Optical Engineering

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Optical Engineering 53(10), 107106 (October 2014)

Metal-semiconductor-metal ultraviolet photodetectors based on gallium nitride grown by atomic layer deposition at low temperatures

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Abstract. Proof-of-concept, first metal-semiconductor-metal ultraviolet photodetectors based on nanocrystalline gallium nitride (GaN) layers grown by low-temperature hollow-cathode plasma-assisted atomic layer deposition are demonstrated. Electrical and optical characteristics of the fabricated devices are investigated. Dark current values as low as 14 pA at a 30 V reverse bias are obtained. Fabricated devices exhibit a 15× UV/VIS rejection ratio based on photoresponsivity values at 200 nm (UV) and 390 nm (VIS) wavelengths. These devices can offer a promising alternative for flexible optoelectronics and the complementary metal oxide semiconductor integration of such devices. [DOI: 10.1117/1.OE.53.10.107106]

Keywords: photodetectors; ultraviolet; deposition; optoelectronics.

Paper 141066 received Jul. 5, 2014; revised manuscript received Sep. 4, 2014; accepted for publication Sep. 11, 2014; published online Oct. 9, 2014.

1 Introduction

In recent years, there has been an increasing interest toward flexible optoelectronic devices. Typically, flexible substrates require low-temperature processes. For this purpose, photodetectors (PDs) based on organic semiconductors[1] and colloidal semiconductor nanocrystals[2–4] have been investigated. In addition, thin films of wide bandgap inorganic semiconductors for ultraviolet PDs are sought.[5–7] Due to their high (3.4 eV) and direct bandgap, efficient ultraviolet (UV) PDs based on gallium nitride (GaN) have been demonstrated. However, deposition of GaN layers with a low thermal budget is still a major challenge. Traditional methods for the deposition of GaN layers are metal organic chemical vapor deposition,[8–10] molecular beam epitaxy,[11,12] and hydride vapor phase epitaxy.[13] However, integration of GaN devices on flexible substrates is hampered by these high temperature growth techniques. On the other hand, low-temperature GaN thin films were demonstrated earlier using sputtering[14] and pulsed laser deposition,[15] but no PD device applications were reported. Among various deposition techniques, atomic layer deposition (ALD) holds significant potential due to its low-temperature self-limiting growth capability. The ALD method offers unique advantages such as high uniformity, high conformality (step coverage), and precise thickness control.[16–19] Recently, our group showed that low-temperature growth of nanocrystalline-GaN (nc-GaN) is feasible using a hollow-cathode plasma-assisted ALD (HCPA-ALD) technique.[20] We also reported successful GaN thin film transistors (TFTs) using the same technique.[21]

In this work, proof-of-concept ultraviolet (UV) PDs based on such low-temperature ALD-grown GaN layers are demonstrated. Metal-semiconductor-metal (MSM) type PDs are fabricated and characterized. To the best of our knowledge, this study represents the first demonstration of MSM UV PDs based on ALD-grown GaN.

2 Film Growth and Device Fabrication

A silicon wafer with a 100-nm-thick thermally grown SiO2 layer is used as the starting substrate. The thick SiO2 layer provides good electrical isolation of the devices. A semi-insulating GaN layer is deposited at 200°C using trimethylgallium (GaMe3) as the Ga precursor and N2:H2 (1:1) plasma as the nitrogen precursor in an Ultratech/Cambridge-Nanotech Fiji F200-LL ALD reactor equipped with a remote hollow-cathode RF-plasma source (Meaglow Ltd., Ontario, Canada). The thickness of the deposited GaN layer (∼20 nm) is measured by spectroscopic ellipsometry (V-VASE, J.A. Woollam Co. Inc., Lincoln, Nebraska). The details of the HCPA-ALD growth of the ultrathin GaN film as well as characterization of morphology and crystal properties were reported by our group elsewhere.[20] Following the GaN deposition, samples are cleaned by acetone, 2-propanol and diluted hydrofluoric acid (HF:H2O 1:50) solution to remove any native oxide on the GaN surface. Finally, Ti (20 nm)/Au (100 nm) contacts are formed using sputtering and lift-off processes. Interdigitated electrodes of 5-μm width and spacing are patterned. Device schematic and scanning electron microscopy (SEM) image of a completed MSM PD are shown in Fig. 1.

