Self-Powered Nanosensors and Nanosystems

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Sensor networks are a key technological and economic driver for global industries in the near future, with applications in health care, environmental monitoring, infrastructure monitoring, national security, and more. Developing technologies for self-powered nanosensors is vitally important. This paper gives a brief summary about recent progress in the area, describing nanogenerators that are capable of providing *sustainable self-sufficient micro/nanopower* sources for future sensor networks.

1. Sensor Networks

Economic development in the last two decades has been driven by information technology. Looking towards world technology trends over the next few decades, self-powered sensor networks are a key field that may drive the world economy. Wireless sensor networks have important applications in implantable biosensors, patient monitoring, environmental and structure monitoring, and national security. Internet connectivity of objects is quickly becoming a hot area of research, which is addressing areas such as radio frequency identification (RFID), sensors, global positioning systems (GPS), and laser scanners that enable this connectivity to carry out communication, identification, positioning, tracking, monitoring, and management. Monitoring of water quality, for example, can be a huge task owing to its large distribution and mobility in the environment; the traditional approach uses finite sampling, which may not be sufficient to reflect water quality and distribution across the area of interest. Health and long-range patient monitoring represents a major societal challenge; as the percentage of elderly people increases worldwide, monitoring of their health will become increasingly important in providing the necessary medical care.

By replacing the traditional finite number of discrete sensors with a large number of independent and mobile sensors distributed in the field, a statistical analysis of the distributed signals – collected through the internet – can give precise and reliable information, so that effective measures can be taken to prevent any major disasters. An "internet of things" that can correlate objects and devices to large databases and networks (the internet) are the future of health care, medical monitoring, infrastructure/environment monitoring, product tracking, and "smart homes". One of the major problems for wireless sensor networks is the electric power needed to drive individual sensors for sustainable and maintainance-free operation. However, such power cannot simply be provided by batteries for two reasons: i) the number of sensors to be involved in the sensor network will be huge, so replacing individual batteries would represent a tremendous task; and, ii) the materials used for batteries are likely to be environmentally unfriendly and potentially hazardous to health, so recycling of these batteries would have to be ensured. Therefore, new approaches for green energy are desperately needed for independent, sustainable, maintainance-free and continuous operations of devices and systems in areas such as implantable biosensors, ultrasensitive chemical and biomolecular sensors, nanorobotics, microelectromechanical systems, remote and mobile environmental sensors, homeland security, and even portable/wearable personal electronics.[1]

It is highly desirable for wireless devices to be self-powered without using batteries; this approach can greatly enhance the adaptability and mobility of such devices. Therefore, there is an urgent need to develop nanotechnology that harvests energy from the environment to self-power these nanodevices.[2,3] A goal for nanotechnology is to build self-powered nanosystems that exhibit ultrasmall size, supersensitivity, extraordinary multifunctionality, and extremely low power consumption. As a result, the energy harvested from the environment may be sufficient to power the system. A nanosensor system is made of components that are capability of sensing, controlling, communicating, and responding (**Figure 1**). Besides the sensing, data processing, and transmitting components, power harvesting and storage are important functions of the system. With the use of nanomaterials and nanofabrication technologies, a nanosensor system is expected to be small size and low power consumption; thus, it is possible to use the energy harvested from the environment to power such a system for wireless and self-sustainable operation. The harvested energy has to be regulated and stored to maintain operation of the nanosystem. Energy storage using nanomaterials are an active and important field of today's research. The main approaches to this challenge are Li-ion batteries[4,5] and supercapacitors,[6,7] both of which use electrochemical processes for storage charges using ions at a high density.

