AIP Applied Physics Letters

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Citation: Appl. Phys. Lett. **79**, 2838 (2001); doi: 10.1063/1.1412592
View online: http://dx.doi.org/10.1063/1.1412592
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v79/i17
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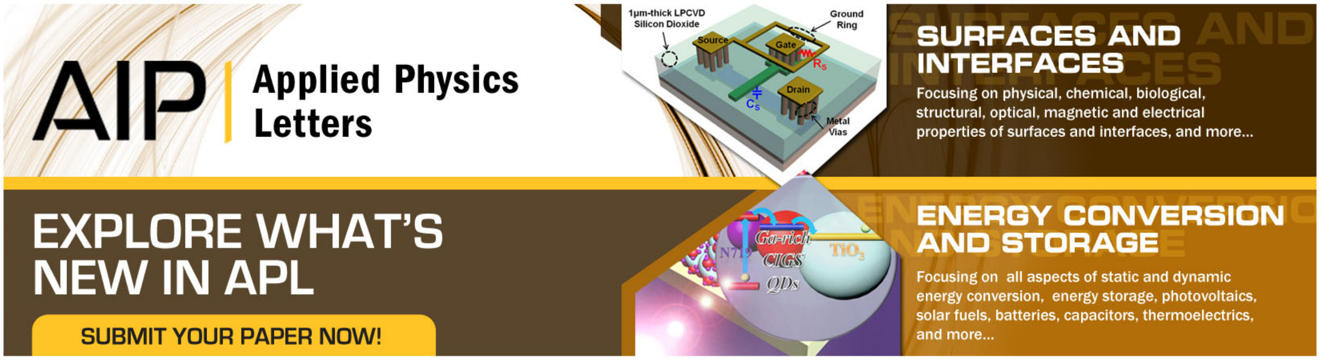

High-speed visible-blind GaN-based indium–tin–oxide Schottky photodiodes

Necmi Biyikli,[a] Tolga Kartaloglu, and Orhan Aytur
Department of Electrical and Electronics Engineering, Bilkent University, Bilkent Ankara 06533, Turkey

Ibrahim Kimukin and Ekmel Ozbay
Department of Physics, Bilkent University, Bilkent Ankara 06533, Turkey

(Received 5 July 2001; accepted for publication 13 August 2001)

We have fabricated GaN-based high-speed ultraviolet Schottky photodiodes using indium–tin–oxide (ITO) Schottky contacts. Before device fabrication, the optical transparency of thin ITO films in the visible-blind spectrum was characterized via transmission and reflection measurements. The devices were fabricated on $n-/n+$ GaN epitaxial layers using a microwave compatible fabrication process. Our ITO Schottky photodiode samples exhibited a maximum quantum efficiency of 47% around 325 nm. Time-based pulse-response measurements were done at 359 nm. The fabricated devices exhibited a rise time of 13 ps and a pulse width of 60 ps. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1412592]

Visible/solar-blind photodetectors are essential components for a number of applications including missile-launching detection, flame sensing, ultraviolet (UV) radiation monitoring, and secure space-to-space communications. Due to their direct band gap, sharp band-edge cut-off characteristics, and good electrical properties, $Al_xGa_{1-x}N/GaN$ is the most promising material system for high-performance UV photodetectors.[1] With the advancing growth technology of epitaxial $Al_xGa_{1-x}N/GaN$ layers, $Al_xGa_{1-x}N/GaN$-based visible/solar-blind photodiodes (PDs) with excellent detector performances have been demonstrated by several research groups.[2–11] The difficulty of p-type doping of $Al_xGa_{1-x}N$ layers, ease of fabrication, and better high-frequency characteristics makes Schottky PDs attractive for high-performance UV photodetection. $Al_xGa_{1-x}N$-based Schottky PDs with different types of thin semitransparent metal contacts have been fabricated successfully. Responsivities as high as 0.18 A/W (Ref. 12) and 3 dB bandwidths of 16 GHz (Ref. 13) were obtained with GaN-based Pd Schottky and Pt metal–semiconductor–metal (MSM) type PDs, respectively.

Due to the very high absorptance of GaN layers, the efficiency performance of GaN Schottky PDs with sufficiently thick (>200 nm) absorption layers is limited by the transmittance of the Schottky contact layer.[14] Semitransparent Schottky metal layers are highly absorptive and reflective, and have huge surface roughnesses, all reducing the quantum efficiency of the devices. Indium–tin–oxide (ITO), which is known as a transparent conductor, has been demonstrated as a transparent Schottky-contact material for PDs operating in the visible[15,16] and infrared spectrum.[17] Both high-quality ITO ohmic[18] and Schottky[19] contacts to GaN layers were reported. However, to our knowledge visible-blind GaN-based PDs using ITO Schottky contacts were not reported before. In this letter, we report a demonstration of visible-blind ITO Schottky PDs with RC limited pulse responses. We also compare the performance of our ITO Schottky PDs with Au Schottky PDs fabricated on the same wafer.

