Great Enhancement Effect of 20–40 nm Ag NPs on Solar-Blind UV Response of the Mixed-Phase MgZnO Detector

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ABSTRACT: High-performance solar-blind UV detector with high response and fast speed is needed in multiple types of areas, which is hard to achieve in one device with a simple structure and device fabrication process. Here, the effects of Ag nanoparticles (NPs) with different sizes on UV response characteristics of the device are studied. Ag NPs with different sizes could modulate the peak response position of the mixed-phase MgZnO detector from near UV range (350 nm) to deep UV range (235 nm), and the enhancement effect of the Ag NPs on the UV response differs much with the crystal structure and the basic UV response of the MgZnO thin film. When high density 20–40 nm Ag NPs is induced, the deep UV (235 nm) response of the mixed-phase MgZnO detector is increased by 226 times, the \( I_{\text{UV}}/I_{\text{dark}} \) ratio of the modified device is increased by 17.5 times. The slight enhancement in UV light intensity from 20 to 40 nm Ag NPs induces multiple tunnel breakdown phenomena within the mixed-phase MgZnO thin film, which is the main reason for the abnormal great enhancement effect on deep UV response of the device, so the recovery speed of the modified device is not influenced. Therefore, Ag NPs with different sizes could effectively modulate the UV response peak position of mixed-phase MgZnO thin films, and the introduction of Ag NPs with high density and small size is a simple way to greatly increase the sensitivity of the mixed-phase MgZnO detector at deep UV light without decreasing the device speed.

INTRODUCTION

High-performance UV detectors at both near UV (300–380 nm) and solar-blind UV (220–280 nm) light have attracted intense research interest, which is mainly because of their wide application area in missile firing alarm, ozone hole detection, ultrahigh-speed UV optical communication, and secure wireless communication.\(^1\)–\(^5\) Especially in communication area, high-performance near and deep UV detectors would be the key devices in an ultrahigh speed UV light communication system and ultrahigh secure wireless communication system based on solar-blind UV light.\(^6\) The study on wide band gap semiconductor (WBSC) materials (AlGaN, diamond, SiC, Ga\(_2\)O\(_3\), MgZnO, etc.) that are used in UV photodetectors has emerged during past 20 years.\(^7\)–\(^20\) Compared with other materials, ternary alloy MgZnO materials with different Mg compositions could detect UV light in a wider range from 220 to 380 nm,\(^12\),\(^13\) and the UV response of MgZnO-based detectors are relative higher at both near UV and solar-blind UV light.\(^14\),\(^15\) Recently, mixed-phase MgZnO-based UV detector have shown a high response and a small dark current at both near and deep UV light,\(^10\)–\(^25\) so the mixed-phase MgZnO thin film is an ideal material for high-performance UV detectors at both solar-blind UV (220–280 nm) and visible-blind UV (300 nm–380 nm) light.

In recent years, the plasmon-enhancement effect of metal nanoparticles (NPs) has been widely utilized to improve the photoelectric properties of optoelectronic devices. The localized surface plasmon (LSP) effect is an optical phenomenon generated by the collective oscillation of free electrons in metal NPs excited by incident light. If the plasmon resonance frequency falls in the light absorption spectrum range of the semiconductor, plasmonic NPs can be employed to enhance the light harvesting capacity of a semiconductor.\(^26\),\(^27\) In previous studies, Au NPs were frequently used to enhance the visible-blind UV response of semiconductors,\(^28\) while Ag, Al, and Pt NPs were more often utilized in the UV detector.\(^29\)–\(^31\) The introduction of a 100 nm Ag NPs can improve the visible-blind UV response
of ZnO detectors by 1.5 times,\textsuperscript{29} and the modification of sparsely distributed Ag NPs can improve the near UV response of single GaN-based UV detectors by 30 times.\textsuperscript{32} Theoretically, a decrease in the size of metal NPs can lead to a blueshift of the plasmonic absorption peak. Therefore, the modification of small size Ag NPs would be a simple way to improve the sensitivity of the mixed-phase MgZnO UV detector at faint solar-blind UV light,\textsuperscript{30,33,35} and the introduction of Ag NPs with different sizes is hopeful to modulate the peak response position of the mixed-phase MgZnO detector from near UV region to deep UV region. Unfortunately, associated studies have rarely been reported.

