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Cu layer derived by accelerated microparticles on ZnO:Al/p-Si heterojunction

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ABSTRACT

Cu micrometalic particles with the supersonic velocity (3 Mac) were applied to determine the optimum microparticle bombardment effect on the ZnO:Al thin-film surface derived by sol–gel method (which allows mixing at the atomic level to form colloidal particles). The mechanical damage deriving by the Cu particles with high kinetic energy has indicated the practical coating parameters (presenting surface related aspects) for its fabrication steps to use in the diot applications. The key parameters of the practical ohmic contact deposition on the film surface (describing the functional behavior of the ZnO:Al/p-Si heterojunction) were examined to develop low ohmic contact resistance (derived by using Cu layer) for use in optoelectronic devices. The annealing of ZnO:Al/p-Si heterojunction (at 700 °C in vacuum) has supported to obtain a suitable metal contact with optimum low resistance by using the cold gas dynamic spraying technique. The conductive and rectifier behaviors of ZnO:Al/p-Si heterojunction have indicated the utilization of the Cu stack layer without the need for the extra thermal annealing treatment of Cu ohmic contact (after the annealing of ZnO:Al/p-Si heterojunction according to the specific analyses for applications in optoelectronics). The generated damage depended on the acceleration of Cu particles through the trapezium structure of the ZnO:Al surface (annealed at 800 °C). The Cu particles with high purity have been provided to avoid the cracked surface (annealed at 700 °C in vacuum). The developed in-depth surface performance has emphasized the relation to the control of the surface properties at the atomic level (by using the sol–gel dip-coating technique). The annealing process (affecting the thickness of the film) has indicated the control of the temperature as the key parameter for avoiding the mechanical damage (depending on the bombardment of the dense micrometallic particles at ultra-high speed) on the film surface.

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1 Introduction

Zinc oxide (ZnO) has potential transparent layer applications in electrical devices and transparent electrodes [1]. ZnO material (as a transparent conducting oxide—TCO layer) has direct bandgap, low resistivity, and high transparency in the visible range of the electromagnetic spectrum. The electrical properties of ZnO can be enhanced by the doped cationic elements such as Al. ZnO film doped with Al has higher mobility, lower resistivity, and better stability than the pure ZnO films. Aluminum-doped zinc oxide (ZnO:Al) thin film is examined to obtain the suitable optoelectronic properties in aggressive environment (including mechanical damage) to develop optimum structural characteristics in electrical devices for innovative technical applications (such as panel display electrodes, surface devices, gas sensors, and light-emitting diodes) [2–11]. Al-doped ZnO film layers are a good candidate to replace indium thin oxide (ITO) which has major marketing as a transparent electrode in optoelectronics. There are various techniques such as chemical vapor deposition, spray pyrolysis, sputtering technique, atomic layer deposition, and sol–gel method [12–22] have been used to fabricate pure and doped ZnO thin films. Al-doped ZnO films (prepared by sol–gel method and applied at large fields) are preferred due to the safety, controllability, simplicity, and low cost. The effect of Al doping concentration changed the resistivity and conductivity of the ZnO thin films, and the higher concentration of Al doping decreased the mobility of the electron and increased the resistivity of the film. Therefore, the required Al concentration for films has the essential role for obtained quality Al:ZnO films [23–25]. The metal powders can be accelerated by using the cold spray (as a solid-state coating deposition technique) operating at low temperatures to utilize an economic and practice thermal spray process [26]. The accelerated Cu powder particles undergo plastic deformation and adhere to the surface during powders impact with the substrate. The accelerated powders cause to a strong adhesion with a high-quality coating without oxidation at the point of impact [26–37]. The optimum effect of the metallic microparticles at high speed (such as Cu microparticles) is important to determine the mechanical resistance of surface for its use in aerospace technology. Because metallic microparticle-rich asteroid particles (for example, copper-rich asteroid microparticles) with high speed are metallic micrometeoroids which have very small pieces of metal (such as copper) broken off from larger chunks of rock and debris of asteroids (which are extremely common) in space [38–40]. The metallic particles (such as copper) with small sizes (named micrometeorites) have high velocity and the velocity of the micrometeorites is high (for example, speeds between 1 and 70 km/s). The micrometeorites demonstrate that the bulk of the material is left over from comet tails consisting of small particles from the interplanetary dust cloud or other small objects including the small material, like comets. The structural damage generates changes in the performance of the optoelectronic devices when the tiny metallic particles hit the surface of the devices in the space environment in ISS orbit. While the tiny metallic particles encounter the upper surface, the particles decelerate and then accumulate on the surface of the devices. Hence, the microparticle bombardment results in destruction at the device's surface. The damage formed by the high kinetic energy of the particles is significant with the generation of deformational effects. The Cu atom has a slightly lower velocity (and the Cu atom has slightly denser) than the Fe atom. Hence, the damage effect with Cu atoms is more dominant than the damage generated with Fe atoms. The coatings with high density (such as the Cu layer) can be derived with no porosity (close to its theoretical density). The preparation of the Cu layer (by masking the application surface provided with the accelerated Cu particles) can be achieved in a practical way (for example, by using the cold spray technique) with a quick process at low temperatures. The details about fabrication parameters of Cu ohmic contact layer (derived by cold gas dynamic spraying technique) are not available to obtain the improvement in electrical properties of ZnO:Al/p-Si heterojunction in the literature. The technical details about the influence of Cu ohmic contact layer on ZnO:Al thin film are not explained in the previous studies. Besides, the importance of the post-annealing treatment is not declared comparing with the structural effects at the critical cold gas dynamic spraying parameters to obtain the proper Cu ohmic contact layer on the Al-doped ZnO film derived by sol–gel technique. Cu micrometallic particles with high velocity [3 Mac = 3675.13 km/h (340 m/second)] were applied to examine the maximum effect (leading to plastic deformation) on ZnO:Al thin film.

Hence, it was possible to make the clear about the problems of ZnO:Al/p-Si heterojunctions for the development of the cost-effective optoelectronic devices in this study.

This study has provided the specific information about the acceleration effect of the dense metallic microparticles (such as copper-rich dense microparticles) at the surface of ZnO:Al/p-Si heterojunction. Cu ohmic contact layer (derived by cold gas dynamic spraying) on Al:ZnO film (heat-treated at different temperatures) has been formed by hitting the surface of the semiconductor thin film. Hence, the characteristic results on ZnO:Al/p-Si heterojunction had convincing evidence to compare the improvement of its electrical performance. The addition of new results to former works in literature has explained the scientific gap of knowledge about the coating process of sol–ge- derived thin film and its post-coating process in this study. The optimum effect of the metallic microparticles at supersonic speed (with Cu powder at $\sim$ 1 μm-average grain size with $\sim$ 3 Mach) was evaluated to determine the mechanical resistance of ZnO:Al thin film for its use in aerospace technology. The accelerated Cu microparticle cloud provided the development of due to their high specific electronic performance of ZnO:Al thin-film layer for its use in aerospace industries. This study indicated the changes in the characteristic properties of ZnO:Al film when the Cu ohmic contact was fabricated with Cu-grid through a mask on the front side by using cold spray. This work added to the existing knowledge of the derived ohmic contact layer importance on the heterojunction. The details on cold spray deposition parameters related to the explanations of the sol–gel-derived thin-film deposition parameters were not available at the literature to gain development in I-V characteristics of economical heterojunction at Cu/ZnO:Al/p-Si/Al configuration. The critical cold gas dynamic spraying parameters were considered to attract potential interest to the Cu ohmic contact layer on sol–gel-derived ZnO:Al thin film and to achieve an economical heterojunction at Cu/ZnO:Al/p-Si/Al configuration. The results on the use of the cold spray method have preliminary novelty about the detailed investigations on the rapid coating process. The cold spray method supported to solve high resistivity problems with the limitation of high corrosion and limitation of wear effect on the Cu ohmic contact surface. The quality of the films was suitable to provide the economic improvement of the electrical conductivity at ZnO:Al/p-Si heterojunction. The present work on the cold spray deposition technique was found to provide significant advances (to manufacture Cu ohmic contact) at the ZnO:Al thin-film surface. The cold spray technique (considering the practical and economical cold spray coating parameters of the Cu metallic ohmic contact layer) had several advantages with respect to the other thermal spray coating techniques. This research has presented insightful investigation to determine the optimum mechanical performance of the ZnO:Al. The important economic and the novel breakthroughs on the superior coating process were determined to avoid cracks on the ZnO:Al thin-film surface by the knock-on of the accelerated micrometal particles (such as Cu).

