Microelectronics Reliability 86 (2018) 54–65

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Evaluation of screen printed silver trace performance and long-term reliability against environmental stress on a low surface energy substrate

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A R T I C L E I N F O

Keywords:
Printed electronics
PPE
Surface modification
Adhesion
Environmental stress
Reliability

A B S T R A C T

Otherwise attractive substrate materials for printed electronics may have such surface characteristics that make patterning challenging. This article focuses on the printability and performance characterization of conductive patterns on a low surface energy substrate. Surface characteristics of a hydrophobic polyphenylene ether (PPE) substrate and the effects of surface modification using chemical and physical pre-treatments were studied. In addition, silver ink performance and its reliability on this substrate were evaluated. The surface was characterized by surface energy measurements and surface profile analysis. Screen-printed test patterns were characterized to evaluate print quality and electrical and mechanical performance. A further inspection of substrate-ink interactions was conducted using environmental reliability tests. It was observed that ink adhesion could be significantly promoted by choosing a suitable surface pre-treatment method. Low sheet resistances were obtained, and thus, suitable inks for further characterization were found. In addition, it was observed that environmental stress has a significant impact on ink-substrate interactions.

1. Introduction

Printed electronics (PE) make it possible to fabricate intelligent applications with the potential to revolutionize the future electronics market. The importance of printed electronics is emphasized in various sensing and monitoring applications, where thin and wireless devices on flexible and stretchable platforms enable device integration into an everyday environment, and are thus one of the key applications on the path towards the Internet of Everything (IoE) [1–6].

Since many sensing applications operate at high frequencies, it is necessary to find materials enabling sufficient functionality in this area. Proper functionality of printed high frequency (HF) structures places requirements on both the coating and substrate materials. For example, conductive material should be selected so that DC sheet resistance is as low as possible. In addition, printed conductors should be smooth to enable fast signal transmission. On the other hand, basic substrate requirements include low relative permittivity and dissipation factor to prevent signal attenuation via the substrate material [1,7,8].

Furthermore, materials should be selected so that ink-substrate interface interactions enable proper wetting of the substrate and sufficient ink adhesion on the used substrate material. These properties may be enhanced by, for example, surface modification prior to printing. Thus, the substrate surface is altered by modifying the chemical compound and surface profile [9,10]. In addition to the initial performance characterization of the printed structures, a reliability study is necessary in the development of printed electronics. For example, relatively thin and soft printed lines can easily be scratched. Additionally, structures have to endure plenty of stress during product lifetime. By using accelerated reliability tests, the long-term reliability of the applications may be inspected efficiently, without the need to wait until the end of product lifetime during normal usage [11]. With these tests, such material interfaces can be found that make printed structures better able to endure environmental stress and remain reliable, even in harsh environments [12].

In this study, the authors continue their earlier benchmark study of silver ink performance on a PPE-based HF substrate material [13]. This polymer compound is designed for GHz applications, with a dissipation factor below 0.001 and a dielectric constant of 2.60 [14]. Therefore, it is an attractive substrate material for applications operating in the GHz range and could be used as a platform for printed large-area antennas and other wireless applications, such as molded interconnect devices. The variety of studied silver inks has been broadened and the effects of new surface pre-treatments on substrate material are studied. Environmental stress tests (85% relative humidity (RH)/85 °C test, cyclic salt mist test) are used to evaluate the effect of elevated temperature and salt exposure in humid conditions on long-term reliability.

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https://doi.org/10.1016/j.microrel.2018.05.010
Received 15 December 2017; Received in revised form 9 May 2018; Accepted 13 May 2018

