

Effects of graphene layers in IGZO / graphite-like +Ni/SiO₂/Si wafer specimens on electrical and optical properties in tribotests

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Abstract: In the present study, graphite-like +Ni/SiO₂/Si wafer specimens were prepared using a co-sputtering system. Then, indium gallium zinc oxide (IGZO) films were deposited onto the graphite-like +Ni/SiO₂/Si wafer specimens at deposition powers of 60, 80, and 100 W, respectively. The effects of IGZO deposition power on the specimen's microstructure and the vacancy defects in the graphite-like +Ni layer are evaluated in terms of the electrical and mechanical properties of the as-prepared specimens. The effects of the graphite-like +Ni film on the electrical resistance of the IGZO film with microcracks is evaluated using a tribotester. The quantity and mean size of microcracks and variations of electrical resistance of the IGZO/graphite-like +Ni/SiO₂/Si wafer specimens with time are used to evaluate the role of the graphite-like +Ni layer as an alternate conductor of electric current when the IGZO film is degraded by microcracks. The growth of hillocks in the graphite-like +Ni layer can be enhanced by increasing the IGZO deposition power. These hillocks cause the graphite-like +Ni layer to be convex and have an uneven film thickness, and lead to vacancy defects in the graphite-like film. The O atoms of IGZO were incorporated into graphene in the graphite-like layer as substitutional impurities. The effects of these impurities on the electrical structure with a characteristic of superconductors occur intermittently in the tribotests, resulting in a sharp reduction in the electrical resistance of a specimen. An increase in the intensity ratio, IR_{O2}, related to oxygen vacancies, increases the peak intensities (PIs) of elemental Ga and the Ga-O bond, and decreases that of the Ga-Ga bond. In the IGZO/Glass specimens, a small reduction of the average transmittance is created in the specimens prepared by increasing the deposition power from 60 W to 100 W. The behavior of reflection is exactly opposite to that of transmittance. An increase in deposition power is favorable for the rise of optical band gap (E_g). Increasing the concentration of Zn2p_{3/2} or Zn2p_{1/2} increases PI_{Green} in photoluminescence profiles. Reductions in either In atoms or C-C and C-O bonds increase PI_{Orange}. PI_{Red} and can be increased by either increasing PI_{Ga-Ga} or decreasing the values of PI_{Ga2p3/2}, PI_{Ga2p1/2}, and PI_{Ga-O}.

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OCIS codes: (250.5230) Photoluminescence; (310.4165) Multilayer design; (310.6860) Thin films, optical properties.

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1. Introduction

Oxide semiconductors are promising candidates for channel layers in thin-film transistors (TFTs) [1–3]. Amorphous indium gallium zinc oxide (a-IGZO) TFTs have attracted much attention for application in active-matrix flat-panel displays due to their relatively large field-effect mobility.

Kim et al. [4] prepared $\text{InGaO}_3(\text{ZnO})_m$ films with superlattice structures and found that they improved the power factor and lowered thermal conductivity. IGZO films have been fabricated using the solid-state reaction method in air with a pulsed laser [5]. The resulting films showed a low electrical resistivity and had an amorphous structure with high carrier mobility and concentration.

Several studies have examined the features of a-IGZO films. For an a-IGZO specimen, its electrical and photosensitivity characteristics degrade with increasing O content and decreasing density of electrons [6]. The addition of hydrogen and heat treatment greatly impact the carrier concentration and electrical resistivity of a-IGZO films [7]. For a-IGZO films, the O 1s, Ga 3d, In 4d, and Zn 3d core-level spectra reveal that the O 1s component (representing the oxygen vacancies) and the intensity ratio of In/Ga both increased but that of Zn/Ga decreased with increasing substrate temperature. The effects of O_2 plasma immersion on the electrical properties and transistor performance of IGZO films can be attributed to a reduction in oxygen-related defects in the films [8]. Annealing of a-IGZO at temperatures of up to 500 °C enhanced the electrical properties, although the amorphous characteristics remained unchanged [9]. This behavior is due to increases in the optical band gap and number of oxygen vacancies.

Defects, including hillocks and nanovoids, are frequently found in bottom-gate TFTs due to stress migration arising at a high annealing temperature [10, 11]. Hillocks form preferentially at grain boundaries or triple points due to fusion creep [12–14]. For all film compositions, the deposition temperature had the most significant effect on hillock density. The number of hillocks increases rapidly with temperature [15]. Nathan et al. [16] carried out a systematic study on the effect of sputter deposition conditions on hillock formation. The threshold value of the annealing stress (σ_{an}) required for the formation of hillocks was determined [17]. The stress change parameter, $\sigma_f - \sigma_{an}$ (σ_f : internal stress after annealing), is a positive value that increases linearly with σ_{an} . The density of hillocks increases linearly with ($\sigma_f - \sigma_{an}$) when ($\sigma_f - \sigma_{an}$) is beyond the critical value.

Graphene is a one-atom-thick planar sheet of carbon atoms. It has been studied extensively due to its unique characteristics. In the study of Zhao et al. [18], large-scale and uniform nanographene (NG) films were directly deposited on substrates for device fabrication. Large-area graphene films produced using chemical vapor deposition (CVD) are polycrystalline and thus contain grain boundaries. Graphene films consisting of well-stitched grain boundaries can retain ultrahigh strength if postprocessing steps avoid rippling [19]. Graphene is stiff and strong, and exhibits brittle fracture at room temperature. Stone-Wales (S-W) defects are generally believed to deteriorate sheet strength, which is manifested by early breakage that nucleates from the defect site and catastrophic rupture quickly afterward [20, 21]. Defects are believed to degrade the in-plane mechanical robustness; they can, however, serve to enhance the stiffness and strength when functionalized or added to polymers to create three-dimensional composites [22]. In molecular dynamics simulations [23], an sp-sp^2 bonding network and an $\text{sp-sp}^2\text{-sp}^3$ bonding network were observed in graphene with vacancy defects and S-W defects, respectively. The electronic and mechanical properties of graphene are highly affected by structural defects, which may appear during growth or processing and deteriorate the performance of graphene-based devices. Graphene has the unique ability to reconstruct its lattice around intrinsic defects [24]. The study of Usachov et al. [25] found that the strong chemical interaction of carbon with nickel gives rise to a noticeable curving of the graphene layer and thus a geometrical nonuniformity on a scale of a few nanometers. Graphene can be functionalized through judicious manipulation of

defects, impurities, and adsorbates. The intrinsic defects in graphene, such as vacancies, interstitials, and line defects, and their potential role in transport have been discussed [26]. Impurities and adsorbates can act as dopants to enhance carrier densities, controlling n- and p-type conduction for transistor applications, and can serve as reactive sites for catalytic applications.

In the present study, a graphite-like layer was deposited to enhance fatigue and microcrack resistance and to improve the electrical properties of specimens with IGZO as the top layer. IGZO film was deposited onto graphite-like + Ni / SiO₂ / Si wafer samples at deposition powers of 60, 80, and 100 W, respectively. A self-designed tribotester with a pendulum-like indenter in tribocontact with the specimen was applied to evaluate the effect of IGZO deposition power on specimen tribological behavior, microcrack length, and electrical resistance (ER) in the testing process. Cyclic motions were carried out to simulate thumb-driven wear on IGZO / graphite-like + Ni / SiO₂ / Si wafer panels. During the test, an electric voltage was applied at the two ends of the specimen in order to measure ER varying with time. Scanning electron microscopy (SEM) was used to investigate the lateral surface of the specimens and evaluate the effect of deposition power on specimen microstructure and the defects formed in the graphite-like + Ni layer. Transmission electron microscopy (TEM) micrographs of the as-prepared and tested specimens and X-ray photoelectron spectroscopy (XPS) spectra of the C 1s core level corresponding to the specimens at these two stages were used to investigate the variations of ER in the tribotests of the specimens. A theoretical model of the substituted impurities and the induced behavior in electrical conductivity is provided to explain the observed behavior. X-ray diffraction (XRD) patterns were used to identify the IGZO chemical compounds and their primary lattices. The intensities of these compounds were used to define the intensity ratio (IR), which is of importance for the optical parameters. XPS analyses provided Ga 2p, Ga 3d, In 3d, Zn 2p, C 1s, and O 1s core-level spectra. The O 1s spectra for these five specimens were further deconvoluted into the O₁, O₂, and O₃ Gaussian profiles, and IR_{O₂}, relating to the oxygen vacancy defects, was evaluated. The C 1s spectra were also deconvoluted into the C-C and C-O bonds in order to investigate the O atoms incorporated into the graphene in the graphite-like film as substitutional impurities and their effect on ER. In order to evaluate the effect of deposition power on the optical properties of the IGZO film, the Si-wafer was replaced by glass as the substrate material. The optical properties, namely transmittance, reflection, and absorption, were obtained as a function of deposition power. The absorption coefficient was thus evaluated and further applied to determine the optical (transition) band gap. The reflection index (n) and extinction coefficient (k) were also provided. Photoluminescence (PL) intensity profiles were obtained. The deconvolutions of the PL spectra were used to establish the correlation between their peak intensity (PI) with the bonds/elements in the XPS analyses.

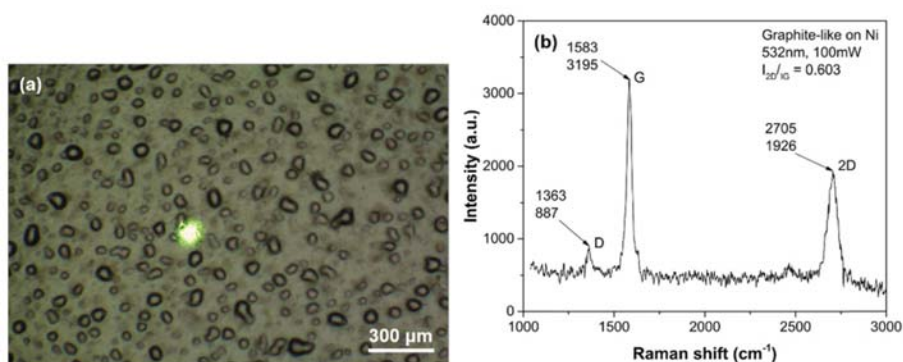


Fig. 1. (a) The SEM image of the graphite-like + Ni / SiO₂ / Si wafer specimen; (b) the Raman spectrum with 532 nm as the excitation.

