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Hydrophobic Surgical Mask Based on Sputtered Amorphous Carbon Embedded Silve Nanocluster (SAC-Ag) Film

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Abstract

The COVID-19 virus transmits *via* contaminated surfaces or respiratory droplets. Masks reduce infection risk by blocking virus-containing droplets from sneezing and talking. However, commercial surgical masks are made of low-melting-point polymers, limiting advanced coating techniques. This report presents a novel low-temperature coating method using Ion Beam Sputtering Deposition (IBSD) to apply an Amorphous Carbon-embedded silver nanocluster (SAC-Ag) film onto surgical masks. This coating significantly enhances surface hydrophobicity while preserving the polymeric substrate morphology during deposition. Improved hydrophobicity was demonstrated by a water contact angle of 136°±2.4°, indicating enhanced droplet repellence and reduced droplet adhesion on the coated surface. Additionally, the silver nanoclusters may provide antimicrobial benefits as reported in previous studies; however, antimicrobial performance was not experimentally evaluated in this work.

Keywords: Coated materials, COVID-19, Hydrophobicity, Mask, Silver
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Introduction

As of 2024, COVID-19 continues to impact global health, with over 776 million confirmed cases and seven million deaths recorded worldwide [1]. The virus transmits through respiratory droplets and contaminated surfaces [2], making medical masks essential for limiting infection spread [3-6]. However, surgical masks have limitations: their hydrophobic surfaces can still retain virus-laden droplets, increasing cross-contamination risk [7], and safe reuse without sterilization remains challenging [8]. Improving mask hydrophobicity and adding protective functionalities are key research directions [9].

Various materials have been explored for water repellence [10], but many require complex chemistries or high-temperature processing unsuitable for polypropylene-based masks. In this study, a low-temperature alternative: depositing amorphous-carbon–embedded silver nanoclusters (SAC-Ag) on surgical masks using Ion Beam Sputtering Deposition (IBSD) was presented. This method achieves film growth at low substrate temperatures with strong adhesion [11]. The SAC-Ag coating enhances surface hydrophobicity (water contact angle: 136°±2.4°), facilitating droplet roll-off. Silver nanostructures are known for plasmonic, photothermal, and antimicrobial properties [12,13], offering potential for future multifunctional mask development. This work introduces a substrate-compatible, adhesion-stable coating approach for enhancing standard surgical mask functionality.

Materials and Methods

SAC-Ag coatings were deposited onto pristine surgical masks using IBSD. A graphite target was sputtered at 2×10^{-5} Torr with Argon (Ar) gas at 1800 *V* and 25 *mA* for 2 *hr*, followed by 30 *s* of silver nanocluster deposition at 0.9 *keV* and 10 *mA*. No post-deposition thermal treatment was applied to prevent substrate deformation. Microstructural and elemental analyses were performed using Field Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive X-ray Spectroscopy (EDS). Raman spectroscopy (532 *nm* laser, 10 *mW*) confirmed amorphous carbon structure and silver–carbon interactions. Wettability was evaluated *via* contact angle measurements using 4-5 μl deionized water droplets, analyzed with ImageJ and the DropSnake plugin. Optical absorption was measured by UV-Vis spectroscopy (200-1100 *nm*), and coating thickness was determined to be approximately 41 *nm* by optical reflectometry.

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Results and Discussion

The coating process is schematically shown in figure 1. As shown, the ion beam bombards a target and ejects particles at the atomic scale from the target to form a thin film on the adjacent substrate surface. The principle of the IBSD technique is that the energy required for thin-film nucleation and growth can be derived from the kinetic energy of an accelerated ion beam of the deposition material. The target-substrate angle was adjusted to approximately 45°.

Ion-beam energy optimization was critical, as polypropylene fibers are susceptible to thermal degradation (melting point below 110°*C*). The appropriate energy for carbon deposition was 1.8 *keV*, eliminating the need for water cooling. Based on prior work [14], 0.9 *keV* with 30 *s* deposition was optimal for silver nanoclusters. During deposition, substrate temperature remained below 100°*C* to prevent damage.

In this research, during the first stage, a graphite target was sputtered by an Ar ion beam to form a carbon film using sputtering at a vacuum of 2×10^{-5} Torr on the mask, which was simultaneously bombarded by another energetic Ar ion beam. Subsequently, a silver target was sputtered by an Ar ion beam to deposit silver clusters on the surface of the carbon film. During the deposition, the temperature of the mask, serving as the substrate, was kept below 100°*C* to prevent surface damage.

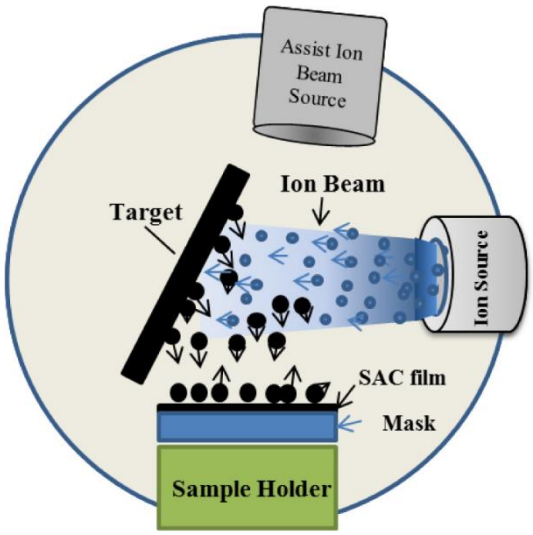

Figure 1. Schematic of IBSD system for SAC-Ag deposition.

