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Single ZnO nanowire–PZT optothermal field effect transistors

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Abstract
A new type of pyroelectric field effect transistor based on a composite consisting of single zinc oxide nanowire and lead zirconate titanate (ZnO NW–PZT) has been developed. Under infrared (IR) laser illumination, the transconductance of the ZnO NW can be modulated by optothermal gating. The drain current can be increased or decreased by IR illumination depending on the polarization orientation of the $Pb(Zr_{0.3}Ti_{0.7})O_3$ (PZT) substrate. Furthermore, by combining the photocurrent behavior in the UV range and the optothermal gating effect in the IR range, the wide spectrum of response of current by light offers a variety of opportunities for nanoscale optoelectronic devices.

(Some figures may appear in colour only in the online journal)

1. Introduction

Recent studies have shown that one-dimensional nanowires (NWs) are important for the development of nanoscale transistors [1–4]. For example, Marcus *et al* demonstrated that carbon nanotube transistors could be gated by light through the photovoltaic voltage generated in the silicon substrate [1]. Liu *et al* investigated a piezoelectric gated hybrid field effect transistor that consists of carbon nanotubes at the bottom and crossed ZnO fine wires on the top with an insulating layer in between [2]. Recently, Omari *et al* proposed the photothermovoltaic effect in carbon nanotube films due to photogenerated heat flow [3]. Meanwhile ZnO NWs have several favorable properties such as a wide direct band gap (3.37 eV at room temperature), large exciton binding energy (60 meV) and piezoelectricity. They have been applied in various scientific fields, such as field effect transistors (FETs), light-emitting diodes (LEDs), nanogenerators and photodetectors [4–9]. In particular, Liao *et al* have reported the fabrication and characterization of ZnO NW transistors based on ferroelectric $Pb(Zr_{0.3}Ti_{0.7})O_3$ (PZT) thin film as the gate dielectric and the charge storage medium. Conducting and non-conducting states of the ZnO/PZT transistors can be obtained by applying positive and negative gate voltage, respectively, resulting in switchable remnant polarization of PZT [4]. However, it is known that in addition to piezoelectricity, PZT is also pyroelectric with changing polarization when temperature is varied [10]. As a result, the bound charge density on the PZT surface can change with temperature, thus generating an induced current in an external circuit [11–13]. Combining the pyroelectricity and the high dielectric constant of PZT, it is possible to create a high-performance FET that can be gated with non-electric means.

In this study, we report a single ZnO NW FET based on PZT substrate whose drain current can be modulated by a novel optothermal gating mechanism where PZT served as the gate dielectric and ZnO NW as the drain conductor. An infrared (IR) laser of 1064 nm wavelength was used as a light source. It was shown that the drain current can be modulated by the incidence of the IR light via the pyroelectric effect of the PZT. The drain current could be increased or decreased

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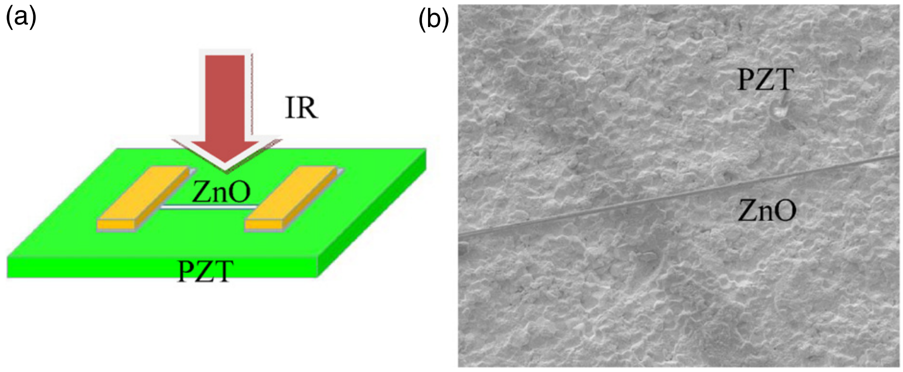

Figure 1. ZnO nanowire based on PZT transistor: (a) a schematic illustration of device configuration under IR illumination; (b) SEM image of the device showing a single ZnO NW bridging two patches of PZT.

by the incident IR light via orienting the polarization of the PZT layer. Furthermore, we also show the drain current of a ZnO NW–PZT transistor can be controlled by UV light to generate photocurrent. By combining the photocurrent feature and optothermal gating effect, the wide range of response to light covering UV and IR radiation can lead to new nanoscale optoelectronic devices that are suitable for remote or wireless applications.

