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Machine Learning Techniques Applied to Development of Flexible Electronic Antireflective Film

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In this study, we aim to optimize the process for developing antireflective and refractive-index-matching films on flexible substrates. The development of these films is crucial in light of the increasing demand in the market for flexible electronics, which are poised to be the next emerging technology and application after semiconductors and flat panel displays. Our research involves the production of these films by physical vapor deposition and sputtering techniques, which can also be applied to various optical thin films. The effectiveness of our coating process has been verified and refined on the basis of feedback. The results of this study are applicable to related industrial technologies and will contribute to improving industry competitiveness.

1. Introduction

1.1 Research motivation

According to the “2020 Display Industry Yearbook” published by the Industrial Economics and Knowledge Center of the Industrial Technology Research Institute, the production value of Taiwan’s display panels in 2022 is estimated to be more than one trillion New Taiwan dollars. The market for flexible and curved displays is expected to grow to 27 billion dollars by 2023 (Fig. 1). Additionally, according to a research report on “Printed and Flexible Electronics for Automotive Applications 2016–2026” published by IDTechEx Research, the market size of flexible electronics in the automotive industry is expected to grow to more than 5.5 billion US dollars in the next decade.

As the era of significant data approaches, the demand for real-time information acquisition and analysis is becoming increasingly strong, so the requirements for various electronic devices are becoming increasingly stringent. For example, the real-time monitoring of blood sugar levels can help people be more aware of their health status and take immediate action.(1) Google has

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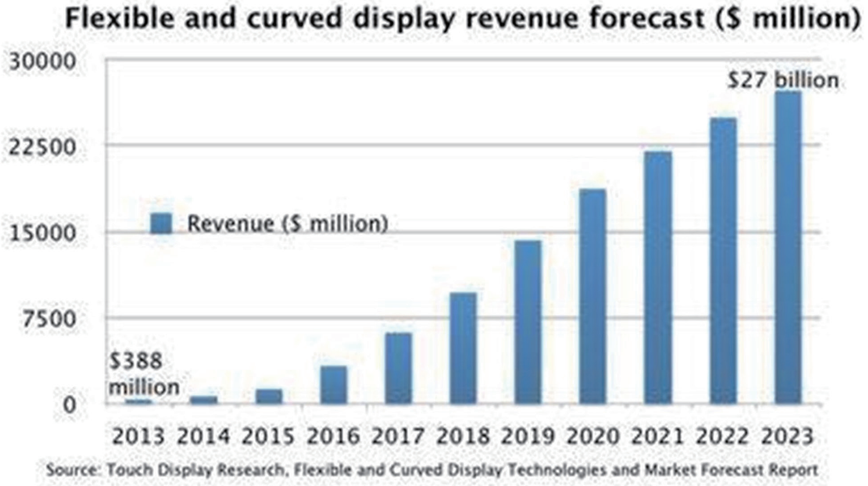


Fig. 1. (Color online) The flexible and curved display market is expected to grow to 27 billion dollars by 2023.

recently proposed combining a sensor with contact lenses to measure blood sugar levels from tears and wirelessly transmit information to mobile devices.(2)

Moreover, in addition to transmitting information to mobile devices, information from mobile devices can also be transmitted to various electronic devices. For instance, EP Global Comm. Inc. has proposed augmented reality contact lenses and is discussing the feasibility of using the iOS system with Apple.(3) All these electronic devices have a common feature: their integration with flexible substrates.

1.2 Research purpose

The development of one-dimensional nanometer-structure optical detectors has become increasingly important in recent years. The literature shows a diverse range of one-dimensional nanometer structures, including nanowires, nanotubes, nanospheres, and nanobelts. Because of their high aspect ratios, one-dimensional nanometer structures exhibit different optoelectronic properties and are widely used in electronics and optoelectronic components. Currently, various processes for the fabrication of one-dimensional nanometer structures are being increasingly emphasized, and they are being applied in gas sensors, piezoelectric devices, field emission devices, solar cells, biosensors, and optical detectors.(4–6)

