Photoresponse and trap characteristics of transparent AZO-gated AlGaN/GaN HEMT*

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AZO-gated and Ni/Au-gated AlGaN/GaN HEMTs are fabricated successfully, and an excellent transparency of AZO-gated electrode is achieved. After a negative gate bias stress acts on two kinds of the devices, their photoresponse characteristics are investigated by using laser sources with different wavelengths. The effect of photoresponse on AZO-gated electrode device is more obvious than on Ni/Au-gated electrodes device. The electrons are trapped in the AlGaN barrier of AZO-gated HEMT after it has experienced negative gate bias stress, and then the electrons can be excited effectively after it has been illuminated by the light with certain wavelengths. Furthermore, the trap state density D_T and the time constant τ_T of the AZO-gated Schottky contact are extracted by fitting the measured parallel conductance in a frequency range from 10 kHz to 10 MHz. The constants of the trap range from about 0.35 μs to 20.35 μs, and the trap state density increased from 1.93×10^{13} $eV^{-1}\cdot cm^{-2}$ at an energy of 0.33 eV to 3.07×10^{11} $eV^{-1}\cdot cm^{-2}$ at an energy of 0.40 eV. Moreover, the capacitance and conductance measurements are used to characterize the trapping effects under different illumination conditions in AZO-gated HEMTs. Reduced deep trap states' density is confirmed under the illumination of short wavelength light.

Keywords: AlGaN/GaN, HEMT, AZO, trap

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1. Introduction

AlGaN/GaN heterostructure transistor is considered as a great candidate in power and switching applications due to its high saturation electron velocity and high breakdown voltage[1,2] Al-doped ZnO (AZO) has many important applications in transparent electronics.[3,4] The transparent gate AlGaN/GaN HEMT has promising applications in transparent electronics. Evaluation of trap characteristics can be implemented on transparent gate device illuminated by light. Recently, the AZO-gated AlGaN/GaN HEMT with excellent characteristics[5,6] and the Ni/ITO-gated AlGaN/GaN HEMTs[7] have been reported. The photosensing characteristics have been reported on AZO-gated AlGaAs/InGaAs HEMTs.[8] However, few results are reported on the photoresponse and trap characteristics of transparent gate AlGaN/GaN HEMT. Thus, the effects of light illuminating on saturation current and trap states characteristic need further studying.

In this paper, the AZO-gated AlGaN/GaN HEMT is fabricated. After introducing the traps charging under the action of negative gate bias stress, the photoresponse of the device is investigated compared with the conventional Ni/Au-gate device on the same epitaxial structure. Moreover, the constants of the trap and the trap states density are extracted by capacitance and conductance measurements in a frequency range from 10 kHz to 10 MHz. In addition, the conductance measurements under the illumination with different wavelengths are also investigated.

2. Material growth and device fabrication

The large-size gate electrode device, named FAT-FET, is used for investigating transparent gate electrode characteristics, which is shown in Fig. 1. The gate length, gate width, and source–drain spacing are 50 μm, 100 μm, and 56 μm, respectively. Meanwhile, Schottky diode circle structures are fabricated. The diameters of the inner and outer circles are 120 μm and 270 μm, respectively. The transparent gate electrode AZO (210 nm) is deposited by using pulsed laser deposition (PLD) system under the optimal deposition conditions, and the transmittance of the AZO is shown in Fig. 2. In addition, the Ni/Au-gated HEMTs are also produced for comparison, and the Ni/Au film has a thickness of 10 nm/200 nm. The detailed device processes have been described in another paper.[5] The measurement instrument used in this paper is Keithley 4200 semiconductor parameter analyzer.

The transfer characteristics and the transconductance characteristics of the AZO-gated HEMTs and Ni/Au-gated HEMTs are shown in Fig. 3. Compared with Ni/Au-gated

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HEMTs, AZO-gated HEMTs exhibit small saturation current and low peak transconductance. This can be explained by the fact that there are some oxygen donors and traps introduced at the gate interface due to the AZO gate electrode that has formed in the oxygen environment,[6] which results in the reduction of two-dimensional electron gas (2DEG). The threshold voltage of the AZO-gated HEMT is about −2.2 V, and that of Ni/Au-gated HEMT is about −2.3 V.

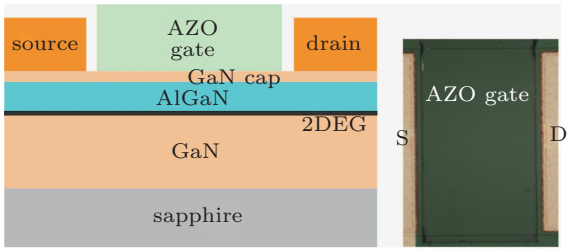


Fig. 1. (color online) (a) Schematic diagram and (b) photomicrograph of the FAT-FET (AZO-gated) used in the study.

