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AIP ADVANCES **3**, 012112 (2013)

Red-green-blue light sensitivity of oxide nanowire transistors for transparent display applications

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In this study, the sensitivity of oxide nanowire transistors under red (R, 470 nm), green (G, 530 nm), and blue (B, 625 nm) light illumination was investigated. As the wavelength of light illuminating the nanowire channel region became shorter, a negative shift of threshold voltage, degradation of subthreshold slope, and increase of on-current were observed. This phenomenon can be explained in terms of photo-induced holes, creating interfacial traps between the gate dielectric and nanowire channel or reacting with oxygen ions on the surface of the nanowires. Thus, the attempt to minimize characteristic changes due to all RGB light sources was performed by employing ultraviolet–ozone treatment and passivation process. As a result, we could successfully fabricate oxide nanowire transistors providing high optical reliability which has broadened the possibilities for applying it to transparent and/or flexible pixel operation circuitry for displays with high optical reliability. *Copyright 2013 Author(s). This article is distributed under a Creative Commons Attribution 3.0 Unported License*. [http://dx.doi.org/10.1063/1.4789405]

I. INTRODUCTION

The development of flexible and/or transparent displays is one of the most critical issues in next-generation electronics technology, with potential applications in transparent monitors, heads-up displays, wrist band displays, and flexible displays. Several recent reports have described attempts to develop flexible and/or transparent electronics using a range of semiconductor nanowire transistors.[1–4] As one-dimensional nanowires are able to provide high mobility, high current, mechanical flexibility and optical transparency, nanowire-based flexible and/or transparent transistors can overcome limitations in conventional polycrystalline silicon and amorphous silicon thin film transistors such as low mobility, poor transparency, poor flexibility and high temperature processing.

Oxide-based nanowire transistors are especially promising candidates for the development of transparent and/or flexible electronics including display devices. In this regard, studies have been conducted on the application of oxide nanowires to circuitry for displays.[5–8] While oxide nanowires exhibit transparency in the visible region, transistor circuitry for transparent displays will also require stability under external illumination. There have been a few studies conducted on the effect of light-color-dependent current-voltage (*I–V*) change in thin film transistors.[9–11] However, the color sensitivity and stability of oxide nanowires under red, blue, and green (RGB) light illumination for transparent display applications have not been reported.

In this study, the color sensitivity of oxide nanowire transistors was investigated. Specifically, the changes of SnO_2, In_2O_3 and ZnO transistor characteristics caused by different wavelengths were

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studied when the respective channel regions were exposed to RGB light. Surface treatment was investigated as a means to obtain stable device characteristics under illumination. Through this, we attempted to identify and remove major obstacles to applying oxide nanowire transistors to transparent displays.

II. EXPERIMENTAL DETAILS

A. Synthesis of SnO_2, In_2O_3 and ZnO Nanowires

Single crystalline SnO_2, In_2O_3 and ZnO nanowires were grown by chemical vapor deposition in a two-temperature-zone furnace using gold nanoparticles (20 nm) as a catalyst. The temperatures of the source and substrate zones were kept at 900°C and 700°C for growing SnO_2 nanowires for 30 minutes respectively. A flow rate of mixed carrier gas (Ar + 1.5% O_2) was maintained at 60 sccm. In the case of In_2O_3 nanowire, the temperatures of InAs source material zone and substrate zone were maintained at 790°C and 550°C with mixed carrier gas (Ar + 0.06% O_2, 100 sccm) for 120 minutes respectively. For ZnO nanowire, the temperatures of the ZnO source material zone and substrate zone were kept at 1060°C and 700°C for 80 minutes respectively with 60 sccm of mixed carrier gas (Ar + 1.6% O_2) flow rate.

B. Fabrication of Nanowire Transistors

Bottom-gated transistors using SnO_2, In_2O_3 and ZnO nanowires were fabricated to evaluate the device performance. First, indium tin oxide (ITO, the thickness of 100 nm) was deposited by sputtering on Si wafer on which a thermally-grown SiO_2 (300 nm) was deposited and formed a gate electrode. On top of that, Al_2O_3 (30 nm, $\varepsilon \sim 9$) as a gate insulator was deposited by atomic layer deposition. Then Al_2O_3 layer was etched on the gate electrode pad area in order to apply voltages to the gate electrode. After that, SnO_2, In_2O_3 and ZnO nanowires were dispersed on the substrate where the devices were to be fabricated. Finally, the source/drain electrodes were formed with Al/ITO (70/50 nm) as double layer. The double layer allows to achieve reliable measurements by producing ITO film at the upper part where the probe-tip comes in contact with and consequently minimizing electrode damage in repetitive *I–V* measurements.