In this letter, Ag NPs with different sizes are modified on top of the metal–semiconductor–metal (MSM) structure solar-blind UV detectors based on mixed-phase MgZnO thin films. The effect of Ag NPs with different sizes on the UV absorption characteristics of mixed-phase MgZnO thin films and the performance of mixed-phase MgZnO UV detectors are studied, and relatively reasonable explanations for the different performances of the mixed-phase MgZnO UV detectors with Ag NPs with different sizes are given according to previous reports and our experimental results.

\section*{RESULTS AND DISCUSSION}

The Ag nanoparticles (Ag NPs) are first fabricated through vacuum annealing on Ag thin films with different thicknesses on fused quartz substrates, and the size and distribution of the Ag NPs could be seen in the scanning electron microscope (SEM) images, as shown in Figure 1a–e. The Ag NPs made by a 2 nm Ag layer distribute densely on the fused quartz, the sizes of most Ag NPs varied within a small range between 10 and 15 nm (Figure 1a). The Ag NPs made by a 4 nm Ag layer distribute less...
densely compared with those from a 2 nm Ag layer, the sizes of most Ag NPs varied within a slightly wider range from 25 to 40 nm (Figure 1b). When the thickness of the annealed Ag thin film increases from 6 to 10 nm, Ag NPs with both smaller and larger sizes are sparsely distributed on the fused quartz, the average size of the larger Ag NPs varied slightly from 80 to 100 nm. Compared with the Ag NPs from the 6 and 8 nm Ag thin films, the Ag NPs made from a 10 nm Ag thin film contained more larger Ag NPs and fewer small Ag NPs (Figure 1c–e).

The extinction spectra of Ag NPs fabricated from Ag thin films with different thicknesses are shown in Figure 1f. When the thicknesses of the annealed Ag thin films are 2 and 4 nm, the extinction peaks of the Ag NPs are located at 420 nm, and the extinction coefficients of the Ag NPs at UV light are small. When the thickness of the annealed Ag thin films is increased from 6 to 10 nm, another extinction peak appears at approximately 380 nm in the extinction spectra of the Ag NPs, and the extinction coefficients of the Ag NPs at UV light are much higher than those of the small size Ag NPs. In addition, for the sample fabricated from a 10 nm Ag thin film, the Ag NPs shows higher extinction coefficient at UV light than the Ag NPs fabricated from the 6 and 8 nm Ag thin films. Therefore, both the size and extinction characteristics of the Ag NPs from a 10 nm Ag thin film differs much from those of the Ag NPs made from the 2 and 4 nm thin films. The Ag NPs made from the 2, 4, and 10 nm Ag thin films are introduced into the MgZnO UV detector to produce a sufficient difference in the modified devices.

To study the effect of Ag NPs with different sizes on the performance of the mixed-phase MgZnO thin film in UV light detection, Ag NPs with obviously different sizes are produced on the mixed-phase MgZnO thin films, which are made from 2, 4, and 10 nm-thick Ag layers based on previous experimental results. SEM images of the Ag NPs/MgZnO made from Ag thin films with different thicknesses are presented in Figure 2a–c. From a 2 nm Ag layer, the Ag NPs with a relatively uniform size and shape are densely distributed on the MgZnO thin film, the size of the fabricated Ag NPs varies within a small range between 10 and 15 nm (named as 10–15 nm Ag NPs), as shown in Figure 2a. From a 4 nm Ag layer, the density of the fabricated Ag NPs is slightly lower than that of the Ag NPs made from the 2 nm Ag layer, the size of the Ag NPs varies within a slightly wider range between 20 and 40 nm (named as 20–40 nm Ag NPs), as shown in Figure 2b. On the surface of the MgZnO thin film, the Ag NPs fabricated from a 10 nm Ag layer distributes sparsely, and both large numbers of big size Ag NPs of 100 nm and small numbers of small size Ag NPs around 25 nm (named 100 nm Ag NPs) exist, as shown in Figure 2c. The mixed-phase MgZnO thin films are prepared by the pulsed laser deposition (PLD) method. Then, to eliminate the influence of vacuum annealing on the performance of the MgZnO thin film, the same vacuum annealing treatment as that used in the fabrication process of Ag NPs is also applied to the bared MgZnO thin film. Peaks corresponding to both cubic MgZnO (c-MgZnO) and hexagonal MgZnO (h-MgZnO) appear in the X-ray diffraction (XRD) result of the vacuum annealed MgZnO thin film (Figure 2d), and the peaks corresponding to h-MgZnO are higher than the peaks corresponding to c-MgZnO. In the UV absorption spectrum of the MgZnO thin film (Figure 2e), the MgZnO thin film can absorb UV light from 200 to 380 nm, which agrees with the UV absorption characteristics of the reported mixed-phase MgZnO thin films.\(^{11,22}\)