2. Experimental details

To fabricate longer ZnO NWs, the ZnO NWs used in this study were grown via hydrothermal (HT) and vapor–solid (VS) methods. A Zn seed layer was deposited on one half side of a sapphire substrate by using the sputtering system (JFC-1600, JEOL, Tokyo, Japan). The thickness of the seed layer was about 150 nm. We then used the hydrothermal (HT) method to grow ZnO nanowires on the Zn-coated sapphire substrate by mixing 0.05 M zinc nitrate hexahydrate $Zn(NO_3)_2{\cdot}D6H_2O$ and 0.05 M hexamethylenetetramine $C_6H_{12}N_4$ (HMT) aqueous solution at 90 °C for 4 h. After that, the as-prepared sample was grown by using the vapor–solid (VS) method. The HT-ZnO nanowire/sapphire substrate was put on the top of an alumina boat which was loaded with high purity Zn powder (99.99 %). After placing the alumina boat at the center of a tube furnace, the reaction chamber was evacuated. Argon and oxygen gases with a high purity of 99.9% were then introduced into the reaction chamber at a flow rate of 200 sccm and 5 sccm, respectively, and a total pressure was kept at 10 Torr. In addition, the growth temperature was maintained at 620 °C with 1 h dwell time. After the growth of ZnO NWs, the substrate was then sonicated in deionized (DI) water to release the individual nanowires. The diameter of the ZnO NWs ranged from 0.8 to 10 μm and the one used for this study was 1.5 μm. The solution containing ZnO NWs is then dropped on the surface of PZT (T105-A4E-602, Piezo Systems, Boston, MA) substrate and the SiO_2 wafer, respectively. The thickness of the PZT layer was 127 μm and the polarization had been poled to orient in the direction perpendicular to the surface. Finally, a mesh 12 μm wide was used to define the source–drain contact pattern and the Ti/Au (30/300 nm) deposition was then carried out to create the source and drain electrodes of the single ZnO NW–PZT and ZnO NW-SiO_2 transistors.

3. Results and discussion

Figures 1(a) and (b) show the schematics of the device configuration and an SEM image of a single ZnO NW–PZT field effect transistor, respectively. We have fabricated two kinds of ZnO NW–PZT FET: one with the polarization of the PZT pointing down and the other with the polarization of the PZT pointing up. By inserting light blockers periodically, the behavior of drain current of a single ZnO NW–PZT FET with a down polarization and that of a single ZnO NW–PZT FET with an up polarization under 1064 nm IR illumination as a function of time are shown in figures 2(a) and (b), respectively. As can be seen in figure 2(a), the drain current of the FET with a down polarization increased when the light blocker was removed and decreased when the blocker was inserted. In contrast, the drain current of the FET with an up polarization shows the opposite results. The drain current of the FET with an up polarization decreased when the IR laser was introduced and increased when the light was blocked. The periods of insertion and removal intervals of blockers were 30 s and 20 s in figures 2(a) and (b), respectively. We also performed a similar study for a single ZnO NW-SiO_2 device. As can be seen from figure 2(a), there was very little response in the drain current under IR illumination when the blocker was removed or inserted. This clearly demonstrates that the behavior seen in figures 2(a) and (b) is due to the presence of PZT whose polarization plays a key role in the observed behavior. In addition, figure 2(b) shows the temperature behavior of the system and the temperature change is directly correlated with the change in drain current.

To understand the above behaviors, we notice that the operation mechanism of the ZnO NW–PZT transistor works on different modes depending on the direction of polarization of PZT substrates. Liao *et al* proposed the ZnO–PZT FET works in an accumulation/depletion mode, which can be controlled by the gate potential [4]. In our experiment, the gating effect is controlled by the incident light. It is known that ZnO is an n-type semiconductor. The presence

