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Analysis of dynamic thermal characteristic of register of roll-to-roll multi-layer printing systems

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ABSTRACT

Register control is essential in the roll-to-roll printing of organic thin-film transistors. Specifically, microscale accuracy is required in the control of the overlay printing register. To achieve such precise control, the characteristics of the substrate under the operating conditions, such as the drying temperature and the tension applied to the substrate, should be considered. In this study, the variations of the elastic modulus and thermal deformation with the drying temperature were investigated, and the correlations among the change in the thermal characteristic of the substrate, the tension, and register error were also analyzed. The results of the analyses showed that the thermal deformation produced by the temperature change generated tension and register error, with the effect increasing with increasing drying temperature. System identification techniques were further used to develop a register model for estimating the register error due to thermal and elastic strains. The maximum estimation ability of 86.27% of the developed model is higher than that of a conventional register model.

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1. Introduction

The recent introduction of printed electronics represented a major breakthrough in the production of sophisticated electronic devices such as flexible organic light-emitting diode (OLED) and thin-film transistors (TFTs) [1]. Several studies have been conducted on the material, process, and structure of the equipment used for the mass production of printed electronic devices. Furthermore, such devices with simple structures, such as antennas and solar cells, are close to being commercialized [2]. Nevertheless, there are challenges to the production of printed electronic devices with complex structures, such as TFTs that require micro-scale channel lengths and pattern sizes, and, most importantly, register control [1]. Fig. 1 is a schematic illustration of the roll-to-roll process for printing TFTs. The left panel of the figure shows the register error (R) and the variables that affect it, namely the span length (L), elastic modulus (E) and tension applied to the substrate (T). The register is the position accuracy between the patterns printed by the upstream and downstream printing rolls [3]. The register error is the difference between the reference position and the actual position of the printed pattern. This error may be generated by elastic deformation such as that caused by velocity disturbance of the driven roll, or by thermal deformation due to variation of the substrate temperature. It can be determined from the register mark, which is generally printed on one side of the substrate. The upper-right panel of Fig. 1 shows an example of register error during the printing of a TFT. The lower-right panel of the figure shows a defect in the printed device due to register error. Register error can cause serious defects in a printed device; hence, register control is essential for maintaining the quality of the electronic device. Unlike a stop-and-repeat printing process that compensates for the register error by stopping the transfer of the substrate [4], it is impossible to control the register of roll-to-roll continuous printing in the static state. In roll-to-roll continuous printing, the register error has to be continuously compensated for. The deformation of the substrate with respect to the dynamics of the motor of the driven roll and drying temperature should therefore be taken into consideration together with the synchronization of the driven rolls to achieve high-precision register control.

Several studies have been conducted on the behavior of the tension and register [5–13] during roll-to-roll continuous printing. Campbell and Grenfell derived a tension model based on the velocity disturbances of the driven rolls and proposed approaches for controlling the tension [5,6]. However, the model cannot be used to predict the tension transfer. Brandenburg, Shelton, and Shin developed a tension model that considered the tension transfer [7–9].

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Nomenclature

R	register error
ε_1	strain in infeed section
ε_2	strain in printing section
v_{10}	velocity of first printing roll
v_{20}	velocity of second printing roll
V_1	velocity variation of first printing roll
V_2	velocity variation of second printing roll
L_1	span length between infeed and first printing roll
L_2	span length between first and second printing roll
A	area of web
E	elastic modulus of web
τ	time constant (L/v)
E_{eq}	equivalent elastic modulus of web considering temperature variation
Δt	sampling time
$\hat{d}$	number of sampling time corresponding to time delay
$u(k\Delta t)$	measurement of process input on kth sampling
$\hat{y}(k\Delta t)$	predicted process output on kth sampling
$\hat{a}_i$, $\hat{b}_i$, $\hat{B}$	parameters of output error model
$\hat{G}_{OE}$	identified output error model
$T_2(z)$	measured tension
$R(z)$	measured register
R_{max}	maximum register in measured register data
R_{min}	minimum register in measured register data
R_t	measured register at tth data point
$\hat{R}_t$	estimated register using identified model at tth data point
n	number of measured data points for normalized root mean square deviation

