Flexibility of Amorphous Silicon Thin-Film Transistors with a New Gate Dielectric Deposited by Plasma Enhanced Chemical Vapor Deposition

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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. 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 about 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, members of the Wagner group have 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, boasting high field-effect mobilities of ~2 cm^2/V·s for electrons and 0.1 cm^2/V·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

TFTs tested in this research were fabricated by Lin Han. During the fabrication process, a gaseous mixture of hexamethyl disiloxane (HMDSO) and O_2 is fed into a single-chamber plasma-enhanced chemical vapor deposition (PE-CVD) reactor. The hybrid SiO_2-silicone film layer is subsequently deposited at nominal room temperature onto a 50 mm-thick DuPont Kapton E polyimide foil substrate.[8] Bending experiments were conducted on three varieties of inverted staggered TFTs: back channel cut TFTs on Kapton passivated on both sides with the hybrid SiO_2-silicone material (conventional “sandwich” structure) [Fig. 1(a)]; back channel cut TFTs on Kapton passivated on the device face only [Fig. 1(b)]; TFTs on single-sided Kapton with an added SiO_2-silicone back channel encapsulation layer [Fig. 1(c)].

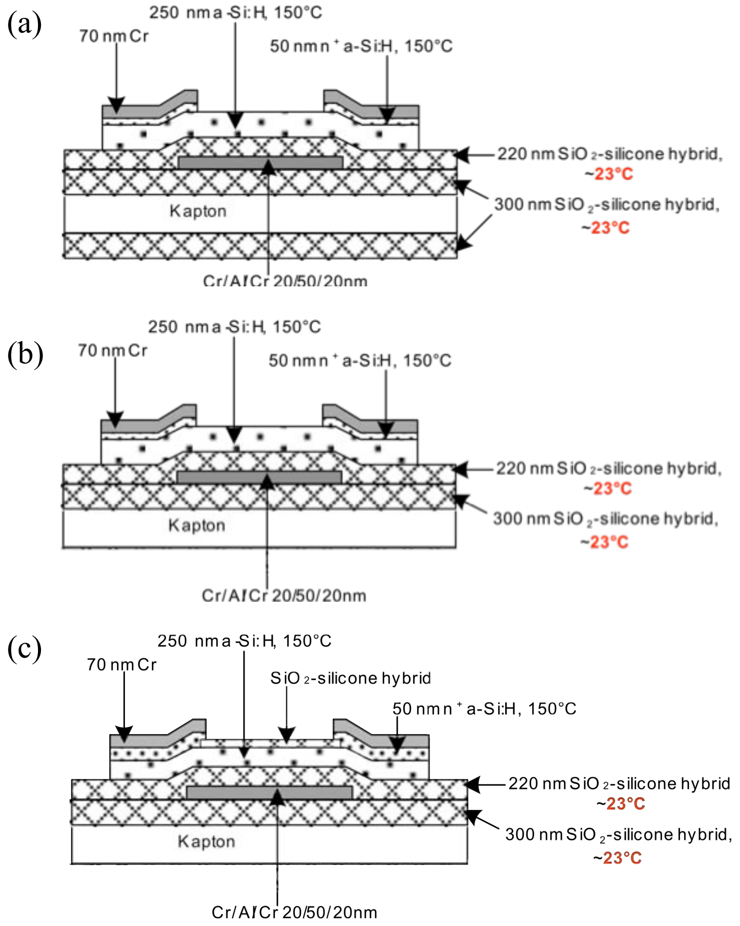

FIGURE 1. Cross-sections of a-Si:H TFTs fabricated on 50 μm thick Kapton: (a) conventional sandwich structure; (b) back SiO_2-silicone removed; (c) back SiO_2-silicone removed and back-channel passivation layer added.

Electrical characteristics after bending

Electrical measurements of TFTs after bending were made primarily in early spring 2009. 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 increments 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 Equation (1),

$$\varepsilon = \frac{t}{2R} \tag{1}$$

where R is the distance from the center of the drill bit to the neutral plane and t is the thickness of the Kapton 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.

In situ measurements

It has been suggested that there exists a range of applied strains under which TFTs physically crack but are able to electrically recover when cracks close upon release of the strain. To determine this range and better understand the dependence of electrical characteristics on mechanical strain in general, TFTs on Kapton passivated on the device side only were measured *during* bending (i.e. before they were re-flattened). These experiments were begun in summer 2009. Small strips of scrap metal were carefully bent around cylindrical objects into half-pipe structures, and their radii of curvature were measured. The corresponding strain ε for each radius was calculated using Equation (1) above. For in situ tension measurements, the half-pipe was placed onto the measurement stage concave down, and a strip of TFTs was taped to the outside of the half-pipe with the device side facing up. For in situ compression measurements, the half-pipe was placed onto the measurement stage concave up, and a strip of TFTs was taped to the inside of the half-pipe with the device side facing up. The first set of electrical measurements of an individual TFT on the sample strip (one not covered by tape) were made approximately 2 minutes after the sample was secured to the half-pipe with the largest radius of curvature, which in these experiments was 15 mm. The tape was then removed, and the TFT strip was re-flattened. The TFT strip was left untouched for approximately 30 minutes to allow for the relaxation of electrical strain induced by the application of voltage during measurement. The same procedure was then repeated on the same TFT for decreasing radii of curvature until the TFT failed to function.