Then, MSM structure UV detectors are made on the mixed-phase MgZnO thin films modified by Ag NPs with different sizes. The structure of the MSM structure UV detector on the mixed-phase MgZnO thin film without and with Ag NPs are shown in Figure 3a,b; 12 pairs of Au interdigitated electrodes are made through standard UV exposure and wet etching processes, the fingers are 500 mm long and 10 mm wide, and the spacing between each Au finger is 10 mm. In the UV response spectra of the device under bias voltages ranging from 5 to 25 V (Figure 3c), two UV response peaks at 350 and 260 nm are observed, which correspond to the UV response characteristics of MgZnO films composed of both h-MgZnO and c-MgZnO.\(^{12}\) Under a 25 V bias voltage, the response of the detector at 350 nm near UV light is 0.16 A/W, and the responsivity of the detector at 260 nm solar-blind UV light is 0.36 A/W. Two peaks at 300 and 350 nm appear in UV response spectra of the MgZnO detector with 10–15 nm Ag NPs (Figure 3d). The response of the modified device at 350 nm is 0.46 A/W at a 25 V bias, which is 2.88 times of that of the bared detector. The response of the modified device at 300 nm is 0.54 A/W at a 25 V bias, which is 2.08 times of that of the bared detector. However, less improvement is found in the response of the MgZnO detector at the deep UV light when 10–15 nm Ag NPs are introduced. Two peaks at 280 and 235 nm appear in the UV response spectra of the MgZnO detector with 10–15 nm Ag NPs (Figure 3d). The response of the modified device at 350 nm is 0.46 A/W at a 25 V bias, which is 2.88 times of that of the bared detector. The response of the modified device at 300 nm is 0.54 A/W at a 25 V bias, which is 2.08 times of that of the bared detector. However, less improvement is found in the response of the MgZnO detector at the deep UV light when 10–15 nm Ag NPs are introduced. Two peaks at 280 and 235 nm appear in the UV response spectra of the MgZnO detector at 350 nm near UV light reaches 15.8 A/W, and the response of the device at 235 nm solar-blind UV light reaches 31.6 A/W. The responsivity of the modified MgZnO detector at 350 nm solar-blind UV light is 51.6 times of that of the bared device, the responsivity of the modified MgZnO detector at 280 nm solar-blind UV light is 56.8 times of that of the bared device, and the responsivity of the modified MgZnO detector at 235 nm solar-blind UV light is 226 times of that of the bared device. The 20–
40 nm Ag NPs induced a great improvement in the UV response of the mixed-phase MgZnO detector at both near UV and solar-blind UV light. However, when Ag NPs of approximately 100 nm are introduced on the surface of the mixed-phase MgZnO detector, the UV response peaks of the device are located at approximately 340 and 235 nm under different bias voltages. The response of the modified device at 340 nm near UV light is 0.117 A/W under a 25 V bias, which is smaller than that of the device without Ag NPs. The response of the device at 235 nm solar-blind UV light is 0.446 A/W, which is 3.91 times that of the device without Ag NPs (Figure 3f). Ag NPs around 100 nm has been reported to improve the near UV response of both ZnO and GaN-based UV detectors because of the LSP enhancement effect. Also, the UV response position, according to the LSP effect of Ag NPs, would undergo a great blueshift with a decreasing particle size. Therefore, theoretically, the LSP enhancement effect of small-size Ag NPs can enhance the UV response characteristics of MgZnO detectors at shorter UV wavelengths. However, from our experimental results, the small size Ag NPs not only induced a great difference in the performance of the mixed-phase MgZnO detector at near UV light; the 20–40 nm Ag NPs could improve the response of the mixed-phase MgZnO detector at 235 nm deep UV light by 2 orders of magnitude, which is extremely difficult to achieve. Because great improvement in the UV response of deep UV detectors at 235 nm UV light has rarely been reported and this abnormal phenomenon cannot be achieved by Ag NPs based on both theoretical and experimental results, the effect of Ag NPs with different sizes on the performance of mixed-phase MgZnO-based detectors can be interpreted by a new mechanism.

