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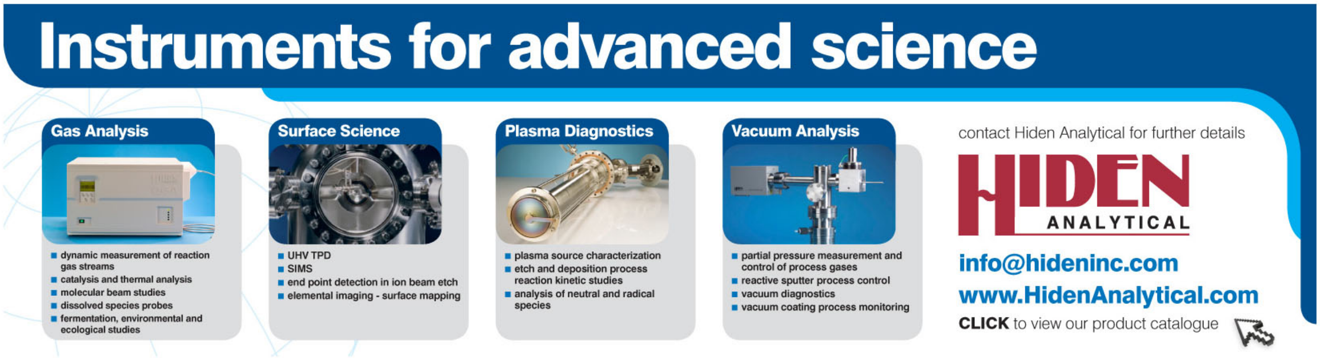

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Effects of persistent photoconductivity on the characteristic performance of an AlGaN/GaN heterostructure ultraviolet detector

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Photocurrent (PC) transient characteristics of an AlGaN/GaN heterostructure UV detector have been studied. We observed that the PC transients of the AlGaN/GaN heterostructure depended strongly on its initial conditions. Under a pulsed laser excitation, the PC responsivity, dark current level, and decay time constant all increased progressively with the number of successive excitation pulses and eventually saturated at constant values after about 30 pulsed laser exposures. Our results indicate that the observed PC transient characteristics are directly correlated with the effect of persistent photoconductivity in the two-dimensional electron gas region caused by deep level impurities and can have a significant influence on the performance of the UV photodetectors based on AlGaN/GaN heterostructures. © *1998 American Institute of Physics.* [S0003-6951(98)04422-2]

The group III nitride wide band gap semiconductors have been recognized recently as a very important technological material system for fabricating optoelectronic devices operating in the blue/UV spectral region and electronic devices capable of operating under high-power and high-temperature conditions.[1] The commercial availability of superbright blue/green InGaN/GaN multiple quantum well (MQW) light emitting diodes,[2] the recent success of cw operation of $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{N}/\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{N}$ ($y>x$) MQW blue-violet laser diodes,[3] and the demonstration of high-performance AlGaN/GaN heterojunction field-effect transistors[4–6] and GaN *p*-*i*-*n* visible blind UV detectors[7,8] are all clear evidence of the great potential of this new material system.

An important aspect remaining to be understood and improved (in III-nitrides) is the defect and doping properties of nitride epilayers, heterojunctions (HS), and alloys. Deep level impurities and the associated persistent photoconductivity (PPC) effect have been observed in Mg-doped *p*-type GaN epilayers,[9,10] *n*-type GaN epilayers,[11–13] and AlGaN/GaN heterostructures.[14] Theoretical investigations on deep level impurities and PPC in GaN have also been carried out recently.[15,16] The effects of deep level impurities and PPC on AlGaAs/GaAs heterojunction device characteristics and on II-VI blue-green light emitting devices have been well documented.[17–19] However, effects of PPC on GaN device performance have not been investigated.

In this work, the photocurrent (PC) transient characteristics of an AlGaN/GaN HS UV detector have been studied. Under a pulsed excitation, the photoresponsivity, decay time constant, and dark current level all increased progressively with the number of successive excitation pulses and eventually saturated at constant values after about 30 pulsed laser exposures. Our results indicate that the observed characteristics are directly correlated with the effect of PPC. Thus the PPC behavior can have a significant effect on the characteristics of the UV photodetectors based on AlGaN/GaN HS, including sensitivity, noise property, dark level, and response speed.