2. Specimen preparation and experiments

In the present study, specimens were prepared using $2\text{ cm} \times 2\text{ cm}$ Si wafers as the substrate material. These wafers had a pre-grown 300-nm-thick thermal silicon oxide film. They were cleaned using the standard RCA cleaning procedures, followed by a rinse in deionized water and hot-plate drying. A thin polycrystalline Ni layer was then deposited with a thickness of about 300 nm, following by the co-sputtering of a Ni and carbon (Ni, C) layer for 1 min using a direct-current co-sputtering system (ACS-4000-C3, ULVAC, Japan). The purities of the Ni and C targets were both kept at 99.99%. After deposition, the samples were loaded into a rapid thermal annealing (RTA) chamber for air annealing. The annealing temperature was elevated to 900 °C. The dwelling time was set as 30 min. The cooling rate of the RTA chamber was then well-controlled at 10 °C/s. The annealing process was performed in the RTA chamber at a pressure of 2×10^{-6} Torr. During the cooling process, carbon atoms were precipitated, due to the lower solubility at lower temperatures, and the graphene layer was grown on the Ni film surface [27–29]. Figure 1(a) shows the SEM image of the graphite-like + Ni / SiO₂ / Si wafer specimen before depositing the IGZO film. In order to identify the film structure, a Raman system (MRI532S, Protrustech, Taiwan) equipped with the mapping technique was used to determine the Raman single-point spectrum. The spectrum of this specimen is shown in Fig. 1(b). The three peaks at 1349 cm^{-1} , 1589 cm^{-1} , and 2690 cm^{-1} are identified as D-band, G-band, and 2D-band, respectively. In general, the G-band peak of graphite is present at $\sim 1580\text{ cm}^{-1}$ and in a form of broad spectrum [30]; the D peak at the edge of graphite consists of two peaks, D₁ and D₂ [31, 32]. However, a slim and sharp peak occurs in this specimen at 1583 cm^{-1} . The results in the literature [30] show that the Raman band for graphene has the value quite close to that of graphite, and it is slightly lowered by increasing the number of the graphene layers if 514.5 nm and 633 nm excitations were applied. 532 nm excitation was used in this study, and the Raman band behavior is demonstrated to be similar to that mentioned above for graphene. It is thus concluded that the film is prepared with a multi-layered structure. The intensity of G band is found higher than that of 2D band, and thus the film is in the graphite-like materials [33]. The 2D to G peak intensity ratio ($I(2D)/I(G)$) is obtained to be < 1 ($= 0.603$). Since 2690 cm^{-1} for the 2D peak in this study is obtained slightly higher than $\sim 2660\text{ cm}^{-1}$ defined for the graphene-based materials, a blue shift is expected to occur in these specimens. In the case of bilayer graphene with the blue shift in the 2D peak, $I(2D)/I(G)$ value can be suppressed to a value lower than 1 [34]. As more layers are added, the Raman spectrum changes towards that of bulk graphite [35, 36]. Obviously, the graphite-like materials prepared in the present study may be the behavior demonstrated in multiply graphene with a blue shift.

Table 1. Details of deposition conditions.

Target	IGZO
Target diameter (mm)	75
Source-to-substrate distance (cm)	5
Substrate temperature	Room temperature
Power (W)	60, 80, 100
Chamber pressure (Torr)	20×10^{-3}
Ar flow rate (sccm)	20
Sputtering time (s)	7200

IGZO thin films were then deposited onto these samples using a radio-frequency magnetron sputter system (Helix, HLLS-87, Taiwan). A single IGZO film with a mole ratio of In:Ga:Zn = 1:1:1 was used as the target. In this study, deposition powers of 60, 80 and 100 W were respectively used to deposit the IGZO films, with the other deposition conditions fixed, as shown in Table 1. The deposition power was varied to investigate its effect on the uniformity and flatness of the graphite-like films formed between the IGZO and Ni films.

These two parameters affect defects in films and the electrical properties, including ER, of the specimen.

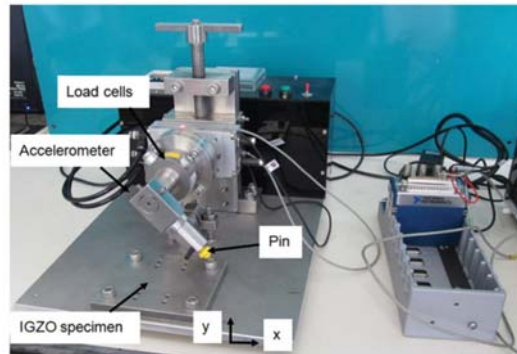


Fig. 2. Photograph of tribotester.

A self-designed tribotester, as shown in Fig. 2, was applied to conduct the friction and wear tests of the three kinds of specimen. This tester is equipped with two load cells (Futek MBA400, FSH07071, USA) for the measurements of the frictional force (F_x) parallel to the horizontal component of the sliding direction of the reciprocating swing and the normal contact force (F_y) vertical to the component. An accelerometer (PCB Piezotronics, Inc. 352C65, USA) was installed for the measurement of vibrations (a_y) arising at the pin in swing contact with the specimen. This pin made of silicone (3M, USA) and whose spherical tip has a diameter of 5 mm, was connected at the bottom of a rod to produce pendulum-like motion. The maximum pendulum angle was measured to be 45° (symmetrical) with respect to the vertical direction. This action was used to simulate the fatigue and wear behavior arising at the thumb-driven display. The other end of the rod was fixed at a certain height by adjusting a screw before the tribological test such that $F_y = 0.5$ N in the vertical direction was obtained. The hardness (H) of the silicone material varied in a range of 0.005 to 0.04 GPa and its reduced modulus (E_r) varied in a range of 0.002 to 0.062 GPa; both values were obtained from nanoindentation tests, and strongly depend on the indentation depth. An oscillation frequency of 0.833 Hz was applied for the swing motion. A data acquisition system (Orion Recorder II, 8 channels, USA) along with NI 9234 and NI 9237 modules (National Instruments, USA) was applied to acquire a_y , F_x , and F_y signals. The sampling rate of the load cells was set at 1024 point/s in continuous recording mode.

In order to investigate the evolution of tribological behavior, two extension cords were adhered onto the specimen's top surface (IGZO film) at two positions symmetrical with respect to the central line of the specimen in order to measure the electrical resistance (ER) variations of the IGZO film. A micro electrical resistor (Picotest M3500A, USA) was employed to acquire the ER during the cyclic testing process. The test current was fixed at 1 mA. The ER varied in a range of 100 to 1000 Ω . The specimens used in the tests were prepared to be 20 mm in length and 20 mm in width.

A surface roughness measurement instrument (Solver-P47H, NT-MDT, Russia) was applied to measure the topographies of the IGZO films. The top and lateral profiles of the IGZO films were prepared using a dual focused ion beam (FIB, FEI Nova-200, USA). Images of the specimens' lateral profile were provided to evaluate the microcracks in the IGZO film and the voids formed at the interface. The TEM diffraction patterns are provided to identify the crystallization behavior in these specimens. XRD analyses were carried out on a diffractometer (Rigaku, ATX-E, USA) in the 2θ range of 30° - 80° using $\text{CuK}\alpha$ X-rays as the radiation source. The 2θ scans show the angular positions of the oxide chemical compounds and their primary lattices. XPS (PHI-5000 Versaprobe, ULVAC-PHI, Osaka, Japan) was

utilized to observe the variation tendency of the chemical state for each element. The optical properties, including the absorption and reflection spectra of the specimens, were recorded on a spectrophotometer (Hitachi U-4000, Japan). A spectroscopic ellipsometry (Horiba Jobin Yvon, France) was used to measure the refraction index (n) and extinction coefficient (k) of specimens. PL spectra (Jobin Yvon/Labram HR, France) were obtained at room temperature with a 325-nm He-Cd laser with a spot size of $0.8\ \mu\text{m}$ and a power of 30 mW incident at the sample. A nanoindentation tester (MTS, Nano Indenter XP, USA) was used to measure the material hardness (H) and reduced modulus (E_r).

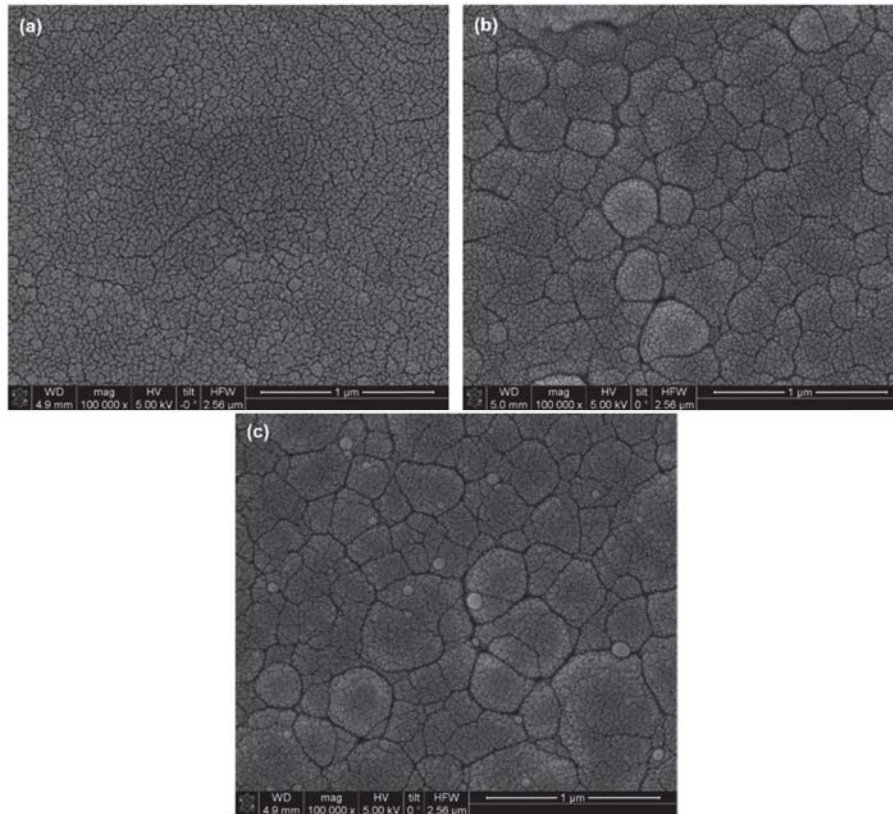


Fig. 3. SEM images of as-prepared IGZO / graphite-like + Ni / SiO₂ / Si wafer specimens prepared with IGZO deposition powers of (a) 60 W, (b) 80 W, and (c) 100 W.

