FUZZY SIMULATION, SYNTHESIS, CHARACTERIZATION AND VOLTAGE MEASUREMENTS OF ZINC OXIDE NANO-RODS BASED NANOGENERATORS

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Harvesting the mechanical energy from environment sources such as wavy motion of plant leaves and branches could power up the low power consumption electrical devices and sensors. Such low power energy harvesting devices will replace the batteries especially at the remote areas where the replacement of batteries is very expensive or sometimes impossible. An environment friendly nano generator using ZnO nanorods can be built easily and useful for energy generation. Although, performance of harvesting ZnO piezoelectric nanorods have gradually improved even then their power is insufficient for real devices. However, the integration of nanogenerator devices for energy harvesting into a single power source is necessary. Therefore, its simulation using MATLAB fuzzy logic and fabrication is presented in this paper with a very low error of 0.24 % which shows its excellence in performance by presenting new technique of energy generation with plant leave movement. The fabricated ZnO nano-wires on aluminum substrate connected in series and parallel were also tested and the results are closely in contrast to the stimulated results. The nano-generator shows an enhanced voltage when connected in series and a high current value when connected in parallel. The nano-generator give a voltage of 0.695 mV when connected in series and a current density of 25 nA cm-2when connected in parallel.

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1. Introduction

Self-powered nano systems have several applications in the field of defense, biomedical, and communication due to their ability of sensing and actuating. Nano-systems exhibit significant advantages over the battery-operated small systems as such systems need less power and may be operated by the nano-generators. An excellent flexible nano-generator can flutter easily with high amplitude of vibration when an air flows with frequency about 20 Hz and a speed of 1.5 m/s. The output power from such nano-generator increases when the speed of air flow is about 0 to 5.5 m/s. An excellent flexible nano-generator is capable to serve as an energy scavenging device under the waving motion of plant leaves. The electrical energy can be attained by attaching a nano-generator to the surface of a leaf of a plant [1-3]. In the situations where mechanical movements or vibrations are available, it is a very practical to harvest this energy. The usual mechanical vibration sources are helicopter, running car, leaves movements and home appliances. All these mechanical vibrations are the potential sources for energy scavenging, as all these vibrational energies may be converted into electrical energy [4-6].

Nanowires are commonly coupled to the MEMS proof-mass structures to harvest the resonant ambient frequencies. ZnO nanowires are biocompatible and environmentally friendly. Nano-generators have been developed to scavenge energy from the sources in the environment.

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These sources should have some sort of vibrational motions such as human body motions, movement of automobiles, machine engines and plant leaves. A flexible nano-generator is reported which responds to a wavy wind. The nano-generator is fabricated by growing an array of nanowires and it is attached to a flag for energy harvesting. Such devices are used for energy harvesting and self-powering of the sensors [7-12]. When the nano-generator was vibrated by some external force at 40 Hz, a corresponding volume normalized output power of 22 mW/cm^3 and the measured output voltage of 21.4 mV were obtained between the top and the bottom electrodes. The piezoelectric potential is produced when the nano rods are mechanically vibrated or dynamically strained by some external source, a corresponding transient current flows through the external circuit or load. This current flows to balance the Fermi levels at the two contacts of the nano generator. The mechanical energy is converted into electrical energy with the movement of the nano rod. A maximum peak output current is influenced by the applied force and inherent properties of nano generator but it is not influenced by the strain rate. The output voltage for such device are reported as ~22mV (±1.2) and -32mV (±0.16) with active device area as $4cm^2$ [13-18].

