Journal of Sensor Science and Technology
Vol. 33, No. 6 (2024) pp. 499-503
http://dx.doi.org/10.46670/JSST.2024.33.6.499
pISSN 1225-5475/eISSN 2093-7563

Resistance Controls of Carbon Black-Polyethylene Oxide (CB-PEO) Gas Sensor Using the Diode Laser (408 nm) Trimming Process

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Abstract

In this study, we performed laser trimming in the depth direction of a carbon black-polyethylene oxide (CB-PEO) gas sensor using a laser diode with a wavelength of 408 nm. The CB-PEO gas sensor was formed on a patterned soda-lime glass substrate (electrode spacing of 10 mm) using a drop-casting technique. The resistance of the CB-PEO sensor can be adjusted from several kΩ to approximately 1000 kΩ using a laser-trimming process. The resistance control mechanism can be explained as follows. The PEO polymer decomposes into a volatile gas form, causing the CB located in the polymer matrix to agglomerate. During the laser process, the CB combines with atmospheric oxygen and is released as carbon dioxide or carbon monoxide. This loss of CB appeared to be the main factor contributing to the increase in resistance. This approach not only aids in circuit design but also simplifies the algorithms by allowing the precise resistance control of the sensors.

Keywords: Gas sensors, Carbon black, Polyethylene oxide, Diode laser, Resistance control

1. INTRODUCTION

Carbon black (CB) and polymer composites are widely used in gas sensor applications by combining the conductive properties of CB with the flexibility and processability of polymers [1-4]. The operation of the CB-polymer gas sensor is illustrated in Fig. 1. When exposed to certain gases, these composites allow gas molecules to adsorb onto the CB surface, thereby affecting the charge carriers on the CB surface [1,2]. Additionally, polymers can expand and swell upon gas exposure, which alters the arrangement of the CB particles within the polymer matrix [3-5]. The sensor detects gases by measuring changes in the electrical resistance or capacitance resulting from the interaction between the gas molecules and the CB polymer. The combined effects of gas absorption and polymer expansion enhance the sensitivity of the sensor to specific gases. CB polymer sensors are generally inexpensive, easy to fabricate, and typically exhibit high sensitivities to various gases, including volatile organic compounds and harmful gases. They have been applied in environmental monitoring, indoor air quality assessments, and industrial safety. However, these sensors often suffer from poor gas selectivity compared with other sensors. To compensate for this issue, a detection method that involves configuring various polymers with different volume expansions in an array according to their gas absorption properties has been developed. In this configuration, the base resistance of each element in the array is maintained constant, thereby simplifying the circuit design and signal-processing algorithms. However, achieving a constant base resistance in CB polymer sensors can be challenging. A potential solution to this problem is laser trimming.

A laser is a device that emits a coherent light beam through optical amplification and exhibits unique properties, such as coherence, monochromaticity, and directionality. Lasers can produce focused, narrow, and intense light of a specific wavelength. These characteristics make lasers valuable tools for various applications, including data communication, medical procedures (such as surgeries and skin treatments), manufacturing processes (for cutting, welding, engraving, and surface treatments of materials), and scientific research across multiple fields [6-10]. High-power lasers, such as infrared (IR) lasers (CO_2 lasers with a wavelength of 10.6 um), Nd:YAG laser (1064 nm), and excimer lasers (vacuum ultraviolet), have been used for this purpose.

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(Received : Nov. 4, 2024, Revised : Nov. 10, 2024, Accepted : Nov. 15, 2024)

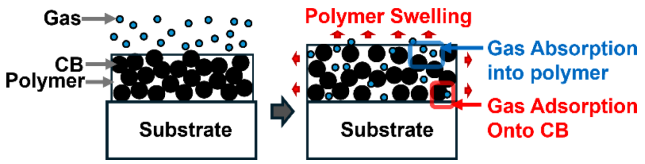

Fig. 1. Schematic of the operation principle for the CB-polymer gas sensor.

However, high-power lasers tend to be expensive and less efficient and have shorter lifespans than laser diodes. In contrast, laser diodes offer several advantages, including small size, high efficiency, wide wavelength range, low cost, and long lifetimes. Despite these benefits, laser diodes are not widely used in material processing because of their low power output, which limits their effectiveness. In this study, a laser-trimming process using a laser diode was investigated for a CB polymer sensor. Laser trimming is a precise process for adjusting electrical components, such as resistors or circuits. This process can achieve the desired specifications by selectively removing material using a focused laser beam. This technique is highly accurate and allows the finetuning of component values without the need for physical adjustments. Laser trimming is commonly applied in electronics manufacturing, where it improves device performance, consistency, and reliability. We performed a laser trimming process in the depth direction of the CB polymer sensor at a wavelength of 408 nm. The effects of laser scan speed and number of scans on the trimming process were studied, and a process mechanism was proposed.

