developed that enables the fabrication of durable and flexible electronics. Here we present this platform capability and its application to create thin, conformable, reflective paper-like displays. Segmented "electronic skins" are demonstrated that can change their appearance upon application of low-power electronic signals. HP proprietary "inks" that can be electrically addressed are shown to enable print-like color performance.

1. Introduction

Hewlett-Packard has developed new roll-to-roll processing capabilities for making fine scale circuitry on plastic substrates that is compatible with the needs of reflective displays and other devices. Plastic circuits enable light-weight and robust devices, while the thin and flexible format enables new design freedom. The processes are scalable to large web widths, and the fine features enable high density circuits and future integration with more complex passive and active elements. These roll-to-roll processes, which utilize imprint lithography and related techniques as key patterning steps, also offer significant cost advantages compared to conventional photolithographic processes [1, 2].

In addition, we have developed a new device architecture compatible with roll-to-roll plastic circuits that can be combined with proprietary electrically addressable "inks" to achieve print-like color performance as well as transparency. By using similar technology as in color printing, we are developing the capability to produce specific "ink" colors within the Pantone Matching System range of colors.

Here we report thin, flexible, segmented, reflective "electronic skins" manufactured with HP's roll-to-roll platform. These electronic skins can change their appearance upon application of low-power electronic signals. We recognize that personalization is a significant trend in consumer products. Examples of consumer electronics include cell phone ringtones and screen display themes/wallpaper, MP3 player and laptop case colors, and adhesive graphic skins, which are all user-selectable options. Others are taking note of these same trends and recently, electronic skins have also been demonstrated using different display technologies [3, 4]. The technology approach described here achieves reflective color quality compatible with standards used in the printing industry while utilizing cost-effective roll-to-roll manufacturing processes.

2. Roll-to-Roll Capability

2.1. Tools and Processes

HP has developed a suite of roll-to-roll tools aimed at enabling the development of a range of novel processes suitable for electronic skin and similar product manufacturing. The custom equipment set reported here (partly shown in Figure 1) is capable of continuous processing of webs with widths from under 0.15 m up to 0.3 m wide. Both plastic and metal webs can be handled in roll-to-roll configuration. The tool set enables unit processes that include coating, imprinting, plasma treatment, electrolytic and electroless plating, and laser micro-machining. All operations are carried out in a clean-room environment, an unusual but necessary approach for this tooling set for defect-free processing.

The coat and imprint processes use proprietary resin materials and novel cylindrical stamps to form the basic patterns for both fine-line circuitry and other architectural components. This can be done in one operation by a technique that allows replication of multiple level patterns continuously down the web.

HP's roll-to-roll plasma tooling enables selective material removal, as well as surface treatments for improved electrical, physical, and environment characteristics of both dielectrics and conducting materials. In-line process control systems on the tool are employed to achieve uniform treatment both across and down the web, as well as uniformity of treatment depth and chemistry.

The electrolytic and electroless roll-to-roll plating tools have been designed to provide a wide range of chemical processing, most notably the deposition of conductor traces, noble metals for contacts, and metal alloy compositions with dielectric and magnetic properties. Deposition is possible on both conductors and insulators, thereby allowing deposition on bussed and unbussed metallic structures, and on plastic and other non-conducting surfaces. Sophisticated electrical current control allows deposition of materials with optimal mechanical and fatigue characteristics. Our goal with this plating technology is to be able to make conductors and integrated passive and active devices at low cost without the need for discrete components.

Figure 1. *Roll-to-roll process equipment.*

HP has had a long history of successful laser processing development for a range of applications. We have extensively leveraged this capability in a flexible laser tool that is used for achieving complex patterns using both direct pattern formation through UV light ablation, and using large-area light exposure for patterning photo-sensitive materials. These approaches enable submicron precision in feature dimensions and positioning, with the advantage of high throughput speed and resulting cost effectiveness.

2.2. Circuit Capabilities

By integrating combinations of these various processes, functional circuits are demonstrated. One example of a completed test circuit is shown in Figure 2. The patterns produced can have features with minimum width dimensions of less than 5 microns, edge definition that is sub-micron, and product lengths up to 30 cm. Areas up to 150 cm^2 have been produced to date. Continuous lengths of repeating patterns are also possible, enabling very long devices. Conductivity, flexibility and other electrical/mechanical properties that are required for a given product implementation are determined by material selection, deposition thicknesses, and process conditions.

3. Integrated Electronic Skin Prototypes

Plastic circuits fabricated using the processes described above have been integrated with HP proprietary inks that can be electrically controlled. Our approach to color and a demonstration of segmented prototypes are described below.