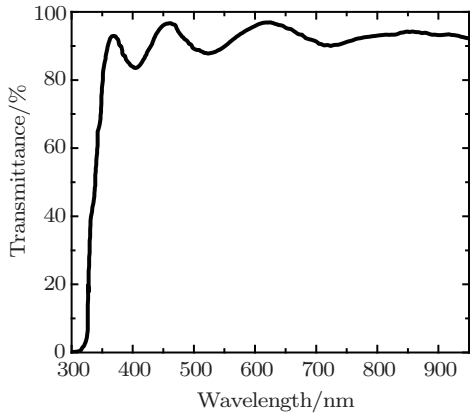


Fig. 2. Transmittance spectrum of AZO materials.

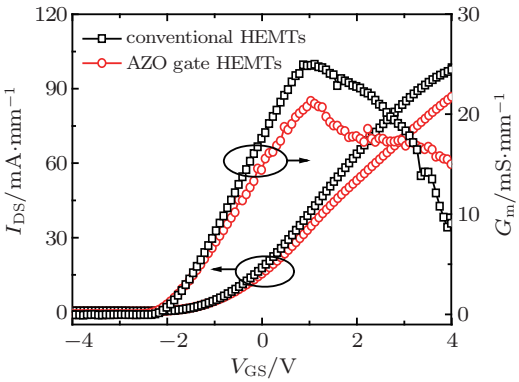


Fig. 3. (color online) Transfer characteristics and the transconductance for the AZO-HEMTs and the Ni/Au-HEMTs, respectively.

3. Photoresponse and traps characteristics

In order to study the photoresponse characteristics of the AlGaN/GaN HEMT with AZO transparent gate electrode, the experiment with electric stress and illumination on AZO-gated HEMT is performed, and the conventional Ni/Au-gated HEMT is also employed for comparison. The stress bias was $V_G = -40$ V, $V_D = 0$ V, $V_S = 0$ V for 100 s for the off-state. After being experienced by the negative gate bias stress, the HEMT is placed in the dark for 100 s and then the slight change of saturation current is observed, indicating that the effect of stress on saturation current cannot recover rapidly with increasing time. Stressing and measuring in a certain illumination each time, may be considered as a circle. After being stressed each time, the device is placed in the ambient of blue, green and red light for measuring, respectively. *I*–*V* characteristics in different ambient conditions are measured. The wavelengths of red light, green light and blue light are 650 nm, 532 nm, and 405 nm, respectively. The total test results are shown in Figs. 4 and 5.

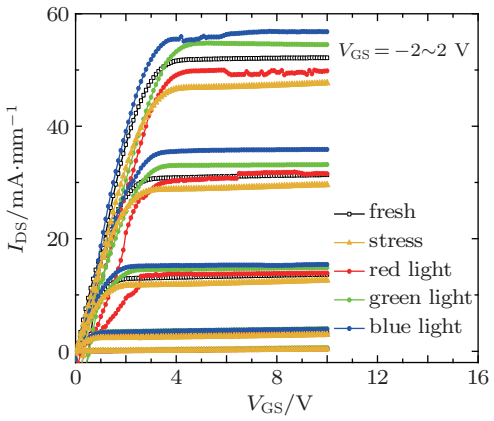


Fig. 4. (color online) I_{DS}–V_{DS} characteristics of the AZO-gated HEMTs with electric stress under different illumination conditions.

As can be noted in Figs. 4 and 5, the output saturation currents of the AZO-gated HEMT and the Ni/Au-gated HEMT both decrease after experiencing the electric stress. It can be explained as follows. Under the stress condition, the large reverse bias voltage is applied to the gate electrode, which results in the strong depletion of channel electrons. Meanwhile, due to the high electric field, the inherent electron trap in AlGaN barrier layer is charged by the massive electrons resulting from the strong reverse bias voltages on the gate electrode. Consequently, the 2DEG concentration in the channel is reduced, thus the drain current decreases. In addition, it is necessary to mention that the Ids values of two kinds of devices both increase slightly after 100 s in the dark as indicated by the experimental result, and the same results were observed by Tapajna *et al.*[9]

In order to investigate the recoveries of two kinds of devices after being stressed, three lasers with varying wavelengths are employed to illuminate the gate electrodes. In the case of AZO-gated HEMT, compared with the output saturation current after being stressed for 100 s, Ids values with the red light, green light, and blue light illuminations are increased by 4.3%, 14.9%, and 19.1%, respectively. The Ids values after green and blue light illuminations exceed the output current in the fresh state. As for Ni/Au-gated HEMTs, compared with the output saturation current under post-stressing condition,

