Influence of trap level on an Al$_{0.6}$Ga$_{0.4}$N/Al$_{0.5}$Ga$_{0.5}$N metal—semiconductor—metal UV photodetector

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The irradiation intensity and temperature characteristics of each response speed sample are measured to clarify the high photosensitivity mechanism in an Al$_{0.6}$Ga$_{0.4}$N/Al$_{0.5}$Ga$_{0.5}$N metal—semiconductor—metal photodetector. A tradeoff relation could be observed between the photosensitivity and response speed when the dependence of the saturated photocurrent on the irradiation intensity was investigated by changing the irradiation intensity from 1 nW cm$^{-2}$ to 45 μW cm$^{-2}$. The rise time of the photocurrent after exposure to ultraviolet light was measured to determine the trap level density that was estimated to be ca. 10$^{15}$ cm$^{-2}$. Further, the decay time constant was obtained by investigating the dependence of the photocurrent decay time on temperature (25 °C–180 °C). By analyzing the Arrhenius plot of the decay time constant versus inverse temperature, trap level depths of 0.23 and 0.67 eV were obtained. Thus, the high photosensitivity in the Al$_{0.6}$Ga$_{0.4}$N/Al$_{0.5}$Ga$_{0.5}$N photodetector can be attributed to the carriers trapped in deep-level traps. © 2019 The Japan Society of Applied Physics

1. Introduction

A deep ultraviolet (DUV) photodetector (PD) can be applied to flame sensors and gas sensing such as O$_3$ and NO$_x$. To achieve such a device, a small size, durability, solarblindness, and high sensitivity characteristics should be achieved. Groups III–V nitride semiconductors, including AlGaN, exhibit wide bandgap energies that correspond to those of the DUV region of the spectrum. Thus, solar-blind characteristics will be obtained. Additionally, AlGaN is a stable material and, easy to mount small devices because process technology is established in LEDs. Furthermore, high efficient light receiving devices are expected because of the direct transition semiconductor. Therefore, several researchers have investigated AlGaN-based DUV PDs with a p–n junction, pin, metal–semiconductor–metal (MSM), metal–insulator–semiconductor transistor, and multi-quantum-well structure. However, the photosensitivity and rejection ratio of the above PD were inferior to those of photomultiplier tubes (PMTs).

Recently, we have reported a high-performance solar-blind PD with a photosensitivity of 10$^9$ A W$^{-1}$ and a rejection ratio of 10$^8$, which is comparable to those of PMTs by inducing a two-dimensional electron gas on the interface of the Al$_{0.6}$Ga$_{0.4}$N/Al$_{0.5}$Ga$_{0.5}$N heterostructure. However, the characteristics of this sensor are too high compared with the sensor using a p-GaN gate type Al$_{0.6}$Ga$_{0.4}$N/Al$_{0.5}$Ga$_{0.5}$N–field-effect-transistor PD which showed a photosensitivity of 10$^3$ A W$^{-1}$ and a rejection ratio of 10$^3$, despite using the same Al$_{0.6}$Ga$_{0.4}$N/Al$_{0.5}$Ga$_{0.5}$N structure. Therefore, the target of this study is to clarify the actual gain mechanism that causes the high photosensitivity. We have reported that fall time was slow over 1000 s in our Al$_{0.6}$Ga$_{0.4}$N/Al$_{0.5}$Ga$_{0.5}$N-MSM PD because of carrier accumulation, even though a high photo current was obtained. Reference 14 reported that the persistent photoconductivity (PPC) effect was caused by carriers trapped in the deep trap level in the Al$_{0.6}$Ga$_{0.4}$N/GaN-MSM type PD. This PPC effect caused the photocurrent to remain after the UV light was turned off and delayed the rise time. With regards to an MSM PD, some groups reported that gain was generated when the carrier was trapped in a deep trap level. Therefore, the deep trap level may be related to high gain in our PD.

