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Opportunities and Challenges of Ambient Radio-Frequency Energy Harvesting

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Introduction

The ''Internet of Things'' (IoT) aims to interconnect physical objects wirelessly and enable almost-ubiquitous sensing and computing. The global number of connected IoT devices is predicted to exceed 20 billion by 2025.[1] How to provide a ubiquitous energy solution to power many of these devices remains a significant challenge. Batteries are not ideal because their chemical composition is typically harmful for the environment and, in many applications, they require regular replacement. Although solar cells and vibration energy harvesters are also widely considered, they have their own set of limitations. On the other hand, electromagnetic (EM) signals operating in the radio frequency (RF) range, such as Wi-Fi (2.4 GHz and 5.8 GHz), cellular telecommunication (700 MHz to 2.7 GHz), and Bluetooth (2.40–2.48 GHz), are becoming increasingly ubiquitous. Take Bluetooth devices as an example: their global annual shipments are expected to reach 5.2 billion by 2022 and keep increasing.[2] Moreover, the recent Bluetooth 5.0 technology improves its wireless (indoor) range from roughly 100 m to 300–400 m^2. All of these indicate a trend where the ambient RF energy around us keeps extending its coverage with increasing power levels. At the same time, there has been steady progress in the field of ultra-low-power circuit design in the past few decades. Koomey's law showed that the energy consumed per bit of computation dropped by one half every 1.6 years since the invention of ENIAC (1946) until 2000.[3] In the post-2000 period, the energy efficiency doubled about every 2.6 years. Now one micro-watt (mW) power is enough to do thousands of bits of computation per second.[3] Figure 1 illustrates the power consumption of typical IoT applications and the measured ambient RF power across different locations. We anticipate that the convergence of these two trends, the increasing reach of RF signals and the development of ultra-low-power circuits, represents an untapped opportunity for harvesting ambient RF energy as a ubiquitous energy solution for the era of IoT.

The long-range propagation and ubiquity of RF EM energy, compared with other alternative energy sources, such as thermal and electrochemical energy, make it particularly attractive for the implementation of a wireless power solution for autonomous IoT devices. Kinetic energy harvesters, such as piezoelectric nanogenerators (PENGs) and triboelectric nanogenerators (TENG),[7] are another important type of ambient energy harvesters with power density up to 200 mW/cm^3. However, they are usually limited to special environments with frequent vibration and exhibit highly variable output performance. Furthermore,

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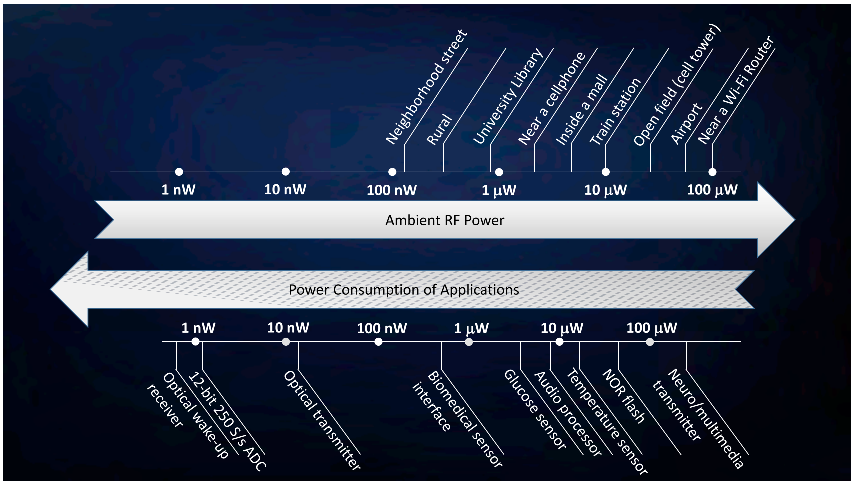

Figure 1. Illustration of Measured Ambient RF Power across Different Locations (Upper Arrow) and the Power Consumption of Typical IoT Applications (Lower Arrow)

The ambient RF power data across different locations are based on measurement data based on the reference by Kwan and Fapojuwo.[4] The power consumption data of typical device examples are mainly based on references by Li et al.[5] and Oh et al.[6] Adapted with permission from IEEE.