2 Experimental procedure

The ZnO and ZnO doped with Al thin-film samples were derived by a colloidal sol–gel solution technique and coated on a side of substrate with dip-coating method. A 0.5 M zinc acetate dehydrate solution was stabilized by diethanolamine (DEA) for 30 min as a dip solution. In order to prepare the aluminum-doped solution, zinc acetate dehydrate and DEA dip solution were prepared under similar condition with the above process and then various amount (0.8–1.0–1.2–1.6 at.%) of aluminum was added individually to stirring for an hour at room temperature as the dip solution. Si glass as a substrate was immersed into the solution and then it has been heated at 150 °C for 10 min in air. The films were annealed at 550–800 °C in vacuum for an hour.

X-Ray diffraction (XRD) analysis was performed by GBC-MMA diffractometer (Cu Kα radiation $\lambda = 0.154$ nm, 40–50 kV, 30–40 mA). The morphology of the film surface was determined by scanning electron microscope (SEM, JEOL 6335F) with 20 kV accelerating voltage. The film's thickness was characterized with a surface profilometer (Veeco Dektak). The surface resistivity of the un-doped and doped ZnO films was measured by four-point resistivity probe with mounting stand (SIGNATONE).

RUSONIC Cold Spray was utilized to obtain Cu ohmic contacts to produce a heterojunction at Cu/ZnO:Al/Si/Al configuration. High-temperature compressed gases (such as air, nitrogen, and helium) can be used as the propulsive gas at cold spray deposition technique according to literature [26, 27]. To prepare the heterojunctions with optimum current voltage characteristic, air was used to determine the economical cold spray deposition parameters and air was utilized as the compressed gases to accelerate Cu powder (for in front of contact and back contact) with a supersonic velocity at max. ~ 3 Mach) obtained from Cu plate with purity ~ 99.5% in this research. The optimum path of the microparticles in the microparticle cloud (such as the Cu powder at ~ 1 µm-average grain size and supersonic velocity accelerated at ~ 3 Mach) was determined to evaluate the accelerated microparticle effect on the electronic performance of ZnO:Al thin-film layer. The application of air as the propulsive gas accelerated Cu powders was performed practically and an economical way. The air pressure has been applied at ~ 6 bar during the cold spray technique to obtain the suitable ohmic contacts at ZnO:Al/p-Si heterojunction. During this method, air (as the compressed gas) was utilized as the propulsive gas and it accelerated Cu powder feedstock (like metal matrix composites and metals) toward higher velocity than 300 m/s. The Cu powder was deposited on the surface of Al-doped ZnO film at the heterojunction by gases induced. Current–voltage (I-V) characteristics in the range − 20 and + 20 under illuminate (Xenon lamp 100 mW/cm^2) and dark conditions were performed via Keithley 4200 Semiconductor Characterization System.

3 Result and discussion

Figure 1a presents XRD patterns about ZnO thin film on p-type silicon wafer substrates via different Al concentrations. Zinc oxide films crystalline exhibited the c-axis oriented. Thus, all these Al concentrations have different responses to the films obtained at 700 °C. The films peak intensity decreased with increased doping concentration. The result of this observation could be doping intensity concentration deteriorated the films crystallinity. The differences are pressed on the grain growth via compression stress depending on the diversity between Zn ionic radius (rZn^{+2} = 0,074 nm) and dopant Al (rAl^{+3} = 0,054 nm) [28–30]. The optimum outcome was obtained at 1.2 at. % Al concentration. The doping concentration (over 1.2 at. % Al amount) caused to decrease slightly the film particle sizes. The rise of Al doping range from 0.8 to 1.6 at.% engendered to increase particle crystallite sizes (from 19 to 41 nm) according to Debye–Scherrer method. Although the Al:ZnO films exhibited crystallinity properties over 550 °C post-heat treatment, all the film's diffraction peaks depict similar results which is wurtzite crystal orientation in the range of 550–800 °C (Fig. 1b) [29, 30]. Due to the post-annealing temperature at 700 °C and 800 °C, the films exhibited hexagonal wurtzite structure. The annealing process at 800 °C resulted with the original characteristic formation such as the trapezium crystals indicating the occurrence of another zinc compound such as zinc silicate (Zn_2SiO_4).

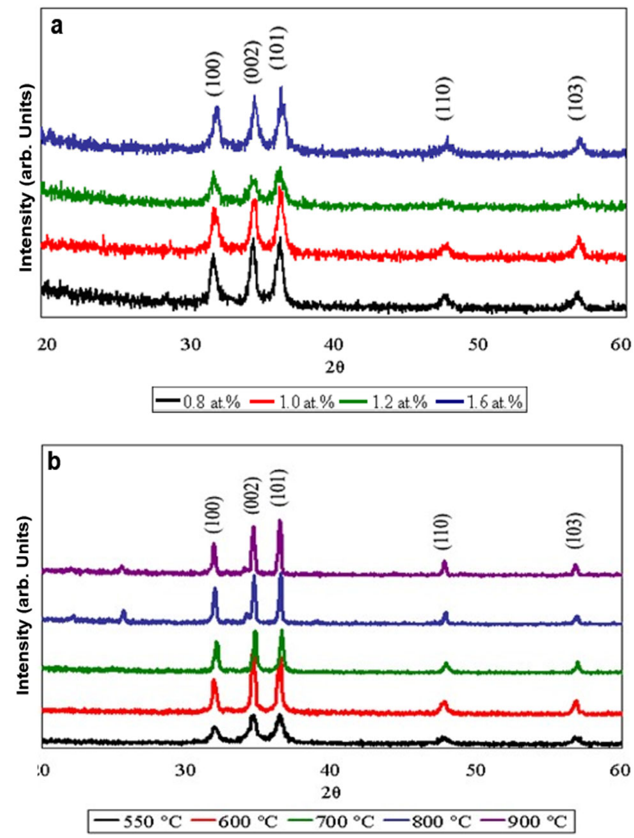


Fig. 1 X-Ray diffraction patterns of ZnO:Al thin films at (**a**) various Al concentration annealed at 700 °C, (**b**) 1.2 at. % Al concentration by different annealing temperature

SEM images demonstrated that cold spray had great capability to produce Cu coating layer with ~ 1 µm-average grain size. Figure 2 shows that Al-doped ZnO thin-film surface morphology was characterized via SEM images explaining the films structure changes after annealing. The surface of the films consists of uniform grains and particle's size

