Materials Letters 193 (2017) 81–84

Contents lists available at ScienceDirect

Materials Letters

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

Tensile and fatigue behavior of polymer supported silver thin films at elevated temperatures

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ARTICLE INFO

Article history:
Received 29 November 2016
Received in revised form 19 January 2017
Accepted 23 January 2017
Available online 25 January 2017

Keywords:
Thin films
Fatigue
Failure mechanism
Elevated temperatures

ABSTRACT

Tensile and fatigue tests were conducted at 50 and 70 °C for evaluating the mechanical behavior of polyethylene-terephthalate (PET) supported silver (Ag) thin films. The strain amplitude-number of cycles (S-N) curves of Ag/PET at elevated temperatures were acquired for determining the failure life under in-situ heating condition. The stretchability at elevated temperature was found to be better than the tensile behavior at room temperature, whereas the fatigue behavior is worse at elevated temperature. The adhesion between silver and PET is better at elevated temperature. However, the tensile and fatigue characteristics were different results because the adhesion of silver and PET is not homogeneous at elevated temperatures. The good adhesion between thin metal films and flexible substrates is not always beneficial effect of the mechanical behavior. Therefore, we suggest a new fatigue failure mechanism for Ag/PET at elevated temperature.

1. Introduction

Development of the electronic devices has been pushed by the demands of consumers. Electronic devices have been made with various functions and designs. Flexible electronic devices utilize a flexible display [1], flexible solar cell [2,3] and thin film transistor (TFT) [4]. Hence, as consumer demand for thin electronics has increased, research trends have focused on the thin metal films that come with the flexible substrates [5–9]. An important factor in the mechanical behavior of thin metal films supported by flexible substrates is the interface effect. Li et al. [7] analyzed the relationship between adhesion and failure mode under tensile loading. If the interface has weak bonding forces, the films lose their bonding strength and rupture occurs after small deformation. Furthermore, Zhang et al. [8] investigated the grain size effect on the ductility of the thin metal films on polymer substrates.

The adhesion of thin metal films on flexible substrates significantly affects the mechanical characteristics. The materials lifetime is especially a crucial factor to assure reliability of electronic devices. The thin metal films were evaluated for their mechanical properties and influences by the tensile and fatigue tests at room temperature [10,11]. This research found that extrusions and cracks were presented at different locations. However, the electronic devices with the thin metal film on flexible substrates have used under normal heating conditions. Therefore, the fatigue test of the thin metal films on flexible substrates should be performed at elevated temperatures for the durability. We focused on the fatigue behavior on Ag/PET at elevated temperature. The relationship between the fatigue behavior and adhesion was investigated at elevated temperatures.

2. Experimental details

The target material of this research was silver thin deposited on polyethylene-terephthalate (PET) substrates. The polymer substrate treated by acrylic-primer coating (Skyrol® SH21 by SKC) was a commercial product with 12 μm thickness. The rectangular shapes of PET substrate were patterned by cutting plotter. The specimen scale of the PET were a total length of 28 mm and 68 mm for the tensile testing and the fatigue testing specimens, respectively. The width of the both of the specimens was 1 mm. The thin silver films of 200 nm thickness were deposited on the PET substrates by electron-beam evaporation (a rate of 4 Å/s). Tensile tests were performed by micro-tensile tester. The strain rate of the tensile test was 1×10^{-4}/s. Fatigue tests at elevated temperatures (50 °C and 70 °C) were carried out using a customized micro fatigue tester [12] with resistance sensing inside a heating cham-

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http://dx.doi.org/10.1016/j.matlet.2017.01.111
0167-577X/

ber under atmospheric pressure. Fatigue loading was applied under displacement range control at a frequency of 1 Hz. The strain ranges were 0.4–1.75%. Furthermore, tape peel tests (3 M-Scotch-magic-tape) were conducted to analyze the adhesion between silver and PET. The tape peel tests were performed at room temperature, 50 °C and 70 °C.

3. Results and discussion

Tensile tests were conducted to evaluate the mechanical and electrical behavior of the thin PET supported silver films. These two characteristics were obtained by in-situ measuring of resistance. The ratio of resistance over the initial resistance is widely used. The criterion for failure was set at the 5% offset line from the theoretical curve ($R/R_0 = (L/L_0)^2$) [6]. The failure strain was 1.5%, 3.5% and 4.2% at room temperature, 50 °C and 70 °C, respectively (Fig. 1-(a)). The stretchability of Ag on PET becomes better at elevated temperatures. Hence, PET softening occurs at the elevated temperatures (Fig. 1-(b)).

The fatigue life was also determined by the ratio of the initial resistance (R_0) to the resistance (R). When the R/R_0 is 1.25, this point is the criterion for failure [5]. Strain amplitude-number of cycles (S-N) curves of Ag/PET at elevated temperatures are represented for evaluating the effect of the strain ranges and environmental temperatures in Fig. 1-(c). The Coffin-Manson relation [11] was used for low-cycle fatigue analysis. The Coffin-Manson relation is given below.

