SELF-DRIVEN NANO-ANTENNA SENSOR DESIGN BASED ON FRICTION NANO-GENERATOR

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ABSTRACT: In order to design self-driven nano-sensor, a new type of sensor is designed to work continuously by utilizing nanotechnology or nano-effect and energy in the environment. In this paper, WS2 gas sensor based on friction nano-generator is designed and prepared. The results prove that the structure of friction nano-generator as the power supply mode of the light source meets the requirements of WS2 gas sensor for the light source parameters and achieves good photosensitive response performance. It is concluded that the short period pulsed luminescence mode of low power led driven by friction nano-generator structure can be used as the energy supply of self-powered sensor.

KEYWORDS: friction nanogenerator; nano sensor; internet of things; energy

1 INTRODUCTION

Sensors are everywhere today in our life, it provides us a lot of information and convenience. For example, there are sensors that extend our skin’s sense of temperature and humidity, sensors that enhance our body’s sense of speed and displacement, sensors that extend our nose’s ability to detect odors, and sensors that enhance our tongue’s ability to detect biological molecules, etc. With the rapid development of nanotechnology, nano-sensors emerged with higher sensitivity, smaller power consumption, more functional integration, and lower costs [1-2]. The research and application of nano-sensors in the fields of biomedical science, electronic information and environmental protection show great prospects. In addition, with the development of sensor networks, the miniaturization, sustainability, distribution and portability of nano-sensors are required [3]. Traditional active sensors use piezoelectric effect, thermoelectric effect and photoelectric effect, etc to generate electrical signals from the detected object without external power supply, so it is to better optimize the sensor system [4]. We hope to design and build self-driven nano-sensor by combining nano-sensor with micro-nano energy. In this way, the self-driven system can be better constructed to serve the society. Solving the energy problem has always been an important subject of scientific research, and micro-nano energy is the rapid development in recent years using micro-nano technology or micro-nano materials to collect and store energy in the environment [5].

The self-driven system based on piezoelectric nano-generator was first proposed by professor Wang zhonglin's team, the sustainable operation of micro-nano system is realized by converting the mechanical energy in the environment into electrical energy. Professor Wang zhonglin's team invented the triboelectric generator based on the collaboration between triboelectrification and electrostatic induction which can effectively collect mechanical energy and friction. The fundamental theory of nanogenerator can be explained by maxwell's displacement current, it has many advantages such as wide material selection, small volume and low cost, high low-frequency mechanical energy conversion rate and multiple working modes. At present, the research field mainly focuses on three directions: self - drive sensing, micro - nano energy and blue energy, they have broad application prospects in artificial intelligence, internet of things, medical monitoring and environmental protection [6].

In this paper, the friction nano-generator and WS2 gas sensor were used to prepare a self-powered WS2 gas sensor based on the friction nano-generator type. Through frictional electrification and electrostatic induction, the mechanical energy is transformed into electrical energy to light up the low-power led, which provides the light source needed for the gas sensor
work, and opens up a new field of energy conversion and application research.

2 LITERATURE REVIEW

The self-driven system based on piezoelectric nano-generator was first proposed by professor Wang Zhonglin's team, the sustainable operation of micro-nano system is realized by converting the mechanical energy in the environment into electrical energy. Professor Wang Zhonglin's team invented the triboelectric generator based on the collaboration between triboelectrification and electrostatic induction which can effectively collect mechanical energy and friction. The fundamental theory of nanogenerator can be explained by maxwell's displacement current, it has many advantages such as wide material selection, small volume and low cost, high low-frequency mechanical energy conversion rate and multiple working modes. At present, the research field mainly focuses on three directions: self-drive sensing, micro-nano energy and blue energy, they have broad application prospects in artificial intelligence, internet of things, medical monitoring and environmental protection [6].

3 RESEARCH METHODS

Friction nano-generator converts mechanical energy into electrical energy based on the combination of frictional electrification and electrostatic induction, charge transfer is caused by the difference of frictional electrode between two layers of film inside the generator and then potential difference formed by electrostatic induction; When there is an external load, the electrons in the two electrodes on the back side of the film will flow to balance the potential difference, and then use the reciprocating mechanical movement to form current output. Compared with the traditional electromagnetic induction generator, the basic principle of friction nano-generator is not complicated, but it greatly changes the way people treat mechanical energy and opens up a new field of energy conversion and application research. In 1861, British physicist James Maxwell creatively established Maxwell's equations describing the relationship between electric field, magnetic field, charge density and current density, it has laid a solid foundation for the development of electromagnetic theory and related applications. Maxwell's equations consist of four lows:

- Gauss’s law: 
  \[ \nabla \cdot \mathbf{D} = \rho_f \]  

- Gauss law of magnetism: 
  \[ \nabla \cdot \mathbf{B} = 0 \]  

- Faraday’s law of electromagnetic induction: 
  \[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]  

- Maxwell-Ampere’s law: 
  \[ \nabla \times \mathbf{H} = J_f + \frac{\partial \mathbf{D}}{\partial t} \]  

In the above formula, \( \mathbf{D} \) refers to the displacement field \( \rho_f \) refers to the free charge density, \( \mathbf{B} \) is the magnetic field, \( \mathbf{E} \) is the electric field, and \( \mathbf{H} \) is the magnetization field, \( J_f \) is the free current density. In Maxwell-Ampere law, it is shown that magnetic field can be generated by conducting current or displacement current.