To study the effect of the Ag NPs with different sizes on the detection ability of the MgZnO detector at deep UV light under a strong noise background, the light current ($I_{\text{lm}}$), dark current ($I_{\text{dark}}$), and $I_{\text{lm}}/I_{\text{dark}}$ ratios of the MgZnO detectors without and with Ag NPs are measured. Under UV light condition at the deep UV response peak positions with density of 5.4 μW/cm², the $I_{\text{lm}}$ values of the four MgZnO detectors are separately measured, as shown in Figure 4a–d. The $I_{\text{dark}}$ of the MgZnO detector without Ag NPs increased from 112.1 to 873.4 nA when the bias voltage increased from 5 to 25 V, and the $I_{\text{lm}}/I_{\text{dark}}$ ratio of the detector is only 5.02 at a 25 V bias voltage (Figure 4a). The $I_{\text{dark}}$ of the MgZnO detector with 10–15 nm Ag NPs increased from 95.8 to 501.5 nA when the bias voltage increased from 5 to 25 V, and the $I_{\text{lm}}/I_{\text{dark}}$ of this detector at different bias voltages are slightly smaller than that of the bared detector. The $I_{\text{lm}}/I_{\text{dark}}$ ratio of the detector is 6.62 under a 25 V bias voltage, which is slightly higher than that of the device without Ag NPs (Figure 4b). When the bias voltage increased from 5 to 25 V, the $I_{\text{dark}}$ of the MgZnO detector with 20–40 nm Ag NPs increased from 179 nA to 1.41 mA, and the $I_{\text{lm}}$ of the modified device increased from 7.73 to 125 mA. The $I_{\text{lm}}$ of the detector at different bias voltages is much higher than that of the bared detector, and the $I_{\text{lm}}/I_{\text{dark}}$ ratio of the detector at different bias voltages is slightly higher than that of the bared detector, so the $I_{\text{lm}}/I_{\text{dark}}$ ratio of this detector reached 74 at a 25 V bias voltage, which is 17.5 times of that of the bared device (Figure 4c). The $I_{\text{dark}}$ of the MgZnO detector with 100 nm Ag NPs increased from 2.22 to 13.5 nA when the bias voltage increased from 5 to 25 V, and the $I_{\text{lm}}/I_{\text{dark}}$ of the detector at different bias voltages is much smaller than that of the bared detector, so the $I_{\text{lm}}/I_{\text{dark}}$ ratio of the detector reached 74 at a 25 V bias voltage, which is 14.7 times of that of the bared device (Figure 4d). The Ag NPs not only enhances the UV response of the MgZnO detector at deep UV light but also greatly decreases the $I_{\text{dark}}$ noise level and increases the signal/noise ratio of the MgZnO detector, which has been reported to be mainly due to the localized Schottky junction at the interface between the Ag NPs and MgZnO thin film. The barriers between the Ag NPs and MgZnO thin film are much thicker and the barriers are much higher at higher bias voltages under dark conditions, so the dark current of the MgZnO detector with 100 nm Ag NPs is much smaller than that of the detector without Ag NPs, and the $I_{\text{lm}}/I_{\text{dark}}$ ratio of the MgZnO detector with 100 nm Ag NPs at a 25 V bias voltage is much higher than that of the bared detector. Ag NPs sized around 100 nm could improve the response intensity of the UV detector at 380 nm near UV light due to the narrow-band quadrupole plasmon resonance effect. The mixed-phase MgZnO-based detector is more sensitive at 350 nm near UV light, so the 100 nm Ag NPs could not improve the near UV response of the mixed-phase MgZnO-based detector. From theoretical model of the narrow-band quadrupole plasmon resonance effect, the small size metal NPs could enhance the response of the detector at a shorter wavelength of UV light, so the 10–15 and 20–40 nm Ag NPs could improve the response of the mixed-phase MgZnO-based detector at approximately 350 nm near UV light. The enhancement effect of the 10–15 nm Ag NPs on the UV response of the UV detector is similar as...
Figure 5. Mechanisms for the different UV response characteristics of the MgZnO detector modified by Ag NPs with different sizes. (a) MIS tunneling junction, (b) bared mixed-phase MgZnO detector with near UV light, (c) bared mixed-phase MgZnO detector with deep UV light, (d) modified mixed-phase MgZnO detector with near UV light, and (e) modified mixed-phase MgZnO detector with deep UV light.