Nanogenerator offers an efficient technique for providing electrical energy by applying force to vibrate the generator. The grouping of these developed nanogenerators provides an output voltage of 1.8 V and an output current as 148 nA [19]. A sandwich-like nanogenerator is demonstrated by using two arrays of nanowires placed in a face to face configuration. The single crystalline nanowires of ZnO are grown by using the aqueous chemical growth. The maximum attainable open circuit voltage is 2.4 V while the short circuit current is 152.2 µA. The output generated voltages by the individual nanogenerators are 80, 90 and 96 mV, respectively and the series integration of three nanogenerators produces an output voltage of 0.243 mV. Similarly, the output generated current by the individual nanogenerators are 6.0, 3.9 and 8.9 nA cm-2, respectively and their parallel integration of three nanogenerators produces an output current of 18.0 nA cm-2. It gives a good demonstration of integrated nanogenerators for the applications where a dynamic stress/strain is available, such as in vibrating leaves of plants. Moreover the estimated power density was 2.7 mW cm-3 which was 6 to 11 times larger than the power density generated by PZT cantilever [20-23].

In the previous paper the authors have presented the simulation for the output power achieved from a nanogenerator for the different orientations and speeds of air flow that strikes the leaves of a plant [24]. The current paper gives a demonstration for the fabrication, simulation and testing of the Zinc oxide nano-rods based on output power of integrated nano-generators using MATLAB fuzzy logic controller by installing them on the plant leaves connected in series and parallel.

2. Materials and methods

Zinc-oxide nano-rods were fabricated on a flexible Anodic Aluminum oxide substrate using three steps. A flexible Aluminum substrate of 2cm x 2 cm was used in this work. After proper cleaning of the Aluminum substrate with DI water and acetone followed by drying, the substrate was subjected for an anodic aluminum oxide membrane growth. For anodic aluminum oxide growth, two steps process was carried out. In the first step, 0.2 M oxalic acid solution, aluminum substrate and lead rod were inserted in Anodization setup. A Voltage of 45 V is applied for 30 min. The applied voltage was gradually increased to 140 V at a rate of 5 volts per minute. The anodization at 140 V was carried out for 15 minutes. The sample was then etched using 5% phosphoric and chromic acid for 20 min at 100 °C. The second step was carried out at 110 V for 4 h. The barrier layer formed was removed by changing the electrolyte to 0.5 M KCl and applying an opposite polarity voltage for 6 minutes. Sample was etched in mercuric chloride solution for 15 min to remove all the impurities. For the growth of zinc-oxide nano-rods, a solution of 20 mM solution of Hexamine and Zinc acetate was dissolved in DI water. The solution was added into self-designed chemical bath deposition setup. The temperature of the water bath was set at 95 ^oC. The AAO substrate was vertically dipped in the solution. The deposition process was carried out at 95^oC for 5 hours. The substrate was then washed with DI water and baked in furnace at 450 ^oC for 2 hours. The prepared nano-rods are further characterized using Scanning Electron Microscopy to study the length and diameter of the prepared nano-rods. The schematic process for the synthesis and fabrication of nano-generators are shown in Fig. 1.

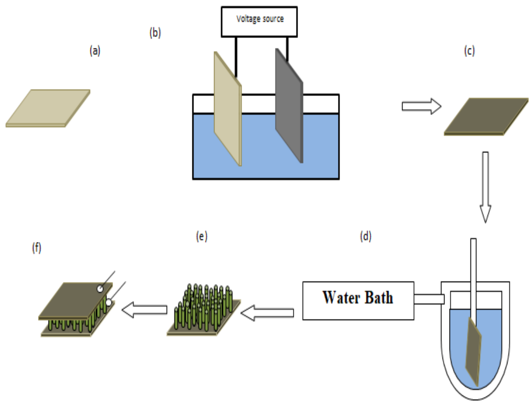


Fig. 1. Schematic diagram of nano-generator fabrication (a) Aluminum substrate (b) Anodization setup using aluminum substrate and lead rod (c) AAO template (d) chemical bath deposition setup (e) ZnO nano-rods grown on AAO substrate (f) nano-generator after deposition of upper layer and metallic contacts.

After the growth of ZnO nano-rods on AAO substrate, a MEMS device is formed by connecting an aluminum substrate on the top of the rods. Metallic contacts are sputtered at the both surfaces of the substrate.

