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Paper based Biodegradable R-C-FET Amplifier

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ABSTRACT: Electronic waste is rapidly increasing, driven by fast tech development and frequent consumer upgrades. This poses a major environmental risk, especially with the rise of single-use electronics for healthcare, environmental monitoring, and logistics. Traditional components make these devices costly and harmful due to poor disposability. Paper-based substrates offer a low-cost, flexible, and eco-friendly alternative, making them ideal for sustainable single-use applications.

I. INTRODUCTION

Electronic waste (E-waste) is currently the fastest-growing category of waste globally, with projections suggesting it could reach nearly 75 million tons annually by 2030. This surge is largely fueled by the rapid advancement of high-performance technologies and the consumer trend of frequent upgrades. E-waste presents a major environmental concern due to the presence of non-recyclable and hazardous materials in many electronic products. This issue is particularly problematic for the emerging field of single-use electronics and sensors, which are gaining popularity for a variety of applications such as point-of-care medical diagnostics, environmental monitoring, detection of food allergens or spoilage, and supply chain tracking. Despite their usefulness and convenience, these disposable devices—when made with traditional electronic components and power sources—can significantly contribute to electronic waste and lead to higher production costs, making widespread implementation less viable. Paper-based substrates offer a promising solution to this challenge. They are cost-effective, widely available, flexible, and biodegradable, making them especially suitable for single-use applications. As society continues to generate increasing amounts of material waste, particularly in recent decades due to rapid technological growth and consumer behavior, finding sustainable alternatives like paper-based electronics becomes crucial for reducing the environmental impact of disposable devices.

II. METHODOLOGY

The Internet of Disposable Things (IoDT) has recently emerged as a cost-effective and practical approach for building wireless sensor networks (WSNs). These systems offer quick and simple deployment, operating for a limited, pre-defined duration before being discarded. Although the IoDT concept was introduced in 2018, its progress has been slowed by technical barriers and the complex, interdisciplinary nature of application-specific WSNs. One of the main challenges is developing disposable yet environmentally friendly devices that prevent a surge in electronic waste.

To tackle this issue, researchers at Binghamton University (State University of New York) have pioneered a fully paper-based electronic system. All components—including resistors, supercapacitors, and field-effect transistors—are fabricated and integrated on paper-based printed circuit boards (PCBs), offering a sustainable and cost-efficient alternative to traditional electronics. This innovative method allows for the simultaneous creation of tunable resistors (ranging from 20 Ω to 285 k Ω), supercapacitors (~3.29 mF), and both p-type and n-type electrolyte-gated transistors within a single sheet of paper by functionalizing specific regions of the paper.

This green electronics platform, nicknamed “papertronics,” represents a significant step toward eco-friendly, single-use devices. The prototype is a basic paper amplifier circuit with integrated components and is designed to naturally decompose after use. Potential applications include healthcare diagnostics, environmental sensing, food quality monitoring, and logistics tracking.

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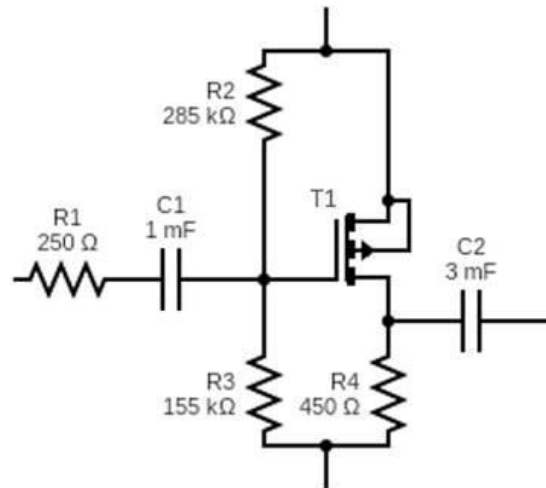


Fig 2.1. This amplifier circuit comprised of resistors, millifarad supercapacitors, and a FET was used to demonstrate the possibilities of the paper printed circuit board.