New technologies that can harvest energy from the environment as *sustainable self-sufficient micro/nano-power* sources offer

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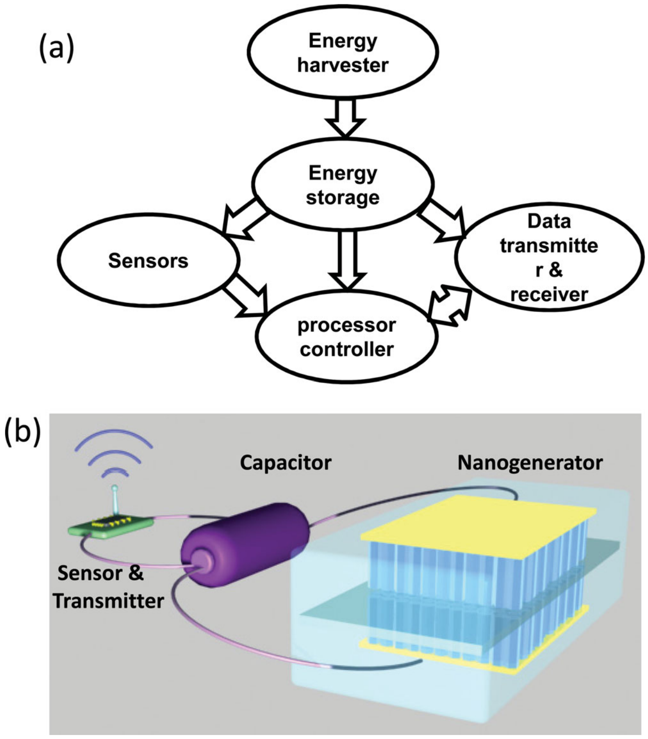

Figure 1. Schematic diagram of the integrated self-powered system. a) An integrated system can be divided into five modules: energy harvester, energy storage, sensors, data processor & controller, and data transmitter & receiver. b) Prototype of an integrated self-powered system using a nanogenerator as the energy harvester.

a possible solution. Potential energy sources are solar, wind, thermal electric, biomass, chemical, mechanical, etc. Solar energy, for example, is one of the important energy sources for green energy, but its application to sensors may have limitations. The use of solar energy for small sensors assumes that the sensors are exposed to light periodically, which may not be the case for numerous of the applications outlined above. Alternatively, gentle airflow (or liquid flow) and mechanical vibrations may exist in most of the places in which the sensors will be placed. But the mechanical energy available in our environment has a wide spectrum of frequencies and time-dependent amplitudes. This type of energy is called *random energy* and can come from irregular vibrations, light airflow, noise and human activity.

There are four typical approaches for harvesting vibration-based mechanical energy. The first technique is based on the well-known electromagnetic induction,[8] which usually has a large size. The second approach is the MEMS-based electrostatic energy harvester,[9] which requires an external voltage source. The third method uses the magnetostrictive effect, which may need a bias magnet.[10] The last method is the piezoelectric resonator, which works at specific frequency setting/range.[11] These approaches may not be readily adapted for use with random energy sources. An objective of our research is to develop an innovative approach that can be adequately applied for harvesting mechanical energy over a wide range of frequencies.

2. Nanogenerators: a Power Source for Small Electronics

A nanosystem is an integration of multiple functional nanodevices. The power required to drive such electronics is in the micro- to milliwatt range and so can be harvested from our physical environment. Once outputs of the order of milliwatts can be achieved, it is possible to have self-powered, maintenance-free biosensors, environmental sensor, nanorobotics, micro-electromechanical system, and even portable/wearable electronics. Taking a nanotobot as an example, it can sense, take action, send signals, and receive feedback if it has sufficient power. We must develop innovative technologies for converting other forms of energy into electricity so that it can be used for our purposes.

Wireless sensors have an active mode but – most importantly – can also have a standby mode, during which the device is “sleeping” with minimum energy consumption. The power generated by an energy havester may not be sufficient to continuously drive the operation of a device, but an accumulation of charge generated over a period of time is sufficient to drive the device for a few seconds. This could be of practical use for devices that have standby and active modes, such as glucose and blood pressure sensors, or even personal electronics such as blue tooth transmitters (driving power approximately 5 mW; data transmission rate approximately 500 kbits s^{-1}; power consumption 10 nW bit^{-1}), which are only required to be in active mode periodically. The energy generated when the device is in standby mode may be sufficient to drive the device when it is in active mode.

