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Backilluminated GaN/AlGaN heterojunction ultraviolet photodetector with high internal gain

S. K. Zhang, W. B. Wang, and I. Shtau
Institute for Ultrafast Spectroscopy and Lasers, and New York State Center for Advanced Technology for Ultrafast Photonic Materials and Applications, The City College of The City University of New York, New York, New York 10031

F. Yun, L. He, and H. Morkoç
Department of Electrical Engineering and Physics Department, Virginia Commonwealth University, P.O. Box 843072, Richmond, Virginia 23284

X. Zhou and M. Tamargo
Department of Chemistry and New York State Center for Advanced Technology for Ultrafast Photonic Materials and Applications, The City College of The City University of New York, New York, New York 10031

R. R. Alfano[a]
Institute for Ultrafast Spectroscopy and Lasers, and New York State Center for Advanced Technology for Ultrafast Photonic Materials and Applications, The City College of The City University of New York, New York, New York 10031

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We report on a backilluminated GaN/$Al_{0.18}Ga_{0.82}N$ heterojunction ultraviolet (UV) photodetector with high internal gain based on metal-semiconductor-metal structures. A narrow band pass spectral response between 365 and 343 nm was achieved. When operating in dc mode, the responsivity reaches up to the order of 10^2 A/W under weak UV illumination, which is due to enormous internal gain up to 10^3. The linear dependence of photocurrent on bias and its square root dependence on optical power are found and explained by a trapping and recombination model. The high photocurrent gain is attributed to trapping and recombination centers with an acceptor character induced by dislocations in GaN. © *2002 American Institute of Physics.*
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Alloys of AlGaN are becoming the semiconductor of choice for ultraviolet (UV) photodetectors and light emitters. Due to their thermal stability and radiation hardness, these materials are remarkable tolerant in aggressive environments. By designing different Al mole fraction, the cutoff wavelength of AlGaN-based detectors can be adjusted in a wide UV range from 365 to 200 nm. This approach makes selective UV spectral detection realizable. Various structures were applied to produce AlGaN photodetectors, such as Schottky barrier,[1–5] $p-i-n$,[6–9] and $p-\pi-n$,[10] and metal-semiconductor-metal (MSM).[11–16] Most of these detectors have a responsivity in the range of 0.1–0.2 A/W, corresponding to an external quantum efficiency below 90%.[1–3,6–11] Some Schottky[4,5] and MSM[12–16] AlGaN detectors show an extraordinary responsivity corresponding to an apparent external quantum efficiency exceeding 100%, typically in the range of $10-10^3$, indicating large internal gains in these detectors.

In this letter, we demonstrate the operation of a backilluminated GaN/$Al_{0.18}Ga_{0.82}N$ heterojunction UV photodetector based on MSM structure, which shows high internal gain.

The schematic structure diagram of the GaN/$Al_{0.18}Ga_{0.82}N$ photodetector is shown in the inset of Fig. 1. The semiconductor layers were deposited on a c-plane sapphire substrate by molecular beam epitaxy growth technique. Gold metal stripes with a width of 1 mm and space of 0.8 mm were produced by evaporating gold in vacuum on the GaN surface to form Schottky contacts. All layers are unintentionally doped.

In the experiments, the sample detector was illuminated from backside. In the photoresponse measurements, the UV light source was a UV-enhanced xenon lamp and wavelengths were selected by a monochromator with a 250-nm-blaze grating. The illuminating light from the monochromator was calibrated by a calibrated UV-enhanced Si photodetector. In ac mode, spectral response measurements were performed by recording the voltage dropping at a 300 Ω load using a lock-in amplifier. A Keithley 236 source measurement unit was used to apply biases to the electrodes. In dc mode, bias-dependent responsivity was measured by re-

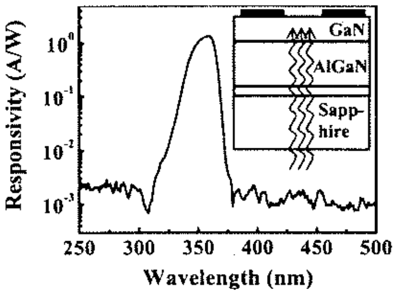

FIG. 1. Spectral responsivity of the GaN/$Al_{0.18}Ga_{0.82}N$ detector measured under 10 V at a chopper frequency of 55 Hz. The inset shows schematic structure of the designed photodetector.