3. Results and discussion

SEM images of the specimens prepared with 60, 80 and 100W as the deposition power of IGZO are shown in Figs. 3(a)-3(c), respectively. The images were obtained before the tribotest. Numerous island-shaped bulges formed whose size depended on the applied IGZO deposition power. Bulges with a small mean size formed in the 60-W specimen. The mean sizes of bulges in the 80 and 100-W specimens were significantly larger than that of those in the 60-W specimen. These bulges directly influence the properties of as-prepared specimens, such as the mean surface roughness (R_a), and the normal contact and frictional forces during testing. The R_a values of the as-prepared 60-, 80-, and 100-W specimens are 9.85, 10.3, and 15.6 nm, respectively. The R_a values increased with increasing IGZO deposition power.

Nanoindentation tests were carried out to evaluate specimen hardness (H) and reduced modulus (E_r). Hardness values of 7.56, 8.63 and 9.17 GPa and reduced moduli of 124.9,

131.0, and 136.8 GPa were obtained for the 60-, 80-, and 100-W specimens, respectively. Both the H and E_r values slightly increased with increasing IGZO deposition power.

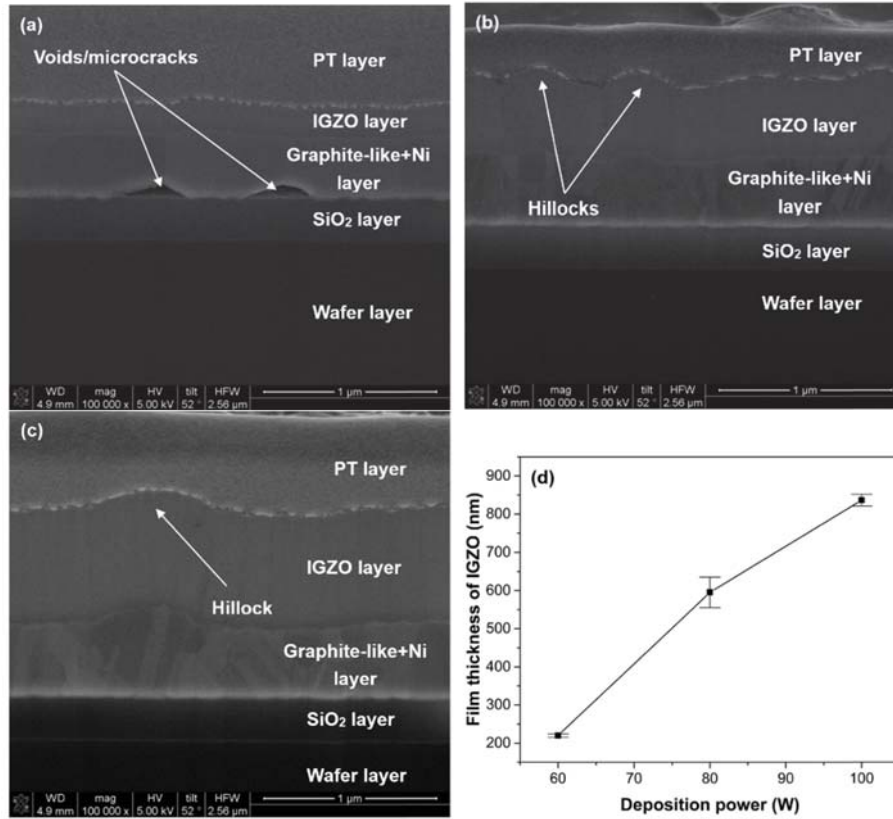


Fig. 4. Lateral surfaces of as-prepared IGZO / graphite-like + Ni / SiO₂ / Si wafer specimens prepared with IGZO deposition powers of (a) 60 W, (b) 80 W, and (c) 100 W. (d) thickness of IGZO film versus IGZO deposition power.

Figures 4(a)-4(c) show the lateral surfaces of the as-prepared 60-, 80-, and 100-W specimens, respectively. Microvoids/cracks formed in the three specimens near the interface of Ni and SiO₂ layers on the Ni side. The microvoids/cracks for the 60-, 80-, and 100-W specimens had mean sizes of 4.435, 3.962, and 4.145 μm, respectively. At the interface of the IGZO and Ni layers, hillocks formed in the three kinds of specimen; the 60-W specimen had the fewest hillocks. In the study of Li et al. [17], defects, including hillocks and nanovioids, were found to be created during the annealing process. The threshold values of the annealing stress (σ_{an}) required for the incipient formation of hillocks was determined. Nanovioids were created independent of the hillocks. In this study, the deposition power of IGZO is the governing factor of the annealing stress in the graphite-like + Ni layer, which is unavoidable due to the coating of IGZO. Nevertheless, hillocks grew in these specimens because the local internal stress in the graphite-like + Ni layer was beyond the threshold value. It is noticed that the formation of hillocks in the graphite-like + Ni layer forced the IGZO film to protrude upward. This behavior may explain why the bulges in the morphologies of the 80- and 100-W specimens are much larger than those of the 60-W specimen, as shown in Figs. 3(a)-(c). Figure 4(d) shows the film thicknesses of IGZO created at the three deposition powers. The results indicate that the thickness of the IGZO film almost linearly increased with deposition power.

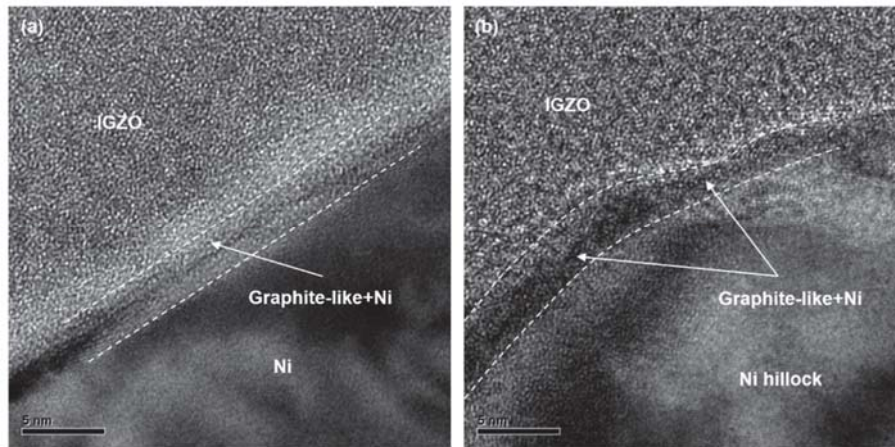


Fig. 5. TEM images of as-prepared 80-W specimen in regions (a) without and (b) with hillock.

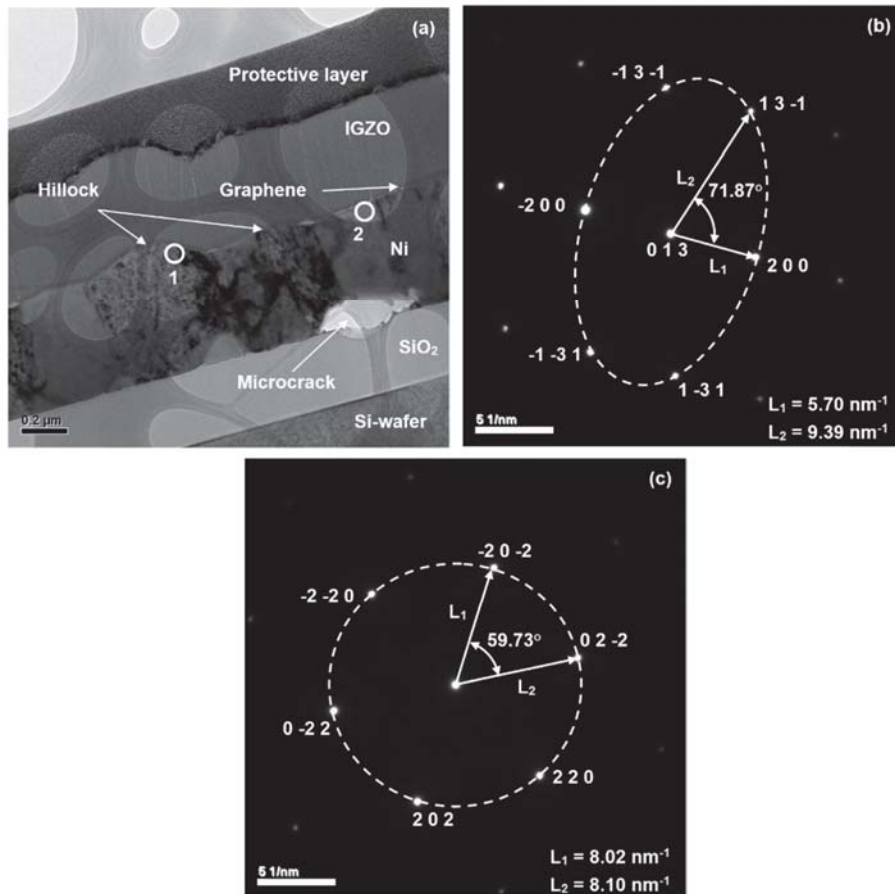


Fig. 6. (a) SEM image of lateral surface of as-prepared 80-W specimen and TEM SAED patterns for areas labeled (b) “1” and (c) “2”.

The lateral-surface TEM images of the as-prepared 80-W specimen for regions without and with a hillock are shown in Figs. 5(a) and 5(b), respectively. In Fig. 5(a), the graphite-like

+ Ni film (between the two dashed lines) was deposited as a flat strip with a uniform thickness of about 3 nm. It is presented to be a continuous pattern in the region without a hillock. In Fig. 5(b), the graphene layer is convex due to the hillock-induced protrusion of the Ni layer. The graphite-like + Ni film has an uneven thickness, becoming especially thin in the area near the hillock peak.

TEM selected area electron diffraction (SAED) patterns were obtained for the as-prepared 80-W specimen for the two small areas marked by “1” and “2” in Fig. 6(a), which are located in regions with and without a hillock, respectively. The Bravais-Miller indices were used to label the diffraction spots. The diffraction spots corresponding to point 1 are shown in Fig. 6(b); they can be regressed by an ellipse such that the lengths of L_1 and L_2 are 5.70 and 9.39 nm^{-1} , respectively. The variations of L_1 and L_2 values depend on the IGZO deposition power and the number of tribotest cycles for a given frequency. Since the lattice constants are changed significantly by these two governing factors, it is of interest to determine whether the change is due to material changes or lattice disorder. It suggests that this L_1/L_2 ($= 0.607$) value is obtained from the specimen with un-flat or hump up Ni films. The ellipse in Fig. 6(b) can be obtained from the SAED pattern of the Ni layer, with a hexagonal ring tilted at an angle. The SAED pattern for the region without a hillock (point 2) is shown in Fig. 6(c). The diffraction spots almost form a hexagonal ring, and the L_1 ($\cong L_2$) value is equal to 8.05 nm^{-1} . The characteristics of this ring indicate that the Ni layer deposited in this region underwent a very small geometric distortion.