2. EXPERIMENTAL

Polyethylene oxide (PEO: $(-CH_2CH_2O-)_n$, Aldrich: average M_v 100,000) was used as the polymer matrix, and CB (Cabot BP2000) served as the conductive material. The PEO (0.4 g) was dissolved in 6 mL of tetrahydrofuran (Samchun Chemicals, 99.8%) at a temperature of 50°C over 20 min. Subsequently, CB (0.08 g) was dispersed in the PEO solution for 10 min. All the dissolution and dispersion processes were performed using ultrasonic techniques. The resulting CB-PEO dispersion was deposited onto a patterned soda-lime glass substrate (electrode spacing of 10 mm) using a drop-casting technique. The patterned electrode was formed using silver paste (Asahi Chemical Laboratory, LS-411AW), which was applied to the soda-lime glass substrate (2 cm × 2 cm) via a bar coating method. The deposited substrates were then dried at a temperature of 150℃ for 15 min. Then, 0.1 mL of the CB-PEO dispersion was dropped onto the silver-patterned glass using a syringe. The resulting CB-PEO layers were dried on a heating plate (Daihan Labtech, LHT-2030D) at a temperature of 50°C for 15 min. Then, the resistance of the sensors ranged from 1 kΩ to 3 kΩ. The CB-PEO sensors were treated using a diode laser (GKTOOLS, FB03-500) with a wavelength of 408 nm (3.04 eV) and a power of 500 mW. The laser beam diameter was 100 μm at the focal length of the collimation lens. The laser was mounted on an xy-stage (GKTOOLS, GK4545Pro), and its position was controlled using a personal computer. In this experiment, the laser scan speeds were set to 2, 4, 6, and 8 mm/s, and the effects of the laser scan speed and number of scans were investigated. The change in the resistance of the CB-PEO sensor during the laser process was measured using a multimeter (Agilent 34401A). The optical properties of the CB-PEO sensor films were analyzed using UV–Vis spectroscopy (Mecasys, OPTIZEN 3320), and the light emission of the diode laser was measured using an optical emission spectrometer (Ocean Optics, USB2000). The cross-sectional morphologies of the CB-PEO sensors were examined using scanning electron microscopy (SEM, FEI Versa 3D).

3. RESULTS AND DISCUSSIONS

Fig. 2 shows the light emission spectrum of the diode laser used in this experiment. The observed emission peak of the laser diode consists of two peaks centered at 408.4 nm (full width at half maximum (FWHM): 1.57 nm) and 410.4 nm (FWHM: 2.41 nm). CB has very good absorption in the UV–visible–near IR region [11], and the CB used in this experiment exhibited high light absorption at a wavelength of 408 nm. PEO exhibits an absorption of less than 10% at 408 nm. PEO exhibits absorption edges in the

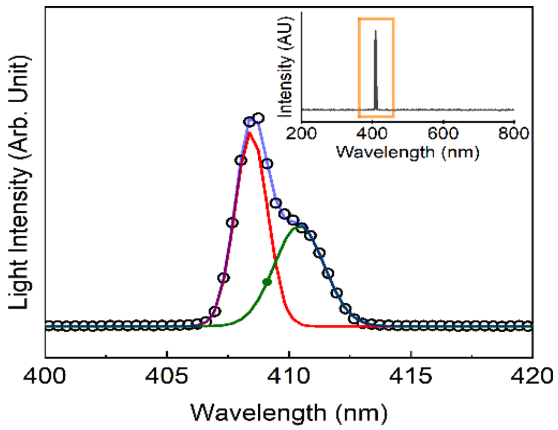

Fig. 2. Optical emission spectrum of diode laser (408 nm) light in this experiment.

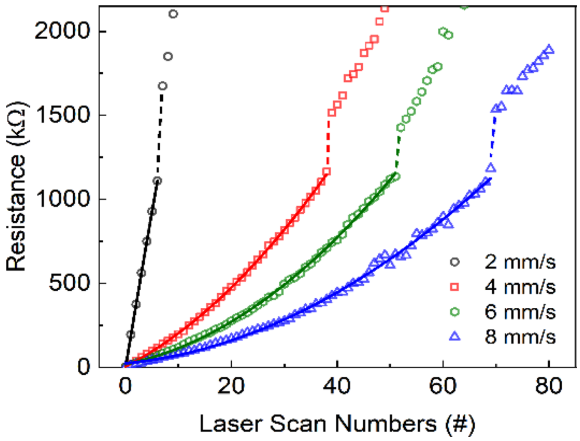

Fig. 3. Changes in resistance according to the number of laser scan at different scan speeds.

