A α-Si:H Thin-Film Phototransistor for a Near-Infrared Touch Sensor

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***Abstract*— This letter presents a highly sensitive near-infrared (IR) *a*-Si:H phototransistor for touch sensor applications. The narrow bandgap of *a*-Si exhibits a wideband spectrum response from IR to ultraviolet region, where the IR bandpass filter layers allow the *a*-Si:H phototransistor to respond to the selective IR light uninterrupted by visible light. The time-resolved photoresponse and transfer *I–V* characteristics for the near-IR *a*-Si:H phototransistor as a function of power at 785-nm illumination allow the observation of fast photoresponse ($\tau \sim 0.1$ ps), high external quantum efficiency (7.52), and high photoresponse. A prototype unit pixel structure for touch sensors composed of amorphous Si-based switching/amplification/near-IR phototransistors and a storage capacitor, is proposed and designed. The overall results suggest that the near-IR *a*-Si:H phototransistor offers unique possibilities for user-friendly, low-cost, and large-area touch sensors, especially aimed at consumer applications and other areas of optoelectronics.**

***Index Terms*— α-Si:H, IR sensor, phototransistor, touch sensor.**

I. Introduction

IN RECENT years, amorphous silicon based electronics and organic electronics have attracted significant attention in the field of thin film transistors (TFTs) and related sensor applications [1]. Touch sensing displays provide user friendly interfaces and the touch panels available in the market incorporate external and internal touch detecting devices. It is anticipated that even higher touch resolution at much reduced cost will be achieved by integrating sensors in each individual pixel [2]. Among many existing types of touch sensors, photosensors have an advantage in that high sensitivity may be achieved without applying an external force. Key challenges for planar photosensor arrays involve large areal coverage at relatively low cost, high sensitivity, and rapid-response. Most of these requirements can be realized in commercial products by implementing hydrogenated amorphous silicon (α-Si:H) devices, which are widely used in large-area applications such as flat panel display backplanes or photodetector arrays [3], [4]. Although α-Si:H is an excellent photosensor material for touch-sensing in displays, a major drawback involves its photo-sensitivity with respect to ambient sunlight while in external light mode, or light emanating from organic emissive layers in organic light emitting diode (OLED) panels. It is thus necessary to develop devices that can react to infrared (IR) radiation without being affected by the presence of ambient visible light. A critical issue that arises while adopting IR as the photon source involves the penetration of ambient visible light into the sensor material, which generates background noise signals (sunlight $\sim \mu$Wcm^{-2}), and inhibits the detection of true touch events. Therefore, the use of an optical filter that prevents the incidence of visible light into the sensor is mandatory in order to reduce the optical noise levels. Such a part is referred to as a bandpass filter. The use of IR signal and a bandpass filter is expected to induce superior photoresponse of the device, regardless of ambient conditions [5]. A number of studies have been reported on the properties of a-SiGe:H photosensors [6], oxide semiconductor photo TFTs [7] and a-Si photo TFTs in the near IR (NIR) regime [8], however α-Si:H touch sensors are most sensitive with respect to NIR radiation. Such properties make α-Si:H devices attractive for next generation electronics including various applications such as satellite navigation, cellular phones, matrix keyboards, electrical switchboards, and computer compatible keyboards.

In this letter, bottom-gated α-Si:H TFTs are fabricated in order to take advantage of their low gate leakage current levels [9] and for compatibility with the conventional TFT process in industry. Highly sensitive α-Si:H IR photosensors are realized, which are activated by an IR laser pen insensitive to ambient conditions. The mobility, spectral responsivity, external quantum efficiency, photocurrent and carrier lifetime are the key parameters that determine the properties of a thin film phototransistor. Therefore, the above parameters are measured and analyzed in the designed experiments.

Fig. 1(a) shows a schematic structure of the inverted-staggered bottom-gate α-Si:H TFTs fabricated on glass substrates (15×15 cm) using a standard back-channel-etch (BCE) process. All patterning was done by photolithography and appropriate use of wet or dry etching. The integration of the TFT devices was done first by direct-current (DC) sputter deposition of a 200-nm-thick Mo gate at room temperature, followed by a continuous plasma-enhanced chemical

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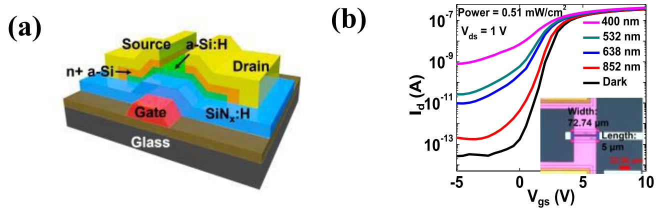

Fig. 1. (a) Schematic structure of α-Si:H photo TFTs. (b) Transfer I-V characteristics of the phototransistor for different wavelengths under bias voltage $V_{ds} = 1$ V. The inset shows the microscope optical image with the width of 72.74 μm and length of 5 μm.

