Wireless Powered Large-Area Electronics for Sustainable Internet of Things

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Abstract

The exponential increase in sensor nodes deployed within the Internet of Things (IoT) ecosystem poses key sustainability challenges. First, wirelessly powered operation is essential to overcome the limitations regarding the economic and environmental sustainability of battery-powered devices. Additionally, circuit technologies with reduced environmental impacts are key to ensuring the eco-friendliness of the IoT sensor node hardware. A promising avenue to address these challenges involves emerging large-area electronics (LAE) technologies, such as those based on organic semiconductors, amorphous metal-oxide semiconductors, semiconducting carbon nanotubes, and two-dimensional semiconductors. Herein, we analyze the status and prospects of emerging LAE for wirelessly powered IoT sensor nodes. First, a system-level analysis allows us to identify the constraints faced by wirelessly powered sensor nodes as well as the LAE-based architectures and design approaches that are most promising. Based on this analysis, we highlight the opportunities and outlook of LAE for wirelessly powered IoT sensor nodes, with a focus on ultra-low-power transistor circuits for digital processing and signal amplification, as well as high-speed diodes and printed antennas for data communication and radio frequency energy harvesting.

1. Introduction

Recent years have witnessed the formidable rise of the Internet of Things (IoT), which holds promise for enhancing the quality and sustainability of our lives by providing intelligence and data connectivity to everyday objects and environments[1–5](**Fig. 1a**). The success of the IoT crucially depends on the size of its physical layer, which is projected to reach one trillion devices by 2035[6]. Essential components of this ecosystem are the IoT sensor nodes ('sensor nodes' for short in the following), which ensure the functionality of the IoT by wirelessly feeding it with inputs from the physical world. Further, by embedding data processing in them, *smart* sensor nodes are realized, which enhance the IoT ecosystem with computing power at its 'edge'.

The ultra-large and growing number of sensor nodes as part of the IoT first poses a critical technological challenge regarding how to power them, especially due to the need for autonomous operation in many application areas and the typical size requirements associated with sensor nodes (typical feature size $\cong$ 10 cm). While batteries have been the conventional solution, solely relying on them is problematic first because of functional constraints. Due to the limited operational lifetime of batteries, sensor nodes with a 1% duty cycle, 10–100 µA current demand on silent mode, and 15–40 mA current demand during data transmission would cause standard batteries to discharge after 4–12 months[7]. Rechargeable batteries could potentially offer a solution; however, their charge-discharge cycles are constrained and their performance drops over time, inducing additional costs due to the need for replacements.

Alongside the aforementioned technological challenges, the traditional battery-centric model of powering sensor nodes poses a critical sustainability challenge due to the environmental impact of mainstream battery technologies[7–9]. For the sake of illustration, the current annual lithium global production[10] would not be sufficient to meet the demands of a one-trillion-node IoT ecosystem running on the lithium-based coin cell batteries[11] that are commonly used to power sensor nodes. Consequently, to ensure the sustainability of the IoT and realize its full potential, it is critical to adopt wirelessly powered sensor nodes (while also often referred to as self-powered sensor nodes, we refrain from using this term herein because of its ambiguity, given that power is not self-generated by the nodes but drawn from the environment). Wirelessly powered sensor nodes function through the energy drawn from the environment by compact energy harvesters (e.g., photovoltaic cells and radio frequency (RF) energy harvesters)[12,13] (**Fig. 1a**, **Table S1**). Such energy could be freely available—leading to ambient-energy-powered nodes—or supplied by dedicated sources (e.g., RF identification (RFID) readers in the context of RF energy harvesting)—leading to dedicated-energy-powered nodes. The former case is the most attractive from a sustainability perspective because it does not require a dedicated infrastructure of energy sources that consume power specifically for harvesting purposes. Importantly, given the limited power density typically available from non-dedicated ambient sources (**Table S1**), the requirement of wirelessly powered operation translates into the need to construct sensor nodes using ultra-low-power electronics.

Beyond the aforementioned challenges, the sustainability of the IoT also critically depends on the minimization of the environmental footprint of the electronics used in its sensor nodes. This aspect is particularly important due to the environmental impact of conventional integrated circuits and printed circuit board (PCB) technologies (as currently used in mainstream sensor nodes), which would be inevitably amplified by the sheer size of the IoT device ecosystem. Conventional silicon-based integrated circuit technologies involve energy-intensive fabrication methods (e.g., at temperatures > 1000°C and using sophisticated vacuum-based techniques) as well as complex production steps requiring transport across continents, which increases their carbon footprint considerably[14]. The same considerations inevitably apply to ultra-thin silicon integrated circuits recently pursued for IoT applications demanding mechanical compliance[15]. Conventional PCBs for the integration of sensor nodes are also highly problematic in terms of harmful emissions[16]. The difficulty of recycling such electronics at their end-of-life exacerbates these sustainability issues, as attested by the regulatory efforts toward greener electronics[17,18].

Alternative semiconductor technologies that have attracted strong interest over the last couple of decades hold significant promise for the realization of sustainable, wirelessly powered sensor nodes. Such technologies encompass thin-film devices that are based on emerging semiconductors (e.g., organic semiconductors, metal-oxide semiconductors, semiconducting carbon nanotubes, and 2D semiconductors) compatible with low-temperature, high-throughput manufacturing (e.g., printing and coating) on unconventional substrates (e.g., plastic films, paper, and fabric) (**Fig. 1a, Table 1**). These technologies are often collectively referred to as large-area electronics (LAE)[19], given their compatibility with a wide range of form factors. The versatility of LAE contrasts with wafer-based electronics (including conventional, thick-wafer electronics and their thinned-wafer variants), whose form factors are limited by the size and cost of the semiconductor wafers used as the base material (e.g., electronic-grade silicon wafers). Due to the aforementioned properties, LAE is compatible with sheet-to-sheet (S2S) and roll-to-roll (R2R), bottom-up manufacturing, thereby allowing considerable flexibility in terms of the area of the resultant circuits, their customizability, and economies of scale starting from significantly lower production volumes[20]. The low-temperature processing (typically < 200°C and often down to room temperature; see Table 1) and low material consumption (e.g., via additive manufacturing) of LAE technologies pave the way for electronics with reduced environmental impacts. Life cycle analyses of technologies based on organic semiconductors and crystalline silicon have confirmed this assertion[21]. Importantly, LAE technologies are suitable for the fabrication of sensing elements[22] and energy harvesters[23] on the same substrate materials that can be used for circuit integration. It can thus be envisaged that, in the future, complete wirelessly powered LAE sensor nodes could be manufactured at single production sites—using a palette of LAE materials that can be sequentially printed/coated to realize the various components of a sensor node (**Fig. 1b**)—thereby reducing the carbon footprint and supply chain issues associated with long-distance transport in conventional integrated circuit manufacturing. Further, the fabrication of LAE on eco-friendly substrates (e.g., paper-based) provides an attractive, environmentally

