

Screen-Printed Ag_2Te -Based Short-Wave Infrared (SWIR) Sensor

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ABSTRACT: Recent advances in smart factories, autonomous drones, and industrial robotic systems have significantly increased the demand for short-wave infrared (SWIR) sensors operating in the eye-safe wavelength region. Although PbS quantum dots (QDs)-based sensors have demonstrated excellent infrared sensing performance, their practical applications are limited by environmental regulations owing to the presence of toxic lead (Pb). In this study, a lead-free single-layer SWIR sensor was developed using Ag_2Te quantum dots as the photoactive material. Ag_2Te QDs exhibiting a distinct absorption peak at 1607 nm were successfully synthesized and incorporated into a composite ink containing PCBM as the electron-transport material and P3HT as the hole-transport material. The composite ink was directly screen-printed onto interdigitated electrodes to fabricate a simplified single-layer sensor. Optical characterization confirmed the successful synthesis of highly crystalline Ag_2Te QDs with strong absorption in the SWIR region, while the optimized composite composition promoted efficient charge separation and carrier transport. Under infrared illumination, the optimized device exhibited a photoresponse of 214.7%, a responsivity of 0.793 A/W, and response and recovery times of approximately 0.35 s. These results demonstrate that the Ag_2Te -PCBM-P3HT composite provides an environmentally friendly, low-cost, and scalable platform for high-performance SWIR sensors with strong potential for applications in smart factories, autonomous drones, industrial automation, and next-generation infrared sensing systems.

KEYWORDS: *Quantum dots, Ag_2Te , SWIR, Photodetector*

1. INTRODUCTION

Recently, with the advancement of technologies in smart factories, industrial robots, drones, and unmanned vehicles, the demand for infrared-based sensors has been continuously increasing. These systems utilize various optical sensors to perceive the surrounding environment in real time and detect objects; in particular, short-wavelength infrared (SWIR) sensors are attracting attention as a next-generation optical sensor technology because they enable stable object recognition even in low-light environments or in the presence of fog, smoke, and dust. SWIR light provides superior image quality due to lower scattering and higher transmittance compared to near-infrared (NIR), and wavelengths above 1400 nm are classified as an "eye-safe" region that does not

reach the human retina. Accordingly, the application of SWIR sensors is expanding in fields such as smart factory automation inspection systems, drone-based remote monitoring systems, logistics automation robots, and distance measurement sensors. Currently, commercial SWIR sensors are primarily fabricated using semiconductors based on InGaAs, Ge, and HgCdTe [1-4]. While these sensors offer high sensitivity and excellent stability, they have limitations in terms of high manufacturing costs due to the need for complex epitaxial growth processes and expensive manufacturing equipment, as well as the requirement for cooling devices to reduce thermal noise generated during room-temperature operation. To address these issues, research on solution-processable quantum dots (QDs)-based SWIR sensors is actively underway. In particular, PbS and PbSe QDs are widely utilized in SWIR sensor research due to their excellent light absorption and wavelength tuning characteristics [5-12]. However, Pb-based QDs contain harmful heavy metals, posing limitations in terms of environmental and human safety, and making it difficult to comply with the European Union's RoHS regulations [13]. Recently, to resolve these problems, research on eco-friendly

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lead-free QDs materials has been increasing, and Ag₂Te QDs are attracting attention as a representative alternative material [13,14]. Ag₂Te QDs enable the realization of an eye-safe SWIR region through particle size control and exhibit infrared absorption characteristics similar to those of Pb-based QDs. Furthermore, they do not contain harmful heavy metals such as lead (Pb) and mercury (Hg), making them suitable for the realization of eco-friendly optoelectronic devices [20-25]. Conventional Ag₂Te-based sensors have been fabricated using a multilayer structure of P3HT/Ag₂Te/ZnO. However, multilayer solution processing can lead to increased process complexity and interfacial degradation issues caused by interlayer dissolution. Therefore, a new device structure is required that can ensure excellent photoresponse characteristics while simplifying the structure. In this study, Ag₂Te QDs, PCBM, and P3HT were prepared as a single composite ink, and a single-layer SWIR sensor was fabricated using a screen printing process [19]. With this strategy, we aimed to simplify the process and reduce manufacturing costs while simultaneously securing excellent infrared sensing performance.