A field-effect transistor (FET) was employed to showcase the potential of paper-based printed circuit boards. The fabrication process began with the use of a 3D printer to deposit wax onto a sheet of paper, forming channels in a straightforward design. This technique is somewhat similar to the use of resist materials in traditional semiconductor manufacturing (see Fig. 2.2).

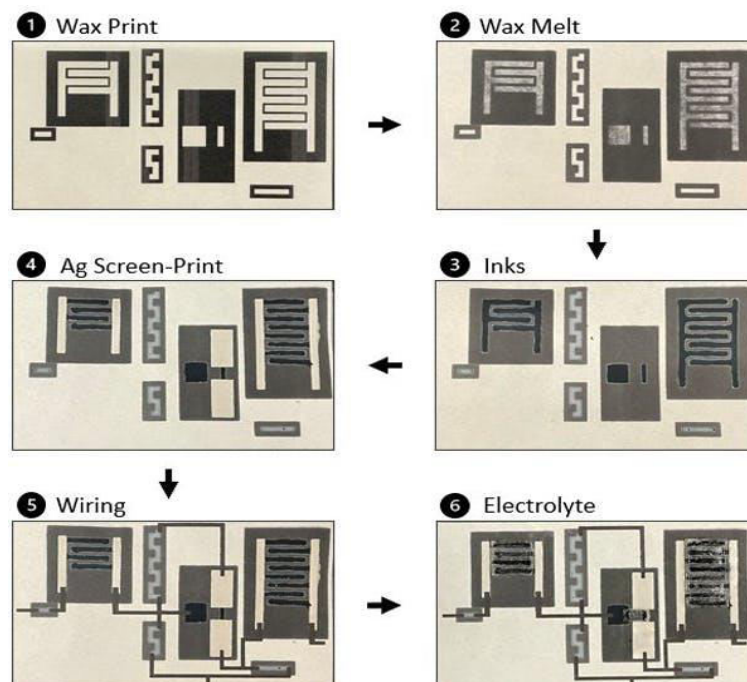


Fig 2.2. Fabrication steps required for making a paper PCB

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The fabrication process of a paper-based printed circuit board (PCB) integrating resistors, capacitors, and transistors involves several key steps:

1. A wax printer is used to create patterns on filter paper.
2. The paper is then baked, allowing the wax to penetrate and form barriers within the paper structure.
3. Functional inks are applied to designated areas.
4. Silver/silver chloride (Ag/AgCl) ink is screen-printed as needed.
5. Conductive pathways are added to interconnect the various components.
6. Finally, gel electrolytes are deposited over the active zones of the supercapacitors and FETs.

Once the wax melts and seeps into the paper, semi-conductive and conductive inks are printed in the unblocked regions. Additional metallic conductive elements are screen-printed, and a gel-based electrolyte is applied across the paper. Each electronic component—resistor, capacitor, and transistor—is constructed with its own unique layered configuration.

