紫外固化用于高耐久柔性电路的制备研究

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摘要　随着人工智能技术迅猛发展，设备与传感器领域的研究开发速度及更新迭代速度显著提升。相应地，柔性电路的市场需求日益多样化，对缩短制备周期要求日益凸显，小批量、定制化的柔性电路需求亦进一步扩大。本研究提出了一种基于紫外（UV）固化技术的柔性电路制造新方法，即在柔性薄膜及织物基材表面通过定向UV固化技术成功构筑电路图案，并利用Ag/Fe_3O_4催化化学镀铜构建了柔性电路，旨在有效应对上述挑战。该方法在温和条件（45 °C）下完成，无需高温烧结或复杂设备。实验研究表明，基于两种基材的柔性电路均表现出优异的导电性、机械耐久性与环境稳定性。薄膜基柔性电路经5 000次摩擦后电阻变化率≤14.6%，织物基柔性电路经2 000次摩擦后变化率为17.6%；本研究提出的方法具备可修复性以及适用于非耐热基材，为低成本、高效制造柔性电路提供了新思路。

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UV curing for high-durability flexible circuit fabrication

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ABSTRACT　With the rapid advancement of artificial intelligence technology, the pace of research, development, and iteration in devices and sensors has significantly accelerated. Accordingly, the market demand for flexible circuits has become increasingly diversified, emphasizing the need for shorter preparation cycles and expanding the

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requirement for small-batch, customized flexible circuits. This study proposes a novel method for fabricating flexible circuits based on ultraviolet (UV) curing technology. Specifically, circuit patterns were successfully constructed on flexible film and fabric substrates through directed UV curing, and flexible circuits were fabricated using Ag/Fe_3O_4-catalyzed electroless copper plating to address these challenges. This method operates under mild conditions (45 ℃), without the need for high-temperature sintering or complex equipment. Experimental results demonstrate that the flexible circuits on both substrates exhibit excellent conductivity, mechanical durability, and environmental stability. The film-based flexible circuits showed a resistance change of ≤14.6% after 5 000 rubbing cycles, while the fabric-based circuits exhibited a 17.6% change after 2 000 cycles. The proposed approach also offers reparability and compatibility with heat-sensitive substrates, providing a new strategy for low-cost and efficient manufacturing of flexible circuits.

KEYWORDS Flexible circuit, UV curing, Electroless copper plating, Ag/Fe_3O_4

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当前柔性电路的制造主要依赖传统蚀刻法、导电油墨印刷以及化学镀铜等技术[1−2]。传统蚀刻法虽然适用于大规模定制化电路的生产，但存在侧蚀效应明显、工艺流程复杂、生产周期长以及酸性清洗带来的环境污染等问题，难以满足快速原型设计和小批量生产的实际需求[3−6]；导电油墨印刷技术（如喷墨印刷和丝网印刷）能够在柔性基材上实现图案化沉积[4,7−8]，具有快速制备的优势[9−11]，但仍面临高温烧结（通常高于200 ℃）导致的能耗问题、设备投资成本高、基材适应性有限（尤其在粗糙织物表面难以形成完整导电线路）以及导电层附着力差、易脱落等技术瓶颈[12−13]、基材适应性有限，尤其在化学镀铜技术无需外加电场且成本相对较低，但其工艺依赖贵金属催化剂（如钯、银），不仅成本高昂，还存在催化剂易扩散、金属层与基材之间的附着力不足、镀层易剥离以及耐洗性差等问题[14−16]。而在智能织物领域，现有的浸涂与化学镀等方法仅能实现整体导电层的构建，无法形成精细电路结构，且导电材料与织物基材之间的结合稳定性较差，影响穿戴舒适性与产品耐久性。因此，亟须开发一种低成本、高效且适用性广（特别是非耐热基体材料）的柔性电路制造技术，以满足柔性电子器件日益增长的应用需求。