2. EXPERIMENTAL

2.1 Synthesis of Ag₂Te QDs

Ag₂Te QDs were prepared using a colloidal synthesis method utilizing AgI-OLAm (silver iodide-oleylamine) precursors and TeO₂-DDT (tellurium oxide-dodecanethiol) precursors [13,14]. First, the Ag precursor solution was prepared by mixing 5 mmol of AgI with 5 mL of OLAm and stirring at 50°C for 1 hour. The Te precursor solution was prepared by mixing 1.25 mmol of TeO₂ with 5 mL of DDT and stirring at 115°C for 30 minutes. Subsequently, 15 mL of OLA and 7.5 mL of 1-octadecene (ODE) were added to a three-necked flask, and vacuum degassing was performed at 120°C for 15 minutes to remove moisture and oxygen from the reaction solution. Afterward, the reaction temperature was raised to 180°C under an argon atmosphere. This temperature was selected to provide a reproducible nucleation rate while allowing the subsequent growth of Ag₂Te QDs with the targeted particle size. After reaching the set temperature, 2 mL of AgI-OLAm solution was injected into the flask and reacted for approximately 10 minutes, after which 5 mL of TeO₂-DDT solution was rapidly added. Immediately after the precursor was injected, the solution turned a deep black color, indicating that the nucleation and growth of Ag₂Te QDs had begun. The reaction was maintained for 30 minutes and then naturally cooled to room temperature. To remove residual precursors and impurities from the synthesized solution, it was washed

with a mixture of methanol and toluene in a 3:1:1 ratio. Subsequently, the Ag₂Te QDs powder was recovered by centrifugation at 3000 rpm for 10 minutes. The finally obtained Ag₂Te QDs were redispersed in hexane, a non-polar solvent, to prepare an Ag₂Te QDs solution with a concentration of 30 mg/mL.

2.2 Preparation of Ag₂Te QDs Composite paste

Ag₂Te QDs composite inks were prepared using conductive polymers to enhance charge transport characteristics. PCBM ([6,6]-phenyl-C61-butyric acid methyl ester) was used as the electron-transport material, and P3HT (poly(3-hexylthiophene)) was applied as the hole-transport material [7,8]. Based on 1 mL of an Ag₂Te QDs solution with a concentration of 30 mg/mL, PCBM and P3HT were mixed according to the compositional ratios shown in Table 1. To verify the sensor characteristics with varying compositions, composite inks were prepared under conditions where the total content of PCBM and P3HT was greater than, equal to, or less than the Ag₂Te QDs content. In addition, to compare the effect of the charge transport layer, an Ag₂Te QDs paste without PCBM and P3HT was also prepared. To ensure viscosity suitable for the screen printing process, 15 mg of ethyl cellulose was added as a rheology modifier [19]. Subsequently, the mixed solution was stirred at 60°C for 3 hours, and then stirred for an additional 12 hours at room temperature to prepare a uniform Ag₂Te QDs composite ink.

2.3 Fabrication of Ag₂Te QDs-Based SWIR Sensors

A SWIR sensor was fabricated using a screen printing process. An alumina substrate measuring 5 × 5 mm² was used, and the substrate was sequentially cleaned using acetone, methanol, and isopropyl alcohol (IPA) to remove surface impurities. On the cleaned substrate, interdigitated electrodes (IDEs) were formed using a screen printing process with silver (Ag) paste.

Subsequently, the prepared Ag₂Te QDs composite ink was printed onto the IDE electrodes using a shadow mask designed to have an active region of 3 × 3 mm². Each sample was

Table 1. Mixing ratio of Ag₂Te QDs and electron/hole extraction layers.

Material (mg)	Sample 1	Sample 2	Sample 3	Sample 4
Ag ₂ Te QDs	30	30	30	30
PCBM	30	30	15	0
P3HT	30	15	30	0
Ethyl cellulose	15	15	15	15

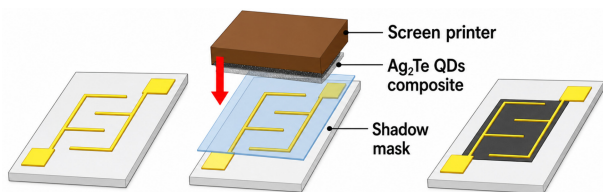


Fig. 1. Schematic diagram of the fabrication of a SWIR sensor based on Ag_2Te QDs composite.

fabricated under identical process conditions according to its composition ratio, and heat treatment was performed at 95°C for 30 minutes to remove residual solvent after printing. Finally, a single-layer SWIR sensor with a sensing region of 9 mm^2 was fabricated.