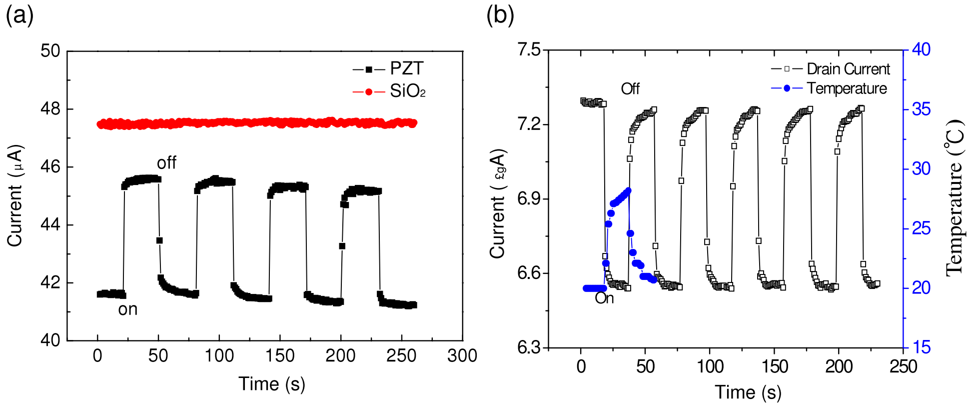

Figure 2. The drain current as a function of time modulated by IR laser of 200 and 250 mW with a light on or off corresponding to (a) downward and (b) upward polarization of the PZT substrate. The periods of the oscillation are 30 and 20 s for (a) downward and (b) upward polarization of PZT, respectively; (a) also shows the behavior of the ZnO–SiO_2 system under the same modulation. There was very little response when the IR laser was introduced to ZnO-SiO_2. Furthermore, (b) also shows the temperature behavior of the system indicating the correlation between temperature and current.

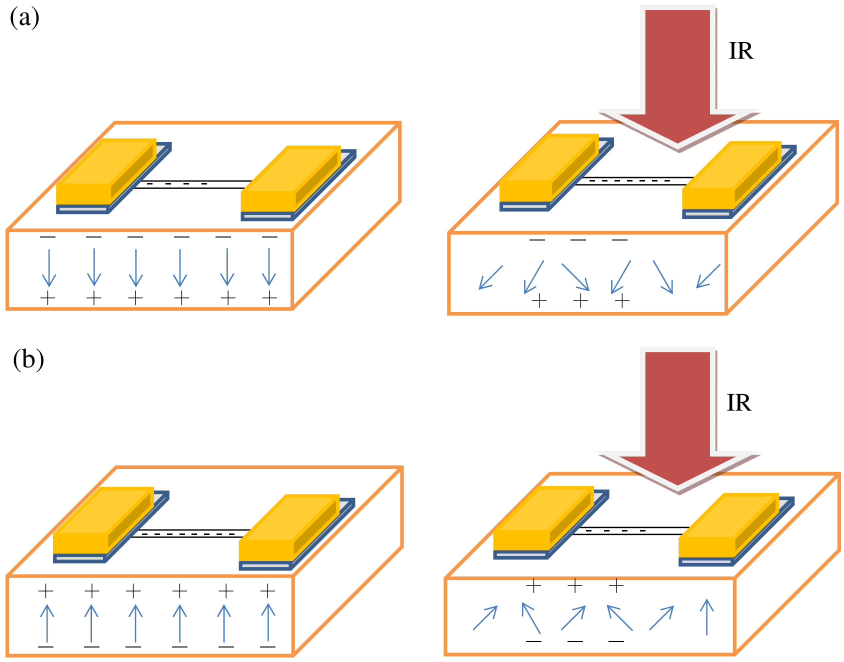

Figure 3. (a) IR illumination on a PZT with a down polarization would decrease the negative bound charge density at the top surface of the PZT (due to the reduced polarization). As a result the electron carrier concentration in the ZnO NW would increase, resulting in an increased drain current. (b) IR illumination on a PZT with an up polarization would decrease the positive bound charge density at the top surface of the PZT, which would act to decrease the electron carrier concentration in the ZnO NW thereby decreasing the drain current.

of intrinsic donor-type defects, such as oxygen vacancies and Zn interstitials, causes ZnO NW to be the n-channel semiconductor [14]. Moreover, we noted that there were bound charges on the surfaces of the PZT. A top surface of a PZT with a down (up) polarization had bound negative (positive) charges. When the n-type ZnO NW was placed on the top of the PZT substrate with a down polarization, the bound negative charges on the PZT surface would repel the electron carriers in the ZnO NW. When illuminated by the IR laser, the increased temperature reduced the polarization and thus decreased the density of the negative bound charges at the top inside surface of the PZT. As a result, the electron carrier concentration in the ZnO NW would increase, resulting in an increased drain current. On the other hand, IR illumination on a PZT with an up polarization would decrease the polarization and positive bound charge density at the top inside surface of the PZT. As a result, the electron carrier concentration in the ZnO NW would decrease, thereby decreasing the drain current. The IR illumination on a PZT substrate with an up polarization worked as a depletion mode, equivalent to the effect of applying a negative gate potential. The behavior is illustrated as schematics in figures 3(a) and (b).