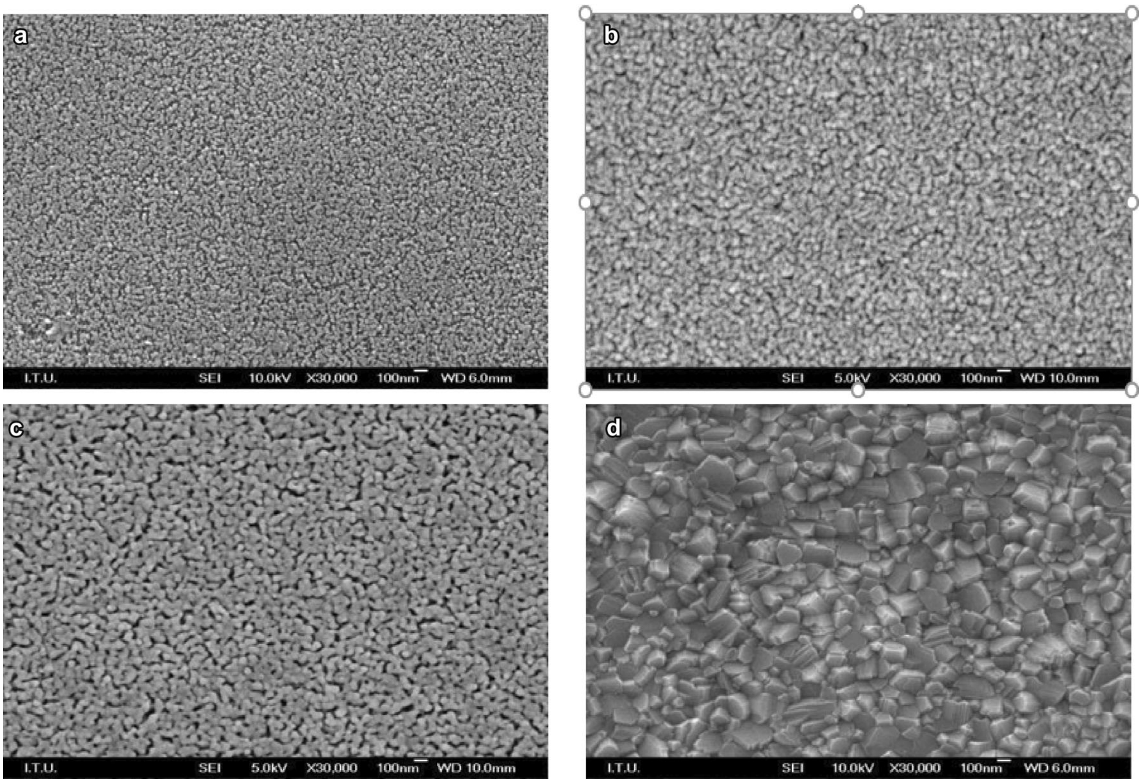


Fig. 2 SEM images of 1.2 at. % Al-doped ZnO:Al thin films annealed at (**a**) 550 °C, (**b**) 600 °C, (**c**) 700 °C, (**d**) 800 °C

increased between 20 and 40 nm by rising temperature. Figure 2b–c displays well-regulated grain boundary because of their form via hexagonal structure. The total film thickness decreased from 400 to 160 nm as the result of the increase of the annealing temperature (from 700 to 800 °C). The finer grains were obtained after the samples were annealed at 700 °C. The derived electrical contact with low electrical resistance has supported the improvement of the electrical properties developed with the practical and cost-effective coating techniques used in this study. Besides, the method was very easy to reproduce the generated mechanical effect by using the cold spray technique. Hence, the mechanical effect (which was able to quantify the data) of the Cu micrometallic particles on the film surface was not a subjective result. The control in microparticle speed at the coating has affected the results of surface damage by using the cold spray method.

3.1 ZnO:Al/p-Si heterojunction features

3.1.1 *Manufacturing of Cu ohmic contact considering Al Concentration at ZnO:Al film*

Si wafer ohmic back contact was deposited via a cold spray of Al. Besides, the front ohmic contact was coated by Cu-grid by a mask. The application of air pressure with ~ 6 bar throughout the cold spray method, and the ranges of Al and Cu electrodes with $0.7 cm^2$ performed to obtain the suitable ohmic contacts at ZnO:Al/p-Si heterojunction. The best candidate was determined with the concentration (1.2 at. %) at 700 °C. Figure 3 illustrates the I–V characteristics of ZnO:Al/p-Si heterojunction samples in different Al amount. The exponential increase of voltage which both of the graphs show a good rectifying behavior. As seen in graphs, it is not observed significant change under forwarding bias for current after illumination. The current was changed via illumination condition under reverse bias conditions. The reverse bias under dark currents just exhibits 5×10^{-6} A (for 0.8 at.% Al concentration) and 1×10^{-5} A (for 1.2 at.% et al. concentration); on the other hand, under illumination, the reverse bias rises

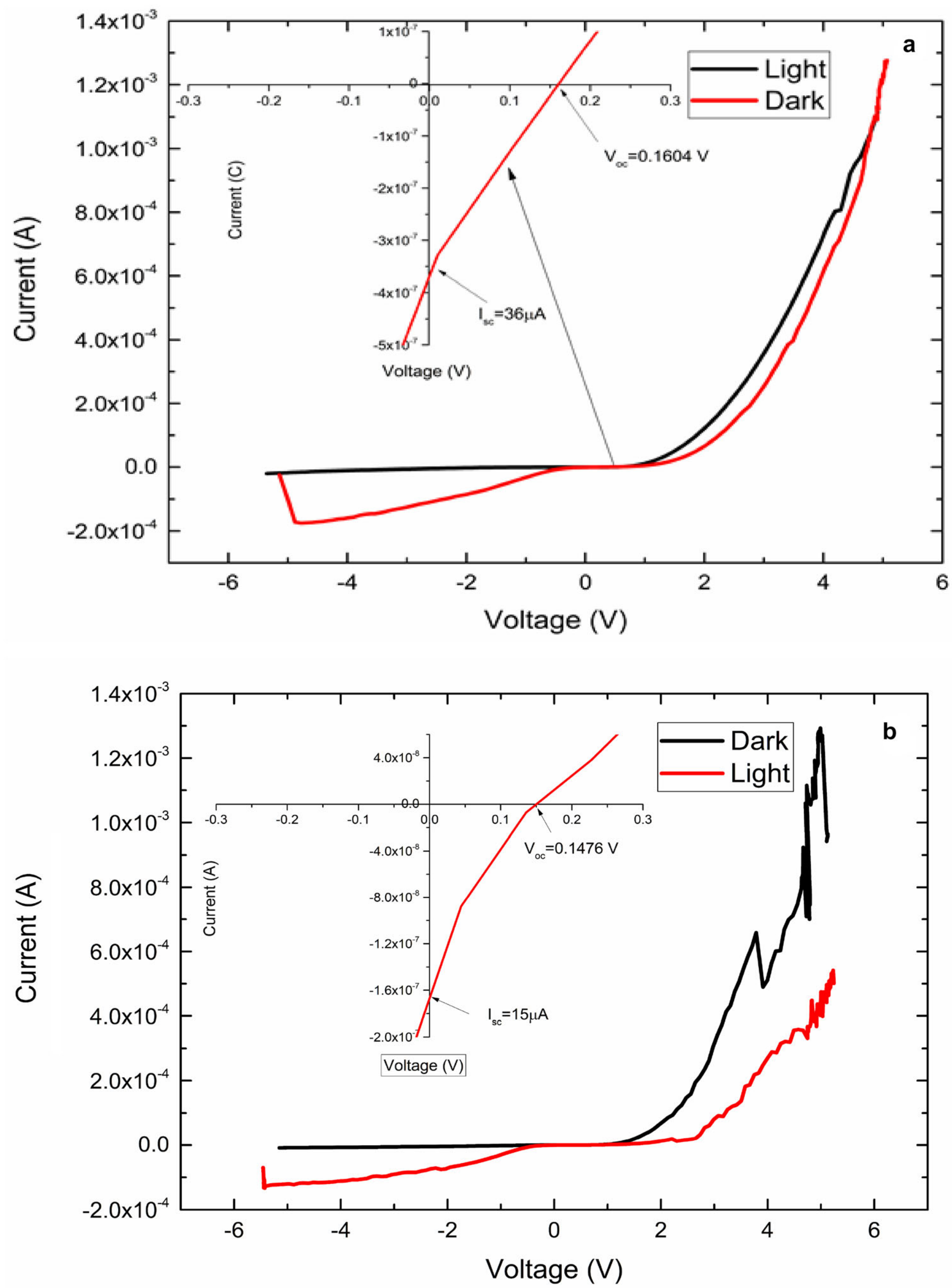


Fig. 3 I-V characteristic of ZnO:Al/p-Si heterojunction at 700 °C in dark and in light for (**a**) 0.8% at. and (**b**) 1.2% at. Al concentrations

