DOI 10.5162/EUROSENSORS2025/M3.3.2

Lock and Key Interconnects for Modular Flexible and Printed Electronics

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Summary:
In rigid electronic systems, various methods such as USB connectors and pin headers enable temporary electrical and mechanical connections between components. Conversely, such solutions are still lacking in the flexible electronics landscape. This work introduces a novel interconnection method for flexible and printed electronics, using mechanically defined grooves in the encapsulation layer to align with contact pads on detachable modules, enabling robust and reliable connections between flexible electronic segments. Inspired by a lock-and-key mechanism, it enhances modularity without requiring additional materials or components, preserving system design while supporting reconfigurable integration, mechanical flexibility, and reduced material usage—a scalable and sustainable solution for next-generation electronics.

Keywords: printed electronics, modular electronics, flexible interconnects, biomedical devices.

Background, Motivation and Objective

The evolution of Modular Biomedical Electronics has significantly advanced the development of lightweight, adaptable, and high-performance devices for applications such as wearable technology and medical sensors [1]. These systems are increasingly gaining attention in the biomedical field due to their flexibility, repairability, and sustainability [2].

A key design strategy is using interchangeable components, enabling upgrades or repairs without replacing the entire device. Modular designs support adding new functions or replacing worn parts, enhancing adaptability and longevity, which is useful in health monitoring, where sensors degrade faster than electronics [3].

However, the modular nature of these systems introduces a significant challenge: ensuring reliable electrical and mechanical interconnection between different counterparts—such as sensors, chips, and circuit segments, especially in wearable biomedical devices due to several interrelated factors. Material mismatches between substrates can cause delamination [4], while the flexibility needed for wearables leads to mechanical fatigue from repeated motion, compromising connection integrity over time [5].

Traditional interconnection methods like soldering, mechanical crimping or conductive adhesives add material, require extra materials and complex processing, reducing flexibility, raising costs, and causing environmental concerns, making them unsuitable for the specific demands of wearable biomedical applications.

To address these challenges, a novel interconnection technique inspired by lock-and-key-inspired is proposed, mimicking male-female connectors to ensure reliable electrical and mechanical contact without extra materials or complex manufacturing. It supports repeated replacements with minimal wear, improving modularity and sustainability. Notably, the connection resistance increases by no more than 10% over 20 insertion cycles—markedly outperforming conventional solutions such as anisotropic conductive films, which show an immediate resistance increase of approximately 30% upon application due to poor compliance with flexible substrates and a tendency to delaminate under stress [6].

Materials and Methods

A modular interconnection system was developed to achieve simple and sustainable device assembly, with electrical contact established through mechanical insertion. Fig. 1 shows the structure of a printed circuit using conductive silver ink on a polyethylene terephthalate (PET) substrate, which was then encapsulated through a lamination process at 120 °C using an anisotropic non-conductive film (ANCF) as an intermediate layer, followed by an additional PET sheet as the top layer. This lamination not only protects the printed structures from environmental

exposure but also enhances the overall robustness and durability of the system.

The ANCF layer was patterned with small grooves, forming recessed pockets that act as connection points for external components—creating a female-type connector.

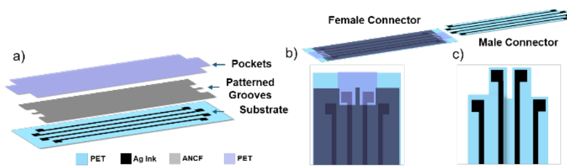

Fig. 1. (a) Exploded view of the female connector, Schematics of (b) Female connector (c) Male connector .

The male counterpart, shown in Fig. 2 (a) is fabricated from the same silver-ink-on-PET material but precisely cut to match the geometry of the female pockets. It is designed to be inserted into the grooved regions of the female connector, shown in Fig. 2 (b), enabling direct electrical contact through mechanical insertion.

When the male and female parts are joined, the embedded pockets in the ANCF guide and hold the male contacts in place, establishing a reliable and reusable plug-in style connection. This modular interconnection approach allows for repeated use, mechanical stability, and electrical continuity even under deformation, as demonstrated in Fig. 2 (c) & (d).

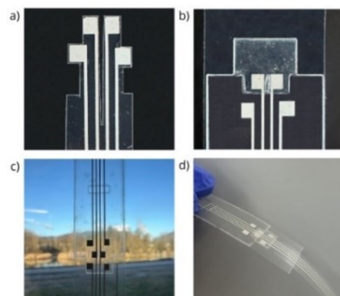

Fig. 2. (a) Male connector with printed structures on PET, cut to fit grooves (b) Female connector with Ag ink circuit on encapsulated PET.(c–d) Interconnection under bending, showing flexible and robust contact.

Results

Electrical performance was assessed by first measuring the resistance between two fixed points on the male part of the modular structure to establish a baseline. The male and female components were cycled through repeated attachments. Resistance was recorded every 5 cycles over a total of 50 repetitions in three different samples, generating a curve (Fig. 3) that illustrates how resistance changed relative to the baseline.

Results show stable electrical performance up to approximately 15–20 cycles, making the connector suitable for point-of-care (PoC) diagnostic systems, where limited sensor replacements are typically sufficient during a device's operational life and can be improved with additional coatings.

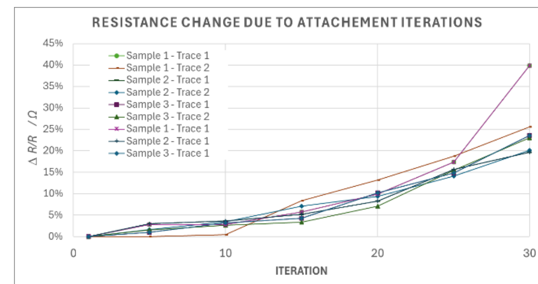

Fig. 3. Resistance variation over 30 attachment cycles across three samples and two circuit traces.

Our connector concept offers a practical solution for modular and disposable sensing elements, ideal for PoC applications where rapid sensor interchangeability, mechanical reliability, and electrical consistency are essential. The fabrication process is compatible with various substrates, including flexible and biodegradable materials, expanding the potential of the system toward sustainable, next-generation sensor platforms in wearable, portable, and eco-friendly medical technologies.

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Acknowledgements

This work has been jointly funded by the EECONE project, supported by the Chips Joint Undertaking and its members, including the top-up funding by National Funding Authorities under grant agreement no. 101112065 and by Silicon Austria Labs (SAL), owned by the Republic of Austria, the Styrian Business Promotion Agency (SFG), the federal state of Carinthia, the Upper Austrian Research (UAR), and the Austrian Association for the Electric and Electronics Industry (FEEI).