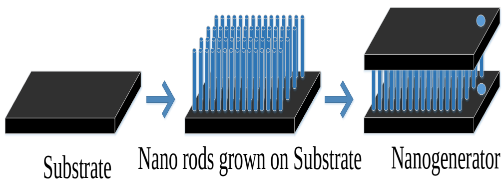


Fig. 2. Process flow steps for MEMS device assembly.

The prepared nano-porous anodic aluminum oxide as well as Zinc-oxide nano-rods was characterized using scanning electron microscopy. For fabrication, testing and simulations, prepared nano-generators are subjected to series and parallel combination as shown in figure 3. Three devices are stacked in series to provide a larger voltage output, three devices are stacked in parallel to provide a larger current output and in the third schematic illustration the device density is considered. A higher device density means a larger number of nano-rods on the same area of the substrate, which will lead to a larger output voltage and current.

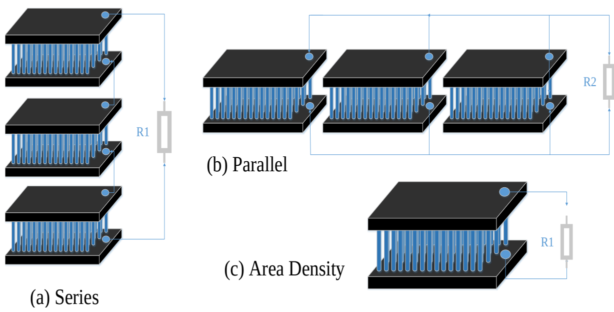


Fig. 3. Schematic illustration of MEMS nanogenerators with (a) Series, (b) Parallel, (c) Device Density.

The prepared nano-generators were characterized using self-designed cam following set-up for current and voltage measurements. The pear shaped cam follower setup was attached with a digital storage oscilloscope model SIGLENT SDS 1052DL. It consists of a frequency control drive and 2 stages. There is a moveable stage and a fix stage. The movable stage is connected with the shaft. The shaft is directly connected to the frequency control drive. The nano-generators are placed in between the movable and fix stage. When the frequency control drive rotates shaft, the movable stage rotates and a force is applied on the nano-generator. The output of the nano-generator is connected with a bridge circuit. The pulsating output voltage and current produce can be seen using the digital storage oscilloscope.

3. Simulation

New control systems are required to design the more complex processes of the devices which have any value between 0 and 1. Fuzzy logic controllers meet the need of such complex systems for which the exact mathematical model is impossible to build. MATLAB Fuzzy Logic model is presented for the MEMS nanogenerator. At the bottom and top surface of nanowires of the nanogenerator, positive and negative potentials are developed which results in a corresponding transient current through the external load. This piezoelectric potential disappears as long the compressive strain is removed by removing the external force, which may be the air flow in this case. This corresponding current flows in the backward direction through the external load by creating an electric pulse in the opposite direction. The nano-generator can be developed easily on a super-flexible Al substrate by integrating in a series and parallel to enhance the output. We have demonstrated the performance by simulating the electrical output of the nanogenerators which are installed on the leaves of a plant.

Fuzzy logic based model for EnergyFLC2 is edited in Fuzzy Inference System (FIS) Editor of MATLAB. There are three input variables Series, Parallel and the Area Density whereas each variable has three membership functions (MFs). Output variable is the Power as illustrated in figure 4.

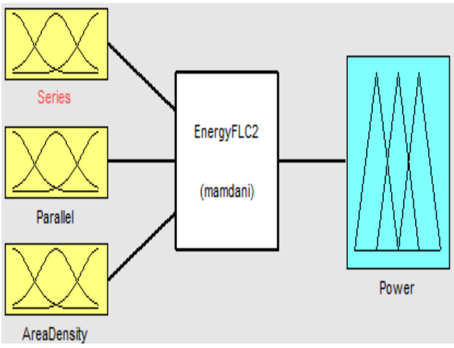


Fig. 4. Fuzzy logic based model. FIS Editor for EnergyFLC2.