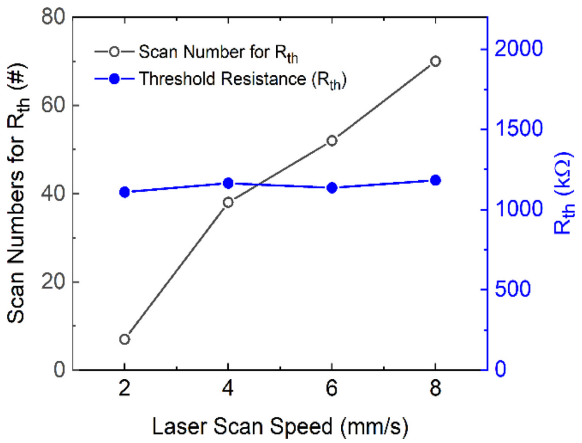

Fig. 4. The change of scan numbers for R_{th} and the variation of R_{th} according to different laser scan speed.

wavelength range shorter than 350 nm, which is attributed to its polyenic domain [12, 13]. This indicates that CB effectively functioned as a laser energy absorber.

Fig. 3 shows the change in resistance as a function of the number of scans at various scan speeds. As the number of scans increased, the sensor resistance also increased, demonstrating a second-order polynomial relationship. In addition, the resistance increased rapidly when the number of scans exceeded a certain resistance (R_{th}, average 1148 kΩ). The relationship between the scan speed and the number of scans required to reach R_{th} is nearly linear, as shown in Fig. 4. This indicates that the product of the exposure time and the number of scans remained constant. The laser scan speed is inversely proportional to the laser exposure time, and the product of the exposure time and the number of scans is related to energy absorption. Therefore, the R_{th} values of the CB-PEO sensors were similar at the same level of energy absorption.

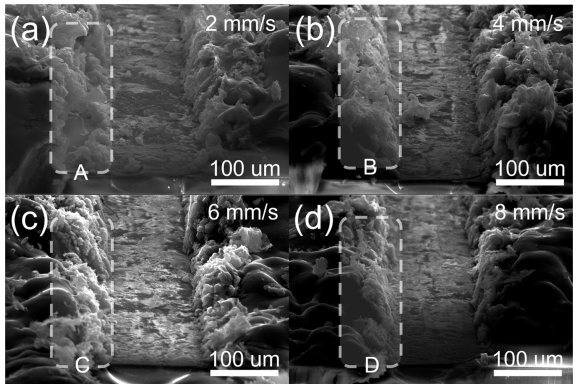

Fig. 5. SEM images of CB-PEO gas sensors laser-treated at different scan speeds with a constant scan number of five times (scan speeds of (a) 2, (b) 4, (c) 6, and (d) 8 mm/s).

Fig. 5 shows the SEM images of the CB-PEO sensor processed at different scan rates. As indicated by boxes A, B, C, and D in Fig. 5, the CB-PEO sensor exhibited a pronounced swelling trace at low scan rates. As the scan rate increased, the swelling trace

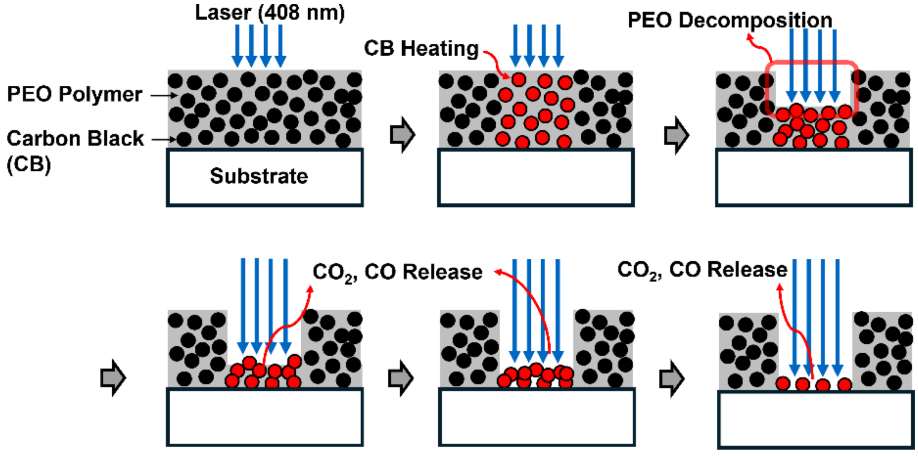

Fig. 6. Schematic illustrations for interaction between diode laser (408 nm) light and CB-PEO sensor.

diminished. This indicates that the CB was heated during the laser irradiation, which caused the decomposition of PEO into volatile gases.