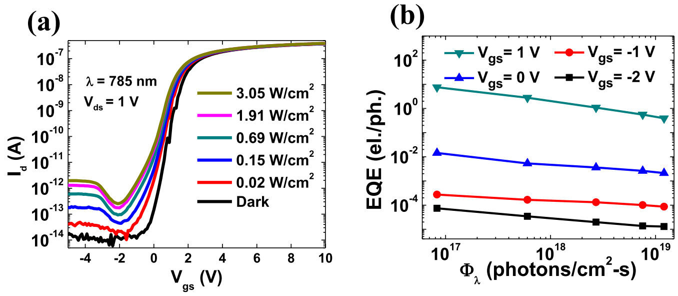

Fig. 2. (a) Transfer I-V characteristics of photoresponse at 785 nm illumination for a bias voltage $V_{ds} = 1$ V. (b) External quantum efficiency as function of photo flux density at $V_{ds} = 1$ V.

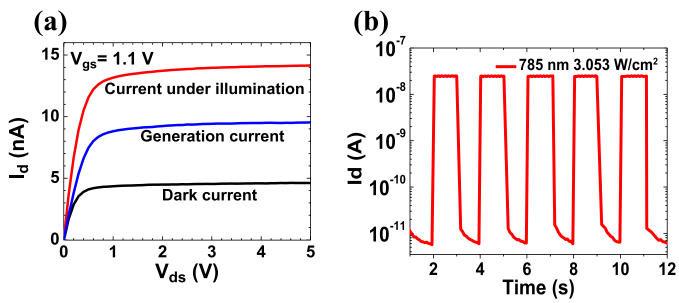

Fig. 3. (a) Output characteristic comparison between dark current and photocurrent under illumination of 785 nm wavelength. (b) The time-resolved photoresponse measurements at $V_{gs} = 1$ V, $V_{ds} = 1$ V under 1s laser pulse duration for 785 nm illumination and power density of 3.05 W/cm^2.

vapor deposition (PECVD) growth of a 150-nm-thick SiN_x gate insulator, a 200-nm-thick α-Si:H active layer and a phosphorus-doped (n^+) α-Si:H layer (50 nm) to form an ohmic contact with the source/drain electrodes. An over-etch process was used to assure complete removal of the n^+ α-Si:H in the back-channel region.

II. Results and Discussion

Fig. 1(b) shows the transfer curves of the α-Si:H photo sensor under dark and illumination with 405, 532, 638, and 852 nm wavelength (power density = 0.51 W/cm^2) at a drain-source voltage (V_{ds}) of 1 V. The power density of the incident light is kept constant during the electrical measurement. The α-Si:H TFTs exhibit a field-effect mobility of 0.13 cm^2 V^{-1} s^{-1}, V_{th} of 0.51 V, and sub-threshold swing of 0.44 V/decade. The photocurrent and spectral responsivity are extracted from the I_d–V_{gs} graph, which show linearity at $V_{gs} = -5$ V and $V_{ds} = 1$ V under different wavelengths. The spectral responsivity can be calculated by the photocurrent and incident light power, which refers to the device performance in terms of the external quantum efficiency (EQE) and the photo gain of the device.

$$R = \frac{I_{total} - I_{dark}/A_{pt}}{P/A_{pd}} = \frac{J_{ph}}{P} \quad (1)$$

In equation (1), R is the responsivity, I_{total} is the total photocurrent under illumination, I_{dark} is the dark current, A_{pt} is the area of the channel, P is the incident illumination power, A_{pd} is the area of the light source J_{ph} is the photocurrent density, and P is the incident light power density. A_{pt} is the product of the channel width and thickness (73 μm $\times$ 200 nm), and A_{pd} is the size of the laser spot (diameter = 1mm). From equation (1), the photocurrent decreases with increasing wavelength of the incident light, which in turn reduces the spectral responsivity due to tail-state trap-assisted absorption [8]. The inset shows the microscope optical image with a width of 72.74 μm and a length of 5 μm. The measured output characteristics for V_{gs} values from 1.1 V to 3.5 V in increments of 0.6 V display a linear triode region at low V_{ds} and a robust saturation region at high V_{ds}. Fig. 2(a) shows the transfer I-V characteristics of a-Si:H TFTs in the dark and under illumination with wavelengths near the infrared region (785 nm) at $V_{ds} = 1$ V. While the dark off currents reach values as low as 0.01 pA, the photocurrent increases exponentially between V_{gs} values of -2 V and -3 V, and demonstrates saturated off currents at V_{gs} values beyond -3 V, due to Poole-Frenkel field-enhanced thermionic emission between the gate and drain interface [8], [10]. As the illumination power density increases, the sub-threshold swing also increases due to trapped photo-generated charge in the tail states [11]. As the gate voltage increases, the difference of the photocurrent produced with a power of 3.05 W/cm^2 and the dark current decreases according to the responsivity in equation (1). The calculated responsivity is 4.75 at $V_{gs} = 1$ V under illumination of 0.02 W/cm^2.