In the last six years, we have been actively developing a nanogenerator (NG) technology for building self-powered system (for a review see Wang[3]). The nanogenerator relies on the piezoelectric potential created in nanowires by an external strain: a dynamic straining of the nanowire results in a transient flow of the electrons in the external load because of the driving force of the piezopotential.[12,13] The output power of a NG is strong enough to drive conventional electronic components, such as an LED or a tiny liquid crystal display.[14–16] The advantage of using nanowires is that they can be triggered by tiny physical motions and the excitation frequency can be one Hz to thousands of Hz, which is ideal for harvesting random energy in the environment, such as tiny vibrations, body motion, or gentle air flows.

Figure 2a shows a new approach we have developed recently for fabricating high-output NGs at low cost.[17] The entire structure is based on a polystyrene (PS) substrate of typical thickness 0.5 mm, on which a Cr adhesion layer is deposited. After depositing a layer of ZnO seed by sputtering, densely packed ZnO nanowires as a quasi-continuous “film” are grown on the seed layer by a solution-based growth technique at a temperature no more than 100 °C. Finally, a thin layer of PMMA is deposited at the top of the film to serve as an isolation layer, followed by a deposition of a thin gold layer as an electrode. The growth of ZnO NWs has a unique and distinguished feature in that they are aligned along the *c*-axis, so that the entire film has a common polar direction. Once the PS substrate is mechanically bent/deformed through the substrate, the film at the top surface is under tensile strain and the one at the