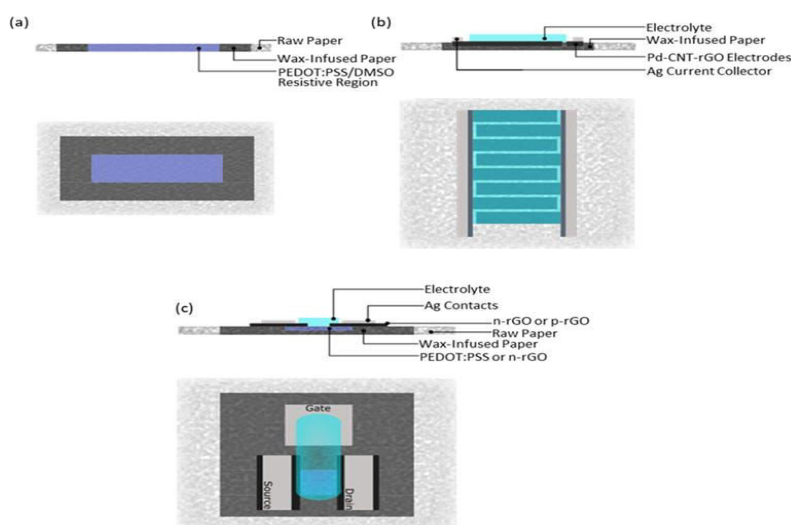


Fig 2.3 Components layering scheme and footprint

Each electronic component—namely the resistor, interdigitated capacitor, and field-effect transistor (FET)—was constructed with its own unique layering structure and physical layout. Performance testing confirmed that all three components operated as intended, closely matching their modeled behavior. Notably, even after integrating these elements, the final paper-based circuit remained extremely thin and highly flexible, maintaining the physical characteristics of regular paper. The researchers also suggested that their fabrication method holds potential for modest scale-up using small-scale batch processing techniques.

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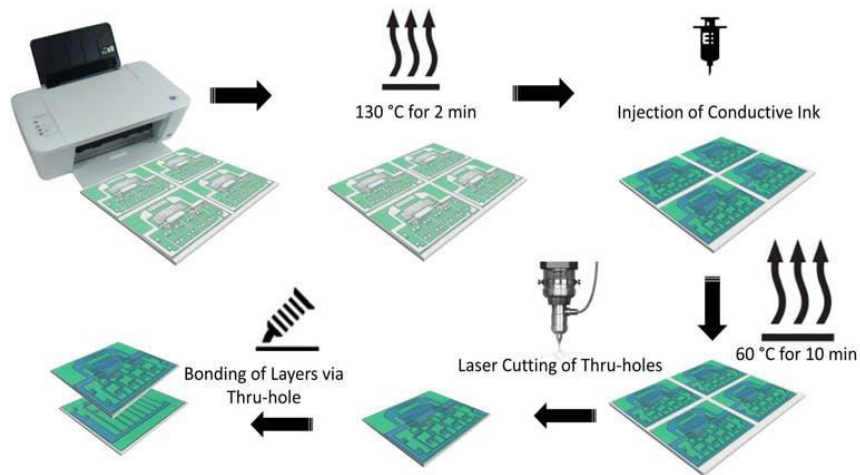


Fig 2.4 batch fabrication processes.

The team believes the technology is compatible with batch fabrication processes. To further demonstrate the quick degradability of the circuit, they showed that the entire unit soon burns to ash after being lit on fire (Fig.2.5). If biodegradability isn't an option, the entire printed-circuit substrate and its layered component can easily be burned, leaving behind a small pile of fine ash