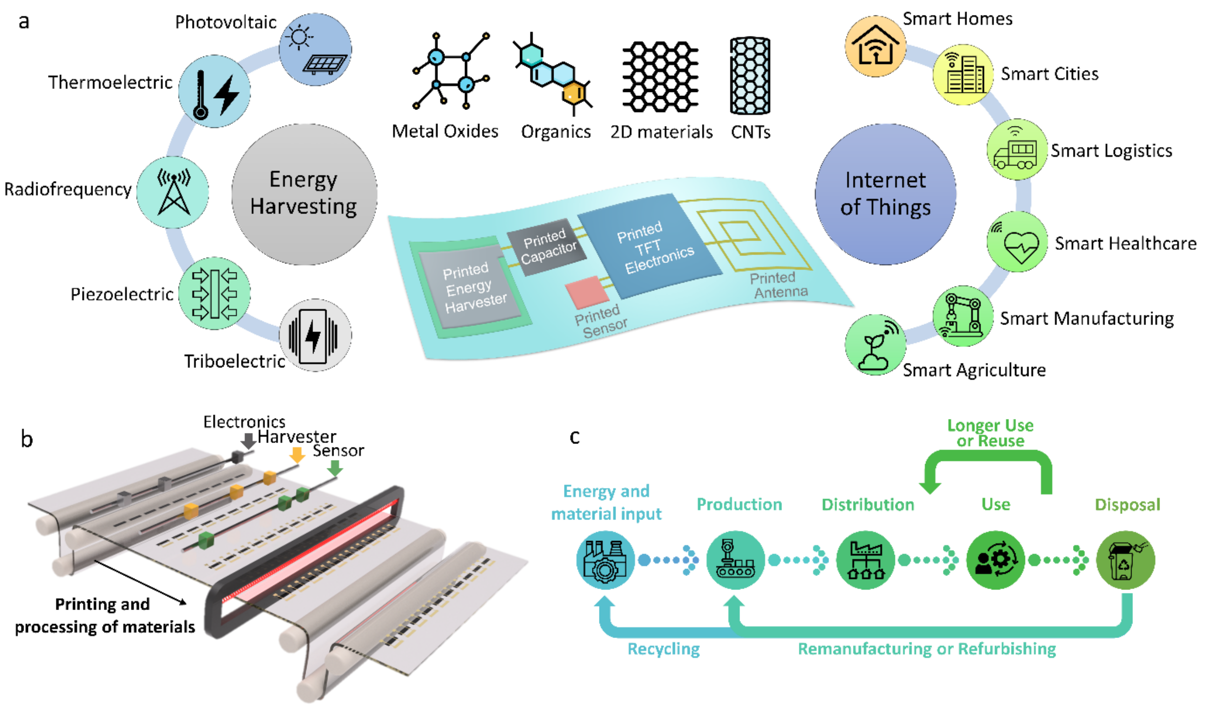

Fig. 1|LAE sensor node for sustainable IoT. a, Wirelessly powered LAE sensor nodes: energy harvesters, LAE materials, general sensor node architecture, and relevant application areas. **b,** Potential monolithic manufacturing of LAE sensor node for sustainable IoT. **c,** Ideal life cycle of a smart sensor node for sustainable IoT.[67]

friendly alternative to sensor-node integration based on conventional PCBs[24]. Finally, the potential for the recycling and re-using of LAE, as recently demonstrated in the context of printed carbon nanotube devices[25], points to the ideal prospect of adopting LAE for realizing truly circular electronics (**Fig. 1c**). Nevertheless, complete life cycle analyses of the different LAE technologies will be required to identify the most promising ones from a sustainability perspective, thus avoiding unintended consequences across their entire value chain[26].

Alongside sustainability considerations, recent milestones in LAE also substantiate their promise for wirelessly powered sensor nodes. Ultra-low-power circuits have been demonstrated with several LAE transistor technologies[27–29], in one instance also in combination with ambient energy harvesting[30]. Moreover, LAE demonstrators with increasing transistor count (Table 1) have been reported over the years, most recently in the form of a flexible 32-bit microprocessor comprising 39,157 TFTs[31] and an 8-bit one capable of operating at a speed up to 71.4 kHz[32]. Finally, LAE-based diodes[33] and printed antennas[34] have been recently demonstrated to be compatible with RF energy harvesting at 5G frequencies. These milestones unlock exciting capabilities and potential opportunities for wirelessly powered LAE sensor nodes. Consequently, based on these milestones and supported by a system-level assessment, herein we identify promising directions for future exploration in LAE toward eco-friendly, wirelessly powered sensor nodes, with a focus on ultra-low-power LAE circuits and LAE-based RF energy harvesting.

Table 1| LAE transistor technologies. Semiconductor polarity, processing temperatures (RT: room temperature), representative circuit implementations, and compatibility with S2S/R2R processing.

Semiconductors	Polarity	Processing temperatures	Representative works (No. of TFTs)	Compatibility with S2S/R2R
Metal oxides	mostly n-channel	from solution: ≥ 150 °C sputtering: RT	32-bit microprocessor[31] (39,157)	Yes
Semiconducting carbon nanotubes	n-channel and p-channel	from solution: RT	16-bit microprocessor[35] (14,702)	Yes
Organic semiconductors	mostly p-channel	from solution: RT zublimation: RT	8-bit microprocessor[36] (3,504)	Yes
2D materials	n-channel and p-channel	from solution: RT exfoliation: RT CVD: ≥ 400 °C	1-bit microprocessor[37] (115)	Yes

2. System View of Wirelessly Powered Sensor Nodes

A wirelessly powered sensor node distinctively features an energy harvester as its power source (**Fig. 2a**). The harvester generally comes with a power management unit and a storage element (e.g., capacitors/supercapacitors in batteryless implementations) to deliver the intended supply voltage over time, based on the typical harvest-energy-use scheme (**Fig. 2a**). Additionally, to provide edge intelligence while achieving wirelessly powered operation, a smart sensor node should comprise digital processing capable of distilling critical data from the sensor signals while minimizing the power consumed by the transceiver during wireless communication (**Fig. 2a**).

