Supporting Information

Study on Electrical Contact of Solid–Liquid Interface between Copper-Based Electrode and Liquid Metal

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Discussion about the transmission line model

The TLM method is widely recognized for its high sensitivity in extracting milliohm-level contact resistances. The precision of our measurement is primarily reflected in the excellent linearity of the total resistance (R_T) versus electrode spacing (L_{LM}) plots. In this study, the high linear correlation coefficient R^2 (as shown in Figure S2) demonstrates the excellent consistency of the contact resistance along the interface, validating the model's reliability for our system. Furthermore, the use of a four-wire measurement configuration minimizes systematic errors by effectively eliminating lead and bulk resistances of the measurement probes. The standard TLM is fundamentally a two-dimensional analytical approach that assumes a uniform current distribution across the conductor's thickness. In practical solid-liquid contacts with finite thickness, three-dimensional effects such as "current crowding" can occur at the electrode edges. However, as supported by the study of Sato et al. (2023 IEEE MEMS),[29] the TLM remains robust for liquid metal systems as long as the experimental geometry is standardized and a 4-wire method is employed. Since our experimental geometry remained constant across all contact pairs, the three-dimensional current distribution effects are systemic and do not affect the relative accuracy of the extracted contact resistance values.

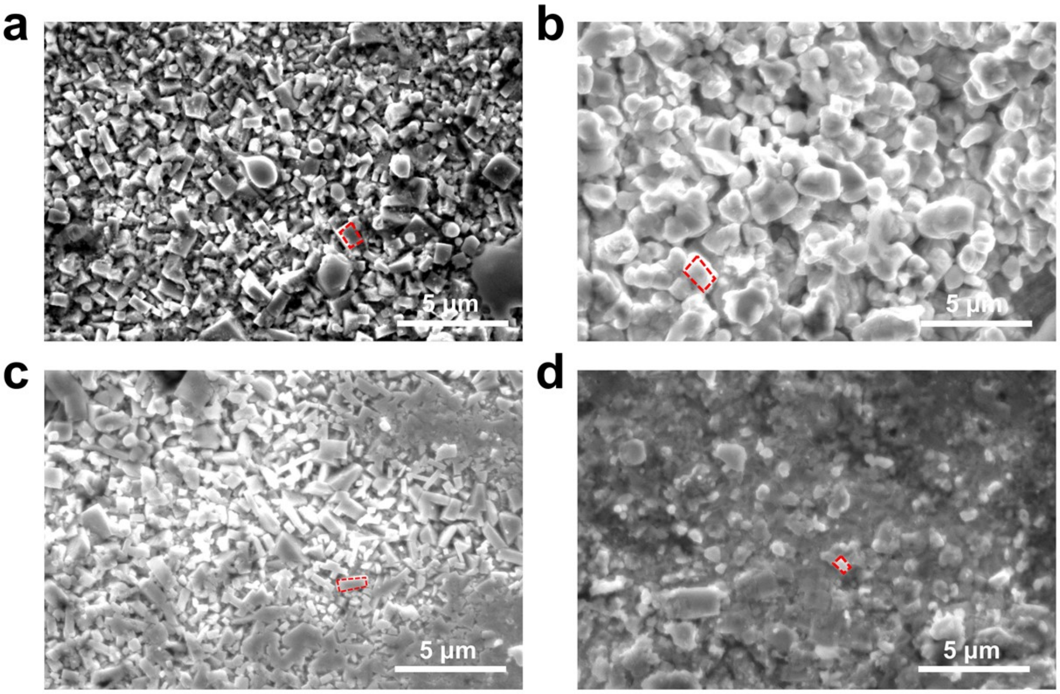

Figure S1. The surface morphology of four copper-based electrodes after 20 days of contact with liquid metal: (a) T2; (b) H62; (c) QSn6.5-0.1; and (d) C15760.

