‘Cut-and-paste’ manufacture of multiparametric epidermal electronic systems

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Our bodies radiate important data about ourselves all the time. Examples include the electrical activity transmitted by the heart, brain, and muscles through the skin. For this reason, wearable devices that can pick up and transmit signals from the human body have the potential to transform mobile health as well as the so-called human-machine interface, which prompted Forbes magazine to name 2014 the ‘year of wearable technology.’ However, because the wafer-based integrated circuits on which the technology relies are planar, rigid, and brittle, state-of-the-art wearable devices are mostly in the form of ‘chips on tapes’ or ‘bricks on straps.’ These bulky structures cannot maintain intimate, prolonged contact with the curved, soft, and dynamic human body required for long-term, high-fidelity physiological signal monitoring.

Recent advances in flexible and stretchable electronics offer viable solutions. In particular, epidermal electronic systems (EESs) are a class of wearable devices whose thickness and mechanical properties match those of the human epidermis. These devices conform to human skin like a temporary transfer tattoo and deform with skin without detachment or fracture. EESs were initially developed to monitor electrophysiological signals, and thereafter skin temperature, hydration, stiffness, and sweat. A near-field communication antenna based on EES technology has also been reported.

The thinness and softness of EESs causes them to collapse and crumple after being peeled off human skin, which makes them ideal for use as disposable electronic tattoos. For the technology to be widely successful, however, will require low-cost, high-throughput manufacture. Current EESs rely on standard microelectronic fabrication processes such as vacuum deposition of films, spin coating, photolithography, and wet and dry etching as well as nonstandard transfer printing. Although these methods are effective, they have a number of disadvantages. For example, the rigid handle (support) wafer required for photolithography is incompatible with roll-to-roll processes typical of flexible electronics. Cleanroom facilities, photomasks, and photolithography chemicals are expensive. High-vacuum film deposition is time-consuming and consequently impractical for thick films. And, finally, standard processes are personnel-intensive, which adds to the cost of EESs and limits their availability.

Our newly invented ‘cut-and-paste’ method offers a very simple and immediate solution to these challenges. We replace...
high-vacuum metal deposition by thin metal-on-polymer lami-
ates of various thicknesses purchased directly from industrial
manufacturers. Instead of using photolithographic patterning,
we use a benchtop programmable cutter plotter to mechani-
cally carve out the designed patterns and remove the excess
(see Figure 1). Thus, the manufacturing process is freeform and
subtractive as opposed to being simply additive, which is the
current popular technology represented by printed electronics.
(Inks used in printed electronics are expensive and often require
high-temperature curing, which is incompatible with many soft
substrates.) The cutter plotter can pattern both thin metal and
polymer sheets up to 12 inches wide and several feet long, sub-
stantially exceeding lab-scale wafer sizes. Because the patterns
can be carved with the support of thermal release tapes (TRTs),
the patterned films can be directly printed onto a variety of tat-
too adhesives and medical tapes with almost 100% yield.

The entire process can be completed on an ordinary laboratory
bench with no wet processing and within 10 minutes, which al-
lows rapid prototyping. Equipment used includes only a desk-
top cutter plotter for thin-film patterning and a hot plate for
TRT heating, enabling portable manufacture. Because no rigid
handle wafer is needed at any point in the process, the cut-
and-paste method is intrinsically compatible with roll-to-roll
manufacturing.

To demonstrate the method, we fabricated multimaterial EESs
and used them to monitor electrical activity from the heart
(electrocardiogram), muscle tissue (electromyogram), and the
brain (electroencephalogram), as well as to measure skin tem-
perature, skin hydration, and respiratory rate (see Figure 2).

A planar stretchable coil of 9 μm-thick aluminum ribbons in a
double-stranded serpentine design is integrated on the EES as a
low-frequency, wireless strain gauge, which could also serve as
a near-field communication antenna in the future.

In summary, we have demonstrated a versatile, cost-effective,
and fast method of manufacturing multimaterial, multiparamet-
ric EESs that can be intimately but noninvasively applied on hu-
man skin to measure a range of physiological signals. Our cut-
and-paste method enables completely dry, benchtop, freeform,
and portable manufacture of EESs within minutes, without need
of vacuum facilities or chemicals. The method has proved effec-
tive in patterning metal-on-polymer laminates and elastomeric
sheets, but it is not applicable to ceramic thin films (e.g., silicon
or indium tin oxide) because indentation by the cutting blade
would easily fracture the intrinsically brittle ceramic film. We
have, however, demonstrated a variation of the cut-and-paste
method to manufacture highly stretchable, transparent intercon-
nects based on brittle indium tin oxide film. In addition to
EESs, we expect the cut-and-paste method to be useful for man-
ufacturing other stretchable devices, including circuit boards
that house rigid integrated circuit chips and highly expandable
sensor networks for health monitoring. Our next step is to
apply the cut-and-paste method to manufacturing transparent
EESs using 2D materials such as graphene and molybdenum
disulfide.

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