Fig. 6 shows the reaction mechanism between the CB-PEO films and laser light. The resistance change mechanism of CB-PEO during laser processing was as follows: First, when the laser was incident on the CB-PEO layer, the CB absorbed the laser energy and was heated.

The PEO polymer then decomposed into a volatile gas, causing CB to agglomerate in the polymer matrix. During the laser process, CB combined with atmospheric oxygen and was released as carbon dioxide or carbon monoxide. This loss of CB appeared to be the main factor contributing to the increase in resistance. Additionally, the transition from a continuous carbon layer to a discontinuous carbon layer during the loss of CB resulted in a rapid increase in the resistance.

Fig. 7 shows a schematic illustrating the principle of resistance control in CB-PEO layers. This principle can be explained as follows: The resistance of the sensor can be considered as the sum of two series resistors, R_1 and R_2, with the total resistance expressed as the sum of $R_1 + R_2$. As the laser-trimmed area is negligible compared with the total device area, the values of R_1 and R_2 can be assumed to remain nearly constant before and after trimming. After the laser treatment, the laser-processed region can be treated as a new resistance (R_{Laser}); thus, the total resistance becomes approximately $R_1 + R_2 + R_{Laser}$. R_{Laser} acts as a variable resistance that changes based on the laser-processing conditions.

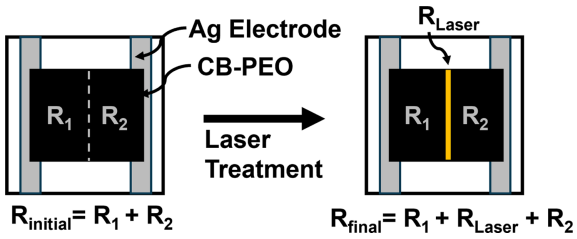

Fig. 7. Schematic for the resistance control of CB-PEO gas sensor using a diode laser ($R_{initial}$: resistance before laser treatment, R_{final}: resistance after laser treatment).

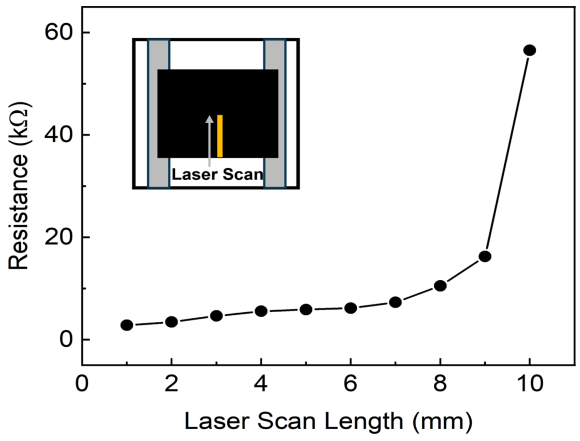

Fig. 8. Changes in the resistance of the CB-PEO sensor according to the laser scan length (The initial resistance of CB-PEO was 1 kΩ.)

Fig. 8 shows the change in the resistance of the CB-PEO sensor according to the laser scan length. The initial resistance of the CB-PEO sensor used in this experiment was 1 kΩ. As the length of the laser scan increased, the resistance of the sensor also increased. The resistance could be controlled very precisely from 1 kΩ to approximately 20 kΩ.

4. CONCLUSIONS

The resistance of the CB-PEO sensor can be adjusted from several kΩ to approximately 1000 kΩ using a laser-trimming process. Considering the number of scans and exposure time, the CB-PEO sensors tend to reach similar R_{th} values at similar levels of irradiation energy. The SEM images indicated that as the scan rate increased, the swelling trace diminished. This mechanism shows that the CB of the laser-treated portion acts as a variable resistor and that the resistance increases as the thickness of the CB decreases. This approach not only aids in circuit design but also simplifies the algorithms by allowing the precise resistance control of the sensors. This sensor holds promise for use as a precision resistor on flexible substrates.

ACKNOWLEDGMENT

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2018R1D1A1B07049180, NRF-2019R1I1A1A01059259).

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