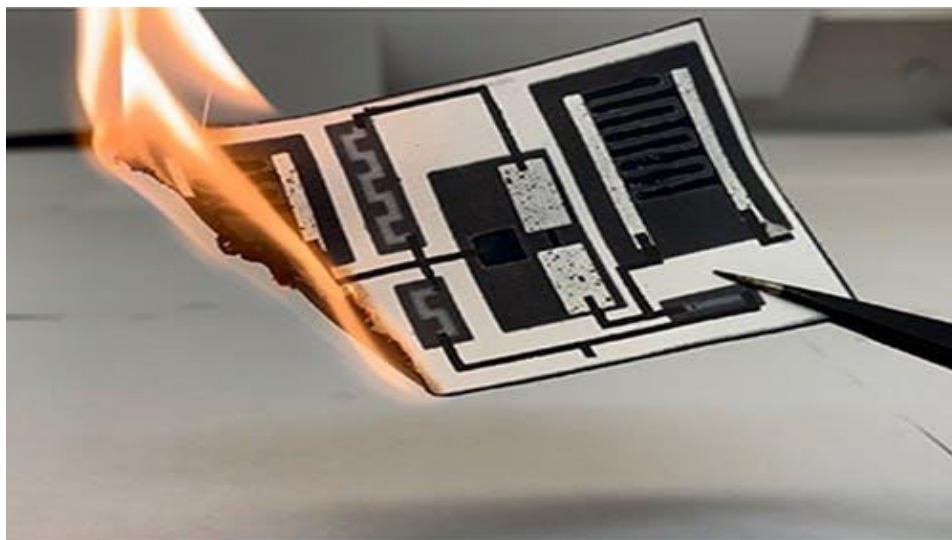


Fig 2.5 Degradability of the circuit



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III. PAPER-BASED CIRCUIT COMPONENTS AND CHALLENGES

Paper's high disposability, flexibility, and low cost make it an attractive substrate for single-use devices. However, effectively integrating electronic circuitry onto paper remains a significant challenge. This difficulty mainly stems from the paper's porous and fibrous surface, which is uneven and rough, preventing the formation of the high-resolution, uniform structures needed for electronic components. Despite these challenges, various attempts at paper-electronics integration have been made, each with its own limitations. One approach involves "paper printed circuit boards" (PCBs), where conductive metal traces are printed onto paper, and off-the-shelf surface-mount (SM) components are attached using conductive epoxy. While this method enables rapid circuit fabrication on paper, the bulky and rigid nature of standard components and coin batteries clashes with the paper's flexibility and disposability, adding weight and reducing overall appeal. Other techniques have relied on specialty-coated paper or intricate multilayer surface structures designed for individual components. However, none have yet demonstrated practical advantages in terms of simple fabrication, compatibility with paper, and flexible design options. These shortcomings highlight a crucial gap: the need for a streamlined process that allows quick design, easy customization, and efficient manufacturing of circuits while maintaining the key benefits of paper substrates—essential for papertronics to become viable in real-world applications.

Highly tunable resistors

Pseudo-resistor circuits simulate high-value resistors by occupying much less space compared to their physical counterparts with the same resistance.

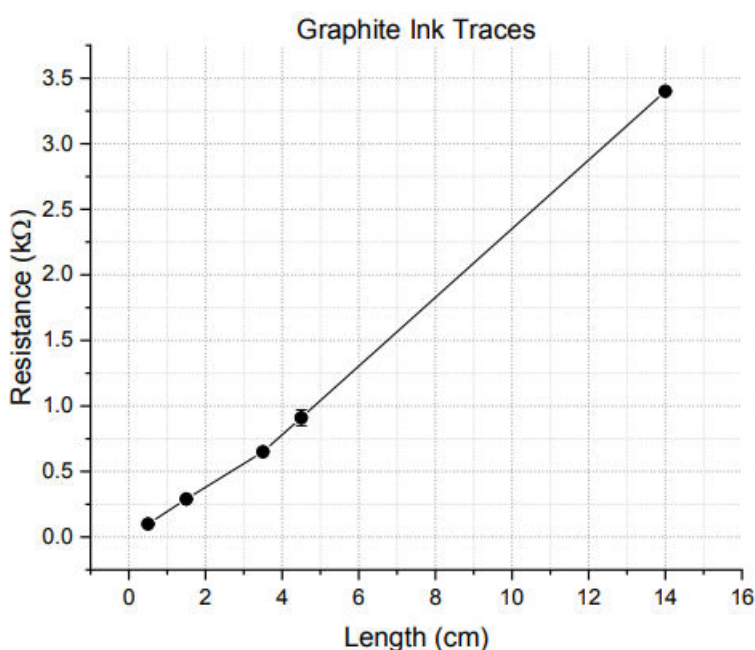


Fig 3.1 Measured resistance values of screen-printed graphite ink on 1 Filter paper at lengths of 0.5 cm, 1.5 cm, 3.5 cm, 4.5 cm, and 14 cm (width = 1mm).