3 Results and Discussions

Fabricated metal-semiconductor-metal GaN PDs consist of two back-to-back Schottky contacts, which are formed by Ti/Au electrodes on top of a GaN layer. The energy band diagram of the MSM device under thermal equilibrium condition is shown in Fig. 2(a). The electron affinity of GaN is ca 4.1 eV where the work function of Au is ∼5.1 eV which

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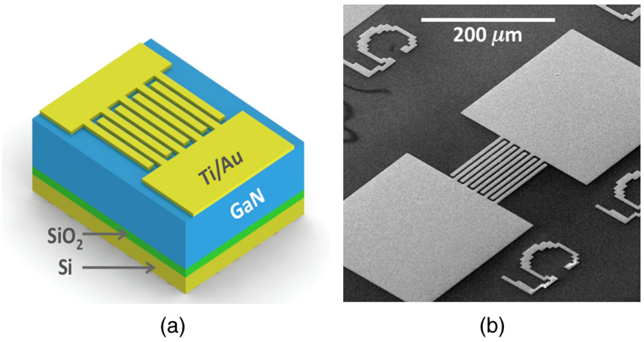

Fig. 1 (a) Schematic and (b) representative SEM image of fabricated GaN metal-semiconductor-metal (MSM) devices.

creates an ~0.9 eV electron injection barrier. Under applied bias, charge carriers are separated and drift with the applied electric field. Generated carriers (thermal and photo) are collected by Ti/Au contacts [Figs. 2(b) and 2(c)].

Fabricated devices are characterized using a Keithley (Cleveland, Ohio) 4200 semiconductor parameter analyzer. The dark current–voltage (I-V) characteristics are obtained for the applied voltage bias up to 30 V as shown in Fig. 3. Devices exhibit dark current levels of 14 pA at 30 V bias, which show that the devices can be operated under a high reverse bias. The symmetric behavior of the current–voltage curve is an indication of back-to-back Schottky contacts.

Spectral photoresponsivity measurements are performed using a 150 W Xenon white light source and Newport Oriel (Irvine, California) 1/8 m Cornerstone monochromator. The incident monochromatic light is mechanically modulated using an optical chopper and the photogenerated electrical current is recorded with an SRS830 dual phase lock-in amplifier. The devices are illuminated from the top focusing the beam spot onto interdigitated electrodes. A measured spectral photoresponsivity in the 200–500 nm spectral range is shown in Fig. 4. The responsivity value decreases significantly at wavelengths larger than 300 nm due to the band edge of the HCPA-ALD-grown GaN film as verified by the previously reported optical characterization results.[20,21] Fabricated devices show responsivity values of 1.687 and 0.101 mA/W at wavelengths of 200 and 390 nm, respectively, under a 13 V reverse bias. Since the GaN films are deposited at temperatures below 200°C, these results signify the first demonstration of functional devices on such layers. The relatively low external quantum efficiency (ca 1%) is due to the low collection efficiency, which is attributed to the nanocrystalline nature of the grown ALD GaN film. In ALD grown nanocrystalline GaN films, there are morphological imperfections such as nano-sized grains with an average grain size of 9.3 nm.[20] We believe that grain boundary scattering reduces che arrier mobility, which results in low carrier collection efficiency. Moreover, nanograins with varying crystal orientations may introduce additional scattering. Overall, carrier collection efficiency is low due to such morphological and crystal imperfections that result in diminished carrier mobility. Devices exhibit a 15× UV/VIS rejection ratio based on photocurrent values at 200 nm (UV) and 390 nm (VIS). Photoresponsivity values increase with an applied reverse bias voltage. The photoresponsivity value saturates for large reverse bias voltages (>10 V), which can be explained by the complete depletion of 20-nm-thick GaN film. The nonzero photoresponsivity at visible wavelengths ($\lambda > 300$ nm) is attributed to deep-level trap states within the forbidden gap that allow the absorption of sub-bandgap photons. The trap states are induced by crystal defects due to nitrogen interstitials.[22,23] Nitrogen interstitials are believed to be responsible for acceptor-like

