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# Indium-gallium-zinc oxide thin-film preparation via single-step radio frequency sputter deposition using mixed-oxide powder targets

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**Abstract:** Indium gallium zinc oxide (In–Ga–Zn–O) thin films, which are transparent conductive films for liquid crystals and electroluminescent displays, were fabricated via single-step sputter deposition using one target containing different proportions of indium oxide, gallium oxide, and zinc oxide powders. Experimental results suggest that the In–Ga–Zn–O thin films can be prepared using the method of single-step radio frequency (RF) sputter deposition, applying a powder target containing indium oxide, gallium oxide, and zinc oxide. The In–Ga–Zn–O thin films were prepared on Si substrates, and the deposition rate depended on the target composition. In these plasma processes, electron density and temperature were essentially independent of target composition. The prepared films were very smooth with a root-mean-square roughness of less than 10 nm. The crystallinity of the ZnO peak was observed in all the films; whereas the In and Ga peaks were not observed in the films prepared. The X-ray photoelectron spectroscopy of the films also revealed that the elemental concentration ratio of In–Ga–Zn–O thin films could be prepared using one target, and that can be easily controlled by ratios in the  $\text{In}_2\text{O}_3/\text{Ga}_2\text{O}_3/\text{ZnO}$  composition in the powder target. The transmittances were  $> 75\%$  at 800 nm for all the target mixtures, and increased with increasing  $\text{In}_2\text{O}_3$  in the powder target.

**Key words:** In–Ga–Zn–O thin-film, plasma processes, powder target, sputtering deposition, transparent conductive film



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## 1. Introduction

Indium gallium zinc oxide (In–Ga–Zn–O:IGZO) thin-film transistors (TFTs) are promising alternatives to Si TFT channels for next-generation active matrix panels used in display applications. IGZO TFTs have excellent features such as high electron mobilities, low threshold voltages, and facile control of carrier concentrations. In addition, IGZO TFTs have production advantages because existing Si:H TFT facilities can be used without modification. However, it is challenging to adjust the commercial sputter deposition conditions for fabrication of high-quality and high-performance IGZO thin films. Usually, separate targets are fabricated first, and then the film is deposited from each of the targets. Hence, high-quality IGZO thin films are costly, and optimum deposition conditions can change after many depositions [1, 2].

Sputtering is widely used to deposit thin films because it requires a simple apparatus, it is an easy process with an expansive choice of materials, and it produces high-uniformity films at high deposition rates [3–15]. In addition, it uses non-toxic gases and low energies to generate the processing plasma. It is thus safer than other plasma processing methods such as chemical-vapor deposition and pulsed-laser deposition. Sputtering has been used to deposit functional thin films composed of multiple materials [16, 17]. Preparing thin films consisting of multiple elements is difficult with conventional sputter deposition because high-density bulk targets ( $> 3 \text{ g/cm}^3$ ,  $> 95\%$  density) are generally used. Therefore, it is necessary to make new targets by other methods, such as spark plasma sintering, and/or conduct sputter deposition using multiple targets [18, 19]. These target preparations are usually time-consuming and costly. As an alternative, plasma processes using multielement powder targets have been used to prepare multielement thin films in single-step processes. Several kinds of powders can be mixed and placed in a target holder in a vacuum chamber. Thin films are then deposited on a substrate mounted on the opposite side of the vacuum chamber with respect to the target holder. It is possible to obtain a few samples with different doping densities during one technological cycle [16]. This approach was also used to fabricate functional thin films containing multiple elements [19–34]. For example, bismuth iron garnet ( $\text{Bi}_3\text{Fe}_5\text{O}_{12}$ ) films used for magneto-optics were fabricated by sputter deposition of mixed bismuth (Bi) and iron (Fe) powder targets. We prepared Sn-doped  $\text{SiO}_2$  thin films using  $\text{SnO}_2$  and  $\text{SiO}_2$  mixed-powder targets [18, 22]. The elemental concentrations in the thin films could be controlled by the composition of the powder mixture. In this experiment, In–Ga–Zn oxide thin films were prepared via one-step sputter deposition using indium oxide, gallium oxide, and zinc oxide mixed-powder targets. The film properties, such as crystallinity, composition ratio, and surface roughness, were characterized.

