Enhancing UV photosensitivity of a ZnO UV nanosensor using electrical stimulation at megahertz frequency*

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We report a novel technique to enhance the ultraviolet (UV) photosensitivity of a ZnO nanosensor with ZnO nanowires bridged on micromachined metallic electrodes. The experimental results reveal that the photoconductivity and the time response of the ZnO nanowire sensor with either Schottky or Ohmic contacts are significantly improved by electrifying the nanowire sensors using an alternating current at the frequency of megahertz. An integrated UV sensor incorporating ZnO nanowires with a constant current mode driving circuit is developed, which demonstrates promising sensitivity and time response to UV illumination with a low power consumption.

Keywords: UV nanosensor, photosensitivity, ZnO nanowires, electrical stimulation

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1. Introduction

ZnO nanowires (NWs) have attracted considerable attention as a promising material with extensive application in ultraviolet (UV) light emitting devices,[1–5] biosensors,[6,7] and UV sensors.[8–23] Due to its exciton binding energy of 60 meV, wide band gap (3.37 eV), and large surface-to-volume ratio, ZnO NW is especially promising for optical applications, such as UV light detection. However, because of some drawbacks, such as the presence of point defects, the confined dimensionality, and the persistent photoconductivity,[13–15] the UV sensitivity of a ZnO nanowire sensor is limited, unstable, and consequently it has hardly been applied in practical photoconductive devices. Much effort has been devoted to improving the sensitivity of the UV response of ZnO NW sensors.[12,17–19,24–26] The works can be categorized into Schottky contact improving and surface functionalizing. A Schottky barrier has been proposed to be applied in the ZnO UV nanosensor for realizing a relatively noiseless and gigantic photocurrent, because the Schottky type detector presents a very low dark current due to the high material resistivity and Schottky barrier height which attribute to the big gain under the UV illumination.[17–19,24,25] Functionalizing the surfaces of the ZnO NWs using different kinds of polymers with different UV absorption abilities and wavelengths to improve the UV responses has been reported.[12,19,26] However, those methods reported are still complicated.

In this paper, we propose a novel and simple technique to enhance the photoconductivity and time response of ZnO UV sensors by utilizing an electrical stimulation with an alternating current at the frequency of megahertz generated by a signal generator (Tektronix AFG3252) through the nanosensors for several minutes, which is defined as the electrical treatment method in this paper. We demonstrate that the UV photoconductivity of ZnO NW sensors with either Schottky or Ohmic contacts can be enhanced up to 40–100 times and the time response can be speeded up to be 2–3 seconds by the proposed electrical treatment. The electrical treatment method can improve the electric conductance of ZnO mainly through changing the carrier mobility and concentration. Based on the proposed technique, an integrated UV sensor incorporating a ZnO NW sensing element with a constant current mode driving circuit is developed, which demonstrates an output voltage of 2 V and a response time of 2.5 s in response to the UV illumination with the intensity of 96.4 mW/cm^2.

2. Experiments

The ZnO UV nanosensor was constructed using a coplanar finger electrode-pair structure with ZnO NWs assembled on the electrodes. The fabrication of the micro electrode structure started with the preparation of a phosphorous-doped silicon substrate covered by a 40 nm SiO_2 layer formed by thermal oxidation. Afterwards, a 100 nm Cr/Au film was sputtered onto the SiO_2 layer. The Cr/Au layer was masked and etched to form the electrode pairs. The ZnO NWs were synthesized by using the conventional chemical vapor deposition (CVD) technique.[6,27] The ZnO NWs, about 5–100 μm in length and 10–500 nm in diameter, were then assembled onto the metallic electrode pairs by using the dielectrophoresis technique.[27] The scanning electron microscope (SEM) image of the fabricated nanosensor with assembled ZnO NWs is shown in Fig. 1.

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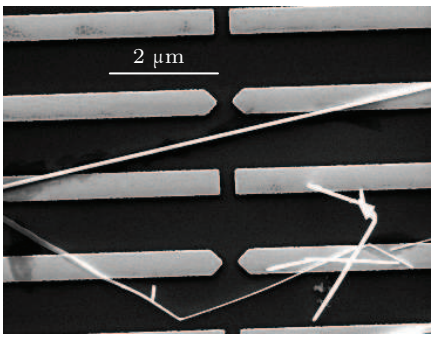


Fig. 1. SEM image of the assembled ZnO NWs on electrodes.