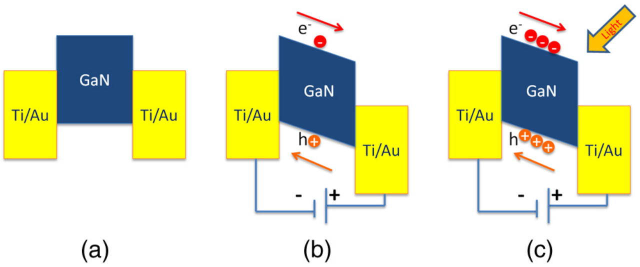

Fig. 2 Energy band diagram of the GaN metal-semiconductor-metal (MSM) photodetectors (PDs) (a) under thermal equilibrium, (b) with applied voltage bias, (c) under photoexcitation with applied voltage bias. Devices are illuminated from the top.

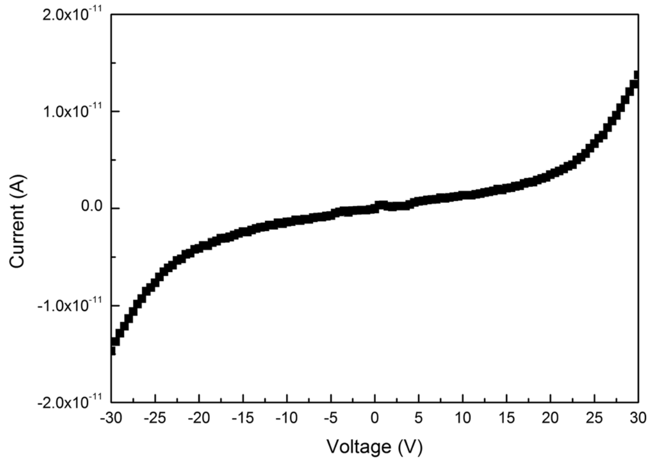

Fig. 3 GaN metal-semiconductor-metal (MSM) photodetector dark current-voltage characteristics.

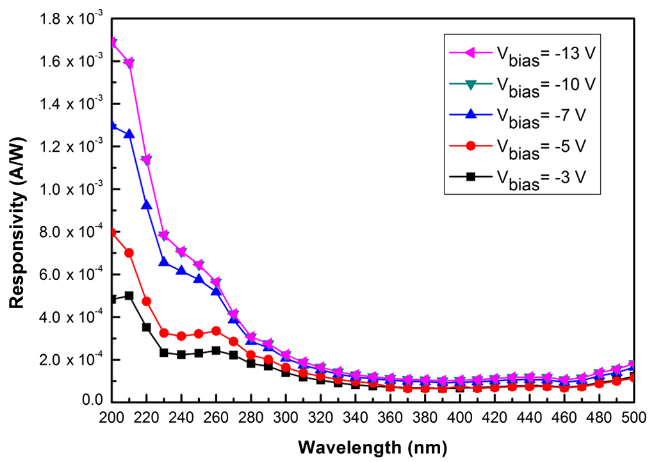

Fig. 4 Spectral responsivity of the fabricated nanocrystalline-GaN (nc-GaN) metal-semiconductor-metal (MSM) photodetectors (PDs) for different applied voltage bias.