Ids values with the red light, green light, and blue light illuminations are increased by 1.9%, 3.8%, and 9.4%, respectively. Under the illumination condition, the output saturation current of the two devices is increased, but the magnitudes of the rise are different. It reveals that the trapped electrons can obtain energy by illumination, so the excited electrons will escape from the traps and the electron concentration in the channel is increased.[9] In addition, photon-generated carriers are induced by illumination, so that the electron concentration in the channel is even more than the normal concentration. However, 10 min later after removing illumination, the Ids reaches its fresh state, which indicates the recombination of photon-generated carriers. Furthermore, because the gate region of the AZO-gated HEMT is transparent, the light can easily transmit it, and therefore the photoresponse is more sensitive, which is beneficial to investigating the trap characteristics of the region underneath the gate as mentioned by Pei *et al.*[7] Thus, frequency-dependent capacitance and conductance measurements are performed to analyze the AZO-gated HEMTs.

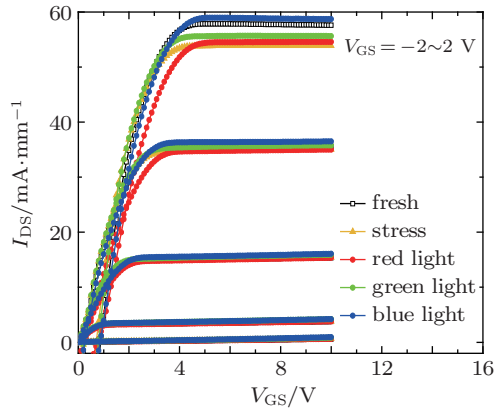


Fig. 5. (color online) I_{DS}–V_{DS} characteristics of the Ni/Au-gated HEMTs with electric stress under different illumination conditions.

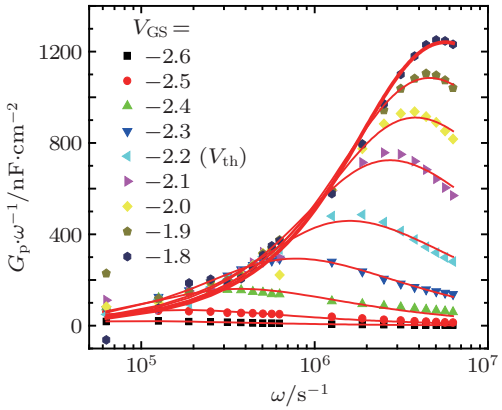


Fig. 6. (color online) Conductance as a function of radial frequency at selected gate biases.

Figure 6 shows the variations of conductance with radial frequency for the AZO-gate HEMTs at selected gate biases. The trap state density D_T and the time constant τ_T can be extracted by fitting the measured parallel conductance G_p as a function of radial frequency $\omega = 2\pi f$ according to equation $G_p/\omega = (qD_T/2\omega\tau_T)\ln[1+(\omega\tau_T)^2]$. G_p/ω has a maximum at $\omega = 2/\tau_T$ at which maximum $D_T = 2.5G_p/q\omega$. The fitted curves and measured data are in good consistence with each other.[10,11]

According to the fitting results, the time constant of the trap state as a function of the gate voltage is plotted in Fig. 7. As can be seen from Fig. 7, when the bias voltage is in a range of −2 V–2.8 V, the constant of the trap is about 0.35 μs–20.35 μs.

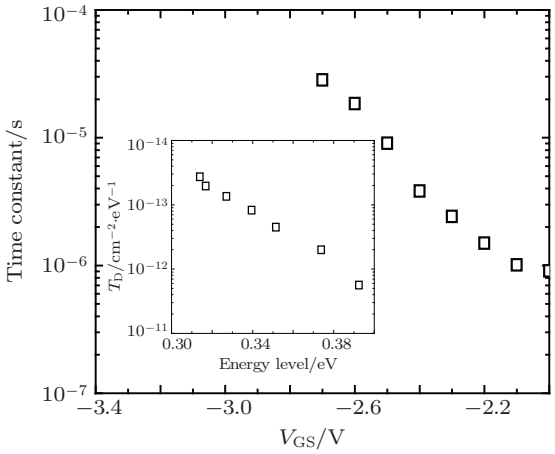


Fig. 7. Trap state time constant as a function of gate voltage, with the inset showing trap state density as a function of their energy.