Super capacitors

A capacitor stores electrical energy as electric charge, with capacitance ranging from picofarads to microfarads. Supercapacitors, with capacitance measured in farads, hold about a thousand times more charge than electrolytic capacitors. Their energy density is higher than that of capacitors but lower than batteries. Various electrode materials—



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such as activated carbon, carbon nanotubes, graphene, and polymers—are explored to improve supercapacitor performance. Recently, graphene has gained attention for its excellent electrical and thermal conductivity, lightweight nature, large surface area, and strong chemical stability. The performance of supercapacitors heavily depends on the electrolyte used. Adequate electrolyte concentration is crucial to prevent charge depletion, especially in organic electrolytes. Supercapacitors commonly use two types of electrolytes: aqueous and organic. Additionally, organic or ionic liquids can be employed as binders within the electrode materials.

Basic applications

Supercapacitors are widely used for backup power due to their high capacity and rapid charging ability. Early designs using micro-power amplifiers and Farad-range supercapacitors operated for over two hours on a single charge and recharged in seconds, unlike traditional batteries that require hours. Their long charge–discharge cycle life makes them environmentally friendly by eliminating disposable parts during operation. Because of their large energy storage, supercapacitors are increasingly found in portable electronics like MP3 players and mobile phones. In transportation, electric vehicle manufacturers aim to match the 500-mile range of combustion cars, which demands advanced battery or supercapacitor solutions. As supercapacitor energy density approaches that of batteries, they are expected to replace chemical batteries in vehicles soon. They serve as electrical equivalents of flywheels in energy storage systems, with applications in wind turbines and hybrid/electric vehicles, where they support regenerative braking and other functions such as power conditioning, smart metering, energy harvesting, inverters, and more.

Most industrially, supercapacitors support uninterruptible power supplies (UPS), helping to handle power disturbances. While rechargeable batteries are still preferred for their high energy density, supercapacitors assist by supplying impulse power and reducing battery stress, thus extending battery life. In power electronics, supercapacitors can replace DC capacitors for short-term charge storage in converters. Hybrid energy storage systems pair supercapacitors with slower but higher-energy devices like fuel cells and batteries, combining fast response with long lifespan to improve overall performance and reduce system size. Supercapacitors also serve as energy buffers in adjustable variable drives (AVDs) and other industrial settings, whose popularity is rising due to cost-effective and efficient inverters.

Table 3.1: Capacitance values of 8 fingered capacitor based on values extracted from CV measurements

Scan Rate (mV/s)	CV Discharge Area (mA.V)	Capacitance (mF)	Specific Capacitance (mF/mg)	Areal Capacitance (mF/cm ²)
10	0.091	3.033	0.276	1.176
50	0.3	2.000	0.182	0.775
100	0.42	1.400	0.127	0.543

3.3. Electrolyte gated field effective transistors (EFET)

Electrolyte materials and electrolyte-gated field-effect transistors (EGFETs) have attracted significant interest for their printability, flexibility, and suitability for large-scale manufacturing, especially in IoT applications. They show promise for emerging technologies such as artificial synapses, wearable electronics, and biological sensors. Unlike traditional organic thin-film transistors that use SiO₂ or polymer dielectrics, EGFETs employ electrolytes—either liquid or solid-state ion-conducting materials—which provide high gating capacitance. This allows them to operate at low voltages below 1 V, enhancing portability.

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Various electrolytes have been evaluated for their advantages and disadvantages:

- **Aqueous electrolytes** are preferred for biological sensing due to their compatibility with biological analytes, similarity to bodily fluids, ease of synthesis, and standardized composition. However, they lack environmental stability, limiting their use in portable or wearable biosensors.
- **Ionic liquids** offer high stability but face limitations similar to aqueous electrolytes because of their liquid form. Their complex synthesis and high cost can hinder large-scale disposable device production.
- **Ion gels** address some ionic liquid issues while maintaining high performance and compatibility with printing methods, supporting high-throughput manufacturing and portability.
- **Polyelectrolytes** have excellent printability but suffer from poor ionic conductivity and environmental sensitivity, often requiring device encapsulation.
- **Polymer electrolytes** can deliver high performance and portability with simple printability, though they may need longer synthesis times.

