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Inorganic semiconducting nanowires for green energy solutions

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Single-crystalline inorganic semiconducting nanowires (NWs) of technologically important materials such as Si, Ge, GaAs, ZnO and so on. have attracted significant attention in providing sustainable energy solutions (generation/storage) due to their attractive physical and chemical properties. Currently, the production processes of these devices is unavoidably wasteful and requires urgent attention. There is need to establish resource efficient and eco-friendly manufacturing for energy devices using inorganic NWs. The present work is dedicated to identifying such a route and materials, through critical analysis of various device development stages, namely (i) NW's synthesis methods, (ii) NW-based electronic layer fabrication, and (iii) metals, interconnects, and packaging forming techniques. We have also presented the current state-of-the-art of NW-based green energy solutions for next-generation of energy autonomous systems on flexible substrates.

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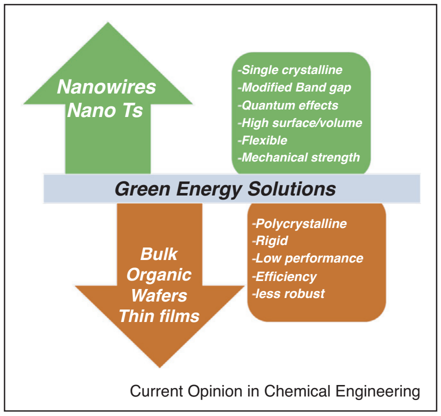
Introduction

The rapidly increasing harmful environmental impact of exhaustible natural resources such as gas, coal, oil, and ethanol and so on. based energy sources call for development of alternative sustainable energy solutions. As a result, many renewable energy sources based on wind, waves, biomass, thermal, light, and mechanical/vibration sources are being actively explored [1]. There is already considerable interest in high-efficiency solid state solar cells for many indoor/outdoor applications [2,3,4•]. Likewise, energy storage devices such as supercapacitors [5,6] have gained considerable attention. A wide variety of nanomaterials have been exclusively explored for energy harvesting and storage in the form of thermoelectric, piezoelectric (PE) and triboelectric (TE) nanogenerators (NGs) [7,8], and batteries and supercapacitors. Among nanomaterials, the inorganic one-dimensional (1D) semiconductors hold huge advantage due to high surface to volume ratio, single crystallinity, controlled composition, and possibility to engineer them as heterostructures (e.g. core-shell, axial, branched NWs etc.) [9,10•]. In the sub50 nm diameter range the semiconducting NWs match the fundamental dimensional dependencies such as visible light wavelength and mean free path of phonons, exciton Bohr radius and confined transport of electrons and so on, and thus, offer the features that are unique for the development of efficient energy devices [11,12]. These special attributes of NWs are compared in Figure 1 with those of traditional materials such as inorganic crystalline and amorphous thin films, organic semiconductors, and single crystalline bulk wafers (Si, Ge, GaAs etc.) and thus, NWs clearly are more advantageous for energy solutions.

Realizing eco-friendly green energy technologies using inorganic semiconducting NWs involves developing environment friendly and resource efficient manufacturing steps including: (1) NWs synthesis/growth, (2) development of NW-based electronic layers, and (3) device fabrication. However, currently, each of the above stages is realized with traditional micro/nanofabrication methodologies which are unavoidably wasteful and rely of chemical that are potentially harmful to the environment. For example, top-down approach for realizing NWs require harsh conditions such as high temperature (>700 °C), corrosive chemicals, high energy plasma, flammable gaseous ambient and so on [13–15]. A significant amount of toxic chemical waste is generated as by-product with conventional microfabrication for device fabrication [16]. To limit the environmental damage, alternative eco-friendly technologies are currently being explored using green NW synthesis methods, degradable and recyclable materials, and resource efficient printing processes. The discussion in this paper aims to highlight such eco-friendly and resource efficient methodologies for NW based green energy solutions, namely (i) NW's synthesis methods, (ii) NW-based electronic layer formation, and (iii) metals, interconnects, and packaging techniques. These are presented in Sections 'Nanowire growth' and 'Resource efficient manufacturing route' of the paper. In the Section 'Prototypes for NWs based

