A Self-Powered, Flexible Triboelectric Nanogenerator for Wireless Sensor Systems

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***Abstract*— Wireless sensor systems face key challenges, including reliance on batteries, complex circuitry, high fabrication costs, and limited durability in harsh or remote environments. These limitations hinder long-term, autonomous sensing, particularly for wearable, military, and environmental applications. To overcome these issues, we present a fully self-powered, battery-free, and flexible wireless force sensing platform based on a 3D multi-nanomaterials printed triboelectric nanogenerator (TENG). Our system uses low-cost, multi-nanomaterials 3D printing to fabricate a mechanically robust TENG integrated with an antenna to form a passive RLC circuit for wireless signal transmission. By incorporating a diode-switch configuration, the high output impedance of the TENG is reduced, enabling direct, efficient resonance-based wireless transmission in the megahertz range. The system transmits force information through shifts in resonant frequency, offering stability against environmental variations. Additionally, we demonstrate wireless power transfer by rectifying the received signal to power an LED remotely. This compact, battery-free, active electronics-free platform provides a promising solution for sustainable, self-powered autonomous wireless sensing in inaccessible or resource-limited environments.**

Keywords— Triboelectric Nanogenerator, Self-power, Wireless, Force sensing, Flexible, Battery-free

I. INTRODUCTION

Wireless sensor systems are becoming increasingly important in fields such as health monitoring [1, 2], environmental sensing [3], and military applications [4, 5]. These systems allow for real-time, continuous data collection and communication without the need for physical wiring, making them ideal for both wearable and remote applications. To enable wireless transmission, traditional systems rely on techniques such as Bluetooth [6] , Wi-Fi [7], which contain wireless modules significantly increase power demands. As a result, most wireless sensors depend on batteries as their primary power source to meet the high power demand. However, batteries add bulk, have limited lifespans, require regular maintenance, and pose safety or reliability concerns in harsh or inaccessible environments. These limitations create a major barrier to truly autonomous, long-term sensing. To address this challenge, researchers have turned to self-powered sensor systems that harvest ambient energy from the environment, offering the potential to extend device lifetime and reduce reliance on batteries or external power supplies.

Several energy harvesting techniques have been studied for self-powered systems, including thermoelectric [8], piezoelectric [9], and photovoltaic methods [10]. While these methods show promise, issues relating to high fabrication costs and environmental stability due to temperature fluctuations, material oxidation, and humidity hinder the use of these energy harvesting mechanisms for long-term self-powered applications [11-13]. Triboelectric nanogenerators (TENGs) offer a more versatile and cost-effective solution by converting mechanical energy—such as force, vibration, or pressure—into electricity using contact electrification and electrostatic induction [14, 15]. TENGs can be made lightweight, flexible, and highly customizable, making them suitable for integration into wearable and portable systems [16]. TENGs are known to have very high impedance in the range of MΩ- GΩ [17, 18] pose challenges when coupled with low impedance antennas (typically less than 50Ω) for wireless sensor systems. This impedance mismatch results in mismatch losses and reduced power transfer efficiency.

To tackle the limitations associated with wireless sensor systems such as complex circuitry, reliance on batteries, complex fabrication methods, limited lifespan, and unsuitability in inaccessible or harsh environments, we developed a fully self-sustained, flexible, and battery-free force sensing platform based on a TENG. Our design integrates a multi-layered, multi-nanomaterial architecture fabricated via 3D multi-nanomaterials printing, offering a low-cost, scalable, and rapid prototyping method that supports customization of both mechanical and electrical properties. The TENG is engineered to operate independently of any external power source, harvesting mechanical energy from applied force and converting it into electrical signals through contact electrification and electrostatic induction. To ensure reliable performance and long-term mechanical integrity, we

