RESEARCH HIGHLIGHTS

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Self-assembled monolayers enhance the performance of oxide thin-film transistors

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Thin-film transistors (TFTs) based on oxide semiconductors have gained a lot of attention in applications such as displays and sensors particularly in recent years due to the advantages of oxide semiconductors like high mobility, good uniformity over large area and low deposition temperature[1–4]. However, the defects/traps at dielectric/channel interface and top surface of oxide TFTs might dramatically degrade device performance including current on/off ratio, mobility and most importantly stability[5, 6], making it quite urgent to systematically make effective interface engineering to improve TFT performance.

Traps on the top channel surface are mainly caused by the adsorbed water and oxygen molecules from air[7], which could be reduced by applying a passivation layer. One effective passivation layer is organic self-assembled monolayer (SAM), which can be formed densely on the surface of oxide semiconductors through the reaction with –OH groups, ensuring a reliable interface coupling between SAM and the channel layer and hence a good chemical stability[5, 8]. Compared with conventional inorganic passivation layers, SAMs can be easily applied on the top channel surface *via* vapor- or solution-based methods[8–10], which are plasma-free processes and can avoid the potential plasma damage to oxide semiconductors.

SAMs with different functional groups might give very different surface energy and dramatically affect the resulting device performance, especially the stability and hysteresis. Recently, Kim *et al.* investigated InGaZnO (IGZO) TFTs treated by SAMs with CH_3, NH_2 and CF_3 functional groups, namely trimethoxy(propyl)silane (TPS), (3-aminopropyl)trimethoxysilane (APTMS), and trimethoxy(3,3,3-trifluoropropyl)silane (TFP) SAMs, respectively, as shown in the insets of Fig. 1(a)[11]. The untreated IGZO film shows a contact angle of 22.5°, after the treatment, it changes to 55.2° ± 1.7°, 81.9° ± 2.1° and 98.1° ± 2.3° for APTMS, TPS, and TFP treated IGZO films, respectively, suggesting a reduced surface energy. Such a reduced surface energy makes oxygen molecules being difficult to be adsorbed on the surface of the treated IGZO films. As a result, a decrease of both clockwise hysteresis and threshold voltage shift under the positive bias was observed after the treatment with a lowest value of 0.11 ± 0.06 V and 0.32 ± 0.26 V, respectively, achieved in TFP-treated IGZO TFTs (the lowest surface energy case), as shown in Fig. 1(a).

Alkyl chain lengths also affect device performance, as reported by Peng *et al.* who studied the relationship between SAM chain lengths and TFT performance by using triethoxysilane (TES) with three different alkyl chains, namely C1-TES, C8-TES and C18-TES[12]. All treated devices show an increased mobility and a decreased hysteresis compared with the untreated one. Among all treated devices, TFTs treated with C18-TES showed best performance with a mobility of 26.6 cm^2/(V·s), which might be due to the formation of a well-ordered and more hydrophobic IGZO surface when treated with SAMs with longer alkyl chains. Similar effects were also reported by Chen *et al.* in InSnZnO TFTs treated with vapor-phase SAMs[9].

At smaller channel thicknesses, the accumulation layer approaches near the adsorbed water molecules on the top channel surface, inducing a strong carrier scattering and a more pronounced influence of top surface. To study whether the SAM treatment also works in TFTs with a thin channel layer, Song *et al.* made n-octadecyltrichlorosilane (OTS)-treated IGZO TFTs with different IGZO thicknesses[8]. As shown in Fig. 1(b), even at an IGZO thickness down to 5 nm, the treated devices show a high mobility of 10 cm^2/(V·s) with a low subthreshold swing of 64 mV/dec and a high current on/off ratio larger than 10^6. Also, the device maintains a high performance even after being stored in air for a year (Fig. 1(c)), indicating that the top surface has been effectively passivated.

Besides being used as an effective passivation layer on the top surface of oxide TFTs, SAMs can also be applied at the dielectric/channel interface, which affects not only the dynamic performance but also the stability. SAM treatment is now a standard process in organic TFTs to reduce dielectric/channel interface traps and surface energy, but was seldom reported in oxide TFTs due to the potential damage to SAMs. By treating AlO_x gate dielectrics with an n-octadecylphosphonic acid (ODPA), Bashir *et al.* reported high-performance ZnO TFTs made by spray pyrolyzing[13]. To study the survival of ODPA after the high-temperature ZnO deposition, they performed a contact angle measurement, and found that a high contact angle maintained even after a heat treatment of the sample at 400–450 °C in N_2 (Fig. 2(a)), demonstrating the high stability of the ultra-thin SAM against heat. The SAM treatment here significantly reduces the gate leakage current, and as a result, the devices show a low operating