A major challenge in fully printed EGFET fabrication is finding compatible and affordable electrodes. Gold is the standard, produced via sputtering or evaporation, but gold nanoparticle inks are costly for mass production. Silver nanoparticle inks are cheaper but face compatibility problems with many electrolytes due to oxidation and corrosion. Developing suitable printable electrolyte materials is critical for realizing disposable, low-cost, all-printed transistors.

Stability is another concern for EGFETs, heavily influenced by material choice and transistor design. Various strategies—such as additive incorporation, composition fine-tuning, encapsulation barriers, and transistor geometry modification—have been explored to enhance stability. Further research is needed to control environmental factors like temperature and humidity, and improve the electrochemical durability of EGFETs.

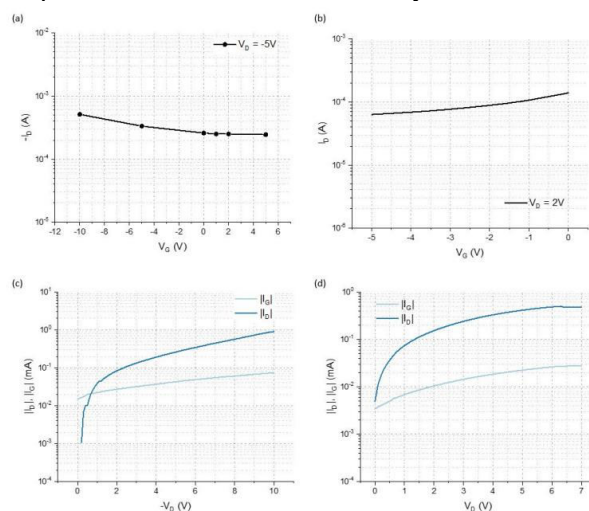


Fig.3.2 Transfer characteristic curve of (a) p-type EFET and (b) n-type EFET on a semilog scale. Comparative plots of drain current and gate current for (c) p-type EFET and (d) ntype EFET ($V_G = 0V$).



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Table 3.2 Summary of paper component design specification used to achieve desired values for paper PCB

Component Type	Nomenclature	Approx. Value	Units	Physical Design Parameters
Resistor	R1	250	Ω	Length: 5 cm Ink: 10 wt% DMSO Volume: 3 μ L
	R2	285	k Ω	Length: 3.5 cm Ink: 1 wt% DMSO Volume: 10 μ L
	R3	155	k Ω	Length: 1.5 cm Ink: 1 wt% DMSO Volume: 5 μ L
	R4	450	Ω	Length: 1 cm Ink: 10 wt% DMSO Volume: 5 μ L
Capacitor	C1	1	mF	Finger #: 8
	C2	3	mF	Finger #: 6
Transistor	T1	-	-	P-Type EFET

Fig. 3.4 Paper-Based Power Sources and Challenges

. Creating an on-board, paper-based power source is crucial for powering papertronic devices. Similar to off-the-shelf surface-mount components, traditional coin batteries are unsuitable because they are too heavy and rigid. A promising alternative is the paper-based microbial fuel cell (MFC), also known as a biobattery. MFCs generate small amounts of electricity by harnessing electrons produced through bacterial metabolic processes. Specifically, paper-based MFCs introduce electrogenic bacteria—those capable of transferring electrons outside their cells—into a conductive paper matrix. The active fibers in the paper capture electrons from the bacteria and transport them through an electrical load to the battery's cathode.

This technology offers clear advantages: low cost, disposability, and potential for on-demand use. However, practical challenges remain. Effective operation requires a reliable source of electrogenic bacteria and a liquid supply to hydrate and nourish the bacteria. These resources can be scarce in remote or dry environments, limiting the device's use outside laboratory conditions. Freeze-drying bacteria within the device has been tried to overcome the bacteria availability problem, but this approach results in a short shelf life and needs specialized equipment, which reduces the overall benefits of the biobattery.

