# Metrology and instrumentation challenges with high-rate, roll-to-roll manufacturing of flexible electronic systems

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## ABSTRACT

In this paper, we discuss the metrology and instrumentation challenges that need to be overcome in order to realize true implementation of roll-to-roll manufacturing of flexible electronic systems. Several metrology and instrumentation challenges involved such as availability of particulate-free high quality substrate, development and implementation of high-speed in-line and off-line inspection and diagnostic tools with adaptive control for patterned and unpatterned material films, development of reliable hardware, etc need to be addressed and overcome in order to realize a successful manufacturing process. Due to extreme resolution requirements compared to print media, the burden of software and hardware tools on the throughput also needs to be carefully determined. Moreover, the effect of web wander and variations in web speed need to accurately be determined in the design of the system hardware and software. Realization of successful metrology and instrumentation by overcoming the challenges for the development of a roll-to-roll manufacturing system for flexible electronic systems opens limitless possibilities for the deployment of high performance flexible electronic components in a variety of applications including communication, sensing, medicine, agriculture, energy, lighting etc.

**Keywords:** roll-to-roll, printing, flexible electronics, inspection, manufacturing.

## 1. INTRODUCTION

Over the last decade, there have been tremendous advances in the area of printed electronics owing to the development of advanced fabrication techniques, development of high-quality substrates and materials, and availability of an abundance of know-how from the mature printing industry. Compared to conventional electronics manufacturing, printed electronics have several unique advantages such as low temperature processing on large area substrates with high throughput, environmentally friendly, low equipment and setup charges, hybrid system fabrication on a single substrate utilizing inorganic, organic and bio-inspired materials, utilization of cheap substrates, and development of truly flexible systems. Moreover, utilization of roll-to-roll compatible methods promise large area, low-cost manufacturing of light-weight, functional electronic devices that can be used in a wide variety of military and civilian applications. There is already a big market for printed electronics in applications such as consumer electronics, logic/memory, OLEDs, displays, sensors, radio-frequency identification (RFID), large area flexible displays, electronic paper, large area conformal and flexible antennas, smart clothing, lighting, photovoltaics, healthcare etc, with the market value expected to increase from \$9.4 billion in 2012 to \$44 billion in 2021 [1]. Several devices have already been demonstrated such as OLEDs, displays, solar cells, sensors, e-paper, RFIDs etc [2-6].

The success of printed electronics depends on three key focus areas – materials, manufacturing processes and inspection, quality control, as shown in Fig. 1. There has been tremendous progress on materials and manufacturing processes for nanoscale and microscale devices. Material progress has been done primarily to produce novel material that can provide high performance. Several manufacturing processes have been developed for printed electronics, with a focus on reducing the overall manufacturing cost. For high rate R2R manufacturing, inspection and quality control is a critical

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area that determines successful outcome. These include defect detection, surface roughness measurement, inspection of layer quality, measurement of electrical properties to ensure proper functionality, registration control, possibility for repair/correction, product testing, etc. As the demand for high resolution and small-dimensions (sub-100nm - 10µm) are continuously increasing, and new technologies and materials are emerging to satisfy the needs, the true challenge for high-rate manufacturing, thus depends heavily on the development and availability of precise instrumentation and metrology tools that can ensure high quality and yield.

