Conceptual demonstration of continuous Roll-to-Roll manufacturing of transparent and flexible UV sensors

Kwangjun Kim[1†], Inhui Han[1†], Jungkeun Song[1], Useung Lee[1], Hyein Kim[1], Hyungi Son[1], Kwangjin Choi[1], Minwook Kim[1], Jong G. Ok[1*]

[1]Seoul National University of Science and Technology, Department of Mechanical and Automotive Engineering, Seoul, 01811, South Korea
[*]E-mail address:jgok@seoultech.ac.kr

ABSTRACT

Although demand for high-performance device development based on micro- and nanopattern has been increasing recently, productivity issues in manufacturing technologies have been raised due to constraints such as the applicability of existing high-end vacuum equipment-based lithography and etching processes and the time required to produce economic documents. To overcome the limitations of this traditional approach, we develop an all-solution-processible, low-temperature fabrication methodology for a flexible UV sensor comprising the ZnO nanowires (ZNWs) directly grown on the Ag microelectrode architecture with superior continuous productivity and substrate versatility based on possible solution processes in low temperature environments.

Keywords: UV sensor, Flexible, Low-temperature, Solution process, Hybrid structure

1. INTRODUCTION

As the demand for micro-nano patterning and flexible device toword to UV sensors increases for simultaneous performance and productivity, the need for productive fabrication processes is emerging, to overcome the limitations of existing processes that rely on expensive vacuum equipment-based lithography and etching.

Usually, UV sensors are fabricated as hybrid structures of semiconductors and conductors. In particular, ZnO is frequently used for UV detection purposes. Because ZnO has its own electrical properties as an n-type wide bandgap semiconductor material and absorbs UV strongly. In order to maximize the sensing properties of ZnO, conventional CVD and hydrothermal synthesis processes are applied to fabricate ZnO nanostructures (nanowires, nanorods, nanoflakes, etc.), which are difficult to control structural characteristics of nanostructures and have substrate constraints due to high process temperature.

In response, we develop a low-temperature solution process based continuous fabricating protocol that enables high-speed production, and also we present ZNW-Ag hybrid flexible sensors that apply it. The micropatterned Ag microelectrode structures are fabricated in all-solution-processible fabrication methodology and Photo Roll Lithography(PRL), which have excellent productivity and repeatability.

Furthermore, the nanoporous surface of the Ag microelectrode structure through the solution process not only eliminates the seedless property in the hydrothermal synthesis of ZNWs but also facilitates the easy control of the structural characteristics of ZnO NWs. Based on this, we would like to inform the excellent response speed, selectivity, and sensitivity of UV sensors and talk about various applications of UV sensors that we have advanced.

2. EXPERIMENTAL PROCESS

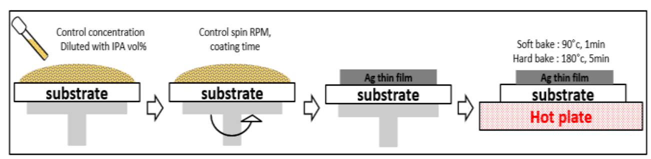

Fig. 1 Schematic of Ag thin film procedure.

Fig. 2 Schematic of PRL/IDT/Hydrothermal procedure

Fig. 1 and Fig. 2 are schematics of Ag thin film procedure and micro-patterning (Interdigitated; IDT) / Hydrothermal procedure. First, the Ag thin film can be fabricated by spin-coating a reductive ionic Ag ink, followed by the simple mild-temperature annealing to reduce the Ag ions to a conductive Ag layer with greater adhesion. Adequate annealing temperatures (up to 120°C) enable the use of various substrates. (Glass, Si, PET, etc.) The mechanical and electrical properties of the Ag thin film can be readily controlled by changing the ink concentration and spin-coating speed. Then the Ag IDT microelectrodes can be fabricated by using a desktop PRL system. PRL is a practical in-house process that integrates the principles of conventional photolithography and rollable processing, which enables continuous and high-speed patterning without resorting to a beefy nanofab facility. We can control the intensity of UV light and rolling speed for optimal fabrication of Ag IDT electrode. Meanwhile, we develop the low temperature hydrothermal ZNWs growth technique which does not require the high-temperature (i.e., up to 350°C) sintering of a textured ZnO seed; ZNWs can be grown on the surface with a proper physical roughness and chemical species, such as the solution-processed Ag layer.