Figure 1



Schemetic illustration of the advantages of NWs based energy systems compared to their bulk counterparts. The upward arrow indictaes the better performance due to the listed features in the box. The performance of the bulk materials are affected due the reasons shown by downward arrow.

energy devices and applications', current state-of-the-art for NW-based energy harvesting/storage device prototypes is presented. Finally, in the conclusion section, the analyzed research is summarized in a tabular fashion, and the green manufacturing pathways have been highlighted.

Nanowire growth

NWs fabrication can be divided into two approaches (Figure 2): bottom-up and top-down based on different physical and chemical techniques. Top-down fabrication approaches uses bulk single crystalline wafers as starting source material to carve out discrete 1D NWs using controlled dry plasma or wet chemical etching with aid of lithography patterning [13,14]. The approach provides excellent control over the NW's dimensions, periodicity, and orientation (both vertically and laterally). However, given the nature of conventional micro/nanofabrication approach followed for top-down method, there are limitations regarding this route for the development of green energy devices, namely: (i) resource inefficient as production processes it follows are unavoidably wasteful, (ii) limited to few materials which are available in wafers form, and (iii) generate toxic waste as by-product which is not environment friendly.

On the contrary, bottom-up category is more versatile in terms of materials selection, dimensional accuracy, hetero-structure synthesis with additional scope of eco-friendly process conditions to produce inorganic NWs [9,17]. Among wide range of reported bottom-up methods such as vapour phase transport, hydrothermal, electrodeposition and so on, the vapour–liquid–solid (VLS) mechanism has proven to be more eco-friendly (Figure 2). This method has been successful in terms of producing environment friendly NW materials (e.g. Si, silica, ZnO, TiO_2 etc.) without compromising the requirement of sub100 nm nanoscale dimensions, single crystallinity and controlled composition — all of which are crucial for high performance energy conversion devices [18,19]. To extend towards green nanofabrication, GaN based NWs have also been grown by VLS mechanism using Au as catalyst, and non-toxic sources such as Ga_2O_3, carbon mixture, and ionized nitrogen [20]. Conventionally, GaN NWs are produced using harmful chemicals such as Trimethylgallium (TMG), Ammonia gas, Ga metal and so on. which are harmful to the environment. Likewise, Si_3N_4 NWs have been produced by VLS method using computer monitor e-waste (as source of Si) and plastic shells (source of carbon) under the flow of nitrogen gas [21]. This method could also help to defuse the e-waste issue, which is huge threat to the environmental sustainability. Additionally, VLS mechanism offers unique advantages such as *in situ* doping (e.g. Si NWs-p type (diborane) and n-type (phosphine)) and ability to produce axial and radial heterostructures which are crucial for the development of energy devices such as photovoltaic cell [3,22,23].