3. RESULTS AND DISCUSSIONS

3.1 Characteristics of the synthesized Ag_2Te QDs

The optical and structural characteristics of the synthesized Ag_2Te QDs were investigated by absorbance spectroscopy and X-ray diffraction (XRD). As shown in Fig. 2(a), the Ag_2Te QDs exhibited a pronounced absorption peak centered at

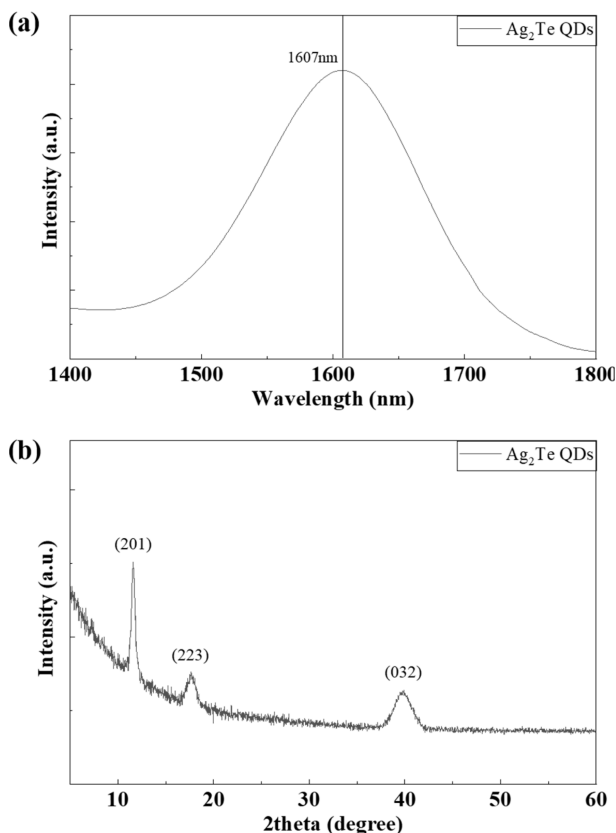


Fig. 2. (a) Absorbance and (b) XRD analysis characteristics of synthesized Ag_2Te QDs.

approximately 1607 nm, with a full width at half maximum (FWHM) of approximately 100 nm [13,14]. The narrow absorption bandwidth indicates that the synthesized Ag_2Te QDs possess wavelength-selective absorption in the short-wave infrared (SWIR) region, demonstrating their suitability as an active material for 1607 nm SWIR sensors. Since the 1607 nm wavelength lies within the eye-safe infrared region, the synthesized Ag_2Te QDs are expected to be applicable to optical sensing systems for smart factories, industrial automation, autonomous drones, and remote monitoring applications.

To examine the crystal structure of the synthesized QDs, a thin film was prepared by spin-coating an Ag_2Te QDs solution (30 mg mL^{-1}) onto a $15 \times 15\text{ mm}^2$ glass substrate at 1500 rpm for 30 s, followed by thermal annealing at 95°C for 30 min. The XRD pattern shown in Fig. 2(b) exhibits well-defined diffraction peaks corresponding to the (201), (223), and (032) crystallographic planes of Ag_2Te [13,14]. These diffraction peaks agree well with the standard crystal structure reported in previous studies, indicating the successful formation of highly crystalline Ag_2Te quantum dots without detectable impurity phases. The excellent crystallinity is expected to facilitate efficient carrier transport within the quantum dot layer, thereby contributing to the enhanced photoresponse characteristics of the fabricated SWIR sensors.

3.2 Characteristics of the fabricated SWIR Sensors

The photoresponse characteristics of the fabricated Ag_2Te QDs-based SWIR sensors were evaluated in a dark optical chamber. Each device was measured at an applied bias of 3 V using a source meter unit (B2902A, Keysight). A Thorlabs SLS201L/M tungsten-halogen light source was used, and the incident optical power at 1607 nm was measured to be $4.6\text{ }\mu\text{W}$. The photoresponse was calculated using Eq. (1) and the responsivity was calculated using Eq. (2)

$$\text{Photoresponse (\%)} = \frac{I_{\text{light}} - I_{\text{dark}}}{I_{\text{dark}}} \times 100 \quad (1)$$

$$\text{Responsivity (A/W)} = \frac{I_{\text{light}} - I_{\text{dark}}}{P_{\text{in}}} \quad (2)$$

where I_{light} and I_{dark} denote the photocurrent under illumination and in the dark, respectively, and P_{in} is the incident optical power ($4.6\text{ }\mu\text{W}$ at 1607 nm). The response and recovery times were determined from the 0 – 90% rising edge and the 100 – 10% falling edge of the photocurrent transient.