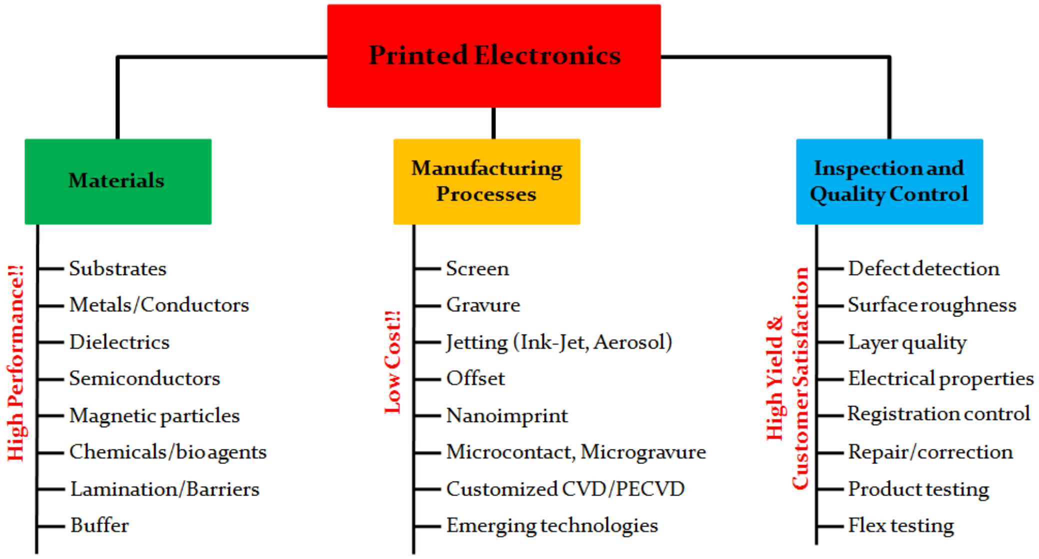


Fig. 1. Key focus areas defining printed electronics

## Manufacturing stages

The different manufacturing stages for a successful product development are shown in Fig. 2. As an idea works its way up through the different difficult stages, several challenges need to be addressed. At the beginning, R&D can help demonstrate the proof of concept. No special requirements for quality control or alignment are required at this stage. However, as the prototype development reaches the pilot stage and beyond, the focus on high-rate, large area, high-through and high-yield process is tremendous [7]. Contrary to the proof of concept demonstration at the R&D stage wherein a simple setup can suffice, demonstrating high yield and throughput through the pilot and volume

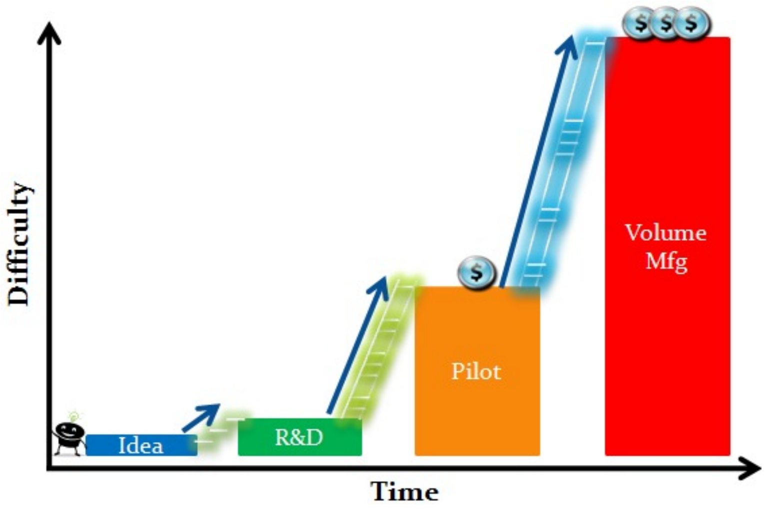


Fig. 2. Different manufacturing stages an idea has to transition through before becoming a successful product

manufacturing stages can be quite risky and challenging. One important feature that distinguishes the pilot and volume scale manufacturing from R&D is the utilization of semiautomatic or automatic tooling for quality and registration control. These tools become utmost necessary to ensure high-yield and profitability through reducing wastage.