The preponderant challenge faced by wirelessly powered sensor nodes concerns the limited power densities available from ambient sources (Table S1). Photovoltaics offers a fitting example in view of its wide applicability: LAE indoor photovoltaics (e.g., organic or perovskite-based devices with efficiencies of approximately 30%) could deliver ≅ 50–100 µW with a 1 cm^2 energy harvester[7] (a desirable size to unobtrusively disseminate sensor nodes in everyday objects and environments). Such a stringent constraint makes it necessary to design smart sensor nodes with minimal energy consumption (for ambient-energy-powered operation) or capable of externalizing the energy-consuming processes (if dedicated-energy-powered operation is the sole priority).

In the ideal scenario of ambient-energy-powered operation, the freely available energy harvested from the environment should be sufficient for the sensor node to generate its own carrier to establish a wireless electromagnetic link with the IoT gateway (active transmission). Establishing such a link is typically the most power-consuming feature of a sensor node. While emerging wireless communication protocols allow reduced power dissipation, standard approaches consume in the range of 10–100 mW[7,38]. Therefore, the alternation of sleep-mode and active-mode intervals (e.g., as in a duty-cycled approach) is essential for the node to operate perpetually (energy-neutral operation). The harvester would then replenish the energy storage element during the sleep-mode intervals to allow the sensor node to cope with the short bursts of higher power dissipation when the wireless link becomes active. In fact, sensor nodes often feature aggressive duty cycles (i.e., ratios between the duration of sleep-mode and active-mode intervals) of 0.01–1 %. Although the power dissipation in sleep mode could be several orders of magnitude lower, such aggressive duty cycling implies that sleep-mode intervals could contribute a significant fraction of the overall energy consumption of the sensor node. Importantly, power dissipation in sleep mode relates to the static power consumption of always-on blocks (e.g., processing and memory blocks). Therefore, a high priority in the development of energy-neutral LAE sensor nodes is also the minimization of sleep-mode power consumption to (sub-)nanowatt levels.

The power constraints and integration complexity required for wirelessly powered smart sensors have made it elusive to date to attain ambient-energy-powered operation with LAE sensor nodes. However, considerable progress has been achieved in dedicated-energy-powered LAE sensor nodes relying on power transfer from dedicated RF energy sources. Key to this progress has been the adoption of backscatter communications, in which the sensor node relies on the impinging signal generated by the reader to carry the data transmitted by the node (see **Fig. 2b,c** for a comparison between active and backscatter communications). While the backscatter scheme may appear as the obvious choice for energy-frugal sensor nodes, regulatory limitations of the power emitted by gateways, the higher total path loss exponent of such links, and the non-zero power consumption of backscatter front-ends justify the use of this option only at shorter ranges. **Fig. 2d-e** compares the approximate energy required to send a bit of information as a function of the maximum range between a sensor node and a gateway for active and backscatter transceivers operating at different carrier frequencies. Under the realistic assumptions considered in this model, backscatter systems allow lower energy consumption per bit for ranges below 200 m.

Alongside wireless data communication, power consumption in a sensor node is also associated with the signal conditioning chain. It is important to note that, to date, circuit blocks needed for the signal conditioning chain of LAE sensor nodes have been implemented mainly with unipolar technologies (i.e., technologies based either on n-channel or p-channel thin-film transistors (TFTs)), given their simpler fabrication processes and wider availability (section 3). This has had considerable influence on the power consumption of such LAE circuit blocks. In