III. RESULTS AND DISCUSSION

Figure 1(a) shows representative field emission scanning electron microscopy (FE-SEM) images of SnO_2, In_2O_3 and ZnO nanowires. The average length and diameter of SnO_2 nanowires were around ~20 μm and around ~50 nm respectively, which indicates successful growth without particles and flakes. The average length and diameter of In_2O_3 nanowires were 5 ~ 7 μm and ~80 nm and those of ZnO nanowire were ~10 μm and ~70 nm, respectively. Using each material, the bottom-gated nanowire transistors were fabricated, typically with a single nanowire in each device. Figure 1(b) shows a cross-sectional view of the fabricated nanowire transistor structure. Figure 1(c) presents the FE-SEM images of SnO_2, In_2O_3 and ZnO nanowire channels. The channel lengths were ~2.5 μm (SnO_2), ~2.5 μm (In_2O_3) and ~4 μm (ZnO) and the corresponding diameters were ~50 nm, ~80 nm and ~70 nm respectively. The drain-current *versus* gate-source voltage (I_{ds}–V_{gs}) characteristics were measured in the dark, and under illumination using red (625 nm), green (530 nm), and blue (470 nm) light emitting diode (LED) source (Mightex). Threshold voltage (V_{th}, V_{gs} at $I_{ds} = 1$ nA, $V_{ds} = 0.5$ V), sub-threshold slope (SS), field effect mobility (μ_{eff}), and on-current (I_{on}) were extracted from the results to investigate the changes. The field-effect mobility

$$\mu_{eff} = \frac{dI_{ds}}{dV_{gs}} \times \frac{L_{ch}^2}{C_i} \times \frac{1}{V_{ds}} \tag{1}$$

was calculated at small V_{ds} using

$$C_i = \frac{2\pi\varepsilon_0 k_{eff} L_{ch}}{\cosh^{-1}(1 + t_{ox}/r_{nw})} \tag{2}$$

for the gate-to-channel capacitance.

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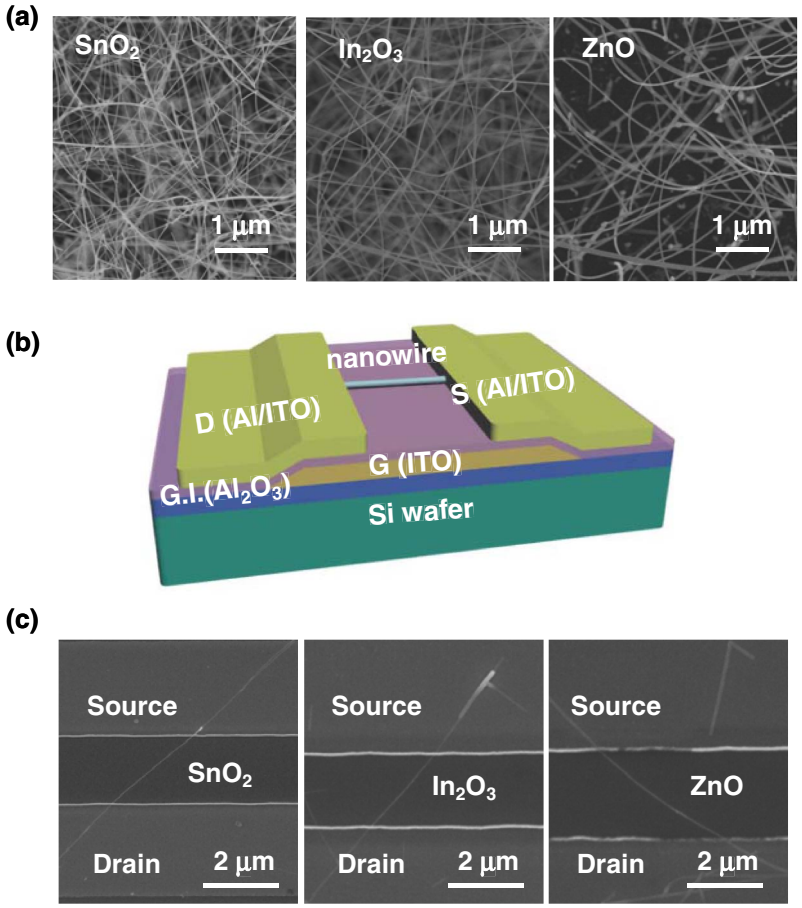

FIG. 1. (a) FE-SEM images of SnO_2, In_2O_3 and ZnO nanowires grown on SiO_2/Si substrates. The scale bar is 1 μm. (b) Cross-sectional view of SnO_2, In_2O_3 and ZnO nanowire transistors. (c) Top-view FE-SEM images of single SnO_2, In_2O_3 and ZnO nanowire regions. The scale bar is 2 μm.

Figure 2(a) shows the measured spectra of the three LEDs used in this experiment, with each LED providing 190,000 lux (red), 160,000 lux (green) and 36,000 lux (blue) of illumination intensity and applied in sequence of R-G-B. Figure 2(b) shows the schematic diagram of the experiment. The drain current versus gate-source voltage (I_{ds}–V_{gs}) measurement was conducted for 5 transistors per RGB light source with no change in conditions.