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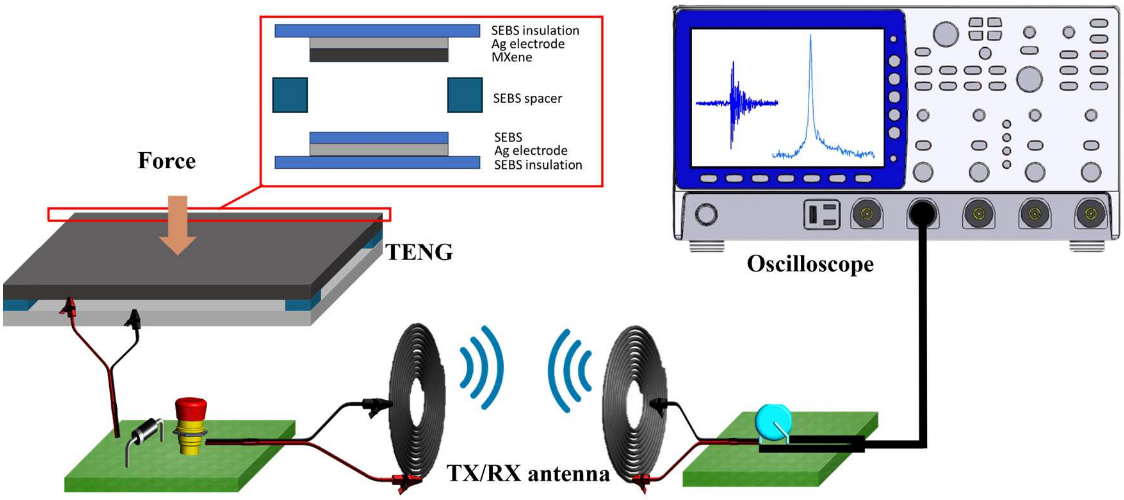

Fig. 1 Schematic illustration of wireless force sensing using self-powered TENG-based force sensor coupled with inductively coupled coil antennas.

selected highly flexible materials with excellent triboelectric properties. For efficient wireless transmission, the inherently high output impedance of the TENG was addressed by integrating a forward diode and a switch into the circuit. As a result, wireless transmission is achieved in the MHz frequency range without the need for active electronics. The integrated system forms a passive RLC circuit, in which the variable capacitance of the TENG, modulated by applied force, tunes the resonant frequency of the transmitted signal. This resonant frequency serves as a stable, environment-insensitive parameter for encoding force-sensing information, enabling reliable wireless sensing in real-world conditions. In addition to force sensing, our system demonstrates wireless power transfer capabilities, as evidenced by the successful illumination of an LED at a distance through inductive coupling. These features highlight the significance of our device as a low-cost solution for self-sustained, self-powered, battery-free, low-power, wireless sensor systems suited for applications in remote areas. Unlike previous TENG-based wireless systems that rely on active circuits, amplifiers, or large-scale device footprints [19, 20], our prototype is fully passive and miniaturized, fabricated through 3D multi-nanomaterials printing. Beyond general-purpose wireless force sensing, this platform has clear biomedical potential. For instance, the force-sensing capability could be adapted for rehabilitation monitoring, where grip strength or joint-loading needs to be continuously tracked during recovery. In such cases, the measured resonant frequency shift directly corresponds to the applied biomechanical force.

II. Results and Discussion

The proposed design depicted in **Fig. 1** presents the envisioned application of self-powered wireless resonance force sensing through the integration of the TENG with inductively coupled coil antennas. Styrene Ethylene Butylene Styrene (SEBS) was used both as the substrate and triboelectric material due to its excellent elasticity, allowing it to endure large deformations, and its favorable triboelectric polarity, which enhances energy generation [16]. On the other hand, MXene was chosen for its high negative surface, owing to its terminated functional groups **[21],** serve as the negative triboelectric material. Polyaniline (PANI) was intercalated between the MXene monolayer sheets to form an environmentally stable MXene/PANI composite, in which PANI has been proven to form a protective barrier that prevents MXene oxidation in previous studies [14]. This prevents performance degradation due to material oxidation in the long term. Unlike other sensors, which require high cost and time-consuming microfabrication [22], our TENG device was fabricated using our previously developed 3D multi-nanomaterials printing methods, which offer rapid prototyping, save time, and allow tuning of materials in terms of mechanical and electrical properties [23]. Silver (Ag) was employed as the electrode material owing to its high electrical conductivity, enabling efficient transfer of generated charges to the external circuit for improved energy output. For electrode connection, thin gold films were attached to the Ag electrodes using conductive silver epoxy. The device (6 cm) assembly was completed by attaching the SEBS spacers between the top and bottom triboelectric layers **(Fig. 2A).**