For simplicity range for every variable are set same for membership function MF1 for all input variables and similarly the ranges are set for the membership functions MF2 and MF3 for all input variables. The ranges membership functions for the output are set different to minimize the error.

Input variables and their membership functions as SMALL, MEDIUM and LARGE are added. Similarly, Output variable and its membership functions as SMALL, MEDIUM and LARGE are added in Membership Function Editor.

Fuzzy Logic Rules: Mamdani's fuzzy inference technique is used as the implication method (Mamdani and Assilian, 1999). Fuzzy IF-AND-THEN rules are formulated to describe a system’s behavior in the fuzzy controller EnergyFLC2. The fuzzy logic controller follows these rules and decides accordingly for the output power. Three graphs for the output power are obtained from the MATLAB surface viewer. First graph is obtained for the output power against the input variable series and parallel set as shown in figure 5. Second graph is obtained for the output power against the input variable series and area density set as shown in figure 6. Third graph is obtained for the output power against the input variable parallel and area density set as shown in figure 7. These three dimensional graphs show the relationship of the output variable with input variables and also represent the effects on the power for the range of changes in the input variables from 0 to 100.

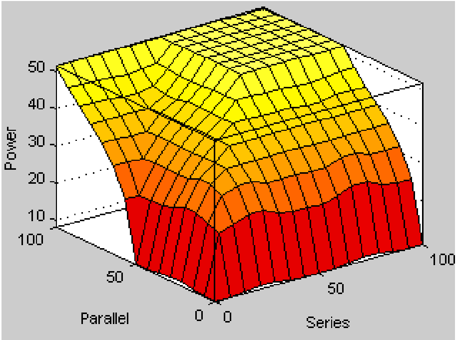


Fig. 5. Surface viewer 3-dimensional graph between input variables "Series", "Parallel" and their effect on output variable "Power".

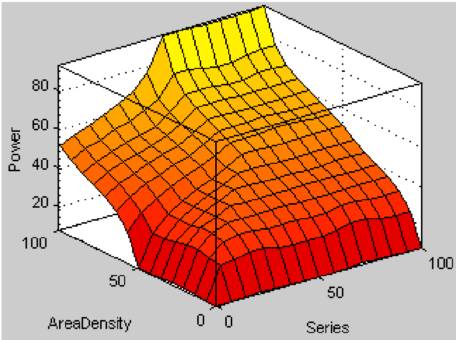


Fig. 6. Surface viewer 3-dimensional graph between input variables "Series", "Area Density" and their effect on output variable "Power".

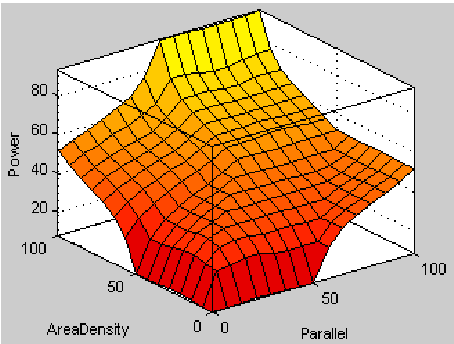


Fig. 7. Surface viewer 3-dimensional graph between input variables "Parallel", "Area Density" and their effect on output variable "Power".

The simulations results are obtained from the MATLAB rule viewer of fuzzy logic controller "EnergyFLC2". The output power value of 56.7 is obtained for the input values of 35.5 for series, 90.3 for parallel and 77.3 for the area density as shown in figure 8. These crisp values for the input and output variables are compared with Mamdani's Model.