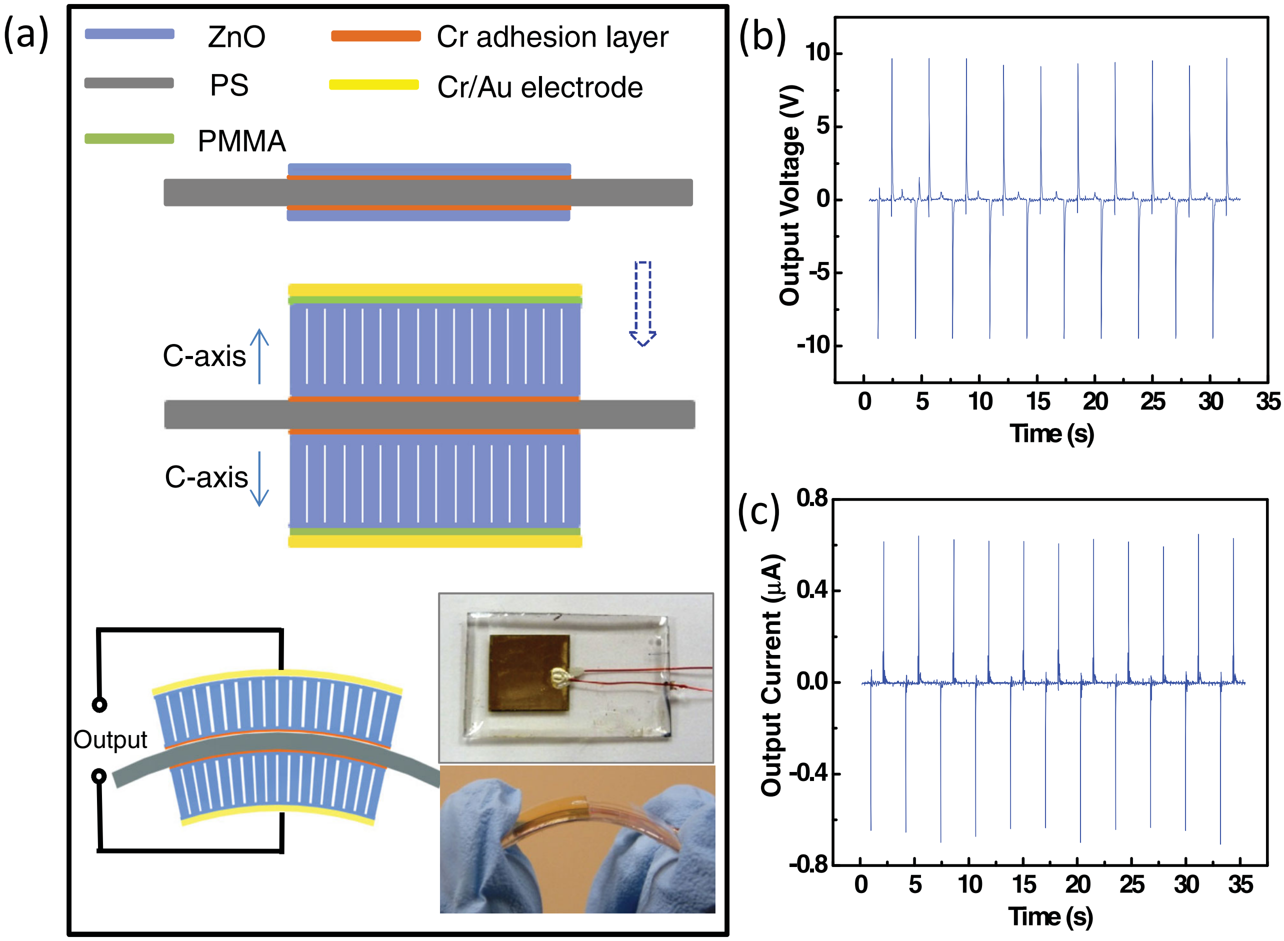

Figure 2. Fabrication of a nanogenerator and its output. a) Fabrication process of the nanogenerator: the lower right part is a photograph of a fabricated nanogenerator after packaging; the bending of the nanogenerator shows its good mechanical flexibility. b) Output voltage, and, c) output current of a typical nanogenerator.

bottom surface is under compressive strain, resulting in a piezopotential difference between the top and bottom electrodes, which drives the flow of electrons in the external load. A cycling mechanical deformation results in the back and forth flow of electrons in responding to the mechanical triggering. By introducing a strain of 0.12% at a strain rate of 3.56% s^{-1}, the measured output voltage reached around 10 V, and the output current exceeded 0.6 μA (corresponding volume current density 1 mA cm^{-3} and power density 10 mW cm^{-3}) (Figure 2b and c). This type of approach is technically easy and demonstrates low cost and high performance, so that it has a high potential for applications. The total output can be enhanced by integrating multiple NGs in serial or parallel depending on application, so that the entire system can be placed in shoes, clothes, plastic sheets, rotating tires, etc.

3. Self-Powered Systems

To demonstrate the operation of an NG driven system (**Figure 3**a), we used a single transistor radio frequency (RF) transmitter to send out the detected electric signal. The oscillation frequency was tuned to be around 90 MHz, and a commercial portable AM/FM radio was used to receive the transmitted signal.[14] The entire system is made of a NG, a capacitor for energy storage so that the output power can be regulated to reach the desired level, a signal modulation, and a wireless data transmitter. To demonstrate synchronization between the sensed signal and the signal transmitted, a phototransistor in a slotted optical switch was added to the system as the photon detecting sensor to demonstrate that the self-powered system can work independently and wirelessly. The signal of the photocurrent generated by the phototransistor as a result of external light excitation was periodically sent out using the energy stored in the capacitor. Each time it was triggered, the signal received by the phototransistor modulated the transmitting signal, and the information was received by the radio, and the demodulated signal was recorded from the headphone jack. Each cycle included an on (16 ms)/off (5 ms)/on (5 ms)/off (10ms) status sequence. Figure 3b is the signal demodulated by the radio. When the phototransistor and the transmitter were triggered, there was a pulse detected beyond the background noise. If we enlarged this pulse, it contained a segment of the information that had the same waveform envelope as the triggering voltage sequence of the LED,