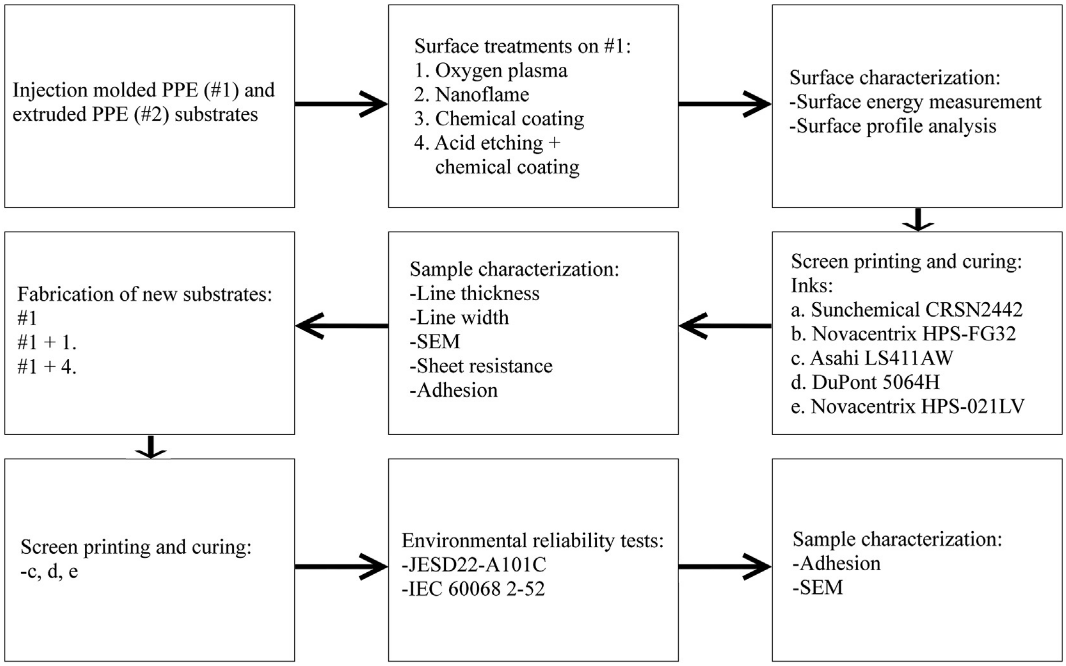

Fig. 1. Test matrix including all variables and process steps.

2. Experimental section

Fig. 1 introduces the reader to the process steps and test variables included in this survey. A detailed discussion of both materials and methods is included in the following sections.

2.1. Materials

The purpose of this study was to continue the authors' benchmark study of silver ink printability on PPE, and therefore, an injection-molded PPE substrate (10 cm × 10 cm) with 3 mm thickness was used. In addition, an extruded PPE substrate (10 cm × 10 cm) with 1 mm thickness was studied to compare the effects of the molding process and substrate thickness on the surface parameters and final performance. These substrates are relatively thick for conventional printed electronics applications. However, since our purpose is to find HF applicable materials, which are suitable for fabrication of three-dimensional (3D) objects, like molded interconnect devices, or large area devices, substrate dimensions are considered sufficient for our purposes.

In our earlier study [13], SunChemical CRSN2442 and DuPont 5064H screen printing inks were used. Since low sheet resistances were obtained, research was continued to inspect the effects of substrate surface pre-treatments further. In addition, three other silver inks were selected for further comparison of the conductive materials. The most critical ink parameters obtained from the datasheets are listed in Table 1.

All of the selected inks have high silver contents, which helps decrease the sheet resistance of the printed structures. In addition, inks with different viscosities were selected to inspect their effect on print quality, and thus, on conductor performance. Furthermore, inks with different solvents were selected to compare their properties. HPS-021LV differs from other inks because it is aqueous. This aqueous ink is more environmentally friendly than other inks, and is therefore an attractive choice. In the extant literature, this ink has been studied, for example, in works by Sipilä [15] and Björninen [16], where it was successfully used to print HF structures on challenging substrates, such as plywood and textiles.

Other studies on the selected inks include, for example, a work by Happonen [17], where 5064H was compared to LS411AW via sheet resistance and bending abilities. The results indicated that excellent electrical performance could be obtained with both inks, but they were not successful with the cyclic bending tests. LS411AW was also included in studies by Jansson [18] and Voutilainen [19], where it was used to fabricate more complex structures, such as moisture sensors [18] as well as inductors and capacitors [19]. The results indicated that low sheet resistances could be obtained and that the structures can endure environmental stress well.

Table 1
Material parameters of the used conductive inks [20–24].

Ink Manufacturer	Ag [%]	Solvent	Viscosity [cP]	Sheet resistance [mΩsq^{-1}@ thickness]
CRSN2442 SunChemical	69–71	Propylene diacetate	2000–3000	10@25 μm
5064H DuPont	63–66	C11-ketone	10,000–20,000	< 14@25 μm
LS411AW Asahi	65–75	Butyl cellosolve acetate, isophorone	20,000–30,000	< 40@10 μm
HPS-FG32 Novacentrix	75	Butyl carbitol	8000	25@25 μm
HPS-021LV Novacentrix	75	Water	2600	≤14@25 μm

2.2. Methods

2.2.1. Surface pre-treatment methods

The authors observed previously that oxygen plasma treatment is a sufficient surface treatment for enhancing the adhesion of a substrate-ink interface [13]. Therefore, it was used in this survey to see if it would also work with other inks. However, etching with sulfuric acid (H_2SO_4) or potassium hydroxide (KOH) did not improve the performance results.

Since sulfuric acid had an increasing effect on the substrate surface energy, though, it was nevertheless used in this survey as a base for chemical coating with ethyltriglycol. To inspect the effect of prior acid