After the fabrication, a post electrical treatment was applied to the prepared ZnO NW sensor. The electrical treatment was electrifying the nanosensor using an alternating current (ac) generated by a signal generator (Tektronix AFG3252) for about 3–5 min. The peak to peak voltage (V_{pp}) of the ac was set to 1 V, and the frequency ranged from 0.5 MHz to 100 MHz. After the above electrical treatment, the conductance and the photoconductivity of the ZnO nanosensor were measured using a pico-amperometer (Keithley, Source Measure Unit 237) at room temperature in ambient air and a UV source (OSRAM halogen lamp 64610 12 V 50 W) specified with wavelengths below 400 nm. The light intensity of the UV light source was adjustable with seven steps, which had been calibrated using a light power meter (Thorlabs, PM121D), and we used some of those steps with different light intensities for the experiments. Specifically, the *I*–*V* characteristics of the nanosensor were tested using the pico-amperometer by setting different voltages incremented in discrete steps from the start voltage to the stop voltage onto the micro electrodes with the assembled ZnO NWs while testing and recording the currents through the NWs at each step. The time response (or UV response) of the ZnO NW sensor was tested in the time-resolved measurement of photocurrents using the pico-amperometer by setting a constant bias voltage onto the electrodes of the NW sensor while testing the current through the NW sensor during the period of instantly turning on and off the UV light. The UV response of the integrated ZnO UV sensor with a constant current circuitry was tested by directly testing the output voltage of the sensor circuit using an oscillograph (Tektronix TDS 2024B) under a constant current during the period of instantly turning on the UV light.

3. Results and discussion

The *I*–*V* characteristics of the ZnO nanosensor illuminated with UV light of various intensities from 0 to 108.5 mW/cm^2 are shown in Fig. 2. The photocurrents of the nanosensor before and after the electrical treatments at different frequencies are compared.

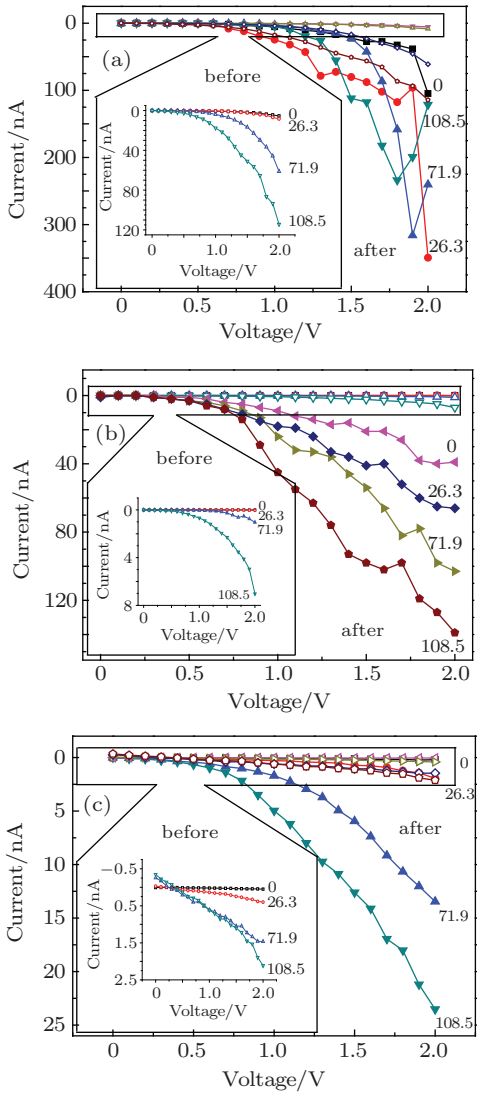


Fig. 2. (color online) The *I*–*V* characteristics of the ZnO NW sensor illuminated with UV light of various intensities from 0 to 108.5 mW/cm^2 at room temperature before (inserts) and after the electrical treatments with the ac voltage of 1 V and frequencies of (a) 0.5 MHz, (b) 1 MHz, and (c) 100 MHz.