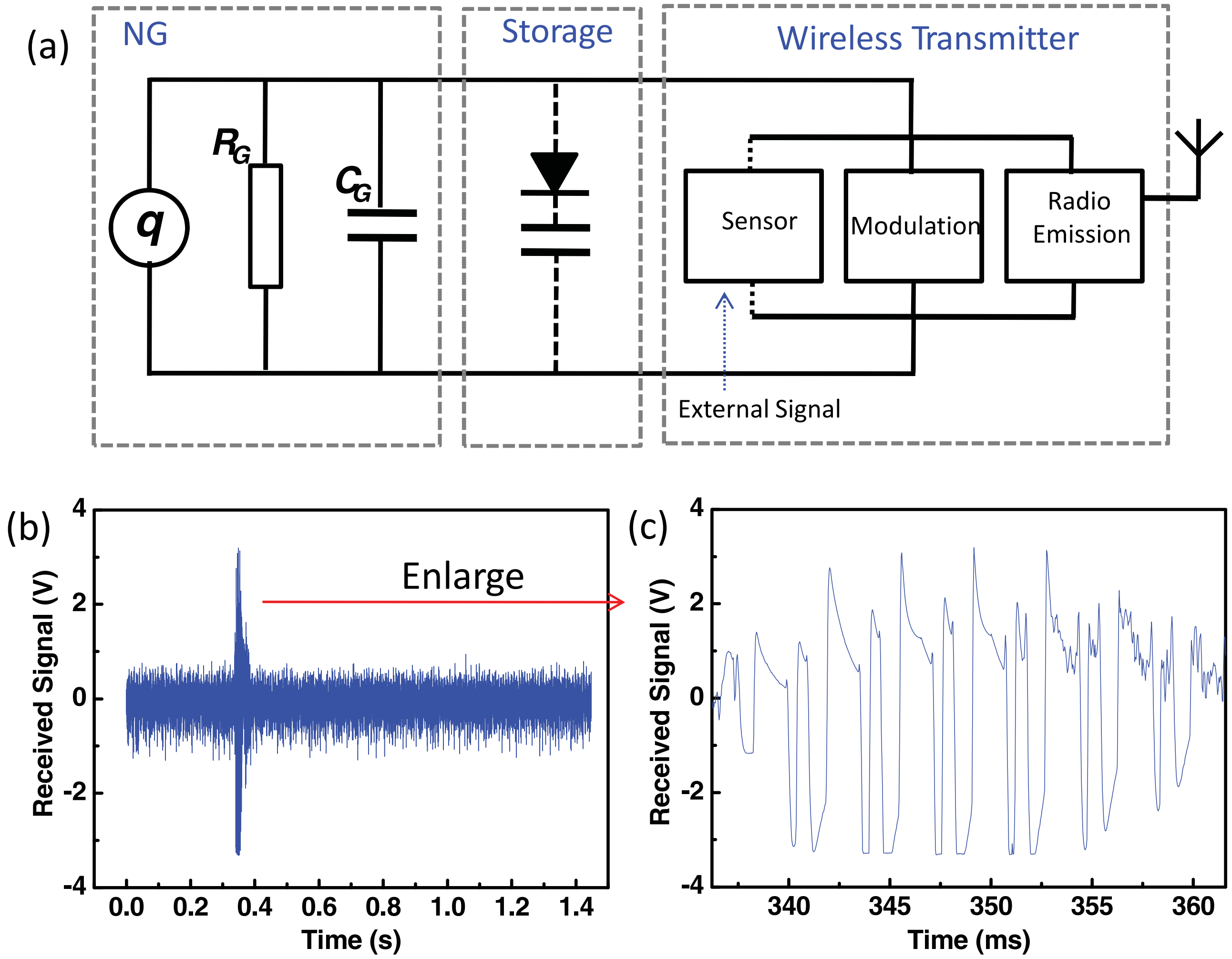

Figure 3. a) Schematic diagram of the designed self-powered system. For the wireless transmitter part, a phototransistor was used as the sensor to detect the light from an LED. The signal detected by the sensor was transmitted wirelessly by a single-transistor RF transmitter. b) Recorded signal from the headphone jack of the radio, which is detected and transmitted by our integrated self-powered system. c) Enlargement of the pulse in (b).

as shown in Figure 3c. This indicates that wireless data transmission was achieved by using this self-powered system over a distance of approximately 10 m. This type of technology can be further developed for even longer distance data transmission.