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[a] Electronic mail: alfano@scisun.sci.ccny.cuny.edu

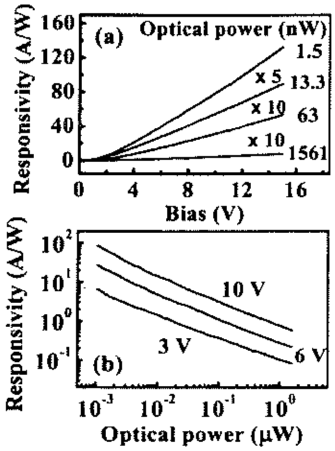

FIG. 2. (a) Responsivity as a function of bias measured by 350 nm illumination with different optical powers. (b) Responsivity as a function of optical power measured at 350 nm under different biases.

cording current–voltage ($I-V$) curves under 350 nm illumination.

The spectral responsivity measured at a chopper frequency of 55 Hz and under a bias of 10 V is shown in Fig. 1. The profile gives a band pass spectral response between 365 and 343 nm. The sharp long- and short-wavelength cutoffs result from band-to-band absorption of the GaN layer and the $Al_{0.18}Ga_{0.82}N$ layer, respectively. The responsivity is found to be dependent on chopper frequency because the decay time of photocurrent is comparable to the transit time for the chopper edge passing across the light beam (on the order of ms). The maximum responsivity is 1.35 A/W at 359 nm, corresponding to an apparent external quantum efficiency of 470%, which indicates the existence of internal gain of the photocurrent.

When operating in dc mode, the internal gain becomes much higher. Figure 2(a) shows responsivity as a function of applied bias measured under 350 nm illumination with different optical powers. It can be seen that the responsivity increases linearly with the increasing of the bias starting from 3 V. It increases much faster under weak power excitation. The responsivity goes up to 133 A/W at 15 V under 1.5 nW excitation, corresponding to an internal gain in the order of 10^3. Under biases above 15 V, Fig. 2(a) predicts a potential of achieving much higher responsivities. The dark current under 10 V is 36 nA, which is 1/25 of the photocurrent signal. Unlike some photodetectors using GaN on Si (111),[13,15] no saturation was observed under voltages up to 15 V.

The responsivity recorded under 350 nm excitation and under different biases was plotted as a function of optical power in Fig. 2(b) after subtracting the dark current at the corresponding bias. With the decreasing of the optical power P, all curves show that the responsivity increases as $P^{1/2}$ relationship. This $P^{1/2}$ relationship indicates bimolecular recombination mode,[17] which suggests the existence of deep traps in GaN band gap acting as recombination centers with an acceptor character.[1]

The linear relationship between responsivity R and bias V, and the $P^{1/2}$ relationship between responsivity and optical power, combine together to give the following equation to describe bias- and optical power-dependent photocurrent I_{PC},

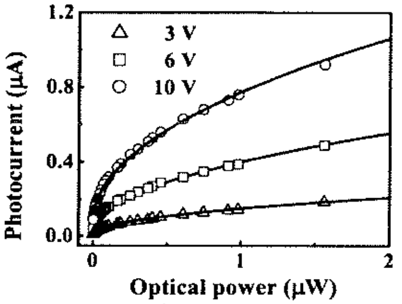

FIG. 3. Photocurrent as a function of optical power at 350 nm under different biases. The symbols show the experimental data and the solid lines are the calculated results according to Eq. (1).

$$I_{PC}=R\times P=(\alpha V+\beta)P^{1/2}+I_{\mathrm{dark}}(V), \tag{1}$$

where α and β are constants and I_{dark} refers to dark current under bias V. By taking $\alpha=0.079$ and $\beta=-0.098$, the plots of the photocurrent as a function of optical power for different applied biases are well reproduced by the calculated curves (solid lines) according to Eq. (1) and are shown in Fig. 3.

A simple explanation to the increasing internal gains with bias is that the gain is equal to the ratio of the carrier lifetime to the transit time while the carrier lifetime is affected by traps and is longer than the transit time.[18] Under large bias, the electric field between the metal stripes is almost uniform as evidenced experimentally by the linear dependence of dark current on bias. This indicates that the transit time is inversely proportional to the applied bias. This model predicts a linear relationship between the responsivity and the bias which was observed in the experiments.