up to 1.255×10^{-4}A (for 0.8 at.% et al. amount) and 9.24×10^{-5}A (for 1.2 at.% et al. amount) under Xenon lamp (100 mW/cm^2). The illumination enhanced the current drift through the heterojunction film in forward bias and the light-induced electron generation at the depletion region (especially near the heterojunction surface) of the p-Si layer. Figure 4 explains the current–voltage density features of the heterojunction characterized in dark and illuminate condition in room temperature. The annealing process (in 700 °C at different Al concentration levels) resulted with higher forward bias and exhibited a diode-like rectifying behavior of the heterojunctions. The junction fabricated at 1.2 at.% (Al concentration) has indicated higher current conduction in the dark and light conditions compared to other Al concentration. The current flows rise up in UV illumination for both of Al concentration. Because of the Al-doped ZnO crystallinity (in XRD analysis), the high photocurrent was measured in reverse bias. Therefore, I–V characteristics of the heterojunction demonstrated rectifying properties under dark condition. On the

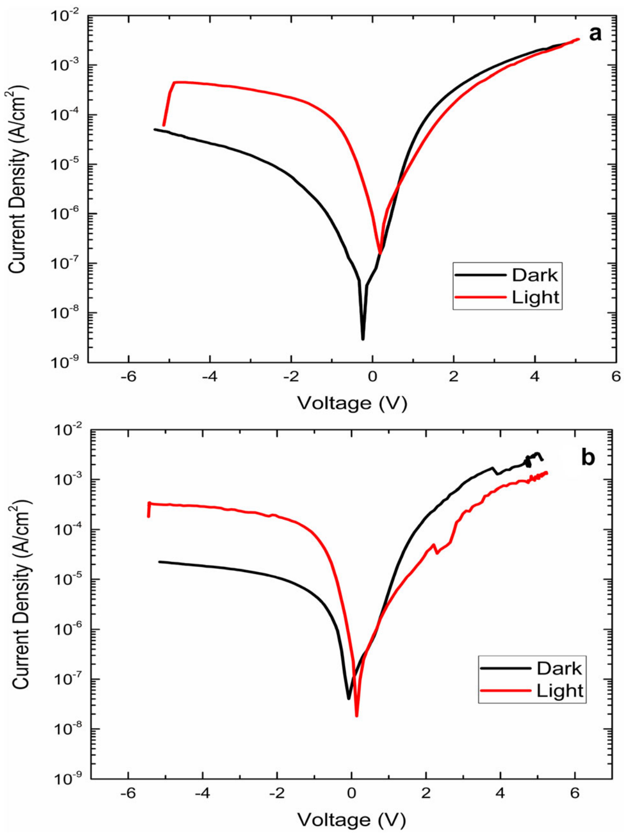


Fig. 4 Current density–voltage characteristics of ZnO:Al/p-Si heterojunctions for different Al concentrations annealed at 700 °C for (**a**) 0.8% at. % (**b**) 1.2% at

other hand, the curves under forward bias illustrate lower behavior throughout to reverse bias in dark condition up to 20 V. The curves in reverse bias have higher values (with a rectifying property) until 5 V than forward bias under light and reverse bias conditions. The heterojunction has indicated that it has an original potential utilization as a smart diode (at 1.2 at. % Al amount) in diode applications. The improvement in electrical properties of the heterojunction was supported by using Cu ohmic contacts derived by cold spray deposition technique.

3.1.2 *Annealing temperature effect of ZnO:Al thin film on Cu ohmic contact layer derived by cold spray technique*

The high kinetic energy causes plastic deformation and residue of energy converts to heat. Therefore, heat produces in microscale enables closing the cracks and pores on the film cause of the high density (< 0.5 vol. % porosity) [26, 27]. There is not the detailed information about the effect of the cold spray technique on the annealed heterojunction with Cu/ZnO:Al/p-Si/Al configuration considering the heterojunction surface morphology in the literature [26, 27, 30, 36]. The application of cold spray technique enables to avoid deficiencies in high-temperature deposition processes. The formation of the ohmic contact derived by cold spray was performed by the particle kinetic energy prior to impact. The Cu powder with high velocity had a kinetic energy at cold spray technique. The deposition process has been performed by local metallurgical bonding and mechanical interlocking. There was a deformation within particle and inter-particle substrate interfaces during deposition. The classical high-temperature deposition processes (phase transformation, oxidation, and residual thermal stress) cause to produce the defects at ohmic contact production process. It was possible to avoid from the creation of the defects by using cold spray technique according to the authentic cross-sectional images of the heterojunction at Cu/ZnO:Al/p-Si/Al configuration (in Fig. 5). Cold-sprayed Cu coating process has affected the ZnO:Al thin-film surface due to the significant changes in physical and mechanical properties of ZnO:Al film as a result of the rise of the annealing temperature of ZnO:Al film. The application of the cold spray deposition has not been required the high-temperature utilization at deposition process. The particle kinetic energy had efficient impact as an influential technique and the feedstock has remained solid state at cold spray technique throughout the deposition process for the production of Cu ohmic contact. The ZnO: Al film nanospheres which were treated at 700 °C attached on the p-Si wafer surface via high-pressure cold spray technique in air after the ohmic contact was fabricated by Cu-grid with a mask at front side by cold spray for economical nanotechnological use as an economical way. Cross-section SEM examinations (in Fig. 5a) indicate that ZnO:Al film on the p-Si wafer deposited on the surface for the junction annealed at 700 °C as a result of the growth nanospheres of the ZnO:Al. However, there was a slight damage on the surface as the high-pressure air process accelerated the Cu particles (with a supersonic velocity at max. ~ 3 Mach) through the trapezium crystals of the ZnO:Al surface after treated at 800 °C (Fig. 5b). The original formation of the trapezium crystals caused defects on the p-Si wafer surface when the Cu particles were accelerated for

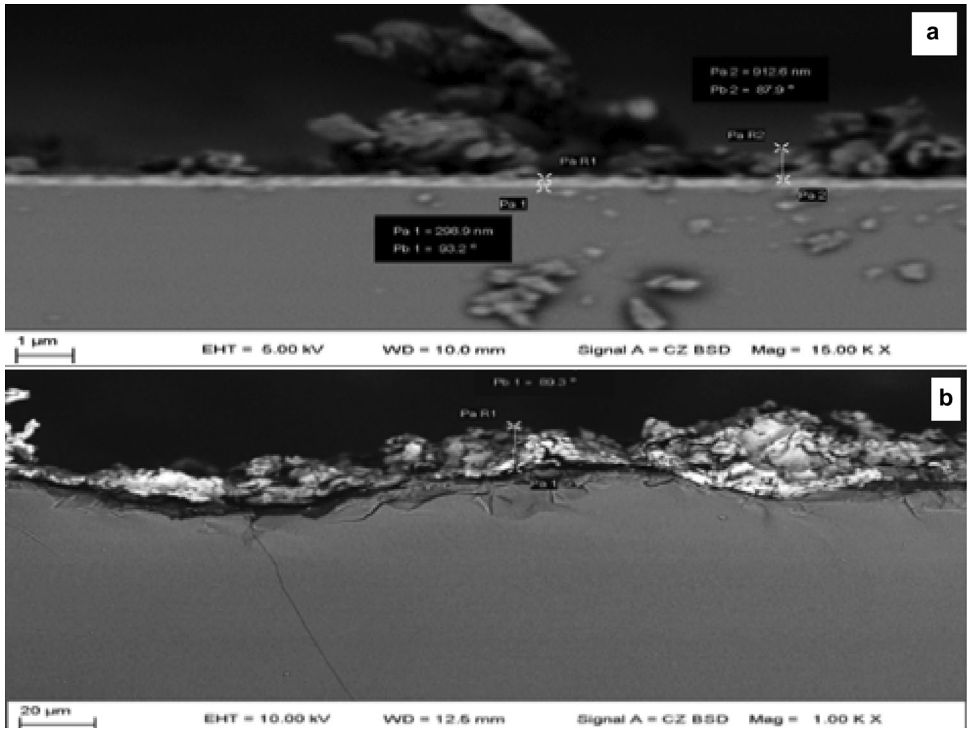


Fig. 5 Cross-section SEM image of the heterojunction at Cu/ZnO:Al/p-Si/Al configuration after annealing at (**a**) 700 °C and (**b**)800 °C

