

Preview

Dielectro-elastic elastomer for strain-invariant stretchable bioelectronics

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The electrical properties of radiofrequency (RF) components in skin-interfaced stretchable electronics change significantly due to skin strain induced by body movements and physiological activities, markedly degrading wireless performance. The choice of substrate materials for stretchable electronics is critical. A novel elastic substrate material with tunable dielectric properties in response to strain effectively regulates RF electronic components, maintaining their high-performance wireless functionalities under various deformations.

Rapid advances in wearable technology and skin-interfaced electronics has created strong demand for wireless communication and energy harvesting modules across various sectors, including healthcare, human-machine interactions, and flexible robotics.^{1,2} These technologies offer extensive applications in medical monitoring, assistive devices, soft robotics, and tactile interfaces. However, dynamic conditions induced by body movements and physiological activities present a significant challenge to the stable performance in epidermal electronics.³ Specifically, the electrical properties of radiofrequency (RF) components, such as the antenna resonance frequency (f_0), undergo substantial changes under elastic strain (Figure 1A).⁴ This strain-induced variability results in a marked reduction in wireless signal strength and power transfer efficiency in stretchable systems, posing a critical challenge to their reliability and effectiveness.

A core issue is the substrate material, whose properties directly govern RF electrical performance. Existing elastomeric substrates suffer from drawbacks that impair the frequency-related characteristics of nearly all RF components. The constant permittivity of these substrates under strain causes significant changes in the electrical performance of electronic devices, especially for RF components highly sensitive to even subtle deformations.⁵ Moreover, traditional elastomer substrates have high dielectric losses and poor thermal properties, leading to substantial electro-

magnetic energy loss and inadequate heat dissipation.⁶

A recent report in *Nature* addresses this critical issue by introducing a novel elastic substrate material named dielectro-elastic elastomer (DEE), tailored for stretchable RF components.⁷ This composite material is developed by embedding high-dielectric-constant ceramic nanoparticles (BaTiO_3) aggregated into micron-sized clusters within an elastomer matrix. This design results in a near-linear decrease in permittivity under strain (Figure 1B), enabling *in situ* RF tuning and preventing f_0 shifts. This behavior can be explained using a parallel plate capacitor model with DEE as the dielectric medium. As the BaTiO_3 clusters are compressed from spheres to ellipsoids, the reduction in the opposing field (E_p) generated by vertically polarized dipoles leads to an increase in E_{net} and an overall decrease in the effective permittivity (ϵ_{eff}). Additionally, DEE exhibits low dielectric loss over a wide frequency range (13.56 MHz–2.4 GHz, 0.0043–0.0074), high thermal conductivity (approximately $0.37 \text{ W m}^{-1} \text{ K}^{-1}$), and softness (80 kPa, 380% fracture strain). These properties make DEE an ideal substrate for maintaining the stable performance of RF components in stretchable electronic devices under dynamic environments.

The DEE supports various RF elements, including far-field antennas, near-field inductive coils, and transmission lines. These can be integrated with Bluetooth, pulse sensors, and functional circuits to build a DEE-based stretchable wireless

medical monitoring system (Figure 1C). To demonstrate the RF characteristics under strain, stretchable coils were fabricated on both Ecoflex and DEE substrates (Figure 1D). Under 0%–30% strain, the fixed ϵ_{eff} of Ecoflex and the increased effective area of the coil raise the capacitance, shifting the resonance to lower frequencies (Figure 1E). In contrast, the decreasing ϵ_{eff} of DEE offsets the increased capacitance, neutralizing the overall f_0 shift. Figure 1F illustrates wireless power transfer to an LED with inductive coils based on Ecoflex and DEE substrates. The LED on the Ecoflex substrate turns off after stretching, while the LED on the DEE substrate remains lit. Comprehensive demonstrations of key stretchable RF components, including antennas and transmission lines, verify DEE's universal ability to maintain strain-invariant RF performance.