We attribute the large internal gain to the dislocations existing in GaN and extending to the surfaces. The dislocations were directly evidenced to be trapping and recombination centers for holes by Rosner *et al.*[19] and Sugahara *et al.*[20] The concentration of the recombination centers is represented by N_t, and capture coefficients for electrons and holes by r_n and r_p, respectively. The density of holes trapped by these recombination centers, p_t, is expressed by[21]

$$p_t=\frac{N_t(r_n n_1+r_p p)}{r_n(n+n_1)+r_p(p+p_1)}, \tag{2}$$

where n and p are the total electron and hole densities, and n_1 and p_1 are quantitatively equal to the electron density on the conduction band and hole density on the valence band when setting the Fermi level at the energy level position of the recombination centers.

To qualitatively explain the experimental results, the following assumptions are made: (i) these recombination centers in n-type GaN are acceptor-like and have an energy level close to the valence band, which indicates $p_1 \gg p$; (ii) the recombination centers partially play a role of "safe" traps,[22] which prevent part of the trapped holes from recombination and hold them for a relatively long time. This indicates their much higher capture ability to holes than to electrons, which means $r_p \gg r_n$. Ignoring r_n-related items and p item in the denominator of Eq. (2), from the variation of Eq. (2), the increment of trapped holes can be written as Δp_t

$=\Delta p N_t/p_1$, where Δp represents the density of photogenerated free holes. In steady state condition, $\Delta n=\Delta p+\Delta p_t$, $G=\Delta n/\tau_n=\Delta p/\tau_p$, where G is optical generation rate of carriers, and τ_n and τ_p are the life times of electron and holes, respectively. Combining these equations together, Δn is obtained:

$$\Delta n=(1+N_t/p_1)\Delta p=(1+N_t/p_1)G\tau_p. \tag{3}$$

It can be seen that due to the existence of the trapping and recombination centers, the density of photogenerated electrons is increased by a factor of $(1+N_t/p_1)$. For instance, considering an acceptor level 0.5 eV above the valence band and a concentration of recombination centers on the order of 10^{13} cm^{-3}, N_t/p_1 reaches 10^3, which indicates Δn becomes 10^3 times larger than that without recombination centers $(N_t=0)$. Accordingly, the photoconductivity is significantly enhanced by 10^3 since it is proportional to Δn, which results in a 10^3 internal gain of the photocurrent. The physical image is that in order to keep the charge neutrality, more electrons stay on the conduction band to balance the positive charges of trapped holes, thus leading to the increasing of conductivity.

To explain the power dependence of the photocurrent, the expression of recombination rate R of free carriers is written as:[21]

$$R=\frac{N_t r_n r_p[(n_0+\Delta n)(p_0+\Delta p)-n_0 p_0]}{r_n(n_0+\Delta n+n_1)+r_p(p_0+\Delta p+p_1)}, \tag{4}$$

where n_0 and p_0 are the electron and hole densities without any carrier injection, respectively, note the steady state condition, $R=G$. Considering the two former assumptions and a high optical power excitation which means $\Delta n \gg n_0$, $\Delta p \gg p_0$, and combining Eq. (4), Δn is solved as a function of G:

$$\Delta n=\gamma G^{1/2}, \tag{5}$$

where $\gamma=[p_1(1+N_t/p_1)/(N_t r_n)]^{1/2}$. Since photocurrent I_{PC} is proportional to Δn, and optical power P is proportional to G, the $I_{PC}\propto P^{1/2}$ relationship is readily explained. From Eq. (3) and $G=\Delta n/\tau_n$, the electron lifetime is obtained to be $\tau_n=(1+N_t/p_1)\tau_p$, which is also greatly increased by a factor of $(1+N_t/p_1)$. This strongly supports our explanation on the linear dependence of the photocurrent on the bias where a long carrier lifetime is required.