Before device fabrication, the electrical and optical properties of thin ITO films were characterized. The films were deposited in a rf magnetron sputtering system in which a composite target containing by weight 90% In_2O_3 and 10% SnO_2 was used under argon plasma. ITO films were grown with a deposition rate of ~10 nm/min. The resistivity of 100 nm thick ITO films deposited on semi-insulating GaAs wafers was determined to be $2\times10^{-4}\ \Omega\,\mathrm{cm}$. A fiber-optic based UV-optical transmission/reflection measurement setup was used for optical transparency measurements of ITO films sputtered on quartz substrates. The UV-absorption spectrum was determined by measuring the transmittivity and reflectivity of the film and subtracting their sum from 100%. For comparison, a thin Au film was also deposited via thermal evaporation on a quartz substrate. The thickness of the Au film was 10 nm, which is the typical Schottky metal thickness used for Schottky PDs.[20,21] Figure 1 shows the absorption spectrum of 80 nm thick ITO and 10 nm thick Au films in the 200–500 nm spectral region. The measurement results showed that the ITO film lost its full transparency for wave-

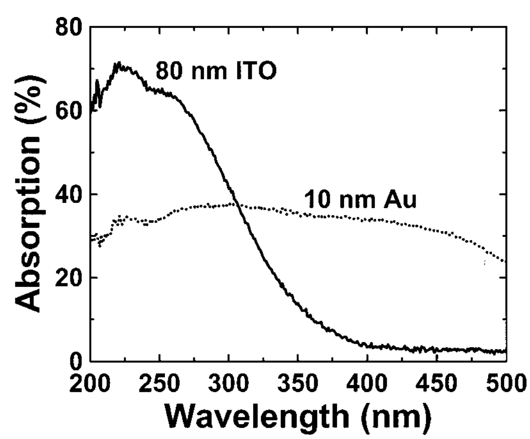

FIG. 1. Spectral absorption of ITO (solid line) and Au (dotted line) films grown on quartz substrates.

[a]Electronic mail: biyikli@fen.bilkent.edu.tr

lengths shorter than 400 nm. However, the 80 nm thick ITO film still exhibited lower absorption than the 10 nm thick semitransparent Au film for $\lambda > 310$ nm. For wavelengths near the band gap edge of GaN ($\lambda \sim 360$ nm), the ITO film absorbed less than 10% of the incident radiation. These results convinced us that ITO films could be used as low-loss Schottky contacts on GaN layers for visible-blind PD operation.

The epitaxial GaN layers of our Schottky PD wafer were grown on a sapphire substrate using metalorganic chemical vapor deposition (MOCVD). First an undoped GaN layer of 1.5 μm thickness was grown which was used as the mesa isolation layer. This was followed by the deposition of a 1.0 μm thick, highly doped ($n^+ = 2 \times 10^{18}$ cm^{-3}) GaN ohmic contact layer. The growth process was completed with a 0.3 μm thick, lightly doped ($n = 1 \times 10^{17}$ cm^{-3}) active layer.

The samples were fabricated by a four-step microwave-compatible fabrication process in a class-100 clean room environment. First, the ohmic contacts were defined via reactive ion etching (RIE) under CCl_2F_2 plasma, a 20 sccm gas flow rate, and 100 W rf power. With an etch rate of ~28 nm/min, an ohmic etch of ~0.6 μm was completed in 22 min. Afterwards Ti/Al contacts were deposited using thermal evaporation and a standard lift-off process. The contacts were annealed at 450 °C for 45 s in a rapid thermal annealing (RTA) system. Mesa structures of the devices were formed via the same RIE process by etching all the layers down to the undoped mesa isolation layer. The third step was the deposition of the Schottky contact material, where 80 nm thick ITO and 10 nm thick Au films were sputtered and evaporated, respectively, on two separate samples. The ITO films were etched to define the contact regions using dilute HF:H_2O solution, whereas the Au films were lifted off in acetone. Finally, a ~0.7 μm thick Ti/Au interconnect metal was deposited and lifted off to connect the Schottky layers to coplanar waveguide transmission line pads. The resulting GaN ITO Schottky PDs had breakdown voltages around 5 V and turn-on voltages around 0.8 V. The ITO Schottky devices displayed leakage currents larger than 1 μA at 1 V reverse bias for 100 μm diam devices, mainly due to the low ITO–GaN Schottky barrier height, which was measured as 0.59 eV by forward current–voltage ($I-V$) measurements. Au Schottky detectors had better $I-V$ characteristics than ITO Schottky devices. The Au–GaN Schottky barrier height was measured as 0.75 eV, which led to breakdown voltages larger than 10 V. Dark currents smaller than 1 nA at 1 V reverse bias for 150 μm diameter devices were obtained. The turn-on voltages were around 0.3 V for Au Schottky PDs. The ideality factors were 1.15 and 1.19 for the ITO Schottky and Au Schottky samples, respectively.

