UV Illumination Technique for Leakage Current Reduction in a-Si:H Thin-Film Transistors

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Abstract—**The high photoconductivity of hydrogenated amorphous silicon thin-film transistors (a-Si:H TFTs) is responsible for the leakage current under illumination—particularly in projectors and displays with high-intensity backlight illumination. This work investigates a leakage current reduction approach, in which the inverted staggered a-Si:H TFTs are exposed to the ultraviolet (UV) laser. An 85% reduction in the leakage current in a-Si:H TFTs is experimentally observed. The general SPICE model (such as the RPI model) lacks the proper term to capture the photo-induced phenomena; therefore, the physical mechanisms that are associated with the illumination of a-Si:H TFTs under UV, including the energy state and the density of traps, are analyzed using device simulation. The *I–V* characteristics of the inverted staggered a-Si:H TFTs under different magnitudes of UV exposure are calibrated with experimentally measured data. The preliminary results show the change of trap states in amorphous silicon film and a shift of the Fermi level with UV illumination. UV illumination may induce traps in the active layer of the device and thereby reduce the OFF-state leakage current.**

Index Terms—**Amorphous silicon thin-film transistors (a-Si:H TFTs), band-to-band tunneling, device simulation and characterization, leakage current, trap-assisted tunneling, ultraviolet (UV) illumination.**

I. INTRODUCTION

HYDROGENATED amorphous silicon thin-film transistors (a-Si:H TFTs) have recently been used widely as switching devices in large-area electronics such as active matrix liquid crystal displays (LCDs) [1] and memory devices [2]. When the TFT turns on, both the liquid crystal capacitance and the associated capacitance are charged; they have to maintain sufficient voltage for the rotation of the liquid crystal. Unfortunately, an a-Si:H TFT has high photoconductivity [3], which may result in a high leakage current under visible light illumination, particularly those projectors and displays with high-intensity backlight illumination. The leakage current thus causes a voltage drop, which may induce an insufficient rotation angle of the liquid crystal. Various leakage current mechanisms in poly-Si TFTs have been reported [4]–[11]. Recently, the incorporation of fluorine and chlorine into a-Si:H has been proposed to suppress the OFF-state leakage current by increasing the acceptorlike density of states in a-Si:H (fluorine) material to shift the Fermi level toward the valence band edge [9]–[11]. Observations of the increase in acceptorlike states motivated this exploration of the mechanism by which the OFF-state leakage current of a-Si:H TFTs is reduced. The influence of prolonged illumination with intense light (600–900 nm) on the metastable changes in a-Si:H film has been reported elsewhere [12], [13]. However, little attention has been paid to study the ultraviolet (UV) illumination-induced metastable increase in hydrogenated materials. The effect of UV exposure on the passivation quality of SiN_x/a-Si:H stacked layers in solar cell fabrication has been examined [14]. The increase of trap density reduces the carrier lifetime caused by UV illumination, which may reduce the OFF-state leakage current in a-Si:H TFTs.

This brief presents a leakage current reduction approach, in which inverted staggered a-Si:H TFTs are exposed to a UV laser. The UV illumination may produce traps in the active layer of the device and thus reduce the OFF-state leakage current. A general SPICE model, such as the well-known RPI model [15], [16], for simulating the a-Si:H TFT circuit lacks a term for photo-induced phenomena. Therefore, the physical mechanism that governs the characteristics of the device should be studied qualitatively and quantitatively. To further study the metastable changes in a-Si:H film, caused by UV illumination, a set of thermodynamic transport equations coupled with trap state models is simultaneously solved using our own simulation platform [17]–[19]. The calculated current–voltage (I–V) characteristics of the inverted staggered a-Si:H TFTs illuminated with different intensities of UV are calibrated with experimentally measured results. The shift in the threshold voltage, the reduction of the leakage current, and the shift in the Fermi level are observed and discussed.

This brief is organized as follows. Section II introduces the experimental measurement and the physical models used for numerical simulation. In Section III, the measurement and simulation results are calibrated for the best accuracy of the analysis. The observed results and the associated phenomena are then studied. Finally, conclusions are drawn.