## 2. Experimental methods

A schematic of the sputter deposition apparatus is shown in Fig. 1. The stainless-steel deposition chamber had a diameter of 400 mm and a height of 450 mm. A powder target was placed in a 50.8-mm-diameter stainless-steel target holder. The spherical shape of  $\text{In}_2\text{O}_3$  (40–300  $\mu\text{m}\phi$ , 2 g),  $\text{Ga}_2\text{O}_3$  (100–500  $\mu\text{m}\phi$ , 2 g), and  $\text{ZnO}$  (20–200  $\mu\text{m}\phi$ , 2 g) powders were mixed mechanically and then placed in the target holder ((1) in Fig. 1). The mixed powder target was placed in a sealed container, and then the container was rotated 60 times per minute for 24 hours to mix the targets

((2) in Fig. 1). The weight ratios of the powders were changed to vary the target composition ((3) in Fig. 1). The chamber was vacuumed to a base pressure of  $5 \cdot 10^{-3}$  Pa using turbomolecular and rotary pumps ((4) in Fig. 1). The total deposition pressure was 30 Pa with argon gas (99.99%) introduced at a 10-sccm flow rate ((5) in Fig. 1). Sputtering deposition was performed by radio frequency (13.56 MHz) plasmas. The plasma was generated by applying 100 W discharge power to the powered electrode ((6) in Fig. 1). Prior to loading in the deposition chamber, substrates were cleaned in an ultrasonic agitator several times, followed by washing with high-purity deionized water. The surface of the substrate was at room temperature and the deposition time was 100 min.

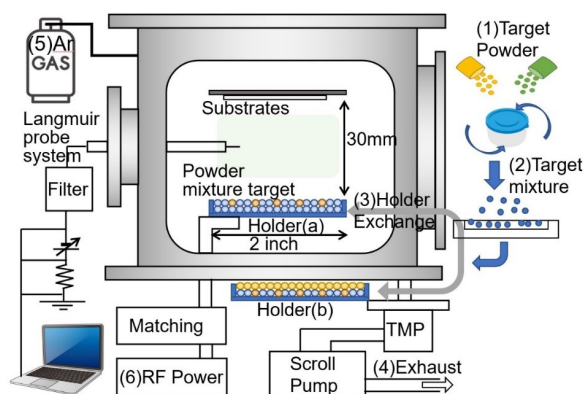


Fig. 1. A schematic of the sputter deposition apparatus

The electron density and temperature of the processing plasma were measured using a Langmuir probe (ARIOS LMP-100). The probe was composed of a tungsten wire with a diameter of 0.3 mm and a length of 0.5 mm. The surface morphology and roughness of the film was measured via atomic force microscopy (AFM; JEOL JSTM-4100). The film thickness was measured using an alpha-step profilometer (Kosaka Lab. Surfcoorder ET4000A). The crystalline structure and composition of the films were measured, respectively, via X-ray diffraction (XRD; RIGAKU RINT2100V) and XPS (JEOL JPS9010).

The light transmittance of the thin films was measured using an ultra violet-visible spectrophotometer (UV-Vis; Shimadzu UV-mini 1240). The resistivity of the thin films was measured by a hand-made four-probe resistivity measurement system.

### 3. Results and discussion

Figure 2 shows the dependence of the electron density and temperature in the processing plasma on the powder target mixture. Both affected the deposition process of the thin films and were measured using a Langmuir probe during sputter deposition. Here, the target powder mixture was in terms of the weight ratios  $\text{In}_2\text{O}_3/\text{Ga}_2\text{O}_3/\text{ZnO}$ , and the plasma measurements were collected 15 mm from the substrate surface. The electron density was approximately  $10^9\text{--}10^{10}\text{ cm}^{-3}$  and almost independent of the powder mixture. For example,  $\text{In}_2\text{O}_3:\text{Ga}_2\text{O}_3:\text{ZnO}$  ratios of 1:1:1, 2:1:1,

and 3:1:1 had electron densities of  $2.0 \cdot 10^9$ ,  $2.4 \cdot 10^9$ , and  $2.8 \cdot 10^9 \text{ cm}^{-3}$ , respectively, as shown in Fig. 2. The electron densities for the ratios 2:1:1, 1:2:1, and 1:1:2 at 100 W were  $2.4 \cdot 10^9$ ,  $2.0 \cdot 10^9$ , and  $1.8 \cdot 10^9 \text{ cm}^{-3}$ , respectively. The electron temperature was approximately 1–2 eV in all cases. Therefore, the electron density and temperature were essentially independent of target composition.