It can be seen from Fig. 2(a) that the electrical stimulation at the frequency of 0.5 MHz results in increasing the electric conductance of the nanosensor, but debasing the photoresponse to the UV light. When the frequency of the electrical stimulation is increased to 1 MHz, as shown in Fig. 2(b), both electric conductance and UV response of the ZnO nanosensor are greatly enhanced, and the photocurrent of the nanosensor is enhanced up to around 40 times higher than that before the treatment. When the frequency is up to 100 MHz, the electric conductance and the photocurrent of the sensor are enhanced but less than 10 times higher than those before the treatment, as shown in Fig. 2(c). These test results are reproducible. The results indicate that the photosensitivity of the ZnO NW sensor

to the UV light can be greatly enhanced by using an electrical stimulation at a frequency of around 1 MHz.

We further investigate the effect of the electrical treatment on the time response of the ZnO NW sensor to the UV light. Figure 3 shows the time-resolved measurements of the UV-response of the sensors at a bias voltage of 3 V illuminated by the UV light of intensity 95.4 mW/cm^2.

It can be seen from Figs. 3(a-1) and 3(a-2) that the UV response of the ZnO NW sensor is debased by the treatment at the frequency of 0.5 MHz, which is consistent with the experimental results shown in Fig. 2(a). When the treatment frequency is up to 1 MHz, the UV photocurrent of the nanosensor is enhanced up to 800 nA (about 100 times higher than that before the treatment), as shown in Figs. 3(b-1) and 3(b-2). When the frequency is up to 100 MHz, as shown in Figs. 3(c-1) and 3(c-2), the UV response after the treatment is improved but less than 10 times higher compared with that before treatment, which is consistent with the results shown in Fig. 2(c). These experimental results of the time responses are reproducible. The results indicate that the time response of the ZnO NW sensor to the UV light can be also improved by applying an ac at a frequency of around 1 MHz.

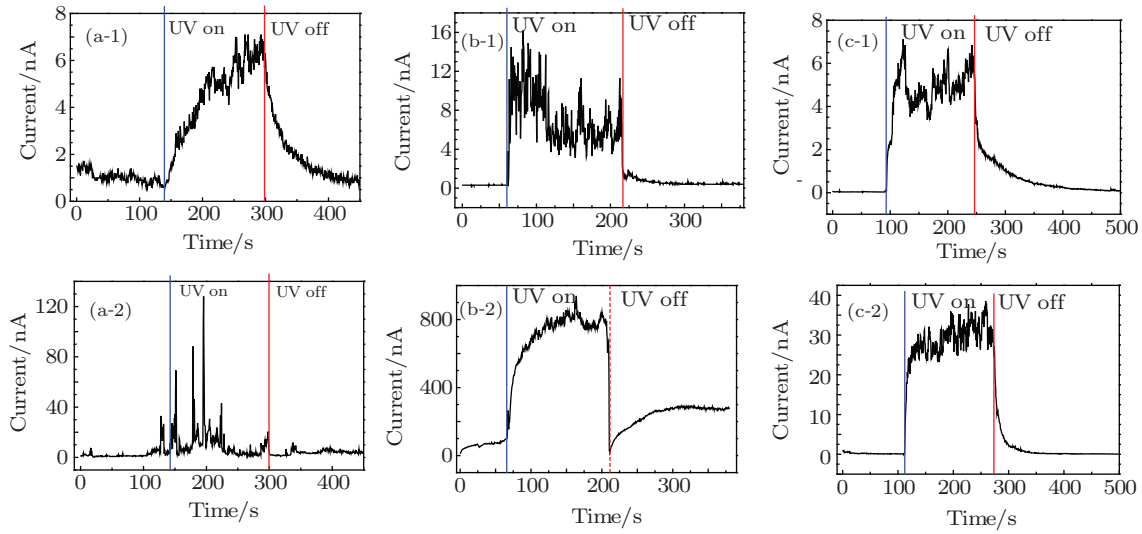


Fig. 3. (color online) Time-resolved measurements of photo response of the ZnO NW sensor at a bias voltage of 3 V illuminated by the UV light of intensity 95.4 mW/cm^2 before (a-1, b-1, c-1) and after (a-2, b-2, c-2) the electrical treatments using ac voltage of 1 V at frequencies of (a-2) 0.5 MHz, (b-2) 1 MHz, and (c-2) 100 MHz.

