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Suppression of persistent photoconductivity AlGaN/GaN heterostructure photodetectors using pulsed heating

Jianwen Sun[1], Teng Zhan[2,3], Zewen Liu[4], Junxi Wang[2,3], Xiaoyan Yi[2,3], Pasqualina M. Sarro[1*], and Guoqi Zhang[1,3*]

[1]Department of Microelectronics, Delft University of Technology, 2628 CD Delft, The Netherlands
[2]Research and Development Center for Solid State Lighting, Institute of Semiconductors, Chinese Academy of Sciences, Qinghua East Road 35A, 100083, Beijing, People's Republic of China
[3]State Key Laboratory of Solid State Lighting, Beijing, 100083, People's Republic of China
[4]Institutue of Microelectronic, Tsinghua University, 100084, Beijing, People's Republic of China

*E-mail: p.m.sarro@tudelft.nl; G.Q.Zhang@tudelft.nl

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This paper demonstrates a method to reduce the decay time in AlGaN/GaN photodetectors by a pulsed heating mode. A suspended AlGaN/GaN heterostructure photodetector integrated with a micro-heater is fabricated and characterized under ultraviolet illumination. We have observed that the course of persistent photoconductivity was effectively accelerated by applying pulsed heating. The decay time is significantly reduced from 175 s by DC heating to 116 s by 50 Hz pulsed heating at the same power (280 mW). With the same pulse duty cycle and a 50 Hz pulsed heating frequency, a reduction of 30%–45% in decay time is measured compared to DC heating. © 2019 The Japan Society of Applied Physics

UV detectors have widespread applications including flame sensing,[1] communication systems,[2] space research,[3] UV environmental monitoring and so forth. Recently, much research has been done on GaN-based UV detectors.[4,5] GaN-based UV detectors can operate under harsh environments such as in the nuclear industry,[6] and space and aeronautics industry,[7] due to their wide bandgap semiconductor material properties compared to silicon-based UV photodetectors.[8] Several types of GaN-based UV detector configurations, including PIN diodes type,[9] Schottky diodes type[10] and metal–semiconductor–metal (MSM) type[11] have been fabricated and demonstrated. In comparison with other UV detectors, AlGaN/GaN heterostructure type detectors have the advantage of high gain[12,13] ($>100\ \mathrm{A\ W^{-1}}$), which is introduced by the high mobility two-dimensional electron gas (2DEG) channel at the surface of the GaN layer.

However, persistent photoconductivity (PPC) effect[14] associated with the 2DEG in an AlGaN/GaN heterostructure device has been observed, which makes the device sensitive to light. The recovery time (decay time) of GaN-based optical photodetector after removing the UV illumination is measured from hours to days.[14–18] This is a significant problem for applications which require reliable and consistent operation.[14,19] The possible mechanisms of the PPC effect in GaN materials or AlGaN/GaN heterostructures have been previously discussed and consist of metastable defects,[20,21] deep-level defects[14,20,22] and gallium vacancy[22] within the epitaxial layers.

The decay time introduced by the PPC effect can be reduced by raising the temperature which speeds up the carrier capture rate.[14,18,20] External power units can be used to achieve suitable temperature. However, it is may not be feasible for some applications. Therefore, an integrated heating unit is an attractive alternative to reduce the PPC effect.[18]

In this study, we report the impact of pulsed heating on the PPC effect in suspended AlGaN/GaN heterostructure photodetectors. The UV photodetector, including an AlGaN/GaN heterostructure and micro-heater unit, was suspended from the silicon substrate for thermal isolation. The temperature of the membrane is modulated by the micro-heater unit based on joule heating. The transient characteristics of the photodetector versus voltage and frequency are studied. The decay time of the AlGaN/GaN photodetectors was remarkably reduced from 450 s without heating to 116 s at 150 °C by 50 Hz pulsed heating. This is an important element in order to develop high accuracy and fast response/recovery UV detectors based on a suspended AlGaN/GaN heterostructure and integrated with a micro-heater.

Figure 1 schematically depicts the device cross-section and 2DEG structure. The photodetector is placed on a suspended membrane and a micro-heater across the gate area is integrated. The contact pads are positioned on the thick silicon frame. The silicon substrate (400 μm) is removed by deep reactive ion etching (DRIE) the silicon substrate from the wafer backside, thus forming a circular membrane (650 μm in diameter). The AlGaN/GaN heterostructure was grown on a 2 inch silicon $\langle 111 \rangle$ 1 mm thick wafers by metal-organic chemical vapor deposition. The heterostructure was formed by subsequent depositions of a 2 μm thick undoped GaN buffer layer, a 1 nm thick AlN interlayer, an undoped 25 nm thick $Al_{0.26}Ga_{0.74}N$ barrier layer, and a 3 nm thick GaN epitaxial cap layer. The electron mobility was measured to be $\sim 1500\ \mathrm{cm^2\ V^{-1}\ s^{-1}}$, with a sheet electron density of $\sim 1 \times 10^{13}\ \mathrm{cm^{-2}}$.