As an example for R&D, our group at Omega Optics, Inc and UT Austin has successfully developed a fully printed 1x4 phased array antenna utilizing carbon nanotube field-effect transistor switches, as shown in Fig. 3(a), using a table top Dimatix-2800 printer. During this stage, apart from achieving good registration between the different print layers and ensuring material printability, emphasis on quality control and yield were not tremendous. Beyond R&D, we are working on developing a high-rate manufacturing process, as shown in Fig. 3(b), in order to achieve high-throughput production of such arrays. This is a complex task since the focus is not only on developing the product at high-rate, but to also ensure good quality and yield. Several challenges need to be addressed for a successful process development.

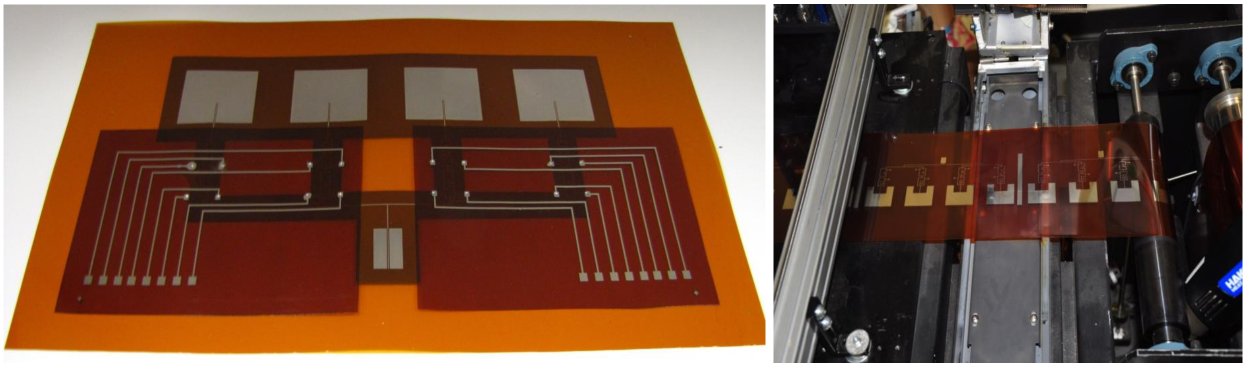


Fig. 3 (a) picture of a 1x4 phased array antenna system developed using a Dimatix-2800 ink-jet printer on a flexible Kapton substrate, (b) high-rate R2R printed 1x4 phased array antenna on a flexible Kapton substrate using a high- rate printer at Omega Optics, Inc.

## 2. INSTRUMENTATION AND METROLOGY CHALLENGES AT HIGH-RATE

There are several challenges that need to be overcome in order to enable high-rate R2R manufacturing of flexible electronic systems. A few key challenges are described below.

### i. Defects

Defects are undesirable for printed electronics since they cause open and short circuits, thus destroying the performance of the devices. There are several factors that cause defects such as missing nozzles in the print head, particles on the substrate, particles on the screen/stamp, web wander, non-uniform web tension, mis-registration etc. A few examples of defects are shown in Fig. 4. Fig. 4(a) is the intended pattern, while Figs. 4(b), (c) and (d) show different kinds of defects that can be produced due to various reasons.

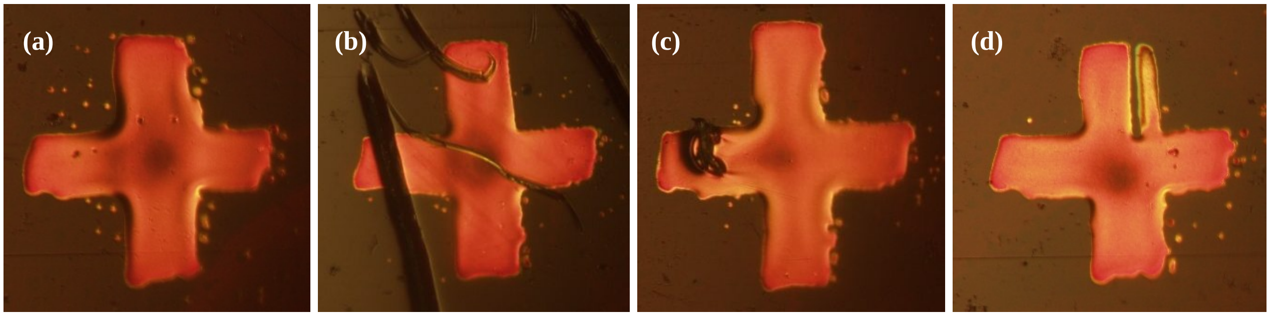


Fig. 4. Optical microscope images of (a) an intended pattern, and (b-d) show defects in the pattern