RESULTS AND DISCUSSION

Electrical characteristics after bending

Bending in tension:

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} are plotted as a function of strain in Figure 2(a) for back channel cut TFTs on Kapton with passivation on both faces and in Figure 2(b) for back channel encapsulated TFTs on Kapton 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 effective electron mobility was extracted from the linear region of the transfer curve for V_{ds} = 10 V, and the threshold voltage was taken to be the value of V_{gs} for a drain-source current of 10^{-10} A and V_{ds} = 0.1 V. 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 Kapton foil with passivation on both faces were bent to tensile strains $\geq$ 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 transistors failed under applied tensile strain is approximately 4 times lower than the value found in the present experiments.

For TFTs on Kapton with a SiO_2-silicone passivation layer on the device face only, there were no substantial changes observed in transfer characteristics for tensile strains $\leq$ 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 in these tensile bending experiments for TFTs on Kapton passivated on the device face only. It was previously reported that conventional a-Si:H/SiN_x TFTs on Kapton foil passivated on the device face only also are more flexible than those on Kapton 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 Kapton with passivation on the device face only did not cause an observable change in flexibility. Like the TFTs without back channel passivation deposited on Kapton with passivation on the device face only, back channel passivated TFTs on Kapton with passivation on the front face only failed when strained in tensile to 4.76% and did not exhibit significant changes in transfer characteristics up to this point. Back channel encapsulation protects the a-Si layer during the etching of n^+-Si (deposited on top of the a-Si layer and below the source/drain metal) during fabrication, a process that, for back channel cut TFTs, etches away a portion of the underlying a-Si layer. Back channel encapsulation thus eliminates 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 Kapton foil with passivation on the device face only (W/L = 60/60 μm) after bent in tension to 4.76% is shown in Figure 3(a). The 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 supports the aforementioned possibility that TFTs can recover from cracking under certain strains for which the cracks are able to close upon re-flattening of the TFT.

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 Kapton foil with passivation on the device face only (W/L = 60/60 μm) 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.