Figure 3 shows the measured I_{ds}–V_{gs} characteristics of representative SnO_2, In_2O_3 and ZnO nanowire transistors under illumination at various wavelengths. The red and green illumination induced modest shifts in the curves, whereas blue illumination produced significant negative shifts in all three device types. As for the parameter change of SnO_2 nanowire transistor, when the I_{on} was defined as current value at $V_{gs} = 7$ V, $V_{th} = 4.33$ V, SS = 0.16 V/dec, $I_{on} = 340$ nA at dark changed to $V_{th} = 4.25$ V, SS = 0.19 V/dec, $I_{on} = 340$ nA with red illumination, to $V_{th} = 4.15$ V, SS = 0.20 V/dec, $I_{on} = 340$ nA with green illumination and to $V_{th} = 3.12$ V, SS = 0.23 V/dec, $I_{on} = 425$ nA with blue illumination. In other words, the transistor curve showed no significant change with red illumination, and V_{th} produced –0.2 V negative shift and SS increased by 0.04 V/dec without any change in I_{on} with green illumination, whereas V_{th} produced –1.2 V negative shift, SS increased by 0.06 V/dec, and I_{on} increased by ~34% with blue illumination. Meanwhile, μ_{eff} changed from 21.2 $cm^2/V \cdot s$ (dark) to 23.0 $cm^2/V \cdot s$ (red), 23.2 $cm^2/V \cdot s$ (green), and 26.1 $cm^2/V \cdot s$ (blue) respectively. This represents a ~20% increase in mobility with blue illumination. To summarize, V_{th} exhibited negative shifts and SS, I_{on} and mobility increased as optical wavelength became shorter (or photo energy became larger) [Fig. 3(a)].

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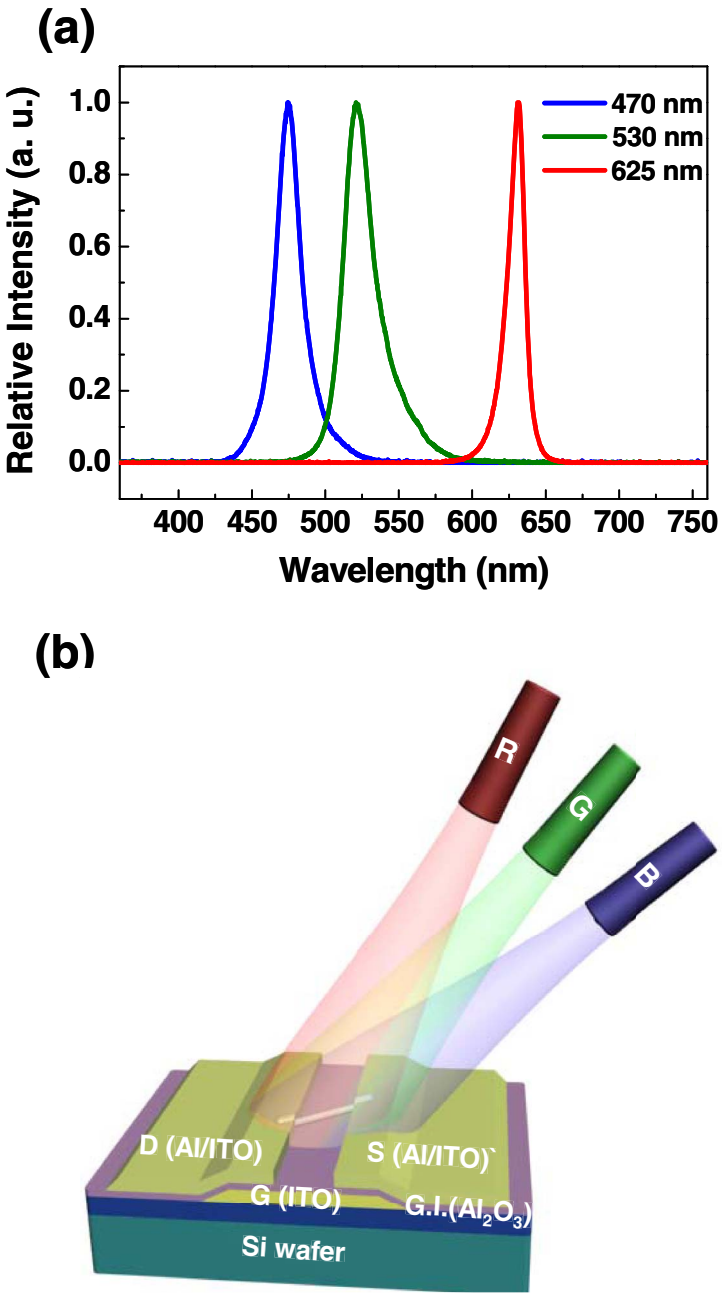

FIG. 2. (a) The spectrum of the employed red, green, and blue LEDs. (b) Schematic of red, green, blue light illumination on SnO_2, In_2O_3 and ZnO nanowire transistors.

In the case of ZnO nanowire transistor, when I_{on} was defined as current value at $V_{gs} = 7$ V, $V_{th} = 4.20$ V, SS = 0.17 V/dec, $I_{on} = 247$ nA at dark changed to $V_{th} = 4.11$ V, SS = 0.21 V/dec, $I_{on} = 252$ nA with red illumination, to $V_{th} = 4.02$ V, SS = 0.22 V/dec, $I_{on} = 266$ nA with green illumination, and to $V_{th} = 2.45$ V, SS = 0.40 V/dec, $I_{on} = 309$ nA with blue illumination. Essentially, the curve did not change significantly with red illumination and V_{th} exhibited –0.2 V negative shift and current increased by ~8% with green illumination. However, with blue illumination, V_{th} produced –1.75 V negative shift, SS increased by 0.22 V/dec, and I_{on} increased by ~25%. μ_{eff} changed from 17.0 $cm^2/V \cdot s$ (dark) to 17.0 $cm^2/V \cdot s$ (red), 17.2 $cm^2/V \cdot s$ (green), and 16.7 $cm^2/V \cdot s$

