Low-Frequency Noise Characteristics of Epitaxial ZnO Photoconductive Sensors

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We report the fabrication of epitaxial ZnO photoconductive sensors on sapphire substrates. With an incident light wavelength of 370 nm and a 5 V applied bias, we achieved a sensor responsivity of 20.5 mA/W. It was also found that low-frequency and high-frequency noises in the fabricated sensors were dominated by 1/f type and shot noises, respectively. With a 5 V applied bias, it was found that noise equivalent power and normalized detectivity of the fabricated sensors were 1.83 × 10−6 W and 6.91 × 108 cm Hz 1/2 W−1, respectively.

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Detectors operating in the short wavelength ultraviolet (UV) region are important devices that can be used in space communications, ozone layer monitoring, and flame detection. Until very recently, the primary means of UV light detection was the use of silicon photodiodes. However, the most sensitive wavelength of Si-based detector is not located in the UV region because room-temperature bandgap energy of Si is only 1.2 eV. Thus, the responsivity of Si photodiodes is low in UV region. With the advent of optoelectronic devices fabricated on wide direct bandgap materials, it becomes possible to produce high-performance solid-state photodetector arrays that are sensitive in UV region. For example, GaN-based photodetectors are already commercially available. 1–6 It has also been demonstrated that ZnSe-based photodetectors can also be used in sensing optical signal in the blue/UV region. 7,11

ZnO is another potentially useful wide direct bandgap material. 12,13 The large exciton binding energy of 60 meV and wide bandgap energy of 3.37 eV at room temperature make ZnO a promising photonic material for applications such as light-emitting diodes (LEDs), laser diodes (LDs), and photodetectors. ZnO is also very attractive as UV optical sensors. Compared with GaN, ZnO exhibits higher electron saturation velocity. Thus, we should be able to achieve ZnO-based photo sensors with higher operation speed. Bandgap energy of ZnO and its alloys such as CdZnO, MgZnO, and BeZnO expands from 2.5 eV (496 nm) to 10.6 eV (124 nm). Thus, ZnO-based photosensor should perform much better than its GaN-based counterpart in the deep UV region. Compared with GaN and Si, ZnO is exhibits stronger radiation hardness. 14 Indeed, ZnO has attracted much attention in recent years. 15–19 ZnO Schottky diodes and metal semiconductor metal (MSM) photodetectors, pn-heterojunction diode, ZnO/GaN heterostructure Schottky diodes, ZnO nanowire photodetectors, detecting in the UV region have also been demonstrated. 17,19–22 In this work, we report the fabrication of ZnO photoconductive sensors with Ni/Au electrodes. Optoelectronic and noise properties of the fabricated sensors is also discussed.

Experimental

The ZnO samples in this study were all epitaxially grown on (1120) sapphire substrates by molecular beam epitaxy (MBE) with an oxygen source supplied from a radio-frequency (rf) activated plasma cell. Elemental Zn (6N) source was evaporated using conventional effusion cell. After cleaning and annealing sapphire substrates, we decreased the substrate temperature to 430°C to grow a 700 nm thick ZnO epitaxial layer. During the growth of ZnO, we kept the oxygen flow rate and beam equivalent pressure (BEP) at 0.8 sccm and 3.2 × 10−6 Torr, respectively. After the growth, we thermally annealed the samples at 700°C in O2 atmosphere. We then deposited Ni/Au (100 nm/2000 nm) ohmic contact onto the thermally annealed ZnO epitaxial layer. Photolithography and etching were subsequently performed to form the two interdigitated electrodes. Room-temperature current-voltage (I-V) characteristics of the fabricated devices were then measured both in dark and under illumination by an HP4156 semiconductor parameter analyzer.

For the spectral response measurements, monochromatic light was extracted from a 300 W xenon arc lamp light source through the monochrometer to serve as the light source. To quantify the measured responsivities, we first measured the intensity of the input light by a calibrated GaP UV detector. We then measured areas of GaP UV detector and our photoconductive sensors so as to precisely estimate the sensor responsivities. Note that we applied various bias voltages onto the fabricated photoconductive sensors during spectral response measurements. Furthermore, noise characteristics of the fabricated ZnO photoconductor sensors were measured in the frequency range from 1 Hz to 1.6 kHz by using a SR570 low-noise current preamplifier and a 35670A dynamic signal analyzer.

Results and Discussion

Figure 1 shows I-V characteristics of the fabricated ZnO MSM photoconductive sensor with Ni/Au electrodes, measured in dark (dark current) and under illumination (photocurrent). It can be seen that I-V characteristics of the fabricated sensors were symmetrical.

