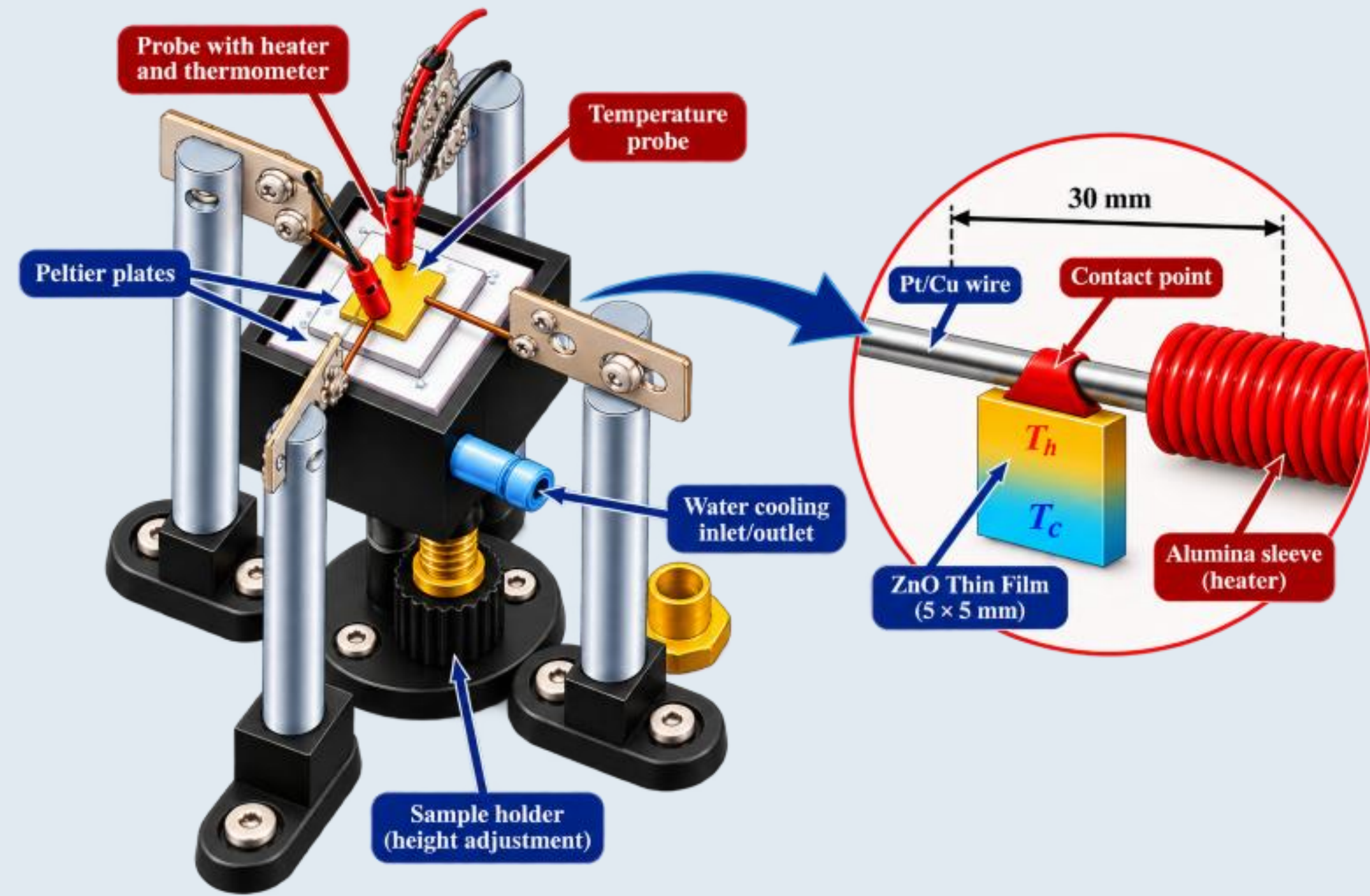


Numerical Design Optimization of a Seebeck Cell for Thermoelectric Sensing



Domain heating blurs the thermal gradient across a sample, making it difficult to resolve the sharp, localized ΔT needed for accurate thin-film Seebeck measurements. To address this, localized point-heating (LPH) was modelled in COMSOL Multiphysics® by self-consistently coupling heat and charge transport, comparing Pt and Cu electrodes and calculating the Seebeck coefficient of ZnO from the resulting voltage response.