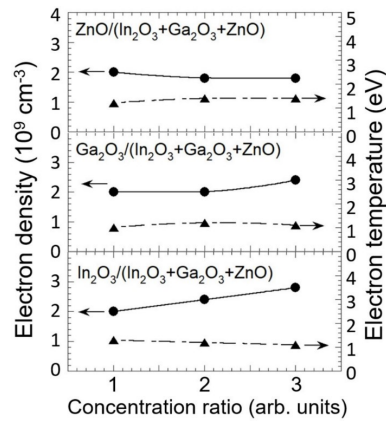


Fig. 2. Dependence of the electron density and temperature in the processing plasma on the powder target mixture

Figure 3 shows the surface morphology of the sputtered film using a 1:1:1 target mixture of In<sub>2</sub>O<sub>3</sub>, Ga<sub>2</sub>O<sub>3</sub>, and ZnO powders, as imaged with atomic force microscopy. The surface was smooth, with a root-mean-square roughness of less than 10 nm. The film deposition rate

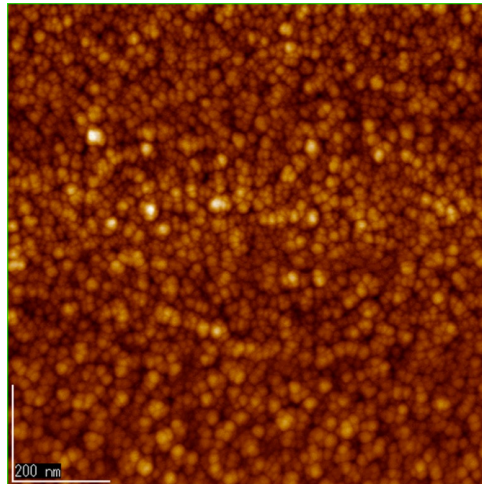


Fig. 3. Surface morphology of the sputtered film using a 1:1:1 target mixture of In<sub>2</sub>O<sub>3</sub>, Ga<sub>2</sub>O<sub>3</sub>, and ZnO powders

was approximately 5–15 nm/min. These results indicated that the deposition rate was almost independent of the composition of the powder target.

Figure 4 shows X-ray photoelectron spectra (XPS) of films prepared using a 1:1:1 mixed target. In $3d_{5/2}$ , Ga $2d$ , Zn $3d$ , and O $1s$  peaks verified that In-Ga-Zn-oxide thin films were prepared. Figure 5 plots narrow-band In $3d_{5/2}$  XPS spectra of films prepared with 1:1:1, 2:1:1, and 3:1:1 target mixtures of In $_2$ O $_3$ , Ga $_2$ O $_3$ , and ZnO powders, respectively. The In $3d_{5/2}$  signal increased accordingly with the increasing In $_2$ O $_3$  ratio in the powder target.

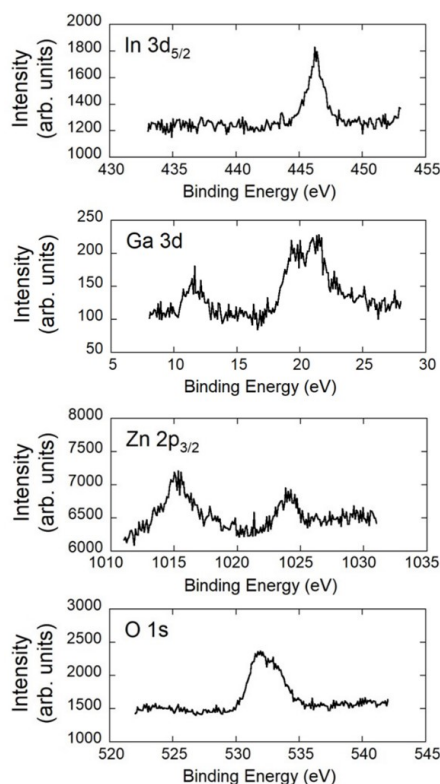


Fig. 4. X-ray photoelectron spectra (XPS) of films prepared using a 1:1:1 mixed target

Figure 6 shows the X-ray diffraction data of In-Ga-Zn-oxide films prepared using targets consisting of 1:1:1, 2:1:1, 1:2:1, 1:1:2 mixtures of In $_2$ O $_3$ , Ga $_2$ O $_3$ , and ZnO powders, respectively. The ZnO peak was observed in all the films; whereas the In and Ga peaks were not observed in the films prepared with the 1:1:1, 1:2:1, and 1:1:2 mixtures. The In peak was observed in the films prepared with the 2:1:1 mixed powder; however, Ga peaks never appeared in any of these films.