EM signals in the optical range are a widely used source of ambient energy. Although solar energy depends on the weather condition and is only available during daytime, its high power density (up to 100 mW/cm^2) makes it play a significant role for IoT applications. Due to space constraints and the existence of numerous review papers on kinetic and solar energy harvesters, this paper will solely focus on RF energy harvesting and the new opportunities in this field enabled by emerging materials, novel diode technologies, and ultra-lower-power integrated circuits (IC) design.

RF Energy Harvesting

Converting far-field RF energy into direct current (DC) energy is typically achieved by rectennas. A rectenna is the combination of an antenna for collecting EM radiation from the environment and an ultrafast diode with nonlinear current-voltage (IV) characteristics that rectifies the RF signals, generating in this way the DC power. A power management module is often needed to regulate and boost the output DC voltage. The rectified DC power can be stored or directly used to power a load. The overall RF-DC power conversion efficiency (PCE) is determined by the product of the efficiencies of each building block. Therefore, it is important to take a synergistic approach to simultaneously optimize the receiver antenna, impedance matching circuits, rectifier design, and system-level integration. Assuming a perfect load resistance matching, the overall RF-DC PCE can be expressed as[8]

$$PCE = \frac{1}{4} P_{in} R_I^2 \eta_M^2 R_j \left[\frac{1}{1+\left(\frac{f}{fc}\right)^2\left(1+\frac{R_s}{R_j}\right)}\right]^2, \qquad \text{(Equation 1)}$$

where P_{in} is the available power from the receiver antenna, R_I is the rectifier's current responsivity (i.e., rectified DC current divided by the input RF power), η_M is the matching efficiency between the antenna and the rectifier, R_j is the nonlinear junction resistance, R_s is the parasitic series resistance of the rectifier, and f_c is the cutoff frequency of the rectifying device limited by the device parasitics (series resistance R_s and junction capacitance C_j). The cutoff frequency f_c can be expressed as[9]

$$f_c = \frac{\sqrt{1+\frac{R_j}{R_s}}}{2\pi R_j C_j}. \qquad \text{(Equation 2)}$$

The current responsivity depends on the nonlinearity of the diode, and it can be calculated by

$$R_I = \frac{d^2I/d^2V}{2(dI/dV)}, \qquad \text{(Equation 3)}$$

where V is the voltage across the diode and I is the current flowing through it. The above equations provide a guideline for improving the PCE of wireless energy harvesting: (1) diode optimization to improve cutoff frequency (f_c) by minimizing parasitics and to improve current responsivity (R_I); (2) circuit optimization to improve impedance matching, especially for broadband operation; (3) antenna optimization to maximize available input power. Although antennas designed for communication purposes have been studied for decades, energy harvesting antennas are still far from being optimized. The design of energy harvesting antennas needs to accommodate unknown polarization of EM waves. Circularly polarized antenna are often advantageous because they can harvest both linearly and circularly polarized RF waves.[7] For RF sources with known locations, a directive beamforming antenna with high gain can collect a larger amount of power. In addition, broadband or multiband antennas are desirable as they can receive RF energy distributed in multiple frequency bands. A tradeoff often exists between efficiency and bandwidth during antenna design.[7]

The choice of diodes for RF-DC rectification is critical as it is a central component that limits the overall efficiency and operation frequency. Here we only discuss zero-bias rectifying diodes, since a non-zero bias diode would require external battery and is not suitable for ambient RF energy harvesting. Schottky diodes are most commonly used for microwave (2.4 GHz and 5.8 GHz) wireless energy harvesting because of their low cost, high reliability, and well-established