IV. RESULTS AND DISCUSSION

A prototype circuit board was created on a sheet of paper, leveraging paper's excellent suitability for single-use applications due to its low cost, wide availability, flexibility, and easy disposability. The biodegradable nature of paper has drawn significant interest as a key to greener electronics, helping to curb the rising problem of electronic waste. Additionally, paper's strong mechanical, dielectric, chemical, and thermal properties make it a breakthrough substrate for next-generation electronics, often called papertronics. The inherent compatibility of paper with processes like wicking, printing, and layering enabled a simplified fabrication approach and reduced device design complexity, while still fully utilizing paper's advantages in an eco-friendly and cost-effective manner. Using techniques such as wax printing, ink injection, and screen printing, metallic wiring was integrated onto the paper substrate while maintaining flexibility.

Looking ahead, these paper-based electronic devices hold promise for disposable wireless sensor networks (WSNs) within the Internet of Disposable Things (IoDT). The innovation of IoDT lies in its ability to create compact, low-cost, functional, and disposable WSN devices that connect wirelessly for a limited time before being discarded. Such devices



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could enable affordable, rapid deployment of applications including personalized point-of-care health monitoring, logistics tracking, food quality assessment, and military surveillance or delivery systems.

This work demonstrated a fully paper-based device, integrating all components—resistors, supercapacitors, and electrolyte-gated field-effect transistors—within a single sheet of functionalized paper. Each component showed good electrical performance, tunability, flexibility, and disposability. The project's goal was not to replace traditional inorganic electronics but to explore new opportunities and markets that reduce electronic waste. Since disposable devices operate for only short programmed periods, they do not require high-resolution, high-reliability integrated circuits. Further research will focus on improving component density and performance.

Components used in paper-based electronics are made from organic and synthetic polymers as well as eco-friendly semiconducting, conducting, and insulating materials. This study aimed to evaluate paper's potential as a substrate and to develop an innovative approach to integrate electronics into paper. Future work will focus on replacing current materials with even more biodegradable alternatives.

Merits and Demerits

These all-paper circuit boards are designed for single-use applications and can be easily and safely disposed of through incineration or biodegradation. When ignited, the paper-printed circuit boards reduce to ashes within about 20 seconds. Although some byproducts produced during incineration may pose environmental risks, limiting disposal to incineration can significantly reduce electronic waste. Modern incineration facilities employ various techniques to ensure complete combustion and minimize harmful emissions.

However, this technology has some limitations. Additional packaging is necessary for all-paper devices because exposure to humidity can significantly alter the paper's structure, reducing both performance and shelf life. Moreover, the paper may be vulnerable to biodegradation by microorganisms through enzymatic activity. Therefore, further research and development are needed to address these challenges and scale up the technology for practical use.

V. CONCLUSION

While conventional electronic components offer great functionality and convenience, their use in single-use applications would significantly increase electronic waste and costs. This work focuses on creating an affordable, environmentally friendly, all-paper device designed for disposable use that can be safely and easily discarded through incineration or biodegradation. All components are paper-based and integrated into paper-printed circuit boards (PCBs), providing an innovative and practical approach for green electronics.

This concept of papertronics is ideal for disposable wireless sensor networks (WSNs) within the Internet of Things ecosystem, referred to as the Internet of Disposable Things (IoDT). The IoDT enables WSNs made up of small, compact, low-cost, and disposable devices that remain functional until their task is complete, after which they can be discarded. Each electronic component is fully embedded in specialized paper regions, offering good electrical performance, tunability, flexibility, and disposability.

A simple amplifier circuit was successfully fabricated within the thin confines of a single sheet of paper, demonstrating the versatility of these components and the potential for parallel fabrication processes, which allows for efficient and rapid device development.

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