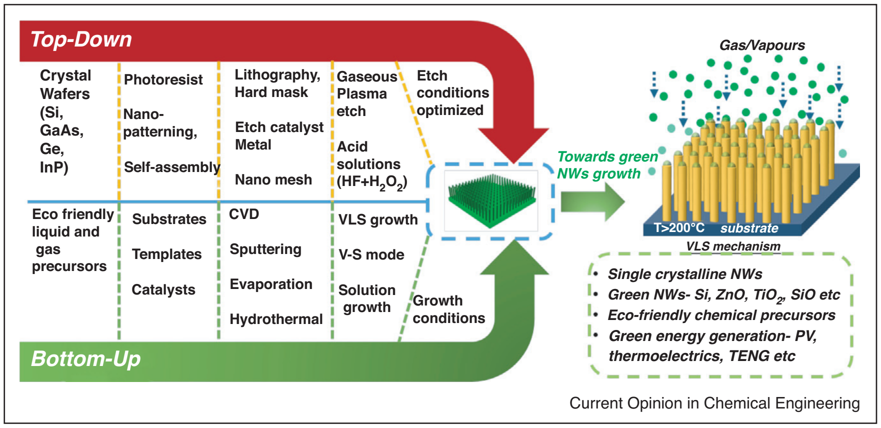
In VLS growth, catalyst particles play a crucial role in deciding the growth conditions, site specificity and dimensional control of the resulting NWs. Based on the binary phase diagrams, Au is one of the most used catalyst for the synthesis of technologically important semiconducting NWs such as Si, Ge, GaAs, InAs and so on. Despite the high utility, the high temperature growth conditions lead to the incorporation of Au impurities in the semiconducting NW's crystal matrix such as Si which is detrimental for energy devices. Recently, low melting temperature catalysts such as Ga, In, Bi and Sn have shown pathways to overcome this problem. The advantages of these catalysts are: (1) they allow NW growth at lower temperatures (<400°C), (2) the unintentional incorporation of these catalysts aid constructive p-type and n-type doping, and (3) assist the fabrication radial core-shell heterostructures for the development of tandem junction solar cells.

From these demonstrations it is evident that the VLS as bottom-up approach for NWs growth could be a viable green synthesis route (Figure 2). Growth of NWs is followed by their transfer, and fabrication of devices. The next section addresses the selection of environment friendly and resource efficient manufacturing route for NWs based energy solutions.

Resource efficient manufacturing route

For decades, conventional micro/nano fabrication processes (lithography, etching, etc.) have been used for the development of electronics. However, the approach relies almost entirely on subtractive manufacturing

Figure 2



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General comparison of various bottom-up and top-down strategies employed in the growth/fabrication of semiconducting and illustrates the utility of chemicals, gases, and plasma in the preparation of NWs. The scheme also depicts that the VLS mechanism has a potential to become a green fabrication strategy to produce high quality inorganic NWs.

methods and so, have following major drawbacks [16]: (i) generates significant amount of waste (both during the fabrication and product's end-of-life), (ii) requires huge investment, and (iii) not compatible with flexible substrates. Separate from the mainstream route of electronics development, Printed Electronics (PE) has attracted significant attention [24•,25,26]. This is owing to excellent attributes such as efficient use of materials as an additive manufacturing route, negligible toxic waste generation, design flexibility (maskless designs), low fabrication cost, and possibility to realize devices on diverse substrates including plastics. Consequently, PE has opened a 'greener' way of manufacturing electronics. Few of the major developments in PE field, incorporating inorganic NWs, is discussed in the following section.

Electronic layers development

Both conventional and unconventional printing techniques have been used to realise quasi 1D materials based electronic layers. Among conventional methods, inkjet, gravure, and screen printing and so on, have been explored to print carbon nanotubes (CNTs), ZnO nanorods, and so on. However, these methods suffer from: (a) poor patterning resolution (50−100 µm), (b) low device mobility (0.2–3 cm^2/Vs), (c) nozzle clogging, and (d) poor process-to-process and device-to-device reproducibility (due to non-uniformity of electronic layers) [27,28]. Towards unconventional printing of NWs, both dry and wet methods have been explored (Figure 3). These techniques aim to achieve high yield, precise alignment, high density, uniform NWs interspacing, monolayer (ML) control and ability to transfer NWs over wide range of rigid and flexible substrates [24•]. They have their own merits and disadvantages depending on the NWs material systems, growth technique and targeted application [13,29]. For example, the transfer printing (TP) allows integration of laterally aligned semiconducting nanostructures using elastomeric stamps, usually PDMS (Figure 3d). The TP has shown enormous potential for realising high performance flexible electronic devices and circuits, but because of viscoelastic nature of stamps, it is challenging to obtain high printing yield, registration, and reproducibility [30•,31]. Motivated by such issues, alternative TP schemes such as 'direct roll transfer printing'