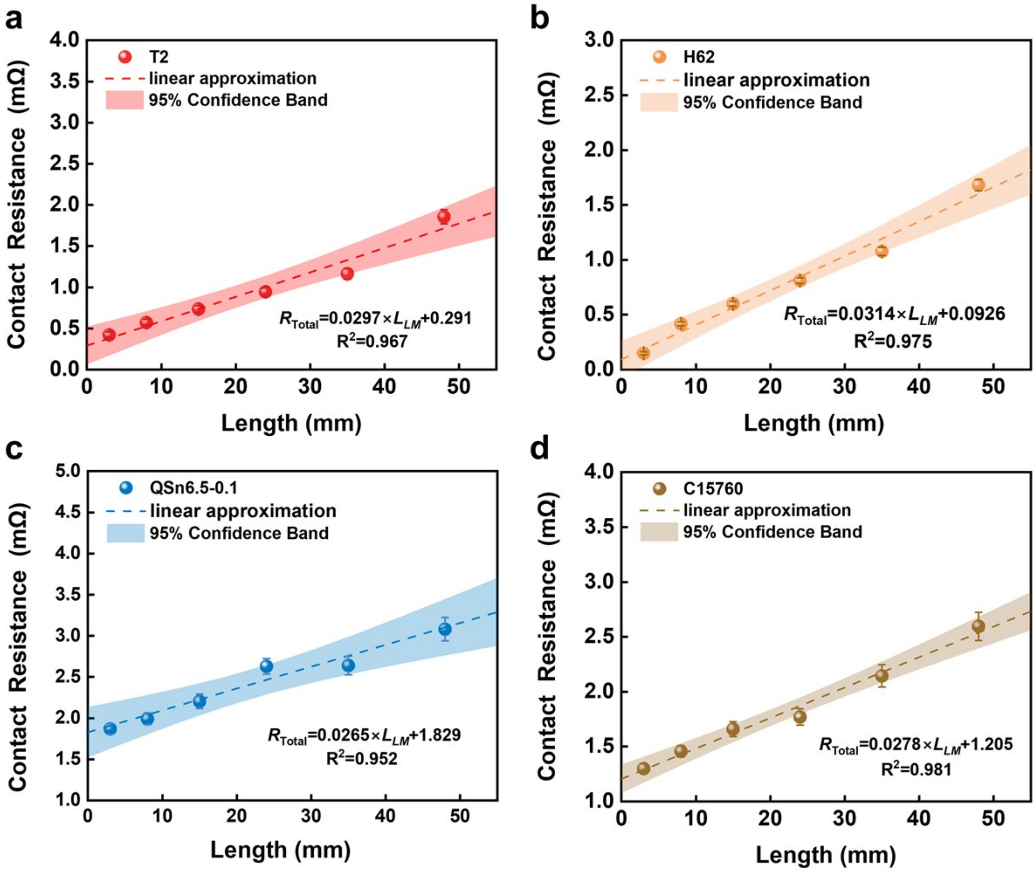

Figure S2. Solid–liquid contact resistances and fitted curves of four copper-based electrodes in contact with liquid metal on day 20, as measured by the TLM method (a) T2; (b) H62; (c) QSn6.5-0.1; and (d) C15760.