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Introduction

Thermoelectric Seebeck cells convert waste heat directly into electrical energy, but their practical deployment is limited by electrode material selection and heat spreading, which degrades the temperature gradient (ΔT) driving the measurement. The Seebeck effect enables direct conversion of a temperature gradient into an electrical voltage:

$$V_{out} = \int_{T_{cold}}^{T_{hot}} S(T) dT \approx S \cdot \Delta T.$$

Where, (S) is the Seebeck coefficient and (ΔT) is the temperature difference across the material. For thin-film thermoelectric materials, accurate Seebeck measurements require a well-defined and localized thermal gradient. However, heat spreading through the electrodes, substrate, and surrounding

components can significantly modify the local temperature distribution, reducing the effective (ΔT) across the active layer and affecting the measured thermoelectric response.

To overcome heat spreading in conventional Seebeck cells, this work introduces a Localized Point Heating (LPH) configuration for ZnO thin films. Localized thermal excitation is used to generate a steep and confined temperature gradient across the active layer. A coupled thermal–electrical FEM model in COMSOL Multiphysics® was developed to investigate temperature distribution, electrode heat spreading, and thermoelectric voltage generation, enabling evaluation and optimization of the proposed Seebeck cell design.

Methodology

A 3D coupled thermal–electrical FEM model was developed in COMSOL Multiphysics® using the Heat Transfer in Solids and Electric Currents physics interfaces with the Thermoelectric Effect Multiphysics coupling to guide the development of a novel localized point-heating Seebeck cell. The cell consists of a 500 nm-thick, 5 × 5 mm² ZnO thin film on a glass substrate, contacted at its mid-edge by a 30 mm Pt/Cu electrode heated through an Al₂O₃ sleeve heater. An inward heat flux of $q_{in} = 2200 \text{ W/m}^2$ heats the electrode and generates localized point heating at the ZnO contact. Electrical ground ($V = 0$) was assigned at the cold end, while a terminal at the heated ZnO region was used to extract the thermoelectric voltage; a fixed lower temperature was applied at the exposed cold end. Pt and Cu were systematically compared to determine their influence on heat localization, thermal spreading, ΔT , and Seebeck voltage. The resulting thermal–electrical response provides a design framework for optimizing the electrode–heater configuration and establishing the proposed LPH architecture for practical Seebeck cell fabrication.

Results

- Thermal localization:** Pt produced a higher probe temperature (85.05 °C) than Cu (69.88 °C), demonstrating stronger heat confinement due to its lower thermal conductivity.
- Enhanced thermoelectric output:** Pt generated 22.22 mV, nearly 2.9× higher than Cu (7.79 mV), resulting from the larger localized ΔT across the ZnO film.
- Reliable Seebeck extraction:** The extracted Seebeck coefficients were $-322.95 \mu\text{V/K}$ (Pt) and $-312.47 \mu\text{V/K}$ (Cu). Their close agreement confirms the intrinsic n-type response of ZnO.
- Comparison with conventional heating:** The obtained values exceed the -150 to $-250 \mu\text{V/K}$ range associated with conventional macro-scale heating, indicating reduced influence of substrate heat sinking and thermal parasitics.

