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Bending Performance of Flexible Organic Thin-Film Transistors with/without Encapsulation Layer

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***Abstract*— Flexible pentacene-based organic thin-film transistors (OTFTs) were fabricated and their performance was investigated as a function of the bending radius and the thickness of the polydimethylsiloxane (PDMS) encapsulation layer. The TFTs were fabricated on a flexible polyimide (PI) film (film thickness: 75 µm), and encapsulated by a PDMS layer. Degradation of the device performance during application of a tensile bending stress of 3 mm was minimized by utilizing an encapsulation layer thickness of 75 µm, because the mechanical strain on the pentacene layer was almost off-set (tensile strain was applied to the bottom layer of the pentacene, and compressive strain was applied to the top layer of pentacene). At the tensile bending stress of 3 mm, the performance of the non-encapsulated TFT was degraded, whereas the encapsulated device showed great stability. This flexibility and bending stability were enabled by the use of the 75 µm PDMS encapsulation layer, due to the location of the pentacene active layer in the neutral region position. A mechanical reliability test was performed for 120 min with a bending radius of 3 mm, demonstrating that only the device with the 75 µm thick encapsulation layer showed stable device performance over a stress time of 120 min.**

***Index Terms*—Flexible Electronics, Pentacene, Encapsulation Layer, Neutral Region, Stability**

I. Introduction

RECENTLY, flexible electronics have attached attention due to their advantages, such as ease of design, lightweight nature, mechanical flexibility, and low costs [1-3]. The main applications of flexible electronics include rollable and foldable displays, radio-frequency identification tags, and flexible biosensors [4-7]. As a prerequisite for the development of flexible displays, the performance of flexible electronic devices under mechanical strain should be improved, which is one of the main issues in plastic electronics [8, 9]. Despite the many advantages, there are still several critical unresolved issues in the field of flexible OTFTs, such as degradation of the device performance at an extreme bending radius [10]. Herein, pentacene-based flexible organic thin-film transistors (OTFTs) are fabricated and their performance is studied with variation of the bending strain. The effects of tensile or compressive strain on the electrical properties of pentacene-based thin-film transistors due to changes in the distance between the pentacene molecules are well known [11]. The device performance also depends on the thickness of the encapsulation layer. Herein, we evaluate the effect of the thickness of the PDMS encapsulation layer (0, 15, 32, 38, 75, and 90 µm) on the device performance. We demonstrate that a PDMS encapsulation layer with a thickness of 75 µm provides more stable performance at different bending radii (20, 10, 8, 5, and 3 mm) because the mechanical strain induced between pentacene and the poly(methyl methacrylate) (PMMA) layer film surface is largely off-set. We also evaluate the electrical reliability during a stress time of 120 min for encapsulation layer thicknesses of 0, 32, and 75 µm.

II. Experimental

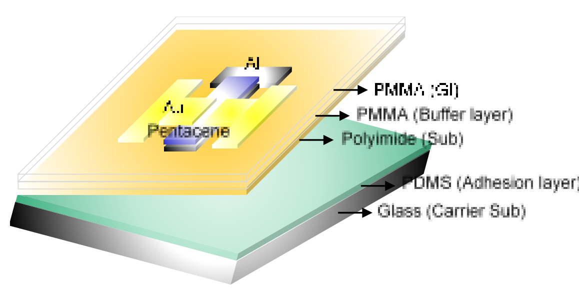

Figure 1. Device structure of flexible pentacene-based organic TFTs.