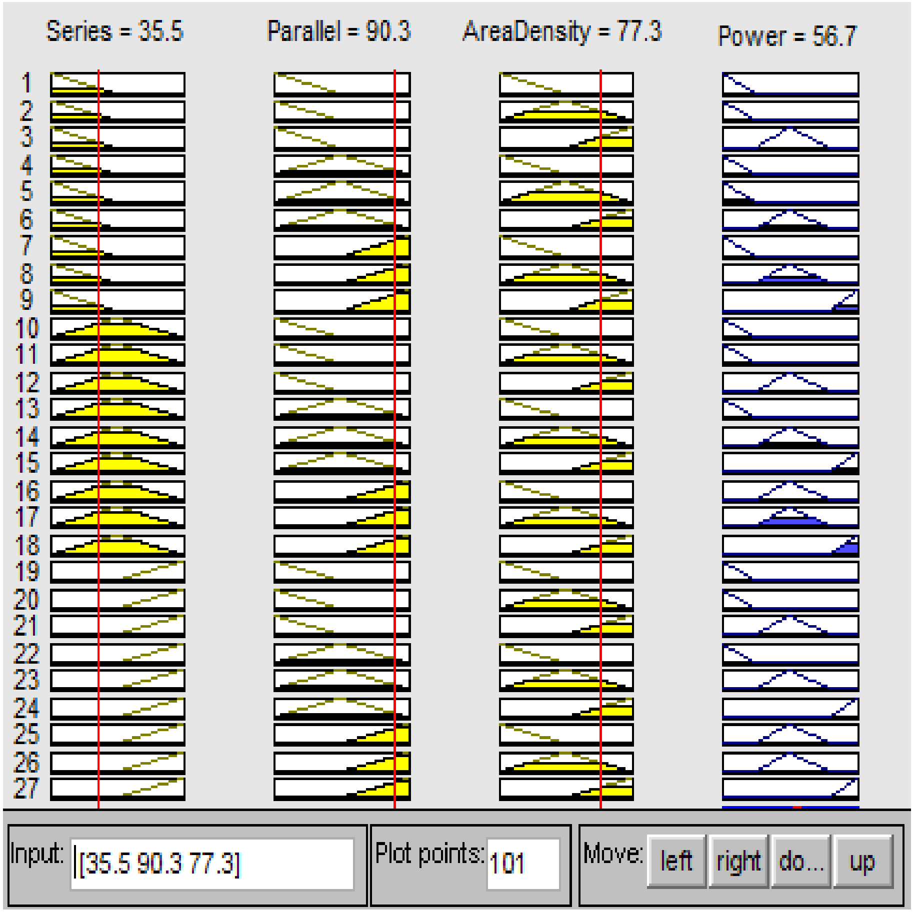
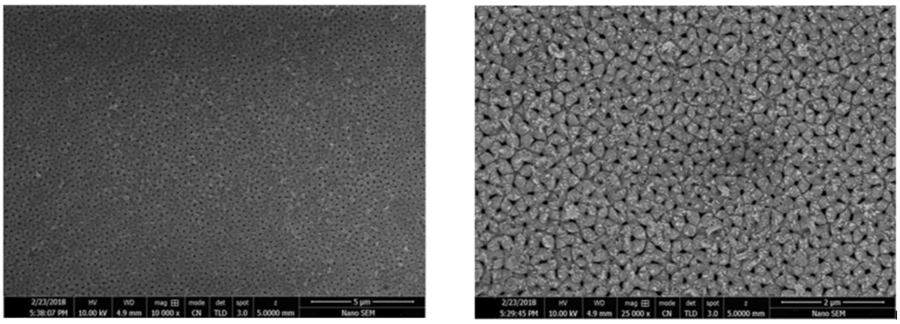


Fig. 8. Matlab simulation results of EnergyFLC2 in the rule viewer.

