April 06, 2022

Maths, Physics & Chem

e-skin: the future of sustainable & recyclable wearable electronics

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This Break was edited by Aleksa Djorovic, *Senior Scientific Editor* - TheScienceBreaker

ABSTRACT

An electronic "skin" can find applications in health care, robotics, and prosthetics, and can benefit the well-being, economy, and sustainability of our society. A sustainable futuristic electronic skin with superior stretching, self-healing, recycling, and reconfiguration capabilities has been developed by combining scientific advances in materials, electronics, mechanics and chemistry.

Image credits: Zepeng Lei, University of Colorado Boulder.

Wearable electronic devices based on hard printed circuit boards (PCB), such as smart watches, bracelets and glasses, have broad applications in healthcare, medical science and artificial intelligence. However, most of these wearable devices are exorbitantly priced and when they are discarded, the electronic devices turn into electronic waste, causing serious environmental pollution. It is estimated that over 55 million tons of disposable smart electronics have been produced by 2021. For these reasons, the ideal wearable electronics should be able to comfortably fit our body and be made from cheap and environmentally friendly, recyclable materials.

Electronic skin (e-skin) is a type of flexible electronic system that imitates natural skin. E-skin can be easily integrated with the human body for monitoring physical activity and various health conditions, as well as enhancing human-computer interfaces, and virtual/augmented reality experiences. We have developed a thin, stretchable e-skin that does not break on the skin and remains soft and flexible. It is made by integrating a combination of rigid (off-the-shelf chip components) and soft (a brand-new polymer film called polyimine) materials through a low-cost fabricating method, where the components are printed onto a substrate. The e-skin is self-healable, fully recyclable, and reconfigurable and is a result of a perfect mixture of technological advances in the materials used, electronics, mechanics and chemistry.

Our e-skin integrates a temperature sensor, an accelerometer and an electrocardiogram (ECG) sensor. It provides high-performance sensing of biophysical signals such as body temperature, physical activities, health monitoring and voice recognition. For example, this e-skin can accurately measure body temperature at different locations of the body in various environments (both indoors and outdoors). When attached to the wrist or ankle, the e-skin monitors and records walking, running and jumping data. When attached to the throat, it captures the vibrations of the vocal cords. In addition, it accurately monitors the ECG signal and heart rate.

The high stretchability of the polymer films used makes the device performance extremely robust to mechanical deformations, such as crumpling, bending, twisting and stretching. The use of liquid metals in the device enables instant re-healing upon these deformations, making the circuit conductive and workable again. As a result, our e-skin can be attached onto a person's neck, arm, wrist, and finger tightly, with a comfortable customized fit.

A special property of our e-skin is that is can self-heal when damaged, in a way similar to human skin. Such self-healing capability is enabled by the brand-new polymer film that grows back together even after the covalent bonds in the polymer are broken. The polymer achieves this by exchanging bonds among many polymer chains across the polymer interface, meaning the broken polymer chain can easily find a new chain to attach to. Importantly, the mechanical and electrical performances of the self-healed device compare well to those of the original device, for example, it can be stretched without affecting the sensing performance at all, just like human skin!

Other than self-healability, another great benefit of the e-skin is that when the device is severely damaged or no longer needed, it can be fully recycled. By immersing the e-skin into a specially formulated recycling solution, the polymer films dissolve and the electronic chips and liquid metal components sink to the bottom, where they are easily separated from the solution using a filter. The solution, electronic chips and liquid metal can all be then reused to make new polymers and devices. The new e-skin prepared using recycled materials shows mechanical and electrical performances comparable to that the original device. The recycling process is performed at room temperature, which saves energy and means no expensive equipment is required. The 100% recyclability of this e-skin promises a truly green technology that could greatly reduce electronic waste and environmental pollution and therefore provides a sustainable alternative to other wearable electronics.

The choice of polymer leads to another interesting property of our e-skin. At high temperatures, the stress from mechanical deformations on the polymer structure is relaxed at the molecular level - allowing impressive malleability. With such malleability, our e-skin can be reconfigured into various shapes and geometries that perfectly match the curvatures of the uniquely different body parts of the wearer, such as neck, arm and finger. The e-skin can be reconfigured into different sizes in order to fit different parts of the body or different sizes of the wearers, providing a truly one-size-fits-all product.

The properties our e-skin system introduces can find applications in many areas, including health care, robotics, and prosthetics, and can benefit the wellbeing, economy, and sustainability of our society. This e-skin work is just the beginning! This exciting platform lends itself to many more possible additions and interesting applications – such as power supplies, wireless communication, and computation. It's also possible to connect the e-skin with the internet of things and virtual/augmented reality (such as the upcoming metaverse!), to expand its application and beneficial impact to our society.

Acknowledgment: We thank our collaborator Mr. Zepeng Lei of University of Colorado Boulder for providing the photo.