In this study, we focus on the deep-level trap which causes the gain. The rise time and decay time were measured to evaluate the trap level density and depth. Furthermore, we measured the dependence of the irradiation intensity on our PD for samples with differing response speeds, and we clarified that there is a tradeoff relation between the response speed and photosensitivity. In summary, the high gain was generated by the carriers that were trapped in deep-level traps.

2. Experimental methods

Figure 1(a) schematically depicts the Al$_{0.6}$Ga$_{0.4}$N/Al$_{0.5}$Ga$_{0.5}$N-MSM PD. The devices were grown using metalorganic vapor phase epitaxy on a sapphire (0001) substrate. After growing the AlN layer, a 150-nm thick unintentionally doped Al$_{0.6}$Ga$_{0.4}$N layer and a 15-nm thick unintentionally doped Al$_{0.6}$Ga$_{0.4}$N barrier layer were grown. Mesa isolation was performed using Cl$_2$ inductively coupled plasma etching. Further, the source and drain electrodes were deposited with the following layers: V (20 nm)/Al (80 nm)/Mo (40 nm)/Au (50 nm). The length and width of the receiving area was 5 and 100 μm, respectively, as depicted in Figs. 1(b) and 1(c). We prepared three types of PDs exhibiting different response speeds of more than 1000 s, 30 s, and 1 s. These three types of PDs were processed on the same Al$_{0.6}$Ga$_{0.4}$N/Al$_{0.5}$Ga$_{0.5}$N wafer; however, the electrode deposition conditions for these PDs were slightly different.

The photocurrent was measured using a semiconductor parameter analyzer (HP-4155B) and a spectroscopy with a Xe...
lamp (HAL-320) as the light source. Further, the irradiation intensity dependence was measured from 10 nW cm\(^{-2}\) to 45 μW cm\(^{-2}\) under a wavelength irradiation of 250 nm by adjusting the slit and the neutral density filter. The temperature-dependent characteristics were measured using the Peltier element and by increasing the temperature from 20 °C to 180 °C.

3. Results and discussion

Figure 2 denotes the photocurrent behavior of slow and fast PDs with an applied \(V_{DS}\) bias of 5 V. In both the samples, the photocurrent rise time was fast after the UV light intensity of 10 μW cm\(^{-2}\) was turned on; further, the photocurrent increased within 1 s. In contrast, the response differed considerably after the UV light was turned off. As can be observed from Fig. 2(a), the photocurrent of the slow PD remained high despite the UV light being turned off. The maximum photocurrent that was achieved for the fast PD (10 × 10^4 A) [Fig. 2(b)] was less than that for the slow PD (10 × 10^5 A) during UV exposure. However, when the UV light was turned off, the photocurrent rapidly decreased to the dark current level. These results indicate that PPC will be observed in the MSM PD with a slow response speed (slow PD).

To perform a detailed investigation, we measured the influence of irradiation intensity on the photocurrent response of three samples, among which each exhibited a different response speed (slow PD, medium PD, and fast PD). The UV light irradiation (wavelength = 250 nm) intensity was varied from 1 nW cm\(^{-2}\) to 45 μW cm\(^{-2}\). Figure 3 depicts the relation between the irradiation intensity and the measured saturation photocurrent. Further, a clear relation can be observed between the irradiation intensity and the photocurrent. The slow PD exhibited a high photocurrent for low irradiation intensity, whereas the photocurrent response for the fast sample was low and was comparable to a dark current. Further, we assume that this difference in the photocurrent between the slow and fast responses at a low irradiation intensity can be attributed to the trap levels. However, the photocurrents of both the slow and fast samples were similar at high irradiation intensities (more than 45 μW cm\(^{-2}\)). This behavior indicates that the trap levels were quickly filled by the carriers at a high irradiation intensity, indicating that the differences between the photocurrent for fast and slow samples may not be readily observed at a high irradiation intensity.