![Figure 1. I-V characteristics of the ZnO photoconductive sensor measured under dark and illumination.](http://example.com/figure1.png)
and linear. With 2 V applied bias, it was found that dark current and photocurrent of our ZnO MSM photoconductive sensor were $3.83 \times 10^{-5}$ and $1.21 \times 10^{-4}$ A, respectively. Figure 2 shows spectral responses of the fabricated ZnO photoconductive sensors measured with various applied bias voltages. As shown in Fig. 2, it was found that measured sensor responsivities were almost independent of incident light wavelength within the wavelength range of 320–370 nm. As the incident light wavelength was further increased, it was found that the responsivity decreased rapidly due to the much smaller below bandgap absorption. On the other hand, it was found that the responsivity became smaller when the incident light wavelength was shorter than 320 nm. This is probably due to the fact that portion of the incident light was absorbed by the Ni/Au contact electrodes in the short wavelength region. It was also found that the peak responsivity increased almost linearly as we increased the applied bias voltage. With incident light wavelength of 370 nm and biased voltage of 5 V, it was found that measured responsivity of the fabricated ZnO photoconductive sensor was 20.5 mA/W. Due to the large lattice mismatch between ZnO epitaxial layer and sapphire substrate, it is known that threading dislocation in ZnO epitaxial layer is large in general. This large dislocation density often results in significant recombination of photogenerated carriers at sample surface and/or in the depletion region. Thus, we believe the relatively small 20.5 mA/W responsivity observed in this study is related to the high defect density in the epitaxial layer.

Figure 3 shows measured noise spectra of the fabricated ZnO photoconductive sensor. During noise measurements, we applied 0.5, 1, 2, 3, 4, and 5 V applied bias onto the sample. For comparison, noise spectrum of a standard resistor was also shown in the same figure. It can be seen clearly that low-frequency noise of the standard resistor was almost independent of the frequency. In contrast, the low-frequency noise spectra measured from the sensor could be fitted well by

$$S_n(f) = K \left( \frac{I_f}{f^2} \right)$$

where $f$ is the frequency, $S_n(f)$ is the spectral density of noise power, $K$ is a constant, $I_f$ is the dark current, and $\beta$ and $\alpha$ are two fitting parameters. As shown in Fig. 3, it was found that $\alpha$ equals unity when $f < 120$ Hz. Such a result indicates that the low-frequency noise in the fabricated sensor was dominated by 1/f-type noise. Figure 4 shows noise power density of our devices as a function of dark current measured at 10 Hz. It was found that $\beta$ was around 2. Such a value agrees well with Kleinpenning’s model that spectral density of the 1/f noise should proportional to $I_f^2$. We can also derive Hooge parameter of the fabricated sensors from the experimental data and

$$\frac{S_n(f)}{I_f^2} = \frac{S_n(f)}{\mu^2} = \frac{S_n(f)}{\sigma^2} = \frac{\alpha_H}{fN}$$

where $\mu$, $\sigma$, $\alpha_H$, and $N$ are the carrier mobility, conductivity of the sample, Hooge parameter, and the total number of charge carriers, respectively. The value of $N$ can be determined by

$$N = \frac{L^2}{\epsilon \mu R}$$

where $L$, $\mu$, and $R$ were electrode length, carrier mobility, and the resistance of the sample, respectively. From our experimental data, it was found that the total number of charge carriers ($N$) and the dimensionless Hooge parameter ($\alpha_H$) were $1.26 \times 10^{-3}$ cm$^{-3}$ and $2 \times 10^{-5}$, respectively. Previously, it has been reported that Hooge parameter $\alpha_H$ of n-type GaN$^{26}$ and SiC$^{27}$ were both around $10^{-3}$. These values are about the same as the Hooge parameter measured from our devices. Note that noise power density was independent of frequency in the high-frequency region (i.e., above 120 Hz), as shown in Fig. 3. In the high-frequency region, shot noise will become dominant because 1/f type noise will continue to decrease in this region. The total noise current power can be estimated by integrating $S_n(f)$ over the frequency range.
Fig. 5, it was found that given bandwidth of 1 kHz, we can thus determine noise equivalent power as the applied bias increased for the fabricated ZnO photoconductive sensor. Thus, the normalized detectivity of the fabricated sensors were 1.83 \times 10^{-6} \text{ W} and 6.91 \times 10^{-5} \text{ cm Hz}^{0.5} \text{ W}^{-1} respectively.

**Conclusions**

In summary, epitaxial ZnO photoconductive sensors were fabricated on sapphire substrates with an incident light wavelength of 370 nm and a 5 V applied bias, we achieved a sensor responsivity of 20.5 mA/W. With a 5 V applied bias, it was found that NEP and normalized detectivity of the fabricated sensors were 1.83 \times 10^{-6} \text{ W} and 6.91 \times 10^{-5} \text{ cm Hz}^{0.5} \text{ W}^{-1} respectively.

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