Defects become even more critical for nanomanufacturing. Since the defect dimensions are on the same order or larger that the structural dimensions (usually in the sub-micron range), their control becomes extremely critical. As an example, Fig. 5(a) and (b) show transparent conductive electrodes for photovoltaic cells formed using a nanoimprint lithography process [8]. Since the dimensions are sub-100nm, any small defect in these structures such as cracks, missing lines, collapsed lines etc can entirely deteriorate the photovoltaic cell performance. Several factors, including unequal stress, imprint resist properties, surface energy issues, defect in the mold etc can cause defects in the nanoimprinting process. Due to the nature of the small dimensions, their detection becomes even more challenging at high-rate R2R nanoimprint processes [9]. Alternative solutions based on R2R optical lithography can be exploited for such applications as well for higher throughput and potentially reduced defect density [10].

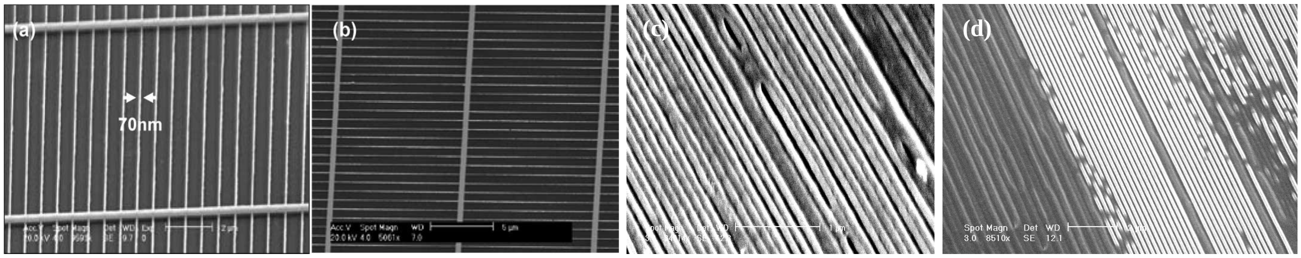


Fig. 5 (a-b) nanoimprinted transparent conductive electrodes [image from reference 8], (c-d) SEM images of defects in the imprint resist and mold, respectively [images courtesy : Prof. L. Jay Guo, U. Mich, Ann Arbor]

Static:

An important contributing factor to defects is the presence of large amounts of static charges on the fabricated substrate surfaces. These static charges on substrates are produced due to the nature of the fabrication process itself, as well as during to their handling. The static charge attracts dust and other particles from the floor or from the air, which can cause unwanted defects on the printed layers [11]. A particle few microns big can either cause a short or an open circuit. Static also greatly influences the material deposition accuracy, as the charged ink can be pulled or pushed, causing ghost tracks, overspray, misregistration etc, which are detrimental to the overall quality of the printed layer. Especially for small feature manufacturing at high rates, mis-registration can produce disastrous results. Manufacturing lines occasionally use static rods or special coatings to alleviate this problem [11], however, with increasing complexity in manufacturing processes, their control also becomes tricky. Special techniques, including in-line web cleaning systems with static control need to be incorporated, thus adding to the overall cost of the system.