II. EXPERIMENT AND SIMULATION

Fig. 1(a) shows the inverted staggered a-Si:H TFTs exposed to a UV laser (355 nm) from the topside of the a-Si:H layer.

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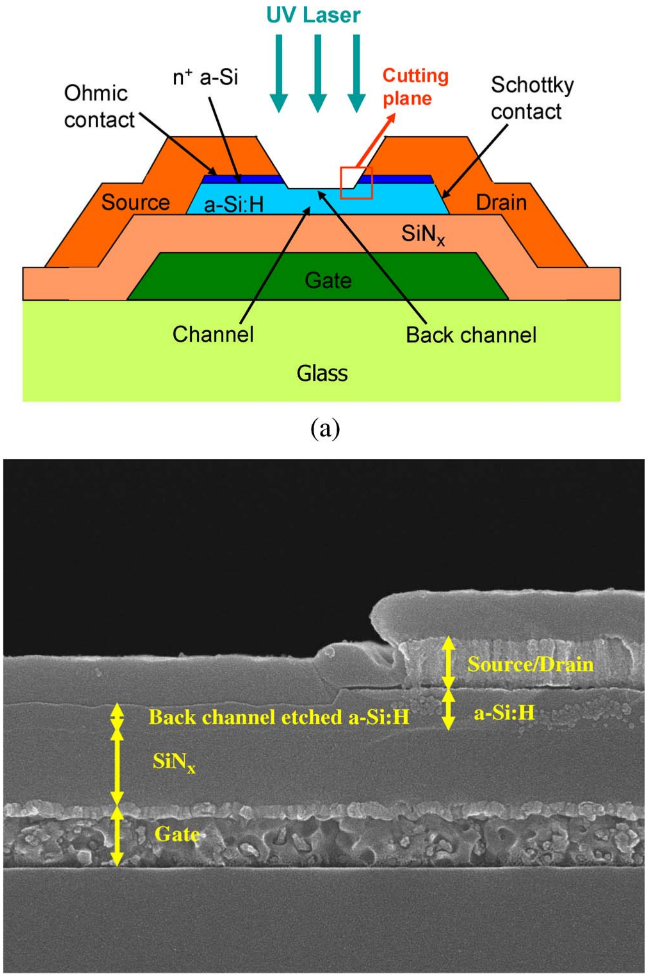

(a)

(b)

Fig. 1. (a) Schematic illustration of the inverted staggered a-Si:H TFTs. (b) SEM image.

Fig. 1(b) shows a SEM picture of the fabricated sample. The device is with an 18-μm channel width, a 5-μm channel length, and a 100-nm channel thickness. The thickness of the nitride is 330 nm. The top of the inverted staggered a-Si:H TFTs is exposed to a UV laser. In the UV laser illumination experiment, the I–V curves of the devices are measured after fabrication (denoted as 0 shot). Then, the a-Si:TFTs are exposed to a UV laser with the particular shot, and their I–V characteristics are measured again. This experiment includes 1, 10, 22, 50, and 101 shots. The I–V characteristics of the thin-film transistor devices were measured using an HP4156C with the source grounded and the body floating. A set of thermodynamic transport equations consisting of the Poisson equation, electron-hole current continuity equations, and the lattice temperature equation are solved numerically to calculate the device characteristics [17]–[19]. The variations of the charge distributions induced by the density and distribution of trap states in the a-Si:H layer are included in the device simulation to estimate the variation of the device characteristics accurately. The density of states in the a-Si:H film are grouped into two types—tail and deep states. Most of the deep states of the inverted staggered TFT with silicon nitride gate insulator [20] are located in the lower part of the amorphous silicon gap. The localized acceptor- and donorlike states in the a-Si:H mobility gap can be modeled by exponentially distributed deep and tail states [21]