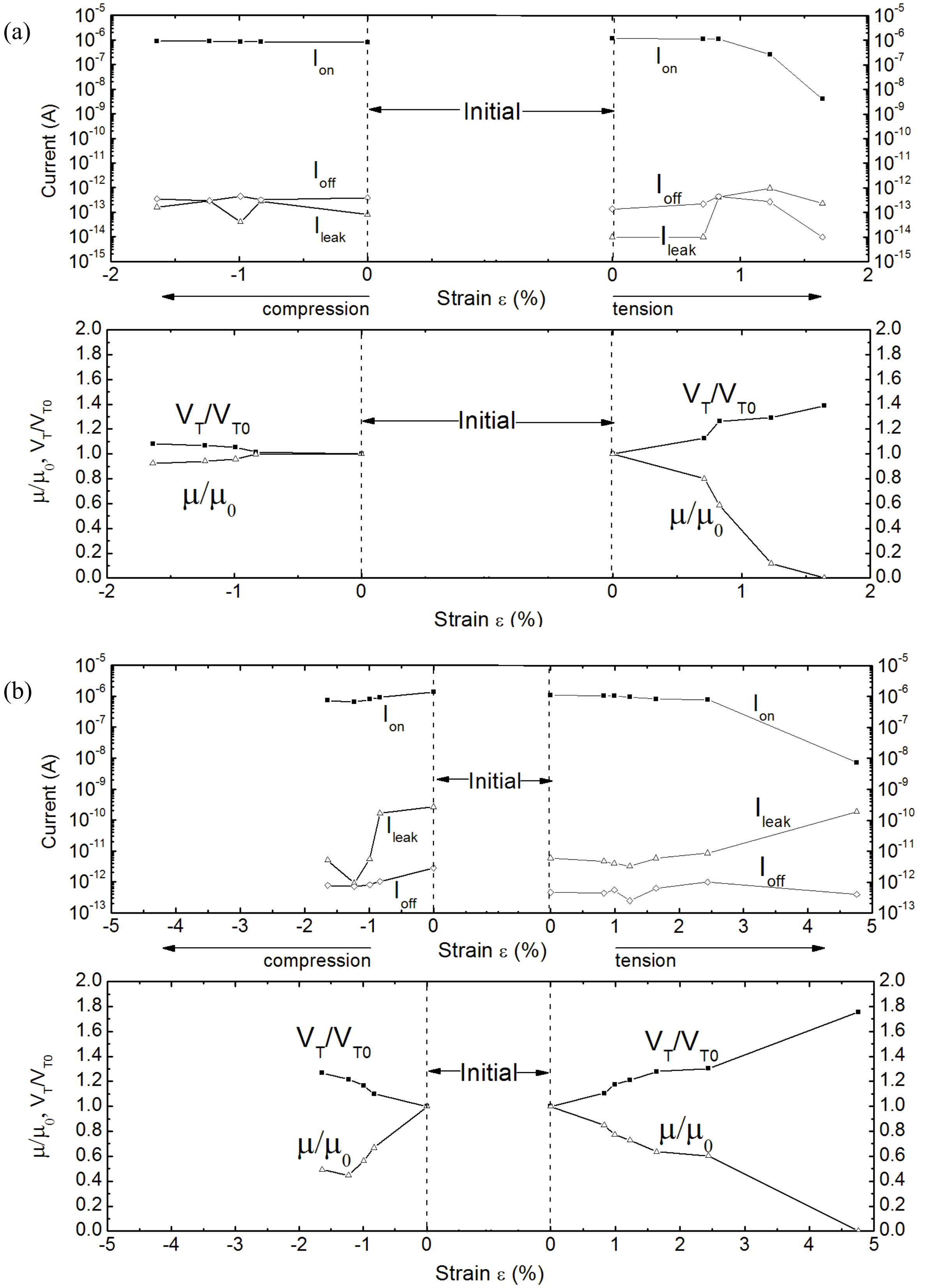

FIGURE 2. On-current I_{on}, off-current I_{off}, gate leakage current I_{leak}, normalized electron mobility μ/μ_0, and normalized threshold voltage V_T/V_{T0} versus strain for (a) back channel cut TFTs on Kapton with passivation on both faces and for (b) back channel encapsulated TFTs on Kapton with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

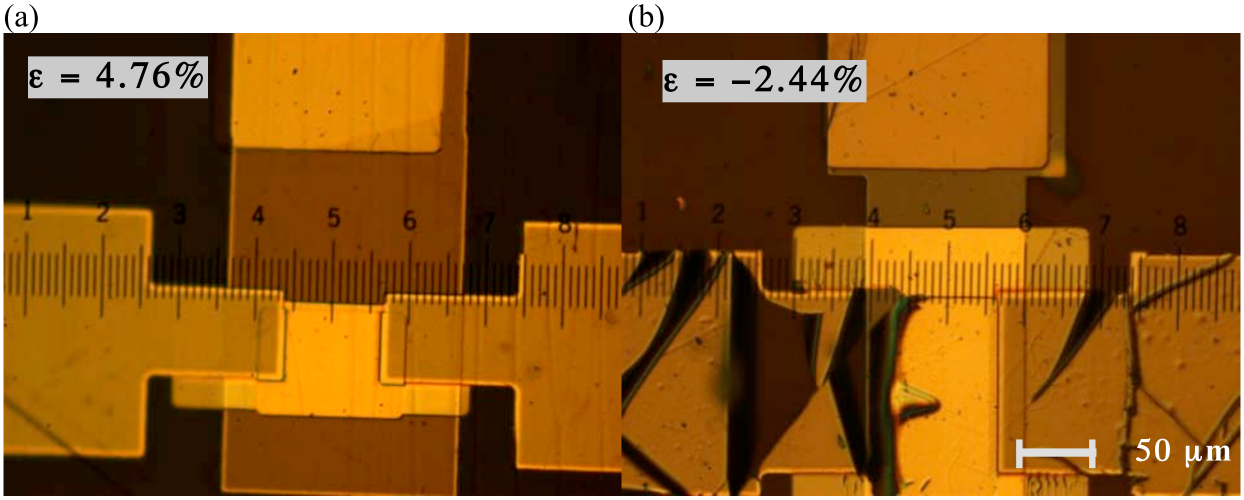

FIGURE 3. Optical micrographs of back channel encapsulated TFTs on Kapton with passivation on the device face only (W/L = 60/60 μm) after applying (a) a tensile strain of 4.76% and (b) a compressive strain of -2.44%.

