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Wirelessly powered large-area electronics for the Internet of Things

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Powering the increasing number of sensor nodes used in the Internet of Things creates a technological challenge. The economic and sustainability issues of battery-powered devices mean that wirelessly powered operation—combined with environmentally friendly circuit technologies—will be needed. Large-area electronics—which can be based on organic semiconductors, amorphous metal oxide semiconductors, semiconducting carbon nanotubes and two-dimensional semiconductors—could provide a solution. Here we examine the potential of large-area electronics technology in the development of sustainable, wirelessly powered Internet of Things sensor nodes. We provide a system-level analysis of wirelessly powered sensor nodes, identifying the constraints faced by such devices and highlighting promising architectures and design approaches. We then explore the use of large-area electronics technology in wirelessly powered Internet of Things sensor nodes, with a focus on low-power transistor circuits for digital processing and signal amplification, as well as high-speed diodes and printed antennas for data communication and radiofrequency energy harvesting.

The Internet of Things (IoT) could enhance the quality and sustainability of everyday life by providing data connectivity to objects and the environment[1,2] (Fig. 1a). Its success will depend on the size of its physical layer, which is projected to reach one trillion devices by 2035[3]. Essential components of the technology are the IoT sensor nodes that wirelessly feed the IoT with inputs from the physical world. Furthermore, by embedding data processing, smart sensor nodes can be created, which enhance the IoT ecosystem with computing power at its edge.

Powering this large—and growing—number of sensor nodes is a technological challenge, especially due to the widespread need for autonomous operation and small device sizes (typically of the order of 10 cm). Batteries are the conventional solution but relying solely on them is problematic. For example, sensor nodes with a 1% duty cycle, 10–100 μA current demand in silent mode and 15–40 mA current demand during data transmission would cause standard batteries to discharge after 4–12 months[4]. Rechargeable batteries could potentially offer a solution. However, their charge–discharge cycles

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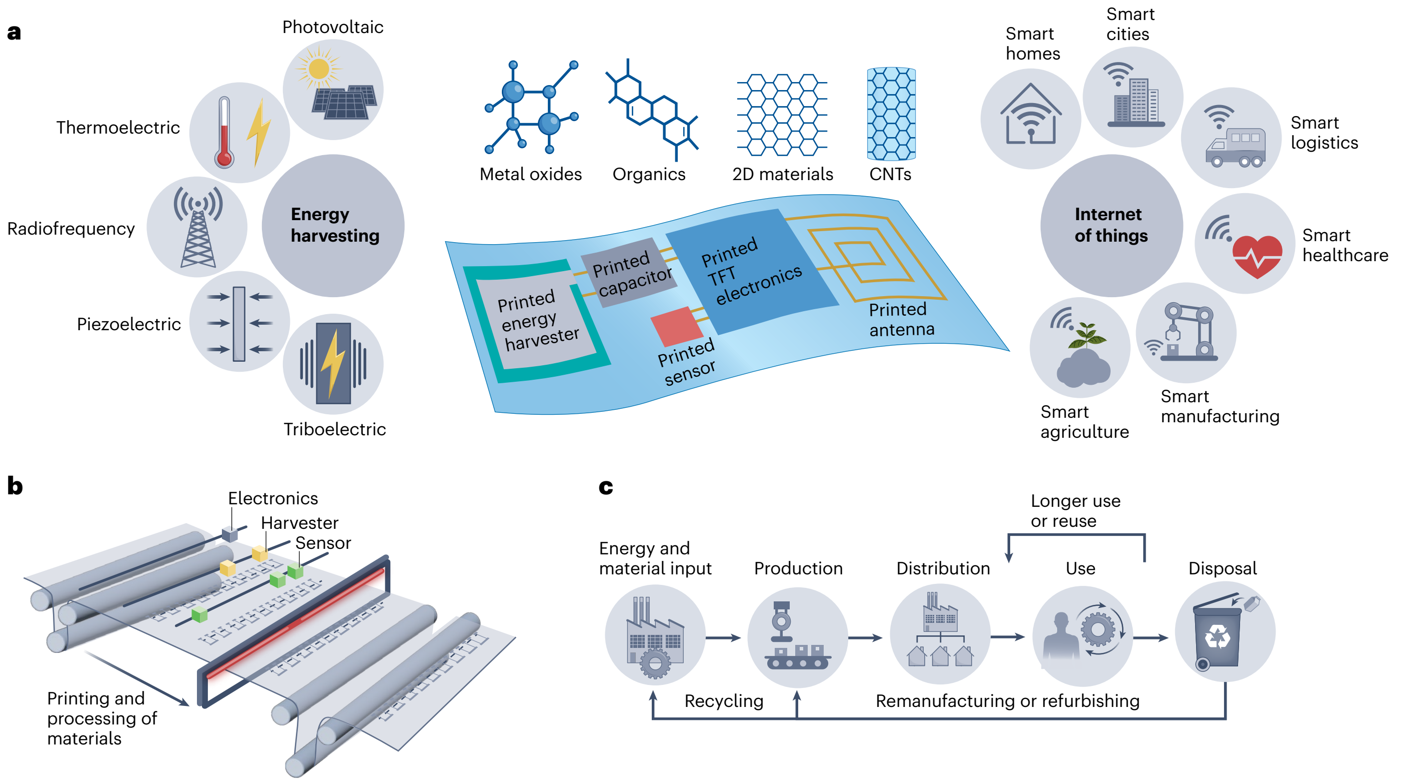