To understand the above behaviors, we consider the electrical transport of the semiconductor (ZnO nanowires). It is well known that the electric conductance of a semiconductor depends on the carrier (electron and hole) concentration and mobility.[25] Excess carriers may exist in addition to the thermal-equilibrium ones if an external excitation is applied to the semiconductor.[28] When electrifying the ZnO NW sensor using ac, the electric transport is probably influenced by the external electrical stimulation, that is, the carrier concentration and mobility may be increased, which induces the improvement of the conductance of ZnO NWs, as shown in Figs. 2 and 3. For a specific nanosensor with a semiconductor, it probably has its own eigenfrequency for the electric transport which depends on the temperature, the semiconductor crystal, etc. Therefore, when the frequency of the external stimulation approaches the eigenfrequency of the nanosensor (assumed to be around MHz), the accretion of the electric transport probably reaches the maximum, and thus a gigantic enhancement in the conductance and photoconductivity occurs. The enhancements of photoconductivity and time response to the UV light may also contribute to the effect of the electrical stimulation on dispelling the surface particles that shield the photoconduction of the NWs due to the surface charge of ZnO NWs.

We also demonstrate the effects of the electrical treatment on Schottky (Fig. 4) and Ohmic UV devices (Fig. 5). Time-resolved measurements of photocurrents of device A (Schottky device) before and after the electrical treatment were conducted, and the results are shown in Fig. 4.

Time-resolved measurements of photocurrents of device B (Ohmic device) before and after the electrical treatment are shown in Fig. 5. The results indicate that the electrical stimulation can effectively enhance the photoconductivity and time response of both devices. The decay time of both Schottky and Ohmic devices is shortened to less than 3 s, which was reported by the others to be more than hundreds of seconds for Ohmic UV sensors.[16,17]

From the experimental results of Schottky and Ohmic devices shown in Figs. 4 and 5, we observe a similar strange phenomenon when the UV light is off: a sharp drop followed by a gradual increase in the recovery process. Suppose that there are two steady states for the devices: a photo-conducting state when the UV light is on and a leakage current state when there

is no UV light. The leakage current state needs an electric field potential which is formed by spatial charge in the device that needs a short period of time to build up. Before that, there is little current that can flow, inducing the deep drop of the current. More in-depth research is still required for clarifying these matters.

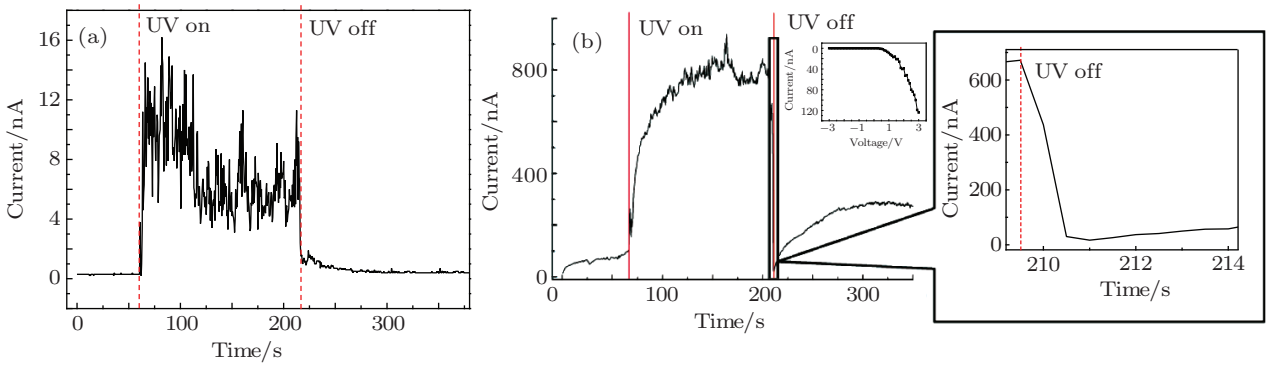


Fig. 4. (color online) UV responses of device A (Schottky device) illuminated by UV light of intensity 95.4 mW/cm^2 under 3 V bias voltage at room temperature (a) before and (b) after the electrical treatment. Insert is the nonlinear *I*–*V* characteristics of the ZnO NW sensor in the dark, indicating that it is a Schottky device. The enlarged curve shows that the decay time of the device is shortened to less than 2 s.