The TENG-based force sensor operates in a vertical contact-separation mode, beginning in an uncharged state when no force is applied. Upon the application of force, the triboelectric-negative MXene/PANI layer is displaced downward and contacts the triboelectric-positive SEBS layer. This interaction initiates charge transfer from SEBS to MXene/PANI through contact electrification. As the force is released, the layers separate, creating a potential difference between the silver electrodes due to the spatial separation of the triboelectric charges. This electric potential drives electron flow through the external circuit. With repeated pressing and releasing, alternating electrical signals are produced as charges continuously transfer between the triboelectric layers. **Fig. 2B** shows the variation of output voltage with applied forces. This indicates increased contact area between the tribolayers, leading to enhanced charge generation. To evaluate the power generation capabilities, different load resistances were connected to the TENG, and the corresponding output voltage and current were measured using an electrometer. At a 40 N force, the TENG device can generate about 700V output voltage and 1.4 μA. The resulting peak power density was 1000 mW/m^2 at the impedance matching conditions **(Fig. 2C)**.

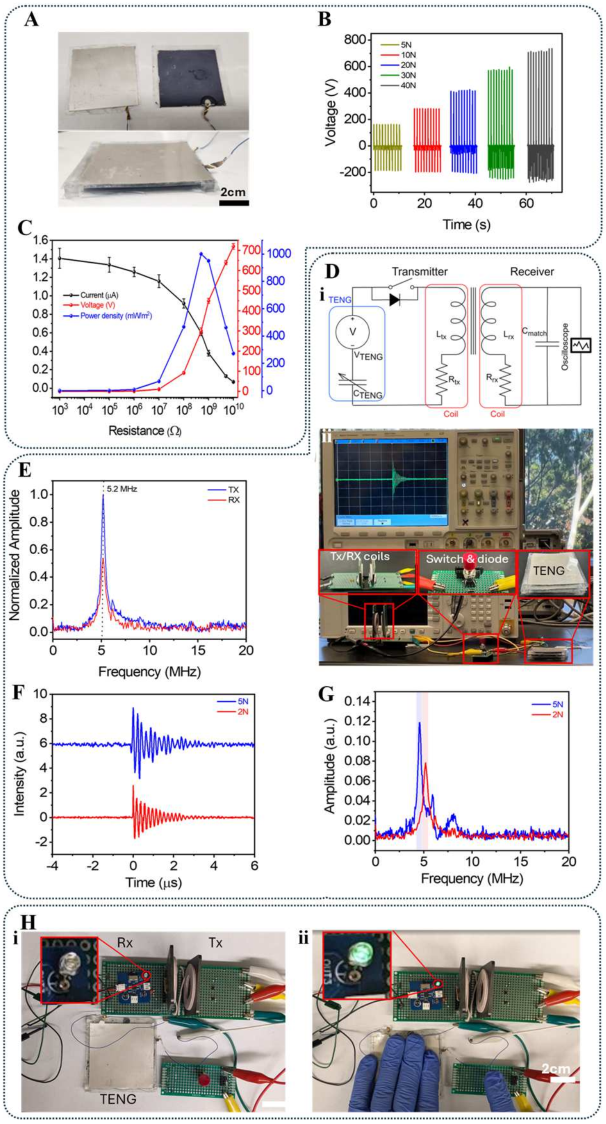

Fig. 2 (A) Photo of 3D multi-nanomaterials printed triboelectric layers and fully assembled TENG device. (B) Variation of output voltage with applied force. (C) Output current, voltage, and instantaneous output power density for different resistive loads. (D) (i) Equivalent circuit schematic and (ii) photo of experimental setup for self-powered wireless force sensing. (E) FFT spectrum of transmitter and receiver signals for the same force. (F-G) Real-time receiver signals and corresponding FFT for different forces. (H) Photo of self-powered wireless LED illumination. (i) LED OFF and (ii) LED OFF.