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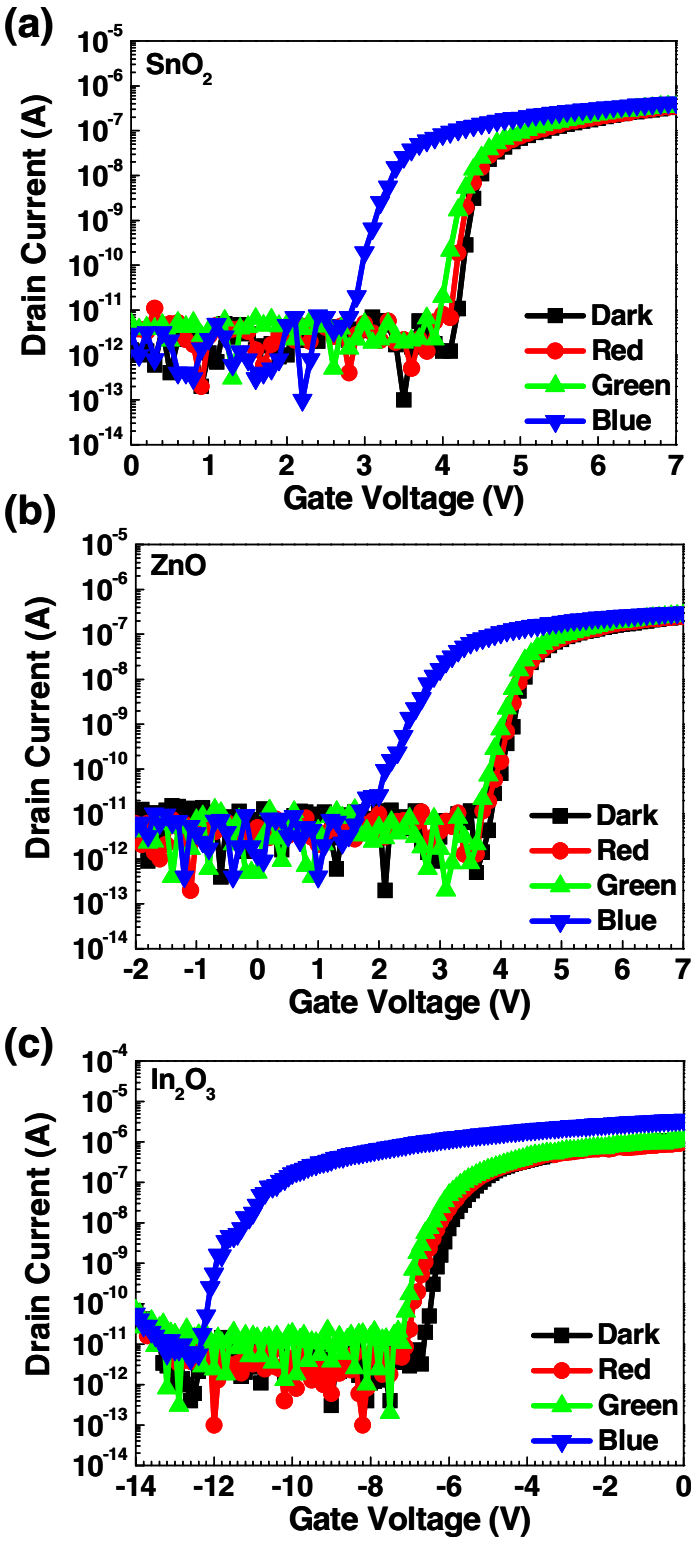

FIG. 3. Log scale I_{ds}–V_{gs} characteristics of the representative (a) SnO_2, (b) In_2O_3, and (c) ZnO nanowire transistors under dark, red, green, and blue light illumination.

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TABLE I. Representative characteristics of SnO_2, ZnO and In_2O_3 nanowire transistors under dark, red (625 nm), green (530 nm), and blue (470 nm) light illumination.

Device	λ	V_{th} (V)	SS (V/dec)	I_{on} (μA)	μ_{eff} ($cm^2/V \cdot s$)
SnO_2	Dark	4.33	0.16	0.34	21.2
	625 nm	4.25	0.19	0.34	23.0
	530 nm	4.15	0.20	0.34	23.2
	470 nm	3.12	0.23	0.43	26.1
ZnO	Dark	4.20	0.17	0.25	17.0
	625 nm	4.11	0.21	0.25	17.0
	530 nm	4.02	0.22	0.27	17.2
	470 nm	2.45	0.40	0.31	16.7
In_2O_3	Dark	−6.28	0.34	1.06	36.5
	625 nm	−6.61	0.40	1.00	36.1
	530 nm	−6.87	0.45	1.04	34.7
	470 nm	−11.96	0.70	3.56	57.8

(blue) respectively. The mobilities were not changed as optical wavelength became shorter. Similar to SnO_2, ZnO showed the negative shift of V_{th}, the increase of SS and I_{on}, [Fig. 3(b)].