the production step of the Cu ohmic contact by using cold spray coating technique. The denser nanospherical ZnO:Al crystallites films were obtained. This novel diode presented the rectifying behavior without the cracks at the ZnO:Al thin-film surface as the result of the application of the suitable Cu stack layer parameters for the Cu ohmic contact and the result of the optimum rectification ratio (I_F/I_R) at a ± 20 V bias voltage of the heterojunction treated at 700 °C (I_F/I_R = 71.2). Figure 6 illustrates the I-V characteristics of the Al-doped

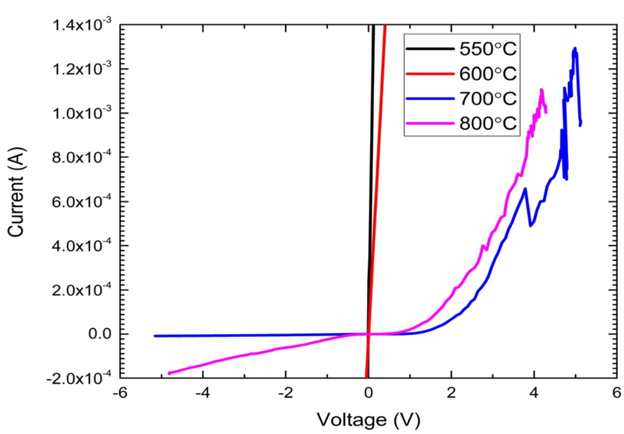


Fig. 6 Measured current density–voltage characteristics of ZnO:Al/p-Si heterojunctions for 1.2% at. Al concentration under dark condition, annealed at different temperatures

ZnO/p-Si heterojunctions measured at room temperature in dark condition. The film samples (with the ohmic contact derived by cold spray technique) exhibited the genuine diode behavior over 600 °C and the best conductivity has been noted in 700 and 800 °C. The junctions annealed at 550 and 600 °C unable to indicate diode-like behavior. The electrons are tunneling from ZnO:Al directly into the empty gap states in Si as the holes make tunneling across the heterojunction barrier from p-Si into n-ZnO:Al [29–32, 36, 37]. Figure 7 presents the semi-log plot of I-V curve which was temperature dependence under

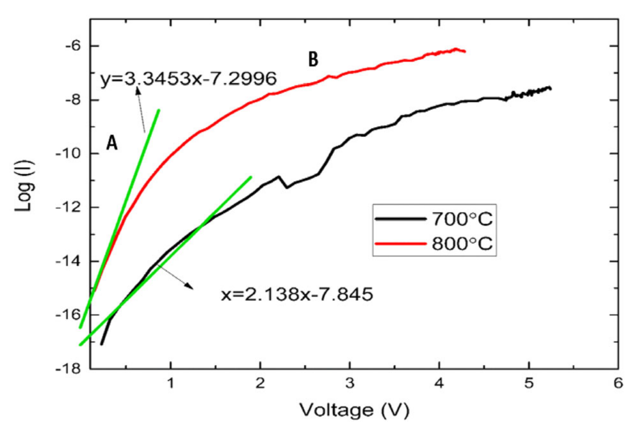


Fig. 7 I-V characteristics of ZnO:Al/p-Si heterojunctions under dark with 1.2% at.Al annealed at 700 °C and 800 °C

dark condition. The forward current was classified into two regions according to the applied voltages. In region B, the forward current deviated from linearity due to the effect of a resistance on the system (above ~ 3.8 V). In region A, the temperature dependence of the forward currents was expressed (below ~ 3.8 V) by $I = I_0\exp(BV)$. In this equation, I is the current subject to the applied voltage V, I_0 is the saturation current, and B is the coefficient. The temperature dependence of the parameter B depends on the dominant current transport mechanism. An almost linear current is obtained at the low voltage in A region for V < 1,2 V. In the region B for higher voltage over 1,2 V, the forward current diverges from linearity because of the resistance effects on the system. The simple series resistance model (as a standard resistance model) $I = I_s \exp[(qV\text{-}IRs)/nKT]$ was utilized in order to linearize the features in diode applications. The B parameter presented stable independence of temperature and indicated an independent feature from temperature according to the I versus V plot (n-ZnO:Al/p-Si heterojunctions). It was assumed that the multi-step tunneling mechanism with a capture-emission process has displayed current and voltage dependency at the semiconductor junction. This improvement has provided the optimum conductivity by Cu ohmic contact on ZnO:Al thin-film layer by the cold spray deposition technique for the use of this semiconductor thin film of the existing knowledge in the diode applications. The values of I_0 (determined in Fig. 7) are presented in Table 1 and the ideality factor (n) of the ZnO:Al/p-Si heterojunction was determined from the slope of the straight line region of the forward bias log I–V characteristics (in Fig. 7) according to the previous studies. The current through the diode (as a function of voltage) was expressed by the ideal diode law (Shockley's equation) in $I = I_o(\exp(qV/nk_BT)\text{-}1)$ equation (as the diode equation). In this equation, I is the net current flowing through the diode; I_0 is the dark saturation current (the diode leakage current density in the absence of light); V is the applied voltage though the diode; q is the absolute value of electron charge (1.6×10^{-19} C); n is the ideality factor; k_B is the Boltzmann's constant (1.38×10^{-23} J/K); and T is the absolute temperature in Kelvin. The ideality factor had a decrease by using cold spray deposition technique to obtain Cu ohmic contact layers in this research. Hence, it was an improvement at the ideality factor of the heterojunction indicating a tendency to obtain an optimum conductivity in heterojunction as the ideality factor (n) decreases by decreasing the value of I_0. I–V features in n-ZnO/p-Si heterojunction (Fig. 8) were measured under light condition. Although the current carrier concentration of the junction increased after annealing at 700 °C under UV light sources, the carrier concentration has not changed considerably in reverse bias at 800 °C. The photoelectric behavior was determined at 1.2 at. % Al concentration in 700 °C under light condition. The current carrier concentration values of ZnO:Al/p-Si heterojunction in dark and UV illumination are illustrated at a 10 V reverse bias (in Table 2). The carrier concentration of current increased gradually in each temperature values under UV illumination. Fill factor (FF) was determined to make an assessment for the quality of power conversion efficiency. FF was controlled by several factors in $FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}} \times 100$ equation. In this equation, V_{mp} is the maximum voltage value, I_{mp} is the maximum power of current, I_{sc} is the short circuit current, and V_{oc} is the open circuit voltage. The value of power conversion efficiency was determined by these parameters. The highest FF was determined at 800 °C (in Table 3) to make the assessment of the diot applications.