Missing or disconnected patterns:

Missing or disconnected patterns constitute another kind of defects. For printed media, this does not cause appreciable change in the aesthetic appeal due to the inherent limitation of human eye. However, for electronic circuits, they can cause open and short circuits. There can be several causes for such missing patterns – a missing nozzle, a deviating nozzle, web wander. For example, as the web moves sideways, as shown in Fig. 6, some regions get printed with excess ink and the others miss some ink. Apart from web wander, defects /particles on the stamp or screen can also cause such defects. Timely inspection of hardware is necessary in order to minimize this effect. Web guiding systems need to be employed in order to ensure accurate web movement.

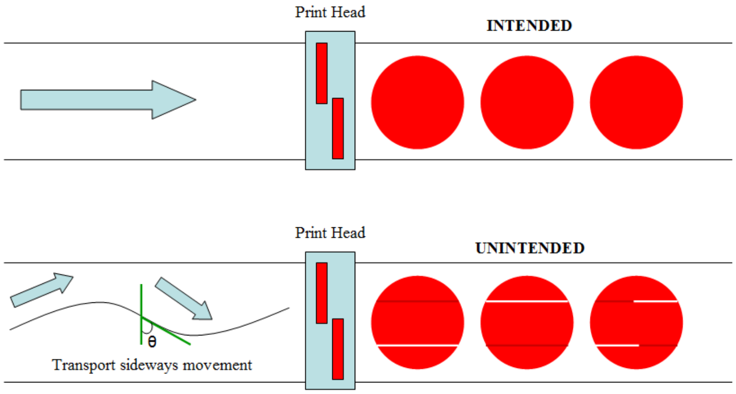


Fig. 6. Effect of web wander on defects in the printed layer. As web moves sideways, some regions receive excess ink, while other regions develop voids.

### ii. Substrate

Another challenge for high rate R2R manufacturing is the unavailability of good quality substrates. The type of substrate used also greatly impacts defect generation in a R2R process. Several substrate parameters such as transparency, surface roughness, surface energy, high temperature operability, chemical and moisture resistance etc are critical for various applications. An important factor affecting device quality is surface roughness. Current substrate surface roughness is five to ten times worse than that of glass [12]. Controllability of roughness to within a few nanometers is crucial for achieving high quality thin uniform printed films. Although suppliers can produce very smooth surfaces, the material cost is prohibitively high for printed electronics applications [13]. If dealing with rough surfaces, effect of such non-uniformities in the printed layer on the device performance has to be extensively modeled. Thresholds determining decent performance criteria should be set for the operator.

### iii. Registration

A third challenge is accurate registration control. For printed electronics, it is extremely crucial to have good registration between different printed layers in order to avoid d edia are inadequate to account for tight registration requirements. Therefore, new hardware and software tools need to be developed, which involves high cost. Registration accuracy is impacted by several factors, for example, drop velocity. If two droplets are fired from the print head at the same velocity, they will land at the same place on the substrate. However, if the velocities are slightly different, and the web is moving at high rate, then the separation becomes large, thus causing mis-registration. Accuracy also depends on web transport stability, type of hardware or software used etc. Very good software tools need to be developed that can detect misalignments and enable automatic correction. We have developed a tool that looks at the alignment mark at high rate and provides error in position information.