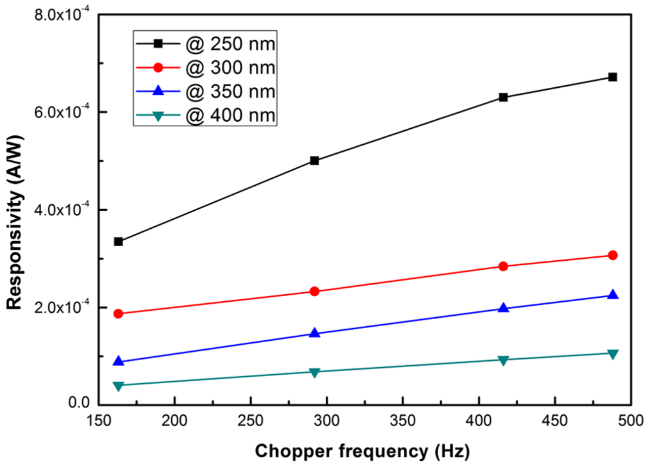

Fig. 5 Responsivity values of the fabricated devices with respect to chopper frequency.

deep trap states.[23] Furthermore, nitrogen-rich GaN favors negatively charged Ga vacancies, which introduce acceptor states as well.[22] Such defect states promote a persistent photoconductive gain that results in increased UV photoresponse.

In addition, spectral photoresponsivity is investigated as a function of the chopper modulation frequency that is shown in Fig. 5. The photoresponse of the devices increases as chopper frequency increases. Trap states—mainly negatively charged Ga vacancies and nitrogen interstitials[22,23]–capture electrons; however, these traps have long relaxation times, i.e.,—electrons remain trapped while holes are mobile longer. As a result, before relaxation occurs, holes continue to contribute to photocurrent. This phenomenon is known as persistent photoconductivity (PPC),[22] resulting in a photoconductive gain. For lower chopping frequencies, the time interval for no-illumination (dark time) is longer, therefore, more traps are relaxed and trapped electrons recombine with holes. As a result of reduced carriers, the gain due to PPC is reduced and the photocurrent decreases. When chopper frequency increases, less relaxation can occur due to shorter dark time intervals; as a result, electrons cannot recombine with holes and holes continue to circulate resulting in the persistent effect.

4 Conclusion

In summary, proof-of-principle MSM UV PDs are demonstrated for the first time using ultrathin nc-GaN layers deposited by HCPA-ALD at 200°C. These devices correspond to GaN-based PDs with the lowest thermal growth and fabrication budget reported to date. The devices exhibit dark currents of 3 pA under a 30 V reverse bias, which means they can operate under a high reverse bias. Spectral photoresponsivity measurements show a 15× UV/VIS rejection ratio comparing 200 nm (UV) and 390 nm (VIS) wavelengths. The sub-bandgap photoresponse is attributed to deep-level traps in the forbidden gap. Persistent photoconductive gain is also shown to exist in PA-ALD grown GaN films. These results show the viability of UV photodetectors based on HCPA-ALD compatible with temperature sensitive and low cost substrates used for flexible and transparent electronics.

Acknowledgments

This work was performed at UNAM – Institute of Materials Science and Nanotechnology, which is supported by the State Planning Organization of Turkey through the National Nanotechnology Research Center Project. This work was supported by the Scientific and Technological Research Council of Turkey (TUBITAK), (Grant Nos. 112M004, 112E052, 112M482 and 113M815). N. B. acknowledges support from European Union FP7 Marie Curie International Reintegration Grant (NEMSmart, Grant No. # PIRG05-GA-2009-249196). A. K. O. acknowledges a Marie Curie International Reintegration Grant (IRG). S. B. acknowledges TUBITAK-BIDEB for PhD fellowship, respectively.