In situ measurements

In general, the electrical characteristics extracted from in situ measurements were quite inconsistent from experiment to experiment, in part because contact between the measurement probes and the TFT metal contacts was often poor. TFTs measured during tensile bending failed at ~0.7% strain. This failure was characterized by extremely high I_{leak}, extremely high I_{off}, and visible burning along cracks (seen in Figure 4), all of which were not observed in the experiments described previously. Because micrographs from the previous experiments support the possibility that TFTs may crack during bending but still function when re-flattened, the fact that TFTs measured during bending failed at a lower strain than TFTs measured after re-flattening is not unreasonable. However, the discrepancy between the critical strain for in situ tension measurements and the critical strain for measurements made after bending in tension was still unexpectedly large. In an attempt to understand this, measurements were done on 2 adjacent TFTs on the same sample strip: one TFT was measured during bending, and the other was measured after the strain was released. The results were rather surprising; the two TFTs both failed at ~0.7% tensile strain, which suggests that cracks formed during bending did not close upon re-flattening, leaving the TFTs irreversibly broken. Both TFTs also exhibited the characteristics of burning and high gate leakage current/high off-current shown in Figure 4.

When measured under compression, TFTs did not burn in this way or exhibit otherwise strange behavior. As was the case with TFTs measured after compressive bending for 1 minute at each strain, TFTs measured during compressive bending delaminated at ~2%. This implies that the reason behind the premature burning of TFTs in tension is related to the brittle fracture mechanism that is responsible for failure in tension but not compression. One possible explanation is that the brittle a-Si layer, and possibly the hybrid silicon oxide – silicone dielectric, is very sensitive to moisture in the air. In situ measurements were conducted during the summer, during which the relative humidity of the laboratory was usually around 55%. On occasion, the relative humidity dropped to around 45%, and on these days, TFTs failed (both when measured after re-flattened and when measured during bending) at tensile strains of ~1.5%. In early spring, when the TFTs remained functional after bending in tension to 2.5% strain as previously described, the relative humidity of the laboratory was around 30%. It is well known that water molecules enhance crack growth in glassy materials by breaking bonds at a crack tip and hence lengthening the crack.[9] This may be why TFTs tested during the humid summer failed at significantly lower strains than those tested during earlier in the year. In addition, oxidation that occurs at crack sites when bending in a humid environment prevents cracks from reclosing to allow the recovery of the TFT, providing a possible reason for the apparent lack of strains from which the TFT may "recover" upon re-flattening.

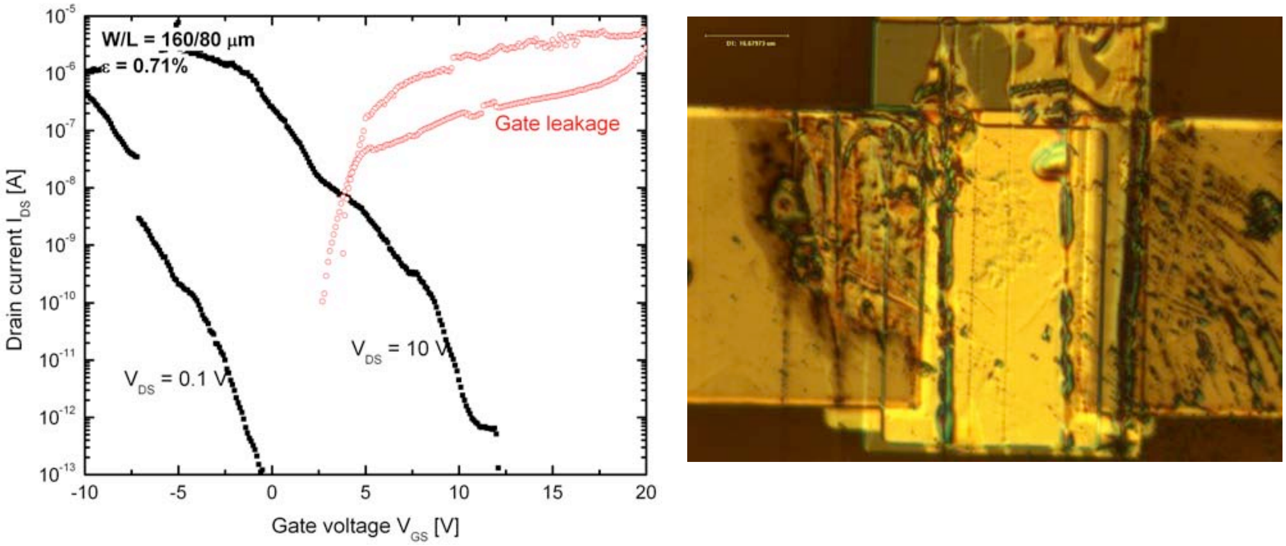

FIGURE 4. Characteristics of TFT failure when measured during bending in tension, as well as when measured after bending in tension on a humid day: high I_{leak} and I_{off}, seen in transfer curves, and burning along cracks, visible under an optical microscope.

CONCLUSIONS AND FURTHER RESEARCH

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. The critical strain of the TFTs under tensile bending seems to be extremely sensitive to humidity. In the future, it would be useful to design and conduct controlled humidity experiments to more fully understand and be able to address problems arising from the dependence of TFT flexibility and performance on moisture in the air.

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