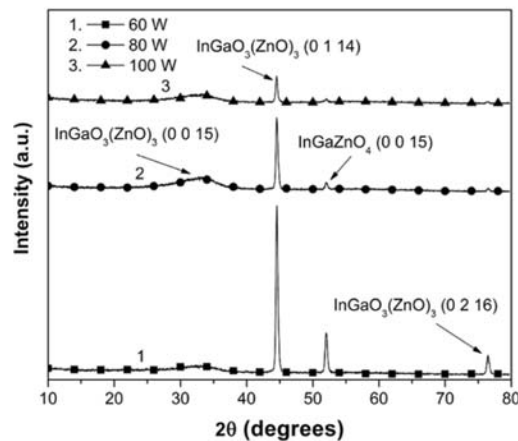


Fig. 7. XRD pattern for as-prepared 60-, 80-, and 100-W specimens.

Table 2. Roughness, mechanical properties, and I_R values for three kinds of specimen.

Specimen	R_a (nm)	Hardness, H (GPa)	Reduced modulus, E_r (GPa)	I_R
60-W	9.9	7.6	124.9	0.9728
80-W	10.3	8.6	131.0	0.9496
100-W	15.6	9.2	136.8	0.9257

Figure 7 shows the XRD patterns for the as-prepared 60-, 80-, and 100-W specimens. The highest peak in each pattern, roughly at $2\theta = 44.51^\circ$, corresponds to $\text{InGaO}_3(\text{ZnO})_3$ (0 1 14); the second highest peak, at $2\theta = 52^\circ$, corresponds to InGaZnO_4 (0 0 15); the third highest peak, at about $2\theta = 76.45^\circ$, corresponds to the lattice of $\text{InGaO}_3(\text{ZnO})_3$ (0 2 16); and the lowest peak, at about $2\theta = 33.01^\circ$, corresponds to $\text{InGaO}_3(\text{ZnO})_3$ (0 0 15). The intensities of all four peaks decrease with increasing IGZO deposition power. Define parameter I_R as:

$$I_R \equiv \frac{I_{\text{InGaO}_3(\text{ZnO})_3((0114)+(0216)+(0015))}}{I_{\text{InGaO}_3(\text{ZnO})_3((0114)+(0216)+(0015))} + I_{\text{InGaZnO}_4(0015)}}. \quad (1)$$

where I denotes the PI of a lattice. The I_R values for the three kinds of specimen are shown in Table 2. The intensity ratio of $\text{InGaO}_3(\text{ZnO})_3$ (0 1 14) decreases with increasing IGZO deposition power. The data in Table 2 show that with increasing I_R value of a specimen, its hardness (H), reduced modulus (E_r), and mean surface roughness (R_a) decrease.

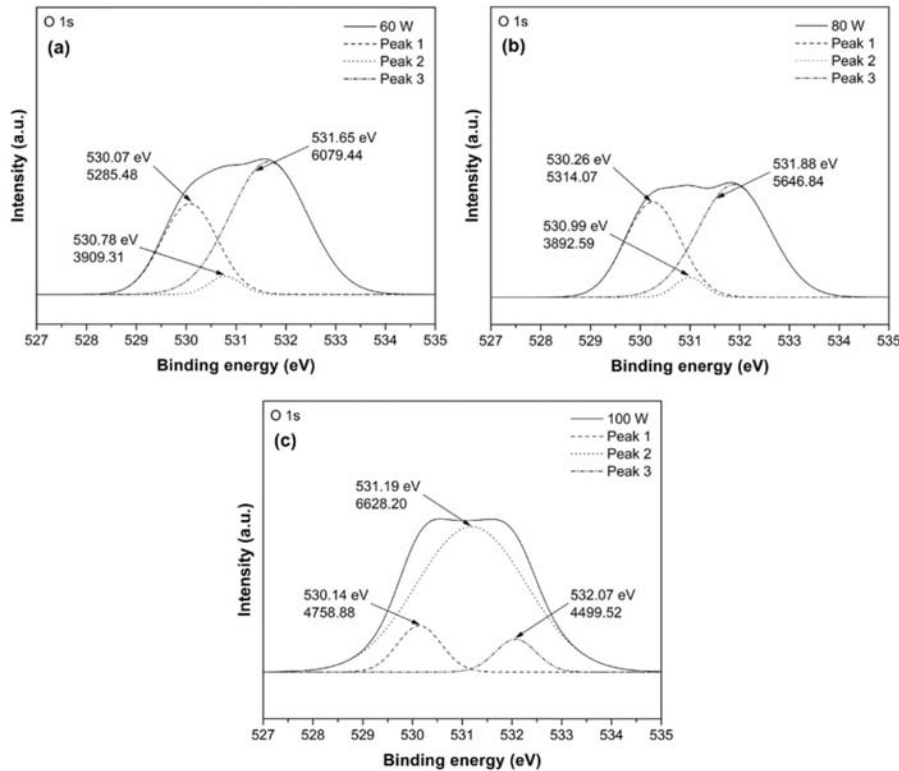


Fig. 8. Deconvolutions of XPS O 1s XPS spectra for (a) 60-, (b) 80-, and (c) 100-W specimens.

Table 3. Peak intensities of O 1s and peak intensity ratios of three kinds of specimen.

Power (W)	Peak intensities of O1s (a.u.)			Peak intensity ratio IR_{O_2}
	O ₁	O ₂	O ₃	$I_{O_2}/(I_{O_1} + I_{O_2})$
60	5285.48	3909.31	6079.44	0.4252
80	5314.07	3892.59	5646.84	0.4228
100	4758.88	6628.20	4499.52	0.5821

XPS analyses were conducted for elemental In, Ga, Zn, and O for the three kinds of as-prepared specimen. The XPS of O 1s core-level spectra for the 60-, 80-, and 100-W specimens are shown in Figs. 8(a)-8(c), respectively. Each of these three spectra can be decomposed into three Gaussian-like spectra with their binding energies at about 530, 531, and 531.8 eV, respectively. The peak at a binding energy of ~530 eV (O_1) is ascribed to the

O^{2-} ions in the a-IGZO structure; it represents oxygen in the oxide lattice without oxygen vacancies. The O_2 peak (≈ 531 eV) reflects the oxygen vacancies or OH groups, and is associated with the presence of oxygen-deficient regions. The O_3 peak (≈ 531.8 eV) corresponds to the existence of weakly bonded oxygen species on the film surface, and is attributable to H_2O and absorbed species integrated into the materials [37–39]. The PIs of O_1 , O_2 , and O_3 for the three kinds of specimen prepared with different IGZO deposition powers are shown in Table 3. Define the PI ratio of O_2 as

$$IR_{O_2} \equiv I_{O_2} / (I_{O_1} + I_{O_2}) \quad (2)$$

The IR_{O_2} values for the three kinds of as-prepared specimen are shown in Table 3. The results show the sequence $(IR_{O_2})_{80W} \leq (IR_{O_2})_{60W} < (IR_{O_2})_{100W}$. The influence of IR_{O_2} on the optical reflection of specimens is discussed in a later section. The XPS C 1s and O 1s spectra for the 60-W, 80-W, and 100-W specimens after a number of 300 cycles have been obtained too. The peak intensity (PI) sequence of the C-C bond shows that $(PI_{C-C})_{80W, 300C} > (PI_{C-C})_{60W, 300C} > (PI_{C-C})_{100W, 300C}$; however, the peak intensities of the C-O bond for these three specimens are lowered to be negligibly small. The O 1s spectra have been deconvoluted into three Gaussian-like spectra associated with O_1 , O_2 , O_3 , respectively. The IR_{O_2} values show the sequence of $(IR_{O_2} = 532.33 \text{ eV})_{100W, 300C} > (IR_{O_2} = 532.23 \text{ eV})_{80W, 300C} > (IR_{O_2} = 531.87 \text{ eV})_{60W, 300C}$ which implies that the oxygen vacancies formed at the 300th cycle increase with increasing the deposition power. Irrespective of the number of cycles, the direct relationship between the electrical resistance (ER) and the IR_{O_2} is unable to establish for these three specimens.

Figure 9 shows the XPS spectra for Zn ($Zn2p_{3/2}$ and $Zn2p_{1/2}$). The binding energy (BE) values corresponding these two spectra are about 1022 and 1045 eV, respectively. The results show that an increase in the deposition power increases the peak intensity, irrespective of the binding energy. The decrease in the atomic percentage of Zn 2p is due to zinc vacancy (V_{Zn}) formation via the out-diffusion of Zn from the film [40]. The reduction of Zn in the atomic percentage ratio implies that the $InGaO_3(ZnO)_3$ content in the IGZO film decreased with increasing IGZO deposition power.

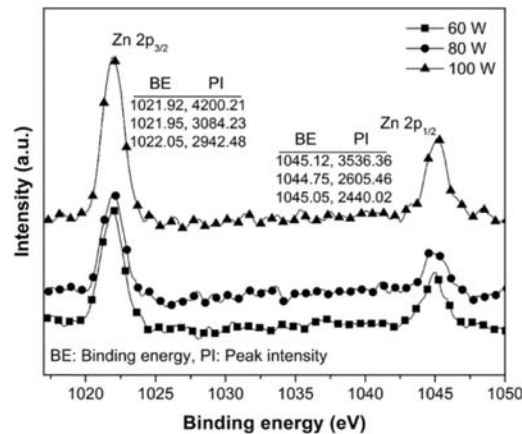


Fig. 9. XPS Zn spectra for three kinds of specimen.