Sample 1 exhibited a photocurrent variation of $0.80\text{ }\mu\text{A}$, a photoresponse of 33.3%, and a responsivity of 0.174 A/W . The response and recovery times were 5.54 s and 5.88 s,

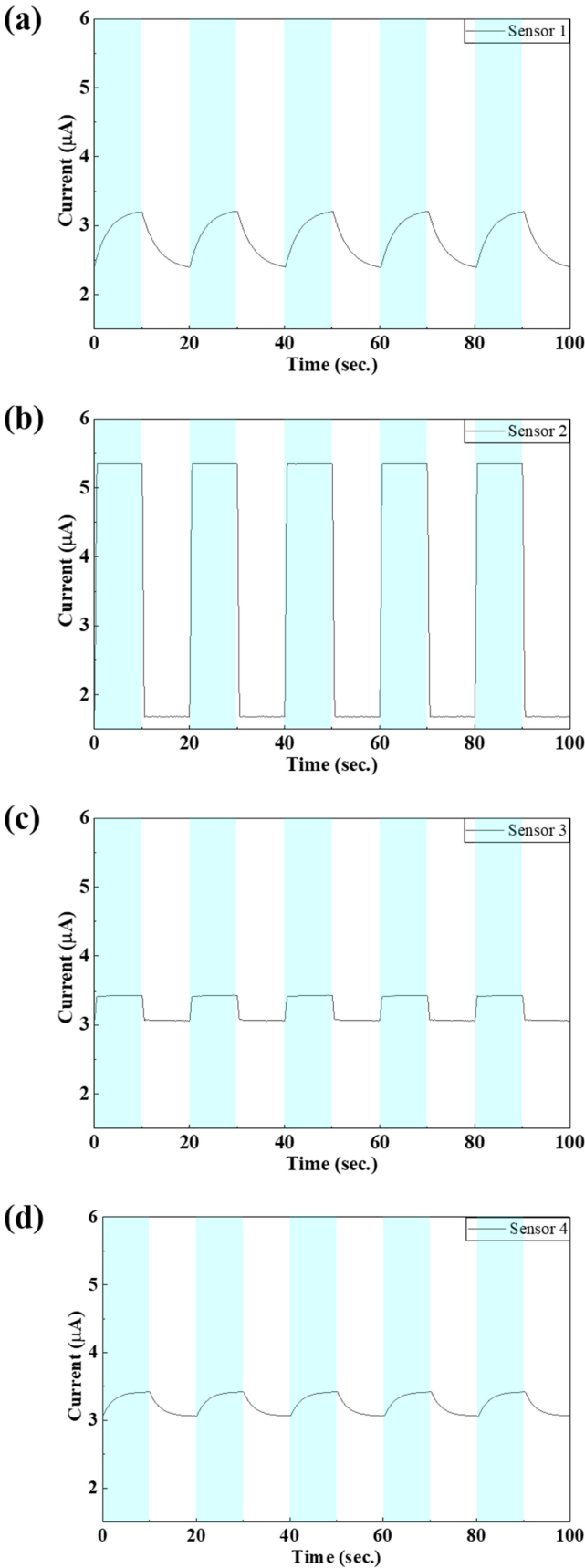


Fig. 3. (a), (b), (c) and (d) Current properties of SWIR sensors according to Ag₂Te QDs composite conditions

Table 2. Response characteristics of the fabricated SWIR sensors.