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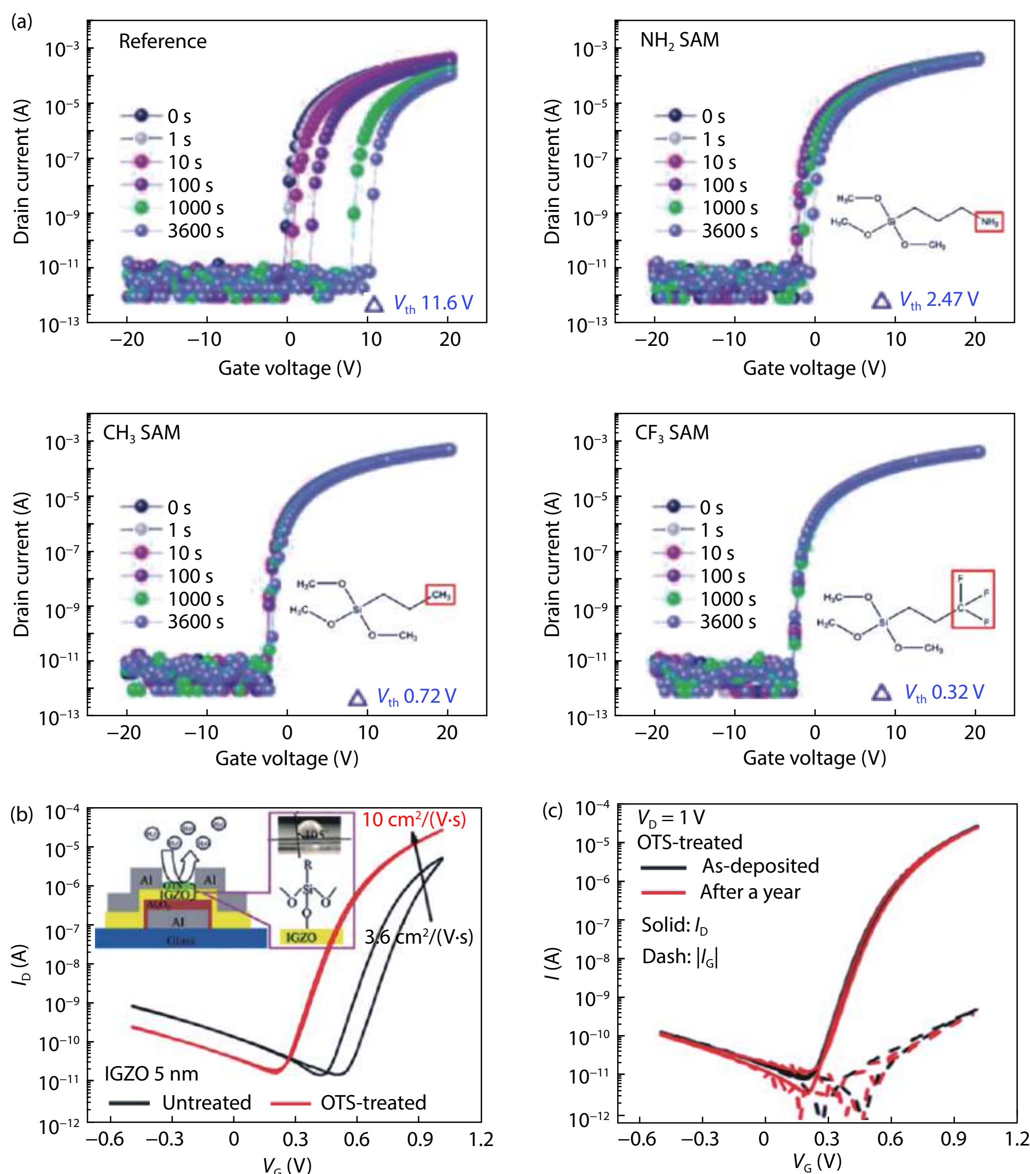

Fig. 1. (Color online) (a) Transfer characteristics of IGZO TFTs treated with different SAMs under positive bias stress. Insets show the chemical structures of SAM molecules. Reproduced with permission[11], Copyright 2021, IOP Publishing. (b) Transfer characteristics of IGZO TFTs with and without OTS treatment. (c) OTS-treated IGZO TFTs before and after being stored in air for a year. Reproduced with permission[8], Copyright 2021, American Chemical Society.

voltage of 1.5 V with a current on/off ratio of 10^3 and a mobility of 8.3 cm²/(V·s) (Fig. 2(b)).