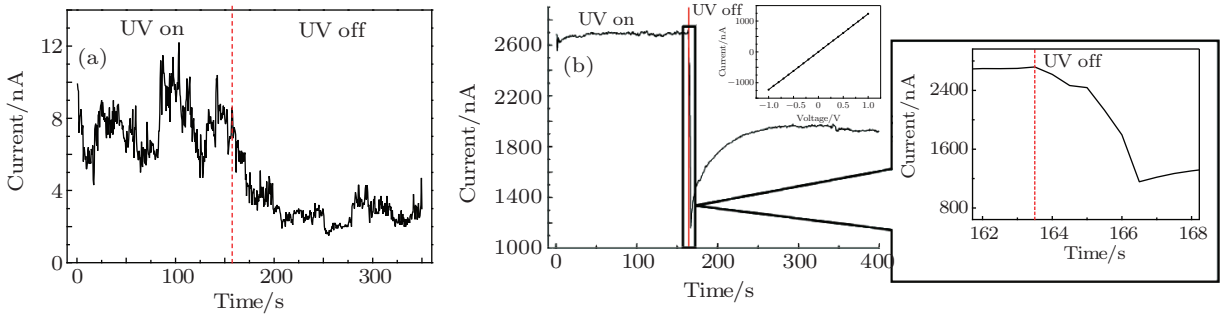


Fig. 5. (color online) UV responses of device B (Ohmic device) illuminated by UV light of intensity 95.4 mW/cm^2 under 3 V bias voltage at room temperature (a) before and (b) after the enhancing treatment. Insert is the *I*–*V* characteristics of the ZnO NW sensor in the dark, indicating that it is an Ohmic device. The enlarged curve shows the decay time of the device is shortened to less than 3 s.

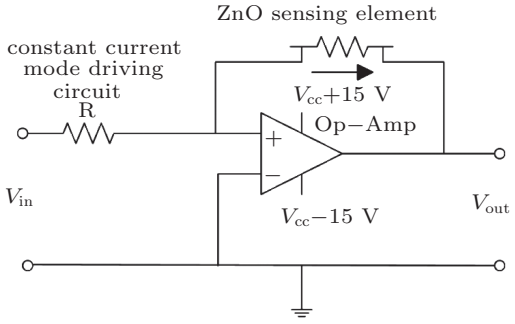


Fig. 6. Schematic diagram of a constant current mode circuit for the integrated UV sensor.

The ZnO NW sensor is further connected into a constant current mode driving circuit to form the integrated UV sensor illustrated in Fig. 6.

The ZnO NW sensing element serves as a feedback resistor of the operational amplifier. The conductance change of the ZnO sensing element responding to the UV illumination results in the output voltage change of the operational amplifier. The measurement result of the UV response for the integrated ZnO UV sensor under a constant current of 58 nA is shown in Fig. 7, which demonstrates a time response of 2.5 s and an output voltage of 2 V upon turning on a UV light of intensity 96.4 mW/cm^2. The power consumption of the UV sensor is about 0.3 mW.

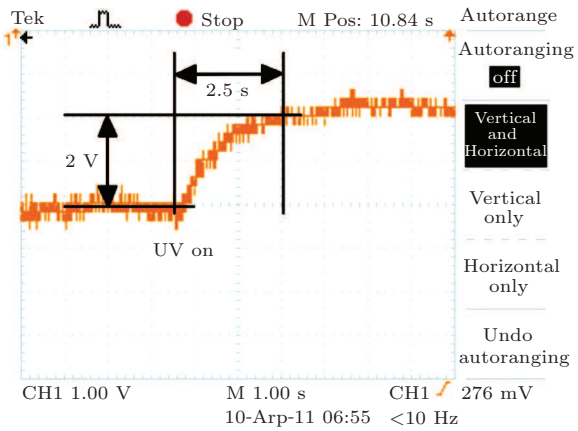


Fig. 7. (color online) UV response of the integrated ZnO UV sensor with the constant current circuit.

4. Conclusion

We demonstrate an approach to enhance the photosensitivity of a ZnO UV nanosensor by applying an ac electrical stimulation at the frequency of megahertz on the ZnO NW

sensor. Experimental studies reveal that this electrical treatment is effective for both Schottky and Ohmic UV detectors. The study demonstrates a promising technique for improving the performances of UV sensors with ZnO nanowires.

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