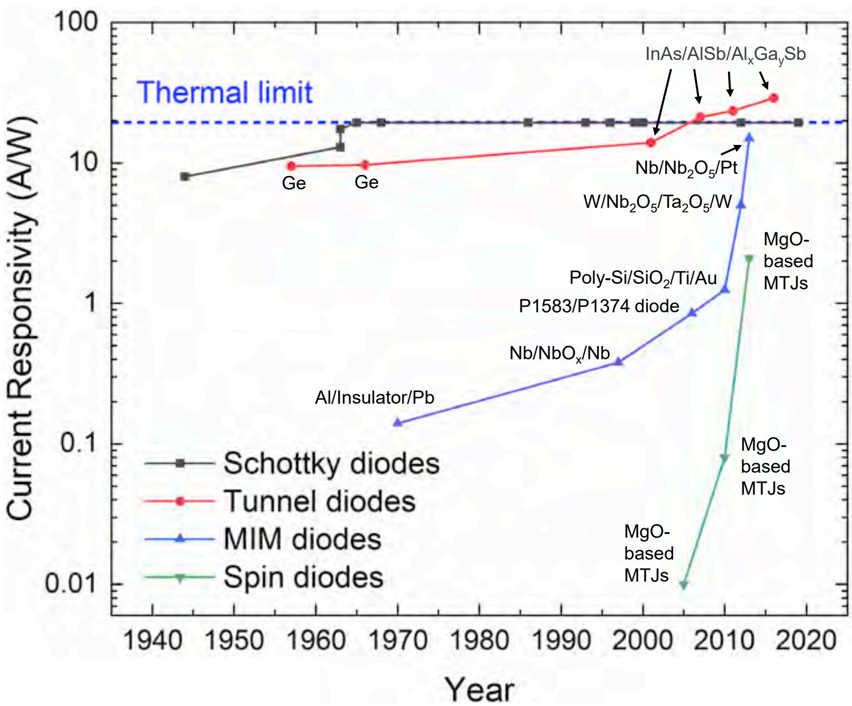

Figure 2. Historical Evolution Trend of Current Responsivity of Schottky Diodes, Backward Tunnel Diodes, MIM Diodes, and Spin Diodes

The data are mainly based on the reference by Hemour and Wu.[8] The materials and device structure are also labeled for tunnel diodes, MIM diodes, and spin diodes. For Schottky technology, the dominant material used is silicon. Adapted with permission from IEEE.

fabrication processes. Despite their success at high input power density (P_{in} > 1 mW), Schottky diodes exhibit poor RF-DC conversion efficiency at low power density (especially below 1 μW). One important reason for this is that the thermionic emission process in Schottky diodes sets a fundamental limit on their current responsivity, $q/2k_BT$ (i.e., 19.4 A/W), which was reached in the 1960s.[10]

Alternative diodes that can potentially break the Schottky limit responsivity (i.e., 19.4 A/W) include backward tunnel diodes, metal-insulator-metal (MIM) diodes, and spin diodes. Figure 2 illustrates the historical evolution trend of the current responsivity of different rectifying diodes for RF energy harvesting. Innovations in emerging materials and device architecture will be important to improve the RF-DC PCE in the new decade, especially for low RF power density scenarios. Backward tunnel diode technology has enabled the best RF rectifiers so far.[8] In the short term, backward tunnel diode has the best chance to advance the development of highly efficient lower-power rectennas thanks to the mature PN diode technology it can benefit from. MIM tunnel diodes can also exhibit nonlinear IV characteristics for rectification by having different tunneling rates under forward and reverse bias, due to different metal selection and device geometry. However, depending on the barrier height, temperature, and insulator thickness, thermionic emission of hot carriers also plays an important role in the MIM transport. How to minimize the thermionic contribution of current is critical to improve the current responsivity. An ultraclean interface is particularly important for the control and fabrication of backward tunnel diodes and MIM diodes. Atomically thin 2D materials-based heterostructures are advantageous in forming defect/trap-free interface because they are free of dangling bonds. Magnetic tunnel junctions (MTJs)-based spin diodes also carry much hope in breaking the Schottky limit responsivity. By further enhancing the nonlinearity of spin diodes, it is very promising for low-power and high-efficiency rectification.

Furthermore, the impedance matching between the antenna and the rectifying circuit also needs to be optimized. This is particularly difficult for broadband RF energy harvesting. Also, for applications that require a high output voltage, voltage multipliers, such as charge pump circuits, need to be incorporated into the energy harvester. Tradeoffs need to be taken into consideration, as adding more stages of voltage multipliers introduces more loss.[7] In addition, due to the temporally and spatially dynamic nature of available RF energy, a maximum power point tracking system, usually consisting of a DC-DC converter with a tracking algorithm, is needed to automatically track and optimize the impedance matching between the rectifier and the output load.