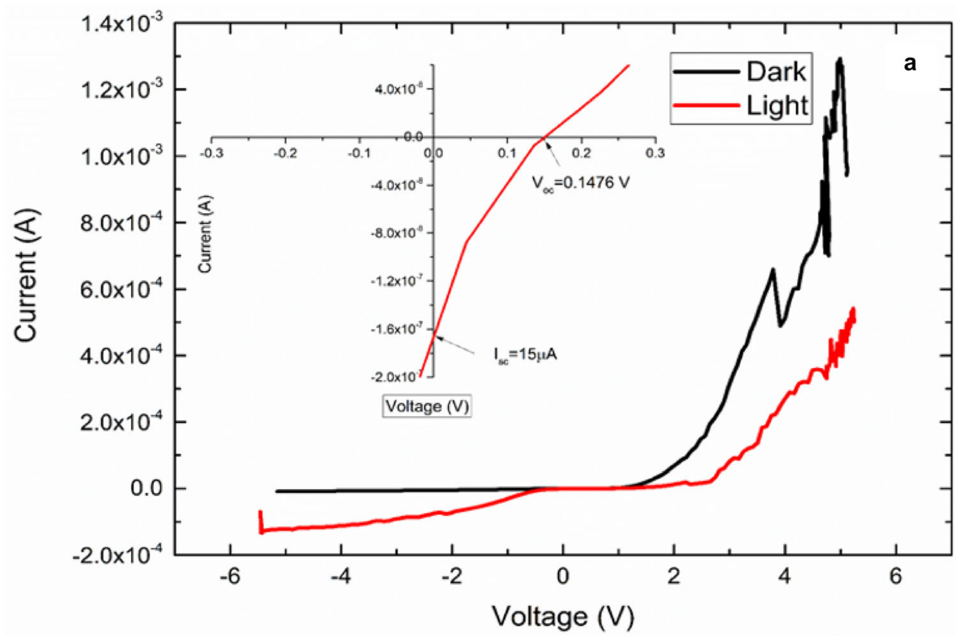
Table 1 I_0, n and I_F/I_R values for ZnO:Al/p-Si heterojunctions annealed at 700 °C and 800 °C

Al temperature (°C)	I_0 (A)	n	I_F/I_R
700	1.428×10^{-8}	2.138	71.2
800	2.488×10^{-4}	3.345	4.63

Current density–voltage characteristics have contributed the valuable data to determine the rectifying behavior of a diode for the use in to semiconductor applications. The current concentration increased with UV illumination, and the curves presented the photocurrent results under reverse bias in Fig. 9. Their results have indicated its novel multidisciplinary approaches about Al-doped ZnO structure quality in XRD results. Current density–voltage properties of the heterojunction explained the rectifying behavior at 700 °C under dark and illumination for its use in semiconductor devices and applications.

Electrically controlled Cu switch layer derived by cold spray method resulted with the rapid coating process avoiding the oxidation at Cu ohmic contact

Fig. 8 I-V characteristics of ZnO:Al/p-Si heterojunctions (at 1.2% at. Al) annealed at (**a**) 700 °C and (**b**)800 °C



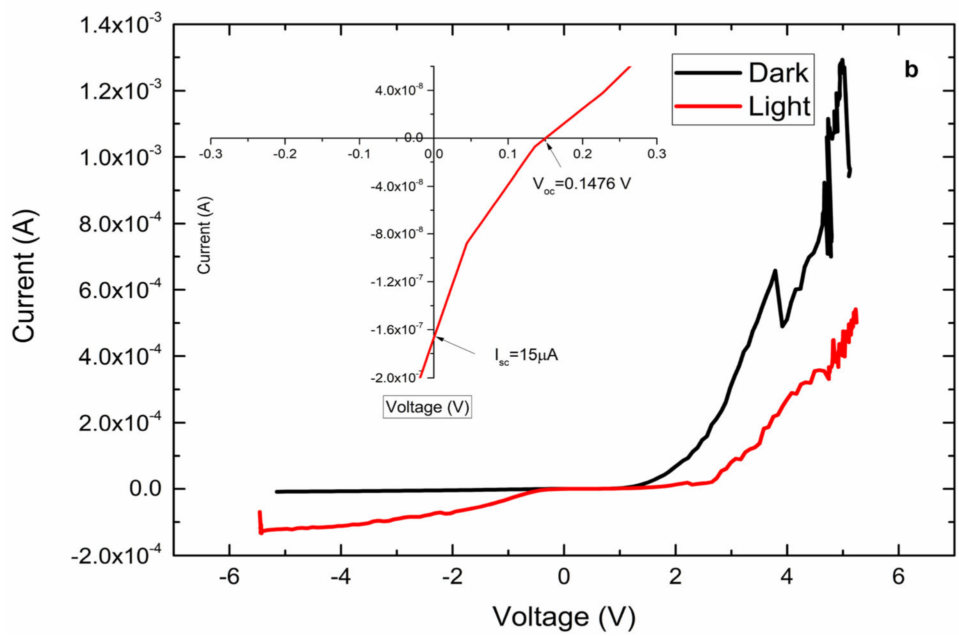


Table 2 Current at − 3 V under dark and light for heterojunctions annealed at 700 °C and 800 °C

Annealing temperature (°C)	I_{dark}	I_{light}
700	-1×10^{-5}	-9.24×10^{-5}
800	-9.9×10^{-5}	-2.004×10^{-3}

layer. The utilization of high-purity Cu particles (with ∼ 1 µm-average grain size) at the cold spray method has supported to improve the I–V characteristics of ZnO:Al/p-Si heterojunction. Hence, the development of this heterojunction was possible for the use in industrial electronics product with cost-effective nanotechnological applications focusing on fabrication of optoelectronics. The development of Cu ohmic contact layer was performed by the cold spray method on ZnO:Al nanospheres and the development of Cu ohmic contact layer indicated the importance of the annealing temperature of the ZnO:Al thin film at 700 °C for the enhancement of the structural characteristics of ZnO:Al thin film and the

Table 3 V_{OC}, I_{SC}, V_{MP}, I_{MP}, and FF of heterojunction under light

Annealing temperature (°C)	V_{OC} (V)	I_{SC} (μA)	V_{MP} (V)	I_{MP} (μA)	FF
700	0.1476	− 15	0.0538	− 760	%18.40
800	0.0646	− 30.75	0.0235	− 18.5	%21.88

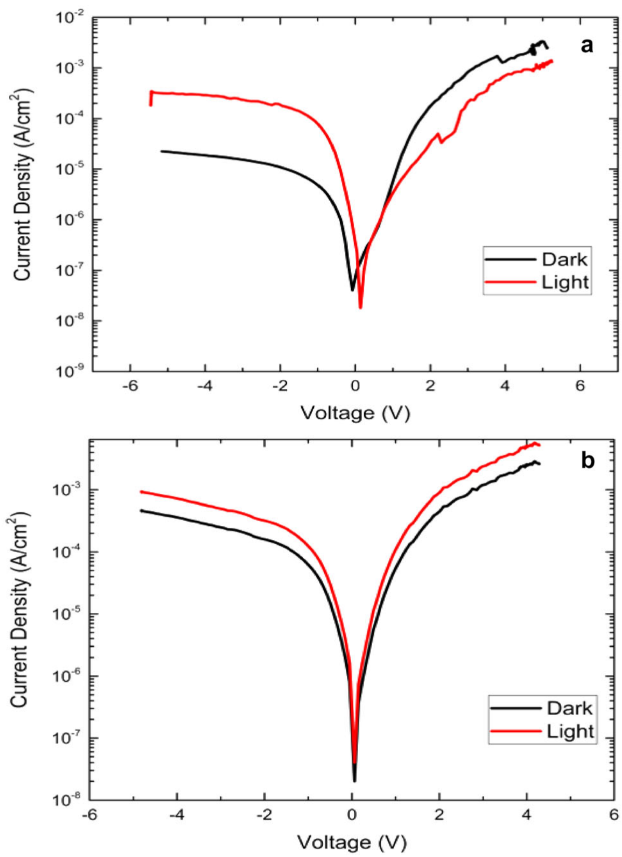


Fig. 9 Current density–voltage characteristics of ZnO:Al/p-Si heterojunctions (at 1.2% at. Al) annealed at (**a**) 700 °C and (**b**) 800 °C

electrical properties of the ZnO:Al/p-Si heterojunction. It was assumed that there was the limitation of corrosion by the cold spraying technique for the use in different analytical solutions and this event has supported to avoid high resistivity and to obtain oxidation resistance with the enhanced functional performance of the heterojunction. The results of this study indicated that the Cu ohmic contact layer (derived by cold gas dynamic spraying on ZnO:Al thin film for Cu/ZnO:Al/p-Si/Al configuration) was suitable for the use in electronic systems including semiconductor equipments at large areas. The Cu ohmic contact layer was applicable at the effective operation of the ZnO: Al/p-Si heterojunction (as the functional system) in harsh mechanical environment with the high-speed microparticles (such as Cu powder with ∼ 1 μm-average grain size) at the supersonic velocity (maximum ∼ 3 Mach). The functional behavior of the ZnO:Al thin film has described the high-performance requirements of the Cu ohmic contact layer (derived by cold gas dynamic spraying) for use in the earth and space systems. The Cu ohmic contact layer (derived by cold gas dynamic spraying) has emphasized the relation to the specific effect level of Al (in at.%) on the effective surface of the ZnO:Al thin film. The electrically controlled switch was developed as the innovative contact layer for practical and economic development of electrical circuit devices.

