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Synthesis of Cu-doped V_2O_5 thin films with improved optical and CO_2 gas sensing

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This study provides a comprehensive investigation of Cu-doped vanadium oxide (V_2O_5) thin films prepared *via* a sol–gel/spin-coating method, correlating dopant-induced structural and optical modifications with improved CO_2 sensing performance at room temperature. XRD confirmed the incorporation of Cu into the V_2O_5 lattice without secondary phase formation, while FE-SEM revealed a morphological transition from nanoplates to nanobelts upon Cu-doping. EDX verified uniform elemental distribution, and UV-Vis measurements indicated a reduced optical band gap, consistent with enhanced charge transport. FTIR spectra exhibited characteristic V–O vibrations, along with CO_2-related absorption bands, indicating favorable surface interactions. Gas sensing experiments demonstrated that Cu incorporation significantly improved sensitivity, response/recovery times, and selectivity. At 8880 ppm CO_2, the 10 at% Cu-doped V_2O_5 films achieved a response of 40.7% with fast response (3.83 min) and recovery (3.3 min) times, excellent repeatability, and stable operation over 30 days. These findings establish 10 at% Cu-doped V_2O_5 thin films as a promising, low-cost material for efficient room-temperature CO_2 detection.

1 Introduction

Monitoring carbon dioxide (CO_2) concentrations is vital in areas such as indoor air quality control, industrial safety, and environmental protection. Elevated CO_2 levels in confined spaces can impair human health, while the steady rise of atmospheric CO_2 continues to drive global climate change. These concerns highlight the need for gas sensors that combine high sensitivity and selectivity with low cost and reliable operation under ambient conditions.[1,2] Metal oxide semiconductors (MOS) are among the most widely studied materials for gas detection due to their chemical stability, tunable electrical properties, and strong surface reactivity.[3–6] Within this class, vanadium pentoxide (V_2O_5) has drawn particular attention. Its layered orthorhombic structure, variable oxidation states (V^{5+}/V^{4+}), and high chemisorption capability make it highly responsive to adsorbed gas species.[7,8] Moreover, V_2O_5 possesses notable catalytic activity and a relatively narrow band gap ($\sim$2.3 eV), allowing efficient gas detection at low operating temperatures—an essential feature for energy-efficient sensors. Despite these advantages, pristine V_2O_5 exhibits only moderate CO_2 sensing behavior. Recent research has shown that doping with transition metals can significantly improve their performance by tailoring the electronic structure, increasing oxygen vacancy density, and facilitating charge carrier transport.[9–11] Among various dopants, copper (Cu) is especially promising due to its ability to stabilize surface states, enhance electrical conductivity, and promote active sites for gas adsorption.[12] Although several studies have reported CO_2 sensing using V_2O_5-based materials, most of these works have focused on bulk powders, glass–ceramic composites, or quartz crystal microbalance (QCM)-type devices. In contrast, this study offers a comprehensive investigation of Cu-doped V_2O_5 thin films prepared *via* a low-temperature sol–gel/spin-coating route, emphasizing the correlation between Cu-induced structural, optical, and electronic modifications and their influence on room-temperature CO_2 sensing behavior. The obtained thin films exhibit phase-pure α-V_2O_5, controlled nanostructure, and reduced crystallite size. The spin-coated Cu-doped V_2O_5 thin films that operate at room temperature, quantifying a $\sim$7× sensitivity enhancement with faster response/recovery and month-long stability, establishing a link between structure and properties among (001) preferred orientation, E_g narrowing, and oxygen-vacancy-mediated adsorption/charge transfer that underpins selectivity, and narrowed optical band gap, which collectively lead to enhanced sensitivity. Therefore, this work highlights Cu-doped V_2O_5 thin films as promising, low-cost, and energy-efficient materials for ambient CO_2 detection, providing new insights into dopant-driven performance enhancement in vanadium oxide systems.

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