如图1所示，本研究巧妙结合UV打印与化学镀技术用于柔性电路制备，即在PET薄膜或织物表面涂覆一层含有Ag/Fe_3O_4催化剂的UV涂料，利用UV光定向照射实现电路结构的精确固化，再使用化学镀工艺在固化区域沉积金属进而形成导电层，其中Ag/Fe_3O_4催化剂是利用电子束辐照还原合成的纳米催化剂。这种增材制造方法消除了对传统蚀刻的需求，减少了材料浪费并简化了生产流程。制备的柔性印刷电路（FPC）可作为导电电路驱动LED发光，证明了其具有可靠的导电性，验证了其作为可穿戴电子设备、柔性显示器和传感器柔性电路的潜力。图2中的数码照片展示了由织物基底制成的柔性电路，且该材料在室内环境中放置约6个月后，在外接直流电源驱动下依然能使LED发光。结果表明，基于该方法制备的织物柔性电路具有出色的耐久性。

图3是FPC的导电层耐久性测试，即通过橡胶与柔性导电层之间周期性摩擦，以评估导电层在动态应力下的稳定性表现及黏附强度。测试过程中，未观察到铜层有任何脱落或剥离迹象，这充分证明了导电层与基底之间具有出色的结合强度（图3（a））。图3（b）和（c）是循环摩擦测试过程中电阻的实时变化率，结果表明，电阻变化率小于20%，稳定较好。图3（d）~（g）展示了FPC在摩擦测试前后的微观结构。初始状态下（未受摩擦），铜颗粒之间界面清晰，存在少量间隙。经过摩擦测试后，观察铜颗粒表面发生局部塑性变形与位移，铜颗粒间的界面接触紧密，且趋于稳定。原因是铜颗粒嵌入柔性电路的涂层结构中，类似于树根深入土壤，有效增强了附着力并抵御了部分摩擦造成的损耗（图3（h）），提高了材料的耐久。图3（i）~（k）是将经过摩擦测试后的样品再固定于弯折测试仪上，用于测试评估材料的抗弯性能。结果表明，最大电阻变化率保持在9.0%以内。相较于前期利用电子束固化制备的柔性电路，本方法除稳定性优异外，其精度更佳[19]。图3（l）展示了对

不完整导电电路实施修复的过程。在FPC板的使用期间，若出现局部电路损伤情况，可借助计算机辅助测量来定位故障区域，进而实现快速修复。这一特性对于未来在机器人、机械臂以及电子设备领域达成柔性电路的高效且稳定维护具有重要价值。