- Displacement field: \( \mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} \)  
- Displacement current: \( J_d = \frac{\partial \mathbf{D}}{\partial t} + \frac{\partial \mathbf{P}}{\partial t} \)

As shown in Figure 1, the basic structure of the friction nano-generator includes two layers of different dielectric for frictional electrification (thickness is \( d_1 \) and \( d_2 \), dielectric constant is \( \varepsilon_1 \) and \( \varepsilon_2 \)), and electrodes on the back of the dielectric for electrostatic induction. As shown in Figure 2, when two dielectric come into contact under external mechanical energy drive, charge transfer will occur at the interface where the two dielectric come into contact due to the electrification effect caused by friction; When the two are separated, the electrostatic field established by the friction charge will drive the electrons in the external circuit to flow due to the electrostatic induction effect.
As shown in figure 3, the surface charge density will gradually reach saturation as the two continue to contact and separate [7,8].

The relative voltage difference between the two electrodes and the displacement current density under the condition of short circuit can be expressed as:

Voltage difference: \( V = \sigma_1(z,t)[d_1/\varepsilon_1 + d_2/\varepsilon_2 + z_1\sigma_1(z,t) - \sigma_0]/\varepsilon_0 \) \tag{7}

Current density:

\[ J_D = \frac{\partial \sigma_1(z,t)}{\partial t} = \sigma_c \frac{dx}{dt} \frac{d \varepsilon_0/\varepsilon_1 + d_2/\varepsilon_2}{[d_1/\varepsilon_1+d_2/\varepsilon_2]} \] \tag{8}

In the above equation, \( J_D \) is the surface charge density of the dielectric, \( \sigma_1(z,t) \) is the cumulative density of free moving electrons in the electrode, \( z(t) \) is the time function of the distance between the dielectric.

The charge density on the friction surface is regarded as a common factor for the performance evaluation criteria of different characteristics of the friction nano-generator. However, different friction nano-generator made of the same material will also have different energy conversion efficiency, because the energy conversion efficiency is affected by the structural design of the generator and external trigger conditions. \( z_1 \) and the like proposed the definition of quality factor for this problem based on the established evaluation model. It can comprehensively reflect the influence of structure and materials on the performance of friction nano-generator, and also provides theoretical support for the improvement of friction nano-generator. The structure quality factor and performance quality factor of friction nano-generator are respectively defined as follows:

\[ \text{FOM}_s = \frac{2\pi \varepsilon_0 E_m}{\sigma_0 \Lambda_{x_{\max}}} \] \tag{9}

\[ \text{FOM}_p = \text{FOM}_s \cdot \sigma^2 = \frac{2\pi \varepsilon_0 E_m}{\Lambda_{x_{\max}}} \] \tag{10}

In the above expression, \( \sigma \) is the surface charge density, \( E_m \) is the energy of the maximum possible energy output cycle, \( x_{\max} \) is the maximum displacement and \( \Lambda \) is the area of the friction surface. In addition, the friction nano-generator has the advantage of high voltage output, but also has its own high impedance and low current shortage, how to make full use of its characteristics in the practical application process is a major challenge we face. At present, the solutions adopted by researchers can be divided into two categories: one is to develop a system that can regulate the output of friction nanogenerator or an energy storage device that can match the output; Second, the self-drive system is designed based on the characteristics of the friction nano-generator itself. Dong et al. realized the effective collection and storage of human motion energy by effectively combining the fiber friction nano-generator with the super capacitor; Liu and the like constructed a health monitoring system that can track and detect human heart rate in real time through the friction nano-generator and power management system integrating the villous structure. Chen and the like designed a kind of intelligent keyboard based on the friction nano-generator by using the contact effect between fingers and keys, directly using and analyzing the generated electrical signals, which can effectively record and identify the characteristics of the keys struck by fingers; Pu and the like demonstrated a highly sensitive friction nano-sensor, which can be used to build a human-computer interaction system by blinking as a control command, and can be used for self-driven smart wear and intelligent control; Li and the like successfully removed heavy metal ions in waste water by using water-driven friction nano-generator and constructed a self-driven electrochemical system; M. Fernandez and the like successfully realized the drive of ion source in the high-sensitivity mass spectrometer by using the high-voltage output of the fixed charge amount of the friction nano-generator, which provided a new idea for the development of the controllable self-drive system of the friction nano-generator [9,10].