The fabrication process flow started with a mesa etching using a chlorine/boron chloride (Cl_2/BCl_3) plasma to define the sensor geometry. Then, Ti/Al/Ti/Au (20/110/40/50 nm) metal contacts were e-beam evaporated and patterned by lift-off technology. After patterning, the contacts were rapid thermal annealed at 870 °C for 45 s under N_2 ambient. Then, a Ti/Pt (30/200 nm) metal layer was evaporated and patterned by lift-off to form the micro-heater, followed by a 200 nm plasma enhanced chemical vapor deposition (PECVD) SiO_2 layer for isolation from the interconnect layer. After the opening window of the SiO_2 layer, the metal interconnect formed using an evaporated Ti/Au (20/300 nm) layer stack. The topside of the wafer was covered by a PECVD SiO_2 layer and the backside was polished down to 400 μm and a 5 μm thick SiO_2 layer was deposited as a hard mask during the DRIE process to etch the silicon substrate. Then backside SiO_2 was patterned by inductively coupled plasma reactive ion etching and the topside SiO_2 layer was etched in a

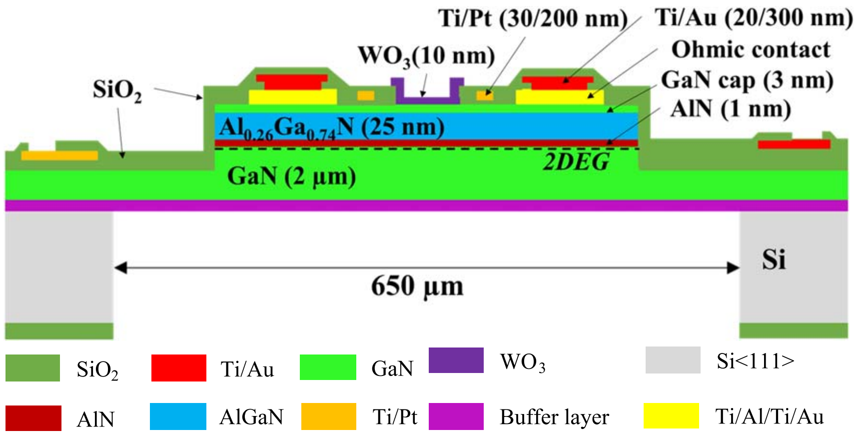

Fig. 1. (Color online) Schematic drawing of the cross-section of the AlGaN/GaN heterostructure UV photodetector and 2EDG structure.

buffered oxide etch solution to form the opening for the contact pads and gate windows. The tungsten trioxide (WO$_3$) (10 nm) layer was deposited on the gate area of 80 μm × 40 μm by physical vapor deposition. The silicon substrate is etched away below the active area in the final step. The micro-heater is around the active area across the gate area, as shown in Fig. 2. The transient response of the WO$_3$ AlGaN/GaN photodetectors was measured by a Keithley 2400 during exposure of the detector to a radiation source emitting at 380 nm at a drain bias of 0.5 V, in air ambient, at room temperature.

In order to quantify the temperature of the membrane at various pulsed heating voltages and frequencies, it is necessary to perform a calibration for extracting the membrane temperature. The surface temperature can be measured by an IR thermal camera[23,24]) or a 4 wire temperature resistive device testing the micro-heater.[25]) Figure 3(a) shows the measured maximum temperature of the suspended AlGaN/GaN heterostructure photodetector at different applied micro-heater voltages and heating frequencies, with a duty cycle of 50%. An IR camera (FLIR T620) was used to record the temperature profile of the chip heated at $V_H = 4$ V as shown in the inset of Fig. 3(a). A uniform profile across the membrane was observed. Figure 3(b) shows the power at different applied voltages and frequencies with a duty cycle of 50%. From Fig. 3 we can observe that the maximum temperature of the membrane and the power slightly decrease from 50 Hz to 100 Hz. However, above 100 Hz, they are basically stable. The temperature of the membrane is directly correlated with the device power consumption.