Figure 3

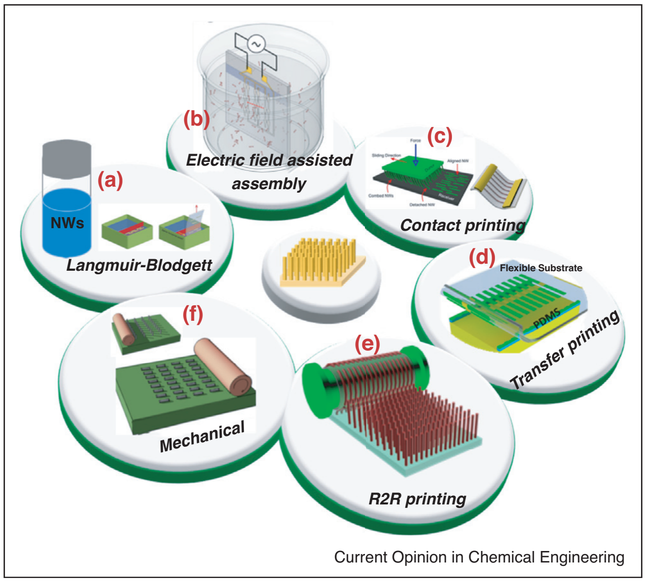

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Illustration of various dry and wet NWs transfer printing techniques. The alignment **(a)** and **(b)** and printing techniques **(c)**–**(e)** lead to development of NWs based devices and systems with the potential scalable manufacturing.

(DRTP) have been developed [6]. The reported technique has the following distinct advantages: (i) unlike conventional TP, DRTP does not require a transfer stamp, thus reducing the number of printing steps which is important not only to reduce the process cost and time but to preserve the morphology, structure and prevent breakage and/or wrinkling of printed nanostructures, (ii) high transfer yield and registration factor, (iii) the process helps to achieve high device-to-device uniformity, and (iv) the process is compatible with roll to roll (R2R) fabrication which is advantageous for future large area electronic (LAE) manufacturing. But the DRTP process is slow and device area is limited to wafer scale. Further, due to the requirement of top-down fabrication of nanostructures on wafers, the TP and DRTP processes generate chemical waste.

To mitigate these challenges, contact printing (CP) (Figure 3(c) and (e)) is a promising dry transfer method, which involves directional physical sliding of NW substrate (donor) over a receiver substrate to produce horizontally aligned arrays of NWs. The technique yields high density of aligned NWs ($\sim$7−10 NWs/μm) with variety of materials such as Si, CNTs, ZnO, Si/Ge (core-shell), SnO_2, InAs, CdSe and so on. The CP process segments largely consist of eco-friendly steps except occasional (depending on the materials for NWs and substrates) use of chemicals for surface functionalization ($–CF_3$ or $N–H_2$ groups) of the substrates for NWs anchoring and directional alignment. As an alternative to chemical functionalization, the use of mild O_2 plasma on the receiver substrates can facilitate the NWs transfer in an environment friendly manner. The engineering design of CP system currently being studied extensively to expand scalability of the process for continuous printing of NWs based electronic layers for the development of sensors and electronic devices [29]. In addition to above printing approaches, many hybrid NWs assembly techniques have also been demonstrated for fabrication of large array of NWs. For example, vertically grown NWs using bottom-up approaches are converted into wafer scale ordered array using a mechanical ‘knocking down’ using a roller (Figure 3f). This is largely a green process as it does not involve harmful chemicals. Likewise, the CP and hybrid NWs assembly techniques can lead to the fabrication of NW based flexible devices over large areas, but these methods also pose practical challenges such as NWs breakage (reducing NW length), need vertically aligned NWs on substrates, poor metal-semiconductor contacts and so on.

