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SiO_2-Passivated Lateral-Geometry GaN Transparent Schottky-Barrier Detectors

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SiO_2-passivated lateral-geometry GaN transparent Schottky-barrier detectors

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We report on a transparent Schottky-barrier ultraviolet detector on GaN layers over sapphire substrates. Using SiO_2 surface passivation, reverse leakage currents were reduced to a value as low as 1 pA at 5 V reverse bias for 200 μm diameter device. The device exhibits a high internal gain, about 50, at low forward biases. The response time (about 15 ns) is RC limited, even in the internal gain regime. A record low level of the noise spectral density, 5×10^{-23} A^2/Hz, was measured at 10 Hz. We attribute this low noise level to the reduced reverse leakage current. © *2000 American Institute of Physics.* [S0003-6951(00)01632-6]

Recently several research groups have reported on i-GaN based photodetectors with low reverse leakage current and high speed and responsivity for visible-blind ultraviolet (UV) detection.[1,2] Carrano *et al.*[3] reported reverse leakage current values of 10^{-5} A cm^{-2} (at -5 V) for their interlaced electrode geometry metal–semiconductor–metal detectors. In the past, using an etched mesa geometry, we have reported on GaN based transparent Schottky-barrier detectors with a very sharp visible-blind cutoff and responsivity values as high as 0.18 A/W.[4] These devices had reverse leakage currents of 10^{-6} A cm^{-2} at -5 V bias. We believed that the leakage currents primarily result from the material defects caused by the mesa etch and the surface recombination. Using SiO_2 surface passivation we now report on lateral geometry transparent Schottky-barrier detectors with significantly reduced values of reverse leakage currents. The selection of the lateral geometry precludes the need for mesa etching and, hence, significantly reduces the reverse leakage. The leakage current was further reduced by surface passivation of the devices using plasma enhanced chemical vapor deposited (PECVD) SiO_2 layer. This SiO_2 deposition technique recently has been used by us to fabricate extremely low leakage current, high transconductance metal–oxide–semiconductor heterojunction field-effect transistors (HFETs) on sapphire[5] and SiC substrates.[6]

The epilayer structure for our devices consisted of a 1.2-μm-thick layer of n^--GaN, which was deposited over basal plane sapphire substrates at 1000 °C and 76 Torr using low pressure metalorganic chemical vapor deposition. Prior to this active layer a 800-A-thick AlN buffer layer was also grown at 600 °C and 76 Torr. The growth conditions and precursors are identical to those reported in our previous work.[5] The room temperature carrier density for the active n-GaN layer was $3\times10^{16}\,cm^{-3}$. Our devices consisted of the lateral geometry transparent Schottky barriers surrounded by annular ohmic contacts (see inset in Fig. 1). The ohmic contacts were formed using Ti/Al/Ni/Au and were annealed at 650 °C for 1 min in forming gas. The transparent Schottky barriers were formed with 50–75-A-thick Pt layer, which was deposited using electron-beam metallization and a standard lift-off process. Schottky barriers with diameters ranging from 50 to 400 mm were fabricated. The ohmic contact and the transparent Schottky barriers were separated by a 10 μm gap. Also, prior to the Schottky and ohmic contact formation, a 0.1-μm-thick layer of SiO_2 was deposited onto a part of the wafer surface using PECVD. The other part of the wafer remained uncovered with SiO_2. Schottky barriers were formed both in the SiO_2 covered and the non-SiO_2 regions.

Figure 1 shows dark current–voltage ($I-V$) characteristics of a 400 μm diameter Schottky diode, on regions with and without SiO_2 passivation. In the voltage range of 10–20 V, the leakage current of the device with SiO_2 passivation was about 10^2-10^4 times less than that of device without passivation. In Fig. 2 we include the dark and light characteristics of a 200 μm diameter SiO_2 passivated Schottky diode. As seen, the dark current is as low as 1 pA at 5 V reverse bias; it increases with reverse bias voltage and then saturates at a value of 1.5 nA at 45 V.

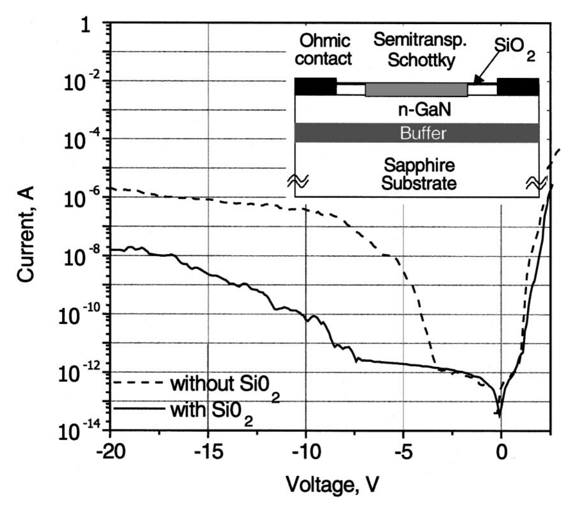

FIG. 1. Typical dark $I-V$ characteristics of 400 μm diameter Schottky diode. Dashed curve—device without SiO_2 surface passivation, solid curve—with SiO_2 passivation. Both devices are fabricated on the same wafer.