Fig. 1 | LAE sensor nodes for sustainable IoT. a, Schematic sensor-node architecture, LAE semiconductors, energy harvesters and application areas. **b**, Potential monolithic manufacturing of ecofriendly LAE sensor nodes. **c**, Ideal life cycle of an IoT sensor node.

are constrained and their performance drops over time, leading to additional costs for replacements.

The battery-centric model of powering sensor nodes also poses a sustainability challenge due to the environmental impact of mainstream battery technologies[4–6]. For instance, current annual global lithium production[7] would not be sufficient to meet the demands of a one-trillion-node IoT relying on common lithium-based coin cell batteries[8] to power sensor nodes. Therefore, to ensure the sustainability of the IoT—and realize its full potential—it is critical to adopt wirelessly powered sensor nodes. (These are also often referred to as self-powered sensor nodes, but we avoid this term here because of its ambiguity—power is not self-generated by the nodes but drawn from the surroundings.)

Wirelessly powered sensor nodes draw energy from the environment using energy harvesters, including photovoltaic cells and radiofrequency energy harvesters[4] (Fig. 1a). This energy could be freely available (leading to ambient-energy-powered nodes) or supplied by dedicated sources (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, wirelessly powered operation implies the need to construct sensor nodes using ultralow-power electronics.

The sustainability of the IoT also depends on minimizing the environmental burden of the electronics used in its sensor nodes. This aspect is particularly important due to the environmental impact of conventional integrated circuit and printed circuit board technologies currently used in mainstream sensor nodes. Conventional integrated circuits involve energy-intensive fabrication methods and complex production steps requiring transport across continents, which considerably increases their carbon footprint[9]. The same considerations apply to ultrathin, flexible silicon integrated circuits. The use of conventional printed circuit boards is also problematic in terms of harmful emissions[10]. The difficulty of recycling such electronics at their end of life exacerbates their sustainability issues, thus driving increasing regulatory efforts towards greener electronics[11,12].

Alternative semiconductor technologies could thus be key in the development of sustainable, wirelessly powered sensor nodes. These include thin-film devices based on organic, metal oxide, carbon nanotube (CNT) and two-dimensional (2D) semiconductors (Fig. 1a), which are often collectively referred to as large-area electronics (LAEs). LAEs are compatible with sheet-to-sheet and roll-to-roll, bottom-up manufacturing, thus providing flexibility in terms of circuit area, customizability and economies of scale[13]. Their processability at low temperatures (less than 200 °C) can further minimize their environmental impact[14]. Importantly, LAE technologies are suitable for the fabrication of sensors[15] and energy harvesters[16] on the same types of substrate as used for circuit integration. Therefore, complete wirelessly powered LAE sensor nodes could potentially be manufactured at single production sites using a range of LAE materials and methods (Fig. 1b), thus reducing the issues associated with conventional sensor-node manufacturing. Additionally, LAEs can be fabricated on paper-based substrates, providing an attractive, environmentally friendly alternative to conventional printed circuit boards[17]. A recent demonstration of the recycling and reuse of LAEs[18] illustrates their potential in achieving circularity in electronics (Fig. 1c). Nevertheless, complete life cycle analyses of LAE technologies will be needed to identify the most sustainable approaches.

Recent milestones in the development of LAEs highlight their potential for wirelessly powered sensor nodes. For instance, ultralow-power circuits have been created with several LAE transistor technologies[19–21] and in combination with ambient-energy harvesting[22]. Additionally, LAE circuits with increasing transistor count—up to tens of thousands—have been reported[23]. Also, LAE-based diodes[24] and printed antennas[25] have been shown to be compatible with radiofrequency