Figure 7 plots the optical transmittances of films prepared with 1:1:1, 2:1:1, and 3:1:1 mixed-powder targets. The transmittances were > 75% at 800 nm for all the target mixtures, and increased with increasing In $_2$ O $_3$  in the powder target.

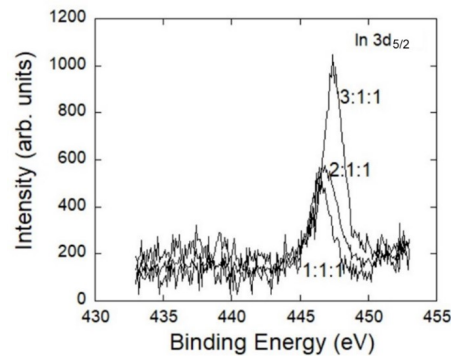


Fig. 5. Narrow-band  $\text{In}3d_{5/2}$  XPS spectra of films prepared with 1:1:1, 2:1:1, 3:1:1 target mixtures of  $\text{In}_2\text{O}_3$ ,  $\text{Ga}_2\text{O}_3$ , and ZnO powders

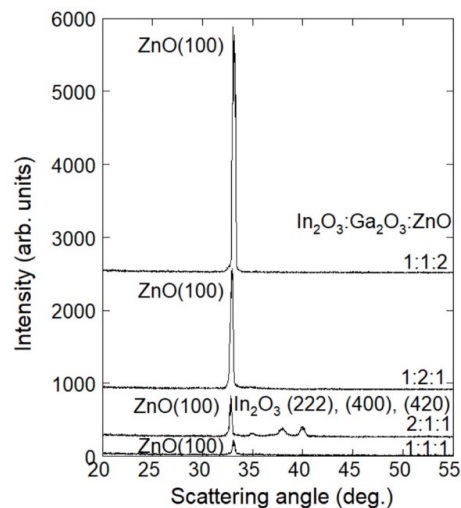


Fig. 6. X-ray diffraction data of In-Ga-Zn-oxide films prepared using targets consisting of 1:1:1, 2:1:1, 1:2:1, 1:1:2 mixtures of  $\text{In}_2\text{O}_3$ ,  $\text{Ga}_2\text{O}_3$ , and ZnO powders

However, the crystallinity of the films changed with the amount of  $\text{In}_2\text{O}_3$  in the powder mixture. As noted above, the In X-ray diffraction peak was not observed for the 1:1:1 mixture, and only appeared in the 2:1:1 mixture. Previously, for Sn-doped  $\text{SiO}_2$  thin films prepared using targets containing Sn and  $\text{SiO}_2$  powders [21–25], the Sn/ $\text{SiO}_2$  ratio was difficult to control. This may have been because of the much lower melting temperature of Sn (504 K) compared with that of  $\text{SiO}_2$  (1 923 K) [26–30]. Here, the melting points of  $\text{In}_2\text{O}_3$  (2 183 K),  $\text{Ga}_2\text{O}_3$  (2 173 K), and ZnO (2 248 K) were comparable; whereas, those of In and Zn are 430 K and 693 K, respectively. Therefore, In atoms in the plasma may affect the high-energy electrons and/or ions in the processing plasma, and the crystallinity could be changed by the powder mixture. The experimental results revealed that the processing plasma and elemental concentration ratio could be controlled

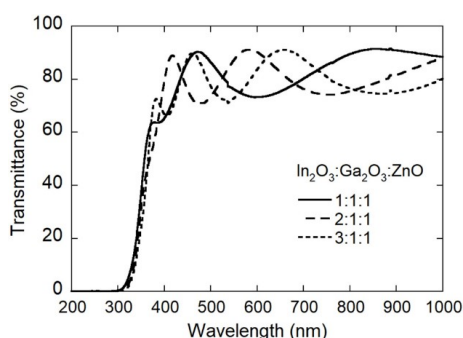


Fig. 7. Optical transmittances of films prepared with 1:1:1, 2:1:1, and 3:1:1 mixed-powder targets

by using metal-oxide powder targets. The controllability of these factors strongly depended on the properties of the powder materials used in the target, such as melting points.