The wetting properties of the pristine mask were examined using Static Contact Angle (SCA). The contact angle of 5 μl water on the pristine mask was approximately 110°±3.2 (Figure 2). Although classified as hydrophobic, droplets frequently adhere to the pristine mask surface, indicating potential for enhancement. SEM characterization (Figure 2) revealed randomly distributed mask fibers with diameters of approximately 10 μm.

To determine the chemical composition of the carbon-coated masks, their phonon vibration modes were analyzed using Raman spectroscopy. The Raman spectrum (Figure 3) confirmed amorphous carbon, with D, G, and 2D peaks at 1366, 1595, and 2639 cm^{-1}, along with a weak D+G peak at 2942 cm^{-1}. The coated fibers were uniformly covered with amorphous carbon nanosheets, and bright silver nanoclusters were distributed across the surfaces. The ~41 *nm* coating preserved the fibrous architecture without pore blockage or fiber network collapse. Reduced airborne particulate accumulation was also observed on coated fibers. EDX analysis identified carbon and silver in the coating. Mechanical bending and tape-adhesion tests revealed no cracking, delamination, or detachment, indicating good adhesion of the SAC-Ag layer.

The SAC-Ag coating increased the water contact angle to 136°±2.4. Based on previous studies on silver-cluster deposition on carbon-based coatings [14], it is plausible that silver nanoclusters preferentially accumulate at energetically favorable surface sites, including defect-rich regions. Such accumulation may reduce the density of active surface sites and consequently contribute to a reduction in surface free energy. However, the present study does not directly verify this

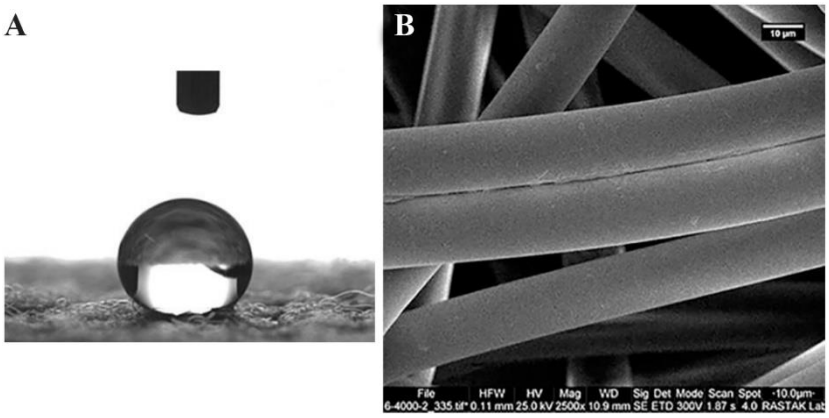

Figure 2. A) Water SCA of the pristine surgical mask; B) SEM image of the pristine surgical mask fibers (scale bar: 10 μm).