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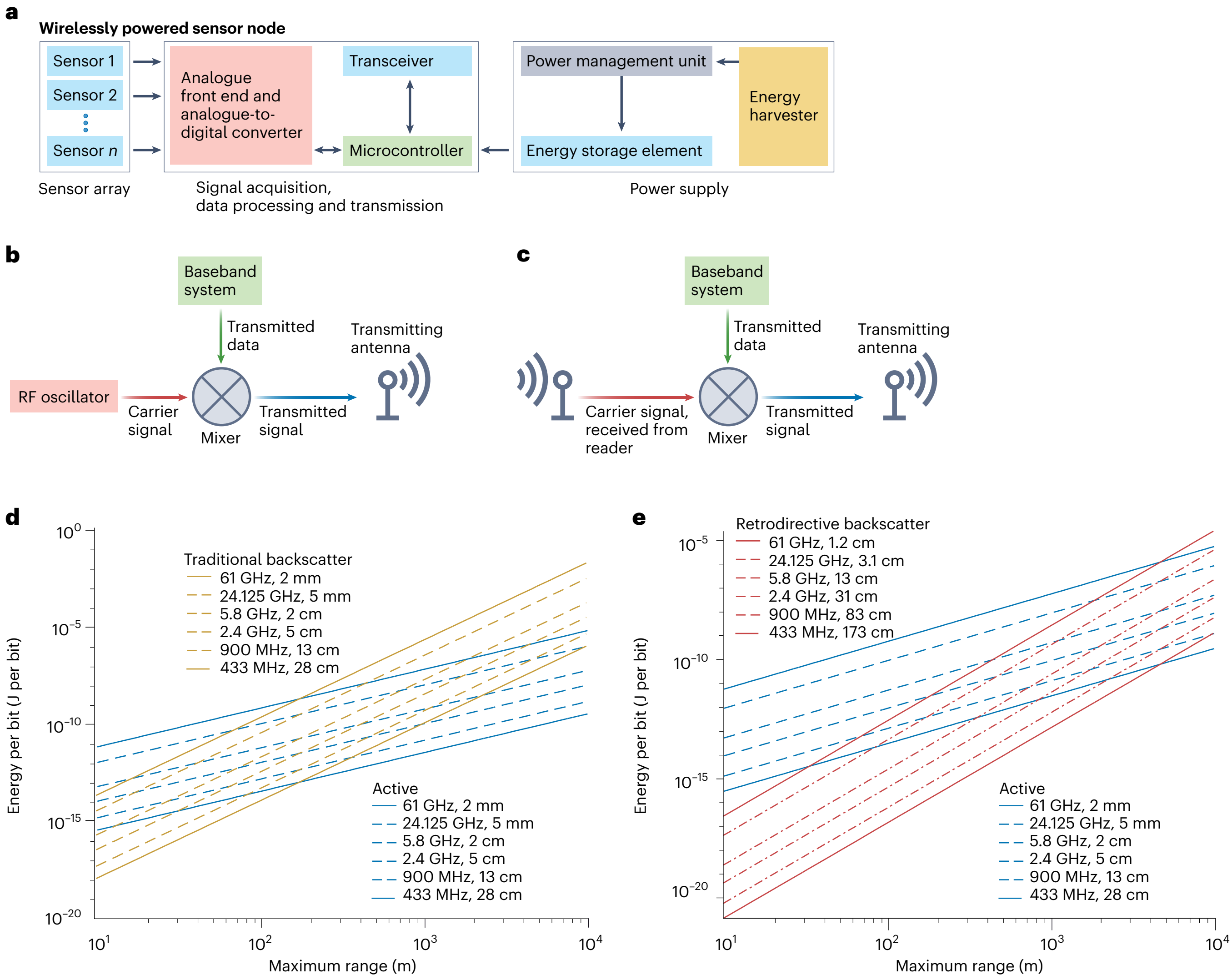

Fig. 2 | System view of wirelessly powered sensor nodes. **a**, Architecture. **b**,**c**, Schematics of active (**b**) and backscatter (**c**) transmitters. The receiving and transmitting antennas of the backscatter transmitter are typically the same antenna. RF, radiofrequency. **d**,**e**, Energy per communicated bit for active and traditional backscatter systems (**d**) and active and retrodirective backscatter systems (**e**). The energy per bit is plotted as a function of the maximum communication range of wireless sensor nodes equipped with standard-sized equigain antennas operating in standard license-free bands. The frequencies of operation and antenna sizes are indicated in the legends.

energy harvesting at 5G frequencies. In this Perspective, we explore the use of LAEs in the development of sustainable, wirelessly powered sensor nodes. We first provide a system-level assessment of wirelessly powered sensor nodes. We then examine the development and potential of low-power LAE circuits. Finally, we consider radiofrequency energy harvesting and data communication schemes.

System view of wirelessly powered sensor nodes

A wirelessly powered sensor node features an energy harvester as its power source (Fig. 2a). The harvester generally comprises a power management unit and an energy storage element (for example, a supercapacitor) to deliver the intended supply voltage over time, based on the typical harvest-energy-use scheme (Fig. 2a). Additionally, to provide edge intelligence, a smart sensor node should comprise digital processing to distil critical data from the sensor signals (Fig. 2a).