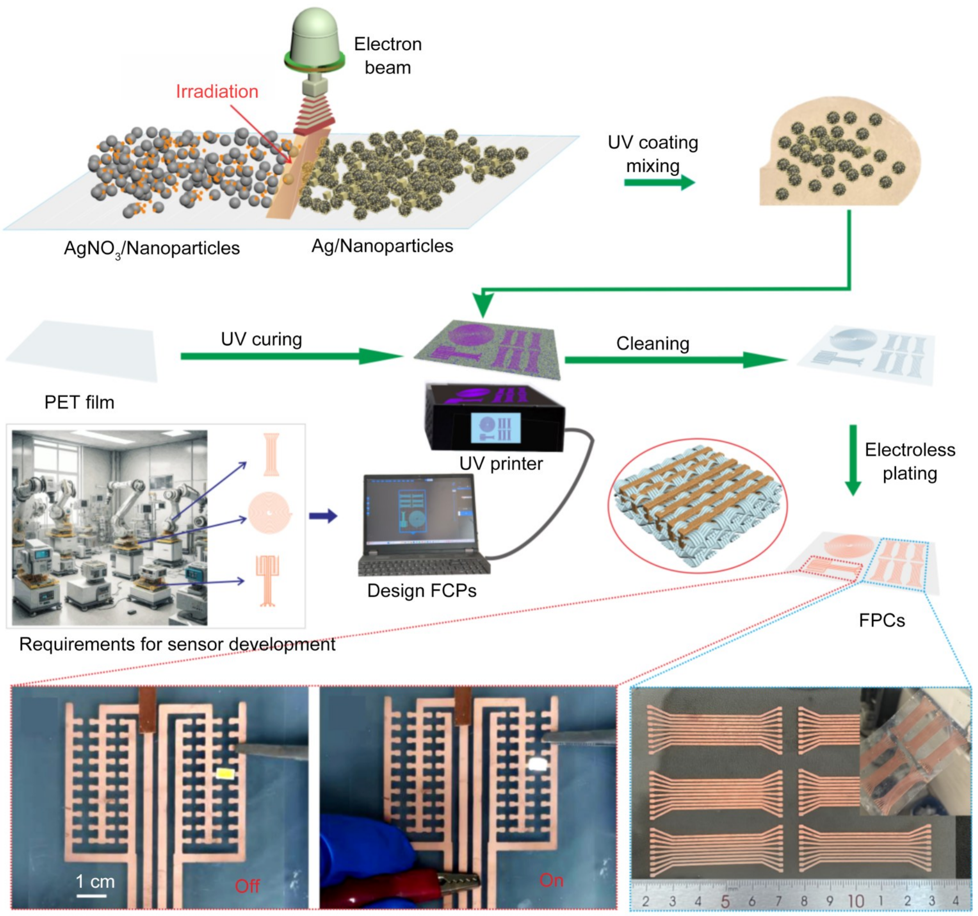

图1 FPC的示意图制备工艺(使用Ag/Fe_3O_4涂层同时固化后进行镀铜制备多个FPC，以及FPC与LED和3 V直流电源串联：开和关状态)[17-18]

Fig.1 Schematic fabrication process of FPCs (multiple FPCs prepared after plating copper using Ag/Fe_3O_4-coating cured simultaneously and FPC connected in series with LEDs and a 3 V DC power source: on and off states)[17-18]

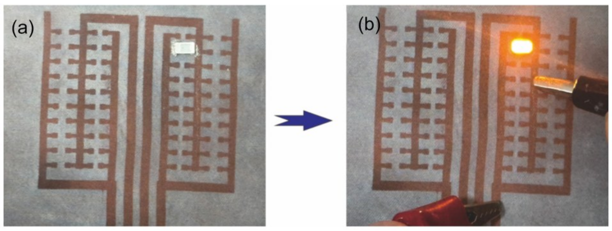

图2 在纺织基底上制作的织物基柔性电路，串联了LED和3 V直流电源，并在环境温度下放置半年(2023年11月至2024年4月)：开路状态(a)和通路状态(b)[18]

Fig.2 Fabric-based finger interconnect circuit fabricated on a textile substrate with a series connection of LED and a 3 V DC power supply left open in an ambient temperature environment for half a year (2023.11−2024.4): open circuit (a) and on circuit (b)[18]