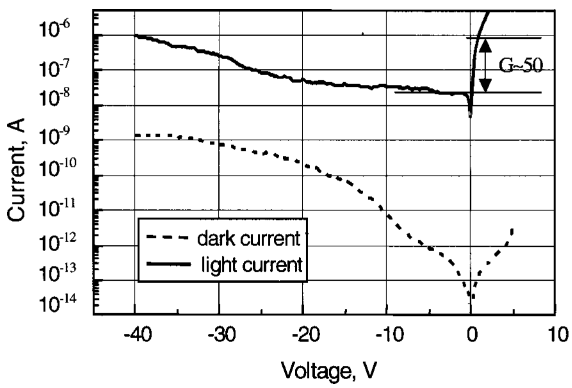

FIG. 2. Dark and light $I-V$ curves for 200 μm diameter lateral Schottky photodiode.

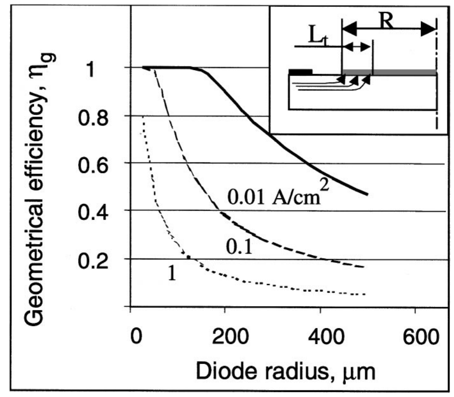

FIG. 3. Geometrical efficiency of lateral Schottky photodiode as a function of device diameter at different values of the photocurrent density J_m. The inset shows schematically the current spreading under planar Schottky electrode. $J_m = I_m/A = S_m P_{\mathrm{opt}}/A$, where S_m is maximal responsivity of the device with uniform photocurrent distribution, P_{opt} is the incident optical power, and A is the device area.

Using a calibrated UV-enhanced Si photodiode we then measured the responsivity for the transparent Schottky detector. A He–Cd laser at 325 nm wavelength was used for these measurements. The responsivity at reverse bias of -5 to -10 V was $S \approx 0.19$ A/W. As expected, the gain at reverse bias condition was nearly 1. However, at small forward biases, below the barrier turn-on voltage (0.7 V), a high gain of approximately 50 was measured (see Fig. 2).

We attribute the Schottky detector gain at forward bias to the trapping of the photogenerated holes at the barrier interface. The following model can describe this effect. The trapped sheet hole concentration, p_s, creates an additional electric field of $F_s = (qp_s)/(\epsilon\epsilon_0)$. This field reduces the barrier height by

$$\Delta V = \frac{qp_s d}{\epsilon\epsilon_0}. \tag{1}$$

Here d is the depletion layer thickness at the metal–semiconductor interface. For the doping level of $3 \times 10^{16}\,\mathrm{cm}^{-3}$ the depletion width d corresponding to 0.7 V built-in barrier potential is about 0.2 μm. From the measured gain, $G \approx 50$, we find that the barrier height reduction must be $\Delta V = V_{\mathrm{th}} \ln(G)$, where $V_{\mathrm{th}} = (kT/q) \sim 26$ mV is the thermal potential at room temperature. Hence, we find, $\Delta V \approx 0.1$ V, and the sheet density of the holes trapped near the interface is then estimated to be

$$p_s \approx \epsilon\epsilon_0 \frac{\Delta V}{qd} \sim 3 \times 10^{10}\ \ \mathrm{cm}^{-2}. \tag{2}$$

This trapping effect is significantly reduced under the reverse bias condition due to the high field, which causes carrier separation. This explains the absence of gain under the reverse biasing. It is worthwhile now to compare the sheet density of trapped holes (2) with that estimated from device reverse current. Since the gain is about 1 under the reverse bias condition, the concentration of photogenerated carriers $n_{\mathrm{ph}} = p_{\mathrm{ph}}$ can be estimated from the reverse photocurrent I as

$$n_{\mathrm{ph}} = \frac{I}{A_{\mathrm{eff}} q v}, \tag{3}$$

where A_{eff} is the effective area of the detector (see below), and v is electron drift velocity. Assuming $I = 5 \times 10^{-8}$ A (see Fig. 2) and $v \sim 10^6$ cm/s we find from (5) $n_{\mathrm{ph}} = p_{\mathrm{ph}} \approx 10^9\ \mathrm{cm}^{-3}$. Since the minimal response time of the detector was measured to be about 15 ns (see our experimental results below), the lifetime of the portion of trapped holes contributing the photocurrent, τ, has to be 15 ns, or less. Then, the sheet density of those trapped holes can be estimated as $p_s = n_{\mathrm{ph}} \tau v \approx 1.5 \times 10^7\ \mathrm{cm}^{-2}$. This trapped holes sheet density is about 2000 times less than that in (2). This implies that most of holes are trapped by very deep traps having lifetimes much longer than 15 ns. Those holes thus practically do not contribute to the pulse photoresponse of the detector. However, their surface charge still decreases the Schottky-barrier height and thus results in internal gain. The presence of distributed deep traps is consistent with our $1/f$ noise measurements for AlGaN/GaN based HFETs.[7,8]