reported results for the surface plasmon effect. The density of the 20–40 nm Ag NPs is slightly lower than that of the 10–15 nm Ag NPs, but a much higher enhancement effect of the 20–40 nm Ag NPs on the near UV response of the UV detector appears, which is much larger than most reported results, so some other factor would cause this abnormal phenomenon.

The Ag NPs could greatly enhance the response of the device at UV light ranged widely from 350 to 235 nm, and the enhancement effect increases with the decrease in wavelength of UV light. The Rayleigh scattering effect of metal NPs can increase the absorption of UV light over a wide wavelength range; only metal NPs with a size below 1/10 the wavelength of irradiated UV light can produce effective Rayleigh scattering, 9,40 and the scattering cross sections $C_{\text{sca}}$ can be calculated from eq 1.51

$$C_{\text{sca}} = \frac{1}{6\pi} \left(\frac{2\pi}{\lambda}\right)^4 |\alpha|^2$$

(1)

where $\alpha$ is the polarizability parameter, both for spherical and ellipsoidal metallic NPs, which is proportional to the square of the volume ($V$) of the metal NPs. Thus, for a certain NP volume, the scattering cross section of both types of Ag NPs $C_{\text{sca}}$ is inversely proportional to the wavelength of UV light

$$C_{\text{sca}} \propto \frac{1}{\lambda^4}$$

(2)

The relationship between the optical enhancement effect from 20 to 40 nm Ag NPs on the UV response of the device is similar to the relationship between the $C_{\text{sca}}$ and the wavelength of the UV light from Rayleigh scattering. In addition, some multistage plasmon resonance effects of coupled plasmonic Ag NP aggregates, such as the Fano resonance effect, can also slightly increase the intensity of deep UV light.33,42–44 Thus, from the Rayleigh scattering and some multistage plasmon resonance effects, the 20–40 nm Ag NPs could increase both the near UV and the deep UV responses of the detector. Also, from the plasmonic effect, the 20–40 nm Ag NPs could also increase the near UV response of the device. However, the optical scattering effect of the metal NPs could only improve the UV light absorptivity at a percentage rate, the 226-fold increase in the UV response of the MgZnO detector is far greater than the probable improvement, and the optical enhancement effect on intensity of deep UV light obey the theoretical and previous experimental results on UV detector-based homogeneous crystal structure materials. Thus, the optical effect of the 20–40 nm Ag NPs could not explain above abnormal phenomenon.

The hole-trapping mechanism has been reported as the main reason for the high response of mixed-phase MgZnO UV detectors,21,45 which is achieved at the expense of decreasing the recovery speed of the device. To find out if the Ag NPs induces much higher internal gain from hole trapping mechanism, the time response curves of the mixed-phase MgZnO-based detectors without and with 20–40 nm Ag NPs are measured, as shown in Figure 4ef. The rise time ($t_r$) of the two MgZnO detectors are obtained through fitting of the photo response rise curves by adopting an exponential relation equation as shown in eq 3, and the decay times ($t_{d1}$, $t_{d2}$) of the two MgZnO detectors are obtained through fitting of the photo response decay curves by adopting a biexponential relation equation, as shown in eq 4.46

$$y = y_0 + y_1 e^{-t/t_1}$$

(3)

$$y = y_0 + y_1 e^{-t/t_{d1}} + y_2 e^{-t/t_{d2}}$$

(4)