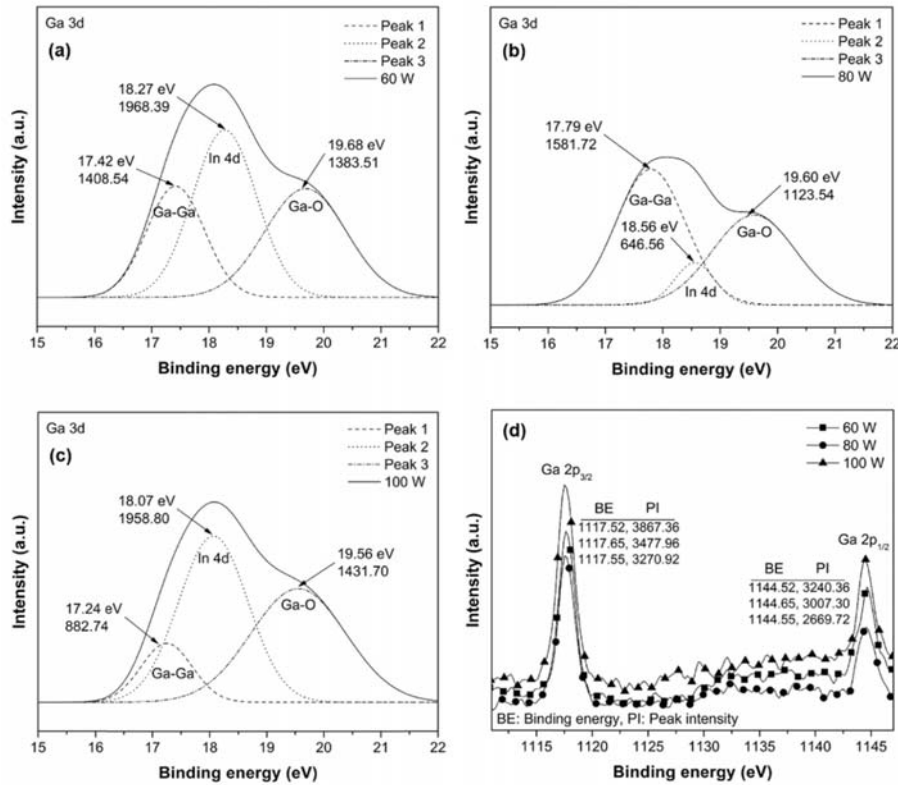


Fig. 10. Deconvolutions of XPS Ga 3d spectra for (a) 60-, (b) 80-, and (c) 100-W specimens. (d) Ga 2p_{3/2} and Ga 2p_{1/2} spectra of above three specimens.

Figures 10(a)-10(c) show the XPS spectra of Ga 3d for the 60-, 80-, and 100-W specimens, respectively. Figure 10(d) shows the XPS spectra of Ga 2p_{3/2} and Ga 2p_{1/2}. Each of these broad spectra can be decomposed into three Gaussian-like spectra with peak binding energies at about 17.5, 18.2, and 19.6 eV, respectively. The binding energies at about 17.5 and 19.6 eV represent the Ga-Ga and Ga-O bonds, respectively [41], and that at about 18.2 eV corresponds to In 4d [42]. No regular trend was found for the variations of the intensities of these three binding energies with IGZO deposition power. However, the peak intensity data show the sequences of $(PI_{\text{Ga-Ga}})_{100\text{W}} < (PI_{\text{Ga-Ga}})_{60\text{W}} < (PI_{\text{Ga-Ga}})_{80\text{W}}$, and $(PI_{\text{Ga-O}})_{80\text{W}} < (PI_{\text{Ga-O}})_{60\text{W}} < (PI_{\text{Ga-O}})_{100\text{W}}$. The sequence of $PI_{\text{Ga-O}}$ due to the change in IGZO deposition power is consistent with that of IR_{O_2} ; however, the sequence of $PI_{\text{Ga-Ga}}$ is exactly opposite to that of IR_{O_2} . It is thus concluded that an increase in the oxygen vacancies, and thus the IR_{O_2} value, can lead to a reduction of $PI_{\text{Ga-Ga}}$ but a rise of $PI_{\text{Ga-O}}$. That is, the decomposition of Ga-Ga bonds allow some Ga^{2+} ions to form Ga-O bonds. In Fig. 10(d), the highest and second highest peaks correspond to Ga 2p_{3/2} (about 1117.5 eV) and Ga 2p_{1/2} (about 1144.6 eV), respectively. The intensities (PI_{Ga}) of these two peaks show the sequence $(PI_{\text{Ga}})_{80\text{W}} < (PI_{\text{Ga}})_{60\text{W}} < (PI_{\text{Ga}})_{100\text{W}}$. This PI_{Ga} sequence is exactly the same as that of IR_{O_2} shown in Table 3. That is, the PI_{Ga} value of a specimen is directly affected by IR_{O_2} related to oxygen deficiencies. Increasing the number of oxygen vacancies increases both IR_{O_2} and PI_{Ga} . The PI_{Ga} rise can be attributed to the fact that the rest part of the decomposition of Ga-Ga bonds without forming Ga-O bonds increase with increasing number of oxygen deficiencies.

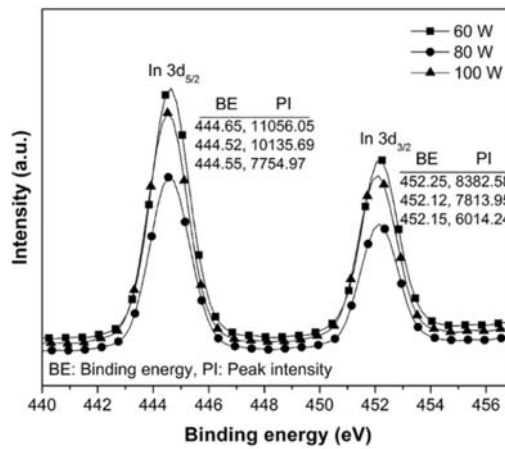


Fig. 11. XPS In 3d_{5/2} and In 3d_{3/2} spectra of three specimens.

Figure 11 shows the XPS spectra of In 3d_{5/2} and In 3d_{3/2} in the three kinds of specimen. The peaks are at about 444.6 and 452.2 eV, respectively. The energy difference (about 7 eV) between the two In peaks indicates that In is in the + 3 oxidation state (In₂O₃) and is substituted into the lattice [43]. The In 3d_{5/2} peak at about 444.6 eV corresponds to the In-In bond [44, 45]. Content changes in In and Ga have a direct effect on light transmittance [46]. Their connection with optical properties is discussed later.

Figure 12 shows the XPS spectra of C 1s for the three as-prepared specimens. The peaks at about 284.8 and 289.0 eV are identified as the C-C and C-O bonds, respectively [47]. The C-C bond is created in the graphite-like + Ni layer irrespective of either the plane or distortion form of this layer. The C-O bond is formed to have points defect in the graphene film during the deposition of the IGZO film; then, substitutional impurities are produced at the interface of the IGZO and graphite-like + Ni layers. The effect of the C-O bonds on the electrical properties and the number of microvoids/cracks in the as-prepared specimens is discussed in a later section.

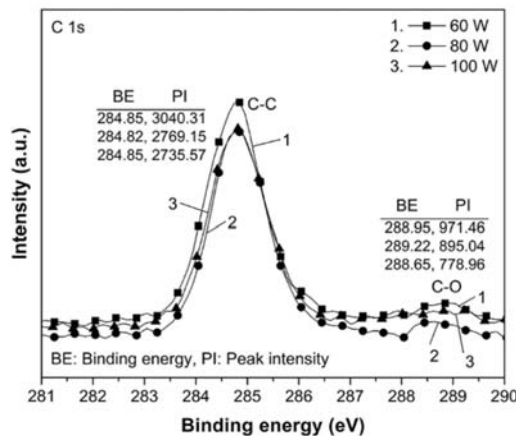


Fig. 12. XPS C 1s spectra of three specimens.

Tribotests were carried out on the three kinds of specimen with different test periods. The experimental results of the acceleration (a_y) in the y-direction, normal contact force (F_y) in the y-direction, and tangential force (F_x) in the x-direction for the 60-W specimen at the 100th

cycle in rightward motion are shown in Figs. 13(a)-(c), respectively, as an example. In Fig. 13(a), the vertical dashed line corresponding to 0.590 s indicates the lowest point of the spherical indenter where the greatest normal contact load was created. The horizontal dashed line corresponding to $a_y = 0$ indicates the border of the vibrations in the y-direction in either the acceleration or deceleration region. Initially, the contacts were operating with deceleration. Then, the contacts were operating with acceleration and great fluctuations appeared near the right dead point. In the entire forward motion of one cycle, two a_y peaks appeared at 0.292 and 0.900 s, respectively, and a_y fluctuated near the right dead point. These two peaks were created due to the contact conditions satisfying the criterion of stick-slip motion. Define q as the tangential traction, p as the applied normal pressure in the sliding contact, μ as the friction coefficient, and α as the angle between the applied oblique load by the spherical indenter and the common normal. If the inclination of the oblique force is less than the angle of friction, which was unavailable in this study, no slip will occur and, moreover, the distribution of frictional stress at the contact surface will be everywhere proportional to the normal contact pressure ($q = p \cdot \tan \alpha < \mu p$). If the inclination of the force exceeds the angle of friction, sliding begins at once and the frictional traction is everywhere equal to its limiting value ($q = \mu p$). It is interesting that the friction coefficients created at these two time points are similar, and that these two time points are on two sides of the lowest point ($t = 0.590$ s) of the spherical indenter and roughly symmetrical with respect to this point. The a_y fluctuations in the rear portion of this forward motion near the right dead point are believed to be due to thermoelastic instability [48]. Barber [49] showed that initial small departures from perfect conformity concentrated the pressure, and hence frictional heating, into particular regions of the interface. These regions expanded above the level of the surrounding surface and reduced the area of real contact, thereby concentrating the contact and increasing the local temperature still further. If sliding continues, the expanded spots, where the pressure is concentrated, wear down until contact occurs elsewhere. The new contact spots become heated, expand, and carry the load; the old ones, relieved of load, cool, contract and separate. This cyclic process was observed in these fluctuations. The critical velocity (V_c) [50] can be expressed in the form $V_c = 4\pi/c\mu E^* \lambda$, where c is the distortivity of the stationary solid, E^* is the reduced modulus defined for the two contact bodies, and λ is the wavelength of contact surface undulations. As the sliding velocity approaches this critical velocity, the fluctuations in a_y , F_x , and F_y increase rapidly in their magnitude, like the patterns of these three parameters near the right dead point.