The external quantum efficiency (EQE = $((J_{ph}/q)/(P/h\nu))$ is a function of the incident photon density for $V_{gs} = -2$, -1, 0, and 1 V in Fig. 2(b) at a wavelength of 785 nm. When an optical gain is constant, the external quantum efficiency, like the responsivity, decreases slightly with increasing photon density, which is related to the power density. The maximum EQE is 7.52 at $V_{gs} = 1$ V under illumination of 0.02 W/cm^2. The incident illumination generates electrons and holes, which contribute additional photocurrent (I_{ph}) under a source-drain electric field. The total power absorbed by the a-Si:H layer of thickness d shows that 35.5% of the power is absorbed in the active channel. The generated photocurrent can be estimated from the I_d-V_{ds} graph, and the carrier lifetime (τ) is found to be 0.1 ps as shown in Fig. 3(a) [12].

Thus, the generated excess carriers of the a-Si:H TFT photocurrent by incident photons can quickly vanish as a result of fast electron-hole recombination. The time-resolved photoresponse measurements (Fig. 3b) are performed at $V_{gs} = 1$ V and $V_{ds} = 1$ V with a 1s laser pulse duration for 785 nm illumination and a power density of 3.05 W/cm^2. Under a 1 s laser pulse width, the photocurrent rises to a

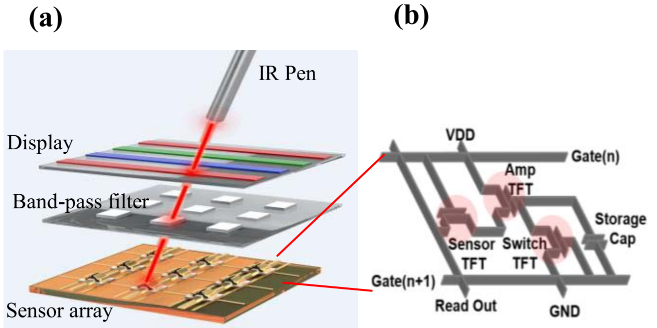

Fig. 4. (a) Schematic view of IR touch panel consisting of block layer, band-pass filter layer, and displays. (b) Circuit diagram of a a-Si photosensor pixel with three transistors and one capacitor.

high value and then falls to a low value quickly once the illumination is removed. Thus, the *a*-Si:H photosensor shows a fast photoresponse near the IR region and has strong potential for future sensing applications.

Fig. 4(a) shows a schematic structure of photo sensors and displays with a block metal layer and a band-pass filter metal layer to sense the external IR beam. The IR source used here is a pen type pointer that radiates a beam onto the block layer. In conventional remote touch sensors, the sensitivity is affected by external visible light and light reflected from the backplane. Thus, such false signals degrade the sensor sensitivity and hinder the sensor from selecting the correct IR light signals. For this reason, to block out the external light (visible light), the block metal layers, which can reflect the incident light and prevent the light absorption of the *a*-Si:H, are patterned above the channel in the switching TFT [7]. Furthermore, in the sensor TFT, unlike the switching TFT, only the selective near IR light can be absorbed by the active channel through the band-pass filter metal layers, which have high transmittance in the near IR region [13]. Although our device has lower sensitivity than metal-oxide [7] or SiGe [4] phototransistors, the sensitivity of the *a*-Si:H phototransistor is just sufficient to prevent the incidence of unnecessary IR light from ambient light and transmit the intended IR signals only. By virtue of the block metal layers and band-pass filter layers, the *a*-Si:H phototransistor can sense the near IR light selectively and is not interrupted by external visible light. The signal-to-noise ratio (SNR) can be improved by blocking the noise from visible light and unintended IR signals, transmitting only the true signals of the near IR light.

A circuit diagram of a unit pixel for a potential touch sensor is shown in Fig. 4(b). To operate the phototransistor, *a*-Si:H TFTs with a near IR photosensor require three TFTs (amp/sensor/switch) and one capacitor. In the sensor part, the amplification TFT amplifies the relatively small photocurrent generated by the sensor TFT with a storage capacitor [14]. In the switching part, the selective switching TFT extracts a selective signal from the readout line with a positive gate pulse voltage applied to the TFT. In response to a positive gate pulse applied to the selective switching TFT, the signals are extracted to the sensor TFT and enable its operation to detect light. In the case of a negative gate pulse, the sensor TFT is reset, and a positive gate pulse is applied to the sensor TFT in the next line. In this way, by modulating a gate pulse, selective sensing of the near IR light is available in touch screen arrays [7].

III. Conclusion

In conclusion, *a*-Si:H TFTs with near IR photosensors are promising candidates for future optical remote touch sensors. We analyzed the *a*-Si:H TFT photoresponse for different wavelengths of 405, 532, 638, and 852 nm of the incident laser and the near IR sensitivity under 0.51 W/cm^2 & 3.05 W/cm^2 power levels. The *a*-Si:H TFTs yield a field-effect mobility of 0.13 cm^{2}V^{-1}s^{-1} and the calculated responsivity is 4.75 at V_{gs} = 1 V. The *a*-Si near IR sensor shows an adequate photoresponse with a responsivity and fast photoresponse of $\tau \sim 0.1$ ps at 785 nm. The maximum EQE is 7.52 at $V_{gs} = 1$ V under illumination of 0.02 W/cm^2. The suggested block and filter layers can improve the sensor selectivity and SNR.

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