4 RESULTS ANALYSIS

4.1 Sensor gas sensitivity test

Firstly, clean the electrode surface with anhydrous ethanol, cut the gold wire to 2-3 cm, and glue the gold wire and the cross-finger electrode pad with gold paste. Then put the prepared fork finger electrode into the orange tube and put it into the tube furnace for firing [11-15]. Start the tubular furnace and set the parameters, the rate of temperature rise is 3°C/min, keep 150°C for 1h, and then 800°C stays 10 minutes, the firing was completed at a speed of 30C/min at room temperature finally. After rubbing the fired electrode with alcohol cotton ball, seal it in dry place and keep it for later use.
Put appropriate amount of ground WS\textsubscript{2} powder into the ethanol solution to form WS\textsubscript{2} film, immerse the electrodes in an ethanol solution, keep the gold line above water at all times, pull out the electrode at an appropriate angle to cover the electrode surface with a layer of WS\textsubscript{2} film evenly, put the electrode horizontally into the crucible and move it to the drying oven for drying finally [16]. Put it in a dry place and keep it sealed for later use. Prepare the experimental lamps of different bands for the experiment, debug the friction nano-generator type equipment, connect the electrode of the friction nano-generator type with the experimental lamp through a wire, and prepare for the test.

The experiment process: first solder the interdigital socket on the breadboard and then place the WS\textsubscript{2} sensor into the static gas distribution system. Fix the two gold wires of the interdigital electrode to the socket, and at the same time, turn on the static box heater, computer, Agilent universal meter and test plug-in, connect the universal meter and the interdigital electrode socket, and finally set the test mode to the resistance test mode, the parameters are set as: test time 2h (response and recovery time), test interval is 4s. At the beginning of the test, the LED lamps of each band are respectively soldered on the breadboard firstly, and the light source is aligned on the surface of the sensor. When the temperature, relative humidity and resistance of the universal meter in the static box are stable, record the data in real time, after 5 minutes, start the friction nano-generator structure lighting experiment lamp and monitor the resistance value change in real time. After the value was stabilized, turn off the LED lamp [17]. During the test, the static box should be shielded with a special shade cloth to ensure that the test box is in a matt state and remains completely closed to prevent the influence of external light source and environmental changes on the sensor’s photosensitivity test.

The gas-sensing performance test structure of the WS\textsubscript{2} sensor under photocatalytic is the same as that of the WS\textsubscript{2} sensor as shown in Figure 4.

Table 1. Comparison of target gas concentration (ppm) and required solution volume (μL)

<table>
<thead>
<tr>
<th>Gas concentration</th>
<th>5</th>
<th>10</th>
<th>30</th>
<th>50</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formaldehyde</td>
<td>0.83</td>
<td>1.65</td>
<td>4.94</td>
<td>8.23</td>
<td>13.18</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.45</td>
<td>0.91</td>
<td>2.73</td>
<td>4.54</td>
<td>7.27</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.66</td>
<td>1.31</td>
<td>3.91</td>
<td>6.53</td>
<td>10.44</td>
</tr>
<tr>
<td>Acetone</td>
<td>0.83</td>
<td>1.65</td>
<td>4.96</td>
<td>8.27</td>
<td>13.23</td>
</tr>
<tr>
<td>Ammonia</td>
<td>0.84</td>
<td>1.67</td>
<td>5.01</td>
<td>8.35</td>
<td>13.37</td>
</tr>
</tbody>
</table>

Figure 4. Gas Sensing Performance Test Platform for WS\textsubscript{2} Sensor
The study found that the WS\textsubscript{2} sensor has the best response to ammonia gas for formaldehyde, acetone, benzene, ammonia, acetone and other gases with a gas concentration of 10 ppm. Other gases are not responding. This exemplifies the excellent selectivity of the WS\textsubscript{2} sensor to ammonia, which can remove the effects of aldehydes and alcohols from the surrounding environment. At the same time, a large number of experiments on the grinding time and working temperature of sensitive materials of WS\textsubscript{2} sensor show that the material grinding time of WS\textsubscript{2} sensor is 15 min, and the sensor shows the highest gas-sensitive response recovery performance. Therefore, the gas-sensitive characteristics of the self-powered WS\textsubscript{2} gas sensor based on the friction nano-generator type under the photocatalysis study selected NH\textsubscript{3} as the target gas, the grinding time of the WS\textsubscript{2} material was 15 min, the gas concentration was 10 ppm, and the test temperature was low temperature. The test procedure is similar to the sensor's photo-sensitivity test. When the test platform is in normal operation, in order to test the gas-sensing characteristics under photocatalytic conditions, it is necessary to use a small amount of syringe to take a certain amount of ammonia water into the heater in the static box to evaporate, ensure that the static test chamber is evenly filled with the target gas to be measured. Table 1 shows the gas concentration and the required corresponding liquid volume in the gas sensitivity test. The test environment is shown in Table 2.