3. RESULTS & DISCUSSION

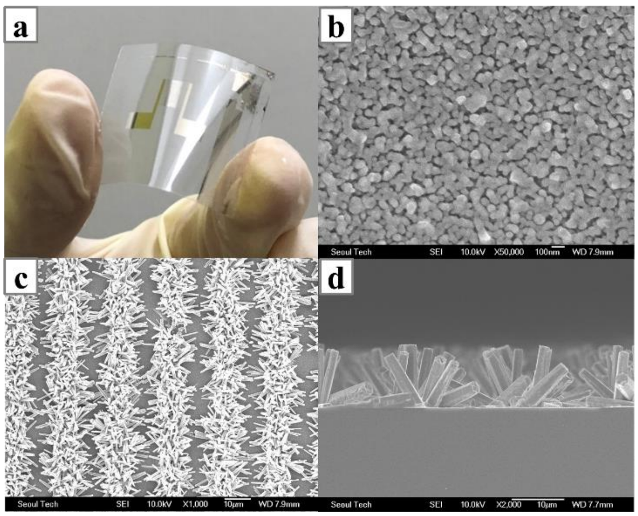

Fig. 3 (a) Photograph of Ag IDT pattern fabricated through PRL process (b) SEM image of Ag nanoporous surface (c), (d) SEM image of ZNWs-Ag hybrid structure.

As shown in Fig. 3 (a), Ag thin films based on solution process can be stably patterned at least c.d. 5μm based on PRL process. The nanoporous surface of the Ag thin film in Fig. 3 (b) is a characteristic of the reductive ionic Ag ink-based deposition process, which allows quantitative control of pore size and surface roughness by controlling the concentration of the ink, coating speed, and annealing temperature. In addition, the easily formed Ag nanoporous surface enables ZNW to grow at a low temperature (optimum temp. 90°C) instead of ZnO seed, where ZNW is grown. For conventional ZNW growth with ZnO seed, sintering process of texture seed with high temperature (i.e., up to 350°C) is essential, so the use of flexible substrates such as PET we used is difficult. Furthermore, the reasonable surface roughness resulting from the reduction of silver ions and evaporation of solvents of ink leads to varying growth directions of ZNW, which increases the reactive specific surface area of ZNW exponentially. This is identifiable in Fig. 3 (c) and (d), and acts as a bridge between the IDT pattern electrodes, increasing the sensitivity and reaction time performance of device based on the photoelectric effect of ZNW.

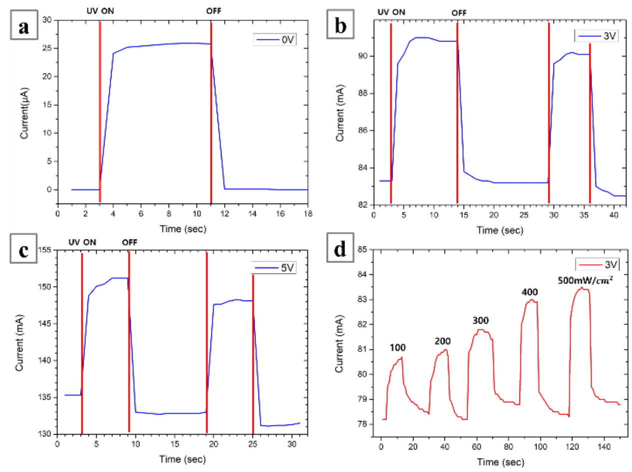

Fig. 4 (a), (b), (c) Graph of electric current according to time with UV intensity and variable voltage given, (d) Graph of electric current according to time with variable UV intensity and 3V given.

Fig. 4 is a graph showing the sensing performance of the fabricated device. Fig. 4 (a), (b), (c) are the results of measuring the current value that changes as UV light (570mW/cm^2) turns on and off when bias voltages of 0V, 3V, and 5V are applied, respectably. Fig. 4 (d) shows the result of measuring the current value while increasing the energy of UV light from 100 to 500 mW/cm^2 when a bias voltage of 3V is applied. As the amount of light increases, the maximum value of the current also increases linearly 80.7mA to 83.5mA. Also, the reaction and recovery time with light on/off confirmed within 1-2 sec at no-bias status. It was also confirmed that the bias voltage increased to 5 V, resulting in shorter reactions and recovery times.

4. CONCLUSION

This favorable ZNW-Ag hybrid structure tactfully realizes the all-solution-processible, low-temperature fabrication of the UV sensing architecture in a flexible substrate, where the ZNWs are directly grown on and interconnecting the Ag IDT electrodes. The developed method may further be applicable to a wider range of devices and systems particularly desiring the low-cost, low-temperature, and scalable fabrication.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grants (No. 2015R1A5A1037668 (MSIT), No. 2020R1F1A1073760 (MSIT), and No. 2019R1A6A1A03032119 (Ministry of Education)) and the Commercialization Promotion Agency for R&D Outcomes (COMPA) grant (No. 2019K000591 (MSIT)), funded by the Korean Government.

REFERENCES

[1] Oh, D. K., et al. "Tailoring zinc oxide nanowire architectures collectively by catalytic vapor-liquid-solid growth, catalyst-free vapor-solid growth, and low-temperature hydrothermal growth." Ceramics International 47(2): 2131-2143. (2021).

[2] Ok, J. G., et al. "Photo–roll lithography (PRL) for continuous and scalable patterning with application in flexible electronics." Advanced materials 25(45): 6554-6561. (2013).