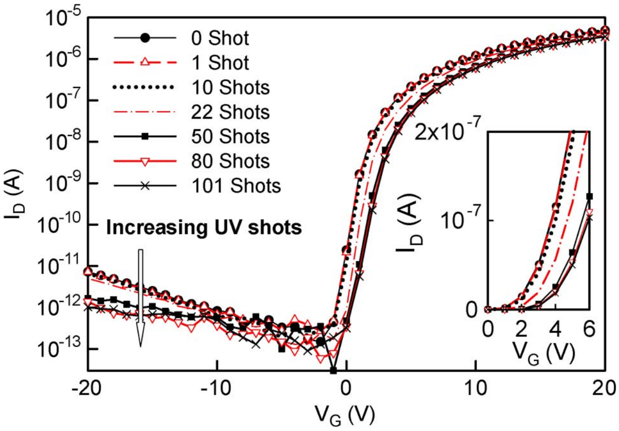

Fig. 2. Measured drain current (I_D) versus the gate voltage (V_G) for the source–drain voltage of 12 V with different magnitudes of UV light illumination. The inset shows the prethreshold characteristics of the TFTs under UV light.

$$N_{\mathrm{Et}} = g_{\mathrm{tc}} \exp\left(\frac{E - E_C}{E_{\mathrm{tc}}}\right) + g_{\mathrm{dc}} \exp\left(\frac{E - E_C}{E_{\mathrm{dc}}}\right) \quad (1)$$

$$N_{\mathrm{Ht}} = g_{\mathrm{tv}} \exp\left(\frac{E_V - E}{E_{\mathrm{tv}}}\right) + g_{\mathrm{dv}} \exp\left(\frac{E_V - E}{E_{\mathrm{dv}}}\right) \quad (2)$$

where E_C is the conduction band edge; g_{tc} and g_{dc} are the densities of states at the conduction band edge for the tail and deep acceptorlike states, respectively. E_{tc} and E_{dc} are the associated gradients of the exponential distributions of the tail and deep acceptorlike states. E_V is the valence band edge; g_{tv} and g_{dv} are the densities of states at the valence band edge for the tail and deep donorlike states. E_{tv} and E_{dv} are the associated gradients of the exponential distribution of the tail and deep donorlike states, respectively, and E is the energy in the a-Si:H mobility band gap. The recombination models that incorporate trap-assisted [22] and band-to-band [23] tunneling effects are included to capture the characteristics of a parasitic Schottky contact under negative gate bias.

III. RESULTS AND DISCUSSION

Fig. 2 shows the measured I–V characteristics of the inverted staggered a-Si:H TFTs that are exposed with different shots from the UV laser. An 85% reduction of the leakage current after multiple shots from the UV laser is observed. Table I summarized the dependences of the characteristics of the device with various numbers of shots from the UV laser, such as the threshold voltage, the ON-state current, the leakage current, the mobility, and the on/off current ratio. The threshold voltage is determined from the current criterion that drain current (I_D) is larger than $10^{-7}(W/L)$ A, where W and L are the width and length of the studied device, respectively. The ON-state current is defined as the drain current at which the gate voltage is 20 V, and the leakage current is defined as the drain current at which the gate voltage is -20 V. The results demonstrate that the threshold voltage increased as the UV exposure time is increased. Increasing the threshold voltage reduces the leakage

TABLE I

THRESHOLD VOLTAGE, ON-STATE CURRENT, LEAKAGE CURRENT, MOBILITY, AND ON/OFF CURRENT RATIO FOR THE STUDIED DEVICE WITH DIFFERENT MAGNITUDES OF UV LIGHT ILLUMINATION

Number of Shots	0	1	10	22	50	80	101
Threshold Voltage (V)	1.73	1.75	1.81	2.72	3.28	3.61	3.67
On-state Current (x10^{-6} A)	4.84	4.823	4.744	4.308	3.671	3.511	3.438
Leakage Current (x10^{-12} A)	7.25	7.23	6.45	4.99	1.66	1.39	1.03
Mobility (cm^2/V-s)	0.509	0.506	0.501	0.492	0.441	0.435	0.429
On/off Ratio (x10^6)	0.667	0.667	0.735	0.863	2.21	2.53	3.34