The DEE-based stretchable wireless medical monitoring system exhibits excellent mechanical conformability (Figure 1G), allowing the entire system to deform and form a conformal contact on the wrist and enabling pulse-rate sensing at the radial artery (Figure 1H). Natural movements of the wrist can induce up to 30% strain on the skin-interfaced system. The Ecoflex-based system experiences RF characteristic changes under strain, leading to wireless disconnection and inaccurate sensor data (Figure 1I). In contrast, the DEE-based system provides continuous data under strain, maintaining high consistency between wireless and wired sensor data. During



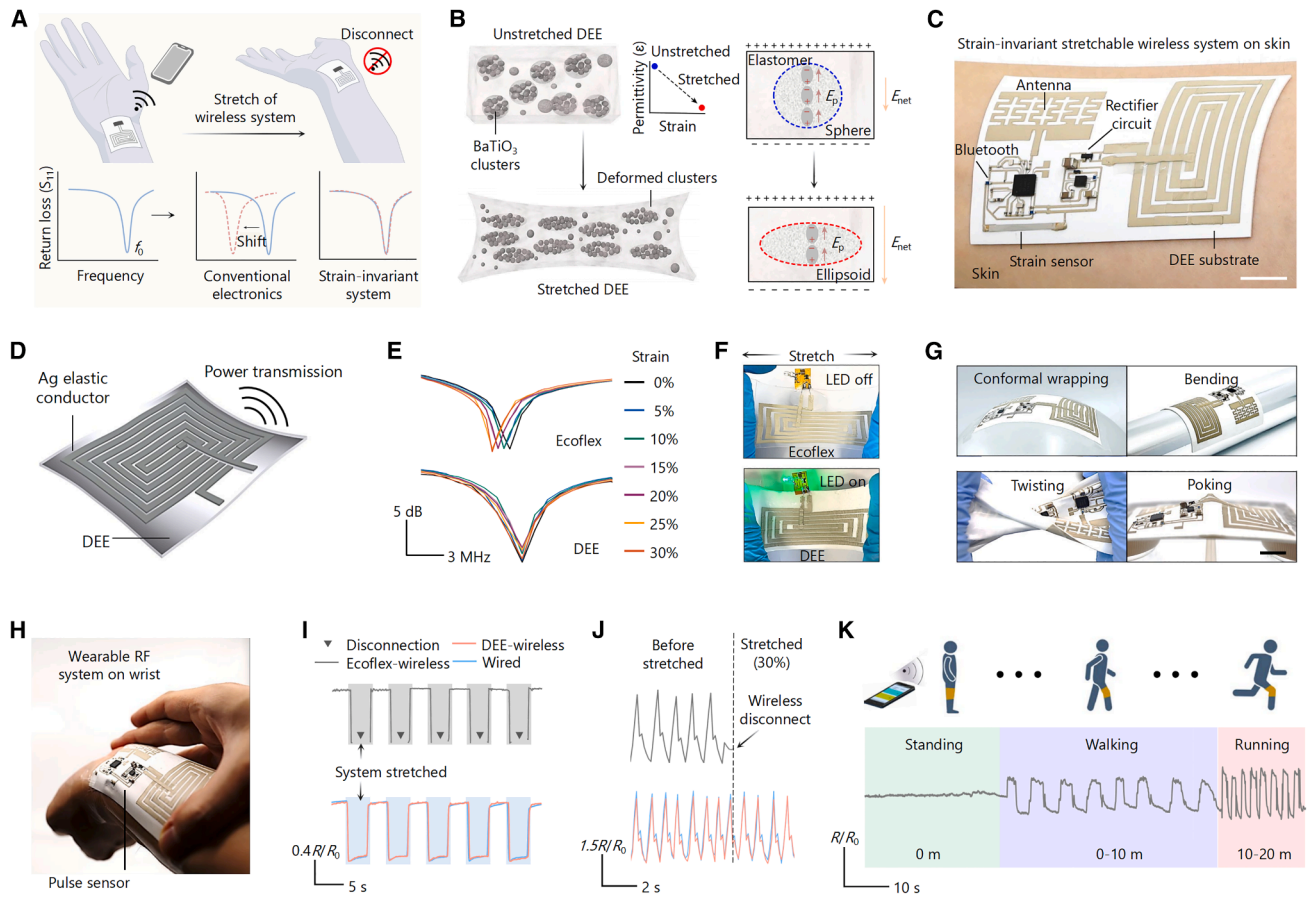


Figure 1. Dielectro-elastic substrate for wireless strain-invariant stretchable bioelectronics