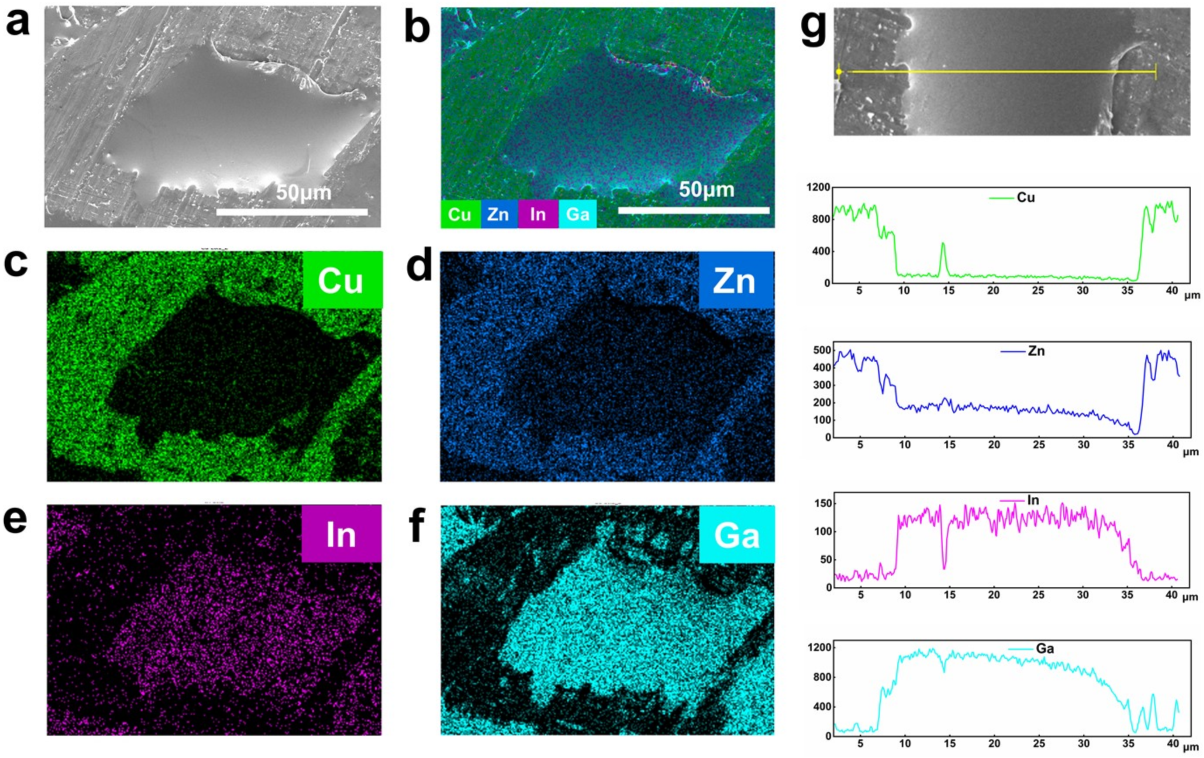

Figure S3. Microscopic morphology of the H62 electrode after reactive wetting with liquid metal: (a) SEM image; (b–f) corresponding EDS surface mapping analyses; and (g) corresponding EDS line scan analysis.

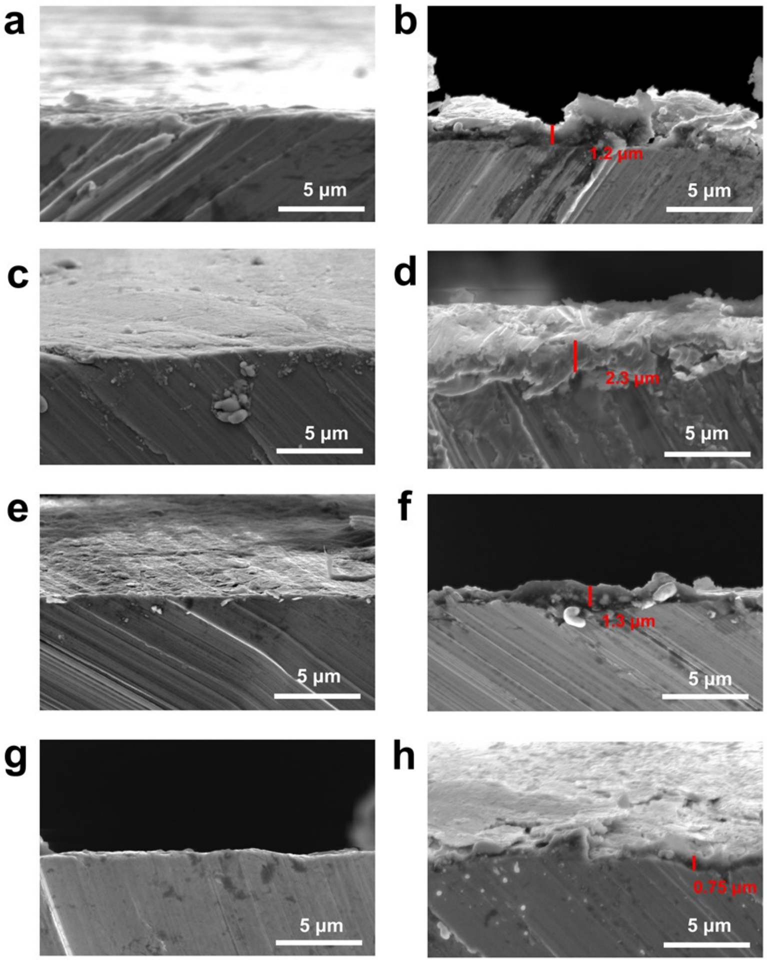

Figure S4. Cross-sectional morphology of four copper-based electrodes after contact with liquid metal: (a) T2–EGaIn on day 1; (b) T2–EGaIn on day 20; (c) H62–EGaIn on day 1; (d) H62–EGaIn on day 20; (e) QSn6.5-0.1–EGaIn on day 1; (f) QSn6.5-0.1–EGaIn on day 20; (g) C15760–EGaIn on day 1; (h) C15760–EGaIn on day 20.

Table S1. Physical Properties of Four Copper-Based Electrodes.[1-4]

Copper Alloy	Electrical Conductivity (%IACS，≥)	Density (kg/dm^3)	Thermal Conductivity （W·m^{-1}·K^{-1}）
T2	96	8.89	390
H62	22	8.43	108.9
QSn6.5-0.1	13	8.65	54.4
C15760	80	8.83	365.2

Reference

1 National Technical Committee for Standardization of Nonferrous Metals, *GB/T 34497-2023*, Standards Press of China, Beijing, 2023 (in Chinese).

2 National Technical Committee for Standardization of Nonferrous Metals, *GB/T 20509-2023*, Standards Press of China, Beijing, 2023 (in Chinese).

3 National Technical Committee for Standardization of Nonferrous Metals, *GB/T 11091-2024*, Standards Press of China, Beijing, 2024 (in Chinese).

4 Copper Development Association Inc., https://www.copper.org, (accessed January 2026).