Algorithmic presentation of printed electronics verification in-process

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Abstract. Printed electronics products manufacturing is in the emerging stage demanding both technological infrastructure and methodological procedures development including performance monitoring system organization. In the study the developed verification in-process algorithm for flexible and wearable electronics products in the case of RFID-antenna, strain-gauge sensor and OLED-pixels based on updated printing techniques and equipment is proposed. It was shown the most valuable monitoring factors impacting deliverable end item quality are production-driven roughness parameters substrate and the underlying layers (elements), their intermixing and thermal post-processing conditions. The tolerance checkpoints parameters, patterns of selected parameters interaction and optimal monitoring stages were fixed.

1. Introduction
Printed electronics products (PEP) manufacturing is differed by both multi-factority and multi-tasking due to strong dependence of numbers and process stage types with respect to the items configurations. It is accompanied with standardized materials absence, their novelty and atypicality for current printing techniques [1, 2] as well as equipment including additive manufacturing [3]. Therefore it makes crucial both software development and existing equipment adaptation partly owing to monitoring systems upgrade and auxiliary equipment design. According to the PEP-configurations related to printing process features – mainly to pre-printing information processing when both typical colour separation and screening procedures are excluded, then substituted by its dividing in accordance with PEP-functional layer volume (number) and types – the following PEP groups can be singled out:

- Integrated branched systems (I type) – RFID-tags, strain-gauge sensors, environment sensors such as temperature, atmospheric pressure, relative humidity, gas concentration sensors and mechanical ones (pressure, touching, moving) etc. [4, 5];
- Hybrid thin-film multilayer systems (II type) – photovoltaic items, among others solar sells, matrix, displays, flexible wide-format light areas based on organic (OLED), inorganic (LED) semiconductors including dye-sensibilized ones, transistors, sport and medical-purpose biosensors, memory cells, etc. [6–11]

Consequently, input variable data coverage is reasonably wide, ranging from PEP-geometry configuration, substrate types – hard (glass, ceramic, metal) or flexible (polymer films, fabric, nonwovens, paper) – and their parameters (barrier, mechanical, roughness, chemical homogeneity, surface energy, porosity, etc.), functional layers characteristics (type, number, geometry, conductivity, etc.) to PEP end-products options (demanded area, service environment).
Beside the considerable input data amount, the variable ones are added at the each PEP-production stage addressed to both technological process parameters and its logical and technical adaptation necessity to the current task. One of the most important demands of complex PEP-production is in-process product quality monitoring organisation, accompanied with drastically variable processing stages presence including different printing methods combination. It should be noted that listed problems are outweighed by the printing production techniques advantages among which is possibility of cost-effective high-speed wide-format microelectronic device production organization.

2. Problem statement
The majority of studies in printed electronics area are concentrated either on functional layers materials development [10] or printing parameters effect on certain PEP-elements performance characteristics [12–14].
While that it is known studies describing stand-alone PEP-processes algorithm simulations as well as mathematical modeling either classic printing procedures or tradition microelectronic device production [15–20]. Whereas for full-circle PEP-production start up both the methodological supported and technical equipped technology is demanded. The logical-built in-process quality monitoring system is the inherent part of any full-production circle.
The one of the main purposes of the study is the universal algorithm design aimed to printed electronics verification in-process system building. Depending on the items configuration the both diagnostic and technological flow chart need to be constructed. Listed points, based on definition of the optimal in terms of functionality providing, quality and PEP-products performance characteristics easy-to-test system architecture including equipment adaptation can be the initial design-data base for criterion analysis optimization model of the novel printed electronics production feasibility study.

3. Methods and materials
For the given generic purpose the special test-chart was developed in aims to complex process factors effect proofing – mechanical, barrier, optical, relief and etc. (figure 1). The test-chart and such PEP-elements as:
- RFID-tags antenna and strain-gauge sensors (figure 2, 3) – the monolayer slur elements, which can be integrated to the united system;
- Monochrome OLED-pixels – the multiunit multilayer thin-films system based on polymethine dyes active layer (figure 4)
were printed using on PET polymer films as the flexible substrates after their surface modification by 3 different ways:
- Corona discharge processing;
- Glow discharge one;
- Oxysfluorination (the full procedures are presented in [21, 22]).
Screen, flexographic and aerosol jet printing methods as well as commercial available silver and carbon conductive inks and special developed functional ones were examined at the various production stages. The printed elements were being comparatively characterized after the each production stage using FE-SEM (Jeol JSM 7500F), surface profilometry (TR-200), XPS (Jeol JPS9200), laboratory contact angle characterization, four-point probe technique for conductive measurement, spectrodensitometry and other methods.

4. Results
Based both on [10, 20, 23] and above described research the predominant PEP-production defects (figure 5 -8) and their triggers were analyzed in the context of the quality system building. The main defined effecting input data for both in-process monitoring procedures and the algorithm design are presented in table 1.
The one of the in-process quality monitoring algorithm segments for PEP-production is presented in figure 7.
According the above classified PEP-production features, such factor as layer succession processing type – negative or positive - was entered to the developed algorithm (figure 9a, block A). In the first