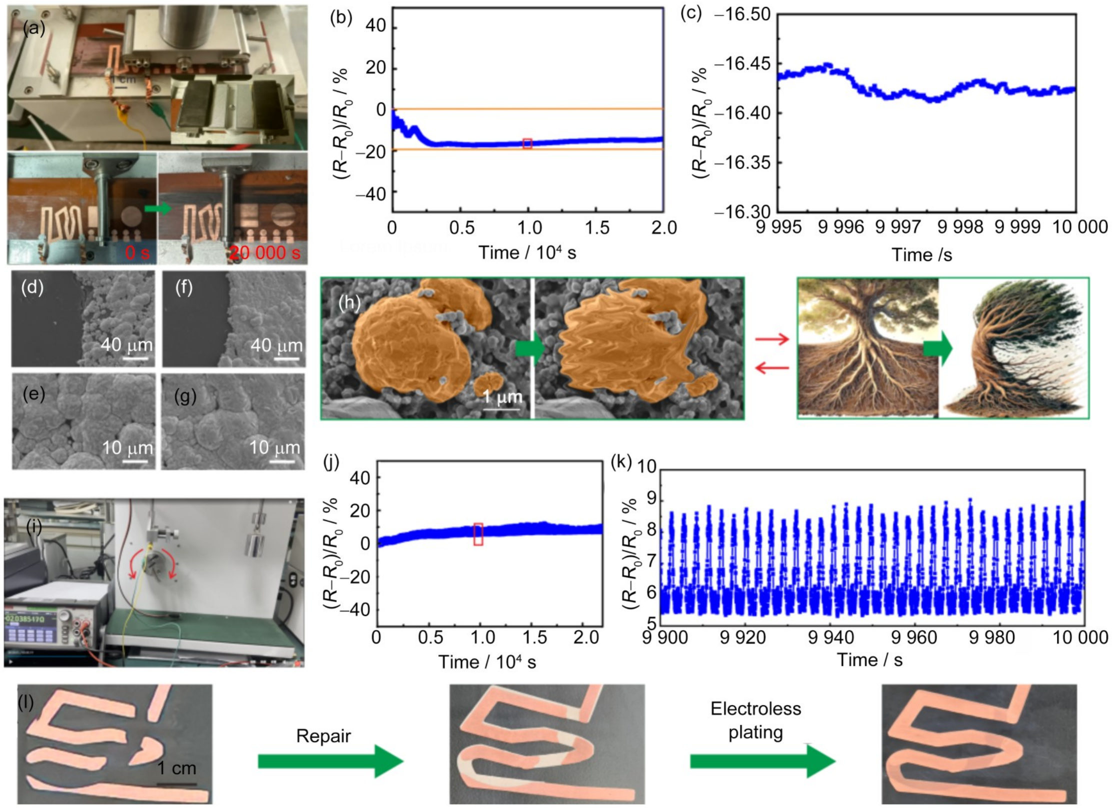

图3 (a)磨损测试设备和5 000次摩擦循环前后的FPC图像;(b)摩擦试验时阻力变化;(c)放大图;FPC循环5 000次前(d、e)和循环5 000次后(f、g)的SEM图像;(h)嵌入导电层的仿生铜颗粒:像树根一样抗风锚定,抵抗摩擦和外力;(i)测试设备和(j、k) Cu/PET导电织物在10 000次弯曲循环中的电阻变化;(l)导电层不完整的电路结构,随后进行修复,形成完整的电路[17]

Fig.3 (a) An abrasion test equipment and FPC images before and after 5 000 friction cycles; (b) resistance variation during friction testing and (c)magnified view; SEM images of FPC (d, e) before and (f, g) after 5 000 cycles; (h) biomimetic copper particles embedded in conductive layer: resisting friction and external forces like tree roots anchoring against wind; (i) a testing equipment and (j, k) the resistance change of Cu/PET conductive fabric during 10 000 bending cycles; (l) incomplete conductive layer circuit structure, followed by repair to form a complete circuit[17]

本研究创新结合UV光固化与化学镀铜技术，开发出基于Ag/Fe_3O_4纳米催化剂的高效柔性电路制造方法。该技术利用电子束辐照合成双功能催化剂，在低温(≤45 ℃)条件下同步实现电路图案精准成型与高导电铜层原位沉积，避免了传统蚀刻工艺复杂工艺和印刷法的高温烧结制约。结果表明：薄膜基柔性电路经10 000次弯曲/5 000次摩擦后电阻变化率≤14.6%，织物基柔性电路在8 000次弯曲/2 000次摩擦后变化率≤17.6%。本文为低成本、高效的柔性电路制造提供了新思路。

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参考文献

1 Li X T, Sidén J, Andersson H, *et al*. Enabling paper-based flexible circuits with aluminium and copper conductors [J]. Flexible and Printed Electronics, 2019, **4**(4): 045007. DOI: 10.1088/2058-8585/ab5cef.

2 Huang J J, Chen Z M, Zhou F, *et al*. High-adhesive electroless copper plating on polyethylene surface modified with primer[J]. Journal of Solid State Electrochemistry, 2017, **21**(6): 1559-1566. DOI: 10.1007/s10008-016-3503-1.

3 Srivastava V, Dubey S, Vaish R, *et al*. Optimized fabrication of flexible paper-based PCBs with pencil and copper electroplating[J]. Advanced Materials Technologies, 2025, **10**(4): 2400688. DOI: 10.1002/admt.202400688.

4 Zhang D, Chi B H, Li B W, *et al*. Fabrication of highly conductive graphene flexible circuits by 3D printing[J]. Synthetic Metals, 2016, **217**: 79-86. DOI: 10.1016/j.synthmet.2016.03.014.

5 Lee C J, Park B G, Jeong H, *et al*. Fabrication of IPL-sintered Ag-MWCNT composite circuits and their flexibility characteristics[J]. Journal of Alloys and Compounds, 2019, **794**: 341-346. DOI: 10.1016/j.jallcom.2019.04.292.