We have also fabricated a self-powered environmental sensor (**Figure** 4a),[18] which can detect Hg^{2+} ions and indicate their concentration via the emitting intensity of an LED. A single-walled CNT (SWNT)-based FET and ZnO NW array served as an Hg^{2+} sensor and as an energy harvesting part, respectively. Firstly, the drain–source current of a sensor was monitored at various concentrations of Hg^{2+} ions in water droplets to characterize the sensing process. Figure 4b shows measured drain–source current and resistance of a sensor at different concentrations. Initially, the least current ($<10^{-8}$ A) was observed as we chose an SWNT FET in *enhancement mode*. When the concentration of solution reached about 10 nM, which is the allowable limit of Hg^{2+} ions in drinking water set by most government environmental protection agencies, a noticeable change of resistance appeared. To demonstrate automatic detection of the local Hg concentration, a light emitting diode was attached on the circuit to serve as an indicator. To accomplish self-powered sensing of environmental pollutants with NGs, a circuit was designed with two independent loops. In the energy-harvesting process, a circuit was connected in loop 'A' (Figure 4a) with NGs and rectifying diode bridge to store generated charge in the capacitor. After sufficient charging, the connection was changed to loop 'B' in Figure 4b, thus the sensor was ready to detect Hg^{2+} ions and lit up an LED with the intensity depending on the concentration of pollutants in the water droplet. Figure 4c shows photographic images of LEDs lit up under various concentrations of Hg^{2+} ions. As shown after the third image of Figure 4c, noticeable LED light was noticed from the 10 nM concentration, getting brighter gradually to a concentration of 1 mM.

The self-powered system demonstrated here may have important applications in environmental monitoring, water quality control, and oil/gas line inspection. By using the turbulence and pressure change in gas/water/oil pipes, electricity can be generated to drive sensors such as temperature, flow,