To utilize the gain, lateral geometry Schottky devices have to be used with a slight positive bias. However, this can significantly reduce the effective device area due to the current crowding resulting from the sheet resistance. We estimated this potential decrease in the device active area by following model for our planar circular geometry device. The current flows under the Schottky diode into a ring with the width of L_t, where L_t is the effective transfer length. Thus, the effective area of the photodiode of a radius R can be expressed as $A_{\mathrm{eff}} = \pi R^2 - \pi(R - L_t)^2$ (for $L_t < R$). The responsivity of the lateral photodiode, S, differs from its maximum value, S_m, that correspond to uniform current distribution, by a geometrical efficiency factor

$$\eta_g = A_{\mathrm{eff}}/\pi R^2 = 1 - [1 - (L_t/R)^2]. \tag{4}$$

If the diode radius is much larger than the gap between the electrodes, the effective transfer length can be estimated as $L_t \approx \sqrt{\rho_{d\ \mathrm{eff}}/R_{\mathrm{sh}}}$, where $\rho_{d\ \mathrm{eff}} = (V_{\mathrm{th}} A_{\mathrm{eff}})/I$ is the effective differential resistance of Schottky contact, $V_{\mathrm{th}} = kT/q$ is thermal potential, R_{sh} is the sheet resistance of the semiconductor film, and I is the device current. In general, for the given current, Eq. (4) must be solved using the expression for A_{eff} above to find the L_t. In the case where the photocurrent is much higher than the dark current, $I = \eta_g S_m P_{\mathrm{opt}}$, where P_{opt} is the optical power. The expression for transfer length then becomes

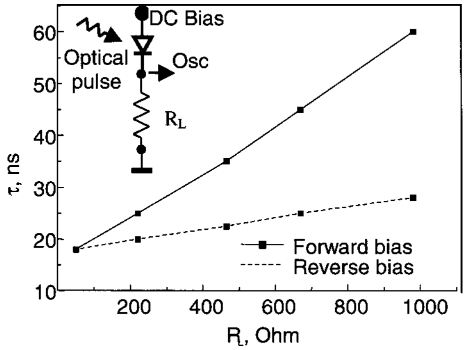

FIG. 4. The detector response time as a function of load resistance.

$$L_t \approx \sqrt{\frac{V_{\mathrm{th}} A}{R_{\mathrm{sh}} S_m P_{\mathrm{opt}}}}. \tag{5}$$

Figure 3 shows the dependence of the geometrical efficiency factor η_g, on the device radius at different values of maximal photocurrent density $J_m = S_m P_{\mathrm{opt}}/A$ calculated from (4) and (5) for the following parameters of the n layer: the electron concentration $n = 3 \times 10^{16}\,\mathrm{cm}^2$; mobility $\mu = 300\,\mathrm{cm}^2/\mathrm{V\,s}$; the thickness of the undepleted layer, $d = 0.5\ \mu\mathrm{m}$, which corresponds to a small positive bias. As can be seen from the figure, for the large area devices at high photocurrent densities, the photodiode responsivity degrades due to the current spreading effect. However, this effect is only pronounced at optical powers in excess of 100 μW for 50 μm diameter device. Hence, a forward biased lateral photodiode can be successfully used as a photodetector with high internal gain.

We also measured the low frequency noise for our transparent Schottky detectors. The major noise contribution was $1/f$ noise. At 10 Hz, the noise spectral density was measured to be $5 \times 10^{-23}\,\mathrm{A}^2/\mathrm{Hz}$. This noise level is about two orders of magnitude better than previously reported[4] for GaN transparent Schottky devices with a mesa etch. We believe that the noise reduction can be attributed to reduced leakage of our device.

The detector speed of response was measured using low-intensity N_2 pulsed laser (337 nm wavelength, 4 ns pulse width) as the radiation source. The detector was connected in series with a load resistor R_L and biased as shown in Fig. 4. As seen from the figure, the response time was around 15 ns (for a 200 μm diameter device at zero load limit) and it was RC limited. This response time was about the same for both reverse and forward bias. This means that the internal gain does not significantly increase the photodetector response time.

In conclusion, our Schottky-diode detectors with lateral geometry showed a very low dark current and a record low $1/f$ noise. This design eliminates a mesa etch leading to a surface leakage current and contributing to noise. Using SiO_2 surface passivation reverse leakage currents were reduced to a value as low as 1 pA at 5 V reverse bias for 200 μm diameter device. The device exhibits a high internal gain of about 50 at small forward bias, below 1 V. This lateral photodiode can be successfully used as a fast photodetector with high internal gain under small forward bias.

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