The structure of the sample used in this study is schematically shown in the inset of Fig. 1. The structure consists of a 2 μm insulating GaN epilayer followed by a 250 Å unintentionally doped *n*-type conducting channel and a Si-doped 250 Å *n*-type $\mathrm{Al}_{0.1}\mathrm{Ga}_{0.9}\mathrm{N}$ epilayer. The typical room temperature electron concentrations were, respectively, $1\times10^{17}\ \mathrm{cm}^{-3}$ and $5\times10^{17}\ \mathrm{cm}^{-3}$ in the GaN and $\mathrm{Al}_{0.1}\mathrm{Ga}_{0.9}\mathrm{N}$ epilayers grown under similar conditions. The structure was grown on a basal plane sapphire substrate with an AlN buffer layer using a low pressure metal-organic chemical vapor deposition system. The typical room temperature 2DEG carrier density and mobility in the AlGaN/GaN HS used here were about $1.5\times10^{12}\ \mathrm{cm}^{-2}$ and $1000\ \mathrm{cm}^2/\mathrm{Vs}$. Two ohmic contacts were formed by indium electrodes and a constant

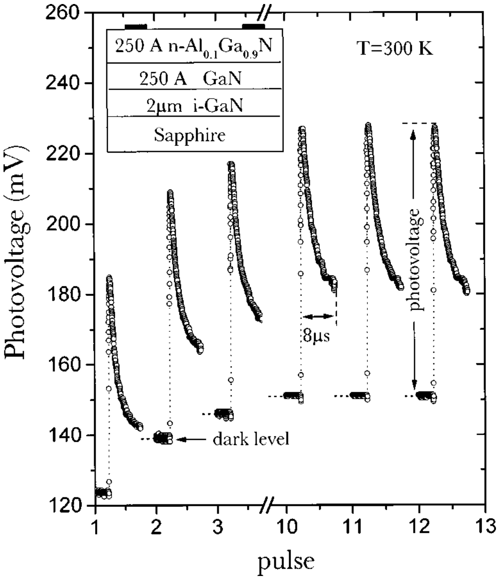

FIG. 1. Typical photoresponses of an AlGaN/GaN heterostructure measured under a successive pulsed laser excitation ($\lambda_{\mathrm{exc}}=337$ nm). The inset shows a schematic diagram of the AlGaN/GaN heterostructure used here.

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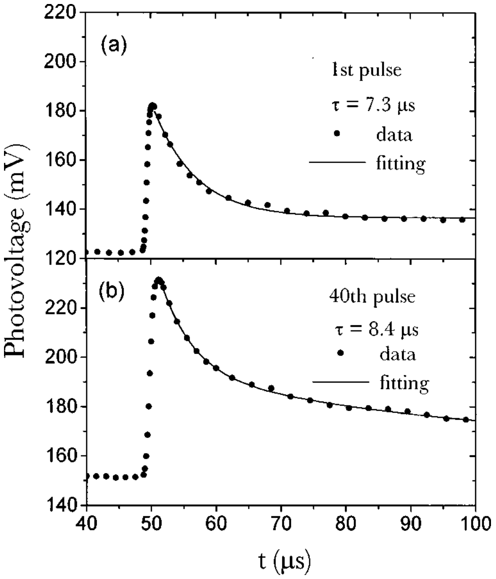

FIG. 2. Photovoltage (or photocurrent) transients measured near (a) the initial dark equilibrium state and (b) the saturation state. The solid curves are the least squares fit of the photovoltage decay transients to an exponential function, $V(t)=V_0+(V_{\max}-V_0)e^{-t/\tau}$.