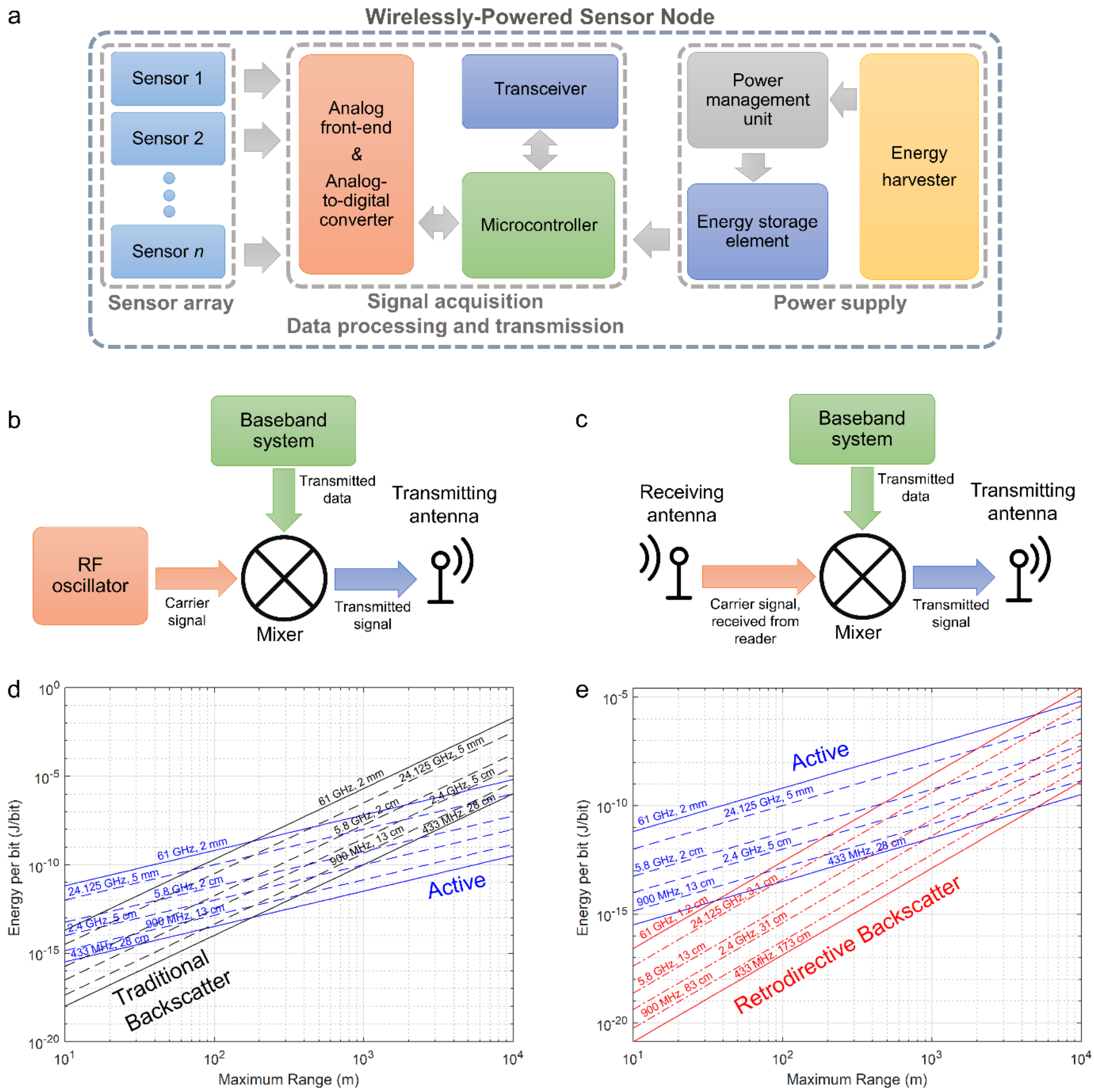

Fig. 2|System view of wirelessly powered sensor nodes. a, Architecture. **b,c** Schematic diagrams of (b) active and (c) backscatter transmitters. The backscatter transmitter uses a carrier signal received from the reader instead of expending power to generate one. In most cases, the receiving and transmitting antennas of the backscatter transmitter are the same antenna. **d,e,** Energy per communicated bit for (d) active and traditional backscatter systems and (e) active and retrodirective backscatter systems. The energy per bit is plotted as a function of the maximum communication range of wireless sensor nodes equipped with standard-sized equigain antennas (therefore, of different sizes—assumed square—at different frequencies) operating in standard license-free (ISM) bands. The frequency of operation and the size of the side of each antenna is placed above its corresponding line.

particular, the contribution of a unipolar LAE analog front-end to the overall power consumption of an LAE sensor node can vary from the µW range[39] to few milliwatts[40]. Further, due to the high power dissipation of digital circuits based on unipolar technologies, unipolar LAE-based analog-to-digital converters can become the most power-hungry circuit blocks in the signal conditioning chain. In the 5-bit successive approximation analog-to-digital converter reported in Ref. [41], based on a unipolar amorphous-metal-oxide technology, the digital circuitry consumed 226 mW, which is generally not compatible with wirelessly powered sensor node operation. To overcome this limitation, state-of-the-art implementations of dedicated-energy-powered sensor nodes based on LAE unipolar technologies have relied on pulse-width modulated data representation in backscatter near-field RFID sensor tags[42]. In this work, a temperature sensor on RFID, fabricated with printed organic TFTs, exploits a time-domain interface to ratiometrically read out a pair of resistive temperature sensors, converting the information to pulse-width modulated form. It uses 76 TFTs and consumes 2 mW[42]. In terms of the ultimate compatibility with standard protocols, a dedicated-energy-powered node fully complying with the ISO14443-A NFC has been shown in Ref. [43] using a unipolar amorphous-metal-oxide TFT technology: it uses 1712 TFTs and consumes 7.5 mW. Ambient-energy-powered operation, however, would require significantly lower power dissipation than normally afforded by unipolar technologies. At a circuit design level, an avenue that may be worthwhile exploring is to optimize unipolar digital logic for minimal power consumption via custom gate-by-gate design, i.e., doing without standard libraries[44].

Departing from the power dissipation constraints of conventional unipolar technologies, complementary LAE technologies (i.e., technologies comprising both n-channel and p-channel TFTs) would be desirable for ambient-energy-powered sensor nodes because they can deliver digital circuits with particularly low static power dissipation, albeit at the price of greater material and process complexity. While the greater manufacturing complexity of complementary LAE technologies may cease to be an issue once they reach their maturity, it also prompts the investigation of alternative, device-level approaches to LAE, which indeed can deliver a formidable reduction in power consumption (Section 3).

While the LAE implementations to date allow or are compatible with the tracking of a base sensor signal[42,43], adding a processing engine is key to realizing *smart* sensor nodes. Given the yield challenges faced by LAE technologies to date and in keeping with the need to minimize power dissipation, the realization of bespoke processors with the bare minimum functionalities should be preferred. A breakthrough in this direction has been the demonstration of the first machine-learning processing engine based on amorphous-metal-oxide TFTs[45]. Due to its reliance on unipolar logic gates, however, this implementation dissipated 7.2 mW, which is not compatible with ambient-energy-powered operation. Therefore, future efforts should not only aim to integrate bespoke processing engines within a complete LAE smart sensor architecture, but also to develop technological solutions to minimize the power consumption of LAE processing engines (Section 3).

3. Ultra-Low-Power LAE Circuits: Developments and Outlook

Electronics with ultra-low power consumption is essential for sensor nodes to function with the limited energy that can be harvested from the environment. Recent years have witnessed dramatic developments in LAE transistor technologies that can address this demand. Herein, we analyze these developments and identify promising directions for the realization of sustainable, ambient-energy-powered, LAE sensor nodes.