#### 4. Conclusions

In–Ga–Zn–O thin films were prepared via sputter deposition using targets consisting of mixed  $\text{In}_2\text{O}_3$ ,  $\text{Ga}_2\text{O}_3$ , and ZnO powders. The processing plasma and elemental concentration ratios of the films were determined by the  $\text{In}_2\text{O}_3/\text{Ga}_2\text{O}_3/\text{ZnO}$  composition in the powder target. The properties of the powder, such as a melting point, strongly affected the ability to control the plasma parameters and the composition of the resulting thin films.

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#### References

- [1] Nomura K., Ohta H., Ueda K., Kamiya T., Hirano M., Hosono H., *Thin-film transistor fabricated in single-crystalline transparent oxide semiconductor*, Science, vol. 300, pp. 1269–1272 (2003), DOI: [10.1126/science.1083212](https://doi.org/10.1126/science.1083212).
- [2] Nomura K., Ohta H., Takagi A., Kamiya T., Hirano M., Hosono H., *Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors*, Nature, vol. 432, pp. 488–492 (2004), DOI: [10.1038/nature03090](https://doi.org/10.1038/nature03090).

- [3] Behrish R., Eckstein W., *Sputtering by Particle Bombardment, Experiments and Computer Calculations from Threshold to MeV Energies*, Springer, ISBN: 978-3540445005 (2007).
- [4] Carter G., Colligan J.S., *Ion Bombardment of Solids*, American Elsevier (1968).
- [5] Maissel L.I., *Applications of Sputtering to the Deposition of Films*, in Handbook of Thin Film Technology, McGraw-Hill (1970).
- [6] Wehner G.K., Anderson G.S., *The Nature of Physical Sputtering*, Handbook of Thin Film Technology, McGraw-Hill (1970).
- [7] Nastasi M., Mayer J., Hirvonen J.K., *Ion-Solid Interactions: Fundamentals and Applications*, Cambridge Solid State Science Series, Cambridge University Press, ISBN: 9780521616065 (2004).
- [8] Liu Y., Sun B., Shu Y., Zeng X., Zhu J., Yi J., He J., *Preparation of superior IGZO ceramics by two-step sintering for application in IGZO thin film fabrication*, Journal of Materials Research and Technology, vol. 9, pp. 5331–5342 (2020), DOI: [10.1016/j.jmrt.2020.03.059](https://doi.org/10.1016/j.jmrt.2020.03.059).
- [9] Baragiola R.A., *Sputtering: survey of observations and derived principles*, Philosophical Transactions A, vol. 362, pp. 29–53 (2004), DOI: [10.1098/rsta.2003.1301](https://doi.org/10.1098/rsta.2003.1301).
- [10] Smentkowski V.S., *Trends in sputtering*, Progress in Surface Science, vol. 64 pp. 1–58 (2000), DOI: [10.1016/S0079-6816\(99\)00021-0](https://doi.org/10.1016/S0079-6816(99)00021-0).
- [11] Song J., Park J., Kim H., Heo Y., Lee J., Kim J., *Transparent amorphous indium zinc oxide thin-film transistors fabricated at room temperature*, Applied Physics Letters, vol. 90, p. 022106 (2007), DOI: [10.1063/1.2430917](https://doi.org/10.1063/1.2430917).