The key challenge faced by wirelessly powered sensor nodes concerns the limited power densities available from ambient sources (for example, leading to a power output of ≅20–100 μW cm^{-2} for LAE indoor photovoltaics)[4]. Therefore, minimal energy consumption is essential for a sensor node to achieve ambient-energy-powered operation. Alternatively, the energy-consuming processes can be externalized if dedicated-energy-powered operation is the main priority.

In the ideal scenario of ambient-energy-powered operation, the harvested energy should be sufficient for the sensor node to generate its own carrier to establish a wireless electromagnetic link with the IoT gateway (active transmission; Fig. 2b). Establishing this link is typically the most power-consuming feature of a sensor node—for example, standard wireless communication protocols consume 10–100 mW (refs. 4,26). Therefore, the alternation of sleep-mode and active-mode intervals is essential for a sensor node to operate perpetually. The harvester would 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 (that is, ratios between the active-mode interval and the overall cycle time) of 0.01–1%. Therefore, power dissipation during sleep-mode intervals—which relates to the static power consumption of always-on blocks—could contribute a substantial fraction of the overall energy consumption. Consequently, a high priority in the development of wirelessly powered LAE sensor nodes is the minimization of static power consumption to (sub-)nanowatt levels.

The power constraints and integration complexity required for wirelessly powered operation have prevented the realization of ambient-energy-powered LAE sensor nodes to date. However, considerable progress has been achieved in dedicated-energy-powered LAE sensor nodes relying on power transfer from dedicated radiofrequency energy sources. Key to this progress has been the adoption of backscatter communications, in which the sensor node relies on the impinging signal to carry the data transmitted by the node (Fig. 2c). However, regulatory limitations, 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. Our model calculations for active and backscatter transceivers (Fig. 2d,e) show that backscatter systems allow lower energy consumption per bit for ranges below 200 m.

Power consumption in a sensor node is also associated with the signal conditioning chain. To date, circuit blocks needed for the signal conditioning chain of LAE sensor nodes have been implemented mainly with unipolar technologies (that is, with either n-channel or p-channel thin-film transistors (TFTs)), given their simpler fabrication and wider availability. The power dissipation of a unipolar LAE analogue front end can vary from the microwatt range[27] to a few milliwatts[28]. Additionally, due to the high power dissipation of digital unipolar circuits, unipolar LAE-based analogue-to-digital converters can become the most power-hungry circuit blocks in the signal conditioning chain[29]. To overcome this limitation, dedicated-energy-powered sensor nodes based on LAE unipolar technologies have relied on pulse-width modulated data representation in backscatter near-field radiofrequency identification sensor tags[30,31]. Ambient-energy-powered operation, however, would require appreciably lower power dissipation. At a circuit design level, an avenue that may be worth exploring to reduce the power consumption of unipolar digital logic involves custom gate-by-gate design[32].

Complementary LAE 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 manufacturing complexity. While this may cease to be an issue as complementary LAE technologies develop further, it also prompts the investigation of alternative approaches to ultralow-power LAE.

Although the LAE implementations to date allow or are compatible with the tracking of a base sensor signal[30,31], adding a processing engine is key to realizing smart sensor nodes. To minimize power dissipation and circumvent the yield challenges of LAE technologies, the realization of bespoke processors with the bare minimum functionalities should be preferred. A breakthrough in this direction has been a machine learning processor based on amorphous metal oxide TFTs[33]. 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 in LAE processors should aim at their integration not only within complete LAE smart sensors, but also based on LAE technologies with much lower power consumption.

Developments and future uses for ultralow-power LAE circuits

Electronics with ultralow power consumption are essential for sensor nodes to function with the limited energy available from the environment. Recent years have witnessed marked developments in LAE transistor technologies that can address this demand.

Complementary LAE technologies

Complementary LAE technologies would potentially be the best candidates to realize wirelessly powered LAE sensor nodes, given their ultralow static power dissipation and wide noise margins in digital gates (Supplementary Fig. 1). By enhancing the gate–channel capacitive coupling, all LAE technologies have delivered low- or ultralow-voltage digital gates[34–36] with complementary approaches (supply voltages 0.1–2 V; Fig. 3a and Supplementary Table 1). However, a key challenge has been to robustly achieve matching characteristics between n- and p-channel TFTs. Given the scarcity of n- and p-channel LAE semiconductor pairs with symmetric charge transport properties, considerable efforts have been devoted to the development of strategies to circumvent this issue—for example, semiconductor doping and different metals for the source/drain electrodes of n- and p-channel TFTs (Supplementary Table 1). However, these strategies inevitably increase manufacturing complexity. Indeed, while complementary technologies have achieved some of the lowest static power consumption figures in the LAE domain (down to 100 fW per inverter gate[36]) (Fig. 3a), they also feature the highest fabrication complexity index (FCI), which we introduce herein as a proxy for the inherent fabrication complexity of an LAE technology (Supplementary Note 1). Complementary LAE technologies typically feature FCIs of ≥2 (Fig. 3b). Higher FCIs may be problematic in terms of yield and cost, given that each additional material to be deposited may increase device variability. Moreover, while sophisticated process engineering may enable circuit scale-up[37], the need for extra materials and process steps could be detrimental from a sustainability perspective. Therefore, while searching for n- and p-channel semiconductor pairs enabling scalable complementary LAE technologies, a high priority is to focus on solutions that minimize fabrication complexity.

