Press release

Keio University

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Keio University

The World's Highest Frequency Operation of Stretchable Semiconductor Devices
The future of wearable tech is elastic and wireless

In a world first, a group including researchers at Keio University and Stanford University has succeeded in operating a flexible and stretchable semiconductor device at the high frequency of 13.56 megahertz (the same frequency used in contactless cards to pay for public transportation). The group was comprised of Naoji Matsuhisa, an Assistant Professor from Keio University's Faculty of Science and Technology, Department of Electronics and Electrical Engineering; Dr. Simiao Niu, a postdoctoral research fellow (at the time of this research project) in Chemical Engineering at Stanford University; Dr. Zhenan Bao, a Professor of Chemical Engineering at Stanford University; and colleagues. Until this breakthrough, the operating frequencies for stretchable semiconductor devices have been limited to roughly 100 hertz, meaning that this development has surpassed previous performance by 100,000-fold.

Skin-like soft electronic devices are expected to have vast applications as next-generation wearable devices due to their ability to attach to the skin and be worn comfortably. One critical obstacle with such devices was power supply. The outcomes of this research involving high-frequency diodes, however, have made the wireless transmission of electrical power and communications possible in stretchable electronic materials. Furthermore, the electronic materials developed for stretchable semiconductor devices in this research also have applications for sensors and light-emitting elements, improvements are expected across all flexible wearable technology, bringing us one step closer to practical implementation in our daily lives.

The outcomes of this research were published in *Nature* on December 8, 2021.

Research outcomes were also shared digitally in a video published by the journal's YouTube channel, nature video, on December 15, 2021. The video can be viewed via the following link.

https://www.youtube.com/watch?v=Km1-LbqoHGI

1. Main Points of Research

- Researchers succeeded in operating a stretchable semiconductor device at the highest recorded frequency of 13.56 MHz.
- The key to development was a design of various materials that simultaneously fulfill requirements for stretchability and electrical properties (mobility, conductivity, work function, etc.).
- Researchers successfully fabricated a stretchable sensor and display system that can be wirelessly operated, positing a prototype for next-generation wearable devices.

2. Background of Research

Wearable healthcare devices can collect various biometric information over long periods of time through simply being attached to the body, aiding in the early detection and prevention of diseases. Such technology has been rendered especially important by the Covid-19 pandemic and worldwide aging populations. Commercialized wearable devices have a small and rigid form factor like watches and rings, but next-generation wearables are expected to include skin-like soft electronic devices. Soft and directly applicable to one's skin, these devices can be worn for long periods of time anywhere on the body without causing discomfort, all the while collecting highly accurate biometric data. Such soft and stretchable electronic devices will find applications in next-generation interfaces for

virtual/augmented reality (VR/AR) and electronic artificial robotic skins.

To realize stretchable electronic devices, researchers have been working to replace conventional non-stretchable electronic materials with stretchable electronic materials such as elastic conductors and semiconductors[1]. Prof. Matsuhisa has developed highly conductive printable elastic conductors (Ref. 1). Recently, high-performance stretchable semiconductors were developed. The electrical characteristics are similar to non-stretchable semiconductor materials while also possessing stretchability akin to a living body (Ref. 2). The invention of stretchable semiconductors has allowed for the development of various soft and stretchable devices[2], including transistor circuits, photovoltaics, and light emitting diodes (LEDs). However, their highest reported operating frequencies were roughly 100 hertz, which is far short of modern electronic devices that operate at frequencies above the megahertz level, presenting a major barrier to their practical usage.

3. Content of Research and Results

In this study, researchers developed the world's first stretchable diode that can operate at a frequency as high as 13.56 MHz (Fig. 1). This high-frequency stretchable diode operates at high frequencies even when stretched to 1.5 times its original length and can maintain high electrical characteristics even when stretched repeatedly. As the record for operating frequencies of stretchable semiconductor devices has been about 100 Hz, this result improved upon previous feats by 100,000-fold, a dramatic scientific breakthrough. The frequency of 13.56 MHz achieved in this research holds special significance as it can efficiently facilitate wireless transmission of electrical power and communications, and is the frequency used for contactless cards to pay for public transportation. This breakthrough was achieved by a development of novel stretchable electronic materials that were fine-tuned for high frequency operation. For example, high electrical properties and stretchability of the semiconductors were achieved by partially incorporating the chemical structure of soft silicon rubber[3] into the chemical structure of a normally glass-like fragile polymer semiconductor. Other electronic materials such as conductive polymer materials and silver nanowires were also newly engineered for this study so that they provide elasticity while simultaneously fulfilling the requirements for high-frequency capability.