6 Sato T, Urata C. Direct micropatterning of initiator layers for surface-initiated ATRP: spatially-regulated growth of polymer brush and subsequent copper electroless plating [J]. Molecular Crystals and Liquid Crystals, 2019, **688**(1): 98-104. DOI: 10.1080/15421406.2019.1651074.

7 Cao L X, Wang Z H, Hu D W, *et al*. Pressure-constrained sonication activation of flexible printed metal circuit[J]. Nature Communications, 2024, **15**: 8324. DOI: 10.1038/s41467-024-52873-7.

8 Sun R, Ma M D, Ma X C, *et al*. Direct-writing flexible metal circuit with polymer/metal precursor ink and interfacial reaction[J]. Langmuir, 2023, **39**(21): 7426-7433. DOI: 10.1021/acs.langmuir.3c00642.

9 Komolafe A, Torah R, Wei Y, *et al*. Integrating flexible filament circuits for E-textile applications[J]. Advanced Materials Technologies, 2019, **4**(7): 1900176. DOI: 10.1002/admt.201900176.

10 Xie J Q, Ji Y Q, Kang J H, *et al*. *In situ* growth of $Cu(OH)_2$@FeOOH nanotube arrays on catalytically deposited Cu current collector patterns for high-performance flexible in-plane micro-sized energy storage devices[J]. Energy & Environmental Science, 2019, **12**(1): 194-205. DOI: 10.1039/C8EE01979G.

11 Fan Y Y, Zhang R, Liu Z, *et al*. Direct metallic nanostructures transfer by flexible contact UV-curable nano-imprint lithography[J]. Applied Physics Express, 2019, **12**(9): 095004. DOI: 10.7567/1882-0786/ab3aa9.

12 Xiang L, Zhang H, Hu Y F, *et al*. Carbon nanotube-based flexible electronics[J]. Journal of Materials Chemistry C, 2018, **6**(29): 7714-7727. DOI: 10.1039/C8TC02280A.

13 Shin D H, Woo S, Yem H, *et al*. A self-reducible and alcohol-soluble copper-based metal-organic decomposition ink for printed electronics[J]. ACS Applied Materials & Interfaces, 2014, **6**(5): 3312-3319. DOI: 10.1021/am4036306.

14 Xiang J L, Zhou G Y, Hong Y, *et al*. Direct additive copper plating on polyimide surface with silver ammonia *via* plasma modification[J]. Applied Surface Science, 2022, **587**: 152848. DOI: 10.1016/j.apsusc.2022.152848.

15 Huang J J, Tian C G, Wang J, *et al*. Fabrication of selective electroless copper plating on PET sheet: effect of PET surface structure on resolution and adhesion of copper coating[J]. Applied Surface Science, 2018, **458**: 734-742. DOI: 10.1016/j.apsusc.2018.07.119.

16 Farraj Y, Layani M, Yaverboim A, *et al*. Binuclear copper complex ink as a seed for electroless copper plating yielding >70% bulk conductivity on 3D printed polymers [J]. Advanced Materials Interfaces, 2018, **5**(8): 1701285. DOI: 10.1002/admi.201701285.

17 Gan J, Wang J H, Zhang M J, *et al*. Ag/Fe_3O_4-catalyzed fabrication of flexible printed circuits: integrated UV-curing and electroless plating process[J]. ACS Applied Materials & Interfaces, 2025, **17**(26): 38515-38531. DOI: 10.1021/acsami.5c07243.

18 Zhang M J, Cui K X, Zhang X W, *et al*. Ultraviolet curing technology plus chemical copper plating: a novel method for producing highly durable fabric-based flexible circuit[J]. Polymers for Advanced Technologies, 2024, **35**(9): e6563. DOI: 10.1002/pat.6563.

19 张茂江, 王京华, 吴彦甫, 等. 电子束辐射固化制备织物基柔性电路[J]. 辐射研究与辐射工艺学报, 2024, **42**(5): 050201. DOI: 10.11889/j.1000-3436.2024-0063.
ZHANG Maojiang, WANG Jinghua, WU Yanfu, *et al*. Fabrication of fabric-based flexible circuits via electron-beam radiation curing[J]. Journal of Radiation Research and Radiation Processing, 2024, **42**(5): 050201. DOI: 10.11889/j.1000-3436.2024-0063.

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