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Effects of Mechanical Strain on the Electrical Performance of Amorphous Silicon Thin-Film Transistors with a New Gate Dielectric

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ABSTRACT

The stiff SiN_x gate dielectric in conventional amorphous silicon thin film transistors (TFTs) limits their flexibility by brittle fracture when in tension. We report the effect on the overall flexibility of TFTs of replacing the brittle SiN_x gate dielectric with a new, resilient SiO_2-silicone hybrid material, which is deposited by plasma enhanced chemical vapor deposition. Individual TFTs on a 50μm-thick polyimide foil were bent to known radii, and measurement of transfer characteristics were made both during strain and after re-flattening. Compared with conventional TFTs made with SiN_x, TFTs made with the new hybrid material demonstrated similar flexibility when strained in compression and significantly increased flexibility when strained in tension. Under bending to compressive strain, all TFTs tested delaminated from the substrate for compressive strains greater than 2%. Conventional a-Si:H/SiN_x TFTs have been previously found to delaminate at a similar compressive strain. Under bending to tensile strain, the most flexible TFTs made with the new hybrid material that were tested after re-flattening did not exhibit significant changes in transfer characteristics up to strains of ~2.5%. Conventional a-Si:H/SiN_x TFTs have been found to remain functional for strains of up to 0.5%, a value only one-fifth of that for TFTs made with the new hybrid material.

INTRODUCTION

Hydrogenated amorphous silicon thin-film transistors (a-Si:H TFTs) are vital components of many large-area electronics such as displays and sensors. The earliest TFTs were fabricated on glass substrates, which are brittle and thus impractical for applications in flexible electronics [1]. In 1999, attempting to address this issue, Suo, Ma, Gleskova, and Wagner studied the mechanics of straining a-Si:H/SiN_x TFTs that were deposited on compliant polyimide foils instead of traditional glass substrates and suggested that such film-on-foil devices could be made to be very flexible [2]. Since then, various approaches have been taken to further enhance the mechanical properties of TFTs [3]. For instance, in 1999, Gleskova, Wagner, and Suo reported that removing the SiN_x encapsulation layer backing the polyimide substrate in the traditional substrate "sandwich" structure resulted in more flexible TFTs [4]. While these efforts have indeed been productive, the stiffness of the SiN_x used as the gate dielectric and substrate encapsulation material in conventional TFTs ultimately limits the greatest degree of flexibility that may be achieved with such structural alterations alone. In order to produce TFTs that function over an even wider range of mechanical strains, the SiN_x itself must be replaced with a new material that is compliant and resistant to crack propagation.

Such a material is also desirable for organic light-emitting diode (OLED) technologies. Because the electrical properties of OLEDs degrade rapidly when exposed to moisture and oxygen, it is necessary to encapsulate the devices with a material that is impermeable and, ideally, flexible. Inorganic materials, such as Al_2O_3 and SiN_x, are effective barriers, but because they are brittle, when mechanically strained they become vulnerable to microcracks that provide a diffusion path for air molecules [5]. Organic materials, on the other hand, are light and flexible but are poor permeation barriers. In 2008, P. Mandlik et al. developed a SiO_2-silicone hybrid material as a permeation barrier to protect OLEDs from the moisture and oxygen in the environment [6, 7]. In addition to being optically clear and being able to be deposited as a single thin film, this material was found to effectively combine the high degree of flexibility and resistance to crack propagation characteristic of polymers with the impermeability characteristic of inorganic materials, a combination that cannot be accomplished with traditional materials [5].

Recently, Lin Han et al. found a second application for this newly discovered SiO_2-silicone hybrid material as the gate dielectric of amorphous silicon TFTs. It has been found that the new TFTs offer advantages of conventional a-Si:H/SiN_x TFTs in terms of electrical performance, posessing high field-effect mobilities of ~2 $cm^2/V{\cdot}s$ for electrons and 0.1 $cm^2/V{\cdot}s$ for holes [8]. Furthermore, because the new hybrid material is more flexible than the conventional SiN_x dielectric, we expected the new TFTs to be more flexible than conventional TFTs. The objective of this research is to determine the flexibility of amorphous silicon TFTs made with the new gate dielectric and the mechanisms of failure under applied tensile and compressive strain.