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f'(2N)^c$$

where ε_p is the plastic strain amplitude, ε_f' is the fatigue ductility coefficient, N is the number of cycles and c is the fatigue ductility exponent. The slope in Fig. 1-(c) represents the fatigue ductility exponent. The range of fatigue ductility exponents on bulk metals is from −0.5 to −0.7 at room temperature [13]. The fatigue ductility exponents of Ag/PET are −0.105, −0.236 and −0.448 at room temperature, 50 °C and 70 °C, respectively. This phenomenon indicates that the sensitivity of the strain applied on Ag/PET is increasing at elevated temperatures. The fatigue life of Ag/PET was pre-stretched by 2% and the strain range is 1% is 831474 cycles, 8051 cycles and 289 cycles at room temperature, 50 °C and 70 °C, respectively. This fatigue phenomenon is different with the tensile loading results. At elevated temperature, the tensile behavior of Ag/PET is better than room temperature. However, the fatigue life of Ag/PET at elevated temperature is shorter than room temperature.

The adhesion between thin metal film and substrate is a main factor contributing to the initiation of a crack under fatigue loading. Crack initiation on thin film occurs at the area with a low adhesion [7]. The results of tape peel tests represent the better adhesion at elevated temperature as shown in Fig. 2-(a), (b). The motive of the adhesion difference at following temperatures was reported that metal nucleation or atomic diffusion between the metal and polymer could occur on wider locations by temperature-dependent mechanism [14]. This phenomenon makes carbon-oxygen-metal bonding from carbon-oxygen bond-breaking of the carboxylic group [15]. The change of the adhesion between silver and PET as temperature makes the different failure modes. The crack formation tends to be a linear crack at room temperature (Fig. 2-(c)), because the crack initiation occurs over a wide area intermittently. The area with the poor adhesion is extensive at room temperature, whereas the poor adhesion parts are reduced at elevated temperatures. The characteristic of the better adhesion at elevated temperature gives rise to the intensive crack formation on the small area which has a low adhesion. The dense cracks form the closed loops of crack propagation. These phenomena lead to

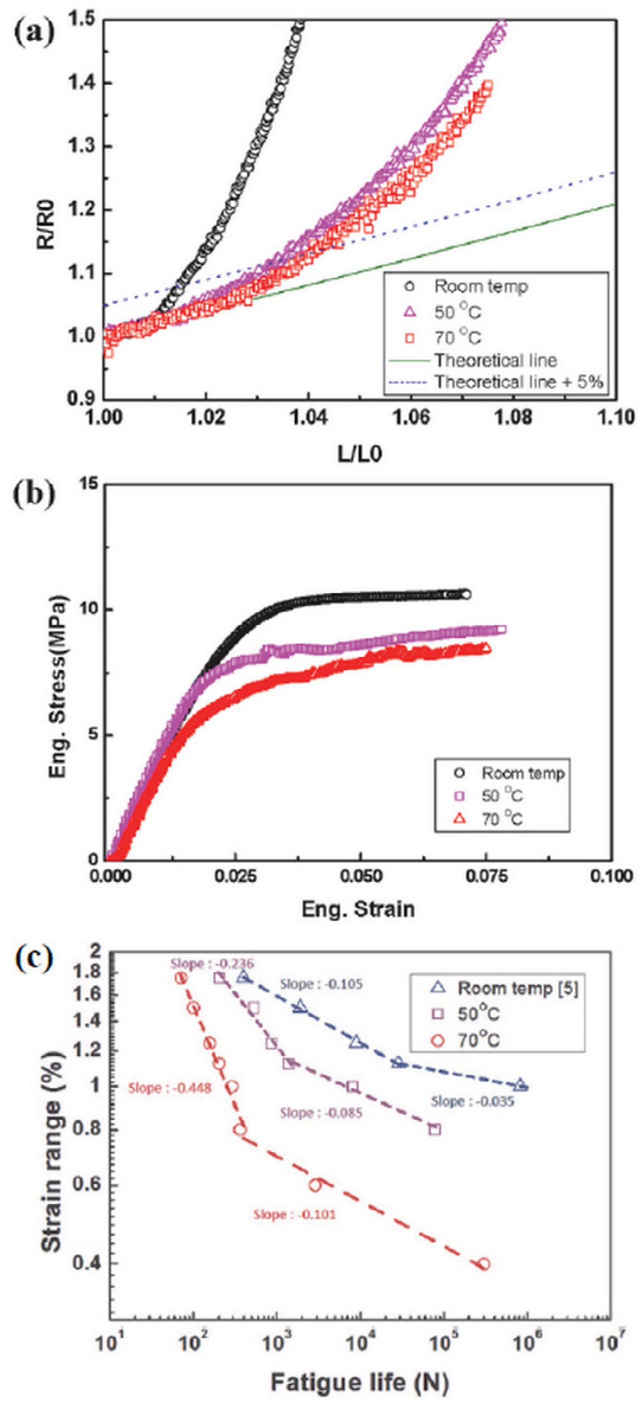

Fig. 1. (a) Resistance curves on Ag/PET at tensile loading conditions, (b) Stress-strain curves of Ag/PET at room and elevated temperatures, (c) Strain amplitude-Number of cycles(S-N curves) at room temperature, 50 °C and 70 °C.

different crack formation, island-shape crack, at elevated temperatures (Fig. 2-(d), (e)).

The two failure mechanisms at room and elevated temperature look dissimilar markedly. The mechanism morphology with room temperature and elevated temperatures is shown in Fig. 3. The low adhesion means fewer bonding chains between silver and PET at room temperature. This leads to make many linear crack formations which prevent proper electrical conduction on the thin silver film. The bonding chains, on the other hand, are substantially built in accordance with the good adhesion between silver and