The solution-processable NWs assembly methods (dielectrophoresis (DEP), Langmuir–Blodgett (LB), etc.) could resolve most of the issues with current dry methods (Figure 3(a) and (b)). These methods have advantages such as simplicity, cost-effectiveness, and scalability. Particularly, DEP offers precise positioning of semiconducting/metallic NWs with a high degree of orientation in multi-directions at a much faster rate. In a standard DEP process, suitable voltage (AC or DC) is applied across pre-defined microelectrodes to induce a non-uniform electric field which leads to a generation of DEP force across the nanostructures to eventually align them [32]. DEP is compatible for site specificity, single or dense NW alignment, large areal coverage and layer by layer assembly. However, DEP demands uniformly dispersed NWs for which surface modification is performed. This could contaminate the NW surface and leads to poor device performance. In summary, all of the presented electronic layer formation approaches are advantageous as they use lesser chemicals/solvents to process the NWs and hence make key contribution to an overall resource efficient or greener electronics fabrication process.

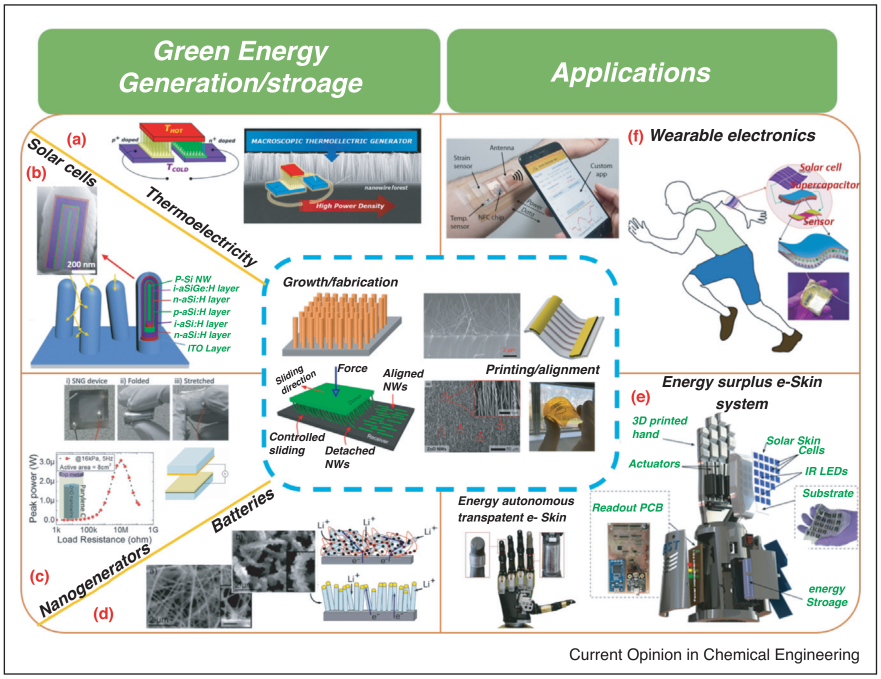
Defining metal contacts, interconnects, and packaging

To complete the fabrication of energy devices, metal contacts and packaging steps need to be carried out. Currently, these steps are carried out using conventional microfabrication process, but as mentioned above they are unavoidably wasteful and generate toxic by-products. To reduce the environmental load of electronics, printing could also be used for defining metals, interconnects, and packaging. This could be achieved by using many different contact and non-contact printers that are nowadays available. The classification is made depending on whether the printing materials are in direct contact (contact printers) with the substrate or not (non-contact printers). The prominent non-contact printing techniques include slot-die coating, screen, and inkjet printing whereas the contact-based printing comprises gravure, gravure-offset, flexographic, transfer, and nanoimprinting. At present, the best printers offer resolution of few μm, which is far larger than the advanced conventional Si electronics (few nanometres). However, just like the growth witnessed by the conventional fabrication, one may see advances in printed technologies leading to printing submicron features in future. Details on printing resolutions, mechanism, advantages and disadvantages of available printing techniques can be found elsewhere [25]. In authors opinion, by combining both contact and non-contact printing techniques, roll-to-roll (R2R) printing could be the way forward. It is a commercially viable approach that could maintain high-throughput, low fabrication cost, and reduced material and energy wastage to drive down the price and allow market accessibility.

