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Electrochemical deposition of active materials towards integrated sensing on mechanical components

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Abstract
The evolution of advanced manufacturing is increasingly defined by the integration of smart functionalities such as sensors and encoders while facilitating active communication on mechanical components; enabling real-time monitoring, control and data-driven decision making in intelligent manufacturing systems. In this context, electrochemical layered micromanufacturing techniques (selective deposition and machining of layers) has the potential to enable integrated active functionalities on mechanical components such as on-machine direct writing of high-bandwidth and high-gauge factor strain gauges on prototype mechanical components.
In the same line, this work investigates electrochemical deposition (ECD) as a low-cost and scalable route for integrating sensing through deposition of active materials (e.g. semiconductors, bimetals) directly onto mechanical components. Zinc oxide (ZnO) layers were electrodeposited on stainless-steel substrates with different electrolyte concentration. The deposited layers exhibit uniform morphology, near-stoichiometric composition and tunable crystal orientation confirmed by SEM/EDS and XRD characterization. UV–Vis analysis indicated a direct bandgap of ~3.34 eV, validating the semiconducting quality. This approach will be extended towards mask-free and low-energy growth directly on metallic substrates, enabling conformal sensing layers on curved and load-bearing components.

Keywords: Electrochemical deposition (ECD), active materials, Integrated sensing.

1. Introduction

Intelligent manufacturing increasingly depends on integrated sensing to enable state monitoring, adaptive control, and predictive maintenance of production equipments[1]. Among various sensing modalities, strain gauges remain widely adopted due to their minimal influence on structural stiffness and dynamic behavior[2].

However, conventional strain gauges rely primarily on adhesive bonding of metallic/semiconductor strain gauges. These approaches suffer from limitations including muti-step processing and restricted compatibility with complex surfaces.

Recent advances in additive and hybrid manufacturing have motivated the exploration of alternative routes for direct integration of sensing functionalities onto mechanical components. In this context, electrochemical deposition (ECD) offers a localized, low-cost, and mask-free fabrication technique capable of depositing functional materials directly on metallic substrates. While ECD has been extensively investigated for metallic coating and bimetallic structures[3], its application to semiconductor sensing layers requires further research.

This work explores the electrochemical deposition of wide bandgap (3.37 eV) semiconductor material zinc oxide (ZnO) as an active piezoresistive materials for integrated strain sensing on mechanical components, with a focus on process feasibility, deposition quality and suitability for sensor integration.

2. Experimental methods and materials

Electrochemical deposition of ZnO was carried out using a conventional and stationary beaker-based two-electrode configuration at 343 K with different precursor concentrations. 0.1 M $NaNO_3$ was added to increase electrolyte conductivity (~11.57 mS/cm). A gold coated steel rod served as the counter electrode and the working electrode was SS304 (5 x 5 mm^2 surface area, i.e. deposition area). These experiments were conducted to investigate the suitable process window and electrolyte concentration to adapted towards more flexible jet-based electrochemical deposition. The experimental parameters employed in this study are summarized in Table 1.

Table 1 Experimental parameters for ECD of ZnO layers

Parameter	Value
$Zn(NO_3)_2{\cdot}6H_2O$	10, 25, 50, 100 mM
Supporting electrolyte	0.1 M $NaNO_3$
Working electrode	SS304 (5 x 5 mm^2)
Counter electrode	Au
Deposition potential	-1.5 V
Current density	~ 1 mA/cm^2
Temperature	343 K
pH	~ 6.5
Deposition time	300 s

During deposition, OH^- is generated at the cathode through the electrochemical reduction of nitrate species, followed by the precipitation and dehydration reactions leading to ZnO formation. The dominant electrochemical reactions on the cathode can be summarized as[4]:

$$NO_3^- + H_2O + 2e^- \rightarrow NO_2^- + 2OH^-$$
$$Zn^{2+} + 2OH^- \rightarrow Zn(OH)_2 \rightarrow ZnO + H_2O - \Delta Q$$

After deposition, the resulting samples were thoroughly rinsed with deionized water.

3. Results and discussion

3.1. Morphology and chemical composition

Prior to the microscopic investigation, the thickness of the deposited layers were determined to be in the range of 10-15 µm by optical microscopy (S neox, Sensofar). This micron-scale thickness ptovides a complete coverage of the SS304 substrate,

which is further supported by the following SEM/EDX analysis. Fig.1 presents the surface morphology of ZnO layers deposited on SS304 substrates at different $Zn(NO_3)_2{\cdot}6H_2O$ concentrations. A clear evolution in microstructure is observed as the concentration decreases. At high concentration (100 mM), the deposited layer consists of densely stacked, plate-like structures, whereas lower concentrations (10 mM) lead to finer features.

EDX analysis reveals a increase in the O:Zn atomic ratio with decreasing precursor concentration (Table 2). The O:Zn ratio increases from 0.327 at 100 mM to 0.817 at 10 mM, suggesting a shift towards less Zn-rich ZnO compositions at lower precursor concentrations. Although the O:Zn values remain below the stoichiometric ratio, this behavior is consistent with the known limitations of EDX for light element (O) quantification. In addition, non-stoichiometric ZnO exhibits enhanced electrical sensitivity, which is beneficial for resistive strain sensing.