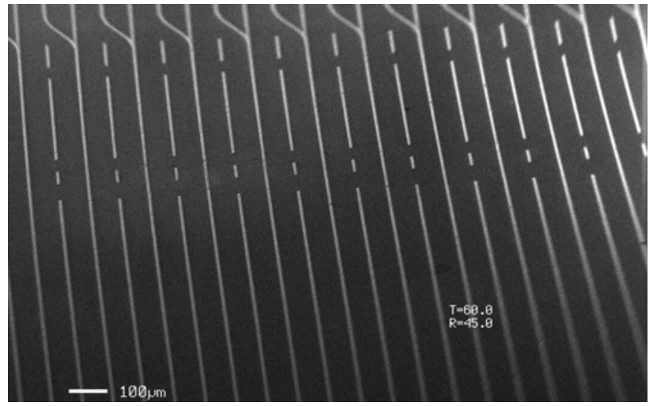


Figure 2. *Example test circuit from roll-to-roll process.*

3.1. Approach to Color

We have approached the challenge of generating high-quality reflective color images from the perspective of printing rather than from the conventional display perspective. Conventional displays typically use a combination of side-by-side color elements to generate additive color (*e.g.*, RGB or RGBW color filters). Conversely, subtractive color is typically generated in printing by layering pigments or dyes (CMYK) on top of one another. Since reflective images rely solely on ambient light, the image will be bright and colorful only if the incident light is reflected efficiently. Side-by-side color approaches devote portions of each pixel to only certain colors, so they inherently absorb the majority of the incident light, and thus are inefficient (<50% efficiency). Similarly, approaches that rely on polarized light typically absorb the majority of the incident light, and are also very inefficient (<50% efficiency). On the other hand, layered colorants enable the ability to address every available color at every location, so they can produce bright and colorful images (with >50% efficiency) when half the incident light is not lost due to polarization effects or other losses.

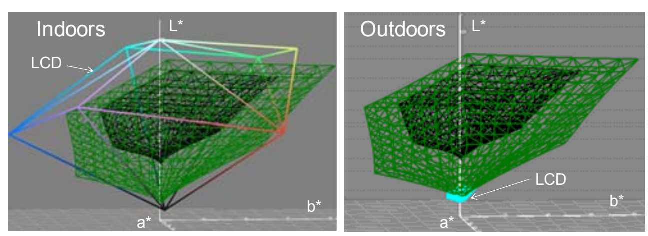


Figure 3. *Color gamut volumes comparing SNAP (black interior wireframe), SWOP (green wireframe), and conventional LCD notebook display performance under typical indoor and outdoor ambient illumination.*

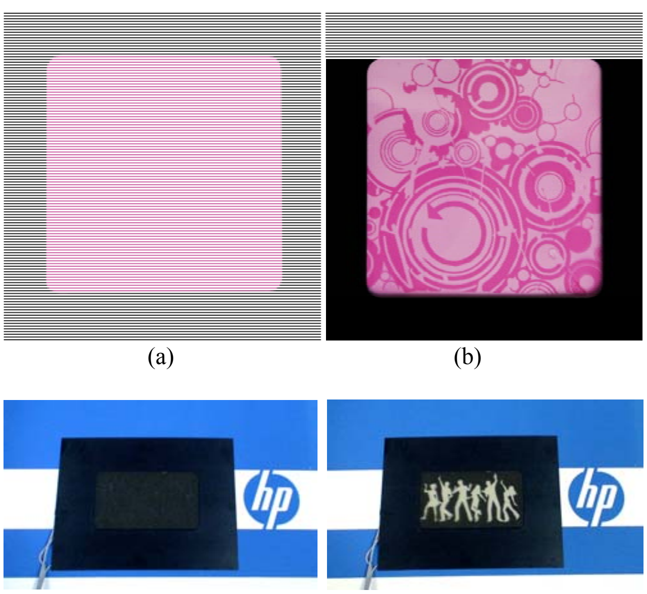
For reflective color devices, printing standards (designed for reflective images) are preferable to conventional display standards (designed for emissive/transmissive images) for evaluating image quality. In the printing industry, advertisers are accustomed to standards such as the Specifications for Newsprint Advertising Production (SNAP) used for newspaper ad inserts and the Specifications for Web Offset Publications (SWOP) used for magazines and other high quality printing. Significantly, SNAP requires ~57% peak reflectivity while SWOP requires ~76% peak reflectivity, neither of which can be achieved by color filter or polarization approaches that are <50% efficient.