The decay time was about 450 s when DC heating $V_H = 0$ V was applied (the temperature was about 20 °C, ambient temperature), and was reduced to about 164 s when the photodetector is DC heated to approximately 150 °C at $V_H = 4$ V (~280 mW), as shown in Fig. 4(b). Under a DC heating mode, the decrease of decay time was mainly determined by the increasing temperature of the micro-heater. The decay time would be further reduced by increasing the micro-heater voltages. The temperature dependence of τ can be described by Eq. (1)

$$\tau = \tau_o \exp\left[\Delta E/\kappa T\right] \qquad (1)$$

where τ_o is the high temperature limit of the time constant, κ is the Boltzmann constant, ΔE is the capture barrier and T is the temperature. As shown in Fig. 4, the decay times of the device become shorter with increasing temperature and power. Figure 3 shows the heating temperature at different applied voltage and frequency with a duty cycle of 50%. It is expected from Eq. (1) that the temperature dependence of PPC decay behavior should fit to a well-known stretched-exponential function.[16,22,26]) Thus the decay times of the AlGaN/GaN photodetectors would be suppressed with increasing temperature. Similar results by DC heating have been reported.[18]) The heating power and voltage can be further optimized by WO$_3$ AlGaN/GaN membrane size and layout.[27,28])

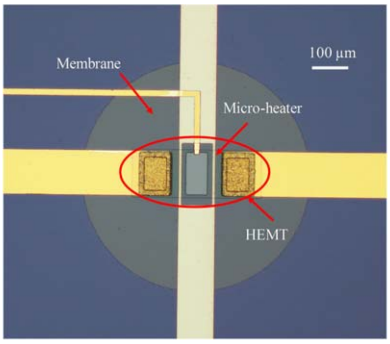

Fig. 2. (Color online) Optical micrograph of a fabricated AlGaN/GaN heterostructure UV photodetector.

The PPC effect in the 2DEG channel implies there is an insufficient amount of energy for carriers to overcome a capture barrier ΔE created by localized defects. This prevents the recapture of electrons by the non-radiative recombination centers caused by the cluster and demonstrates metastability of the defect in Al$_{0.26}$Ga$_{0.74}$N. The normalized transient photocurrent responses of the AlGaN/GaN heterostructure detectors under 380 nm UV light illumination at various frequencies are shown in Fig. 5. The decay time of the photodetector is defined as the time required for the photocurrent changes from 90% to 10% of its saturated response value. The photodetector shows a rapid response under illumination, but the photocurrent decay depends on the frequency. During a pulse cycle in the micro-heater, the decay time is reduced. Due to deep-level defects concentration increase compared to DC heating, more electrons fill the extra defects with the pulsed stress in the gate area of the AlGaN/GaN heterostructure. The basic theory of pulsed

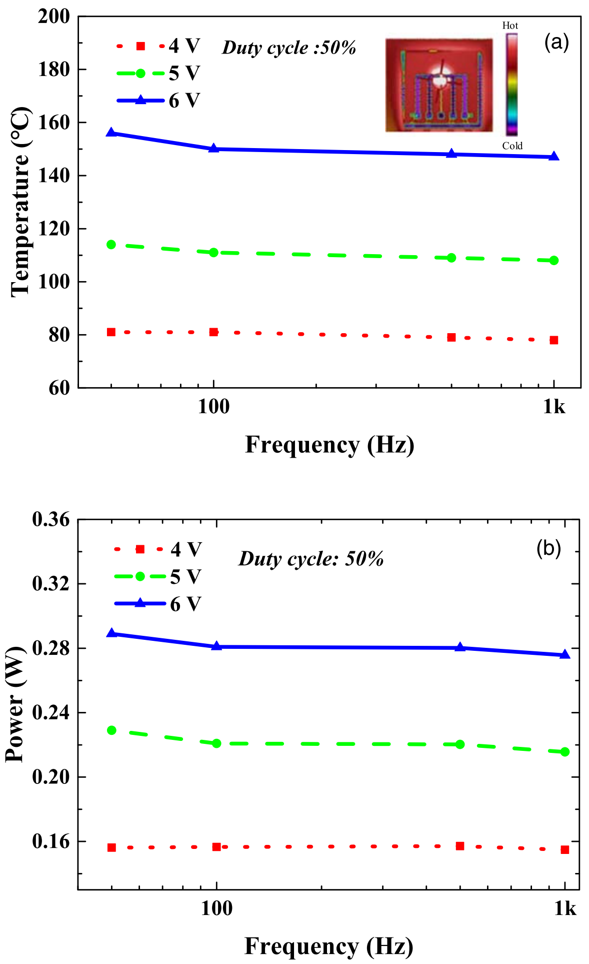

Fig. 3. (Color online) (a) Measured heating temperature at different applied voltages and heating frequency with a duty cycle of 50%. The inset shows the temperature profile (IR camera image) of the heated (4 V) AlGaN/GaN photodetector. (b) Measured power consumption at different applied voltages and heating frequency with a duty cycle of 50%.