In 2005, IEEE first defined flexible electronics as “a general term for technology based on components and materials built on flexible or bendable substrates such as thin plastic or metal sheets”. According to this definition, there are many components and devices based on flexible electronics, such as flexible solar cells and thin-film batteries in energy; electronic paper and flexible displays made with organic light-emitting diodes (OLEDs) in displays; head-mounted displays such as Google glasses, augmented reality contact lenses proposed by EP Global Comm. Inc., and automotive heads-up displays; and flexible intelligent sensing systems that integrate various sensors, soft antennas, logic elements/memory, and CPUs onto soft substrates. In the foreseeable future, flexible electronic systems will integrate flexible batteries, flexible displays, and flexible smart sensing systems. Moreover, these integrated systems can be separated as needed, creating a wide range of optoelectronic products more closely related to everyday life. The various applications of flexible electronics are mainly due to the advantages of their soft substrates, which are flexible, lightweight, thin, and low in cost.

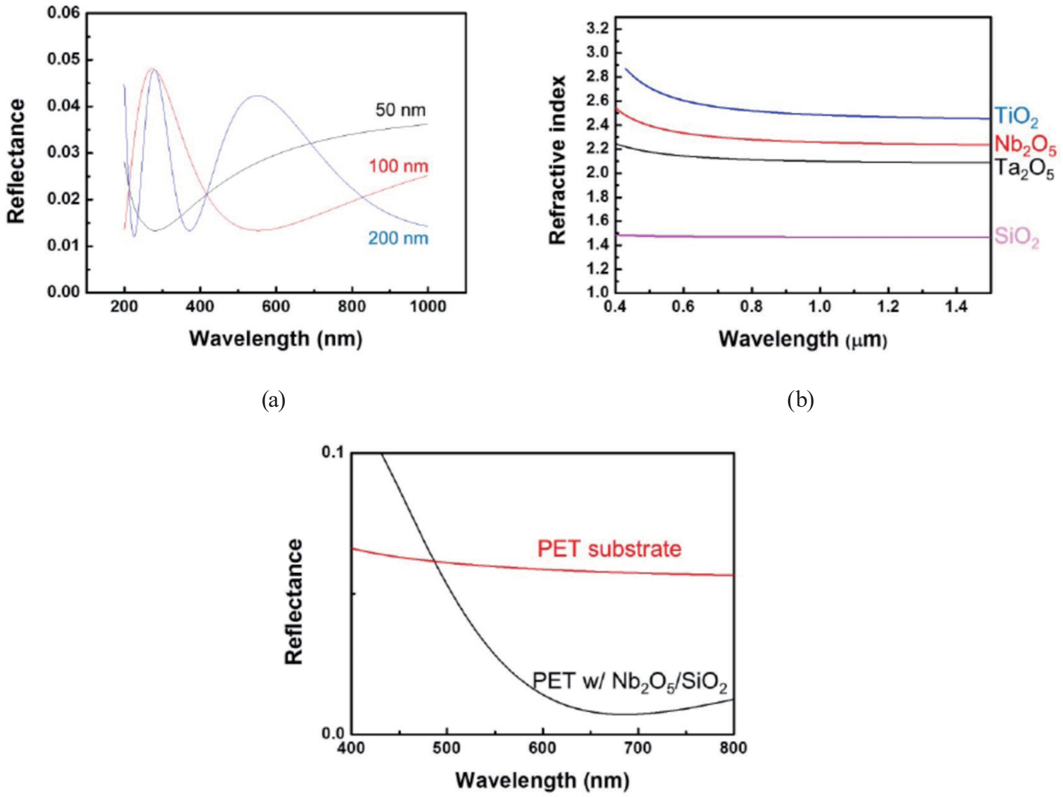
There are many methods for producing antireflective films and films with matching refractive indices. For example, etching techniques may be used to roughen the surface of the substrate to produce antireflective and antiglare thin films and substrates.(7) Nanoimprint or photolithography can be used to produce moth-eye substrates for antireflective purposes, and physical vapor deposition or sputtering may be used to produce antireflective films.(8,9) Each of these methods has distinctive characteristics and advantages and disadvantages. For example, the antiglare substrate and moth-eye substrate technologies both require the use of chemicals in the fabrication process, so there is a waste liquid treatment problem.(10) Although the cost of preparing the antiglare substrate is low and the process is simple, the transmittance of the substrate is lower than those of antireflective thin films and substrates, and its color and image quality are also inferior. The moth-eye substrate not only has a considerably more difficult fabrication process, but the nanostructure on its surface is also easily destroyed, and currently, only Sharp can produce it(11). On the other hand, the antireflective films produced by physical vapor deposition or sputtering have a higher initial equipment purchase cost. Overall, they have the advantages of environmentally friendly processing, high transmittance, anti-UV property, good color saturation, high hardness, and advanced equipment technology.(12–14)