By comparison, the V_{th} and I_{on} change of In_2O_3 nanowire transistor increased more sharply compared to SnO_2 and ZnO nanowire transistors, while characteristic change by RGB illumination showed a similar trend as that of SnO_2 nanowire transistor or ZnO nanowire transistor. When I_{on} was defined as current value at $V_{gs} = 0$ V, $V_{th} = –6.28$ V, SS = 0.34 V/dec, $I_{on} = 1.06$ μA at dark changed to $V_{th} = –6.61$ V, SS = 0.40 V/dec, $I_{on} = 1.00$ μA with red illumination, to $V_{th} = –6.87$ V, SS = 0.45 V/dec, $I_{on} = 1.04$ μA with green illumination and to $V_{th} = –12$ V, SS = 0.70 V/dec, $I_{on} = 3.56$ μA with blue illumination. In other words, V_{th} produced –0.34 V negative shift and SS increased 0.06 V/dec without any change in I_{on} with red illumination and V_{th} produced –0.6 V negative shift and SS increased 0.1 V/dec without any change in I_{on} with green illumination. In contrast, with blue illumination, V_{th} produced ∼ –5.7 V negative shift, SS increased by 0.36 V/dec, and I_{on} increased by ∼3 times. μ_{eff} changed from 36.5 $cm^2/V \cdot s$ at dark to 36.1 $cm^2/V \cdot s$, 34.7 $cm^2/V \cdot s$, 57.8 $cm^2/V \cdot s$ with red, green and blue illumination respectively. Especially, blue illumination caused ∼60% of increase [Fig. 3(c)]. The results are summarized in Table I.

Figure 4 shows the average value and standard deviation of the shift in V_{th} with blue light illumination for SnO_2, ZnO, and In_2O_3 nanowire transistors; for each device type, 5 devices were measured and the error bars correspond to standard deviation ($\pm 1\sigma$) with respect to the mean. As shown in the figure, the shift in V_{th} for SnO_2 was –2.4 ± 0.8 V, ZnO was –2.6 ± 0.6 V, and In_2O_3 was –5.5 ± 0.9 V. While V_{th} decreased by ∼0.4 V with SiO_2 passivation, the effect did not seem to be dramatic. Thus the change in V_{th} was not significant in SnO_2 and ZnO nanowire transistors, whereas the change in In_2O_3 nanowire transistor considerably increased by over ∼3 V compared to SnO_2 and ZnO nanowire transistors.

To quantitatively estimate the effect of the illumination, a series of MEDICI simulations were performed to fit the experimental I_{ds}–V_{gs} data of the nanowire transistors measured in the dark, and under blue illumination as shown in Fig. 5. In the simulation, only electrons were considered as the carriers to fit the *n*-branch of the experimental data. Electron mobility of the nanowire channel was selected as the same value obtained from the experimental data. It is well known that donor-like oxygen vacancies present at the surface of oxides such as ZnO, SnO_2, In_2O_3 nanowires significantly affect the electrical conductivity. Furthermore, due to the high surface-to-volume ratio of nanowires, the carrier transport is known to be heavily affected by the interface trap densities.[12] In order to explain the shift of the I_{ds}–V_{gs} curves upon illumination, the doping density (N_D, oxygen vacancies) and the voltage-variable interface trap density (D_{IT}) near the gate insulator-nanowire interface were taken into account. The best-fit parameters are summarized in Table II. As a result, the negative shift of V_{th} under blue light illumination was explained by the increased values of N_D and D_{IT}. The increased SS upon light illumination was also in good correlation with the increased D_{IT}. When the

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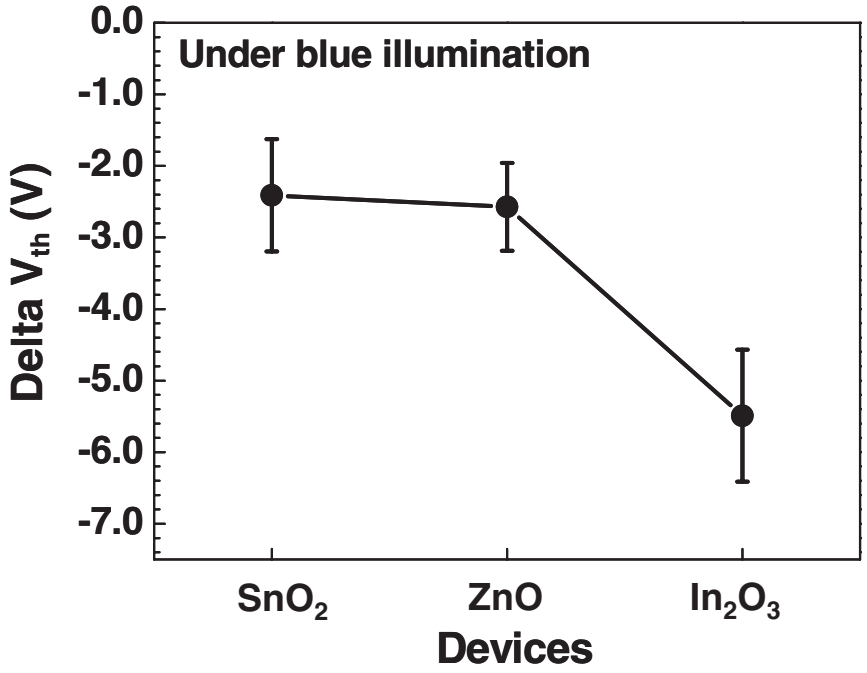