stress has been reported in early publications.[29,30]) The decay time comparison of the two heating mode at the same heating power (temperature) are shown in Fig. 4(b). The decay time of the AlGaN/GaN heterostructure photodetectors can be reduced obviously from 380 s, 300 s, 175 s by DC heating to 227 s, 164 s,116 s by 50 Hz pulsed heating at the same power (150 mW, 220 mW, 280 mW), respectively. A reduction of 30%–45% in decay time is measured compared to DC heating. In this work, we have demonstrated that a pulsed heating method can be utilized to cut down decay time and power consumption, which is an important step to solve the relative long recovery time by the PPC effect in previous reports.[14,18])

In summary, a suspended WO_3 AlGaN/GaN heterostructure UV photodetector integrated with a micro-heater were fabricated and characterized. The relative long decay time introduced by the PPC effect is an important disadvantage limiting the wide application of GaN-based photodetectors. We demonstrate that the pulsed heating method effectively reduces the decay time of the AlGaN/GaN heterostructure photodetectors. The decay time is significantly reduced from 175 s by DC heating to 116 s by 50 Hz pulsed heating at the same power (280 mW). With the same pulse duty cycle and 50 Hz pulsed heating, a reduction of 30%–45% in decay time is measured compared to DC heating. These findings are an important step towards the development of high accuracy and fast response/recovery UV detector based on a suspended AlGaN/GaN heterostructure integrated with a micro-heater.

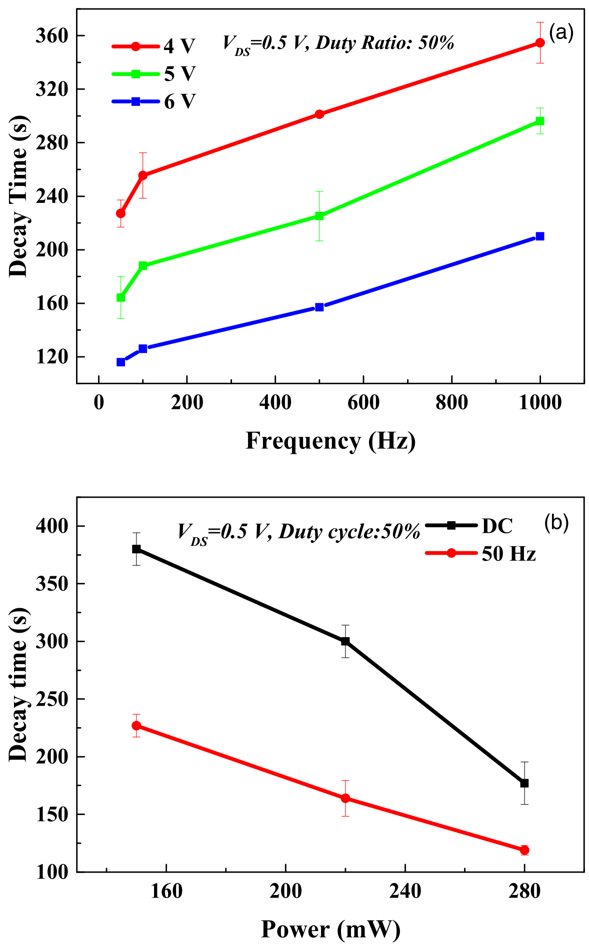

Fig. 4. (Color online) (a) Measured decay time of AlGaN/GaN heterostructure photodetector at different frequencies and for $V_{DS} = 0.5$ V. (b) Measured decay time comparison of AlGaN/GaN heterostructure photodetector for changing power/temperature at DC heating and 50 Hz pulsed heating mode ($V_{DS} = 0.5$ V , Duty cycle = 50%).

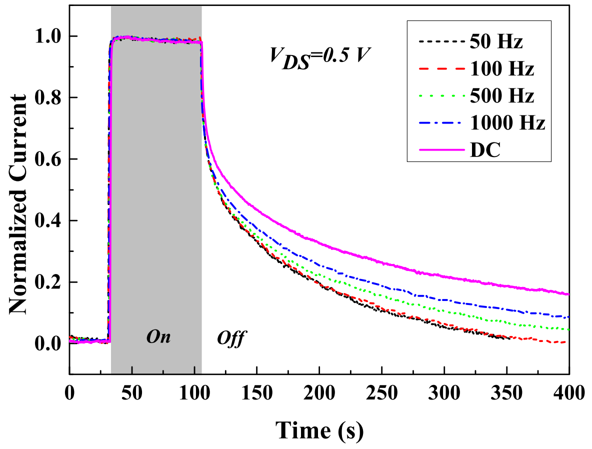

Fig. 5. (Color online) Normalized transient photocurrent response (0% is dark and 100% maximum photocurrent under 380 nm illumination) of suspended WO_3 AlGaN/GaN photodetector at various frequencies with a 50% duty cycle ($V_{DS} = 0.5$ V, $V_H = 5$ V).

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ORCID iDs Jianwen Sun https://orcid.org/0000-0003-2769-1123

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