Spectral photoresponse measurements were done in the 250–400 nm range. A xenon lamp was used as the light source and was coupled into a single-pass monochromator. The monochromated output light was coupled into a multimode UV fiber by which the samples were illuminated. Calibration of the light source output was done by using a calibrated Si photodetector. Figure 2(a) shows the measured spectral quantum efficiency under zero bias on a linear scale. The ITO Schottky PD samples showed higher efficiency performance, with efficiency values >40% in the 290–360 nm region and a maximum efficiency of 47% at 324 nm. As expected, lower efficiency was observed at smaller wavelengths, due to the increased absorption of the ITO film. Au Schottky PD samples exhibited quite flat spectral efficiency with a maximum quantum efficiency of 27% around 300 nm. The corresponding device responsivity curves are shown in Fig. 2(b). Peak responsivity values of 0.13 A/W around 350 nm and 0.07 A/W around 310 nm were achieved for ITO Schottky PD and Au Schottky PD samples, respectively. UV/visible contrast of more than three orders of magnitude was observed in both samples.

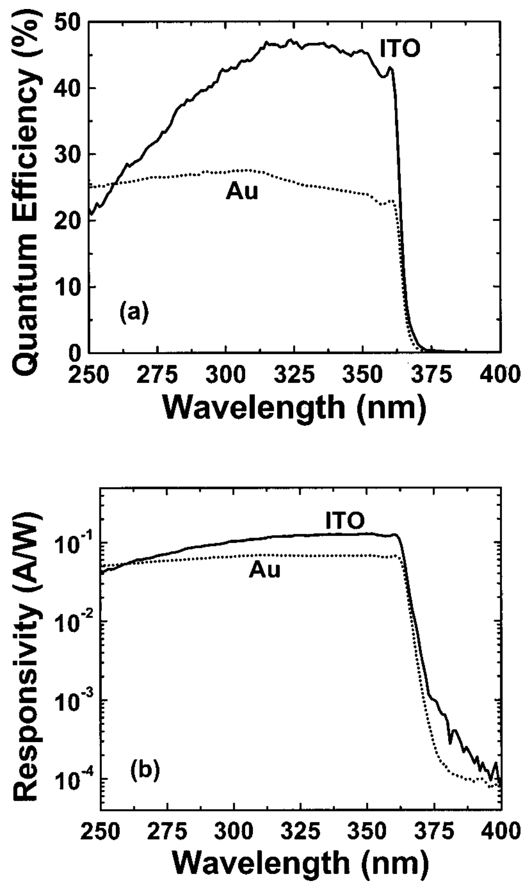

FIG. 2. (a) Measured spectral quantum efficiency of the ITO Schottky PD (solid line) and Au Schottky PD (dotted line). (b) Corresponding responsivity curves of the devices.

To characterize the high-frequency response of our ITO Schottky devices, we frequency doubled the 718 nm output of a picosecond mode-locked Ti:sapphire laser using a β-BaB_2O_4 (BBO) crystal. The outcoming 359 nm UV light was focused onto the devices using an UV grade fused silica lens with a focal length of 15 mm. High-speed characterization of the detectors was obtained by using a microwave probe station and a 50 GHz sampling scope. The pulse response obtained from an 80 μm diameter device at zero bias is shown in Fig. 3. The detector had a 10%–90% rise time of 13 ps and a full width at half maximum (FWHM) of 60 ps. The decay portion of the pulse response exhibited RC limited type behavior. By fitting an exponential to the decaying part, we obtained an RC time constant of 82 ps. This is in good agreement with the calculated RC time constant of 90 ps. The fast Fourier transform of the pulse response yielded a 3 dB bandwidth of 2.6 GHz.

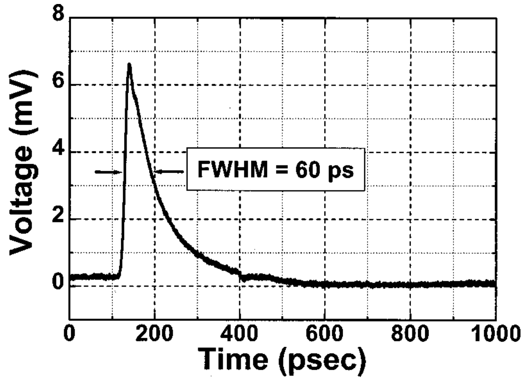

FIG. 3. Temporal pulse response of an 80 μm diameter ITO Schottky PD.

In summary, we have demonstrated high-speed, visible-blind GaN PDs using ITO Schottky layers. We observed a nearly twofold enhancement of quantum efficiency compared with semitransparent Au Schottky PDs. We achieved maximum external quantum efficiency of 47% at 325 nm and peak responsivity of 0.13 A/W at 350 nm. High-speed performance of a 13 ps rise time and 60 ps FWHM was achieved with the fabricated ITO Schottky PDs.

This work was supported by NATO Grant No. SfP971970, National Science Foundation Grant No. INT-9906220, Turkish Department of Defense Grant No. KOBRA-001, and Thales JP8.04.

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