where $y_0$ is the steady-state photocurrent, $t$ is the time, $y_1$ and $y_2$ are constants, $t_1$ is the rise time constant, and $t_{d1}$ and $t_{d2}$ are the relaxation time constants corresponding to two components (fast and slow). The rise time ($t_r$) of the bared MgZnO-based UV detector is 20 µs, and the two decay times ($t_{d1}$ and $t_{d2}$) of the device are 0.6 and 9.8 ms, respectively (Figure 4e). The rise time ($t_r$) of the MgZnO-based UV detector modified by 20–40 nm Ag NPs is 6.8 µs, and the two decay times ($t_{d1}$ and $t_{d2}$) of the device are 0.64 and 9.8 ms, respectively (Figure 4f). The 20–40 nm Ag NPs could improve the response speed of the MgZnO detector at solar-blind UV light, the recovery speeds of the mixed-phase MgZnO UV detector with 20–40 nm Ag NPs is similar as that of the bared device, so the 20–40 nm Ag NPs did not induce a much higher internal gain arising from the hole-trapping mechanism.

The response speed of the modified mixed-phase MgZnO detector at deep UV light is faster than the bared device, which is similar as the amplification process arising from the breakdown mechanism.46,47 The electric breakdown phenomenon has been widely reported in MIS structure devices with two types of different resistance materials, avalanche, and tunneling breakdown mechanism. The two types of breakdown devices have been widely used in high-performance infrared detectors,48,49
near UV response of the device is relatively small (Figure 5b). MgZnO blocks the collection of the photogenerated carriers, the in the low-resistance h-MgZnO. Because most high-resistance c-MgZnO-based UV detector, electrons and holes are generated (Figure 5a). When near UV light irradiates the mixed-phase large number of carriers in the low-resistance part would break down through the high-resistance part by the photo-
breakdown probability is also not high enough, the deep UV response of the device is also relatively small (Figure 5c).
Both high-resistance c-MgZnO and low-resistance h-MgZnO exist in the MgZnO thin film. Based on the basic theory of the avalanche and tunneling breakdown mechanisms, if the carrier density in the low-resistance h-MgZnO is high enough or the effective thickness of the high-resistance c-MgZnO is thin enough, the breakdown probability would be much higher, a large number of carriers in the low-resistance part would break through the high-resistance part under a high bias voltage (Figure 5a). When near UV light irradiates the mixed-phase MgZnO-based UV detector, electrons and holes are generated in the low-resistance h-MgZnO. Because most high-resistance c-MgZnO blocks the collection of the photogenerated carriers, the near UV response of the device is relatively small (Figure 5b). When deep UV light irradiates the bared device, electrons and holes are generated in both h-MgZnO and c-MgZnO. Because the breakdown probability is also not high enough, the deep UV response of the device is also relatively small (Figure 5c).
When near UV light irradiates the mixed-phase MgZnO-based UV detector with 20–40 nm Ag NPs, because of both the quadrupole plasmon resonance and Rayleigh scattering effects of the Ag NPs, the h-MgZnO in the device can absorb more near UV light. Although the density of the photogenerated carriers could just increase by several times, some part of the c-MgZnO could be broken down. Therefore, the near UV response of the modified device is 51.6 times of that of the bared device (Figure 5a). When near UV light (235 nm) irradiates the modified device, because of the intense Rayleigh scattering effect of the Ag NPs, both the c-MgZnO and h-MgZnO in the device can absorb more deep UV light. Not only does the density of the photogenerated carriers in the h-MgZnO increase but also the effective thickness of the high-resistance c-MgZnO decreases. Therefore, a large amount of c-MgZnO could be broken down by the photogenerated carriers, and the deep UV response of the modified device was 226 times of that of the bared device (Figure 5e). Because the scattering cross section of Ag NPs is proportional to the size of the Ag NPs, the 10–15 nm Ag NPs could just cause slightly higher absorption of the device, and there is no obvious electronic breakdown process in the modified detector under both near and deep UV conditions. Thus, 10–15 nm Ag NPs could not cause a great enhancement in the UV response of the device as the 20–40 nm Ag NPs. The 100 nm Ag NPs do not have an effective optical function at 350 nm near UV light as small size Ag NPs, so the near UV response of the modified device did not change. Only the sparsely distributed small-sized Ag NPs slightly increase the deep UV response of the device.
There are two problems in our analysis, one is that what type of breakdown effect exist in the mixed-phase MgZnO, and the other one is that if the effect of the Ag NPs is associated with the mix crystal structure and the UV response of the bared device. Figure 6a,b shows the IV curves of the mixed-phase MgZnO UV detector and the device with 20–40 nm Ag NPs under different temperature conditions. The current of the bared device nearly increased linearly with bias voltage under different temperature conditions, so less breakdown phenomenon appeared in the bared device (Figure 6a). The current of the modified device increased greatly at a given bias voltage under different temperature conditions, and the breakdown voltage decreased obviously under higher temperature, so the tunnel breakdown phenomenon is main reason for the high UV response of the device with 20–40 nm Ag NPs, and the modification of the Ag NPs introduces tunneling breakdown and high gain of the mixed-phase MgZnO detector at deep UV light (Figure 6b). For MIS tunneling junction with one high resistance layer and low resistance layer, the tunneling probability would increase greatly with the thickness (d) of the high resistance layer and the numbers of carriers in the low resistance parts, as shown in eq 5