Figures 13(b) and (c) show the tangential (frictional) and normal contact forces, F_x and F_y , respectively. Due to the differences in the deformations and contact areas formed on two sides of the lowest point of the spherical indenter, the F_x and F_y profiles with fluctuations are unsymmetrical. Figure 13(c) shows the variations of F_y . In the acceleration region (on the left-hand side of the lowest point), F_y , which has a positive value at the left dead point, decreases to zero first, and then increases in the opposite direction until the maximum value is attained. In this region, a positive F_y value is created at a large oblique angle, at which the elastic deformation of the indenter is negligibly small. As the oblique angle toward the lowest point decrease, the spherical indenter becomes compressed, exhibiting elastic deformation, such that a significant outward expansion of the indenter lateral surface occurs. In this time period, the compressive force in the -y direction monotonically increases. As the contact enters the deceleration region, F_y (negative value) decreases due to the reduction of the contact area with time, which is related to the elastic recovery of the indenter deformation. The decreasing trend stops at $t = 0.90$ s, at which stick-slip behavior occurs. After this time point, the stick-slip motion allows the elastic recovery to be so strong that the contact area quickly enlarges to withstand the compressive load again. This slip motion also causes the tangential force of the indenter to be in the same direction as that of the forward motion, as shown in Fig. 13(b).

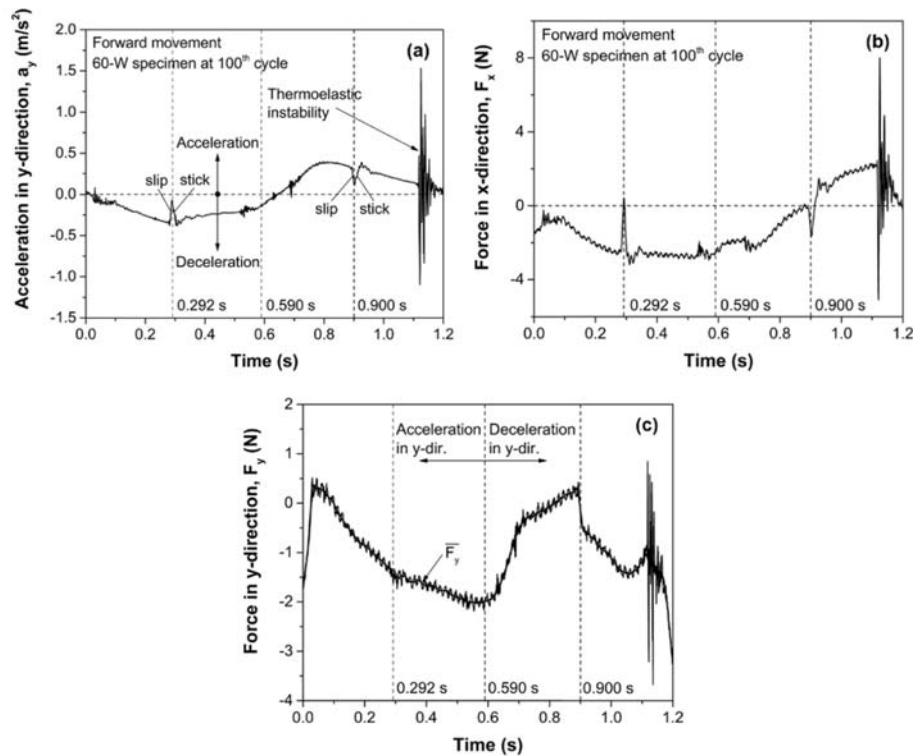


Fig. 13. (a) Acceleration in y-direction, (b) frictional force in x-direction, and (c) normal contact force in y-direction for 60-W specimen at 100th cycle.

Figures 14(a)-14(c) show SEM micrographs of the three kinds of specimen after 100 cycles in the tribotest. Numerous worm-like microcracks formed; their mean microcrack length (MML) in an area of $250 \text{ nm} \times 250 \text{ nm}$ was determined using SolidWorks software. The lateral surface of the 100-W specimen after the 300th cycle is shown in Fig. 14(d). Microcracks that formed near the top surface of the IGZO film penetrated downward; however, their depth is much smaller than the IGZO film thickness. Furthermore, the IGZO film did not delaminate from the graphite-like + Ni layer even after 300 cycles. The graphite-like + Ni layer is thus a good alternate conductor for the surface current if the connection between the IGZO and graphite-like + Ni layers can be retained even after many tribotest cycles. The conductivity in this study is strongly governed by the number and size of microcracks formed in the IGZO film, voids in the graphite-like + Ni layer, quality of the graphite-like films, and number of tribotest cycles.

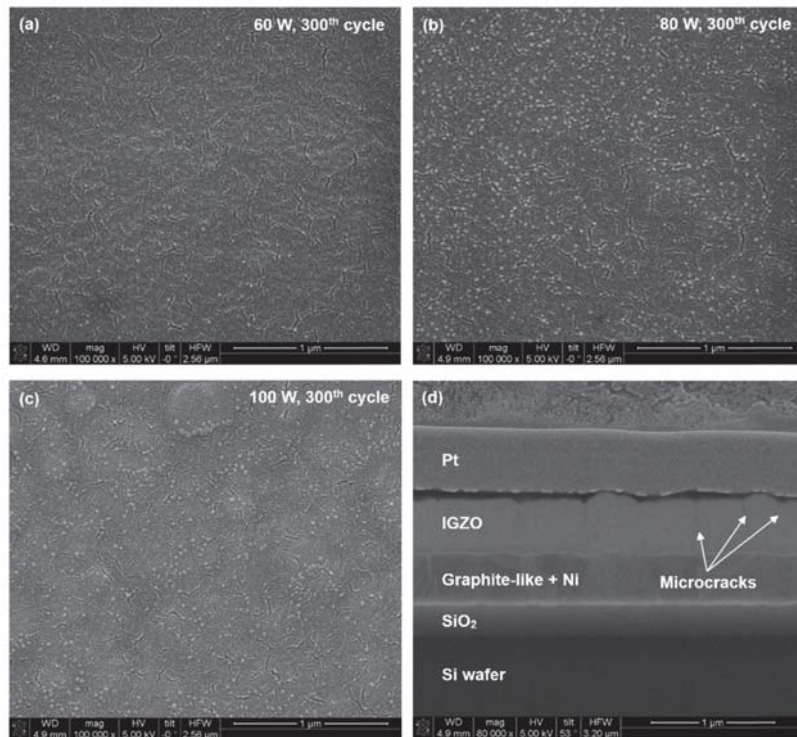


Fig. 14. SEM images of worn surfaces of (a) 60-, (b) 80-, and (c) 100-W specimens at 300th cycle. (d) Penetration depths of microcracks in lateral surface of 100-W specimen obtained at 300th cycle.

The variations of ER in the 60-, 80-, and 100-W specimens with the number of cycles are shown in Figs. 15(a)-15(c), respectively. In this study, 9800, 2050, and 1080 cycles were set for the 60-, 80-, and 100-W specimens, respectively. These numbers of cycles were decided temporarily based on the growth rate of ER exhibited in these specimens. The starting value of ER in the 60-W specimen was 8.86Ω . The ER value increased to about 8.97Ω after 9800 cycles. A negligibly small increase (0.11Ω) was found after a large number of cycles (9800). This behavior occurred even though the MML and number of microcracks increased with time. This result can be attributed to the graphite-like + Ni layer to be operating in a sturdy structure with few flaws during the time of tests. The graphite-like layer acted as an alternate path with low ER for the electric current despite the noticeable increases in the MML and number of microcracks. The ER variations of the 80-W specimen are shown in Fig. 15(b). The starting ER was 4.8Ω . The ER curve before the 168th cycle slightly decreases; then, the ER sharply drops at this cycle. After this cycle, the ER curve increases monotonically until the second sharp drop at the 1158th cycle. Monotonic increases in ER continue after this cycle until the third sharp drop at the 1924th cycle. The maximum ER at this cycle is 5.69Ω . Therefore, there is a total increase of 0.89Ω after 2065 cycles. The variations of ER for the 100-W specimen are similar to those for the 80-W specimen, as shown in Fig. 15(c). 6.9Ω is the starting ER for this specimen. The highest ER is 7.71Ω . Therefore, a total increase of 0.81Ω occurred after 1183 cycles. The increasing rate of ER for the 60-W specimen is the lowest although its MML is the largest of the three kinds of specimen. For the 80-W specimen, increases in the MML led to intermittent reductions of ER. There exist sudden changes of electrical resistance (ER) in these three kinds of specimen with different value of drop. These ER drops occurred intermittently in the entire tribotest process of every specimen. The average drop (ΔER) results show the sequence of $(\Delta ER)_{80W} > (\Delta ER)_{100W} >>$

(ΔER)_{60W}. This unusual behavior can be attributed to the graphite-like layer in this time period still serving as a good conductor. The number and size of microcracks created in the tribotests are not the dominant factors of the increase in ER. The microstructural integrity of the graphite-like + Ni layer after a tribotest becomes the controlling factor.

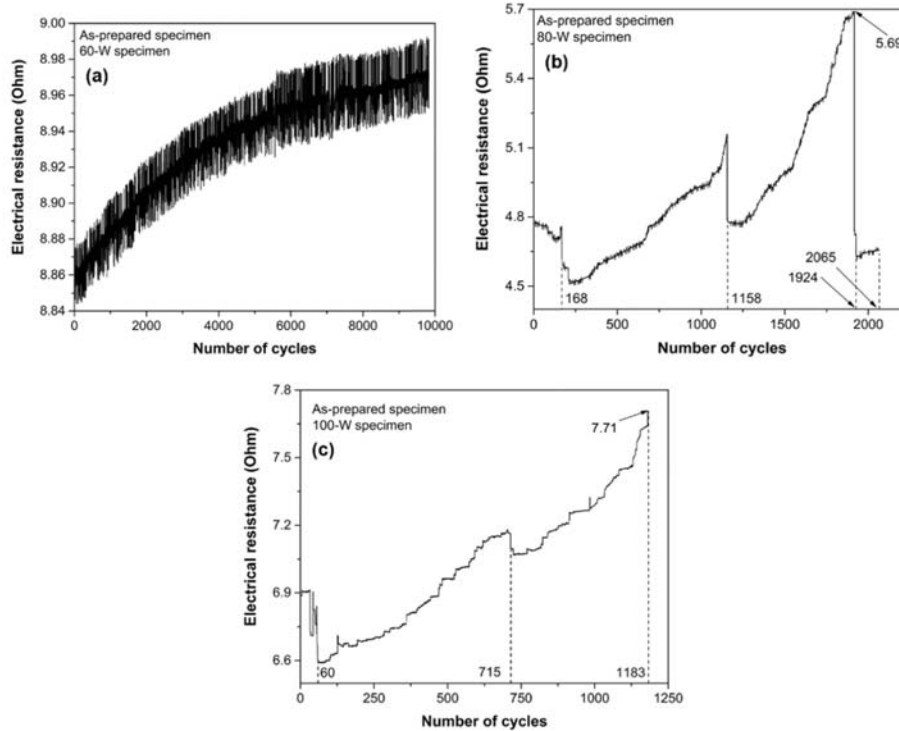


Fig. 15. Variations of electrical resistance with number of cycles for (a) 60-, (b) 80-, and (c) 100-W specimens.