EXPERIMENT

Bending experiments were conducted on three varieties of inverted staggered TFTs: back channel cut TFTs on 50-μm thick polyimide foil passivated on both sides with the hybrid SiO_2-silicone material (conventional "sandwich" structure) [Fig. 1(a)]; back channel cut TFTs on polyimide foil passivated on the device face only [Fig. 1(b)]; and TFTs on single-side passivated polyimide foil with an added SiO_2-silicone back channel encapsulation layer [Fig. 1(c)]. A 10-nm layer of SiN_x was deposited between the substrate and the hybrid passivation layer(s) to serve as an adhesive. The TFTs were fabricated using virtually the same steps and processes as conventional a-Si:H/SiN_x TFTs with two material substitutions. As just mentioned, the hybrid

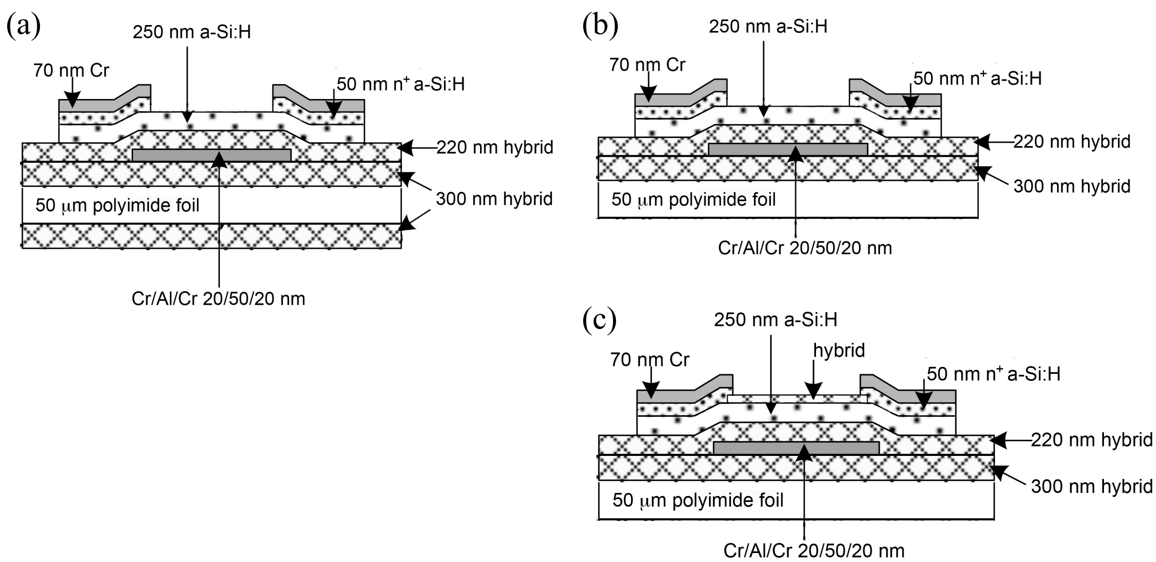

Figure 1. Cross-sections of a-Si:H TFTs fabricated on polyimide foil: (a) conventional sandwich structure; (b) back SiO_2-silicone removed; (c) back SiO_2-silicone removed and back-channel passivation layer added.

was used instead of SiN_x for the substrate and backchannel passivation layers and the gate dielectric. In addition, the gate, conventionally made out of brittle Cr, was fabricated with Cr/Al/Cr sandwich metal for enhanced flexibility. For deposition of the hybrid SiO_2-silicone layer, a gaseous mixture of hexamethyl disiloxane (HMDSO) and O_2 is fed into a single-chamber plasma-enhanced chemical vapor deposition (PE-CVD) reactor [8].

A TFT was first bent around a drill bit with a radius of 3.5 mm for one minute and then re-flattened for measurement of transfer characteristics, which consisted of a linear sweep of gate voltage V_{gs} from +20 V to -10 V at drain voltage V_{ds} = 0.1 V followed by an identical sweep at V_{ds} = 10 V. This procedure was then repeated on the same transistor using drill bits of decreasing radius (in decrements of 0.5 mm) until the transistor failed to function. The applied mechanical strain ε on the surface of the TFT for each bending radius was estimated by the equation $\varepsilon = d/(2R)$, where R is the distance from the center of the drill bit to the neutral plane and d is the thickness of the polyimide substrate. When the TFT faces outward during bending, it is under tensile strain, and ε is defined to be positive. When the TFT faces inward (toward the surface of the drill bit), it is under compressive strain, and ε is defined to be negative.