3.1 Complementary LAE Technologies

To realize wirelessly powered LAE sensor nodes, complementary LAE technologies would potentially be the best candidates, given their inherent ultra-low static power dissipation in digital gates, ideally coupled with wide noise margins (Fig. S1). By enhancing the gate-channel coupling through ultrathin gate dielectrics (e.g., based on self-assembled monolayers or high-k oxide dielectrics), all LAE technologies have delivered low- or ultra-low-voltage digital gates (e.g., see Refs. [46–49]) with complementary approaches (supply voltages = 0.1–2 V; **Fig. 3a** and Table S2). However, a key challenge has been to robustly achieve matching characteristics between n- and p-channel TFTs. Indeed, given the scarcity of n- and p-channel semiconductor pairs with symmetric charge transport properties within the LAE domain, considerable efforts have been devoted to the development of materials- and device-based strategies to circumvent the issue—e.g., semiconductor doping, the adoption of different metals for the source/drain electrodes of the n- and p-channel TFTs, and the incorporation of different self-assembled monolayers in the gate dielectric stack (Table S2). However, these strategies inevitably increase the material and process complexity of complementary LAE technologies. Indeed, while the latter technologies have achieved some of the lowest static power consumption figures in the LAE domain (down to the record-low value of 100 fW per inverter gate[50] (**Fig. 3a**), they are also burdened with the highest fabrication complexity index (FCI), which we introduce herein as a proxy for the inherent complexity of an LAE fabrication process (detailed definition in Note S1). Complementary LAE technologies typically feature FCIs ≥2 (**Fig. 3b**). Importantly, such higher complexity may be problematic in terms of yield (and/or cost), given that each additional material to be deposited can introduce additional variability in device performance. This is due to variations in materials properties and process parameters, whose control may result in additional process complexity and costs. Furthermore, while sophisticated process engineering can ultimately enable the scale-up to circuits with high gate count[35], the need to adopt many extra materials and process steps—often involving subtractive processing—is demanding in terms of the material and energy consumption of the fabrication process. This is expected to negatively impact the sustainability of the technology. Therefore, in the ongoing pursuit of n- and p-channel semiconductor pairs enabling scalable complementary LAE technologies, a high priority is to scale up or develop materials and device solutions that minimize fabrication complexity (the minimal FCI being 1 for complementary technologies) to realize their full sustainability potential.

3.2 Deep-Subthreshold Unipolar LAE for Ultra-Low-Power Amplifiers

While unipolar LAE technologies are much simpler than their complementary counterparts in terms of fabrication process (FCI = 0 in most cases; **Fig. 3b** and Table S2), they traditionally deliver digital circuits that suffer from high static power consumption (**Fig. 3a** and Fig. S1) and noise immunity issues, which makes them unattractive for the digital circuitry of wirelessly powered sensor nodes and typically unsuitable for ambient-energy-powered operation. However, it has been recently demonstrated that unipolar LAE technologies have considerable potential for ultra-low-power signal amplification, which is highly relevant to the analog front-end of smart sensor nodes. This breakthrough was based on the operation of unipolar TFTs in the deep-subthreshold regime, as demonstrated with both n-channel metal-oxide and p-channel organic semiconductors[27,29]. Importantly, the power dissipation of such TFTs exponentially decreases with the gate bias in the deep-subthreshold regime. Concurrently, by introducing a Schottky barrier at the source-semiconductor interface, such TFTs achieve a high, bias-independent intrinsic gain in the range of 500–1000 V/V[27,29] (i.e., approximately one order of magnitude higher than conventional above-threshold LAE TFTs[51]), making them attractive for ultra-low-power sensing with high resolution. For instance, the implementation of this concept with organic TFTs in Ref. [27] delivered a signal-to-noise ratio as high as 63 dB. Further, the use of a Schottky barrier at the source-semiconductor interface enables these TFTs to have geometry-independent output characteristics, thereby accommodating the large dimensional variations stemming from inkjet-printed features. The capability of this approach for ultra-low-power signal amplification was demonstrated with single-ended common-source amplifiers featuring zero-V_{GS} active loads, which achieved voltage gains in the region of 200–400 V/V (**Fig. 3c**) while consuming < 1 nW[27,29]. Given the zero-V_{GS} TFT loads adopted, however, the functionality of such implementations depended on the availability of a depletion load[29] (inherently resulting in higher process complexity and leading to FCI = 1) or an appreciably larger geometric footprint for the load TFT[27], additionally requiring robust control of the process parameters and bias point (given the exponential dependence of the current on the gate voltage). Also, while the speed limits of this LAE unipolar deep-subthreshold approach have not been fully explored[52] and its lower currents are expected to lead to larger time constants, this may not be an issue due to the comparatively low-frequency nature of the signals relevant to LAE sensor nodes (e.g., bio-signals). Therefore, deep-subthreshold unipolar TFTs offer an attractive platform for ultra-low-power signal amplification, yet further research is needed to assess the optimal circuit topologies to achieve functionality with low FCI and small footprint, while concurrently aiming for device architectures with intrinsically low parasitic capacitance for fast operation.

3.3 Deep-Subthreshold Balanced Ambipolar TFTs for Ultra-Low-Power Digital LAE

Ambipolar TFTs (i.e., TFTs based on semiconductors that allow both electron and hole conduction depending on the bias point) are attractive for easy-to-fabricate LAE because, once connected in CMOS fashion, they can deliver digital circuits with complementary-like characteristics (e.g., wide noise margins and small geometric footprint) while relying on one single ambipolar semiconductor (thereby typically leading to FCI = 0; **Fig. 3b** and Table S2). However, given that the channel of ambipolar TFTs can conduct both electrons and holes, conventional ambipolar TFT technologies are affected by high power dissipation (**Fig. 3a** and Fig. S1); hence, they are unattractive or unsuitable for wirelessly powered sensor nodes. Nonetheless, a novel paradigm in ambipolar TFT electronics was recently demonstrated to overcome this limitation, which resulted in easy-to-fabricate digital circuits (i.e., with FCI = 0; **Fig. 3b**) with the lowest supply voltage (down to 0.2 V) and static power consumption (down to the fW/µm range) to date (**Fig. 3d**)[28]. Key to this milestone was the adoption of ambipolar TFTs with balanced n- and p-channel conduction in the deep-subthreshold region. This concept was experimentally implemented with ambipolar printed-carbon-nanotube TFTs, whose deep-subthreshold characteristics were rendered symmetric by tuning the flatband voltage with a solution-deposited self-assembled monolayer at the active interface[28]. Functional NAND gates with static power consumption down to 100 pW were also demonstrated, indicating that this technology could deliver digital circuits with a gate count compatible with smart sensor nodes (e.g., tens of thousands of equivalent NAND gates) and power dissipation within the budget of ambient-energy-powered operation (Section 2).