In order to investigate the effect of the Ni film in the graphite-like + Ni layer on the electrical properties of graphite-like film, two kinds of specimen were prepared for the Hall measurements. Three graphene/Si-wafer specimens were made by the direct transfer of the graphene layers into the Si-wafer substrate; and three Ni/Si-wafer specimens were made by sputtering the Ni film onto the Si wafer. The mean values of the sheet resistivities and sheet carrier concentrations of the three graphene/Si-wafer specimens are obtained as 1.502×10^7 Ohm·cm and 2.412×10^8 cm⁻², respectively; the mean value of sheet resistivity and carrier concentration of the Ni/Si-wafer specimens are 0.2641 Ohm·cm and 1.596×10^{17} cm⁻², respectively. Obviously, the sheet resistivity of the Ni film is much lower than that of the graphene film. This implies the influence of the Ni layer on the sheet resistivity of the graphite-like + Ni layer in this study to be insignificant. Conversely, the sheet carrier concentration of the Ni layer became the dominant role in that of the graphite-like + Ni layer.

In order to explain the sharp drops in ER demonstrated in Fig. 15(b) for the 80-W specimen, the XPS spectra for the variations of C-C and C-O intensities in the XPS analysis with the number of cycles are provided. The XPS C 1s spectra of the as-prepared 60-, 80-, and 100-W specimens are shown in Fig. 12. The C-C characteristic peak at about 284.85 eV is identified as a graphene-related intensity. The C-O peak at about 288.95 eV is created due to the structural defects produced in the graphite-like + Ni layer and the subsequent formation of graphene oxide. In this study, vacancies (or defects) were first created in the growth of the graphite-like film and then were produced during the deposition of the IGZO film onto the

graphite-like + Ni / SiO₂ / Si-wafer specimen. A removal of a carbon atom from graphite-like sheet may create three two-fold coordinated atoms in a form of dangling bonds. Both vacancies and adatoms were formed and varied continuously during the tribo tests of swing motion, they have a tendency to form clusters. The formations of different kinds of vacancy may amount to small voids. Similarly, the diatoms may be incorporated into the lattice, resulting in the complexes in the forms of pentagon and hexagon. They coalesce in the vicinity of the vacancies and generate the defects buckling out of the graphene sheet [51]. The most likely residual defects are the multivacancies and adatom pairs in a form of 7-5-5-7 hillocks [12]. The theoretical calculations [52] show that a vacancy can catch an external molecule (CO in this literature) to heal itself. Vacancy clusters are immobile even at a few hundred degrees Celsius, whereas adatoms and adatom complexes can move easily even at low temperatures [53]. Replacement of a carbon atom by oxygen shifts the Fermi level of graphene into the conduction band, and also changes the electronic structure of graphene [54, 55]. The bulk substitution promotes the onset of a semiconducting-metal transition [56]. Such a localized substitutional impurity makes the impurity site chemically and electrically active [57]. In the present cyclic motion, dislocations occurred continuously such that they separated over a variable distance. As the distance increased to a value on the order of α , the dislocations led to an effective flux of electrons through an area of the perimeter [58]. The construction of the semilocalized state around a vacancy in a honeycomb lattice can lead to the Dirac equation in the continuum limit. One particular case is the nearest-neighbor square lattice with two flavors of half flux per site. It has been studied [59] in relation to the effects of impurities on the electronic structure with a feature of d-wave superconductors. This behavior is probably the main cause of the intermittent and abrupt drops of ER in the tribotests observed here. The covalent bonds open an intriguing possibility for tunnel junctions between the IGZO and graphite-like + Ni layers. At high IGZO deposition powers, oxygen impurities are expected to form at high densities, charge-carrier motion becomes diffusive with weak-localization effects present [60].

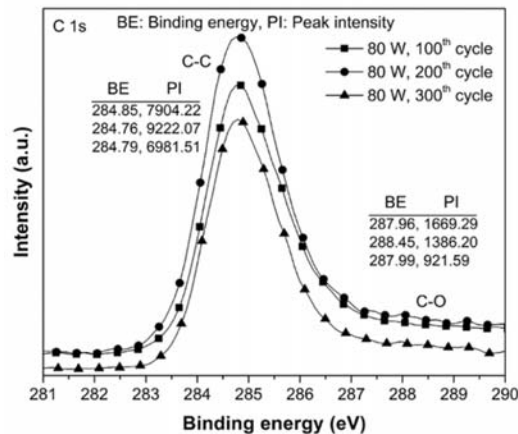


Fig. 16. XPS C 1s spectra for 80-W specimen at 100th, 200th, and 300th cycles, respectively.

Figure 16 shows the PIs of the C-C and C-O bonds for the 80-W specimen after 100, 200, and 300 cycles, respectively. Both types of PI are much higher than the PI values shown in Fig. 9 for the as-prepared 80-W specimen. The PI values follow the sequence $(PI_{C-C})_{300C} < (PI_{C-C})_{100C} < (PI_{C-C})_{200C}$ and $(PI_{C-O})_{300C} < (PI_{C-O})_{100C} < (PI_{C-O})_{200C}$. The ER variations in Fig. 15(b) show the sequence $(ER)_{300C} \cong (ER)_{200C} < (ER)_{100C}$. Comparisons between PI_{C-O} , PI_{C-C} , and ER at these three cycles demonstrate that increasing the values of PI_{C-O} and PI_{C-C} lowers ER, even though ER is determined to be the combined effect of the adhesion of the IGZO and the graphite-like layers and the number and size of microcracks in the IGZO film.

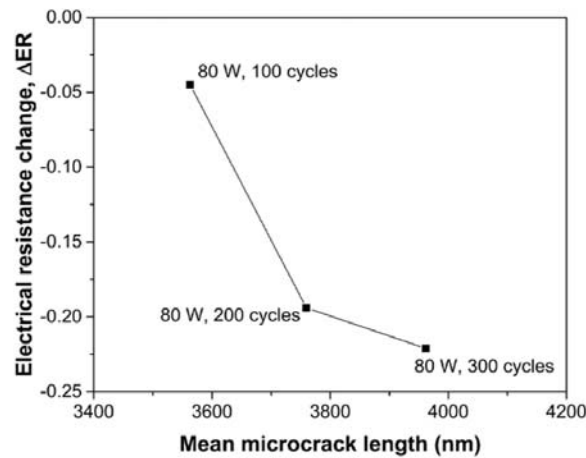


Fig. 17. Electrical resistance changes in 80-W specimen as function of mean microcrack length at various cycles.

Figure 17 shows the ER variations with MML for the 80-W specimen at the 100th, 200th, and 300th cycles, respectively. The MML increases with increasing number of cycles. However, the ER decreases with increasing MML. This extraordinary behavior is attributed to the retention of a graphite-like + Ni film on the IGZO film after a number of tribotest cycles, which acts as a conductor for electric current even though the number and size of microcracks increase with increasing number of cycles. This characteristic is also shown in the rises of ER for the three specimens at a given number of cycles.

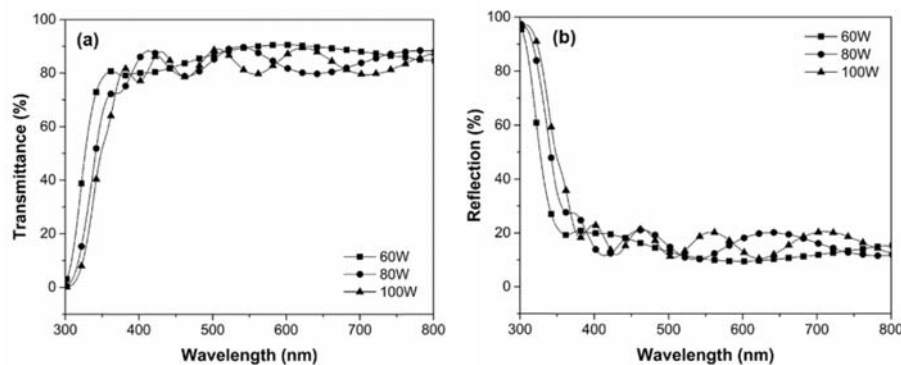


Fig. 18. (a) Transmittance, (b) reflection data of the IGZO/Glass specimens prepared with different deposition power.

The optical properties of transmittance (Tr), reflection (Re), and absorption (Ab) of the IGZO/Glass specimens prepared with different deposition power are shown in Figs. 18(a) and 18(b), respectively. The transmittance spectra in the visible-light region (380–780 nm) have a quite stable and high transparency. 86.7, 84.1, and 83.8% are evaluated as the average Tr values for the deposition powers of 60, 80, and 100 W, respectively. Significant differences in Tr due to different deposition power (P) are shown in the wavelength region ≤ 360 nm (near ultraviolet). Increases in the deposition power have resulted in a small reduction of the average Tr only. This P - Tr characteristic is also valid in the wavelength region ≤ 360 nm with big Tr differences among these three specimens. The optical spectra for reflection (Re) in the visible light region have 13.2, 15.9, and 16.6% as the average Re value for these three deposition powers. The behavior of reflection demonstrated in the near ultraviolet region due

to the change in deposition power is exactly opposite to that of transmittance. The A_b values in the visible-light region for these three specimens are lowered to be far less than 1%; in the wavelength ≤ 360 nm they are varied between 0 and 3%.