References

1. P. Peumans, A. Yakimov, and S. R. Forrest, "Small molecular weight organic thin-film photodetectors and solar cells," *J. Appl. Phys.* **93**(7), 3693–3723 (2003).
2. S. Alkis et al., "A plasmonic enhanced photodetector based on silicon nanocrystals obtained through laser ablation," *J. Opt.* **14**(12), 125001–125005 (2012).
3. S. Alkis et al., "Thin film MoS2 nanocrystal based ultraviolet photodetector," *Opt. Express* **20**(19), 21815–21820 (2012).
4. B. Liu et al., "ZnO-nanoparticle-assembled cloth for flexible photodetectors and recyclable photocatalysts," *J. Mater. Chem.* **22**(18), 9379–9384 (2012).
5. H. Karaagac et al., "A baseball-bat-like CdTe/TiO2 nanorods-based heterojunction core–shell solar cell," *J. Scripta Mat.* **69**(4), 323–326 (2013).
6. W. Tian et al., "Flexible ultraviolet photodetectors with broad photoresponse based on branched ZnS-ZnO heterostructure nanofilms," *Adv. Mater.* **26**(19), 3088–3093 (2014).
7. T. P. Chen et al. "Photoelectrical and low-frequency noise characteristics of ZnO nanorod photodetectors prepared on flexible substrate," *IEEE Trans. Electron. Devices* **60**(1), 229–234 (2013).
8. J. C. Carrano et al., "Comprehensive characterization of metal-semiconductor-metal ultraviolet photodetectors fabricated on single-crystal GaN," *J. Appl. Phys. Lett.* **83**(11), 6148–6160 (1998).
9. A. Osinsky et al., "Visible-blind GaN Schottky barrier detectors grown on Si(111)," *J. Appl. Phys. Lett.* **72**(5), 551–553, (1998).
10. N. Biyikli et al., "High-speed visible-blind GaN-based indium–tin–oxide Schottky photodiodes," *Appl. Phys. Lett.* **79**(17), 2838–2840 (2001).
11. M. Mikulics et al., "Ultrafast metal-semiconductor-metal photodetectors on low-temperature-grown GaN," *J. Appl. Phys. Lett.* **86**(21), 211110–211113 (2005).
12. H.Z. Xu et al., "Fabrication and characterization of metal–semiconductor–metal (MSM) ultraviolet photodetectors on undoped GaN/sapphire grown by MBE," *J. Cryst. Growth* **218**(1), 1–6 (2000).
13. K. A. McIntosh et al., "GaN avalanche photodiodes grown by hydride vapor-phase epitaxy," *J. Appl. Phys. Lett.* **75**(22), 3485–3487 (1999).
14. E. C. Knox-Davies, J. M. Shannon, and S. R. P. Silva, "The properties and deposition process of GaN films grown by reactive sputtering at low temperatures," *J. Appl. Phys.* **99**(17), 073503 (2006).
15. R. D. Vispute et al., "Growth of epitaxial GaN films by pulsed laser deposition," *Appl. Phys. Lett.* **71**(1), 102 (1997).
16. C. Ozgit et al., "Self-limiting low-temperature growth of crystalline AlN thin films by plasma-enhanced atomic layer deposition," *Thin Solid Films* **520**(7), 2750–2755 (2012).
17. N. El-Atab et al., "Diode behavior in ultra-thin low temperature ALD grown zinc-oxide on silicon," *AIP Advances* **3**(10), 102119–102126 (2013).
18. S. Alkis et al., "UV/VIS range photodetectors based on thin film ALD grown ZnO/Si heterojunction diodes," *J. Opt.* **15**(10), 105002–105006 (2013).
19. F. B. Oruc et al., "Thin film ZnO charge trapping memory cell grown in a single ALD step," *IEEE Electon. Device Lett.* **33**(12), 1714–1716 (2012).
20. C. Ozgit-Akgun et al., "Hollow cathode plasma-assisted atomic layer deposition of crystalline AlN, GaN and AlxGa1-xN thin films at low temperatures," *J. Mater. Chem. C* **2**(12), 2123–2136 (2014).
21. E. Goldenberg et al., "Optical characteristics of nanocrystalline AlxGa1-xN thin films deposited by hollow cathode plasma-assisted atomic layer deposition," *J. Vac. Sci. Technol. A* **32**(3), 031508 (2014).
22. E. Muñoz et al., "Photoconductor gain mechanisms in GaN ultraviolet detectors," *Appl. Phys. Lett.* **71**(7), 870 (1997).
23. M. A. Reshchikov and H. Morkoc, "Luminescence properties of defects in GaN," *J. Appl. Phys.* **97**(6), 061301–061396 (2005).

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