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A 75 µm thick Polyimide (PI) film substrate from DuPont, was cleaned by sonication in isopropanol for 20 min and oven-dried at 75 °C for 10 min to remove the residual solvent. The PI film was temporarily attached to a glass support by using polydimethylsiloxane (PDMS), and a 250 nm poly (methyl-methacrylate) (PMMA) buffer layer was deposited by spin-coating to improve the surface roughness. An aluminum layer was then vacuum-deposited on the PMMA buffer layer as a gate electrode by thermal evaporation (thickness: 40 nm) at a vacuum level of 6.6×10^{-6} Torr. As a gate insulator, a 250 nm PMMA layer was deposited by spin-coating. Pentacene and gold layers (70 and 80 nm thick, respectively) were sequentially deposited by thermal evaporation. The carrier substrate consisting of the glass and PDMS layer was then removed. Thus, we fabricated a bottom gate top contact (BGTC)-structured OTFT and with a total thickness of 440 nm, excluding the thickness of the PI film, buffer, and encapsulation layer. All the film thickness was measured by alpha-step (KLA-Tencor Alpha-Step 500 Profiler). Figure 1 shows the device structure of the flexible pentacene-based organic TFTs. A PDMS layer was also spin-coated to form an encapsulation layer. The PDMS layer prevents degradation of the organic TFT by preventing penetration of O_2 and H_2O to the pentacene grain boundary; the thickness of the encapsulation layer was controlled [12].

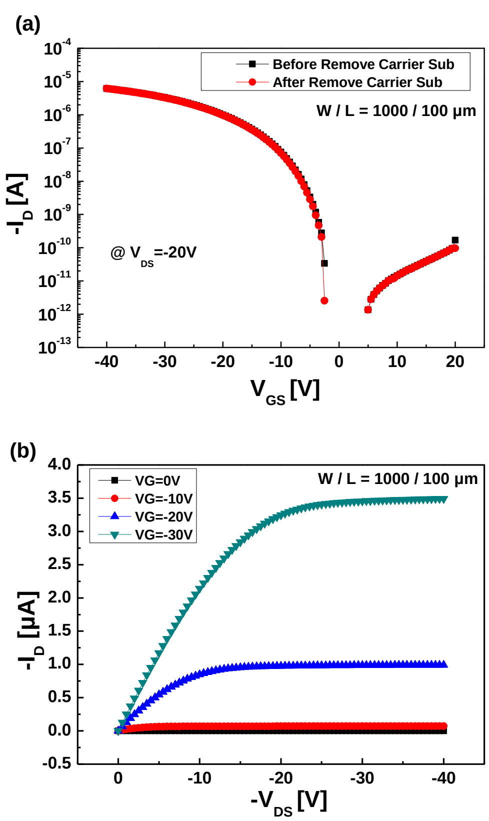

Figure 2. (a) Transfer characteristics of pentacene-based flexible organic TFT before and after removing carrier substrate. (b) Output characteristics of flexible pentacene-based organic TFT with a maximum saturation current of about 3.5 µA.

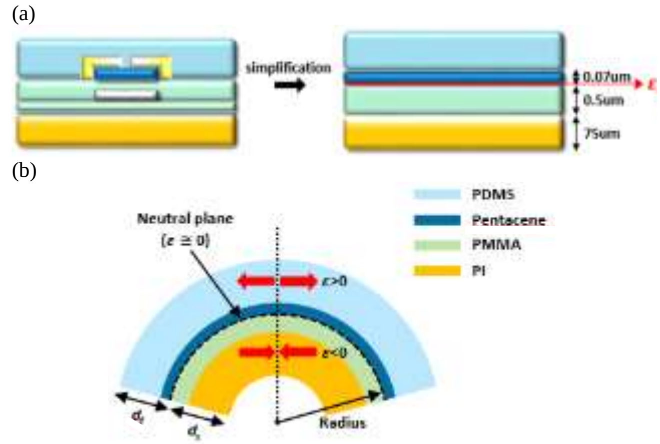

Figure 3. (a) Simplified device structure considering the mechanical properties of the layers. (b) Model used to calculate the surface strain (ε) between pentacene and PMMA.