FIG. 4. The change and standard deviation of V_{th} for the representative SnO_2, In_2O_3 and ZnO nanowire transistors under blue light illumination.

transistors are illuminated, photo-generated electron-hole pairs are induced in the oxide nanowires. The generated holes are captured in the gate-insulator interface to increase the number of interface trap density or react with oxygen ions on the surface of nanowires, creating O_2.[13,14] The generated traps (D_{IT}) as well as the increased number of oxygen vacancies, which produce charge carriers, and hence larger doping concentration (N_D), produce the negative V_{th} shift of oxide nanowire transistors. The large V_{th} shift shown in light-illuminated In_2O_3 NWTs is presumably due to the relatively lower formation energy of oxygen vacancies compared to SnO_2 and ZnO,[15,16] which results in larger number of oxygen vacancies on the surface and thus more active reactions to photo-generated holes. Here, blue light illumination produces more negative V_{th} shifts compared to other wavelengths (red and green). The higher photo-energy of blue light causes more electron-hole pairs to be separated and consequently more oxygen ions are removed from the surface of nanowires by the increased population of generated holes. In contrast, electron-hole pairs generated by red light with relatively low energy disappear during recombination. As a result, red light illumination produces almost no V_{th} shift of oxide nanowire transistors. Also, note that while there are small shifts in μ_{eff} for ZnO and SnO_2 NWTs, there is a large increase in μ_{eff} of In_2O_3 NWT upon blue light illumination (Table I). The traps on the nanowire-to-gate dielectric interface or nanowire surface can be in either two types: (i) the shallow-level (tailing) states or (ii) deep-level states in the forbidden bandgap of the nanowires.[17] As the tailing trap states are known to be responsible for the degradation of μ_{eff}, the increase in such shallow traps is not expected to be the dominant mechanism for deterioration of SS in In_2O_3 NWTs. Larger amount of photo-generated holes (acceptor-like deep-level trap states) in In_2O_3 NWTs compared to ZnO and SnO_2 NWTs are expected be responsible for large increase of μ_{eff} upon blue illumination.

In order to verify whether the characteristic change with light illumination is caused by reaction between photo-generated carrier and nanowire surface, the same experiment was performed after the sputtering of a passivating SiO_2 (100 nm) thin film on the SnO_2 nanowires (power of 300 W and a gas mixture of Ar (30 sccm) / O_2 (1 sccm)). Not shown in the figure, the change of V_{th} with blue illumination was –2.01 ± 0.6 V, which was not distinctly different from the V_{th} change of SnO_2 nanowires without passivation.

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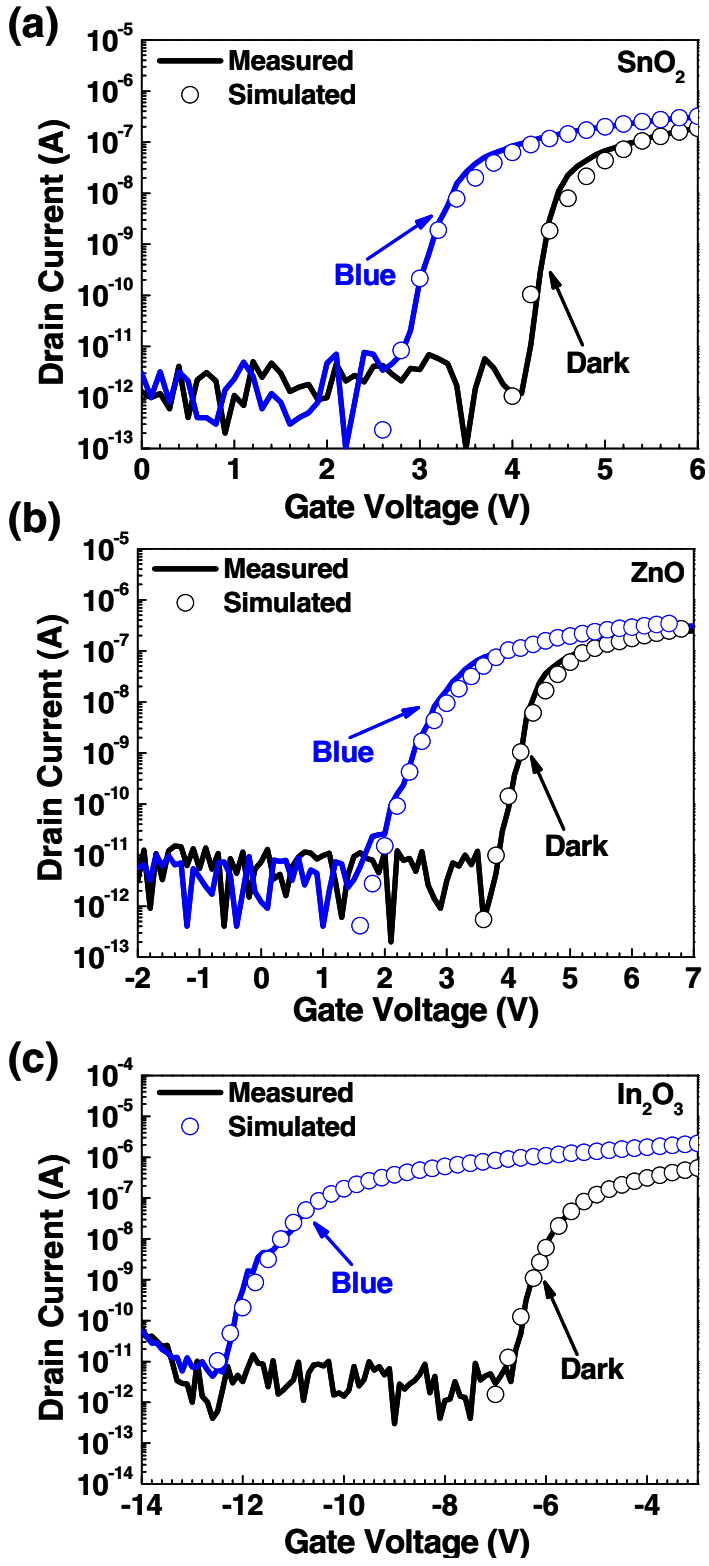