RESULTS AND DISCUSSION

Bending in tension

On-current I_{on}, off-current I_{off}, gate leakage current I_{leak}, normalized threshold voltage V_T/V_{T0}, and normalized electron mobility μ/μ_0 are plotted as a function of strain in Figure 2(a) for back channel cut TFTs on polyimide with passivation on both faces and in Figure 2(b) for back channel encapsulated TFTs on polyimide with passivation on the device face only. The definition of these are as follows: I_{on} is the drain-source current for V_{ds} = 10 V and $V_{gs} = V_{th}$ + 10 V; I_{off} is the smallest drain-source current at V_{ds} = 10 V; and I_{leak} is the gate-source current for V_{ds} = 0.1 V and V_{gs} = 10 V; the threshold voltage is estimated to be the value of V_{gs} for a drain-source current of 10^{-10} A and V_{ds} = 0.1 V; the effective electron mobility is extracted from the linear region of the transfer curve for V_{ds} = 10 V (taking into account the shift in V_T). The increase in threshold voltage and decrease in mobility with increasing strain in both the tension and compression directions is in part due to electrical stress from repeatedly applying a voltage – an unstrained TFT subject to repeated electrical measurements exhibits similar trends.

When TFTs on polyimide foil with passivation on both faces were bent to tensile strains ≥ 0.83%, I_{on} was noticeably degraded. However, the transistors remained functional until a tensile strain of 1.64% was applied. In 1999, Gleskova, Wagner, and Suo found double-sided a-Si:H/SiN_x TFTs to exhibit significant changes in transfer characteristics at ~0.4% tensile strain, remaining functional up to a tensile strain of only 0.5% [4]. This value at which conventional a-Si:H/SiN_x transistors failed under applied tensile strain is approximately 4 times lower than the value found in the present experiments.

For TFTs on polyimide with a SiO_2-silicone passivation layer on the device face only, there were no substantial changes observed in transfer characteristics for tensile strains ≤ 2.44%. When a tensile strain of 4.76% was applied, all of the TFTs tested failed to function. Because of the limited selection of drill bit sizes and thus limited selection of possible applied strains, no intermediate state of noticeably deteriorated electrical performance before failure was observed