III. Result

Figure 2(a) shows the typical transfer characteristics of the pentacene TFT (W/L = 1000 µm/100 µm) before and after removing the glass/PDMS carrier substrate. The performance parameters for this device were: saturation field effect mobility (μ_{eff}) = 0.13 $cm^2/V \cdot s$ and threshold voltage (V_{TH}) = -7.4 V, extrapolated using the standard equations of the TFT current model [13]. These parameters were almost the same before and after removing the carrier substrate. The output characteristics of the same organic TFT are shown in figure 2(b). The drain-source maximum saturation current, I_{DS}, was about 3.5 µA for an applied gate-source voltage, V_{GS}, of -30 V.

We calculated mechanical strain, ε, with variation of the bending radius and the PDMS encapsulation layer thickness. The strain, ε, developed on the top of a thin film deposited on a flexible substrate is given by:

TABLE I
YOUNG'S MODULUS
FOR DIFFERENT MATERIALS

Material	Young's modulus (GPa)
Polyimide (PI)	2.5
PMMA	1.8
Al	69
Pentacene	1
Au	79
PDMS	0.01

$$\varepsilon = \left(\frac{d_s + d_f}{2R}\right)\frac{(1 + 2\chi\eta + \chi\eta^2)}{(1+\eta)(1+\chi\eta)} \qquad (1)$$

where d_s and d_f are, respectively, the thicknesses of the substrate and the film, R is the curvature radius, χ and η are defined by $\chi = Y_f/Y_s$ and $\eta = d_f/d_s$, respectively, and Y_s and Y_f are, respectively, the young's modulus of the substrate and the film [14, 15]. The actual structure of present TFTs comprises a stack of seven films, with individual thicknesses and Young's moduli. Table I shows the Young's modulus of the different materials (polyimide, PMMA, Al, pentacene, Au,

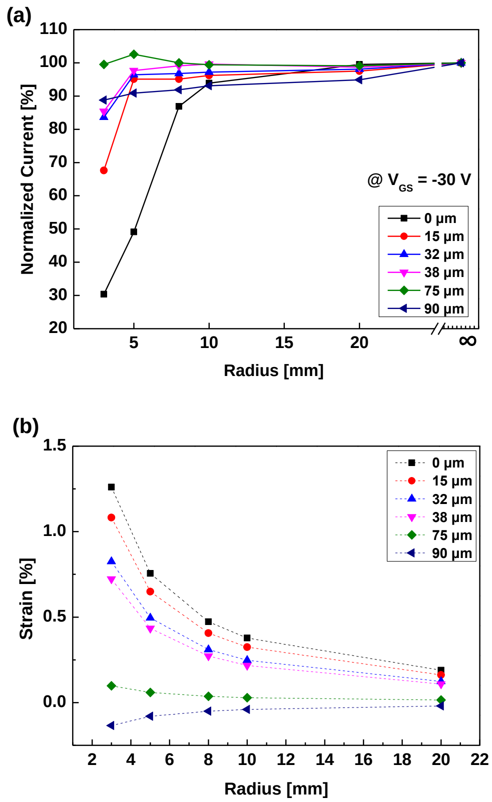

Figure 4. (a) A normalized drain-source on-current for different encapsulation PDMS layer thickness at gate-source voltage, V_{GS} = -30 V. (b) Mechanical strain between pentacene and PMMA surface for different bending radius.

TABLE II
NORMALIZED CURRENT AT GATE-SOURCE VOLTAGE OF -30 V FOR DIFFERENT ENCAPSULATION THICKNESSES AND BENDING RADII [%]

Encapsulation thickness	0 µm	15 µm	32 µm	38 µm	75 µm	90 µm
flat	100	100	100	100	100	100
20 mm	99.5	97.5	98.1	98.7	99.1	94.9
10 mm	93.9	96.2	97.2	99.6	99.4	93.1
8 mm	86.9	95.1	96.8	99.1	100	91.9
5 mm	49.1	95.1	96.4	97.7	102.6	90.9
3 mm	30.4	67.6	83.6	85.4	99.5	88.8

and PDMS). The mechanical behavior of the structure is mainly driven by the behaviors of the PI substrate, the PMMA layer, pentacene film, and PDMS encapsulation layer. In figure 3(a), therefore, the actual structure is simplified for the four films because these layers are thicker than other metal layers (Al, Au) [14]. Further, the PMMA buffer and gate insulator layer, having the same Young's modulus, can be combined in a single layer. Figure 3(b) shows the model used to calculate the surface strain between pentacene and PMMA.