Flexible Rectenna

Since their invention in the 1960s, rectenna devices have mainly been demonstrated on rigid substrates, which limit many of the IoT applications, especially for healthcare and wearable applications. The recent advances in flexible rectennas based on flexible semiconductors are important steps to allow RF wireless energy harvesting technology to become truly ubiquitous. Compared to its conventional rigid counterparts, a flexible rectenna can be seamlessly integrated with daily objects of arbitrary shapes. Unfortunately, most flexible semiconductors, especially organics, have poor transport properties, such as low mobility, which have traditionally prevented their use at the GHz frequencies of Wi-Fi and cellular communications. However, the recent use of novel materials and fabrication technologies has allowed a significant improvement in the operating speed of flexible electronics. As the cutoff frequency of flexible semiconductor-based diodes has been increased into the GHz range, it opens up new possibilities in building fully flexible and ultralight rectenna fast enough to cover the Wi-Fi and cellular frequency bands, i.e., the two most ubiquitous RF sources around us. For example, a flexible rectenna based on atomically thin MoS_2 phase junction Schottky diodes has been demonstrated. It exhibits a cutoff frequency of 10 GHz, which is enough to cover Wi-Fi, cellular, and most of daily electronics' operation frequencies.[9] Additionally, an all-printed diode-enabled rectenna has also been built to harvest the Global System for Mobile Communications (GSM) band signals of a mobile phone.[11] Flexible diodes based on amorphous indium gallium zinc oxide (IGZO) have also been shown to exhibit a cutoff frequency beyond 2.4 GHz.[11]

Low-Power Design

The development of ultra-low-power electronics is just as important as increasing the PCE of energy harvesters. Power has been a key constraint for decades, and there are now many efficient techniques that allow significant reduction in both dynamic and static power consumption. Examples of such techniques, covering digital, analog, and mixed-signal design, include: (1) dividing the chip into multiple voltage domains to allow voltage scaling, which could go all the way to completely powering off a certain domain to save static power; (2) minimizing short-circuit power (i.e., power consumed during the change in the output level of a CMOS logic gate); (3) subthreshold operation or the reduction of voltage swing, among many others. Voltage scaling has proven to be the most effective way to decrease dynamic power, since it has a quadratic dependence on the supply voltage. However, as technology scales down, leakage power becomes a significant player, and its optimization cannot be neglected, especially for those blocks that cannot be powered off, such as voltage references, timers, etc.

Based on these techniques, basic building blocks, such as sensors, analog to digital converters (ADCs) and digital to analog converters (DACs), readout circuitry, oscillators, logic, etc., can be designed to consume from picowatts to hundreds of nanowatts, as Figure 1 illustrates. These ultra-low-power building blocks allow the design of sensor-based nodes for the now-called "Internet of Tiny Things," where the performance requirements are low, but so is the power budget.[6] Furthermore, performance of individual blocks can be scaled to fit power sources, allowing the adaptation of the electronics to the available harvested energy. Although reduced power typically implies a performance penalty, fairly complex computations with microwatts- and nanowatts-level power consumption have been reported recently in the context of edge computing.[6,12]

Outlook

The next few years will witness an upsurge in wireless RF energy harvesting, especially for IoT applications, due to the convergence of three trends: (1) rapid increase of RF sources with a wide range of power levels and frequencies; (2) development of ultra-low-power IC design; (3) advances in ultrathin and flexible energy harvesters with improved power efficiency and new form factors. The prospect of seamlessly integrating efficient flexible energy harvesters with arbitrary objects is particularly attractive. The atomic thickness and large-scale manufacturing capability of 2D materials have inspired a vision of "smart skin," which is promising to bring ubiquitous sensing to a wide variety of everyday objects. Complementary to this, their great potential in EM energy harvesting also opens up new opportunities in using these 2D materials as "energy skin" that can be seamlessly integrated with almost all objects to ubiquitously harvest energy. In order to further improve the PCE and sensitivity of RF energy harvesting, it is important to take a holistic approach to optimize the antenna design, matching circuits, device structure, and low-power IC design. In summary, electromagnetic energy harvesting is a very promising strategy to bring power and enable future Internet of Things, smart city, structural health monitoring, wearable and biomedical applications without the need of batteries.

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