Building on this ultra-low-power capability, deep-subthreshold balanced ambipolar TFT electronics has already enabled the first demonstration of LAE circuits powered by mm-scale

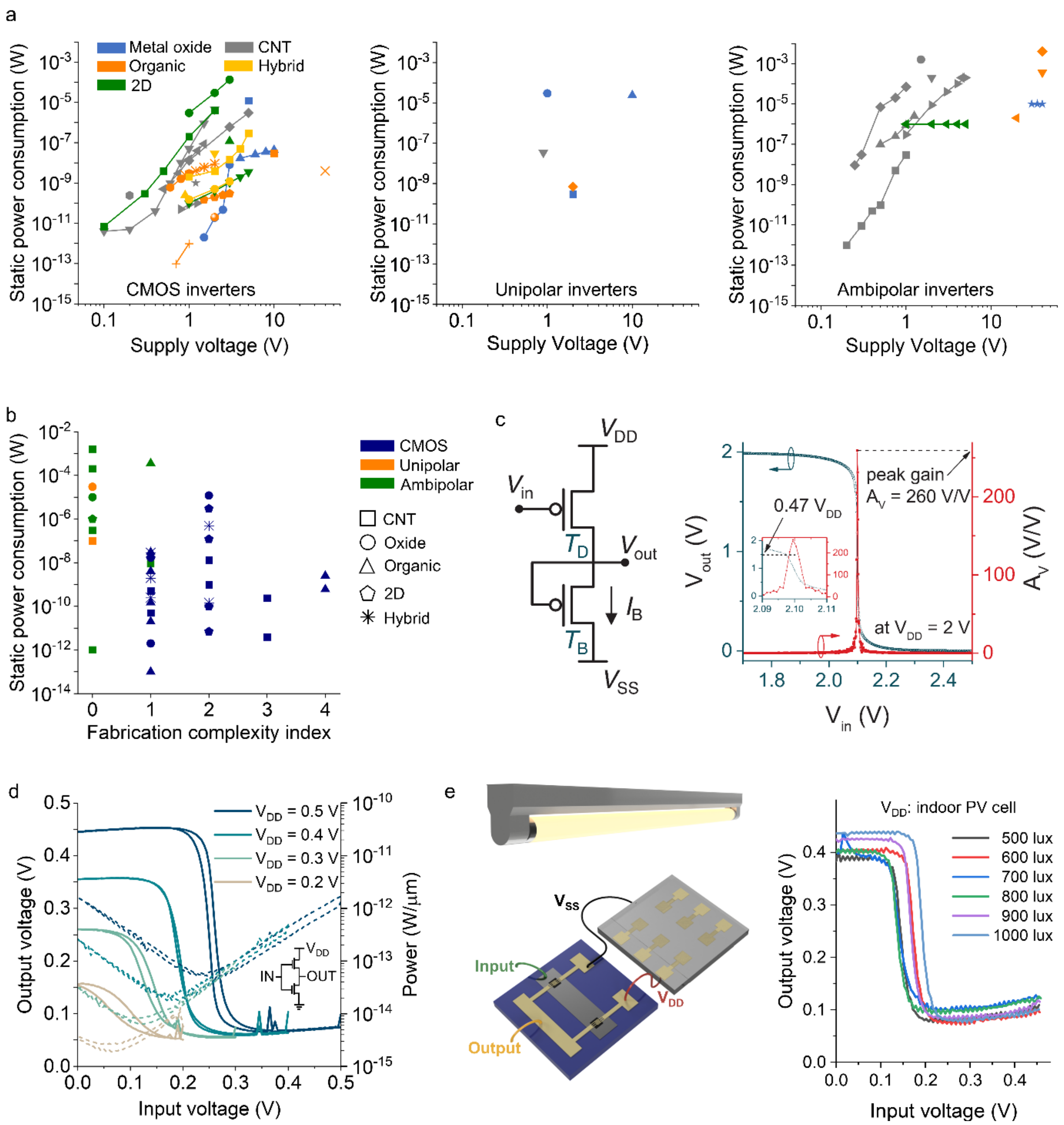

Fig. 3|Ultra-low-power LAE. a, Static power dissipation of inverter gate implementations from the literature—complementary (left), unipolar (center), ambipolar (right)—based on semiconducting carbon nanotube (CNT) networks, or organic, metal-oxide, or 2D semiconductors (Table S2). **b,** Corresponding fabrication complexity index versus static power dissipation. **c,** Ultra-low-power amplifier based on deep-subthreshold organic TFTs with a Schottky barrier at the source-semiconductor interface[27]. From Ref. 27. Reprinted with permission from AAAS. **d,** Voltage transfer characteristics and static power dissipation of deep-subthreshold balanced ambipolar inverters[28]. Copyright © 2020 American Chemical Society. Reproduced from Ref. 28 under CC BY license. **e,** Demonstration of LAE digital circuit based on the deep-subthreshold balanced ambipolar paradigm powered by indoor light via a mm-scale indoor photovoltaic cell[30]. Reproduced from Ref. 30 (© 2020 The Authors. Advanced Energy Materials published by Wiley-VCH GmbH) under CC BY 4.0 license.

LAE indoor photovoltaics[30] (**Fig. 3e**). In light of these demonstrations, deep-subthreshold balanced ambipolar TFTs provide an attractive platform for ambient-energy-powered smart sensor nodes. Consequently, the scaling-up of this technology and its monolithic integration with compact LAE energy harvesters are promising directions for future investigation.

The potential of deep-subthreshold balanced ambipolar TFTs for ultra-low-power LAE goes beyond the capabilities of its implementation to date, as ambipolar TFTs with a subthreshold slope approaching the thermodynamic limit have been projected to lead to digital circuits with even lower required supply voltage and power dissipation[28]. Therefore, to realize the full potential of the deep-subthreshold ambipolar paradigm, various opportunities lie ahead at both materials and device levels, not only in terms of the engineering of the active interface of printed-carbon-nanotube TFTs toward a steeper subthreshold slope, but also in regard to the application of this paradigm to other ambipolar LAE semiconductors.