The trap state energy can be calculated by using time constant $\tau_T = (\sigma_T N_c v_T)^{-1}\exp(E_T/kT)$, in which the trap state capture cross section $\sigma_T = 3.4\times10^{-15}$ cm^{-2}, the effective density of states of conduction band $N_c = 2.2\times10^{18}$ cm^{-3}, and the average velocity of thermal motion of carrier $v_T = 2.6\times10^7$ cm/s are used. The trap state density as a function of energy level is shown in the inset in Fig. 7. The trap state density in the AZO-gated HEMT increases from 1.93×10^{13} eV^{-1}·cm^{-2} at an energy of 0.33 eV to 3.07×10^{11} eV^{-1}·cm^{-2} at an energy of 0.40 eV. It was observed to accord with the result reported by Hori *et al.*[12]

In order to further study the trap characteristics of transparent AZO-gated HEMT the interface state analysis and comparison are carried out under the illumination condition. The capacitance and conductance measurements in a frequency range from 10 kHz to 10 MHz are utilized to characterize the trapping effects under different illumination conditions. With the 5-min illumination of light with different wavelengths, the fitting results of the test data measured from CV variable-frequency scanning are shown in Fig. 8. As Roy *et al.* reported that the photo-responsivity was found to decrease with increasing illumination wavelength,[13] meanwhile, there is an interface reflection effect on the gate interface, therefore, the red light response is weak and slightly affects the device. Thus, it mainly focuses on the responses under the green and blue light in this part. Moreover, due to the limited frequency range, some deeper level traps cannot be analyzed, but the

more important significance of this research is to indicate the trend of the trap characteristics after illumination of transparent AZO-gated HEMT.

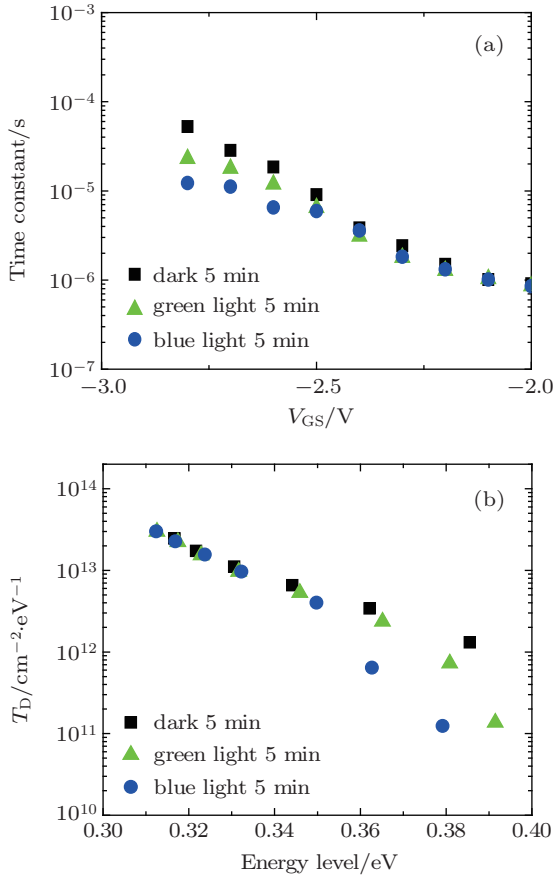


Fig. 8. (color online) Plots of trap state time constant versus (a) gate voltage and (b) energy level, with the illuminations of different-wavelength light.

As figure 8(a) displays, under the illuminations of green and blue light, the trap state time constant decreases, especially under the blue light illumination, and it indicates that the light illumination can make the trap level shallower. The shorter the wavelength, the more easily the deep level trap can be excited, so that the blue light condition can lead to the obvious result.[14] It is observed from Fig. 8(b) that the trap concentration of the deep level is reduced under the illuminations of green and blue light, which indicates that the deep level traps will decrease by illumination. The shorter the wavelength, the higher the degree of reduction is. Accordingly, the increase of output current verifies that the concentration of deep level traps is reduced by illumination, which makes the electron released by deep level trap capture, so that the concentration of 2DEG could be increased, leading to the rise of the output saturation current.

4. Conclusions

AlGaN/GaN high-electron-mobility transistors (HEMTs) with AZO transparent gate electrodes are fabricated and investigated. The effect of photoresponse on AZO-gated electrode device is more obvious than that of Ni/Au-gated electrode device. The capacitance and conductance measurements in a frequency range from 10 kHz to 10 MHz are utilized to characterize the trapping effects under different illumination conditions in AZO-gated HEMTs. The quantitative analysis results of the trap density and time constant are obtained. Under different illumination conditions in AZO-gated HEMTs, the reduction of the deep trap density is founded in illumination of the shorter wavelength.

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