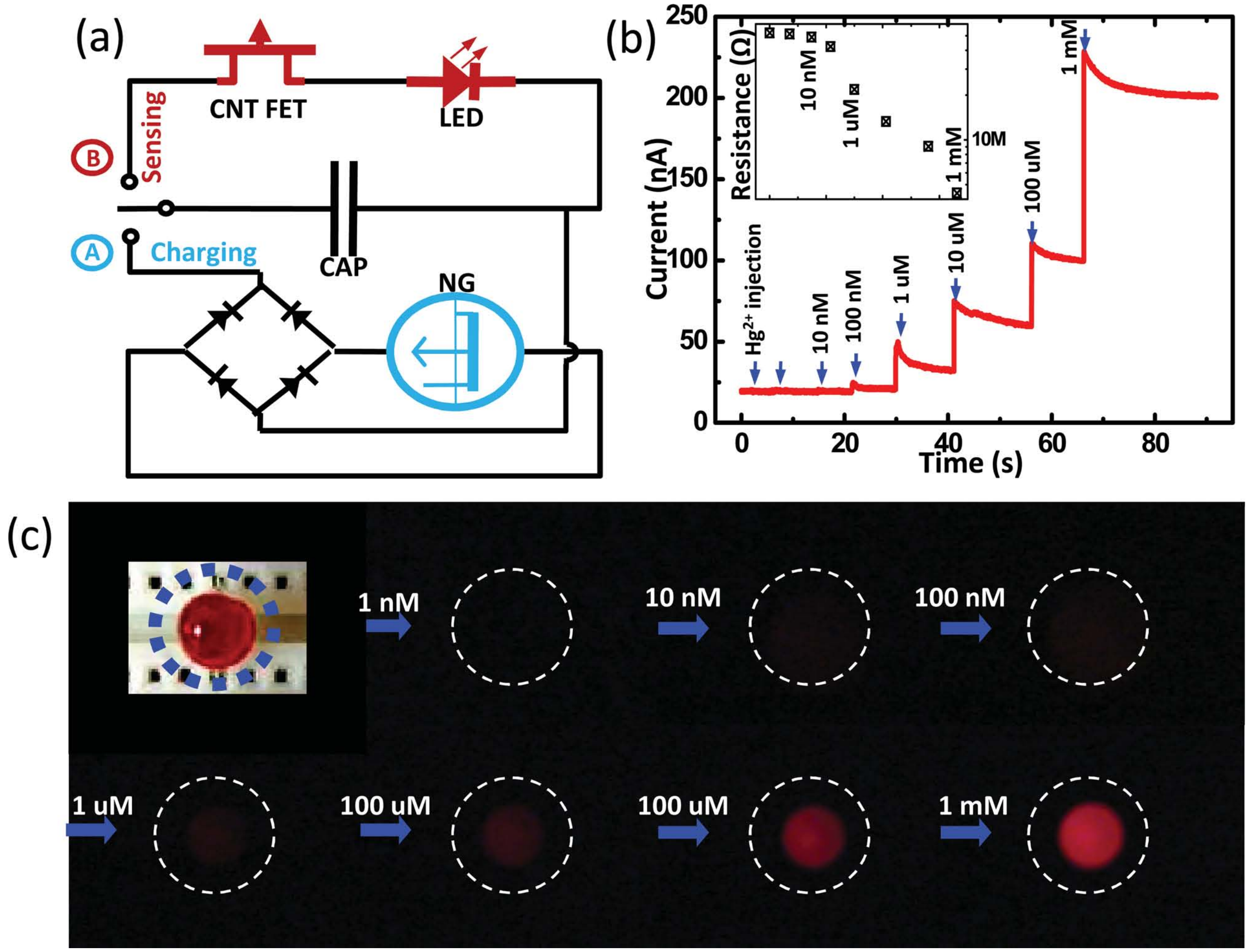

Figure 4. Characteristics of a self-powered Hg^{2+} sensor driven by nanogenerators. a) Circuit diagram depicting our self-powered sensor, composed of nanogenerator, rectifying bridge, capacitor, Hg^{2+} detector, and light emitting diode with eq \o\ac(○,a) *charging* and eq \o\ac(○,b) *sensing* process selecting switch. b) Sensing behaviour of our fabricated sensor with various concentrations of Hg^{2+} ions in water solution. The inset shows the plot of resistance depending on mercury ion injection. c) Optical images of a laser emitting diode representing intensity changes owing to resistance changes in the detector depending on the concentration of Hg^{2+} ions in water solution. All measurements were conducted with energy stored by nanogenerators.

velocity, or pressure. This may represent a good technology for monitoring water quality in residential areas in cities, even at large scale.

The instantaneous output power of the NG reached 6 μW with a power density of 1 mW cm^{-}3. Depending on the driving frequency of the external agitation, the power generated by a nanogenerator may not be sufficient to continuously drive the operation of a device, but an accumulation of charges generated over a period of time is sufficient to drive the device for a fraction of a second, and the output power can reach over 0.1 to 1 W. This could meet the working mode needs of many sensors that are required to detect species periodically. The energy generated when the device is in standby mode is likely to be sufficient to drive it when in active mode.

Since a sensor can work under various conditions, we anticipate harvesting all of the available forms of energies in the environment. Thus, technology has to be developed for simultaneously harvesting solar, thermal, mechanical, and chemical energy. Owing to the fact that these different forms of energy are being converted into electricity using distinct and diverse approaches, a hybrid device that simultaneously harvests several sources of energy would be invaluable. Solar energy is available only during the daytime, thermoelectric energy is available only where there is temperature gradient, and mechanical energy is available only where there are mechanical vibrations. We have developed approaches for simultaneously harvesting solar and mechanical energy,[19,20,21] or chemical and mechanical[22] energy. These studies are developing new fields in energy research.

4. Conclusions

The near future market in electronics may move toward personal, portable, and polymer-based flexible electronics. The development of nanotechnology may follow this trend, requiring the rational synthesis of nanomaterials, measurements of nanoscale properties, fabrication of nanodevices both singly and in arrays, integration of various nanodevices into systems with multi-functionality, and harvesting energy to build a self-powered system. A self-powered nanosystem is one that can operate wirelessly, independently, and sustainably. The self-powering idea we proposed in 2006 could be a new paradigm in nanotechnology for truly achieving sustainable self-sufficient micro/nanosystems, which are of critical importance for sensing, medical science, infrastructure/environmental mornitoring, defense technology, and even personal electronics. We anticipate that nanogenerators will play a key role for driving small electronics in a few years.[23]

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