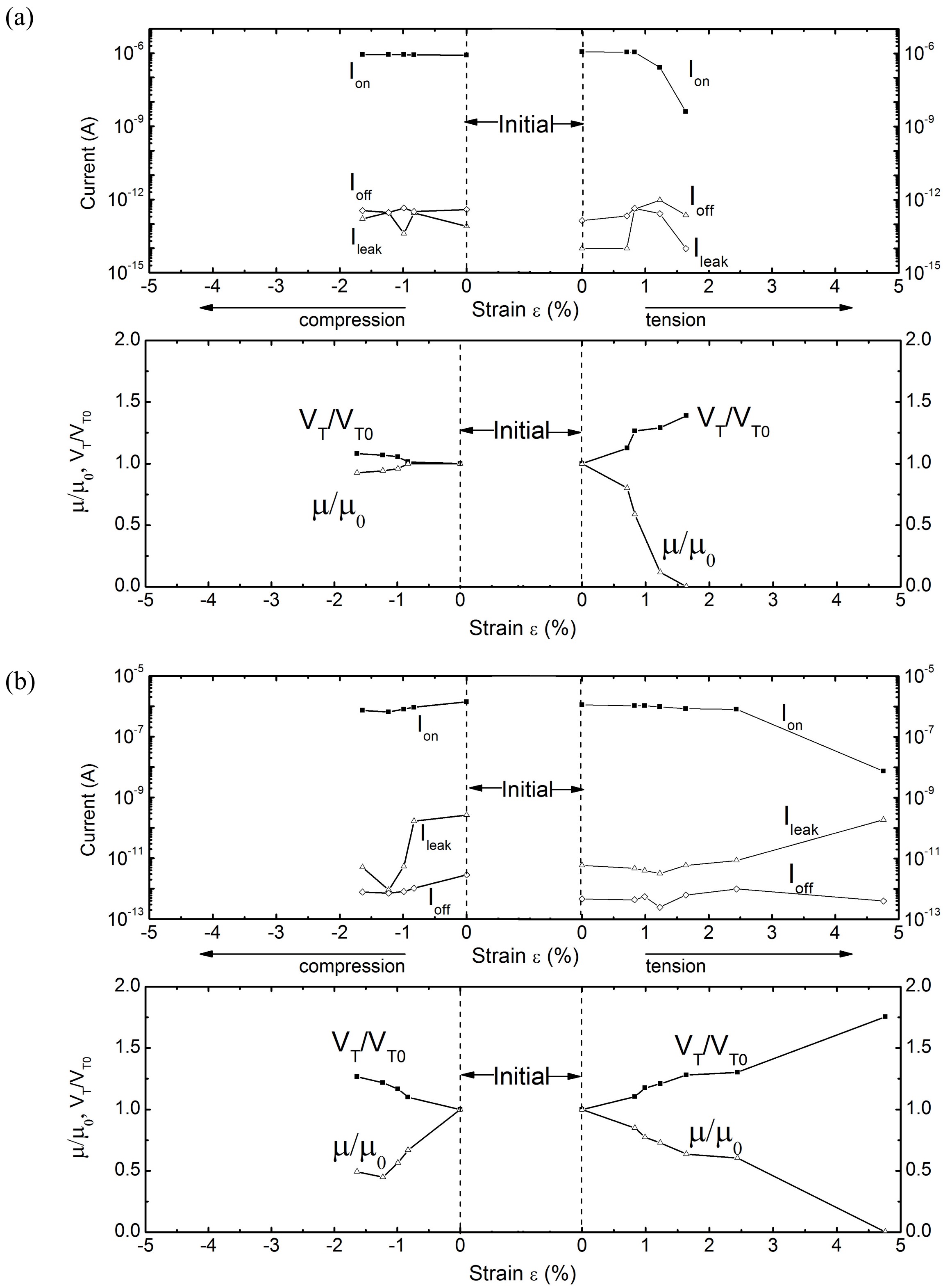

Figure 2. On-current I_{on}, off-current I_{off}, gate leakage current I_{leak}, normalized electron mobility μ/μ_0, and normalized threshold voltage V_T/V_{T0} versus strain for (a) back channel cut TFTs on polyimide with passivation on both faces and for (b) back channel encapsulated TFTs on polyimide with passivation on the device face only.

in these tensile bending experiments for TFTs on polyimide passivated on the device face only. It was previously reported that conventional a-Si:H/SiN_x TFTs on polyimide foil passivated on the device face only also are more flexible than those on polyimide passivated on both sides [4]. However, the effect was not nearly as pronounced, with TFTs exhibiting deteriorated performance at ~0.5% tensile strain, a value 5 times less than that for the TFTs made with the new hybrid material.

Adding a SiO_2-silicone back channel passivation layer in the TFT stack deposited on polyimide with passivation on the device face only did not cause an observable change in flexibility. Like the TFTs without back channel passivation deposited on polyimide with passivation on the device face only, back channel passivated TFTs on polyimide with passivation on the front face only failed when strained in tension to 4.76% and did not exhibit significant changes in transfer characteristics up to this strain. For back channel cut TFTs, when etching n^+ a-Si (deposited on top of the a-Si layer and below the source/drain metal) in fabrication, a portion of the underlying a-Si layer is also etched away. Back channel encapsulation protects the a-Si layer from being etched during this processing step, thus eliminating the need to grow an a-Si layer that is thicker than desirable. It was originally hypothesized that reducing the thickness of this brittle layer would enhance flexibility, but we could not confirm this with our limited selection of drill bit sizes.