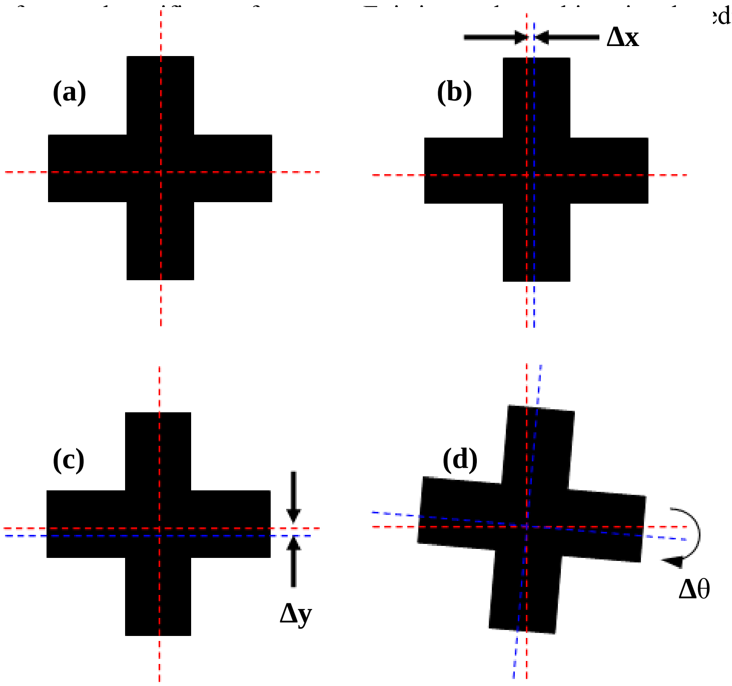
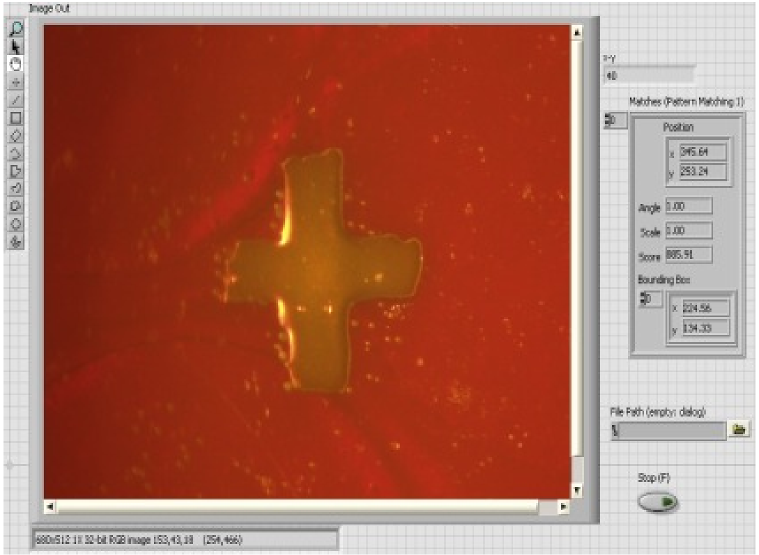


Fig. 7. Copies of patterns with error coordinates of (a) $x=0$, $y=0$, $\theta=0^o$ (Intended Pattern), (b) $x=\Delta x$, $y=0$, $\theta=0^o$, (c) $x=0$, $y=\Delta y$, $\theta=0^o$, (d) $x=0$, $y=0$, $\theta=\Delta\theta^{\,o}$

Consider an alignment mark, such as a cross mark, printed along with each layer as shown in Fig. 7(a). Figs. 7(b), (c) and (d) denote various lateral, longitudinal and angular offsets. A high speed camera looks at specific alignment marks that are printed along with the electronic circuits. The imaged alignment marks are compared against a set of standard patterns preloaded in the computer software, and the misalignment coordinates in terms of x, y and rotation (theta) are calculated and displayed. This error information needs to be fed back to the controller in order to correct for the deviation in-line. An example of the software tool we developed in order to measure mis-registration parameters is shown in Fig. 8. As can be seen in the display tab on the right, the x, y and theta errors are displayed. This information is fed back to a printer for automatic in-line registration. Such tools should be capable of detecting and providing feedback to the printer at high rates. The type of camera to be used and the software threshold depends on how tightly the registration needs to be maintained. However, the higher the requirements, the better the camera system needs to be. The processing time also increases considerably, which ultimately affects the throughput.