- [12] Itagaki N., Iwasaki T., Kumomi H., Den T., Nomura K., Kamiya T., Hosono H., *Zn-In-O based thin-film transistors: Compositional dependence*, Physica Status Solidi A, vol. 205, pp. 1915–1919 (2008), DOI: [10.1002/pssa.200778909](https://doi.org/10.1002/pssa.200778909).
- [13] Fujiyama H., *Inner coating of long-narrow tube by plasma sputtering*, Surface and Coatings Technology, vol. 131 pp. 278–283 (2000), DOI: [10.1016/S0257-8972\(00\)00801-X](https://doi.org/10.1016/S0257-8972(00)00801-X).
- [14] Morisaki E., Fujiyama H., *Development of a transported coaxial ECR plasma source for inner coating of metallic tubes*, Surface and Coatings Technology, vol. 98, pp. 834–838 (1998), DOI: [10.1016/S0257-8972\(97\)00305-8](https://doi.org/10.1016/S0257-8972(97)00305-8).
- [15] Kawasaki H., Ohshima T., Yagyu Y., Ihara T., Shinohara M., Suda Y., *Preparation of metal doped SiO<sub>2</sub> films by magnetron sputtering deposition using metal oxide mixture powder target*, Transactions on the Materials Research Society of Japan, vol. 43, no. 1, pp. 27–30 (2018), DOI: [10.14723/tmrsj.43.27](https://doi.org/10.14723/tmrsj.43.27).
- [16] Gao X.T., Nagaie Y., Kawasaki H., Aouki S., Munagata M., Ohkoshi M., *Perpendicular magnetic anisotropy in 4-layer Ni/Pt thin films*, Journal of the Magnetics Society of Japan, vol. 31, pp. 81–84 (2007), DOI: [10.3379/jmsjmag.31.81](https://doi.org/10.3379/jmsjmag.31.81).
- [17] Timpheev A.A., Grishin P.A., Munakata M., *The influence of intergranular interaction on the magnetization of the ensemble of oriented Stoner–Wohlfarth nanoparticles*, Journal of Applied Physics, vol. 105, p. 083905 (2009), DOI: [10.1063/1.3098227](https://doi.org/10.1063/1.3098227).
- [18] Guillon O., Gonzalez-Julian J., Dargatz B., Kessel T., Schiering G., Räthel J., Herrmann M., *Field-Assisted Sintering Technology/Spark Plasma Sintering: Mechanisms, Materials, and Technology Developments*, Advanced Engineering Materials, vol. 16, no. 7, pp. 830–849 (2014), DOI: [10.1002/adem.201300409](https://doi.org/10.1002/adem.201300409).
- [19] Hase T., Sakuma T., Miyasaka Y., Hirata K., Hosokawa N., *Preparation of Pb(Zr, Ti)O<sub>3</sub>. Thin Films by Multi-Target Sputtering*, Japanese Journal of Applied Physics, vol. 32, p. 4061 (1993), DOI: [10.1143/JJAP.32.4061](https://doi.org/10.1143/JJAP.32.4061).
- [20] Kawasaki H., Taniyama D., Takeichi S., Ohshima T., Yagyu Y., Ihara T., Tanaka Y., Suda Y., *Characteristics of plasma parameters in sputtering deposition using a powder target*, Journal of Physics: Conference Series, vol. 518, p. 012003 (2014), DOI: [10.1088/1742-6596/518/1/012003](https://doi.org/10.1088/1742-6596/518/1/012003).