It is also important to consider the complete color gamut achievable, not just the peak reflectivity of the white state. Figure 3 compares the color gamut volumes of the SNAP standard, SWOP standard, and a conventional LCD notebook display, measured both in a typical indoor office environment (ambient illuminance level = 300 lux) and in a typical outdoor environment on an overcast day (ambient illuminance level = 3000 lux). You can clearly see the dramatic reduction in both the contrast and color gamut volume of the LCD display when viewed outdoors, where the gamut becomes negligible compared to print.

The HP technology presented here is predicted to exceed the SNAP printing standard using a system of layered colorants (based on optical simulations). It is also capable of providing custom colors within the Pantone Matching System range of colors using single layer devices.

3.2. Demonstrated Performance

Figure 4 shows electronic skin prototypes fabricated with plastic circuits and electronically addressable inks. The examples shown here are segmented devices with an effective resolution >100 ppi. Figure 4(a) shows a magenta prototype with no power applied. The colorfulness of this sample (C* = 67) exceeds the magenta specification in the SNAP standard (C* = 44), and approaches that of the SWOP standard (C* = 70). Figure 4(b) shows the same magenta device with a low-power holding voltage applied (<50 µW at 3V) to make selected regions of the device transparent, exposing a white background (in this case, simply a sheet of HP photo paper). The active area is 80 mm x 80 mm. Figure 4(c) shows a black prototype with no power applied, and Figure 4(d) shows that a selected region of the white stripe behind the skin can be revealed. The active area is 45 mm x 80 mm.



(a) (b) (c) (d)

***Figure 4**. Plastic electronic skin prototypes shown over a paper background.*

Figure 5 shows the same device as in Figure 4(c,d) placed over the printed HP logo to show the switchable and patternable transparency. The measured transmittance for these prototypes in the transparent state is ~60% (at 550 nm). Further optimization is underway to increase the transparency. This transparency is key to enabling the layered approach to subtractive color described above in Section 3.1. It also enables backlighting and additional design flexibility for electronic skins, compared with display technologies that do not have a transparent state.

***Figure 5**. Switchable and patternable transparency.*

The examples shown so far demonstrate that these electronic skins can be used as decorative and dynamic surfaces for personalization and customization. Figure 6 shows that they can also provide functionality, such as status icons, mode settings, etc. The active area is 35 mm x 80 mm. Importantly, these skins are daylight readable, like printed images, so that key information can remain visible in bright sunlight even when a conventional LCD display would be washed out. They are also ultra-low power, so information can be conveyed even when a conventional LCD display may be turned off to conserve battery life.

Figure 6. Functional surfaces that are daylight readable and ultra-low power.

Table 1 contains the key characteristics of these prototype devices. Importantly, they are very thin, as shown in Figure 7(a), and flexible, as shown in Figure 7(b), so they can be incorporated as surface skins on a wide range of possible products. We conducted initial reliability tests and observed that these devices maintain their switching characteristics after high voltage electrical soaks (>12 hr at constant 60 V DC), intensive electrical cycling (>500,000 cycles at +/-80 V, 1 Hz square wave), low pressure cycling (to 700 mbar), thermal soaks (>500 hr at 55° and 70°C), and across a broad temperature range (-30° to 80°C).

Table 1. Prototype Characteristics

Attribute	Value
Thickness	<0.4 mm
Transparency	>60%
Contrast ratio	~10:1
Switching time	<500 ms (depends on voltage)
Switching voltage	20-40 V (depends on switching time desired)
Holding power	<1 μW/cm^2 (at ~5 V)
Bend radius (minimum)	5-10 mm

(a) (b)

Figure 7. The devices are thin and flexible.

Figure 8 shows four devices based on proprietary electrically addressable “inks” for the subtractive primary colors of cyan, magenta, and yellow, as well as black. The active area is 80 mm x 80 mm. The colorfulness of each device (cyan C* = 66, magenta C* = 67, yellow C* = 69) exceeds the specification in the SNAP standard (cyan C* = 35, magenta C* = 44, yellow C* = 55) described above.

Figure 8. Proprietary electrically addressable CMYK “inks”.

4. Conclusions

Key achievements demonstrated with this platform capability are plastic circuits with fine feature sizes <5 microns using imprinting and an integrated continuous roll-to-roll process. Thin, flexible, segmented electronic skin prototypes based on a new architecture and proprietary electrically addressable “inks” enable reflective color with print-like performance and high resolution patterns.

References

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Author Biography

Tim Koch received his B.S. in Mat. Sci. & Eng. from Cornell University (1982) and his M.S. in Mat. Sci. & Eng. from Stanford University (1985). Since joining Hewlett-Packard in 1982 he has held a variety of engineering and management positions in both semiconductor and MEMS research and development. He is currently managing an effort for the development of flexible electronics that includes amorphorous metal oxide devices and reflective electronic ink devices.