x-y: 40

Matches (Pattern Matching 1): 0

Position x: 345.64

Position y: 253.24

Angle: 1.00

Scale: 1.00

Score: 885.91

Bounding Box: 0

x: 224.56

y: 134.33

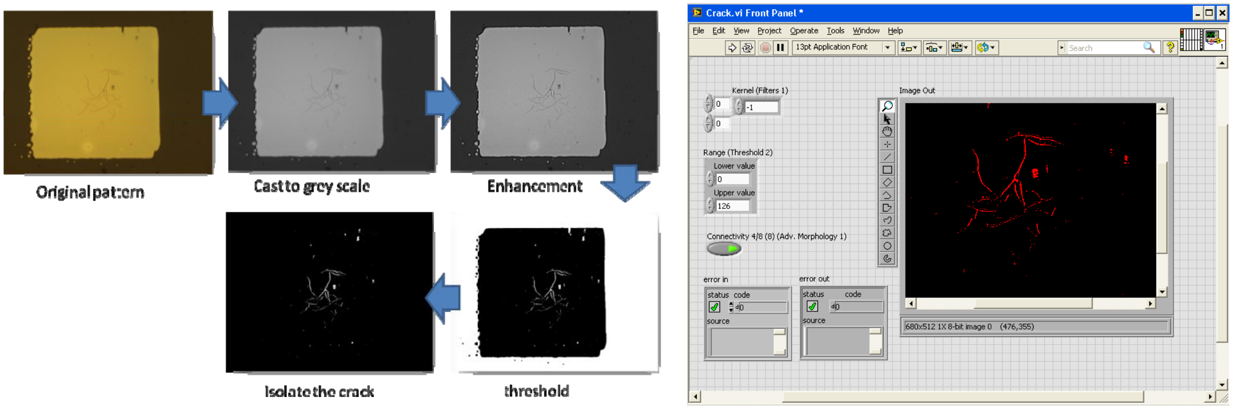
680x512 1X 32-bit RGB image 153,43,18 (254,466)

Fig. 8. Automatic in-line registration tool developed by Omega Optics, Inc and UT Austin for determining mis-registration parameters for feedback control

### iv. In-line/off-line optical inspection and quality control

A fourth and critical challenge is in-line optical inspection and quality control. Since the performance of the fabricated device depends strongly on the quality of the printed layers, there is a need to measure the uniformity, surface roughness, dimensions, registration error etc [14]. The defects not only need to be identified at high rate, but they also need to be displayed to the operator so that timely action can be taken to correct these defects. The inspection tool should also be able to mark of flag bad devices so that it becomes easy to identify waste. If the defect can be corrected, suitable corrective options should be provided. Such correction will tremendously improve throughput and yield. Overall, such tools help in achieving low wastage, high productivity, high quality and customer satisfaction [14, 15].

We have developed a solution utilizing a high-speed camera, together with associated software that can highlight the image and displays it on the user's panel, as shown in Fig. 9. The software is developed using LabVIEW and a high speed camera from DALSA is utilized.



Kernel (Filters 1): 0, -1, 0

Range (Threshold 2): Lower value 0; Upper value 126

Connectivity 4/8 (8) (Adv. Morphology 1)

error in: status ✓ code 0; source

error out: status ✓ code 0; source

680x512 1X 8-bit image 0 (476,355)

Fig. 9 (left) LabVIEW software developed by Omega Optics and UT Austin to high light defects in a printed layer, (right) highlighted defect is displayed to the user

<u>How frequently should the image be captured?</u>

The next question is, how often should be process the captured image? If we continuously capture the images and process them, it becomes computationally extensive. However, if we do it infrequently, then our sample size becomes too small and inspection becomes less effective. There is a tradeoff between throughput and sample selection and every process needs to optimize the relationship for high yield. If high resolution, high zoom images need to be processed, for example in the case of nanostructures, throughput should carefully be assessed since the computation time increases considerably.