<table>
<thead>
<tr>
<th>parameter name</th>
<th>parameter settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature</td>
<td>low temperature</td>
</tr>
<tr>
<td>humidity</td>
<td>40%</td>
</tr>
<tr>
<td>Friction nano-generator contact area</td>
<td>5*5 (cm)</td>
</tr>
<tr>
<td>Friction nano-generator contact frequency</td>
<td>100Hz</td>
</tr>
<tr>
<td>Friction nano-generator contact distance</td>
<td>10mm</td>
</tr>
</tbody>
</table>

4.2 Sensor photometric test

The inspiration for this experiment comes from the concept of a friction nano-generator, which combines a frictional nano-generator with a WS\textsubscript{2} gas sensor, it prepares a self-powered WS\textsubscript{2} gas sensor based on friction nano-generator type, which uses the friction nano-generator structure analog sensor to convert the energy of the surrounding "idle" mechanical energy into electric energy to illuminate the low-power LED, and provide the required light source for gas sensor operation. The experimental process is shown in Figure 5.

Figure 5. Photosensitive performance test platform for WS\textsubscript{2} sensor
The photosensitive characteristics of self-powered WS$_2$ gas sensor based on friction nanogenerator were tested and verified during the research. At the same time, the gas-sensing response of gas sensor was tested under photocatalytic conditions, the role of low-power LED illuminating under the action of a friction nano-generator structure in enhancing the gas-sensing response characteristics of WS$_2$ gas sensors is discussed in detail. The WS$_2$ gas sensor based on the friction nano-generator has excellent gas-sensing response characteristics under light catalysis, and the response amplitude is also greatly enhanced. Especially under the illumination of 365nm light source, WS$_2$ sensor shows excellent gas sensitivity response sensitivity, and it also shows very good 850nm and 940nm light source in WS$_2$ photosensitive performance test. In the test of NH$_3$ gas under the photocatalysis of WS$_2$ sensor, it also showed very good gas-sensitive response.

### Table 3. Comparison of gas sensitivity of WS$_2$ sensor under photocatalysis

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>365</th>
<th>562.5–565</th>
<th>591–594</th>
<th>850</th>
<th>940</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No photochemical effect</strong></td>
<td>365</td>
<td>330</td>
<td>344</td>
<td>348</td>
<td>264</td>
</tr>
<tr>
<td><strong>Response time (s)</strong></td>
<td>21.07</td>
<td>20.11</td>
<td>22.27</td>
<td>27.53</td>
<td>20.98</td>
</tr>
<tr>
<td><strong>Recovery Time (min)</strong></td>
<td>84.8</td>
<td>137.2</td>
<td>111.1</td>
<td>121</td>
<td>123.5</td>
</tr>
</tbody>
</table>

The comparison of the gas-sensing response performance of the WS$_2$ gas sensor under photocatalysis as shown in Table 3 confirms this conclusion. It can be clearly seen from the table that the WS$_2$ gas sensor based on the friction nanogenerator has better response sensitivity and gas-responsive recovery characteristic under the catalysis of the light source than the non-light source. Especially at 365nm, 940nm, 850nm, the light source exhibits a higher sensitivity to gas sensitivity than in the absence of light, while still maintaining very good gas-sensitive response recovery characteristics. The experimental results of the conventional power supply mode are in agreement.

### 5 CONCLUSION

Through the research of this paper, we designed and prepared a self-powered WS$_2$ gas sensor based on friction nano-generator. Research shows that the self-powered gas sensor based on friction nanogenerator has a good response to its sensitive parameters. For the current research of friction nano-generator type, compared with the traditional sensor, we can improve the sensor performance by modifying the surface of the friction material in the sensitive material, which is of great significance for the wide application of this new type of sensor. In terms of theoretical research, the research on sensitive parameters such as temperature, humidity, pressure, gas flow rate and low concentration of sensitive gas is not comprehensive; In practical applications, the miniaturization, environmental adaptability, stability and aging degree of the friction nano-generator self-powered sensor still need to be greatly optimized and improved. Therefore, the future research of friction nanogenerator self-powered systems requires us to make great efforts in sensitive materials, theoretical research and practical applications, Synthesize high-quality sensitive materials, improve theoretical research, optimize device structure to put into use as soon as possible, and contribute to the promotion of stable and rapid development of society and improve the quality of human life.

### 6 REFERENCES

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