The crisp inputs values are selected in MATLAB rule viewer as 35.50 for series, 90.30 for parallel and 77.30 for the area density. The 35.50 value lies in the region 1 for the input variable "series", where the membership functions are "SMALL" and "MEDIUM". The 90.30 value lies in the region 2 for the input variable "Parallel", where the membership functions are "MEDIUM" and "LARGE". The 77.30 value lies in the region 2 for the input variable "Area Density", where the membership functions are "MEDIUM" and "LARGE". For these membership function values of a rule the min value is chosen in Mamdani's fuzzy inference technique as the implication method.The comparative analysis for the calculated and the simulated results was carried out. The error is found only 0.24% which is small enough to propose this power scavenging system to draw energy from the movement of plant leaves. Therefore, the movement of leave is source of mechanical energy which can be transformed into electrical energy.

4. Results and discussion

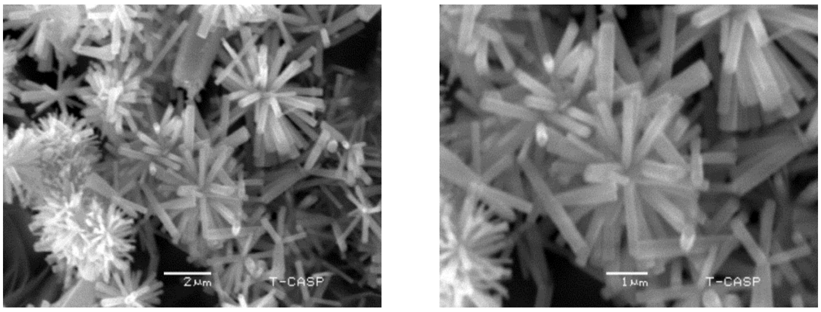
SEM Micrographs image for anodic aluminum oxide membrane are shown in figure. Hexagonal shaped highly regular pores can be seen in the figure. The pores are extremely systematic, even and uniform. The pore diameter was in range of 80-100 nm as shown in figure 9.



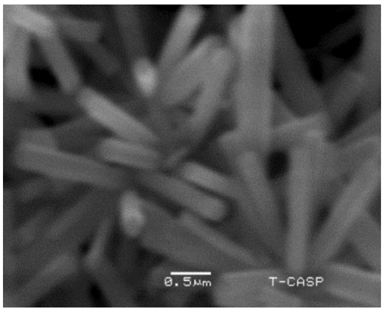
a) *b)*

Fig. 9. SEM Micro-graphs of anodic aluminum oxide template (a) 5 µm (b) 2 µm.

Scanning electron microscopy shows the formation of highly symmetric and aligned nano-rods as shown in figure 10. The length of the fabricated nano-rods was 1-2 µm and diameter of the nano-rods was in range of 200-400 nm.



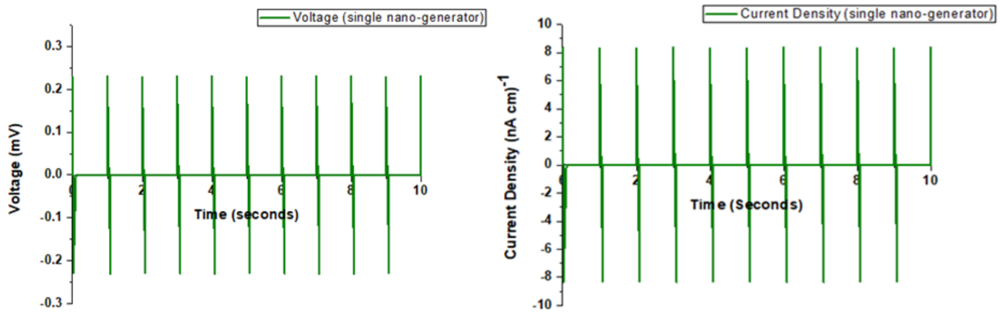
a) *b)*



c)

Fig. 10. SEM Micro-graphs of ZnO nano-rods with a scale of (a) 1 um (b) 2 um.