Prototypes for NWs based energy devices and applications

The NW’s growth and manufacturing route described in the previous sections lead to the realization of efficient and sustainable green energy devices which is needed for energy autonomous operation in applications such as Internet of Things (IoT), mobile healthcare and so on. Over the past two decades, there has been substantial increase in the interest in energy harvesting from ambient (green or eco-friendly sources) and storage for continuous operation of devices. This includes energy sources based on light (solar cells), wind, wasted heat (thermoelectric), mechanical (piezo and triboelectricity), and tides/waves and so on. This section describes NWs based energy generation/storage devices, high-performing prototypes, and their application in emerging areas, as summarised in Figure 4. Because of their high energy output and flexibility, NW based solar cells (Figure 4b) are well suited for wearable applications. Among different materials and device prototypes investigated, Si NW based radial p-n junction based solar cells have shown the highest efficiencies of 15.02% [33]. The performance of these cells is promising compared to their bulk and thin film counterpart due to their strong light trapping capability, possibility of reducing absorber layer thickness (<50 nm), efficient charge extraction, stable performances irrespective of ambient lighting conditions, and flexibility [3,22,23]. Instead of the commonly used Au droplet as the catalyst, low melting point metals such as Sn, Bi, Ga and so on, have been explored for fabricating SiNW based solar cells (see Section 'Nanowire growth'). The use of low melting point metals enables direct integration of NWs over flexible substrates. Notable example is the fabrication of radial tandem junction (RTJ) solar cells from VLS grown Si NWs using Sn as catalyst. The engineered, stacked p-i-n junction structure efficiently absorbs wide spectrum (400−850 nm) due to the high surface area of NWs compared to the planar tandem PV cells. The cells displayed an open circuit voltage of 1.2 V, filling factor of 61.5% and conversion efficiency of 8.1%. Importantly, Si NWs RTJs have been demonstrated over a flexible thin foil (thickness-15 μm) with minimum bending radius of 10 mm and the power to weight ratio (PTWR) ∼1628 W/kg. With the increasing interest for portable high performance solar cells, the demonstrated NWs based RTJs show promise with their enhanced PV cell figure of merits and this can be further extended by printed III-V compound semiconductor NWs [34,35]. Materials for thermoelectric devices (Figure 4a) are expected to have a low thermal conductivity and a high-power factor to enable the figure of merit $ZT > 1$. Thin film and bulk thermoelectric materials based on Bi, Te, Pb and Ag have high $ZT = 2.2–2.4$ [36–38] at room temperature. NWs of these materials such as Bi_2Te_3 have also shown impressive ZT of 2.3–2.5 [39] and it can be further enhanced by twin containing microstructures [40] and doping [41]. Whilst these convnetional thermoelectric materials have high ZT values, most of them are toxic to humans. The ZT of Si NWs is low ($ZT = 0.6–1$) but it is non-toxic and flexible [42–44]. The TP method has shown potential to develop flexible micro thermoelectric generators (μ-TEGs) using Si microstructures. A TEG module, consisting of an array of 34 alternately doped p-type and n-type Si microwires, has been developed on a

Figure 4



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Scheme showing various NWs based green energy device prototypes and their potential applications, **(a)** thermoelectricity [38], **(b)** solar cells [23], **(c)** TENGs [46], **(d)** battery anodes [55], **(e)** e-skin systems [58•], **(f)** wearable health monitoring system [56,57,58•] (Reprint with permission).

SOI wafer using standard photolithography and etching techniques. Although the device showed moderate performance (maximum of 9.3 mV open circuit voltage), the use of lithography and etching results in generation of chemical wastage.