In summary, we have investigated a GaN/Al$_{0.18}$Ga$_{0.82}$N heterojunction MSM UV photodetector with large internal gains operating by backside illumination. Sharp long- and short-wavelength cutoffs were experimentally observed at 365 and 343 nm. We proposed a trapping and recombination model which can well explain the origin of extraordinary large internal gain of photocurrent; the $P^{1/2}$ dependence of photocurrent on illuminating power and the linear relationship of photocurrent on bias.

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[1] F. Binet, J. Y. Duboz, N. Laurent, E. Rosencher, O. Briot, and R. L. Aulombard, J. Appl. Phys. **81**, 6449 (1997).
[2] M. Asif Khan, J. N. Kuznia, D. T. Olson, M. Blasingame, and A. R. Bhattarai, Appl. Phys. Lett. **63**, 2455 (1993).
[3] C. Wang, Appl. Phys. Lett. **80**, 1568 (2002).
[4] O. Katz, V. Garber, B. Meyler, G. Bahir, and J. Salzman, Appl. Phys. Lett. **79**, 1417 (2001).
[5] V. Adivarahan, G. Simin, J. W. Yang, A. Lunev, M. Asif Khan, N. Pala, M. Shur, and R. Gaska, Appl. Phys. Lett. **77**, 863 (2000).
[6] J. M. Van Hove, R. Hickman, J. J. Klaassen, P. P. Chow, and P. P. Ruden, Appl. Phys. Lett. **70**, 2282 (1997).
[7] G. Y. Xu, A. Salvador, W. Kim, Z. Fan, C. Lu, H. Tang, H. Morkoç, G. Smith, M. Estes, B. Goldenberg, W. Yang, and S. Krishnankutty, Appl. Phys. Lett. **71**, 2154 (1997).
[8] D. Walker, A. Saxier, P. Kung, X. Zhang, M. Hamilton, J. Diaz, and M. Razeghi, Appl. Phys. Lett. **72**, 3303 (1998).
[9] W. Yang, T. Nohova, S. Krishnankutty, R. Torreano, S. McPherson, and H. Marsh, Appl. Phys. Lett. **73**, 1086 (1998).
[10] A. Osinsky, S. Gangopadhyay, R. Gaska, B. Williams, M. A. Khan, D. V. Kuksenkov, and H. Temkin, Appl. Phys. Lett. **71**, 2334 (1997).
[11] E. Monroy, F. Calle, E. Munoz, and F. Omnès, Appl. Phys. Lett. **74**, 3401 (1999).
[12] E. Munoz, E. Monroy, J. A. Garrido, I. Izpura, F. J. Sánchez, M. A. Sánchez-García, E. Calleja, B. Beaumont, and P. Gibart, Appl. Phys. Lett. **71**, 870 (1997).
[13] B. Shen, K. Yang, L. Zang, Z. Chen, Y. Zhou, P. Chen, R. Zhang, Z. Huang, H. Zhou, and Y. Zheng, Jpn. J. Appl. Phys., Part 1 **38**, 767 (1999).
[14] F. Binet, J. Y. Duboz, E. Rosencher, F. Scholz, and V. Härle, Appl. Phys. Lett. **69**, 1202 (1996).
[15] K. S. Stevens, M. Kinniburgh, and R. Beresford, Appl. Phys. Lett. **66**, 3518 (1995).
[16] J. C. Carrano, T. Li, P. A. Grudowski, C. J. Eiting, R. D. Dupuis, and J. C. Campbell, J. Appl. Phys. **83**, 6148 (1998).
[17] V. S. Vavilov, *Effects of Radiation on Semiconductors* (Consultants Bureau, New York, 1965), pp. 80–81.
[18] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981), pp. 744–746.
[19] S. J. Rosner, E. C. Carr, M. J. Ludowise, G. Girolami, and H. Erikson, Appl. Phys. Lett. **70**, 420 (1997).
[20] T. Sugahara, H. Sato, M. Hao, Y. Naoi, S. Kurai, S. Tottori, K. Yamashita, K. Nishino, LT. Romano, and S. Sakai, Jpn. J. Appl. Phys., Part 2 **37**, L398 (1998).
[21] M.-F. Li, *Modern Semiconductor Quantum Physics* (World Scientific, Singapore, 1994), p. 261.
[22] R. A. Smith, *Semiconductors* (Cambridge University Press, London, 1961), pp. 307–309.