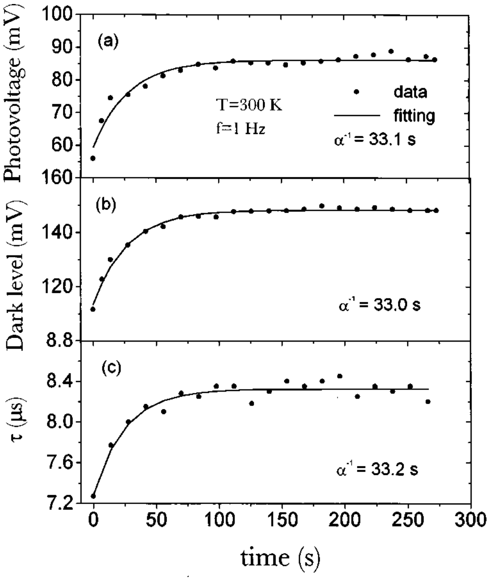

FIG. 3. Characteristic parameters of PC transients vs pulsed illumination time. (a) The photoresponsivity, (b) the dark conductivity level, and (c) the PC decay time constant, τ. The solid curves are the least squares fit of experimental data with Eq. (1) by replacing $y(t)$ with the photovoltage, dark level, or decay time constant. The fitted values of α^{-1} for all three characteristic parameters are identical, $\alpha^{-1}=33.1\pm0.1$ s.

voltage of 1.5 V was supplied to the ohmic contacts by a battery. The PC transients were measured as a photovoltage signal across a 10 kΩ series load resistor by a digital oscilloscope with a time resolution of 5 ns. The overall RC time constant of the circuit was about 0.1 μs. The excitation source was a N_2 laser ($\lambda_{\mathrm{exc}}=337$ nm) with a pulse width of about 700 ps.

Figure 1 illustrates the typical room temperature photoresponses of the AlGaN/GaN HS to successive pulsed laser excitations starting from a dark equilibrium condition. The repetition rate of the laser was 1 Hz. For each pulse, only the first 8 μs transient is shown here in order to illustrate the progressive change of the photoresponse to the successive excitation laser pulses. As we can see from Fig. 1, the PC transient characteristics are different for the initial and the subsequent pulses. The changes are progressive and can be summarized as follows: (i) the PC responsivity of the earlier pulses is smaller than that of the later pulses; (ii) the quasidark level of the previous transient is always lower than that of the subsequent transient; and (iii) the earlier PC transients decay faster than the later transients. The results shown in Fig. 1 imply that the detectivity (or sensitivity), dark level, and response speed of UV detectors fabricated from AlGaN/GaN HS will depend on the device history.

Figure 2 presents a more detailed view of the PC transients obtained near (a) the initial dark state (first pulse) and (b) the saturation state (40th pulse). We see that the PC decay transients can be described very well by an exponential function and the decay time constant, τ, is 7.3 μs for the first excitation pulse and 8.4 μs for the 40th excitation pulse. In Fig. 3 we replot (a) the photovoltage (or the photoresponsivity), (b) the quasidark level, and (c) the PC decay time constants as functions of the pulsed laser illumination time. A striking feature exhibited in Fig. 3 is that all three of these characteristic parameters have a systematic dependence on the pulsed laser illumination time,

$$y(t)=y_d+(y_{\max}-y_d)(1-e^{-\alpha t}). \tag{1}$$

Here, $y(t)$ describes the time dependence of the three characteristic parameters (photoresponsivity, dark level, and PC decay time constant), y_d ($y_{\max}$) denotes their values near the initial dark (saturation) state, and α^{-1} is a characteristic time that is required for the device to reach the saturation (or steady) state. The solid curves in Fig. 3 are the least squares fit of data with Eq. (1). The fitted values of α^{-1} obtained from Figs. 3(a)–3(c) are all identical, i.e., $\alpha^{-1}=33.1\pm0.1$ s. This clearly demonstrates that a single physical mechanism is responsible for the observed PC transient characteristics.

We have observed previously that, even for excitation photon energies below the energy gap of GaN, the photoinduced increase in the conductivity of the 2DEG channel at the AlGaN/GaN interface persists for a long period of time after the removal of illumination (PPC effect).[14] At room temperature, the typical PPC decay time constant in the structure used here is about 1000 s. Detailed investigations have shown that photoionization of deep level impurities in the AlGaN barrier and the large electron capture barrier (230 meV) of these impurities are the main cause of the PPC effect.