Further, we estimated the trap level density by focusing on the rise time for different UV irradiation intensities ranging from 1–100 nW cm\(^{-2}\). Figure 4(a) depicts the photocurrent behavior of slow PD over time. The UV light was turned on...
Further, the increase rate of the photocurrent was dependent on the irradiation intensity. A steep rise time was observed at an irradiation intensity of 100 nW cm\(^{-2}\). In comparison, a gentle increase was observed under low-intensity UV light (1 nW cm\(^{-2}\)). In this study, we define the saturation time \(T_{\text{sat}}\) as the time required to reach the saturation photocurrent. Figure 4(b) shows the graph that has been replotted as the irradiation intensity versus saturation time; an inverse proportion was observed between the irradiation intensity and saturation time. This result indicates that the product of both these values is constant. The irradiation intensity can be converted to photon count per time \(N_{\text{photo}}\). Therefore, we estimated the trap density \(N_{\text{tr}}\) using formula (1) as follows:

\[
N_{\text{tr}} = T_{\text{sat}} \times N_{\text{photo}},
\]

where the light reflectance and absorption of the Al\(_{0.6}\)Ga\(_{0.4}\)N barrier layer were considered. Further, the estimated trap level density was observed to be \(10^{12}\) cm\(^{-2}\).

We estimated the trap state depth from the temperature-dependent characteristics of the decay time depicted in Fig. 5(a). The temperature was changed using the Peltier element from 20 °C to 180 °C. After turning off the UV light with an irradiation intensity of 10 \(\mu\)W cm\(^{-2}\), the decay time constant of the slow PD was estimated by

\[
I = I_0 \exp \left( \frac{-t}{\tau} \right)^\beta
\]

for the data measured at each temperature. (b) Arrhenius plot using the decay time constant and inverse temperature in K. The dashed line at 100 °C shown in Fig. 5(a) denotes one result of the fit

\[
\ln \left( \tau T^2 \right) = \frac{E_t}{kT} + \ln \left( \frac{\hbar^3}{2(2\pi)^2 \epsilon_0 m e^2 g \sigma_c M_c} \right),
\]

where \(k\) denotes the Boltzmann constant, \(h\) denotes the Planck constant, \(m_e\) denotes the effective mass of the electron, \(m_0\) denotes the electron mass, \(\sigma_c\) denotes the degeneracy of the states, \(g\) denotes the captured cross section, and \(M_c\) denotes the shape factor. From formula (3), the trap level depth can be estimated based on the decay time constant and temperature. A two-trap level depth of 0.23 and

Fig. 4. (Color online) (a) Photocurrent of slow PD with respect to time for a \(V_{GS}\) bias of 5 V under 1-, 2-, 4-, 5-, 7.5-, 20-, 30-, and 100-nW cm\(^{-2}\) UV light with an illumination wavelength of 250 nm. (b) Dependence of the saturation time on the UV light irradiation intensity.

Fig. 5. (Color online) (a) Temperature dependence of the photocurrent behavior when the \(V_{GS}\) bias is 5 V. Measurements were performed at 20 °C, 60 °C, 100 °C, 140 °C, and 180 °C, and the temperature was changed using the Peltier element. After turning off the UV light with an irradiation intensity of 10 \(\mu\)W cm\(^{-2}\), the time decay constant of the slow PD was estimated by

\[
I = I_0 \exp \left( \frac{-t}{\tau} \right)^\beta
\]

where \(I_0\) denotes the saturated photocurrent and \(\beta\) denotes the decay exponent (0 < \(\beta < 1\)).
0.67 eV were obtained from the Arrhenius plot. Further, the deeper trap level will have an important role for gain.