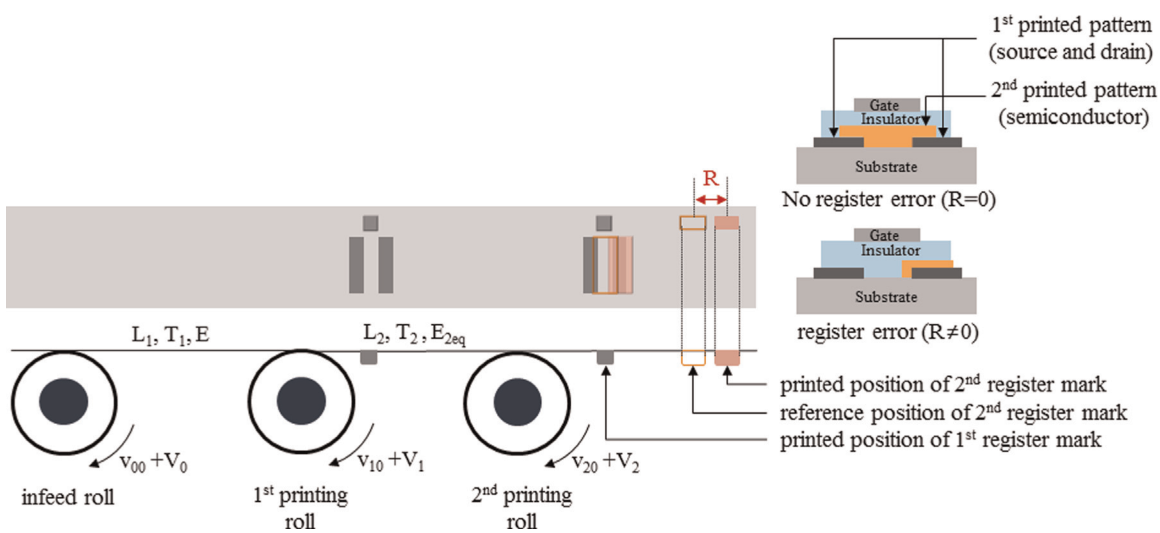

Fig. 1. Schematic of roll-to-roll printing of a thin-film transistor (TFT).

Using this tension transfer model, several other studies were conducted on the behavior of the tension, taking into consideration the elastic and thermal deformation [10–12]. Brandenburg developed the fundamental linear register model [7] and Yoshida developed a nonlinear register model that considered the actual strain in each printing section [13]. Kang designed a register controller in which the Brandenburg model was used to compensate for the register error [3]. On the other hand, Lee and Kim studied the effects of the thermal deformation of the plastic substrate on the behavior of the tension. Working from the tension transfer model, Lee developed a tension model that considered the thermal deformation of the substrate [14]. In this model, the average deformation was assumed to be the sum of the elastic deformation and the thermal deformation. Kim designed a tension model that considered the additional strains caused by the thermal and gravity effects during the continuous annealing process [15]. These previous works revealed that different tension and register models were required depending on the characteristics of the tension and the register error. They suggested that analyses of the characteristics of the substrate such as the elastic modulus and coefficient of thermal expansion should first be undertaken in the design of the control logic of the register.

In this study, we investigated the thermal characteristics of the plastic substrate with respect to the drying temperature. We also analyzed the effects of the variation of the elastic modulus and the thermal deformation on the tension and register error. Finally, we experimentally developed a register model using system identification (SI) techniques and used an output error (OE) model to estimate the register errors due to elastic and thermal deformations. The estimation quality of the developed OE model was evaluated by the normalized root mean square deviation (NRMSD). The evaluation results showed that the model estimated the register error due to thermal and elastic deformations more accurately than the generally employed Brandenburg model.

2. Analysis of the thermal characteristics of the plastic substrate

2.1. Thermal characteristics of the plastic substrate

To analyze the thermal characteristics of the substrate, the elastic modulus and thermal deformation were measured under drying temperatures of 80, 100, and 120 °C. The bare substrate was PET (Sh34, SKC), which has an elastic modulus of 3.1 GPa and thickness of 100 μm at room temperature. The aforementioned properties of the substrate were measured three times in accordance with the standard requirements for tensile and coefficient of thermal expansion (CTE) tests. Table 1 gives the applied standards and conditions of the test. The strain rate and load cell

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