In theory, it is possible that temperature can affect the property of ZnO NW directly. On one hand, higher temperature can create more lattice vibrations and scattering events leading to higher resistance. On the other hand, higher temperature may excite more electrons into the conduction band, thus increasing the charge carrier density. In either case,

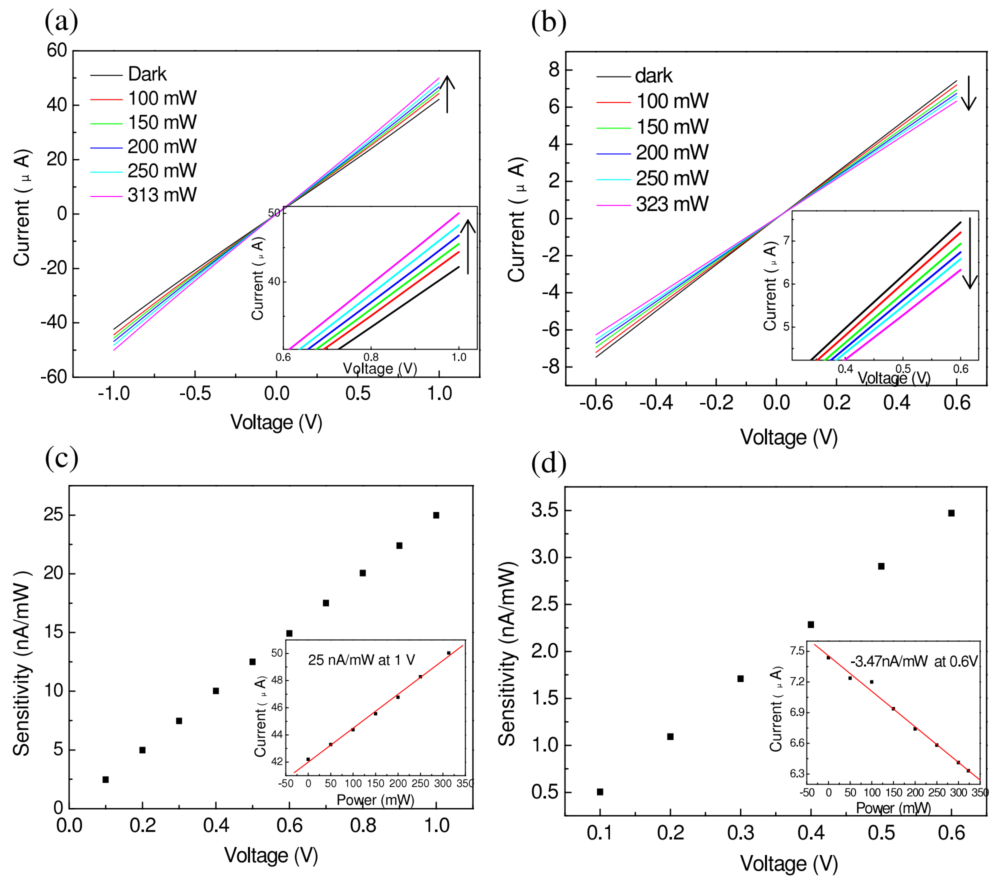

Figure 4. The drain current as a function of drain voltage for the ZnO–PZT transistor with (a) downward and (b) upward polarization subjected to laser of different power. The average sensitivity as a function of drain voltage for ZnO–PZT transistor with (c) downward and (d) upward polarization. The drain current behaves linearly with increasing laser power, indicating the optothermal gating effect is linear in nature. The insets of (c) and (d) show the maximum sensitivity is about 25 nA mW^{-1} at 1 V and 3.5 nA mW^{-1} at 0.6 V, respectively.

the behavior would not be dependent on the polarization of the PZT substrate. Our results show an increased and decreased drain current by laser depending on the polarizations of PZT. This clearly demonstrates that the behavior seen in figures 2 and 3 is due to the presence of PZT whose polarization plays a key role in the observed behavior. In fact Dai *et al* [15] showed that for ZnO NW under IR irradiation, higher temperature leads to higher resistance rather than more charge carriers. Furthermore, in our experiment, the IR irradiation is mostly on the PZT substrate rather than focused on the ZnO NW. Consequently, we do not expect a direct temperature effect on ZnO NW.