The results of this study have indicated the futuristic researches that the practical collection conditions of the cost-effective metallic microparticles can be developed for the microsize metal-rich asteroid particles (such as Au microparticles) with worth quadrillions in space.

4 Conclusion

The development of the cold gas dynamic spraying parameters (with the accelerated metallic microparticles through the nanospherical ZnO:Al thin film) has been provided to avoid the oxidation of the ohmic contact layer with high purity.

(1) The determination of the critical cold spray deposition parameters has provided the improvement of the electrical properties of the ZnO:Al thin film.
(2) The ZnO:Al thin film was fabricated by low-cost sol–gel dip-coating technique and annealed at two different annealing temperatures such as 700 and 800 °C in vacuum. Substantial improvements at the ZnO:Al thin-film surface resulted in adding new information about the cold spray deposition parameters.
(3) The bombarded ZnO:Al thin film with Cu micrometallic particles at the ultrahigh-speed supported the modification of the functional modification of ZnO:Al/p-Si heterojunction. The

acceleration of Cu powder (with the supersonic velocity at max. ~ 3 Mach) has emphasized the relation to in-depth surface-specific density. Because the well-regulated grain boundary resulted with the dense packet form (via hexagonal ZnO:Al thin film annealed at 700 °C).

(4) The determination of the optimum cold spray deposition parameters of the Cu ohmic contact layer had supported the improvement of the rectifying diode behavior (with the enhancement of the electrical conductivity due to the modification of the performance of I–V characteristics). The improvement of mechanical resistance of ZnO:Al thin film has been targeted against the accelerated high-density particles (as Cu powder with high purity) to use in the optoelectronics at aerospace industry. The comprehensive examination of cold-sprayed Cu coating derived on ZnO:Al has provided to determine the utilization conditions of Cu microparticles (not be larger than ~ 1 μm-average grain size with the purity at least 99,5%).

(5) The developed heterojunction has provided to determine the optimum rectifying behavior. The heterojunction has been derived without the cracks after the grains of surface ZnO:Al was annealed at 700 °C. Hence, the accelerated Cu microparticles have not had the considerable damage at the ZnO:Al thin film (as 1.2 at. % Al) with finer grains. Consequently, the Al doping controlled at the atomic level (as 1.2 at. %) in ZnO:Al thin film has presented new advantages for its use in the advanced semiconductor devices. The development of the rectifying behavior (with the result of the optimum rectification ratio $I_F/I_R = 71.2$ at a ± 20 V bias voltage of the heterojunction treated at 700 °C) has indicated the novel critical fabrication parameters of the Cu ohmic contact layer (derived by cold spray deposition) of this smart diode (without the cracks at the ZnO:Al thin-film surface at 1.2 at.% Al concentration).

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Author contributions

NB contributed to conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing—original draft, writing—review, and editing. YK contributed to investigation, methodology, software, visualization, writing—original draft, writing—review, and editing. OU contributed to investigation, methodology, software, visualization, writing—original draft, writing—review, and editing. HC contributed to investigation, methodology, software, visualization, writing—original draft, writing—review, and editing.

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Data availability

There are no data supporting results.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval There is not disclosure of potential conflict of interest.

Reasearch involving human and animal rights There is no research involving human participants and/or animals.

Informed consent There is no informed consent.