However, for commercialization, high-performance oxide semiconductors are still mainly deposited by sputtering. To study the effectiveness of a SAM treatment on gate dielectrics in TFTs with a sputtered channel layer, in 2020, Song *et al.* prepared OTS-treated Al_xO_y and HfO_x as the gate dielectrics in sputtered IGZO TFTs[14]. Surprisingly, they found that by carefully controlling the sputtering condition, a reduced interface trap density and hence an enhanced device performance could be realized. Under optimized conditions, the devices exhibit a more than two-fold increase of mobility, an increase of current on/off ratio by ~100 times and a reduction of trap density by >50% (Fig. 2(c)). The bias stress stability of the TFTs also showed a substantial improvement after the OTS treatment (Fig. 2(d)), mainly due to the significantly reduced interface trap density, demonstrating the potential of the method in manufacturing display back plane drivers.

In summary, the SAM treatment, as a simple and yet effective interface engineering method, gains wide attention in oxide TFTs not only on the top surface but most importantly at the dielectric/channel interface. To make this method a standard process in the manufacture of low-cost, oxide-based electronic devices, it is necessary to further study the large-area compatibility as this method may require scrupulously choosing SAMs and carefully controlling the deposition condition. Further enhancement in device performance could be realized through the combination of the treatments at both top surface and dielectric/channel interface.

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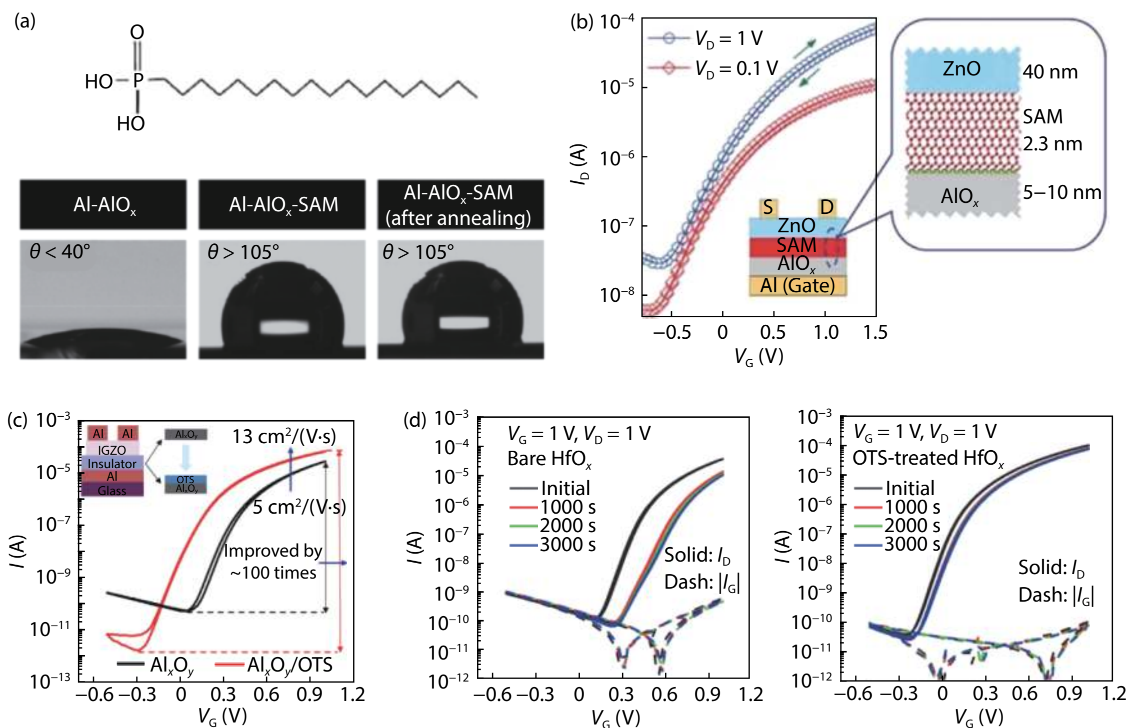

Fig. 2. (Color online) (a) Chemical structure of ODPA and contact angles of AlO$_x$, SAM-treated AlO$_x$ before and after annealing. (b) Transfer characteristics of ZnO TFTs. Reproduced with permission[13], Copyright 2021, Wiley-VCH. (c) Transfer characteristics of IGZO TFTs with bare Al$_x$O$_y$ and OTS-treated Al$_x$O$_y$ as gate dielectrics. (d) Transfer characteristics of IGZO TFTs with bare HfO$_x$ and OTS-treated HfO$_x$ under positive bias stress. Reproduced with permission[14], Copyright 2021, Wiley-VCH.

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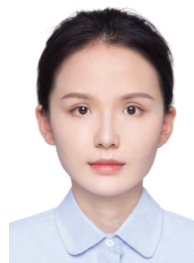

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