- [21] Dzibrou D., Grishin A.M., Kawasaki H., *Pulsed laser deposited TiO<sub>2</sub> films: Tailoring optical properties*, Thin Solid Films, vol. 516, pp. 8697–8701 (2008), DOI: [10.1016/j.tsf.2008.05.010](https://doi.org/10.1016/j.tsf.2008.05.010).
- [22] Grishin A.M., Khartsev S.I., Kawasaki H., *980nm Bi<sub>3</sub>Fe<sub>5</sub>O<sub>12</sub> / Sm<sub>3</sub>Ga<sub>5</sub>O<sub>12</sub> magneto-optical photonic crystal*, Applied Physics Letters, vol. 90, p. 191113 (2007), DOI: [10.1063/1.2737933](https://doi.org/10.1063/1.2737933).
- [23] Kawasaki H., Ohshima T., Yagyū Y., Ihara T., Mitsuhashi K., Nishiguchi H., Suda Y., *Preparation of functional thin films with elemental gradient by sputtering with mixed powder targets*, Japanese Journal of Applied Physics, vol. 61, p. SA1019 (2021), DOI: [10.35848/1347-4065/ac1488](https://doi.org/10.35848/1347-4065/ac1488).
- [24] Kawasaki H., Nishiguchi H., Ohshima T., Yagyū Y., Ihara T., *Preparation of Ni-doped stainless steel thin films on metal to prevent hydrogen entry via sputter deposition with a powder target*, vol. 60, p. SAAB10 (2020), DOI: [10.35848/1347-4065/abba10](https://doi.org/10.35848/1347-4065/abba10).
- [25] Kawasaki H., Ohshima T., Yagyū Y., Ihara T., Suda Y., *Preparation of Multielements Mixture Thin Film by One-Step Process Sputtering Deposition Using Mixture Powder Target*, IEEE Transactions on Plasma Science, vol. 49, no. 1, pp. 48–52 (2020), DOI: [10.1109/TPS.2020.3025306](https://doi.org/10.1109/TPS.2020.3025306).
- [26] Kawasaki H., Ohshima T., Yagyū Y., Ihara T., Shinohara M., Suda Y., *Preparation of Sn doped SiO<sub>2</sub> thin films by magnetron sputtering deposition using metal and metal oxide powder targets*, Japanese Journal of Applied Physics, vol. 58, p. SAAD04 (2018), DOI: [10.7567/1347-4065/aaea67](https://doi.org/10.7567/1347-4065/aaea67).
- [27] Kawasaki H., Ohshima T., Yagyū Y., Ihara T., Shinohara M., Suda Y., *Preparation of two-dimensional thin films by backside irradiation pulsed laser deposition method using powder target*, Japanese Journal of Applied Physics, vol. 59, p. SAAC01 (2020), DOI: [10.7567/1347-4065/ab4e76](https://doi.org/10.7567/1347-4065/ab4e76).
- [28] Kawasaki H., Ohshima T., Yagyū Y., Ihara T., Yamauchi M., Suda Y., *Thin-film preparation by back-surface irradiation pulsed laser deposition using metal powder targets*, Japanese Journal of Applied Physics, vol. 56, p. 01AB06 (2016), DOI: [10.7567/JJAP.56.01AB06](https://doi.org/10.7567/JJAP.56.01AB06).
- [29] Ohshima T., Maeda T., Tanaka Y., Kawasaki H., Yagyū Y., Ihara T., Suda Y., *Sputtering deposition of Al-doped zinc oxide thin films using mixed powder targets*, Japanese Journal of Applied Physics, vol. 55, p. 01AA08 (2015), DOI: [10.7567/JJAP.55.01AA08](https://doi.org/10.7567/JJAP.55.01AA08).
- [30] Kawasaki H., Ohshima T., Yagyū Y., Ihara T., Tanaka Y., Suda Y., *Preparation of mixed bismuth and iron thin films by pulsed laser deposition using powder targets*, Japanese Journal of Applied Physics, vol. 55, p. 01AA14 (2015), DOI: [10.7567/JJAP.55.01AA14](https://doi.org/10.7567/JJAP.55.01AA14).
- [31] Kawasaki H., Ohshima T., Yagyū Y., Ihara T., Yamauchi M., Suda Y., *Optical Study of Laser Ablation Plasma Irradiation for the Bacteria Sterilization using Metal Oxide Target*, Transactions of the Materials Research Society of Japan, vol. 41, pp. 205–208 (2016), DOI: [10.14723/tmrj.41.205](https://doi.org/10.14723/tmrj.41.205).
- [32] Nakano K., PVP-Vol302, *Composites for the pressure vessel industry*, Book No. H00 965, ASME, pp. 283–289 (1995).
- [33] Kawasaki H., Nishiguchi H., Furutani T., Ohshima T., Yagyū Y., Ihara T., Shinohara M., Suda Y., *Coating of inner surface of cylindrical pipe for hydrogen entry prevention using plasma process*, Japanese Journal of Applied Physics, vol. 57, p. 01AB02 (2018), DOI: [10.7567/JJAP.57.01AB02](https://doi.org/10.7567/JJAP.57.01AB02).
- [34] Nishiguchi H., Ohshima T., Kawasaki H., Fukuda T., *Strength of plasma coating and effect of a plasma coating on hydrogen entry*, Japanese Journal of Applied Physics, vol. 55, p. 01AF05 (2016), DOI: [10.7567/JJAP.55.01AF05](https://doi.org/10.7567/JJAP.55.01AF05).