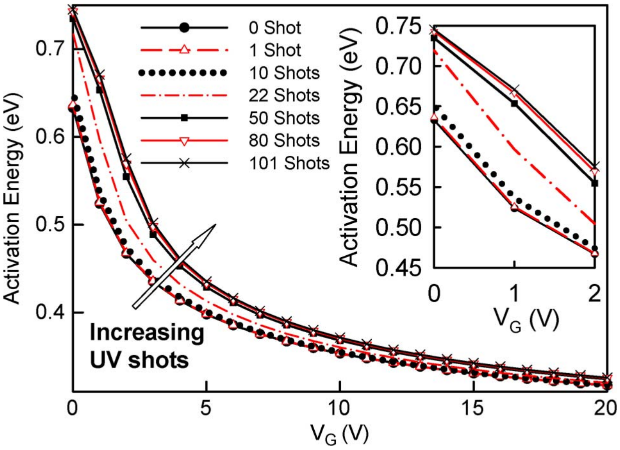

Fig. 3. Activation energy as a function of gate voltage (V_G). The activation energy is increased as the number of UV shot increases, which indicates the shift of Fermi level toward valence band edge after UV illumination.

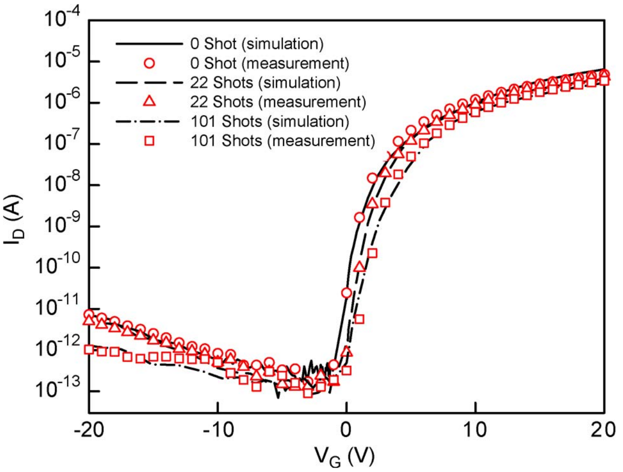

Fig. 4. Calibrated I_D–V_G characteristics for all shots, where the source–drain voltage is equal to 12 V. Without loss of generality, only 0, 22, and 101 shots are shown. The inset is a zoom-in plot.

current at the cost of the decreased mobility and ON-state current. The UV exposure approach improves the on/off current ratio by a factor of five. The increase of the on/off current ratio reveals the effectiveness of this leakage current reduction approach. Fig. 3 shows the activation energy as a function of gate voltage (V_G), where the activation energy E_{act} decreases when the V_G increases. The activation energy is strongly related to the position of the Fermi level, which is estimated using the following:

$$I_D \cong \exp\left(-\frac{qE_{\mathrm{act}}}{kT}\right). \tag{3}$$

As shown in Fig. 3, the activation energy increases with the number of UV shots, indicating a shift of the Fermi level toward the valence band edge upon UV illumination. Based on the charge neutrality, the Fermi level can be lowered in two ways to produce a positive threshold voltage shift [24]—by reducing the density of donorlike states or increasing the density of acceptorlike states. The inset of Fig. 2 shows the prethreshold characteristics of the TFTs under UV light. Since the prethreshold slope is sensitive to the acceptorlike states and illumination causes a metastable increase in the bulk density of states in the semiconductor, the change of the electrical characteristics are mainly caused by an increase of acceptorlike states. The charge state and energy position of the defect states cause the Fermi level to move away from the conduction band upon illumination and therefore increase the threshold voltage of the device. We noted that the UV exposure affects the switching characteristic of the device due to the increase of the defect density of states.