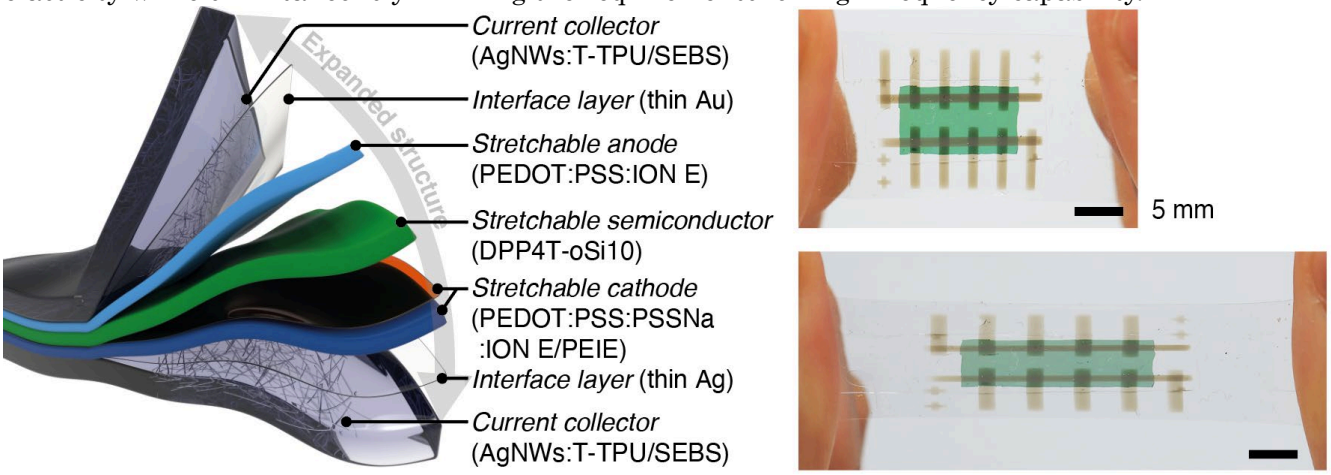

Figure 1. The high-frequency stretchable diode developed in this study.
(Left) Structure. (Right) Photo.

Furthermore, researchers demonstrated a wireless stretchable sensor and display system by the integration of the high-frequency stretchable diode, a stretchable sensor, display, and antenna (Fig. 2). The system is wirelessly powered by the power supply circuits on textiles and can display the sensor signal in real time by the color change of the display pixel. The system works even when stretched

greatly, suggesting the potential for excellent mechanical durability as well as comfort in next-generation wearable devices.

Figure 2. Stretchable wireless sensor and display system.

4. Future Developments

The stretchable high-frequency diodes realized by this research will enable wireless charging and communication of future wearables. Stretchable wearable devices that attach to our skin will enable highly accurate biological monitoring with high comfort of wear. This study will further realize charging of such devices from their surrounding environments (e.g. clothes or desks). Furthermore, the novel stretchable electronic materials developed in this study can be applied to other stretchable semiconductor devices, which will accelerate the improvement of all stretchable electronic devices, such as solar cells and LEDs. By abandoning the hard and fragile form-factor of conventional electronic devices, this study's achievement of skin-like stretchable electronics is expected to be implemented in a variety of fields such as healthcare, sports, VR/AR, robots, etc.

References

1. N. Matsuhisa, *et al.,* "Printable elastic conductors by in situ formation of silver nanoparticles from silver flakes"
Nature Materials **8,** 834-840 (2017). doi: https://doi.org/10.1038/nmat4904
2. J. Xu, *et al.,* "Highly stretchable polymer semiconductor films through the nanoconfinement effect"
Science **355,** 59-64 (2017). doi: https://doi.org/10.1126/science.aah4496

Details of Journal Article

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Glossary

[1] Semiconductor: Materials that can fully control the ease with which electricity flows. They also have the function of converting electricity and light into one another. Silicon is a typical example.
[2] Semiconductor device: A general term for electronic components that use semiconductors. It includes transistors that are important as circuit elements for IC chips and displays, and diode-like elements (solar cells, photodiodes, LEDs, etc.).
[3] Silicone rubber: A type of rubber material which is commonly used for smartphone cases and medical tubes.

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