### v. In-line/off-line testing

A fifth challenge is in-line or off-line testing. Just optical quality assurance is not sufficient for electronic devices, although they are required to some extent. Tools are required that can test the fabricated devices at high rate. These tests should include standard tests such as measuring the resistance, capacitance, I-V curves etc, along with flex tests that can check for failures, performance variations etc. Regular needle probes cannot be used at high rates since they can damage the devices. Other alternatives such as rollers integrated with testing pads or use of flexible probes is required. For devices that can only be tested after all fabrication processes are complete, an off-line testing scheme, as shown in Fig. 10, for example, can be used to test the devices. One critical aspect for the software handling the test data is that it should be able to establish the difference between a good and a bad device. Proper thresholds need to be established that can enable good decision making.

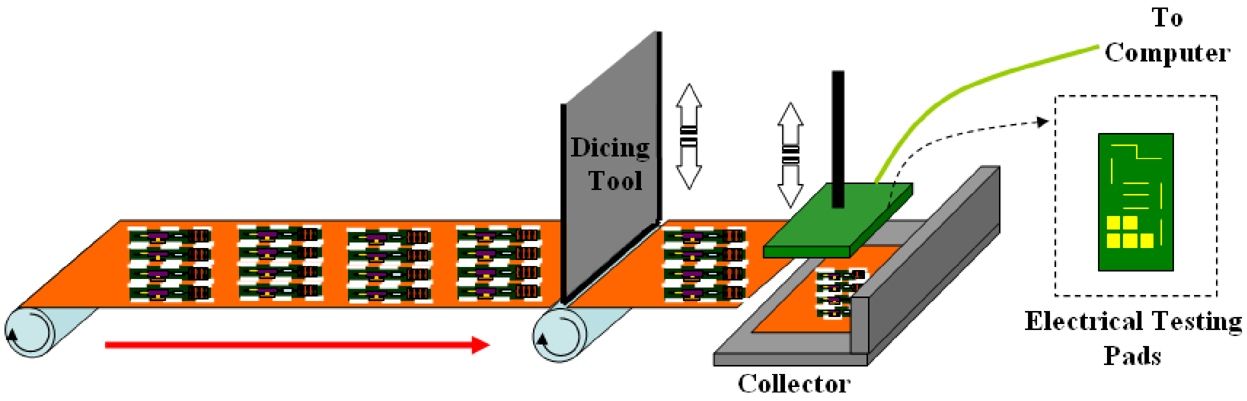


Fig. 10. An electrical testing scheme that utilizes an off-line testing solution for electrical characterization

### vi. High-rate interconnection and packaging

The sixth challenge is to be able to fully package the devices at high rate. Similar to silicon semiconductor devices, flexible electronic systems also require multiple layer metal interconnects in order to develop fully packaged circuits. Multilayer interconnection will also increase device density, increase functionality, provide passivation to the underlying layers, and reduce cost. Several promising techniques such as molding, ink-jet printing, laser ablation, micromachining have been demonstrated for printed electronics. Accurate alignment between the via holes and the underlying contact pads need to be achieved at high rate. Quality of the interconnected lines also need to be tested under flexing conditions [16].

### What can be done?

There are several things that can be done in order to address the challenges and developing a successful high-rate manufacturing process for electronic systems. There is a need to identify and standardize hardware and software solutions for addressing manufacturing challenges. Since conventional electronics industry has established tricks and techniques, we can borrow ideas and solutions. We need to conduct more workshops, roadmaps and set common target specifications, establish standards and establish libraries with common components.

## 3. CONCLUSIONS

In conclusion, we have presented several challenges that need to be overcome in order to realize successful high-rate roll-to-roll manufacturing of flexible electronic systems. Specifically, challenges pertaining to defect detection, substrate availability, registration control, in-line optical inspection, in-line/off-line electrical testing and high-rate interconnection/packaging need to be carefully addressed. Standards need to be defined and libraries with standard components need to be established in order to effectively bridge the gap between R&D and volume manufacturing.

## 4. ACKNOWLEDGMENTS

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