To explore further the influence of UV illumination on the metastable changes in a-Si:H films, the measured I_D–V_G characteristics were used to calibrate the simulator, as shown in Fig. 4. The calibration result agrees closely with the measured data, in which the acceptorlike states from 0 to 101 shots are calibrated. Fig. 5 shows the simulated extracted density of states in the a-Si:H layer for 0, 22, and 101 shots. A shift in the Fermi level is observed, and the simulated position of the Fermi level is similar to the Fermi level shown in Fig. 3. Fig. 6 shows the calibrated tail (g_{tc}) and deep (g_{dc}) acceptorlike states in the a-Si:H layer after UV illumination. Both g_{tc} and g_{dc} increase with the number of shots and then saturate after 22 shots due to the limited trap states in silicon. The tail states are the silicon conduction band states, which are broadened and localized by the disorder, to form a "tail" of localized states just below the conduction band mobility edge. These states are so-called weak silicon bonds [25]. The deep states originate from defects in the a-Si:H network. They are thought to consist of Si dangling bonds, which have a wide range of energies [25]. UV laser illumination weakens the bonds in the a-Si:H network and then breaks them. Therefore, both g_{tc} and g_{dc} increase. The

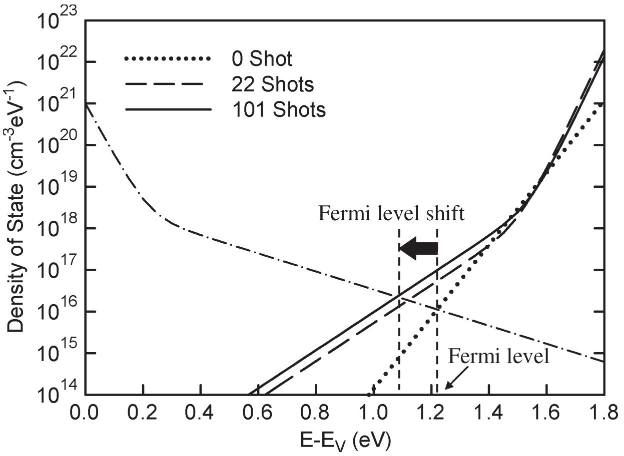

Fig. 5. Modeled density of states used in a-Si:H with 0, 22, and 101 shots, respectively.

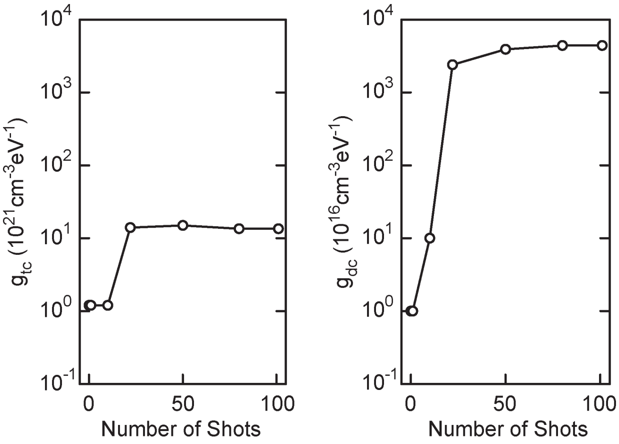

Fig. 6. Simulated tail ($g_{\rm tc}$) and deep ($g_{\rm dc}$) acceptorlike states with different magnitudes of UV light illumination.

illumination causes a metastable increase in the bulk density of states in the semiconductor, which may account for the aforementioned findings.

IV. CONCLUSION

This brief presented a leakage current reduction approach in which the tops of inverted staggered a-Si:H TFTs are exposed to a UV laser. While exposure to visible light produced a leakage current in the a-Si:H film, UV illumination produced traps in the active layer of the device, reducing the OFF-state leakage current. The reduction of the device leakage current by UV illumination was then studied by solving the thermodynamic transport equations with trap state and recombination models. The simulations suggest that the density of acceptorlike states in a-Si:H increase with UV exposure. The shift in Fermi level away from the conduction band to the valence band upon UV illumination is responsible for the shift of threshold voltage and the reduction of the OFF-state leakage. Although the ON-state current, mobility, and switching characteristic of the a-Si:H TFTs are affected, the device on/off current ratio is significantly improved. The proposed UV illumination approach is useful for reducing leakage current and can be incorporated into the industrial manufacturing process.

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