\[ T_i = \exp\left(-\frac{2d\sqrt{2qm \times \phi_T}}{h}\right) \]  

(5)
When the deep UV light is added on the mixed-phase MgZnO detector with 20–40 nm Ag NPs, high-resistance c-MgZnO absorbs more deep UV light, the decrease in resistance of the c-MgZnO is equal to a decrease in effective thickness of the high-resistance c-MgZnO, and more deep UV light could also increase the carrier density in the low-resistance h-MgZnO, so the tunneling breakdown probability between one c-MgZnO/h-MgZnO increased greatly, from eq 1. Because many pairs of c-MgZnO/h-MgZnO are broken down in the mixed-phase MgZnO thin film, the $I_{\text{sh}}$ and the deep UV response of the device is much higher than the bared device.

Figure 6c–e shows the effect of the 20–40 nm Ag NPs on the UV response characteristics of c-MgZnO-based UV detector, h-MgZnO-based UV detector, and mixed-phase MgZnO-based detector with much smaller UV response. The 20–40 nm Ag NPs do not influence the UV response of the c-MgZnO-based device with a peak response at 250 nm (Figure 6c). The 20–40 nm Ag NPs increase the response of the h-MgZnO-based device at 330 nm by 2.8 times, which is similar as the reported results on the ZnO UV detector (Figure 6d). For the mixed-phase MgZnO-based UV detector with much lower response (0.0019 A/W at 240 nm UV light), the 20–40 nm Ag NPs do not influence the UV response of the device at 240 nm, and the response of the modified device at 330 nm is increased by 14.8 times (Figure 6e). Therefore, both optical function of the 20–40 nm Ag NPs on UV light and the tunneling breakdown phenomenon cause the great enhancement in deep UV response of the mixed-phase MgZnO detector. Although theoretically, Rayleigh scattering effect of Ag NPs could enhance the amount of deep UV light that is absorbed by the MgZnO thin film, the quadrupole plasmon resonance effect of the Ag NPs could enhance much more in intensity of the absorbed near UV light, so the deep UV response of the c-MgZnO-based detector could not be improved by 20–40 nm Ag NPs, and the near UV response of the h-MgZnO-based detector could be improved by several times. There is a potential tunneling breakdown phenomenon in the mixed-phase MgZnO-based detector, which could induce high internal gain and UV response to the device. For the mixed-phase MgZnO detector with a higher UV response (0.446 A/W at 235 nm), the tunneling breakdown phenomenon occurs much easier. Compared with the quadrupole plasmon resonance effect of 20–40 nm Ag NPs on near UV light, the Rayleigh scattering effect of the Ag NPs on deep UV light could cause breakdown phenomenon through much more c-MgZnO particles and amplification times in the mixed-phase MgZnO detector, so the deep UV response of the modified device could be enhanced by 226 times, which is bigger than its enhancement times on the near UV response of the device. But for the mixed-phase MgZnO detector with low UV response, the tunneling breakdown phenomenon occurs much harder, the Rayleigh scattering effect of the Ag NPs on deep UV light could not cause obvious breakdown phenomenon through c-MgZnO particles in the device, so the deep UV response of the modified device do not increase. From the effect of the 20–40 nm Ag NPs on the UV response of different structures of MgZnO-based detector, the electric tunneling breakdown phenomenon makes much more function in deep UV response of the modified mixed-phase MgZnO-based detector. Compared with the reported results on the enhancement effect of Ag NPs on the near UV response of the ZnO detector making use of the optical surface plasma effect, both the optical Rayleigh scattering effect of the 20–40 nm Ag NPs and the electric tunneling breakdown between different structures of MgZnO caused the great enhancement in deep UV response of the mixed-phase MgZnO detector.