Figures 4(a) and (b) show the *I*–*V* curves of ZnO NW–PZT transistor with a downward and upward polarization illuminated by the IR laser at various powers. For the ZnO NW–PZT transistor with a downward (upward) polarization, the drain current would increase (decrease) when the power of incident IR laser was increased at a fixed drain voltage as shown in figures 4(a) and (b). This result is consistent with the behavior shown in figures 2(a) and (b). Following the analysis of traditional pyroelectric detectors with metal electrodes, we define the drain current sensitivity $R_d = I_d/W$, where W is the radiation power that causes the drain current I_d to change. For our transistor with a downward and upward polarization of PZT, the maximum current sensitivity was $\sim$25 nA mW^{-1} and $\sim$3.5 nA mW^{-1} at $E_d = 83$ kV m^{-1} and 50 kV m^{-1}, respectively, where E_d is the electric field across the drain and source electrodes. The different magnitude in drain current change between the down polarized and up polarized devices is due to the fact that individual ZnO NWs have different properties. The average current sensitivity versus drain voltage for the transistor with downward and upward polarization was also shown in figures 4(c) and (d), respectively. The maximum is about three orders of magnitude higher than the typical 20 nA W^{-1} at $E_d = 50$ kV m^{-1} of the photogating transistors based on carbon nanotube on SiO_2/Si substrate [1]. Moreover, figures 4(c) and (d) show that the increase and decrease in drain current behave linearly with increasing laser power indicating the optothermal gating effect is linear in nature.

The results presented so far relate to IR illumination which has energy smaller than the band gap of ZnO. On the other hand, UV light has energy larger than the band gap of ZnO and as a result can generate photocurrent in ZnO NW directly [8, 9]. This photocurrent is independent of the polarization of the PZT substrate. Consequently, it is possible to illuminate both UV and IR on the ZnO NW–PZT FET and have the combined effects. Figure 5 shows *I*–*V* curves of a ZnO NW–PZT transistor with an upward polarization under ultraviolet (UV) laser of

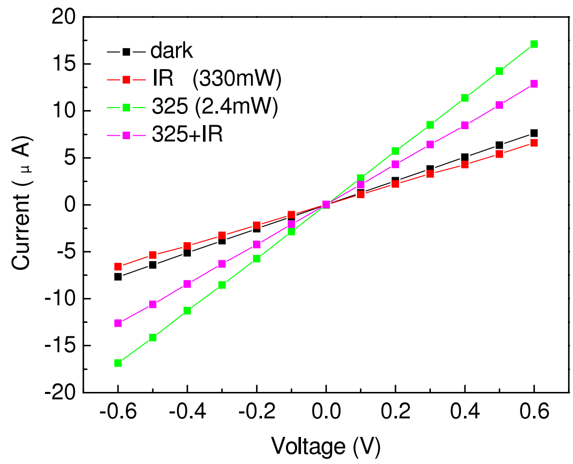

Figure 5. The drain current as a function of drain voltage of a ZnO–PZT transistor with an upward polarization under UV laser of 325 nm wavelength and IR illumination. The drain current can be easily modulated by tuning the powers of incident UV and IR lasers separately or simultaneously.

325 nm wavelength and IR illumination, separately and simultaneously. In comparison with dark current, the drain current increased under UV illumination, but decreased under IR illumination, respectively. When ZnO NW is illuminated by UV light, it is likely that electron–hole pairs are generated and the holes can neutralize the negatively charged oxygen molecules which then desorb at the surface of the ZnO NW. Thus the remaining electron carriers of electron–hole pairs contribute to the photoconductivity, resulting in increased drain current. The ZnO NW has been applied for photodetectors mostly in UV ranges. Using optothermal gating, we can easily fabricate photodetectors in the UV and IR ranges by combining ZnO NW with PZT substrate. As shown in figure 5, the drain current of a ZnO–PZT transistor can be easily controlled by tuning the powers of incident UV and IR lasers separately or simultaneously, indicating the photo/optothermal-controlling feature has potential in remote or wireless applications.

4. Conclusion

In conclusion, we have developed a new single ZnO NW–PZT optothermal field effect transistor that can be tuned by IR light illumination. By applying light heating, the drain current can be increased or decreased depending on the direction of polarization in PZT substrate. Furthermore, by adding UV to the IR radiation we can combine the photocurrent feature and the optothermal gating effect in ZnO NW–PZT transistor to create nanoscale optoelectronic devices that can respond to a wide range of wavelengths.

Acknowledgments

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