Deep-subthreshold unipolar LAE for ultralow-power amplifiers

Unipolar LAE technologies typically allow much simpler fabrication processes than their complementary counterparts (FCI = 0 in most cases). However, they traditionally deliver digital circuits with high static power consumption (Fig. 3a and Supplementary Fig. 1) and noise immunity issues. These properties make unipolar LAEs 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 ultralow-power signal amplification, which is highly relevant to the analogue front end of sensor nodes. This breakthrough was based on the operation of unipolar TFTs in the deep-subthreshold regime[19,21], which allows an exponential reduction of their power dissipation. By introducing a Schottky barrier at the source–semiconductor interface, such TFTs achieved a high, bias-independent intrinsic gain in the range of 500–1,000 V V^{-1} (refs. 19,21) (that is, approximately one order of magnitude higher than conventional above-threshold LAE TFTs[38]), making them attractive for ultralow-power sensing. Indeed, single-ended common-source amplifiers based on this approach delivered voltage gains of 200–400 (Fig. 3c) while consuming <1 nW (refs. 19,21). Given the zero-gate-source-voltage (zero-V_{GS}) TFT loads adopted, however, the functionality of such implementations depended on the availability of a depletion load[21] (resulting in higher process complexity, FCI = 1) or an appreciably larger geometric footprint for the load TFT[19]. Moreover, while the speed limits of these unipolar deep-subthreshold technologies have not been fully explored[39], this may not be an issue due to the comparatively low frequency of the signals relevant to LAE sensor nodes.

Deep-subthreshold ambipolar TFTs for ultralow-power logic

Ambipolar TFTs (which allow both electron and hole conduction depending on their bias point) are attractive for easy-to-fabricate LAEs because, once connected in complementary metal–oxide–semiconductor (CMOS) fashion, they can deliver digital circuits with complementary-like characteristics while relying on a single semiconductor (thus typically leading to FCI = 0; Fig. 3b and Supplementary Table 1). However, conventional ambipolar technologies suffer from high power dissipation (Fig. 3a and Supplementary Fig. 1), making