The gain value (G) is given by formula (4), as described by the Shockley–Read–Hall process:

\[
G = \frac{\Delta n}{\Delta p} = \frac{\tau_n}{\tau_p} = 1 + \frac{N_{tr}}{N_F}
\]  

(4)

where \(\tau_p\) and \(\tau_n\) denote the carrier lifetimes; further, \(N_{tr}\) is quantitatively equal to the hole density in the conduction band while the Fermi level is positioned at the energy level of the recombination centers. Figure 6 depicts the gain values that are calculated using formula (4) with respect to each trap level density. We assumed that the trap level can be observed in a distribution from 1–50 nm. The reason for this assumption is that we speculate the origin of the trap level to be the interface between the electrode and AlGaN or the damaged layer, as will be described later. Based on this assumption, the trap level density was observed to range from \(2 \times 10^{17}\) to \(1 \times 10^{19}\) cm\(^{-3}\). When the trap state depth became 0.23 eV, no gain could be observed despite the high trap level density. However, for the deep trap level of 0.67 eV, a gain ranging from \(2 \times 10^3\) to \(8 \times 10^4\) was obtained. As depicted in Fig. 3, a difference of approximately \(10^3\) could be observed between the photocurrents (photosensitivity) of the sample with fast response and that with slow response. Therefore, these gain values do not largely deviate from the result, even though they are only an approximation. Further, we speculate that the carriers generated by the UV light are captured in deep trap levels. Thus, the carrier life time is longer than that of a no-trap state PD. Based on these results, we can conclude that the high photosensitivity of our PD could be attributed to the trap level. Therefore, we have to control the trap level in order to develop high-quality PDs.

Finally, we discuss the position and origin of the trap level. Some groups have reported that such a deep trap level was generated by impurities, dislocation densities, or the surface level. However, the actual cause has not been clarified. We indicate that the trap level can be observed at the interface between the electrodes and AlGaN or the damaged layer. Therefore, it is necessary to control the trap state density and depth to improve the high photosensitivity of the Al\(_{0.6}\)Ga\(_{0.4}\)N/Al\(_{0.5}\)Ga\(_{0.5}\)N-MSM PD. Based on the results, we can conclude that the high photosensitivity of our PD could be attributed to the trap level. Therefore, we have to control the trap level in order to develop high-quality PDs.

We discuss the position and origin of the trap level. Some groups have reported that such a deep trap level was generated by impurities, dislocation densities, or the surface level.26–28) However, the actual cause has not been clarified. We indicate that the trap level can be observed at the interface between the electrodes and the Al\(_{0.6}\)Ga\(_{0.4}\)N barrier layer. At times, we obtained an asymmetric \(I–V\) curve that has been denoted in Fig. 7 while measuring our samples. The asymmetric \(I–V\) curve indicates that the trap levels were only formed on one side because the same electrodes were considered as both source and drain. If dislocations, impurities, or the surface level acted as the origin of the trap level, the trap levels would be uniformly distributed. Therefore, when the source and drain electrodes were replaced, the \(I–V\) curve was expected to be symmetric. We employed the same Al\(_{0.6}\)Ga\(_{0.4}\)N/Al\(_{0.5}\)Ga\(_{0.5}\)N structure wafer and device pattern. The most likely process that could be considered to be the source of asymmetry was the electron-beam deposition, and the surface treatment condition could be easily disturbed. This situation indicates that the trap levels were likely to be formed at the interface between the electrodes and the Al\(_{0.6}\)Ga\(_{0.4}\)N barrier layer during electron-beam deposition and/or the surface treatment process.

4. Conclusions

In this study, the high photosensitivity mechanism of the Al\(_{0.6}\)Ga\(_{0.4}\)N/Al\(_{0.5}\)Ga\(_{0.5}\)N-MSM PD was clarified. This high photosensitivity was attributed to the gain generated by the carriers trapped in deep trap levels. There was a tradeoff relation between the photosensitivity and response speed. Further, the trap level density based on the rise time was observed to be ca. \(10^{12}\) cm\(^{-2}\) by varying the irradiation intensity. Trap level depths of 0.23 and 0.67 eV were observed by examining the trend of the decay time constant for inverse temperature (Arrhenius plot). Further, the trapped states can be observed at the interface between the electrodes and the Al\(_{0.6}\)Ga\(_{0.4}\)N barrier layer. Therefore, it is necessary to control the trap state density and depth to improve the photosensitivity of the Al\(_{0.6}\)Ga\(_{0.4}\)N/Al\(_{0.5}\)Ga\(_{0.5}\)N-MSM PD.

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