Piezoelectric Nanogenerators (PENGs) and Triboelectric Nanogenerators (TENGs) are other emerging class of energy harvesters (Figure 4c), where inorganic 1D NWs have gained immense interest due to their ability to convert mechanical energy into electric power in an efficient manner. The PENGs are based on piezoelectric (PE) effect which is the ability of materials to generate electrical charges under external mechanical force, pressure, or strain [45–47]. NWs of one of the most common PE materials used for commercial applications, that is, lead zirconium titanate (PZT), have been employed to realize flexible energy harvesters [48]. However, the major drawback of this material is presence of the lead and, consequently, international standards are aiming to stop its usage in commercial applications because of adverse environmental impact. Accordingly, various environment benign lead-free PE inorganic NWs have been identified and exploited as an active material for PENGs. It includes ceramics such as barium titanate [49], and semiconductors including ZnO [46,47], gallium nitride [50] and so on. Among them, ZnO is the most extensively studied and has found practical uses for energy recovery under various device geometries. The use of ZnO NWs as active PE material in PENGs has been largely driven by distinct advantages over the other lead-free materials, including (i) coupled PE and semiconducting properties, (ii) cost-effective synthesis methods that offer single-crystalline materials production, (iii) substrate independent synthesis method, (iv) environmental compatibility, and (v) biodegradability. Accordingly, ZnO NWs have been used to fabricate flexible PENG device prototypes in mainly three configurations, namely vertically integrated nanogenerators (VINGs), laterally integrated nanogenerators (LINGs), and nanocomposite generators (NCG) [51]. For ZnO NW based high performance LING development, all NWs must be laterally oriented in same direction. This is not possible with solution-based assembly approaches such as LB deposition. To achieve such feature, CP method ensure that the crystallographic orientations of the horizontal NWs are aligned along the sweeping direction. Consequently, the polarity of the induced piezopotential is also aligned, leading to a macroscopic potential contributed constructively by all the NWs [8]. Despite having perfectly aligned NWs, the performance of LING devices was not enough for practical applications as it was difficult to have high-quality Schottky contacts on multiple NWs. To overcome this challenge, capacitive coupling was explored in NCG and VING devices. By adopting NCG device prototype, performance as well as stretchability of the PENG devices was greatly enhanced. In such a structure, PE NWs are dispersed in an elastomeric matrix, which can also be treated as device substrate. In this case, no need of any NW assembly technique is required. Stretchable PENGs have also been fabricated by combining VING and NCG device prototypes. Towards this, a facile, cost-effective, and industrially scalable process was developed to realize mechanically robust, stretchable nanogenerator (SNG) on biocompatible and biodegradable PDMS substrate [46]. The active PE nanomaterial, that is, vertically aligned ZnO NWs, is directly grown on PDMS (direct integration approach) using low-temperature hydrothermal growth process. An inorganic/organic composite type PENG is realized by encapsulating the ZnO NWs in a parylene C polymer matrix. The SNG devices exhibit excellent performances with a high open-circuit voltage $\approx$10 V, short-circuit current density $\approx$0.11 μA cm^{-2}, and peak power $\approx$3 μW under a vertical compressive force.

The TENG operation, on the other hand, is based on coupled triboelectrification and electrostatic induction phenomenon. Accordingly, owing to high surface to volume ratio, NWs have been employed to enhance the surface area of the TE materials in contact with each other and thus, the triboelectrification. There have been different TENG device prototypes reported exploiting various working modes namely contact-separation, sliding, free standing and single electrode. Among them, contact-separation is by far one of the most investigated one. This is owing to its design simplicity and high device output. For instance, ZnO NWs were incorporated into the electrospun polyvinylidene fluoride (PVDF) and nylon 11 nanofibers to enhance the output power [32]. The maximum power density of ZnO NWs incorporated PVDF/nylon 11 TENG reached as high as 0.3 mW/cm^2. ZnO NWs were also used to fabricate hybrid NGs by combining TE and PE features. For this, the ZnO NWs were grown on bottom TE electrodes via a hydrothermal method. The hybrid NG displayed an output power density of 0.21 mW/cm^2, which was higher than that of the TENG without NWs [52]. In summary, both mechanical energy harvester devices (PENGs and TENGs) are very promising for next generation of energy autonomous systems. However, both device types give high output voltages under open-circuit condition (high internal impedance). The output performance degrades dramatically with the decrease of the external load resistance. Therefore, one of the critical challenges is to decrease the device impedance while keeping the output performance intact.