The strain developed in the simplified structure was calculated using the strain equation. The TFTs with different PDMS encapsulation layer thicknesses (0, 15, 32, 38, 75, and 90 µm) were bent to different radii, *R*, (20, 10, 8, 5, and 3 mm) under tensile strain. The bending stress time was fixed to 1 min for all devices. Figure 4(a) shows the normalized on-current at -30 V for the gate-source voltage for the PDMS encapsulation

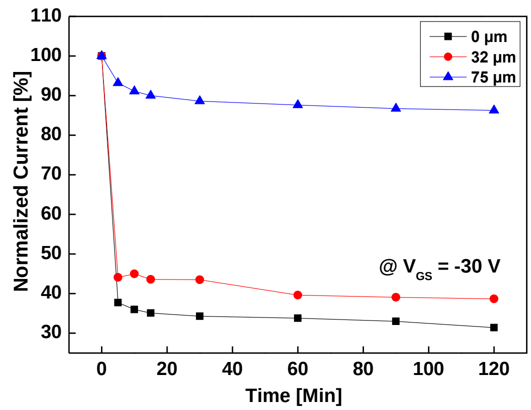

Figure 5. Measurement of device reliability with different stress times for 75, 32, and 0 µm encapsulation layer thickness at a bending radius of 3 mm.

layers with different thicknesses. Table 2 presents the normalized current value a gate-source voltage of -30 V for different bending radii. The device with the 75 µm encapsulation layer showed the most stable performance; only 0.5 % degradation occurred at *R* = 3 mm compared with the initial condition. In this case, the pentacene layer was located in the neutral strain position and thus almost off-set the bending-induced mechanical strain. The device with an encapsulation layer thickness of 0 µm underwent 69.6 % degradation at *R* = 3 mm. It is well known that the distance between the pentacene molecules expands under tensile strain, resulting in degradation of the performance of organic TFTs due to interruption of the hopping charge-carrier transport [16]. However, the distance between the pentacene molecules can be reduced if compressive strain is applied to the upper layer of pentacene [16, 17].

We also evaluated the bending reliability of the fabricated organic TFTs, along with that of the pentacene-based TFTs on the flexible polyimide substrates at a bending radius of 3 mm. Figure 5 shows that the device reliability was greatly improved at different stress times when the encapsulation layer thickness was varied from 0 µm to 75 µm. The organic TFT with an encapsulation layer thickness of 75 µm underwent 13.7 % degradation over a bending stress time of 120 min, whereas the device without the encapsulation layer underwent 68.6 % degradation during same bending stress time.

IV. CONCLUSION

Pentacene-based organic TFTs were fabricated on a flexible polyimide substrate (thickness: 75 µm) and the performance was investigated with variation of the bending radius and encapsulation layer thickness. The results show that 75 µm thick PDMS encapsulation layer was the most effective for reducing degradation of the performance of the OTFT device. The normalized on-current of this device was degraded by only 0.5 % at a bending radius of 3 mm. This is because the similarity of the thickness of the encapsulation layer to that of the polyimide substrate can off-set the mechanical strain applied to the pentacene-PMMA surface (tensile strain was applied to the bottom layer, and compressive strain was applied to the top layer of the pentacene-PMMA surface).

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A device reliability test was also performed using encapsulation layers of 75 μm, 32 μm, and 0 μm thickness, and only a 13.7 % decrease in the normalized on-current of the TFT device with the 75 μm thick encapsulation layer was induced by tensile mechanical strain, whereas that of the device without the encapsulation layer was degraded by 68.6 % at a bending radius of 3 mm over for 120 min.

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