3.4 Future Scenarios in Ultra-low-Power LAE for Wirelessly Powered Sensor Nodes

LAE is inherently attractive because of its compatibility with simple manufacturing processes, which would enable fit-for-purpose sensor-node electronics not only with a superior sustainability profile but also with a production cost of around $ 0.01 per circuit[53]—i.e., much lower than conventional Si-based electronics for circuits of comparable transistor count. In particular, complementary LAE technologies capable of ultra-low power dissipation have reached an advanced development stage, which points to the concrete opportunity for their integration with compact energy harvesters and energy storage elements to realize ambient-energy-powered smart sensors in the near future. To realize this potential, however, it is essential to focus on complementary technologies that do not counter the very purpose of LAE electronics by requiring elaborate manufacturing processes. Therefore, a key remaining challenge and high priority in the realm of complementary LAE technologies is to scale up the most promising complementary LAE technologies or develop alternative complementary schemes that feature low material and process complexity (FCI = 1) while adopting additive processing methods and materials that do not pose scarcity and/or toxicity issues (e.g., involving electrode materials or dopant molecules). For example, an approach to complementary LAE that is particularly attractive for future scaling up is the one reported by Zschieschang *et al.*[50], who achieved the lowest static power consumption (10^{-13} W at 0.7 V for inverter gates) with a minimal FCI of 1 (Figure 3b). This impressive result was achieved based on the use of two semiconductors for n- and p-channel TFTs alongside a single source/drain metal for all devices. However, it is important to note that this particular implementation employed vacuum-deposited organic semiconductors and gold source/drain electrodes[50]. Overcoming the reliance on vacuum processes might turn out to be a necessary breakthrough to scale up this promising, low-FCI technology while ensuring ease of fabrication and potential eco-friendliness. Moreover, the use of scarce materials (e.g., Au) can be minimized by using additive fabrication techniques that consume minute amounts of materials or by entirely replacing these materials with more sustainable alternatives—the assessment of which will require comprehensive life cycle analyses.

The considerable potential of deep-subthreshold unipolar TFTs toward ultra-low-power analog front-ends of LAE sensor nodes prompts future efforts toward their scale-up to circuits applicable to wirelessly powered sensor nodes, while also pursuing novel materials- and device-based strategies for minimal fabrication complexity (FCI = 0 for unipolar technologies) and circuit footprint.

The ultra-low-power complementary-like functionality and minimal complexity (FCI = 0) of deep-subthreshold balanced ambipolar LAE make it a highly attractive alternative to complementary technologies toward ambient-energy-powered sensor nodes with a potentially high sustainability profile. As this technology is nascent, however, a key priority is to scale it up to larger circuits relevant to wirelessly powered sensor nodes. Additionally, given its semiconductor-agnostic character, the deep-subthreshold balanced ambipolar paradigm opens many opportunities in terms of the ambipolar LAE semiconductors that it could be applied to, which could ultimately contribute to the realization of its performance potential toward the theoretical limit.

4. RF Energy Harvesting and Data Communication Schemes

Ultra-low-power RF data communications are essential to realize wirelessly powered LAE sensor nodes, while RF energy harvesting could enhance their energy self-sufficiency for perpetual operation. Considerable progress has been recently achieved in LAE diodes that can harvest energy up to the 5G frequency range, while advances in antenna technologies have enabled ultralow-powered backscattering communications with unprecedented data ranges. Herein, we analyze these developments and discuss the remaining challenges and future directions for these approaches to enable wirelessly powered LAE sensor nodes.

4.1 Recent developments in LAE diodes

Amongst the various approaches to wirelessly powering sensor nodes, RF energy harvesting is a viable option due to the availability of omnipresent energy sources such as Bluetooth, WiFi, and cellular signals, making it an eco-friendly solution, especially for densely populated urban areas[54]. However, since RF power levels can vary, RF energy harvester should be capable of operating over a wide range of input powers and frequency bands to ensure optimal performance[55].

The most crucial components in RF energy harvesters are the antenna and the rectifier as they determine the frequency of operation, operating distance, and ultimately the power conversion efficiency. Therefore, the widespread adoption of RF energy harvesting depends on the specific technical requirements and cost. To this end, the increasing demand for antennas in wireless applications has played a catalytic role and major strides have been achieved in different directions. For example, breakthroughs in printed antennas have led to the development of inexpensive, efficient, lightweight, and durable antennas that are able to operate from kilohertz to hundreds of gigahertz (i.e., millimeter waves)[55].

An overview of the efficiencies achieved by various RF energy harvesters based on CMOS and Schottky-type rectifiers for a range of input powers and frequencies is shown in **Fig. 4a**. For millimeter-wave rectifying circuits, the use of standard (i.e., Si-based) CMOS technology is constrained by its low sensitivity, limited mechanical compliance, high leakage current, large turn-on voltage, and costly manufacturing[55]. Alternative solutions based on diodes have been exploited, including point contact diodes, PIN diodes, tunnel diodes, Schottky and varactor diodes[55]. Among those, Schottky diodes offer key advantages such as low junction capacitance, low turn-on voltage, and fast switching, making them a popular choice for microwave- and millimeter-range applications[55]. Notably, Schottky diodes are attractive for use in emerging large-area RF electronics manufactured using printable semiconductor materials and processing technologies that can be scaled up for industrial production[56]. Unfortunately, the conventional sandwich-type device configuration typically exhibits large parasitic and overlap capacitance, which limits the operating frequency. Notwithstanding, sandwich-type metal-insulator-graphene diodes have shown operating frequencies up to 49.4 GHz in RF power detector circuits[57] due to their reduced parasitic capacitance[58]. More generally, planar device architectures provide a straightforward solution to drastically reduce the device capacitance and improve the frequency response[33,59,60]. The extrinsic cut-off frequency, $f_{C,ext}$, extracted from rectifier measurements at the half-power point is an important figure of merit for Schottky diodes in RF applications. Indeed, the highest $f_{C,ext}$ reported to date using emerging semiconductor technologies featured planar structures (**Fig. 4b**). Another recent important development involves the combination of innovative device architectures with emerging materials that possess comparatively high carrier mobility, atomic-scale thickness, and mechanical robustness. For instance, wafer-scale printed ZnO[33], IGZO[61], and polymer-based[62] Schottky diodes with an intrinsic cut-off frequency of >100 GHz have been reported, as well as MoS_2-based flexible rectifier and RF mixer circuits with a cut-off frequency of 10 GHz and RF-to-DC power conversion efficiency above 40.1% at 2.45 GHz[59]. All these studies featured planar device architectures, clearly highlighting the viability of these alternative architectures for deployment in future LAE RF applications.