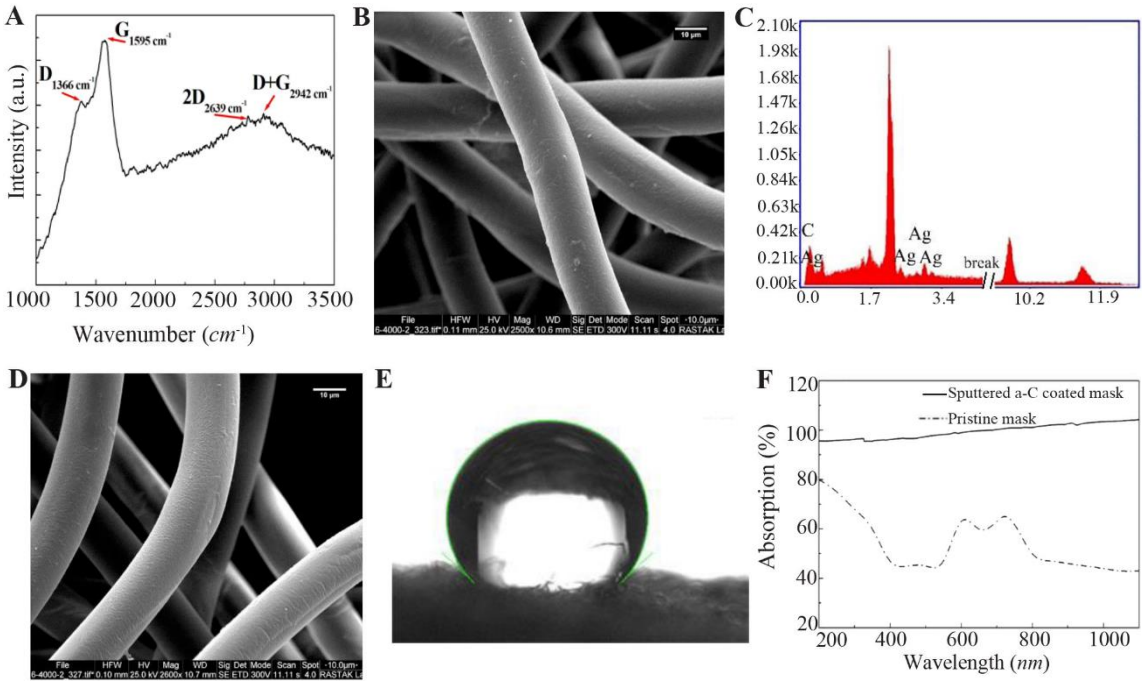

Figure 3. Properties of the SAC-Ag-coated surgical mask: A) Raman spectrum; B) SEM image of SAC-Ag-coated fibers; C) EDX spectrum; D) SEM image after bending and tape-adhesion tests; E) Water contact angle; and F) Optical absorption spectra of pristine and SAC-Ag-coated masks.

mechanism, and therefore it should be regarded as a plausible interpretation rather than a definitive conclusion. In any case, what is observed indicates that the surface free energy decreases, leading to an increased contact angle. Indeed, for carbon-based surfaces, defects are crucial factors influencing hydrophobicity and hydrophilicity [15]. Surface free energy calculated *via* the Young-Dupré equation decreased from ~48 to 20 *mJ/m²* after deposition. This reduction correlates with increased contact angle and enhanced hydrophobic characteristics. Figure 3 also compares the optical absorption of pristine and coated masks. The SAC-Ag coating exhibited broadband absorption exceeding 95% across 200-1100 *nm*, attributed to amorphous carbon and silver nanoclusters.

Previous studies [16,17] have reported that photothermal materials can be utilized for thermal inactivation of micro-organisms and that silver-containing coatings may exhibit antimicrobial activity through the release of silver ions. Furthermore, SEM observations indicate reduced accumulation of environmental particulate matter on the SAC-Ag-coated fibers, which is consistent with the enhanced hydrophobicity of the coating. Nevertheless, neither photothermal sterilization, antimicrobial performance, nor self-cleaning behavior were directly evaluated in the present study. Therefore, further investigations are required to evaluate the possible photothermal and antimicrobial functionalities of the SAC-Ag coating. The broadband optical absorption of the SAC-Ag coating and the presence of silver nanoclusters suggest potential opportunities for future investigations of photothermal and antimicrobial functionalities. However, direct evaluation of these properties was beyond the scope of the present study. The enhanced hydrophobicity of the SAC-Ag coating may contribute to improved droplet repellence on the mask surface. Additional studies involving filtration efficiency, breathability, antimicrobial activity, and photothermal performance are required before the practical applicability and long-term performance of the coated masks can be fully established. The preservation of the fibrous morphology observed by SEM, together with the nanometer-scale thickness of the deposited SAC-Ag layer, suggests that the coating process does not substantially alter the pore structure responsible for air transport. Therefore, major deterioration of mask breathability is not anticipated, although quantitative air-permeability measurements should be performed in future investigations.

Conclusion

In this study, an IBSD technique was successfully employed to produce an amorphous-carbon film embedded with silver nanoclusters on temperature-sensitive surgical masks. The resulting SAC-Ag coating demonstrated enhanced hydrophobic properties, offering improved resistance to droplet adsorption while maintaining the structural integrity of the polypropylene mask fibers due to the intrinsically low-temperature nature of the IBSD process. Mechanical bending and tape-adhesion evaluations indicated that the deposited SAC-Ag layer remained attached to the mask fi-

bers without visible delamination, suggesting satisfactory coating stability during routine handling. In addition, SEM observations revealed reduced accumulation of environmental particulate contaminants on the coated fibers, suggesting enhanced resistance to surface contamination. Given the well-documented plasmonic absorption properties and previously reported antimicrobial behavior of silver nanoclusters, the presence of Ag within the deposited film may provide additional functional benefits; however, antimicrobial activity was not experimentally evaluated in the present study. Furthermore, the broadband optical absorption exhibited by the SAC-Ag coating suggests potential opportunities for future investigations of photothermal functionality. Nevertheless, the combined hydrophobic enhancement, reduced particulate accumulation, and potential functional contribution of silver suggest that SAC-Ag coatings may represent a promising approach for improving the surface characteristics of protective masks. As the demand for reliable and high-performance personal protective equipment continues to grow, the SAC-Ag–coated masks developed in this work present a practical and substrate-compatible approach that aligns well with clinical and public health needs.

Future studies should focus on evaluating filtration efficiency, breathability, long-term stability, antimicrobial activity, and photothermal behavior of these coatings. Such investigations will be essential for further assessing the applicability of SAC-Ag films in advanced mask technologies and validating their suitability for practical healthcare applications.

Conflict of Interest

The authors have no conflict of interest.

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