| Parameter                                                                 | Symbols, measurement units |
|---------------------------------------------------------------------------|-----------------------------|
| 1  PEP type                                                                | I or II                     |
| 2  Substrate type                                                          | Flexible, F or hard, H     |
| 3  Layer succession processing type                                        | Positive, P / negative, N  |
| 4  Substrate thickness / tolerance                                         | D₀, m / Δ D₀, m             |
| 5  Functional layers number                                                | N, n                        |
| 6  Functional layers thickness / tolerance                                 | dᵢ, m / Δ dᵢ, m             |
| 7  Functional layers geometry                                              | scheme                      |
| 8  Minimum element (x, y) linear dimensions / tolerance                   | bₘᵢₙ m / Δ bₘᵢₙ m          |
| 9  Optical-selective active layer (element) presence and type              | Organic or inorganic       |
| 10 Effective electromagnetic radiation range                              | ΔΕₘᵢₙ, nm                   |
| 8  Active elements linear dimensions / tolerance                           | Bₑₘₑ m / Δ Bₑₘₑ m          |
| 10 Active layers (elements) numbers                                        | M, m                        |
| 11 PEP area                                                                | X, m²                       |
| 14 Bending deformation / tolerance                                         | εₑ / Δ εₑ                   |
| 15 Extension elongation / tolerance                                        | δ / Δ δ                     |
| 16 Oxigen permeability factor / tolerance                                  | µₒ₂, mkm²                  |
| 17 Functional layers electrical resistance (or conductivity) / tolerance   | R, Ωm                       |
case the substrate serves as transparent barrier screen through that the electromagnetic radiation photons of the certain energy are penetrated to the PEP-active layers. So, one of the first input control parameters (in combination of mechanical and barrier properties) will be transparency or, more precisely, light-transmission factor in the effective electromagnetic radiation range of the active layers. In the second type substrates are only a PEP carrier-bases, it follows that their optical properties are no accounts.

The important items production quality-meaning factor is substrates (mainly polymer films) surface energy. Its values in order of 28-40 mJ/m² are not allow to print (excluding screen printing method) using any functional inks in case of films pre-processing absence. Therefore the first PEP-production stage is polymer substrates modification.

It is well known that the most technological at the high-speed roll-to-roll printing is the corona-discharge polymer films processing. As the modification result the polymer surface is oxidized due to both carboxylic and carbonyl groups forming accompanied with polymer amorphous phase etching and crystallites “outcrop”. Other methods of polymer physical modification (in particular, glow discharge [21]), and also chemical ones (by oxifluorination as an example [21, 22, 25]) can be effectively applied for some PEP-production type varies but some parts of them are characterized by area limitation.

The algorithm design distinguish feature is accounting of relief inhomogeneity monitoring of substrate modification localisation as well as all underlying layers (figure 5) in terms of their area. This parameter is valuable for the low-linear size elements formation (figure 9a, block B). So, research presented in [25, 26] shown at the polymer films oxifluorination procedures the local modified areas are formed resulted in roughness parameters increasing (Rz-value, especialy) in comparison to other discussed methods. It can be the reason of PEP-elements in-production damage that particularly true at the nano-scaled functional elements presence (which thickness is about 30 nm and more).

Both modification degree and inhomogeneity are analysed mostly in a laboratory environment by various techniques: gravimetrical [27], by contact angle definition [28], SEM, XPS and etc. Layers roughness parameters are also drastically differed depending on used materials, types and modification conditions. All the above points need to be resulted in both equipped periodical and in-process line monitoring procedures development necessity.
In summary, one of the integral technological criteria, which are significant effect the production process as well as the quality monitoring system, is the PEP-substrate choice and pre-processing methodology.

Figure 9a. The printed electronics verification in-process algorithm segment
Figure 9b. The printed electronics verification in-process algorithm segment
Another key control point of developed algorithm at the next production stages is the elements spread monitoring, including its tolerance definition and (figure 6, block C). As a rule the first conductive layer has discrete layer with complex geometry because it constitutes an electrical array and looks like divided lines with the interline size initially depended on provided PEP-configuration. So, the spread value raising can lead to local conductive array elements connection. It should be noted that spread value depends on a lot of the factors, moreover it can be changed due to the processes parameters shifting. As the previous stage spread value should periodical and in-process line monitored.

Additional attention is demanded the fact that in the vast majority cases functional layers are post-heated (using convectional [29], laser [30], IR- techniques and etc.) before the next functional layer coating for necessary conductivity providing (figure 9b, block C). The layer-to-layer post-heating stages are not typical for traditional printing process line. Consequently, it needs to develop the specific machine units including monitoring both procedures and devices.

The next feature of high-speed process is layers overprinting in a laminar flow during split seconds. Therefore the surface layers partial intermixing was happened (figure 8) – it is totally unacceptable effect for PEP-production. Taking into account thermal layer post-processing the neighbor layers intermixing factor should be also monitored (figure 9b, block D).

The same factors and monitoring stages listed above for the first functional layer performance are accurate for all other ones up to and after active layers deposition (for II type PEP), providing for underlying layers transparency condition depending on chosen the succession processing type. Summarizing, the second integral technological criteria of PEP-quality providing is the combination of functional layer materials operational parameters control and printing process ones, among others ink viscosity fitting, layers adhesion strength maintenance, intermixing absence guaranteeing, stable behaviour supporting in the printing contact zone and at the heating procedure with conductive functionality provision and finally both layer relief (roughness) and homogeneity monitoring. Other integral technological criteria in particular the active PEP-layers deposition process monitoring will be presented later.

**Conclusion**

The presented verification in-process algorithm is meant to be the base for automated printed electronics process monitoring and diagnostic system. The algorithm novelty and practical relevance lies in the fact production factors accounting which were not be previously considered such as functional layer intermixing, underlying layers relief, heating procedure consequences monitoring. The in-process quality monitoring technique development issues necessity was noted for listed critical production stages in terms of fault defectiveness and end printed electronics items capability stepwise diagnostics.

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