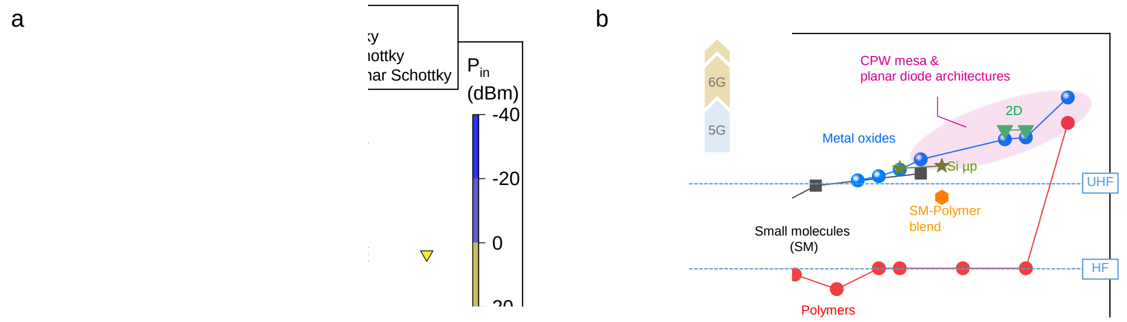

Fig. 4| High-speed diodes for RF energy harvesting. a, Overview of the power conversion efficiency versus operational frequency for RF energy harvesters grouped by the type of rectifier element. The additional color scale indicates the range of input powers (P_{in}). **b,** Notable reported extrinsic cut-off frequencies $f_{c,ext}$ of metal-semiconductor-metal Schottky diodes over the past 20 years, classified according to the active semiconductor used. Here, CPW and Si µp refer to co-planar waveguides and Si microparticles, respectively.

<u>4.2 Ultra-Low-Power Communications via Backscattering</u>

Alongside ultra-low-power electronics and energy harvesting, backscatter communications offer an extremely appealing option to enable self-powered LAE sensor nodes with the ability to communicate information wirelessly. However, once path loss, regulatory, and front-end power-consumption constraints are considered, this option loses a lot of its allure. Indeed, as can be observed in **Fig. 2d**, beyond a communication range of 200 m between the node and the gateway, it becomes more energetically advantageous to utilize an active transceiver which, while consuming more *power*, is able to transmit a given amount of data in a period of time short enough to offer a superior *energy* budget.

However, recent efforts have demonstrated that it is possible to, at low cost, compensate for the Achilles' heel of backscatter schemes—i.e., the path loss—using high-gain yet quasi-isotropic backscatter antenna systems: retrodirective front ends[63,64]. These structures use the phase gradient of the wave impinging from the gateway to (passively, nonetheless) reflect the modulated wave with high gain in the very direction of the reader; a feat which, when implemented in active systems (like in mm-wave 5G), requires complex energy-hungry schemes and myriads of costly RF components. This capability, uniquely accessible to backscatter schemes, lends much greater practicality to the backscatter option (**Fig. 2d,e**). Indeed, a retrodirective backscatter system keeps its energetic advantage up to a maximum communication range of 800 m compared to an active system of identical size (**Fig. 2e**), i.e., 4 times as far as a traditional backscatter system. Furthermore, in the context of LAEs, retrodirective structures also allow the use of ultra-large (and, therefore, ultra-long-range) antennas capable of providing energy-efficient communications with compact readers at distances exceeding 4 km: at a distance of 1 km, for instance, a printed 900 MHz retrodirective LAE system of 83×83 cm^2 in size would require less than 25 times the energy per bit of a typical active device operating at the same frequency (such as a LoRa module). By reducing the energy required for communications and enabling long-range communications at mm-wave frequencies, retrodirective backscatter architectures set the stage for the emergence of fully-passive 5G-powered RFIDs, as we will see next.

4.3 Future scenarios of RF energy harvesting and communication using LAE

Any attempt to power devices remotely must contend with the fact that any power sent isotropically (through any medium) will suffer from a dilution of $A/(4\pi R^2)$, where A is the size of the receiver and R its range to the transmitter. Therefore, for reasonably sized receivers, wireless power transfer rapidly becomes unworkable. However, systems capable of focalizing energy in narrow solid angle ranges can provide practical solutions. It was recently recognized that a dense deployment of electromagnetic transmitters offering this capability is currently being built in the form of mm-wave 5G networks[34]. Through the clever use of an old component—the Rotman lens, which can also be used as a retrodirective backscatter front-end—it was shown that such mm-wave energy will become usable at ranges far exceeding that of current systems. This opens the door to the implementation of fully-solution-processed wirelessly powered LAEs with long-range communication capabilities.

Furthermore, in RF energy harvesting, antennas and rectifiers are on the brink to satisfy the communication and power demands. However, the main challenge to meeting the 5G/6G requirements will be in the development of reliable, efficient, low-cost, and scalable manufacturing protocols for solution-processed Schottky diodes, transistors, and antennas that can be embedded into the billions of IoT devices projected for the future. Ideally, these manufacturing technologies should be circular and rely on eco-friendly materials and processing schemes. Fortunately, significant developments in solution-processed diodes (Section 4.1) are promising to provide the cornerstone for the emergence of such systems, while recent developments in the eco-friendly printing of liquid metals pave the way for the sustainable fabrication of antennas[65,66].

5. Conclusions

The *raison d'être* of LAE has long been linked to the goal of realizing ultra-low-cost, flexible circuits, which recent developments have brought closer and closer to fruition. The emergence of IoT and its exponentially growing device ecosystem, however, provide a greater challenge and a far greater opportunity: that of realizing sustainable electronics for sustainable smart devices that can function anywhere and anytime by drawing energy from the environment. Recent developments in TFT technologies have delivered LAE with unprecedentedly low power dissipation, eventually enabling the demonstration of ambient-energy-powered printed-TFT circuitry drawing energy from indoor light via a printable energy harvester. For LAE to be up to the sustainability challenge it is called upon to tackle, however, manufacturing simplicity will be key: not only to ensure its straightforward scaling-up, but also to converge toward the ideal of wirelessly powered smart sensor nodes realized from a palette of materials sequentially printed/coated within a single production site with minimal environmental impacts. Moreover, the great strides in backscattering communications and emerging RF diodes technologies substantiate the opportunity to develop LAE sensor nodes capable of drawing energy from ubiquitous electromagnetic waves and transmitting data with ultra-low-power consumption over long distances. However, further advances in LAE diodes are needed—both in terms of performance and manufacturing—for this opportunity to be fully realized and thus unlock the potential of LAE for easy-to-fabricate and eco-friendly sensor nodes for the IoT revolution.

Data Availability Statement

Data associated with the original plots presented in this article (Fig. 2d-e, Fig. 3a-b, and Fig. 4) are available from the corresponding authors upon reasonable request.

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