(A) Disconnection and resonance frequency shift induced by the strain of the wireless sensing system. (B) The DEE material design strategy and permittivity (ϵ) variation from composite geometrical deformation. (C) Photograph of the strain-invariant stretchable wireless system based on a DEE substrate. Scale bar, 10 mm. (D) Strain-invariant stretchable near-field inductive coils for wireless power transfer. (E) The variation in S-parameters of coils based on traditional and DEE substrates under 0%–30% strain. (F) Photographs of coils based on traditional and DEE substrates for powering an LED under 30% strain. (G) Mechanical conformability of the stretchable wireless system. Scale bar, 5 mm. (H) Photographs of the wireless system used for monitoring wrist pulse signals. (I and J) The resistance changes of strain sensors based on traditional and DEE substrates under stretching and the pulse signals obtained. (K) Real-time motion data transmission to a mobile device during activity. From Kim et al.⁷ Copyright 2024, the Nature Publishing Group.

practical pulse detection, the Ecoflex-based wireless system loses signal completely after strain and fails to provide pulse rates (Figure 1J). However, the DEE-based system maintains stable wireless communication under strain, showing nearly identical pulse rates to the wired sensor system.

Moreover, DEE-based RF components can be widely used to enhance wireless connectivity performance in various wearable platforms. For example, when integrated with biomimetic bands, they enable real-time transmission of strain, EEG, and EMG signals. Figure 1K demonstrates real-time data transmission of knee motion from a wireless biomimetic band over a 20-meter wireless range,

proving the significant potential of DEE-based stretchable RF electronics in enhancing the wireless connectivity of wearable devices adaptable to various body parts.

The proposed strategy of incorporating high-dielectric-constant nanoparticle clusters into elastomers enables the substrates of electronic devices to have tunable dielectric properties, effectively compensating for any RF performance changes induced by strain. However, integrating these RF devices into wearable electronic systems while ensuring stable, high-quality physiological signal acquisition still faces several challenges:

(1) *Motion artifacts in physiological monitoring.* Physiological data collected

by sensors can be significantly affected by motion artifacts due to body movements and physiological activities.³ These include mechanical, biopotential, and impedance instability motion artifacts that can severely interfere with target signals. Even with strain-invariant wireless communication, acquiring high-quality physiological signals from a dynamic skin surface remains challenging. Advanced circuit management and algorithmic intervention strategies are necessary to mitigate these artifact signals.

(2) *Power supply for wireless medical systems.* Reliable power supply is pivotal for stretchable wireless medical monitoring systems, which integrate numerous electronic components requiring external

power sources. The size, weight, and modulus of batteries can impact the comfort and wearability of the system. Additionally, as the functionality and data processing requirements of the system increase, so do the demands on power management. To ensure stable and autonomous operation, it is essential to optimize power consumption, employ efficient energy management systems, and integrate flexible battery components.^{8,9}

Addressing these challenges would enhance RF device functionality and ensure reliable physiological signal acquisition, facilitating the widespread adoption of medical monitoring and wearable technology.¹⁰

ACKNOWLEDGMENTS

J.C. acknowledges the Verroy Makoto Watanabe Excellence in Research Award at the UCLA Samueli School of Engineering, the Office of Naval Research Young Investigator Award (award ID: N00014-24-1-2065), National Institutes of Health Grant (award IDs: R01 CA287326 and R01 HL175135), National Science Foundation Grant (award number: 2425858), the American Heart

Association Innovative Project Award (award ID: 23IPA1054908), the American Heart Association Transformational Project Award (award ID: 23TPA1141360), the American Heart Association's Second Century Early Faculty Independence Award (award ID: 23SCEFA1157587).

DECLARATION OF INTERESTS

The authors declare no competing interests.

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