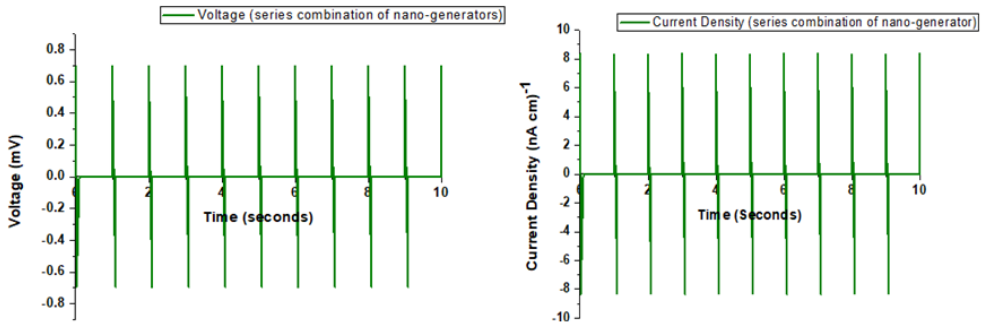
The results of IV characteristic of the prepared nano-generators are shown in Figs. 11, 12 and 13. The IV plots for a single Nano-generator is shown in figure 19. A voltage of 0.229 mV to 0.231 mV and a current density of 8.30 nA cm-2 to 8.33 nA cm-2 is shown on the output of the digital oscilloscope.



a) b)

Fig. 11. Voltage and current density curves of single nano-generator (a) Voltage (b) current density.

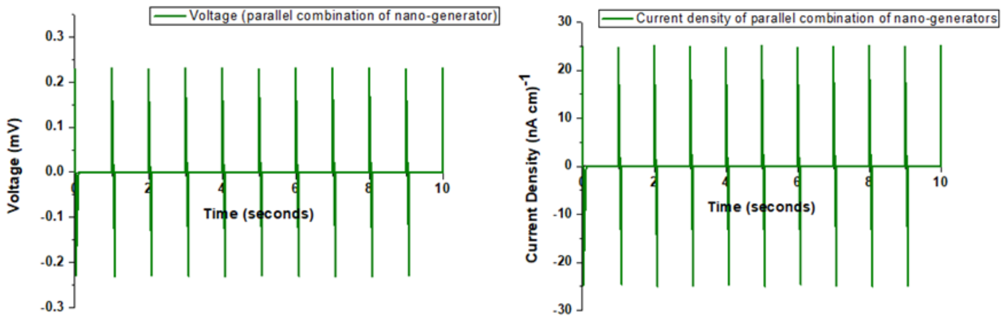
When the nano-generators are connected in series, a voltage of 0.692 mV to 0.695 mV and a current density of 8.30 nA cm-2 to 8.33 nA cm-2 is shown on the output of the digital oscilloscope as shown in figure 19. The increases in voltage are due to the addition of voltages when devices are connected in series.



a) b)

Fig. 12. Voltage and current density curves of series combination of nano-generator (a) Voltage (b) current density.

When the nano-generators are connected in parallel, a voltage of 0.229 mV to 0.231 mV and a current density of 24.5 nA cm-2 to 25 nA cm-2 is shown on the output of the digital oscilloscope as shown in Fig. 20. The increases in voltage are due to the addition of voltages when devices are connected in series.



a) b)

Fig. 13. Voltage and current density curves of parallel combination of nano-generator (a) Voltage (b) current density.

5. Conclusions

Simulation analysis and testing of nano-generators for the output power of the nanogenerator was performed by using the MATLAB fuzzy logic model for its three input variables series, parallel and Area Density with three membership functions for each variable. The integration of nanogenerator devices for energy harvesting into a single power source is necessary to enhance the output power, therefore its simulation is presented with a very small error of 0.24 % which shows its excellence in performance.

Positive and negative potentials are developed at the bottom and top surface of nanowires of the nanogenerator which results in a corresponding transient current through the external load. Moreover, the ZnO nanowires are environment friendly. Practically we are able to fix these devices on the plant leaves to harvest the energy from the movement of leaves because when connected in series and parallel the nano-generator give enhanced current density and voltage. When connected in series, increase in voltage is seen while in parallel combination, increase in current density is observed.

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