Sensor	Photo response (%)	Responsivity (A/W)	Response (s)
1	33.3	0.174	5.54
2	214.7	0.793	0.35
3	11.5	0.076	0.36
4	11.5	0.076	4.59

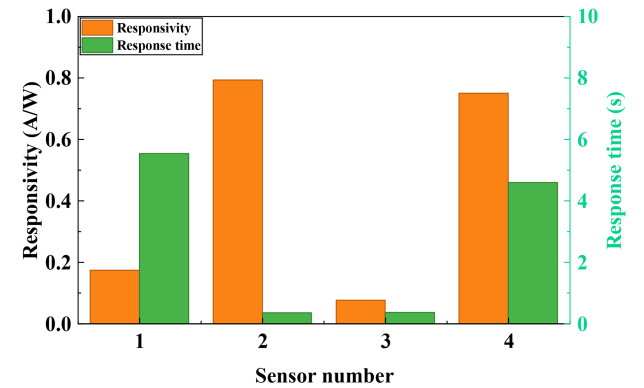


Fig. 4. Responsivity and response time characteristics of the fabricated SWIR sensors.

respectively. Excessive PCBM and P3HT reduced the effective Ag₂Te QDs fraction and increased carrier recombination [12,20]. Sample 2 exhibited the best performance with a photocurrent variation of 3.65 μA, a photoresponse of 214.7%, a responsivity of 0.793 A/W, and response/recovery times of 0.35 s/0.35 s. The optimized PCBM/P3HT composition enabled efficient charge separation and balanced carrier transport [15,21]. Sample 3 exhibited a photoresponse of 11.5% and a responsivity of 0.076 A/W. Although the transient response remained relatively fast (0.36/0.37 s), the reduced PCBM content limited electron extraction. Sample 4 exhibited a photoresponse of 11.5%, a responsivity of 0.076 A/W, and slower response/recovery times of 4.59 s and 4.57 s because dedicated charge transport materials were absent [20,21]. Quantitatively, the photoresponse of Sample 2 was approximately 6.4 times higher than that of Sample 1 and 18.7 times higher than those of Samples 3 and 4, while its responsivity was approximately 4.6 and 10.4 times higher, respectively. In addition, its response time was approximately 16 times shorter than that of Sample 1 and 13 times shorter than that of Sample 4, quantitatively supporting the enhanced charge separation and transport achieved by the optimized composition. Overall, Sample 2 showed the highest photoresponse and responsivity together with the fastest transient characteristics, indicating that the Ag₂Te QDs:PCBM:P3HT composition of 30:30:15 mg provides the optimum balance between infrared absorption and charge transport.

4. CONCLUSIONS

In this study, a single-layer SWIR sensor based on a lead-free Ag_2Te QDs composite was successfully fabricated using a solution-processable screen-printing technique. Ag_2Te QDs exhibiting a distinct absorption peak at 1607 nm were successfully synthesized, and their high crystallinity was confirmed by X-ray diffraction analysis. To improve charge transport within the active layer, PCBM and P3HT were incorporated as electron- and hole-transport materials, respectively, to form a printable Ag_2Te QDs composite ink. Among the fabricated devices, the optimized composition of Ag_2Te QDs:PCBM:P3HT = 30:30:15 mg exhibited the best overall performance, achieving a photoresponse of 214.7%, a responsivity of 0.793 A/W, and rapid response/recovery times of approximately 0.35/0.35 s under 1600 nm infrared illumination. The improved performance is attributed to the optimized balance between infrared absorption and charge transport, which effectively promoted charge separation while suppressing carrier recombination. Compared with conventional multilayer quantum dot sensors, the proposed single-layer architecture simplifies the fabrication process by eliminating multiple coating steps while maintaining stable photoresponse characteristics. In addition, the screen-printing process offers excellent compatibility with large-area and low-cost manufacturing, making the proposed device attractive for practical production. The proposed Ag_2Te QDs composite provides a promising lead-free alternative to conventional Pb-based QDs sensors while maintaining excellent SWIR detection performance. Although the proposed device demonstrated promising SWIR sensing performance, further studies are needed to evaluate its long-term stability and performance under various operating conditions. Future work will focus on optimizing the material composition and device structure to improve sensitivity, reliability, and practical applicability. Furthermore, the combination of environmentally friendly materials and scalable fabrication technology suggests considerable potential for future applications in non-destructive inspection, industrial process monitoring, agricultural and food quality inspection, and wearable or flexible infrared sensing systems, where low-cost, lightweight, and large-area SWIR sensors are increasingly required.

CRedit Authorship Contribution Statement

Jinbeom Kwon : Carried out all aspects of the research and manuscript preparation.

Declaration of Competing Interest

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.

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