Light wavelength effect on tungsten oxide dielectric properties

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It has been reported that tungsten oxide (WO_x) behaves like a dielectric material when the oxygen partial pressure is high enough, e.g., 0.2 mbar, during the deposition. [1] Due to the good insulator properties and thermal stability, WO_x has been used as the high-*k* gate dielectric in the transparent MISFET. [1] WO_x has also been used as the gate oxide in ion-sensitive field-effect transistors and photochromic devices. [2,3] In this study, the dielectric properties of the sputter deposited WO_x used in the MOS capacitor was investigated. The light illumination effect to this kind of device is important in many electronic and optoelectronic applications. The device's electrical properties were investigated in dark and under different light wavelengths' exposure conditions.

The WO_x thin film was sputter deposited on the *p*-type Si (100) wafer. The deposition pressure and power were 5 mTorr and 60W, respectively, in the Ar/O_2 (1:1) atmosphere. The sample was treated with a post deposition annealing (PDA) step under the N_2 atmosphere at 1000^oC for 3 min. The ITO film was sputter deposited and wet etched into the 100 µm round dots as the gate electrodes. The backside of the wafer was deposited with aluminum to form the ohmic contact. The post metal annealing was done at 400°C for 5 min under the H_2/N_2 (1/9) atmosphere. The capacitor's capacitance-voltage (*C-V*), conductance-voltage (*G-V*), and current density-voltage (*J-V*) curves, were measured with an Agilent 4284A LCR meter and an Agilent 4155C semiconductor parameter analyzer, separately. The flat-band voltage (V_{FB}) and the interface state density (D_{it}) of the capacitor were extracted from the *C-V* curve using the NCSU CVC program and the Lehovec's method, separately. Three different LEDs, i.e., red at 625 nm, green at 530 nm, and blue at 470 nm were used for the light exposure experiment. The power density of the light was fixed at 28.4 W/m^2.

The XPS W 4*f* core level spectra of the WO_x film shows two main peaks, i.e., W $4f_{7/2}$ peak at binding energy (BE) 35.5 eV and W $4f_{5/2}$ peak at BE 37.6 eV. Both of them show that the film is composed of WO_3. [4]

Figure 1 shows the *C-V* hysteresis curves of the same capacitor under different light exposure conditions. The gate voltage (V_g) was swept from −5 V to +5 V (forward) and then back to −5 V (backward). The curves were drawn in the small V_g range of −1.5 V to 0 V in order to provide a clear view of the hysteresis phenomenon of the light illumination. The forward V_{FB} ($V_{FB,\,forward}$) shifts to the $+V_g$ direction with the decrease of the light wavelength, i.e., −0.56 V, −0.53 V, −0.52 V, and −0.47 V in the dark, red, green, and blue light illumination conditions, separately. There are several possible explanations. First, the illumination lights have larger photon energies (E_{ph}'s) than the band gap of Si, i.e., 1.1 eV, which caused the generation of electron-hole (*e-h*) pairs in the Si substrate [5]. The efficiency of generating the *e-h* pairs in Si increases with the increase of the E_{ph} of the incident light, i.e., 2.64 eV for the blue light, 2.34 eV for the green light, and 1.98 eV for the red light. Second, the light exposure makes the WO_x film more conductive than that in the dark [6] If the conductive film is less prone to retain the injected charges than the insulating film, the $V_{FB,forward}$ will shift toward the positive V_g direction. This effect can be more pronounced with the increase of the E_{ph}. Third, if *e-h* pairs can be generated in the WO_x film under the light exposure condition, the injected charges can be neutralized in the film. For example, in the forward bias condition, the injected holes are neutralized by the extra electrons generated in the WO_x film. At the same time, the additional holes are transferred to the gate electrode. Therefore, the $V_{FB,forward}$ shifts toward the positive V_g direction. When the above effect becomes more pronounced with the decrease of the wavelength, the magnitude of the $V_{FB,\mathrm{forward}}$ shift increases in the order of red < green < blue [7]. The same explanation can be applied to the $V_{FB,backward}$ shift phenomenon in the positive V_g range.

Figure 2 shows the *J-V* curves of the WO_x sample in the negative V_g range. The leakage current density increases with the light exposure, which can be contributed by the generation and transfer of the photo-generated carriers as well as the photoexcited *Vo*'s at the WO_x/Si interface [8]. The magnitude of the leakage current increases with the wavelength and magnitude of the $-V_g$. The former may be due to the more effective in neutralizing the injected holes in the WO_x film under the short wavelength exposure condition. The latter is due to the higher charge transfer rate through the WO_x film at the large magnitude of the bias V_g. The *C-V* hysteresis and the *J-V* curves provide complimentary information on the light exposure effect on the WO_x film.

[1] M. Lorenz, H. V. Wenckstern, and M. Grundmann, Adv. Mater. **23**, 5383 (2011)
[2] J. L. Chiang, S. S. Jan, J. C. Chou, and Y. C. ChenSens. Actuators B **76**, 624 (2001)
[3] D. R. Rosseinsky and R. J. Mortimer, Adv. Mater. **13**, 783 (2001)
[4] R. Sivakumar, R. Gopalakrishnan, M. Jayachandran, and C. Sanjeeviraja, Smart Mater. Struc. **15**, 877 (2006)
[5] H. C. George, A. O. Orlov, R. A. Joyce, Y. Tang, and G. L. Snider, JVST B **27**, 3158 (2009).
[6] P. Jain and B. K. Mishra, IJCEA **2**, 1282 (2012)
[7] Y. Kuo, X. Liu, C. H. Yang, and C. C. Lin, MRS Proc. **1430**, 21 (2012)
[8] B. Luo, C. H. Lin, and Y. Kuo, ECS Trans. **41**, 93 (2011)

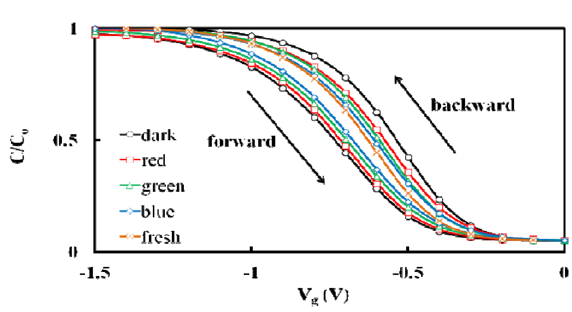

Figure 1. *C-V* hysteresis of the WO_x sample from −5 V to +5 V to −5 V at 1 MHz under different light illuminations.

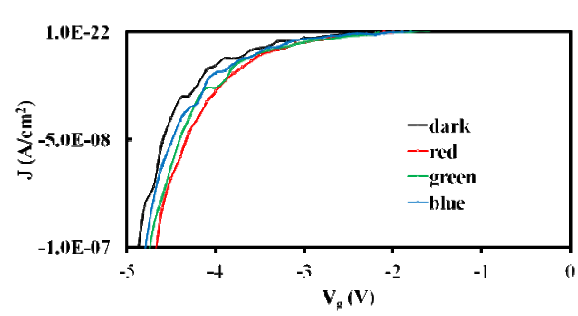

Figure 2. *J-V* curves of the WO_x sample under the $-V_g$ range.