An optical micrograph of a back-channel passivated TFT on polyimide foil with passivation on the device face only after bent in tension to 4.76% is shown in Figure 3(a). The vertical periodic cracks running parallel to the axis of bending indicate that the mechanism of failure under bending in tension is brittle fracture. No such cracks were visible for strains of less than 2.44%. Cracks were faintly visible after the TFT was bent in tension to 2.44%, but electrical measurements after bending to this strain showed the TFTs to remain functional. This suggests that for a certain range of mechanical strain, the TFTs may physically crack but can recover electrically if the cracks close upon re-flattening. This observation has also been previously made for conventional a-Si:H/SiN_x TFTs [3].

The aforementioned measurements were conducted during the winter, when the relative humidity in the laboratory was ~30%. During the summer, the humidity in the laboratory jumped up to >50% r.h., and under these conditions, the application of a voltage caused the TFTs to burn

(a) (b)

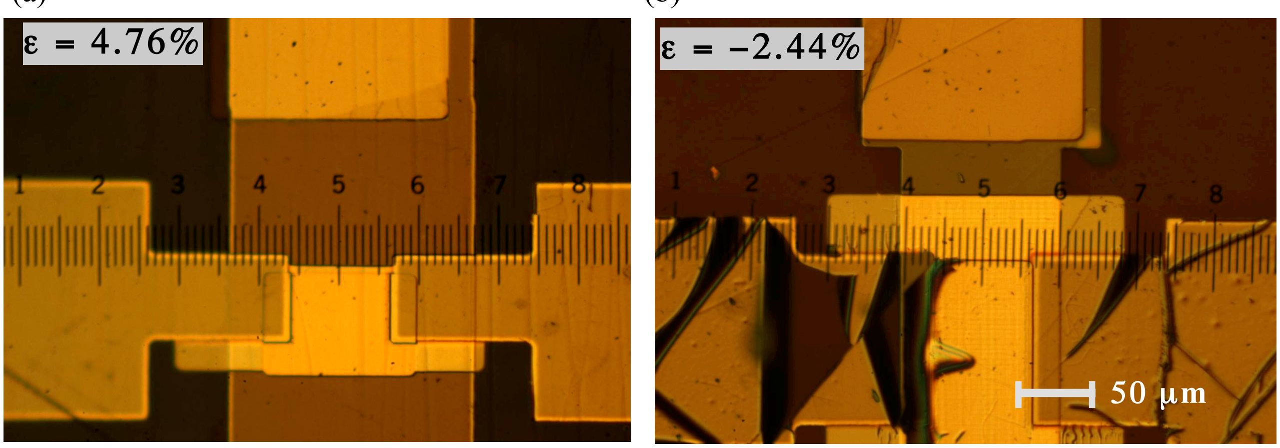

Figure 3. Optical micrographs of back channel encapsulated TFTs on polyimide with passivation on the device face only after applying (a) a tensile strain of 4.76% and (b) a compressive strain of -2.44%.

along cracks after being bent to strains of only ~1%. This was accompanied electrically by extremely high gate leakage current and extremely low on-current.

Bending in compression

All TFTs tested, regardless of substrate and back channel encapsulation, behaved almost identically when bent in compression. Virtually no changes in transfer characteristics were observed for applied compressive strains up to ~-2%. For greater compressive strains, TFTs delaminated from the substrate and could not be further evaluated for electrical performance. The reported results of Gleskova, Wagner, and Suo's experiments in applying compressive strain to a-Si:H/SiN_x transistors are very similar, with TFTs showing no degradation in electrical performance for compressive strains up to ~-2% and delaminating thereafter due to buckling of the film [4]. An optical micrograph of a back-channel passivated TFT on polyimide foil with passivation on the device face only after being bent in compression to -2.44% is shown in Figure 3(b). As seen in the figure, delamination indeed appears to be the mechanism of failure in compression for these TFTs as well. These compression results were independent of humidity.

CONCLUSIONS

We have fabricated high-performance, highly flexible a-Si:H TFTs that can recover from bending to 2.5% strain in tension and 2% in compression by replacing the brittle SiN_x dielectric material in conventional TFTs with a flexible hybrid material. TFTs made with the new dielectric material are several times more flexible than their a-Si:H/SiN_x counterparts and have potential to enhance the flexibility and durability of large area electronics. The mechanisms of failure for the new TFTs are the same as those for conventional TFTs: under bending in tension, the mechanism is brittle fracture, and under bending in compression, the mechanism is delamination of the film from the substrate.

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