FIG. 5. I_{ds}–V_{gs} relationships from measured data and MEDICI simulations with parameters corresponding to 'best-fit' curves for (a) SnO_2, (b) ZnO, and (c) In_2O_3 nanowire transistors. The solid lines are the measured data and the scattered plots are the simulation data.

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TABLE II. Best-fit parameter values obtained from the MEDICI Simulation of SnO_2, ZnO and In_2O_3 nanowire transistors under dark blue (470 nm) light illumination.

Device	λ	D_{IT} (/cm^2 · eV)	N_D (/cm^2)
SnO_2	Dark	6.6×10^{12}	1.1×10^{14}
	470 nm	7.7×10^{12}	1.0×10^{15}
ZnO	Dark	8.1×10^{12}	5.0×10^{15}
	470 nm	1.5×10^{13}	1.1×10^{16}
In_2O_3	Dark	1.8×10^{13}	3.0×10^{17}
	470 nm	3.0×10^{13}	4.4×10^{17}

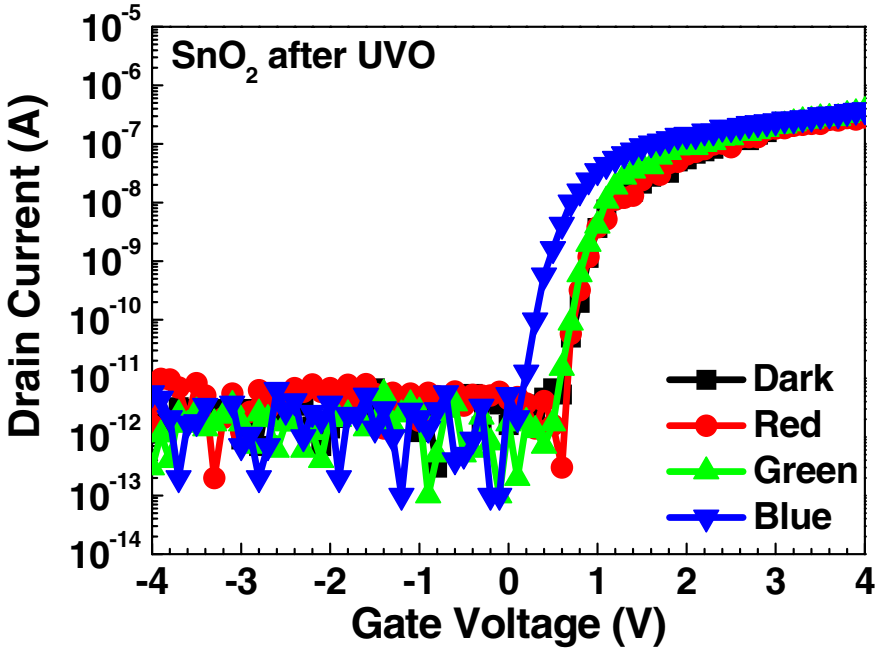

FIG. 6. Log scale I_{ds}–V_{gs} characteristics of SnO_2 nanowire transistor after UVO treatment under dark, red, green, and blue light illumination.

Ultraviolet–ozone (UVO, λ = 254.7 nm, 28 mW/cm^2) treatment on SnO_2 nanowire transistor for 5 minutes was also employed. Generally speaking, V_{th} exhibits negative shifts after the UVO treatment because UV-generated holes release oxygen from the surface of nanowires and generate oxygen vacancies. When I_{on} was defined as current value at V_{gs} = 4 V, V_{th} = 0.89 V, SS = 0.27 V/dec, I_{on} = 319 nA at dark changed to V_{th} = 0.88 V, SS = 0.30 V/dec, I_{on} = 283 nA with red illumination, to V_{th} = 0.83 V, SS = 0.26 V/dec, I_{on} = 362 nA with green illumination, and to V_{th} = 0.44 V, SS = 0.26 V/dec, I_{on} = 380 nA with blue illumination. The extent of change in V_{th} was minimized under blue illumination, decreasing to 0.44 V shift after the UVO treatment (Fig. 6). It can be inferred from the result that oxygen vacancy on nanowire surface was saturated by the UVO treatment. As a result, minimized additional oxygen vacancies were produced by light illumination.