Most important, under a continuous light illumination, the PPC buildup kinetics are identical to Eq. (1) by replacing y with PPC current (I_{PPC}),[14]

$$I_{\mathrm{PPC}}(t)=I_d+(I_{\max}-I_d)(1-e^{-\alpha t}). \tag{2}$$

Here, I_d is the dark current and $I_{\max}$ is the PPC saturation level. It has been shown that such a buildup behavior is a natural consequence of a very slow process of electron capture by deep level impurities (or DX centers) in all types of semiconductors.[10,20] Because the time interval between consecutive excitation pulses (1 s) in this study is much shorter than the PPC decay time constant (~1000 s), we conclude that the pulsed illumination time dependence of the dark level seen here is a direct consequence of the PPC

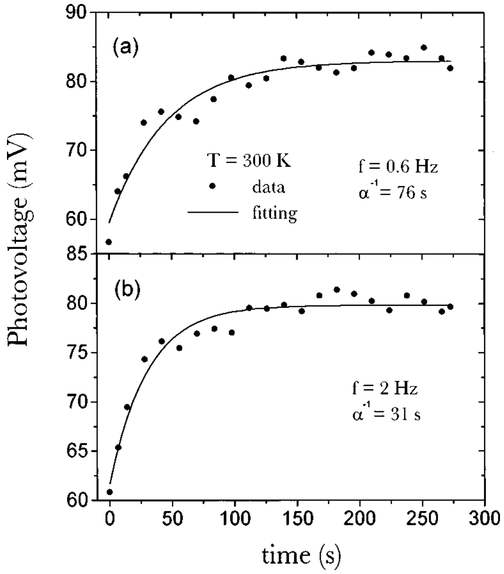

FIG. 4. Photovoltage as a function of pulsed illumination time measured at two different laser frequencies, (a) $f = 0.6$ Hz and (b) $f = 2$ Hz. The solid curves are the least squares fit of experimental data with Eq. (1) by replacing $y(t)$ with photovoltage.

buildup process. As we shall discuss below, the increases in the photoresponsivity and decay time constant with the number of successive pulsed laser exposures are also directly correlated with the PPC effect.

Under the present experimental conditions, two dominant excitation processes are involved. First, photoionization of deep level impurities in the AlGaN barrier allows the electrons to fall into the 2DEG region and gives rise to PPC. Due to slow electron capture by deep level impurities, the 2DEG density n_S builds up gradually with the illumination time following exactly the same kinetic buildup equations as PPC, $n_S(t) = n_d + (n_{\max} - n_d)(1 - e^{-\alpha t})$. At the same time, the ionized impurity concentration near the AlGaN/GaN interface, and hence the interface depletion layer thickness (d_p) also increases with the pulsed illumination time in the same fashion. Second, photoexcitation of charge carriers (electrons and holes) in the GaN layer gives rise to PC. However, photoexcited electrons and holes in the GaN layer are quickly separated spatially by the electric field inside the interface depletion layer and exhibit a recombination rate that is dependent on d_p. As d_p increases gradually, the recombination rate of the photoexcited charge carriers is expected to gradually decrease. Figure 3(c) well demonstrates this effect, where a gradual increase of the PC decay time constant with the pulsed illumination time, following exactly $\tau(t) = \tau_d + (\tau_{\max} - \tau_d)(1 - e^{-\alpha t})$, is clearly illustrated. On the other hand, the photocurrent flowing between the electrodes is directly proportional to the carrier recombination lifetime.[21,22] Thus the photovoltage (or photoresponsivity, R) is also expected to increase gradually with the pulsed illumination time as $R(t) = R_d + (R_{\max} - R_d)(1 - e^{-\alpha t})$, which is demonstrated in Fig. 3(a). Because the variations of these three characteristic parameters are due to the same physical origin, we obtain an identical value of α from Figs. 3(a)–3(c).

Figure 4 shows the room temperature photovoltage (or photoresponsivity) as a function of pulsed illumination time for different laser frequencies, f, measured at a fixed excitation intensity. We see that the time required for the photoresponsivity to reach the steady-state decreases as the excitation laser frequency increases. This is expected since the accumulated 2DEG density and hence the interface depletion layer thickness depends on the total excitation photon dose. At a fixed excitation intensity, higher excitation frequency implies a shorter illumination time required for the device to reach the steady state.

In summary, we have investigated the PC transient characteristics of an AlGaN/GaN heterostructure UV detector. We found that the photoresponsivity, dark conductivity level, and PC decay time constant initially all increase progressively with the number of successive excitation pulses. These results imply that the device characteristics (detectivity, dark current, noise property, and response speed) of UV detectors fabricated from the current AlGaN/GaN heterostructures could depend on the device history. This effect should be taken into consideration in the design of practical devices. We have demonstrated that the observed PC transient characteristics are directly correlated with the PPC effect caused by deep level impurities.

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