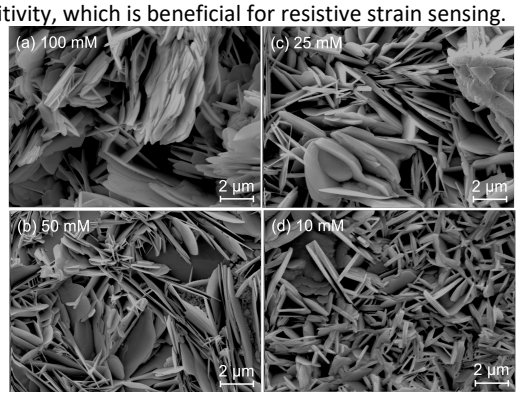

Figure 1. Surface morphology of electrodeposited ZnO layers at different $Zn(NO_3)_2{\cdot}6H_2O$ concentrations. (by XL30 FEG, Philips)

Table 2 Atomic ratio (O:Zn) at different $Zn(NO_3)_2{\cdot}6H_2O$ concentration

Concentration (mM)	Value (O:Zn)
100	0.327
50	0.428
25	0.695
10	0.817

3.2. Structural properties

Fig.2 demonstrates the XRD spectra of various ZnO structures obtained at different precursor concentrations. The major diffraction peaks of ZnO layers can be readily indexed to wurtzite structure (PDF 01-079-5604). A clear dependence of crystal orientation on precursor concentration is observed. For the ZnO layer deposited at 10 mM $Zn(NO_3)_2{\cdot}6H_2O$, the diffraction pattern is dominated by the (002) reflection, indicating a strong preferential orientation along the c-axis. In contrast, ZnO layers deposited at higher concentrations exhibit multiple reflections, suggesting a more randomly oriented polycrystalline structure.

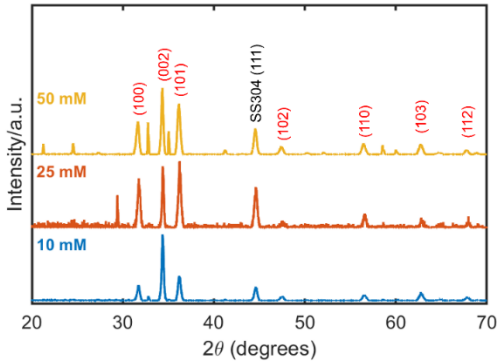

Figure 2. X-ray diffraction patterns of electrodepositied ZnO layers. (by D8 Advance, Bruker)

The enhanced (002) orientation at lower precursor concentration is attributed to a reduced growth rate and improved control of nucleation during ECD[4], which favors polar-axis growth. Such orientation control is particularly relevant for strain sensing applications, as stress applied along the [0001] direction in ZnO is expected to induce enhanced signal change.

2.4. Semiconductor properties

Fig. 3 shows the optical absorption behavior of ZnO layers electrodeposited at different $Zn(NO_3)_2{\cdot}6H_2O$ concentrations, evaluated using UV–Vis diffuse reflectance spectroscopy. The optical bandgap was estimated using the Kubelka–Munk transformation combined with Tauc analysis, assuming a direct allowed transition for ZnO. The extracted bandgap values range from 3.323 eV to 3.356 eV, which are consistent with reported values for intrinsic ZnO. Only minor variations in bandgap are observed as a function of electrolyte concentration, indicating that changes in deposition parameters primarily affect microstructure and crystal orientation rather than the intrinsic semiconducting nature of the deposited layers. The preservation of a stable and well-defined bandgap across different process conditions confirms the suitability of electrochemically deposited ZnO as an active semiconducting layer for integrated sensing applications.

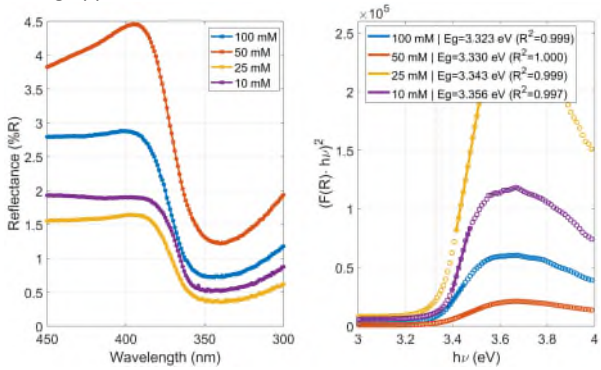

Figure 3. Optical characterization of electrodeposited ZnO layers by UV–Vis diffuse reflectance spectroscopy and Tauc analysis. (by Gary 60 UV-Vis, Agilent Technologies)

4. Summary

This work demonstrates the feasibility of electrochemical deposition as a micromanufacturing route for integrating ZnO-based active sensing layers directly onto mechanical component relevant steel substrates. By systematically varying the $Zn(NO_3)_2{\cdot}6H_2O$ concentration, the morphology, composition and crystal orientation of electrodeposited ZnO layers could be effectively controlled. The results highlight the potential of electrochemical deposition for producing uniform, orientation-controlled semiconductor layers on metallic substrates without post processing. This approach provides a promising foundation for the development of integrated, semiconductor-based strain sensing elements on mechanical components in intelligent manufacturing systems.

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