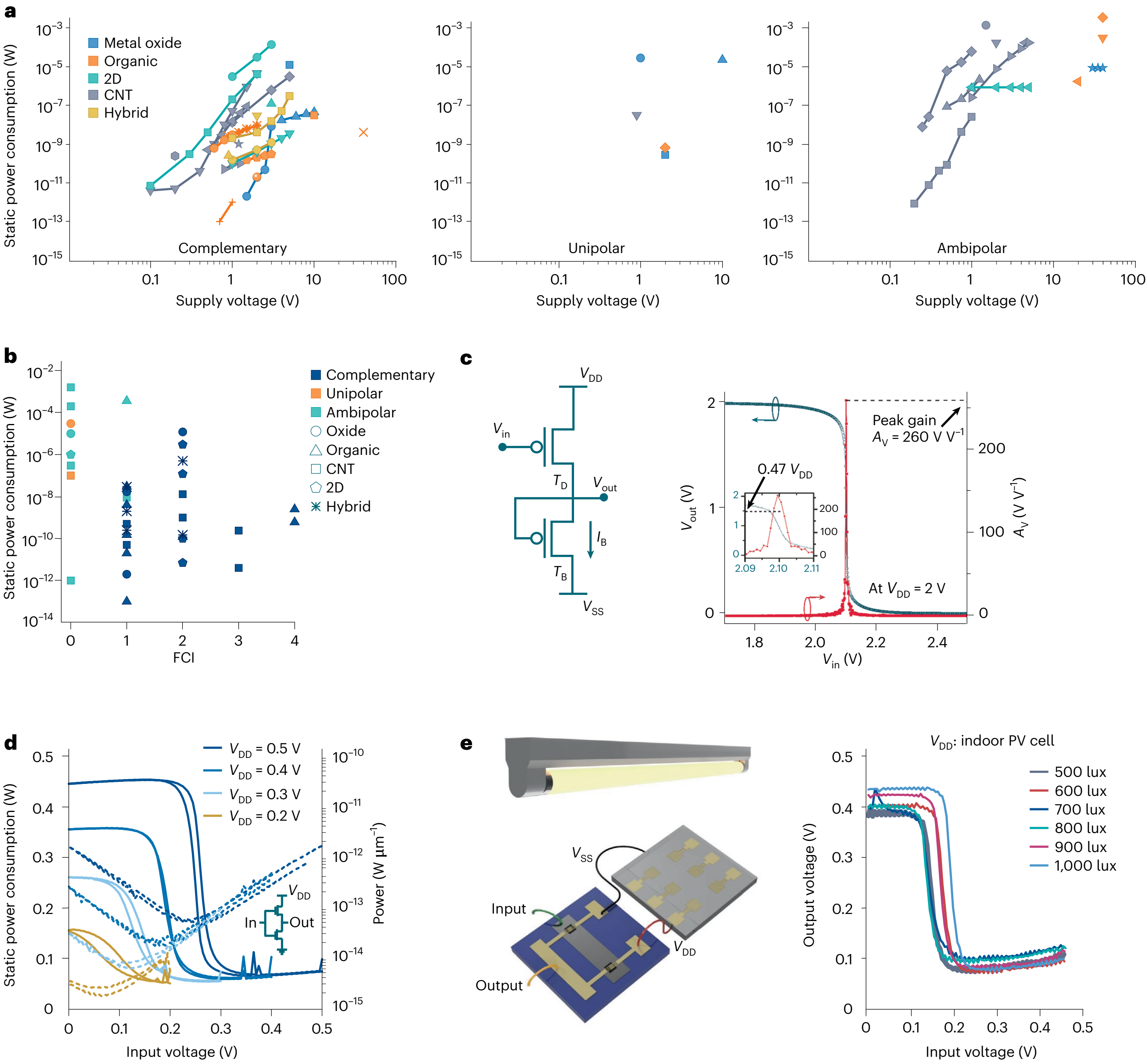

Fig. 3 | Ultralow-power LAEs. a, Static power dissipation of inverter gates from the literature—complementary (left), unipolar (centre), ambipolar (right)—based on CNT, organic, metal oxide and 2D semiconductors (Supplementary Table 1). **b**, FCI versus static power dissipation. **c**, Ultralow-power amplifier based on deep-subthreshold unipolar organic TFTs[19]. **d**, Voltage transfer characteristics and static power dissipation of deep-subthreshold ambipolar inverters[20]. **e**, Deep-subthreshold ambipolar inverters powered by indoor light via a millimetre-scale indoor photovoltaic cell[22]. Panels reproduced with permission from: **c**, ref. 19, AAAS; **d**, ref. 20 under a Creative Commons licence CC BY 4.0; **e**, ref. 22 under a Creative Commons licence CC BY 4.0.

them unsuitable for wirelessly powered sensor nodes. Nonetheless, an approach to ambipolar TFT electronics—based on printed CNTs—was recently demonstrated to overcome this limitation, resulting in easy-to-fabricate digital circuits (FCI = 0; Fig. 3b) with the lowest supply voltage (0.2 V) and static power consumption (fW μm^{-1} range) to date (Fig. 3d)[20]. Key to this breakthrough was the adoption of ambipolar TFTs with balanced n- and p-channel conduction in the deep-subthreshold region. Functional NAND gates with static power consumption down to 100 pW were also demonstrated, indicating that this technology could potentially deliver digital circuits with a gate count compatible with smart sensor nodes while allowing ambient-energy-powered operation. In fact, this approach has already enabled the demonstration of LAE circuits powered by millimetre-scale LAE indoor photovoltaics[22] (Fig. 3e). Consequently, the scaling up of this technology and its monolithic integration with compact LAE energy harvesters are promising directions towards easy-to-fabricate, ambient-energy-powered sensor nodes. Moreover, ambipolar TFTs with a subthreshold slope approaching the thermionic limit could lead to digital circuits with even lower supply voltage and power dissipation[20], which prompts further efforts to realize the full ultralow-power potential of this technology.