In this study, we introduced a TENG-based wireless transmission system that operates without batteries for self-powered wireless force sensing. The active-electronics-free force transducer side comprises a passive RLC circuit formed by an induction coil and the TENG capacitance (C_{TENG}), which varies as the tribolayer separation gap changes with applied force. The system leverages the resonant frequency of the RLC circuit as a reliable and stable reference for force calibration. Unlike signal amplitude, which can be significantly influenced by environmental factors such as humidity, temperature, and transmission distance, the resonant frequency remains largely unaffected by these external variations [24]. This stability arises because the resonant frequency is primarily determined by the intrinsic electrical properties of the RLC circuit, specifically the inductance of the coil and the capacitance of the TENG, which varies only with applied force. As a result, using frequency as a sensing parameter enhances the accuracy and repeatability of force measurements, especially in dynamic or uncontrolled environments like remote areas. For effective transmission of this resonant frequency during compression cycles, we configured the TENG in series with a switch-and-diode arrangement, alongside a standard coil, forming the transmitter (Tx) setup. This configuration enables rapid discharge of the generated charges, effectively lowering the output impedance and allowing the system to drive a low-impedance resonant antenna directly. This configuration enhances the output voltage of the TENG during the force-sensitive pressing cycles. The receiver (Rx) side was equipped with a coil antenna similar to the transmitter's, complemented by an impedance-matching capacitor connected in parallel to the coil. An oscilloscope was used to capture the signals received in real time **(Fig. 2D).**

To confirm synchronized operation of the transmitter and receiver resonant circuits, we performed Fast Fourier Transform (FFT) analysis of both signals under a fixed applied force of 2 N and a separation distance of 2 cm, as proof of concept. As shown in **Fig. 2E**, both Tx and Rx exhibit a matching resonant frequency of 5.2 MHz, indicating stable and consistent wireless resonant coupling. Real-time signals received at different force levels are displayed in **Fig. 2F**, where increasing force corresponds to higher oscillation amplitudes. The associated FFT spectra in **Fig. 2G** reveal a clear shift in resonant frequency with applied force, confirming that force information is successfully transmitted wirelessly via frequency modulation. To further demonstrate wireless power transmission, the Rx coil was connected to an LED through a rectifier circuit **(Fig. 2H(i)).** Upon applying finger-tapping force to the TENG and simultaneously activating the switch, the Rx-side oscillating voltage was rectified into DC, effectively powering the LED **(Fig. 2H(ii)).**

III. Conclusion

In this work, we presented a compact, self-powered, flexible wireless force sensing system based on a 3D-printed TENG integrated with a passive resonant circuit. Using flexible triboelectric materials (SEBS and MXene) and a rapid prototyping 3D nanomaterials printing process, the device achieves stable resonant frequency modulation for force detection and demonstrates dual functionality by enabling short-range wireless power transfer to drive an LED. This passive, low-power, battery-free, active electronics-free approach represents a step toward sustainable autonomous sensing platforms for remote health monitoring, environmental detection, and defense applications. In particular, the frequency–shift–based sensing offers a direct pathway to biomedical integration. For instance, quantifying grip strength during rehabilitation or localized muscle contractions, where resonant frequency shifts act as reliable indicators of physiological metrics. Nonetheless, current limitations include short transmission distances, limited harvested power, and the absence of on-body biomedical validation. Future work will address these challenges through coil optimization, optimizing the triboelectric properties of the nanomaterials for high power generation, and system-level integration for practical on-body integration.

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