### CONCLUSIONS

In conclusion, the effects of the Ag NPs with different sizes on the performance of mixed-phase MgZnO-based UV detectors are studied. When densely distributed, Ag NPs with sizes ranging from 20 to 40 nm are introduced, the response of the mixed-phase MgZnO detector at 350 nm near UV light is greatly enhanced by 51.6 times. Surprisingly, the response of the modified mixed-phase MgZnO-based detector at 235 nm deep UV light get 226 times enhancement, which is much greater than those of Ag NPs with the other sizes. The electrical quasi-tunneling breakdown phenomenon that is caused by the Rayleigh scattering effect of the 20–40 nm Ag NPs is the main reason for their great enhancement function in the solar-blind UV response of the MgZnO detector. Also, relative less electrical breakdown phenomenon that is caused by both the LSP enhancement effect and Rayleigh scattering effect of the 20–40 nm Ag NPs is responsible for the improvement in the near UV response of the modified mixed-phase MgZnO detector. In addition, the 20–40 nm Ag NPs could improve the response speed of the mixed-phase MgZnO-based detector. The enhancement of the Ag NPs also relies on the structure and basic UV response of the MgZnO thin films. Therefore, an effective and simple modification method of densely distributed small-sized Ag NPs is developed, which is beneficial for both the sensitivity and response speed of mixed-phase MgZnO detectors at both near UV and deep UV light.

### EXPERIMENTAL SECTION

#### Preparation of the Ag NPs.
Ag NPs with different sizes are fabricated in two steps. First, Ag thin films with thicknesses ranging from 2 to 10 nm were deposited on fused quartz substrates and then the Ag thin films were annealed at 350 °C for 45 min under vacuum (10⁻² Pa) conditions.

#### Preparation of the MgZnO Thin Film.
MgZnO thin films are deposited on quartz substrates by pulsed laser deposition. During the deposition process of the MgZnO thin films, a KrF pulsed excimer laser with a 30 J cm⁻² laser energy density was applied to the Mg₃Zn₅O₇ ceramic source target material. The deposition temperature was maintained at 350 °C, and high purity O₂ with a 30 scm flow rate was injected into the chamber to maintain the oxygen pressure at 3.3 Pa. Then, Ag NPs with different sizes were produced on the MgZnO films by the same method as for the Ag NPs on fused quartz substrates.

#### Characteristics of the Ag NPs and MgZnO Thin Film.
The structural characteristics of the MgZnO thin film were measured by a D/max-RA X-ray diffractometer (XRD). The morphology of the Ag NPs was characterized by a Hitachi SU-70 field-emission scanning electron microscope (SEM). The absorption spectrum of the MgZnO thin film and the extinction spectra of Ag NPs with different sizes were measured on a Shimadzu UV-2450PC scanning spectrophotometer.

#### UV Response Characteristics of the Bared and Modified MgZnO Detectors.
The UV response characteristics of the MSM structure MgZnO UV detectors were measured by a 200 W UV-enhanced Xe lamp and a monochromator. The $I_{\text{sh}}$ and $I_{\text{det}}$ of the MgZnO UV detectors were determined by a Keithley 4200A semiconductor analyzer. The time response curves of the mixed-phase MgZnO-based UV photodetectors are measured by a high-speed oscilloscope.
connected to a pulsed deep UV laser ($\lambda = 266$ nm) source with a pulse width of 30 ns.

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**Notes**

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