References

1. X. Jiang, F.L. Wong, M.K. Fung, S.T. Lee, Aluminum-doped zinc oxide films as transparent conductive electrode for

organic light emitting devices. Appl. Phys. Lett. **83**, 1875 (2003). https://doi.org/10.1063/1.1605805
2. T. Sekitani, Stretchable active-matrix organic light-emitting diode display using printable elastic conductor. Nat. Mater. **8**, 494–499 (2009). https://doi.org/10.1038/nmat2459
3. G. Zhao, Stable ultrathin partially oxidized copper film electrode for highly efficient flexible solar cells. Nat. Commun. (2015). https://doi.org/10.1038/ncomms9830
4. J.A. Selvan, H. Keppner, A. Shah, The growth of surface textured aluminum doped ZnO Films for a-Si solar cells by RF magnetron sputtering at low temperature. Mater. Res. Soc. (1996). https://doi.org/10.1557/PROC-426-497
5. G.M. Nam, M.S. Kwon, Transparent conducting Ga-doped ZnO thin film for flat-panel displays with a sol-gel spin coating. J. Inf. Disp. (2008). https://doi.org/10.1080/15980316.2008.9652056
6. S. Khadtare, A.S. Bansode, V.L. Mathe, N.K. Shrestha, C. Bathula, S.H. Han, H.M. Pathan, Effect of oxygen plasma treatment on performance of ZnO based dye sensitized solar cells. J. Alloys Compd. (2017). https://doi.org/10.1016/j.jallcom.2017.07.013
7. T.W. Kim, D.C. Choo, Y.S. No, W.K. Choi, E.H. Choi, High work function of Al-doped zinc-oxide thin films as transparent conductive anodes in organic light-emitting devices. Appl. Surf. Sci. (2006). https://doi.org/10.1016/j.apsusc.2006.03.032
8. R. Wang, L.L.H. King, A.W. Sleight, Highly conducting transparent thin films based on zinc oxide. J Mater Res (1996). https://doi.org/10.1557/JMR.1996.0208
9. Z.Y. Zhong, H. Saka, T.H. Kim, E.A. Holm, Y.F. Han, X.S. Xie, Synthesis of surface acoustic wave filter with Al/ZnO thin film deposited on silicon wafer. Mater. Sci. Forum **475**, 3771–3774 (2005)
10. W., Wang, D., Han, J., Cai, Y., Geng, L., Wang, Y., Ren, Y.H., Deng, S., Wang Zhang, (2012). Al-doped ZnO Thin-film Transistors on Flexible Plastic Substrate, 2012 19th International Workshop on Active-Matrix Flatpanel Displays and Devices (AM-FPD), Kyoto, 175–178.
11. M. Hjiri, L. El Mir, S.G. Leonardi, A. Pistone, L. Mavilia, G. Neri, Chemical Al-doped ZnO for highly sensitive CO gas sensors. Sens. Actuator, B. Chem. (2014). https://doi.org/10.1016/j.snb.2014.01.068
12. M. Suchea, S. Christoulakis, N. Katsarakis, T. Kitsopoulos, G. Kiriakidis, Comparative study of zinc oxide and aluminum doped zinc oxide transparent thin films grown by direct current magnetron sputtering. Thin Solid Films **515**, 6562–6566 (2007). https://doi.org/10.1016/j.tsf.2006.11.151
13. T. Schuler, T. Krajewski, I. Grobelsek, M.A. Aegerter, Influence of structure zone model parameters on the electrical properties of ZnO: Al sol–gel coatings. Thin Solid Films **502**, 67–71 (2006). https://doi.org/10.1016/j.tsf.2005.07.246
14. K. Bergum, P.-A. Hansen, H. Fjellvag, O. Nilsen, Structural, electrical and optical characterization of Ti-doped ZnO films grown by atomic layer deposition. J. Alloys Compd. (2014). https://doi.org/10.1016/j.jallcom.2014.07.177
15. L.V. Mercaldo, E. Bobeico, I. Usatii, M.D. Noce, L. Lancellotti, N.L. Serenelli, M. Izzi, M. Tucci, P.D. Veneri, Potentials of mixed-phase doped layers in p-type Si heterojunction solar cells with ZnO: Al. Sol. Energy Mater. Sol. Cells **169**, 113–121 (2016). https://doi.org/10.1016/j.solmat.2017.05.014
16. H. Zhou, J. Mei, P. Gui, P. Tao, Z. Song, H. Wang, G.J. Fang, The investigation of Al-doped ZnO as an electron transporting layer for visible-blind ultraviolet photodetector based on n-ZnO nanorods/p-Si heterojunction. Mater. Sci. Semicond. Process **38**, 67–71 (2015). https://doi.org/10.1016/j.mssp.2015.04.005
17. J. Kim, J.H. Yun, Y.C. Park, W.A. Anderson, Transparent and crystalline Al-doped ZnO film-embedded heterojunction Si solar cell. Mater. Lett. **75**, 99–101 (2012). https://doi.org/10.1016/j.matlet.2012.01.144
18. D. Kang, D. Lee, K.-S. Choi, Electrochemical synthesis of highly oriented, transparent, and pinhole-free ZnO and Al-Doped ZnO films and their use in heterojunction solar cells. Langmuir **32**(41), 10459–10466 (2016). https://doi.org/10.1021/acs.langmuir.6b01902
19. A., Kaya, H., Cansizoglu, H.H., Mamtaz, A.S., Mayet, M.S., Islam, (2016). Comparison of heterojunction device parameters for pure and doped ZnO thin films with IIIA (Al or In) elements grown on silicon at room ambient, Proc. Volume 9924, Low-Dimensional Mater. Devices https://doi.org/10.1117/12.2239341
20. K. Abe, T. Komiyama, Y. Chonan, H. Yamaguchi, T. Aoyama, Sol-gel undoped and Al-doped ZnO films crystallized under an electric field and the ZnO/Si heterojunction characteristics. Phys. Status Solidi C **10**, 1272–1275 (2013). https://doi.org/10.1002/pssc.201200962
21. H. Karaagac, E. Yengel, M. Saif Islam, Physical properties and heterojunction device demonstration of aluminum-doped ZnO thin films synthesized at room ambient via sol-gel method. J. Alloys Compd. **521**, 155–162 (2012). https://doi.org/10.1016/j.jallcom.2012.01.103
22. M. Jing-Jing, J. Ke-Xin, L. Bing-Cheng, F. Fei, X. Hui, Z. Chao-Chao, C. Chang-Le, Rectifying and photovoltage properties of ZnO: a1/p-Si heterojunction. Chin. Phys. Lett. (2010). https://doi.org/10.1088/0256-307X/27/10/107304
23. J. Yoo, J. Lee, S. Kim, K. Yoon, I.J. Park, S.K. Dhungel, B. Karunagaran, D. Mangalaraj, Y. Junsin, High transmittance and low resistive ZnO: Al films for thin film solar cells. Thin

Solid Films **480–481**, 213–217 (2005). https://doi.org/10.1016/j.tsf.2004.11.010

24. Z. Wu, K. Cheng, F. Zhang, R. Guan, X. Wu, L. Zhuge, Effect of Al Co-doping on the electrical and magnetic properties of Cu-doped ZnO nanorods. J. Alloys Compd. **615**, 521–525 (2014). https://doi.org/10.1016/j.jallcom.2014.06.204
25. J. Liu, W. Zhang, D. Song, Q. Ma, L. Zhang, H. Zhang, L. Zhang, R. Wu, Investigation of aluminum gallium Co-doped zinc oxide targets for sputtering thin film and photovoltaic application. J. Alloys Compd. **575**, 174–182 (2013). https://doi.org/10.1016/j.jallcom.2013.04.075
26. O., Tazegul, (2012). Surface Modification of Electrical Contacts by Cold Gas Dynamic Spraying Process, Istanbul Technical University, Institute of Science and Technology, MSc. Thesis (323861 thesis no) https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp
27. S. Yina, P. Cavaliere, B. Aldwell, R. Jenkins, H. Liao, W. Li, R. Lupo, Cold spray additive manufacturing and repair: fundamentals and applications. Addit. Manuf. **21**, 628–650 (2018). https://doi.org/10.1016/j.addma.2018.04.017
28. K. Shou-Yi, C. Wei-Chun, L. Fang-I, C. Chin-Pao, K. Hao-Chung, W. Shing-Chung, H. Wen-Feng, Effects of doping concentration and annealing temperature on properties of highly-oriented Al-doped ZnO films. J. Cryst. Growth **287**, 78–84 (2006). https://doi.org/10.1016/j.jcrysgro.2005.10.047
29. O., Karacasu, (2010). Nanocrystalline ZnO:Al Thin Films Prepared By Sol-Gel Dip Coating Technique and ZnO:Al/P-Si Heterojunctions, Istanbul Technical University, Institute of Science and Technology, MSc. Thesis (310405 thesis no) https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp.
30. Y., Kose, (2015). Capacitance-Voltage and Current-Voltage Characteristic Properties of ZnO:Al/p-Si Heterojunction, Istanbul Technical University, Institute of Science and Technology, MSc. Thesis (421255 thesis no) https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp
31. N. Baydogan, O. Karacasu, H., Cimenoglu, Effect of annealing temperature on ZnO:Al/p-Si heterojunctions. Thin Solid Films **520**(17), 5790–5796 (2012)
32. N. Baydogan, O. Karacasu, H. Cimenoglu, ZnO: Al thin films used in ZnO: Al/p-Si heterojunctions. J Sol-Gel Sci Technol **61**, 620–627 (2012)
33. O. Urper, N. Baydogan, Influence of structural changes on electrical properties of Al:ZnO films. Mater. Lett. (2019). https://doi.org/10.1016/j.matlet.2019.126641
34. O. Urper, O. Karacasu, H. Cimenoglu, N. Baydogan, Annealing ambient effect on electrical properties of ZnO:Al/p-Si heterojunctions. Superlattices Microstruct. **125**, 81–87 (2019)
35. H. Tugral Arslan, O. Urper, T. Ozdurmusoglu, C. Arslan, N., Baydogan, Acta Scientific Ophthalmology 2, 10 (2019)12–15
36. Y. Köse, MSc Thesis, Istanbul Technical University, Material Science Engineering, Thesis No: 421255, (2015) https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp
37. N. Baydogan, M. Baydogan, H. Cimenoglu, Y. Gökçe, Capacitance voltage C V properties of ZnO Al p Si heterojunctions. Defect Diffus. Forum **334**(335), 349–352 (2013)
38. K. Łuszczek, A.M. Krzesinska, Copper in ordinary chondrites: proxies for resource potential of asteroids and constraints for minimum-invasive and economically efficient exploitation. Planet. Space Sci. (2020). https://doi.org/10.1016/j.pss.2020.105092
39. A. Collette, E. Grün, D. Malaspina, Z. Sternovsky, Micrometeoroid impact charge yield for common spacecraft materials. J. Geophys. Res. Space Phys. (2014). https://doi.org/10.1002/2014JA020042
40. K. Fiege, M. Guglielmino, N. Altobelli, M. Trieloff, R. Srama, T.M. Orlando, Space weathering induced via microparticle impacts: 2. dust impact simulation and meteorite target analysis. J. Geophys. Res. Planet. (2018). https://doi.org/10.1029/2018JE005564