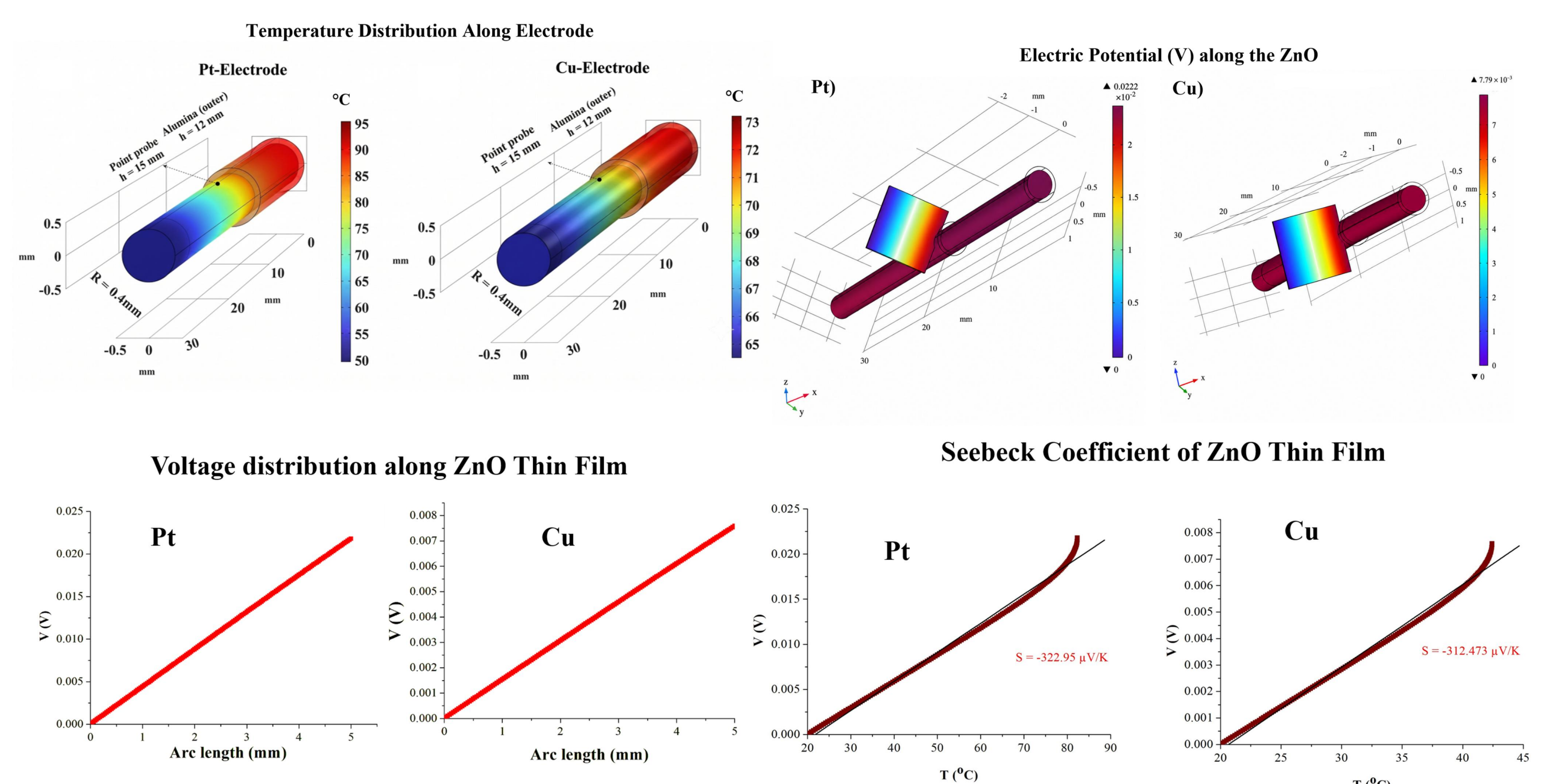


Figure 2. Simulated temperature and electric potential distributions along the Pt- and Cu-electrodes, with corresponding voltage-vs.-arc-length profiles and extracted Seebeck coefficients obtained from V–T curves along ZnO .

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