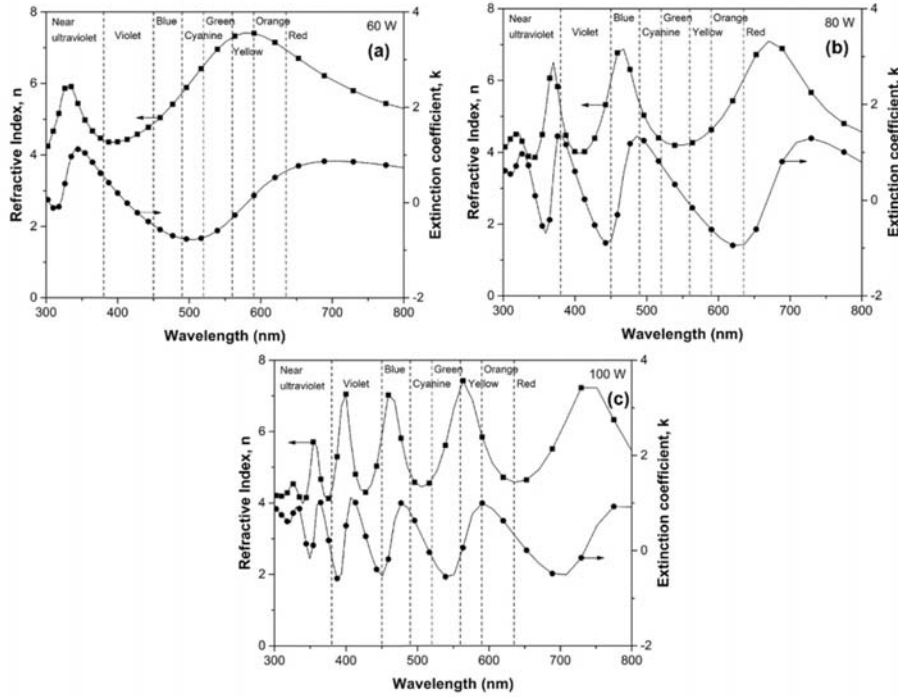


Fig. 19. Refractive index and extinction coefficient data evaluated for (a) 60-W, (b) 80-W, and (c) 100-W IGZO/Glass specimen.

The refractive index (n) and extinction coefficient (k) have been obtained as a function of wavelength for the three deposition powers, they are shown in Figs. 19(a) to 19(c), respectively. These curves of n and k are presented to be a wavy form. The peaks and valleys are presented at the wavelengths strongly dependent upon the deposition power. The number of either peaks or valleys increases with increasing the deposition power. The average values of refractive index and extinction coefficient show the sequences of $(n = 6.35)_{60W} > (n = 6.04)_{100W} > (n = 5.61)_{80W}$, and $(k = 0.341)_{80W} > (k = 0.238)_{100W} > (k = 0.207)_{60W}$. The absorption coefficient (α) can be calculated [61]

$$\alpha = \ln(1/T) / t_f. \quad (3)$$

where T is transmittance; t_f denotes film thickness. The optical (transition) band gap, E_g , which is evaluated on the basis of the absorption coefficient can be expressed as [62]

$$(\alpha h\nu)^2 = A(h\nu - E_g). \quad (4)$$

where A represents a constant. E_g can be determined by extrapolating the linear portion of the curve to intersect the $h\nu$ axis. Figure 20 shows the variations of α^2 with photon energy. The results show the sequence of $(E_g = 3.945 \text{ eV})_{100W} > (E_g = 3.931 \text{ eV})_{80W} > (E_g = 3.888 \text{ eV})_{60W}$. That is, an increase in deposition energy is favorable for the rise of E_g in the specimens.

Table 4. Intensity and wavelength results of PL decompositions into three Gaussian-like profiles with peaks-1 to 3 for each of the three specimens.

Peak code Wavelength, intensity, color Power (W)	Peak-1		Peak-2		Peak-3	
	Wavelength (nm)	Intensity (a.u.)	Wavelength (nm)	Intensity (a.u.)	Wavelength (nm)	Intensity (a.u.)
60	Green 543.59	64.94	Orange 600.99	152.80	Red 682.38	85.36
80	Green 546.42	101.16	Orange 627.81	211.65	Red 708.73	91.29
100	Green 536.07	110.26	Orange 632.98	192.17	Red 745.53	72.46

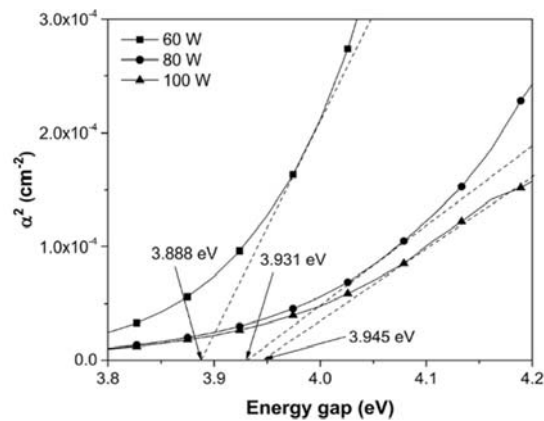


Fig. 20. Band gap energy of the three specimens prepared with different deposition power.

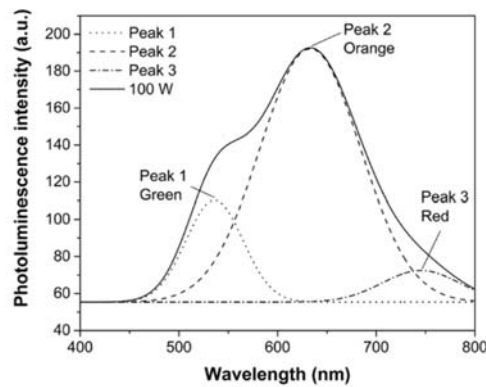


Fig. 21. Deconvolutions of PL intensity for 100 W specimen.

In this study, the PL intensity profiles for the three as-prepared specimens were obtained. They were decomposed into Gaussian-like profiles with three peaks (peaks 1 to 3). Only the PL profile for the 60-W specimen is shown in Fig. 21. The PIs, wavelengths, and colors corresponding to these three peaks for the three specimens are shown in Table 4. Peak 1 to peak 3 correspond to wavelengths of 536.07, 632.98, and 745.43 nm, respectively, which are the colors green, orange, and red. The results of PI show the following sequences: $(PI_{\text{Green}})_{60\text{W}} < (PI_{\text{Green}})_{80\text{W}} < (PI_{\text{Green}})_{100\text{W}}$, $(PI_{\text{Orange}})_{60\text{W}} < (PI_{\text{Orange}})_{100\text{W}} < (PI_{\text{Orange}})_{80\text{W}}$, and $(PI_{\text{Red}})_{100\text{W}} < (PI_{\text{Red}})_{60\text{W}} < (PI_{\text{Red}})_{80\text{W}}$. The intensities of these three peaks strongly depend on the PIs of atoms and bonds in the XPS spectra for the three kinds of specimen. According to the results

of the Zn $2p_{3/2}$ and Zn $2p_{1/2}$ peaks shown in Fig. 9, the PI sequences for these two kinds of atom are the same as that for PI_{Green} . Therefore, increasing the concentration of Zn $2p_{3/2}$ or Zn $2p_{1/2}$ will increase the PI_{Green} value. The PIs of In $3d_{5/2}$, In $3d_{3/2}$, and In 4d and the C-C and C-O bonds are responsible for the intensity of peak 2. Lowering the PIs of above atoms or bonds will increase PI_{Orange} . PI_{Red} is found to be affected by the concentrations of Ga-Ga and Ga-O bonds and Ga $2p_{3/2}$ and Ga $2p_{1/2}$ atoms. PI_{Red} can be increased by either increasing the $PI_{\text{Ga-Ga}}$ value or decreasing the values of $PI_{\text{Ga}2p_{3/2}}$, $PI_{\text{Ga}2p_{1/2}}$, and $PI_{\text{Ga-O}}$.

4. Conclusions

The size and height of island-shaped bulges increase significantly when the deposition power of IGZO film is increased. They are related to the formation of hillocks in the Ni layer. The mean surface roughness (R_a), hardness (H), and reduced modulus (E_r) of a specimen increase with increasing IGZO deposition power. The intensity ratio, I_R , related to the PIs of $\text{InGaO}_3(\text{ZnO})_3$, decreases with increasing IGZO deposition power. The growth of hillocks can affect the thickness and integrity of the graphite-like + Ni layer. A flat graphite-like + Ni layer with relatively few defects can be created with a deposition power of 60 W. For deposition powers of 80 and 100 W, the Ni hillocks induced by thermal stress protrude, making the graphite-like + Ni layer convex with an uneven thickness. After tribotests, the rise in the ER of a specimen is quite small if the thickness and the integrity of the graphite-like + Ni layer is retained. The rise in ER becomes significant if the quantity of defects in the uneven thickness increases with increasing tribotest cycles. It is the defects generated in the graphite-like + Ni layer, rather than the size of the microcracks formed in the IGZO film, that is the dominant factor of ER rise of a specimen. After tribotests, the graphite-like + Ni layers of the three kinds of specimen well adhered to the IGZO films, without delamination or microcracks, providing a path for electric current with a relatively low resistance. The O atoms created by the defects (oxygen deficiencies) in the IGZO film serve as foreign atoms that become incorporated into graphene as substitutional impurities. An increase in the graphene content, substitutional impurities, or both can increase the content of the C-C and C-O bonds. The effects of impurities on the electrical structure with a feature of superconductors occur intermittently in the tribotests, resulting in a sharp drop in ER. The presentations of sharp drop are benefit for lowering the growth rate of electrical resistance. The growth rate of ER increases with increasing IGZO deposition power. The oxygen vacancies created during the deposition process of IGZO influence the IR_{O_2} parameter. An increase in IR_{O_2} increases the values of PI_{Ga} and $PI_{\text{Ga-O}}$ and decreases the value of $PI_{\text{Ga-Ga}}$. In the IGZO/Glass specimens, increases in the deposition power in a range of 60 W and 100 W have resulted in a small reduction of the average transmittance only. The behavior of reflection demonstrated in the same wavelengths is exactly opposite to that of transmittance. The absorption in these three kinds of specimen is negligibly small. Due to the change in deposition power, the sequence of the refractive index (n) is exactly opposite to that of the extinction coefficient (k). The optical band gap (E_g) of specimen increases with increasing the deposition power. Increasing the concentrations of Zn $2p_{3/2}$ or Zn $2p_{1/2}$ increases the PI_{Green} value. The atoms of In $3d_{5/2}$, In $3d_{3/2}$, and In 4d and the C-C and C-O bonds control PI_{Orange} . Lowering the concentration of In atoms or these two bonds increases PI_{Orange} . PI_{Red} can be increased by either increasing $PI_{\text{Ga-Ga}}$ or decreasing the values of $PI_{\text{Ga}2p_{3/2}}$, $PI_{\text{Ga}2p_{1/2}}$, and $PI_{\text{Ga-O}}$.