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# Amorphous IGZO TFTs and circuits on conformable aluminum substrates

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ABSTRACT

This paper reports the characteristics of a-IGZO TFTs and circuits fabricated on conformable aluminum substrates. TFTs with field-effect mobility of up to 15.3 $cm^2/V$ s, average threshold voltage of 5.2 V, and off current less than $10^{-12}$ were demonstrated at zero strain; applying mechanical tensile strain up to 1.25% through bending was found to have a beneficial result to the device characteristics as mobility increased and threshold voltage decreased. These results highlight the potential of aluminum substrates for the use in future display and other large area electronics applications.



## 1. Introduction

Flexible electronic systems are attracting significant research interest worldwide because of their potential to realize novel applications such as flexible or conformal displays, and novel sensors. This type of electronic systems encompasses a wide range of device and materials technologies that are built on flexible and conformal substrates. Most of the flexible electronics reported to date are based on hydrogenated amorphous silicon (a-Si:H), polycrystalline silicon (poly-Si) thin film transistor (TFT) technologies or organic semiconductors. Both organic semiconductors and a-Si:H TFTs suffer from low mobility which may limit their application in high performance flexible electronic systems. The poly-Si TFT technology also has certain disadvantages. For example, the fabrication cost of the poly-Si TFTs is considered to be relatively high due to certain critical fabrication steps which include the excimer laser crystallization of the starting amorphous silicon film, the doping of the source and drain regions and finally the activation of the dopants. Furthermore, grain boundaries present within the poly-Si layer may deteriorate the device performance uniformity. Due to the aforementioned disadvantages of existing TFT technologies, there has been significant interest for developing an alternative thin film transistor technology based on the metal oxide semiconductors. In particular, amorphous indium–gallium–zinc-oxide (a-IGZO) TFTs was demonstrated to have higher mobility and superior stability than a-Si:H TFTs while due to its amorphous phase it did not exhibit any non-uniformity issues such as those observed in polycrystalline silicon. Overall, the a-IGZO TFT technology is presenting good uniformity, good bias stability, low power consumption, and very low off current; these advantages are making it a good alternative to either amorphous or polycrystalline silicon for both AMLCD and AMOLED flat panel displays [1–5].

In many mobile electronics, mechanical characteristics of the electronic system such as weight, flexibility, and durability are becoming important [6]. Inexpensive, light-weight, flexible, durable displays are desirable for laptops, tablets, smart phones and e-readers. This new class of displays requires substrate materials with different mechanical properties with respect to those of presently used glass substrates [7]. Since OLEDs can be made to emit light from the top surface, transparency of substrates is not required for OLED/TFT integration, lending more freedom to the choice of substrates [8,9]. So far, several groups have reported the electrical characteristics of a-IGZO TFTs on plastic substrates, such as polyethylene naphthalate (PEN) or polyethylene terephthalate (PET) for flexible or rollable display applications using a low-temperature process [10,11]. However, the low-temperature process for an a-IGZO active layer decreases the performance of a-IGZO TFT including field-effect mobility and bias stress stability, which reduce the merits of oxide-based TFTs. Susceptibility to gas permeation is the other drawback of plastic substrates. On the other hand, stainless steel is compatible with high-temperature processes and available in large-area sheets but it is considered

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heavy and expensive. Specifically, rolling thin and smooth stainless steel in wide width is very costly. For these reasons, further advances in developing engineered flexible substrates with enhanced mechanical and chemical properties is essential for continuing advances in the field of flexible electronics. In this study, we investigate the use of aluminum as substrate for flexible electronics by means of fabricating a-IGZO TFT devices and circuits. Compare to plastics or other metals, aluminum offers certain distinct advantages such as light weight due to its low density, high strength, and low cost. Furthermore, the use of aluminum substrates for fabrication of electronic devices, especially TFTs offers significant merits for flat panel displays and other flexible electronics such as excellent barrier to moisture, ease of recycling, high corrosion resistance, and compatibility with higher processing temperatures compared to polymer substrates.

Despite the significant advantages that aluminum is offering, there is limited information about characteristics of IGZO TFTs fabricated on aluminum substrates. In this paper, we report the successful demonstration of a-IGZO TFTs on aluminum substrates. The compatibility with conventional fabrication processes coupled with good performance IGZO devices as described in the following sections, suggests that TFT fabrication on aluminum substrates has the potential to be a robust process suitable for display and other large area electronics manufacturing.