Future scenarios in ultralow-power LAE circuits

LAEs are inherently attractive because of their compatibility with simple manufacturing processes, which would enable fit-for-purpose

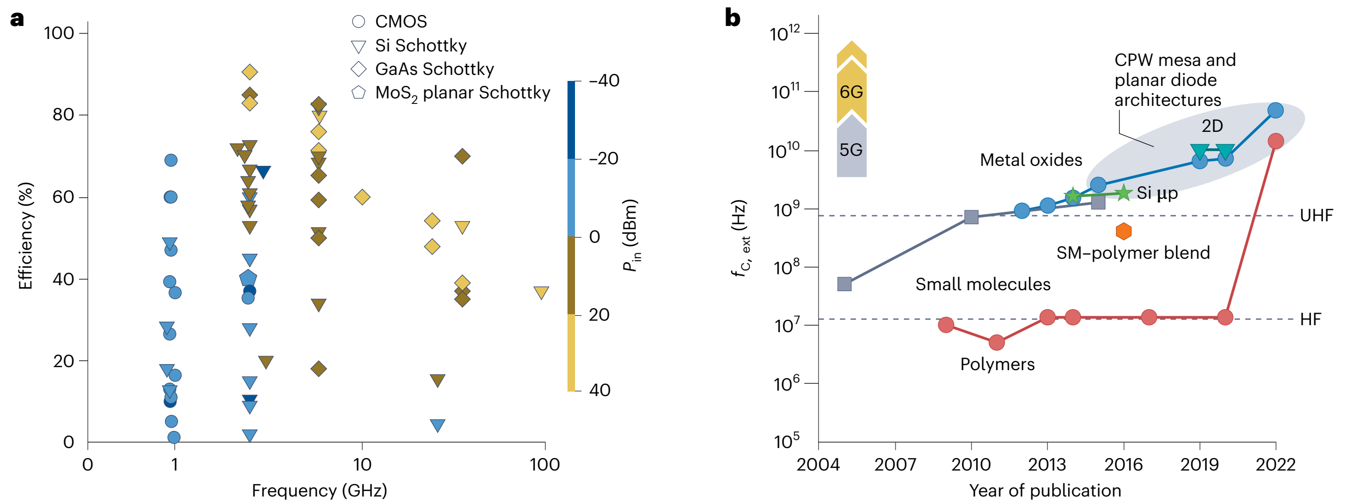

Fig. 4 | High-speed diodes for radiofrequency energy harvesting. **a**, Overview of the power conversion efficiency versus operational frequency of radiofrequency energy harvesters (Supplementary Table 2) at variable input power (P_{in}). **b**, Notable reported extrinsic cut-off frequencies $f_{c,ext}$ of metal–semiconductor–metal Schottky diodes (Supplementary Table 3). CPW and Si µp refer to co-planar waveguides and Si microparticles, respectively. HF, high frequency; UHF, ultrahigh frequency.

sensor-node electronics with a superior sustainability profile and a production cost of around US\$0.01 per circuit[40] (that is, much lower than conventional Si-based electronics). Complementary LAE technologies capable of ultralow power dissipation have reached an advanced development stage, which points to the opportunity for their integration with compact energy harvesters and energy storage elements to create ambient-energy-powered smart sensor nodes. To realize this potential, it is essential to focus on low-FCI complementary technologies (FCI = 1). Moreover, to ensure a high sustainability profile, a key priority is to adopt additive processing methods and materials that do not pose scarcity and/or toxicity issues.

The potential of deep-subthreshold unipolar TFTs for ultralow-power signal amplification prompts future efforts towards their scaling up to circuits applicable to wirelessly powered LAE sensor nodes. Moreover, the pursuit of novel materials- and device-based strategies for minimal fabrication complexity (FCI = 0) and circuit footprint could further unlock the potential of this technology, while the minimization of parasitic capacitance could enable faster operation.

The ultralow-power complementary-like functionality and minimal complexity (FCI = 0) of deep-subthreshold ambipolar LAEs make this technology an attractive alternative to complementary counterparts for ambient-energy-powered sensor nodes. As this technology is nascent, however, a key priority is to scale it up to larger circuits relevant to wirelessly powered sensor nodes. Moreover, to realize the full ultralow-power potential of deep-subthreshold ambipolar TFTs, various opportunities lie ahead at both materials and device levels. In addition to engineering the active interface of printed ambipolar CNT TFTs towards steeper subthreshold slopes, the application of this approach to other ambipolar LAE semiconductors could deliver further reductions in power dissipation.

Radiofrequency energy harvesting and data communication schemes

Ultralow-power radiofrequency data communications are essential to realize wirelessly powered LAE sensor nodes. Additionally, radiofrequency energy harvesting could enable the perpetual operation of such nodes. Considerable progress has been recently achieved in LAE diodes that can harvest energy up to the 5G frequency range. Moreover, advances in antenna technologies have resulted in ultralow-power backscattering communications with unprecedented data ranges.

Recent developments in LAE diodes

Radiofrequency energy harvesting is a viable option for wirelessly powering sensor nodes due to the wide availability of radiofrequency energy sources (for example, Wi-Fi and cellular signals), which make it an environmentally friendly solution[41]. However, radiofrequency energy harvesters should be capable of operating over a wide range of input powers and frequency bands to ensure optimal performance[42].