2. Experiments

In the project considered in the study, the industry will provide coating machines for the production of thin films, while the school team will design antireflective films and films with matching refractive indices, as well as conduct thin-film analysis in the execution phase.

2.1 Design of antireflective films and films with matching refractive indices

The school team will use software packages and write programs to design antireflective films and films with matching refractive indices. For a single-layer antireflective film, the optimal material refractive index is (ns)1/2, where ns is the refractive index of the substrate. Taking thin glass as an example, its refractive index depends on the type of glass. Assuming a refractive index of 1.51, the optimal refractive index for the antireflective film is n = 1.23. However, there is no material with such a low refractive index. Generally, MgF_2 is the material with the lowest refractive index. The reflectamce of MgF_2 of different thicknesses (50, 100, and 200 nm) on glass was calculated, as shown in Fig. 2(a). For visible light (400–800 nm), 100 nm is the best among the three thicknesses of MgF_2. Figure 2(b) shows the refractive indices of TiO_2, Nb_5O_2, Ta_2O_5, and SiO_2 as a function of wavelength.



(a) (b)

(c)

Fig. 2. (Color online) (a) Reflectance of MgF_2 of different thicknesses (50, 100, and 200 nm) coated on glass. (b) Relationship between refractive index and wavelength of TiO_2, Nb_5O_2, Ta_2O_5, and SiO_2. (c) Calculated reflectance versus wavelength for a 10-nm-thick Nb_2O_5 and 150-nm-thich SiO_2 thin-film stack on a PET substrate.

Compared with single-layer antireflective films, the selection of materials for double-layer or multilayer antireflective films is greater selection. The refractive index is not necessarily (*ns*)1/2. Generally, materials with high and low refractive indices are paired. We will use TiO_2, Nb_2O_5, Ta_2O_5, and SiO_2 as materials in this project. However, the refractive indices of these materials are related to the coating conditions and their exact composition. Figure 2 shows the reflectance of a 10-nm-thick Nb_2O_5 (high refractive index) and 150-nm-thick SiO_2 (low refractive index) thin-film stack on a PET substrate as a function of wavelength. The reflectance of the PET substrate as a function of wavelength is also shown for reference. The results show that the double-layer reflective film can reduce the reflectance. These calculation results are only preliminary and have not been optimized. Also, double-layer or multilayer antireflective films can be symmetrically coated on both sides of the substrate [Fig. 2(c)].

2.2 Film fabrication

Since the film deposition conditions can affect the quality and composition of the films, it is necessary to test the films under different deposition conditions and study their properties to determine optimal deposition parameters. The film thickness and refractive index are measured using an ellipsometer and are shown in Fig. 3, and the surface morphology is observed by SEM. X-ray diffraction (XRD) is used to investigate the crystal structure and phase purity of the film, and its optical properties are characterized using a spectrophotometer.

In this study, we aim to design and fabricate antireflective films and fims with matching refractive indices for glass and PET substrates. The optical properties of the films are optimized using single-layer, double-layer, and multilayer films made of TiO_2, Nb_5O_2, Ta_2O_5, and SiO_2. The films are deposited using industry-provided coating machines, and their properties are analyzed using various characterization techniques.