## 2. Experimental

Aluminum sheets with the thickness of ~480 μm were used as the substrates in this experiment for the fabrication of a-IGZO TFT devices and circuits. The particular thickness chosen in this study enables a finished electronic system to conform to a curved surface while the substrate can be free standing during device processing. These substrates, manufactured and engineered by Alcoa Incorporation, had a smooth surface and an insulating layer on both sides of the substrate in order to electrically isolate the substrate and to balance the stress. An atomic force microscopy (AFM) image (Fig. 1) showed a root-mean-square (rms) surface roughness of less than 10 nm with a $Z_{max}$ of less than 50 nm for the engineered aluminum substrates. It should be mentioned that improvement in surface characteristics of the substrates was crucial for achieving high performance devices as several studies have shown that high surface roughness of a substrate can lead to inferior properties of the gate dielectric as well as significant degradation of molecular structure of the active layer [12].

The a-IGZO TFTs in our experiment (Fig. 2) had a modified bottom gate etch stopper structure and were fabricated with a maximum process temperature of 300 °C. The etch stopper structure was incorporated to prevent plasma induced damage to the active layer which could degrade device performance [13].

Square plates 125 × 125 $mm^2$ were prepared from larger aluminum sheets and were used as free standing substrates during TFT processing. As shown in Fig. 2, a bottom gate electrode was first formed by patterning a 120 nm thick AlNd (aluminum doped with Nd) layer that was deposited by sputtering. Afterwards a 110 nm thick silicon dioxide film was deposited, to serve as gate dielectric, by plasma enhanced chemical vapor deposition (PECVD) at a substrate temperature of 270 °C using diluted silane and nitrous oxide as reactant gases. After the gate dielectric, a stack consisting of 40 nm a-IGZO and 50 nm $SiO_x$ layers were then RF sputtered to form the thin film semiconductor channel layer and the first passivation layer, respectively. IGZO sputtering was carried out at a chamber pressure of 0.8 Pascal (10 vol% $O_2$ diluted with Ar) using a ceramic target consisted of $In_2O_3$:$Ga_2O_3$:ZnO (1:1:1 mol%). Since energetic ion bombardment during IGZO sputtering may damage the underlying gate dielectric surface resulting in deep interface state creation and degradation of TFT performance [14], a low power density of 0.8 $W/cm^2$ was chosen to deposit the IGZO layer. Surface imaging with AFM revealed that the as-deposited films on silicon test wafers possessed a very smooth surface with minimal surface roughness of less than two nanometers. However, since characteristics of the substrate also influences the roughness of the deposited IGZO film and considering that the engineered aluminum substrates in our experiment had a RMS surface roughness of less than 10 nm, it is expected that the RMS roughness of the IGZO films deposited on aluminum substrates will be the same as underlying substrate. After the TFT active regions were lithographically patterned, the $SiO_x$ layer was dry etched by Reactive Ion Etching (RIE) and then the IGZO layer was wet etched by a diluted HCl solution. After removal of the photoresist layer, a second passivation layer of $SiO_x$ having a thickness of 50 nm was deposited by RF sputtering. Then, openings in the gate pads and the source/drain contact windows were formed using RIE. Finally, source and drain electrodes were formed by patterning a double layer of Mo (70 nm) and AlNd (100 nm) by lift off process. The finished TFT substrates were then annealed in $N_2$ ambient at 300 °C for a total of two hours. TFTs having a variety of geometries in terms of channel length and width were fabricated on each substrate. From each substrate, a total of 16 dies were characterized at room temperature under dark condition using an HP 4145A semiconductor parameter analyzer and an automated probe station.

One of the important design concepts of a-IGZO is the component ratios of metal cations in the IGZO layer [5,15,16]. For example, Indium ions are considered as the main component of band conduction minimum and are reported to have a dominant

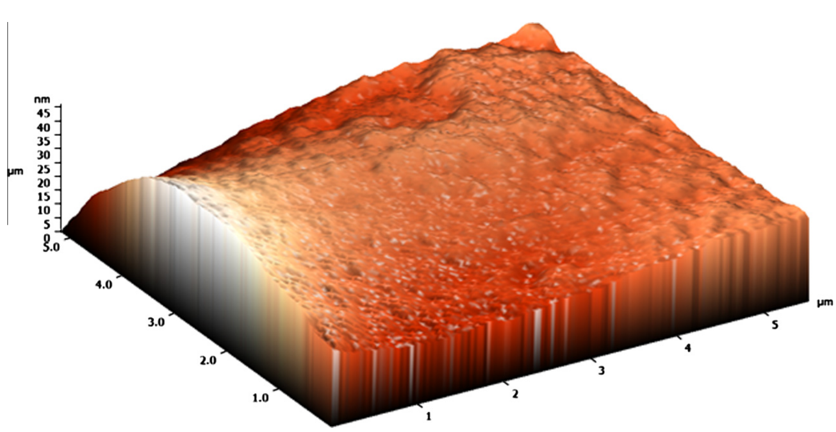


**Fig. 1.** Surface topology of an engineered aluminum substrate.