The most crucial components of radiofrequency energy harvesters are the antenna and the rectifier, as they determine the frequency of operation, operating range and power conversion efficiency. Therefore, their performance and cost have a direct impact on the deployability of radiofrequency energy harvesting. For instance, recent developments have led to printed antennas that are inexpensive, efficient, lightweight, durable and able to operate from kilohertz to hundreds of gigahertz[42]. In regard to radiofrequency rectifiers, Si-based CMOS devices (see Fig. 4a for a comparison among various technologies) suffer from low sensitivity, limited flexibility, high leakage current, large turn-on voltage and costly manufacturing[42]. Among the alternative solutions, Schottky diodes offer key advantages—for example, low junction capacitance, low turn-on voltage and fast switching[42]. Notably, LAE Schottky diodes are attractive due to their scalability for industrial production[43]. Planar device architectures typically allow lower device capacitance and higher operating frequencies when compared with conventional sandwich-type devices[24,44,45]—apart from a few exceptions[46,47]. Indeed, amongst LAE technologies, the highest values of the extrinsic cut-off frequency—an important figure of merit for radiofrequency Schottky diodes—were achieved with a planar device structure (Fig. 4b). For instance, printed ZnO[24], indium gallium zinc oxide[48] and polymer-based[49] Schottky diodes with an intrinsic cut-off frequency of >100 GHz have been reported, as well as MoS_2-based flexible rectifiers and radiofrequency mixer circuits with a cut-off frequency of 10 GHz (ref. 44). These results highlight the viability of planar LAE rectifiers for future radiofrequency applications.

Ultralow-power communications via backscattering

Backscatter communications offer an appealing option to enable wirelessly powered LAE sensor nodes. However, they have been typically regarded as unfavourable for long communication ranges due to their lower energy budget. Recently, high-gain, quasi-isotropic backscatter antenna systems with retrodirective front ends have been demonstrated to overcome this limitation[50,51]. These structures use the phase gradient of the wave impinging from the gateway to passively reflect the modulated wave with high gain in the very direction of the reader—a feat that requires energy-hungry schemes and costly radiofrequency components when implemented in active systems. 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 when compared with an active system of identical size (Fig. 2e), that is, four times as far as a traditional backscatter system. Furthermore, in the context of LAEs, retrodirective structures allow the use of ultralarge antennas capable of providing more energy-efficient communications than their active counterparts up to distances of 4 km: at 1 km, for instance, a printed 900 MHz retrodirective LAE system 83 × 83 cm^2 in size would require approximately 25 times less energy per bit of a typical active device operating at the same frequency. By reducing the energy required for communications and enabling long-range communications at millimetre-wave frequencies, retrodirective backscatter architectures set the stage for the emergence of fully passive 5G-powered radiofrequency identification.

Future LAE scenarios for radiofrequency harvesting and communication

Attempts to power devices remotely must contend with the dilution by $A/(4\pi R^2)$ of any power sent isotropically, where A is the size of the receiver and R its range from 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. A dense deployment of electromagnetic transmitters offering this capability is currently being built in the form of millimetre-wave 5G networks[25]. Through the clever use of the Rotman lens, it was shown that such millimetre-wave energy will become usable at ranges far exceeding that of current systems. This could potentially enable wirelessly powered printable LAEs with long-range communication capabilities.

Antennas and rectifiers are on the brink of satisfying the communication and power demands for radiofrequency energy harvesting. The main challenge to meeting the 5G/6G requirements involves the development of reliable, efficient, low-cost and scalable manufacturing for solution-processed Schottky diodes, TFTs and antennas that can be embedded into future IoT sensors. Ideally, these manufacturing technologies should be circular and rely on environmentally friendly materials and processing. Fortunately, recent developments in solution-processed diodes may enable the emergence of such systems, while the environmentally friendly printing of liquid metals may pave the way for the sustainable fabrication of antennas[52].

Conclusions

Recent developments in TFT technologies have delivered LAEs with ultralow power dissipation. In turn, this has led to the creation of ambient-energy-powered printed TFT circuitry that draws energy from indoor light via a printable energy harvester. To realize environmentally friendly, ambient-energy-powered LAE sensor nodes, manufacturing simplicity will be key. This will ensure that LAE technologies can be easily scaled up and that wirelessly powered smart sensor nodes can be created from a range of materials that are sequentially printed/coated within a single production site with minimal environmental impact. Improvements in backscattering communications and emerging radiofrequency diode technologies will further support the development of LAE sensor nodes capable of drawing energy from electromagnetic waves and transmitting data with low power consumption over long distances. However, further advances in LAE diodes are needed—in terms of both performance and manufacturing—to unlock the potential of LAEs for easy-to-fabricate, environmentally friendly sensor nodes for the IoT revolution.

Data availability

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

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Competing interests

The authors declare no competing interests.

Additional information

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