Energy storage is equally important as generation for a continuous and stable device operation. Towards this, Si has shown huge potential as green material to replace graphite in commercial lithium-ion battery (LIB) as anode active material. This is owing to its high theoretical specific capacity (4200 mA h g^{-1}) and abundance in

Table 1

Three domains of NWs research area in energy field highlighting the green manufacturing route in each category. The text in green shows potential future green technology

NWs growth methods	Resource efficient manufacturing		Energy generation/storages
	NW based electronic layer development	Metal, interconnect, and packaging	
• Dry etching • Chemical etching • VLS growth • Solution synthesis • Template growth • Hydrothermal	• Contact printing • Transfer printing • DEP • Langmuir-Blodgett • Flow assisted techniques	• Conventional microfabrication • Printed Electronics	• Thermoelectric • TENG • PENG • Dye sensitized PV • P-I-N PV • LIBs • Supercapacitors

nature. However, because of the enormous volume change during the lithiation/delithiation processes, Si crystal structure gets distorted which eventually decreases the initial coulombic efficiency (ICE), cycle stability and rate performance [53]. To mitigate these issues, Si NWs has been widely studied as an active anode material [54]. This is because 1D structure provides large specific surface area, efficient charge transport, and improved mechanical properties such as reduced internal stress, high crack resistance and so on [55]. (Figure 4d). To further improve the electrochemical performance of Si NWs, doping with suitable elements as well as mixing with different additives such as metal oxides, carbon-based materials and so on, has been attempted [53,54]. Alternatively, supercapacitors [56] can offer high power densities compared to LIBs and fuel cells. Composite of CNTs/V_2O_5 NWs have shown to be excellent supercapacitor anode with an energy density of 40 Wh kg^{-1} at a power density of 210 W kg^{-1} which is above par with traditional bulk porous carbon and metal oxides films [6]. The ability of 1D NWs to provide large surface area, mechanical robustness, enhanced electrochemical properties along with the environment compatibility brings huge benefits to the supercapacitors which includes large cyclic stability (>10 000 cycles), and improving energy density while keeping high power density (range ~20 kW kg^{-1}). The eco-friendly energy generation/storage solutions using NWs will provide energy autonomy to the emerging applications including smart health monitoring systems, e-skin, IoT sensing and so on [57,58•,59•], (Figure 4(e and f)). Moreover, the flexible form factor and light weight features of these devices have extra benefit for above-mentioned applications where conformability to curved objects is needed. Currently, many different NW-based energy technologies are being investigated and the field is rapidly evolving. They have shown potential to be futuristic energy solution for energy autonomous operation, for both outdoor and indoor applications.

Conclusions

Inorganic semiconducting NWs have been proved to be an important class of nanostructures for the development of green energy devices including renewable energy harvesting and storage for many applications. However, even renewable energy harvesting/storage devices may negatively affect the environment if the adopted manufacturing route is not resource efficient. In this regard, the discussion in this short review is timely. The discussion has shed lights not only on the greener devices, but also the greener pathways to process the inorganic NWs starting from their growth or synthesis, to transfer or integration process and finally to the device development for energy generation/storage. We have discussed different routes developed so far for the growth and integration of NWs and highlighted eco-friendly and resource efficient processes in both domains (Table 1). The discussion here shows the feasibility of NWs based approach for green technologies and sustainable energy requirements.

Conflict of interest statement

Nothing declared.

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Declaration of Competing Interest

The authors report no declarations of interest.

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