Original characteristics are restored with the passage of time after the UVO treatment due to surface reaction between atmospheric oxygen and nanowires. The donor-like oxygen vacancies are known to be significantly affected by the chemisorption of ambient gases, especially oxygen. Oxygen molecules absorbed at the oxygen vacancies generate oxygen ions (O^-, O^{2-}, and O_2^-) which act like electron acceptors.[18] Chemisorbed oxygen species, which work like charge trapping sites, increase the scattering of the charge carriers, deplete the electrons at the nanowire surface, and hence decrease the channel conductivity and modify V_{th}. As mentioned before, UVO treatment is

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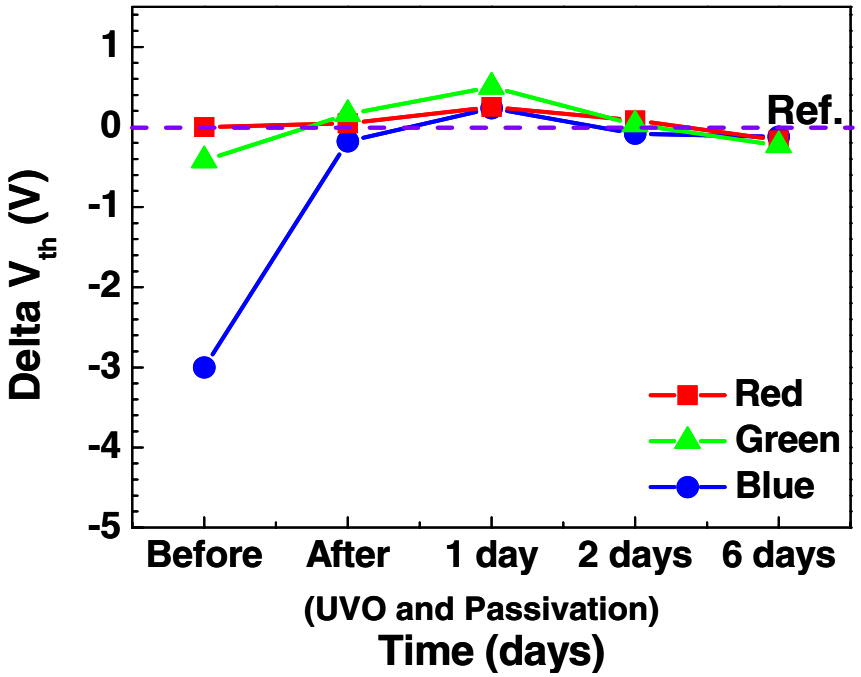

FIG. 7. Time variation of V_{th} under dark, red, green, and blue light illumination after UVO treatment (5 min) and SiO_2 passivation (100 nm).

expected to remove the oxygen species from the nanowire surface, increase the number of oxygen vacancies, and therefore negatively shift the V_{th}. However, when the channel region of the UVO treated nanowire transistor is exposed in air, oxygen in atmosphere and oxygen vacancy at the nanowire surface combine over time, and therefore V_{th} tends to recover to its original value where no UVO treatment was performed. Hence, in order to maintain the modified device performances of the UVO-treated nanowire transistors, passivation of the nanowire is necessary to prevent the oxygen absorption to the nanowire surface.[18] In such context, previous studies have reported passivation of ZnO nanowire transistors using SiO_2, polymer, or Si_3N_4/SiO_2 layers to maintain (or improve) the device performances.[19–21] In this study, the UVO treatment on SnO_2 nanowires was conducted for 5 minutes and SiO_2 (100 nm) thin film was deposited as a passivation layer. Then the same experiment about RGB light illumination was performed and V_{th} change was monitored for 6 days. As shown in Fig. 7, the change amount of V_{th} with blue light decreased from –3.0 V negative shift before the UVO treatment and passivation to –0.18 V after the process. According to measurements over 6 days, the effect of UVO treatment remained consistent at –0.12 V. In addition, the change in V_{th} due to red or green light illumination decreased after the UVO treatment and the effect was maintained the same by passivation.

IV. CONCLUSIONS

In summary, oxide nanowire transistors were fabricated to investigate changes in transistor characteristics caused by RGB light illumination. Blue illumination produced more significant changes of transistor characteristics in oxide nanowires in comparison with red or green illumination. The larger photo energy of blue light significantly led to more negative V_{th} shift, the degradation of SS, and the increase of I_{on}. The holes, separated from photo-generated electron-hole pairs, play the role of donor-like traps in nanowire channels. The V_{th} of In_2O_3 nanowires show a larger shift compared to those of SnO_2 and ZnO nanowires because of the relatively lower formation energy of oxygen vacancies. The variation of interface traps and oxygen vacancies was quantitatively estimated by the MEDICI simulation. Furthermore, we were able to ensure the stability of nanowire transistor

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characteristics with light illumination through effective surface treatment using UVO. This enables application of oxide nanowire transistors to transparent displays and/or flexible displays which require high optical reliability.

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