3. Results and Discussion

For the index-matching film, we preliminarily adopt the structure shown in Fig. 4, with the addition of an index-matching layer to reduce the difference caused by the inconsistency

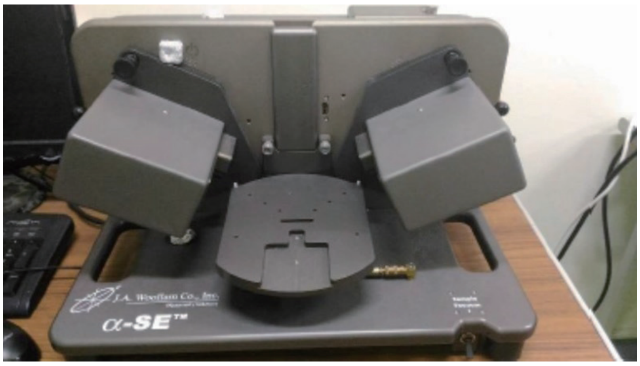


Fig. 3. (Color online) Ellipsometer used for thin film analysis.

Fig. 4. (Color online) Design concept of the index-matching layer.

between ITO and glass reflection (due to the difference in refractive index). Further changes of the relevant process parameters (e.g., substrate temperature, gas atmosphere, growth pressure, and laser power) and machine learning analysis will improve the thin-film quality and device sensing characteristics for various applications (e.g., electrical, optoelectronic, and biomedical).

We use the multilayer perceptron (MLP) to analyze a computational model that estimates complex nonlinear functions and handles difficult-to-analyze data. It is a machine learning method that enables the system to have the ability to infer results. Its features include a simple network configuration, a high data training speed, and a strong approximation ability. In this project, MLP will be used to classify the feature parameters of the fabrication process and measurement.

The MLP structure is divided into three levels: input layer, hidden layer, and output layer. In this study, we plan to initially use the feature parameters in the process as the input layer of MLP, and the initial center vector is the location where the above parameters are evenly distributed in a specific area and an appropriate number of hidden-layer neurons are given. After training MLP, the results indicate the optimal threshold used as the reference value, as shown in Fig. 5. To evaluate performance, two index parameters, accuracy (*ACC*) and root mean square error (*RMSE*, to measure “average error”), are defined. The analysis results are shown in Table 1. Overall, the study has the advantages of being environmentally friendly, pollution-free, highly transparent, and UV-resistant, and having good color saturation, high hardness, and mature equipment technology.

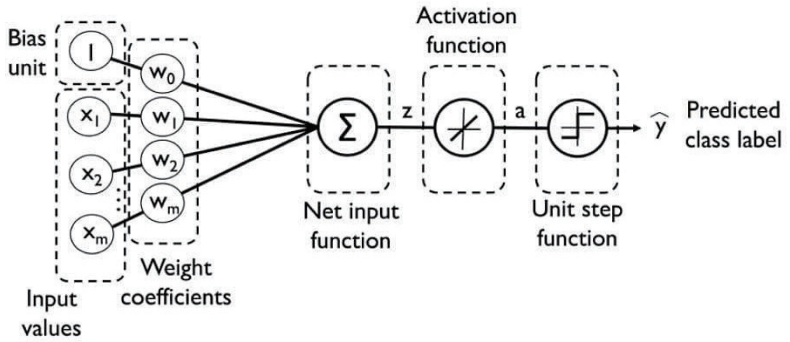


Fig. 5. Architecture for analyzing the process parameter characteristics using MLP. (From https://www.simplilearn.com/tutorials/deep-learning-tutorial/multilayer-perceptronf)

Table 1
Results of MLP analysis of the process parameters (Inputs) and performance evaluation.

Input	*ACC* (%)	*RMSE*
1 (Substrate temperature)	75.39	0.958
1 (Pressure)	77.25	0.842
2 (Substrate temperature and gas flow)	87.16	0.729
3 (Substrate temperature, pressure, and gas flow)	90.72	0.562

4. Conclusions

In this project, it is necessary to integrate different fields of technology. To develop a new material processing technology is helpful to research and learn both the theoretical(15) and practical applications. Through the combination of theoretical and practical verifications planned in this project, the research on process development can be advanced further.

Acknowledgments

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