

Controlling Interconnection Density in 3D ZnO Networks for Optimized Charge Transport and Multimodal Sensing

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Summary:

Three-dimensional (3D) tetrapodal ZnO (t-ZnO) networks are promising for multifunctional sensing but often suffer from poor interparticle connectivity, which limits charge transport and sensitivity. We introduce interconnection density as a tuneable design axis governing both electronic and sensing behaviour in 3D semiconductor frameworks. Through a UV-driven photoelectrochemical approach, nanoscale ZnO bridges are selectively formed

between tetrapodal arms, enabling controlled tuning of network connectivity. The optimized interconnected networks show a 25-fold enhancement in UV response and highly efficient gas detection (10x enhancement), while preserving low-cost and scalable fabrication. Interconnection engineering thus emerges as a general route toward next-generation multimodal sensors [5].

Keywords: ZnO, nanobridge interconnections, photoelectrochemical growth, UV sensing, gas sensing

Background, Motivation and Objective

Tetrapodal ZnO networks [1,2] feature large surface area and mechanical stability, offering a suitable platform for UV and gas sensing. Yet, their performance is constrained by random and poorly defined inter-tetrapod junctions that impede carrier transport [4]. Traditional synthesis routes like CVD, hydrothermal or sputtering cannot independently control network connectivity.

This work decouples building-block formation from connection engineering and introduces interconnection density [2] as a fundamental design variable. The targeted goal is to establish how controlled nanoscale bridging affects charge transport, photoresponse, and gas-sensing behavior in a 3D ZnO framework.

Description of the New Method or System

A UV-pulse driven photoelectrochemical process was developed to induce localized ZnO nanobridges between t-ZnO arms (Fig 1(b)). The mechanism combines photocatalytic growth with selective chemical dissolution. Spatial and temporal control is achieved by modulating the UV pulse duration, which defines bridge density without high-temperature processing. The method is inherently scalable and compatible

with 3D-printed ZnO architectures [4] (Fig 1(a)), using direct-ink writing with a printable binder.

The controlled formation of nanobridged interconnections enhances the percolation network within the 3D architecture, facilitating the transition from percolation-limited to optimized charge transport and significantly improving carrier mobility across the network.

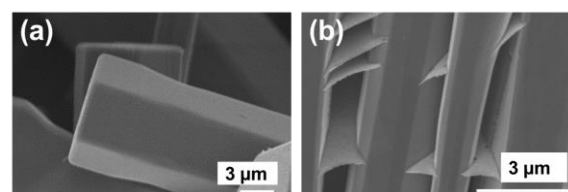


Fig. 1. SEM comparison of (i) point-contact-limited pristine t-ZnO and (ii) nanobridged IC t-ZnO, demonstrating the formation of interconnected junctions and increased contact area.

Results

SEM and TEM confirm controlled bridge formation, transforming discrete point contacts into a continuous percolating network. The interconnection-controlled ZnO (IC-t-ZnO) exhibits markedly higher conductivity and faster transient photoresponse than pristine t-ZnO,

with nearly 25× higher photocurrent under UV illumination (Fig 2(a)).

Gas-sensing tests for acetone reveal a multi-fold increase in response [3] and improved recovery kinetics, particularly in moderately interconnected samples (Fig 2(b)).

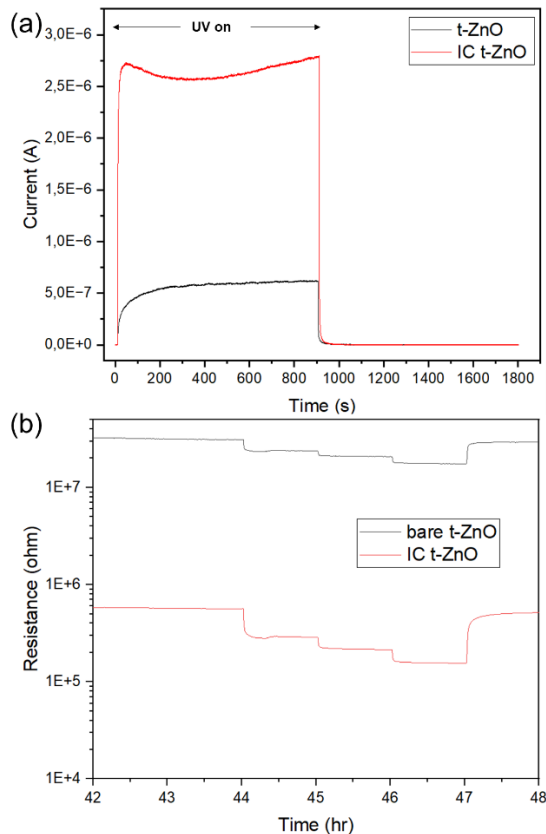


Fig. 2. (i) UV photoresponse and (ii) acetone sensing response of t-ZnO and IC t-ZnO, highlighting enhanced response magnitude and improved sensing performance in the interconnected network

The nanobridged interconnections increase effective contact area and enable efficient charge transfer, resulting in improved sensitivity and stability down to ppb-level concentrations (up to 125 ppb). A non-monotonic dependence [3] on interconnection density is observed, where optimal connectivity maximizes performance, while overly dense networks suffer from recombination and diffusion limitations.

Equations

The transient photoresponse was analyzed using a combined exponential–diffusive model, capturing both rapid surface-controlled recombination and slower diffusion-limited transport. The model shows excellent agreement with experimental data, enabling extraction of characteristic time constants and diffusion contributions. This fitting reveals a transition from percolation-dominated to

diffusion-influenced transport with increasing interconnection density.

The UV sensing response was quantified using the normalized photocurrent change, defined as $\text{Response} = \frac{I_{UV}}{I_{dark}}$, capturing the relative increase in conductivity under illumination. For gas sensing, the sensor response was calculated as $\text{Response} = \frac{R_{air} - R_{gas}}{R_{gas}}$, reflecting resistance modulation upon exposure to reducing gases [3]. These formulations enable consistent comparison of sensitivity across different operating conditions and interconnection densities.

Table 1. Comparative overview of ZnO sensor architectures highlighting performance

System	Response	Key Limitation
ZnO Nanowires	Moderate	Poor Connectivity
ZnO Thin Films	Low - Moderate	Limited Pathways
Hierarchical ZnO	High	Complex Synthesis
This work	Very High	Limited control over junction formation

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