Applied Physics Letters

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Cite as: Appl. Phys. Lett. **90**, 223507 (2007); https://doi.org/10.1063/1.2745208
Submitted: 13 February 2007 . Accepted: 08 May 2007 . Published Online: 31 May 2007

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Photocurrent gain in 4*H*-SiC interdigit Schottky UV detectors with a thermally grown oxide layer

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(Received 13 February 2007; accepted 8 May 2007; published online 31 May 2007)

A large photocurrent increase in 4*H*-SiC interdigit Schottky UV detectors was observed in the presence of a thermally grown silicon oxide layer. In particular, internal quantum efficiency higher than unity indicated the presence of an internal gain strictly correlated with the presence of the superficial oxide on SiC. Moreover, a long recovery time, in the range of 10–19 s, was evaluated by fall-time photocurrent measurements due to the detrapping of charges in the oxide after the irradiation switching off. The photoresponse of the device was analytically described considering the lowering of the surface potential barrier due to charges trapped at the oxide/semiconductor interface. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2745208]

Silicon carbide (SiC) photodetectors have been receiving a great attention in the last years for their application in the ultraviolet (UV) radiation detection, particularly where the visible blindness is required.[1–3] Most of these applications require high sensitivity and high speed performances. However, in some cases (i.e., in biological agent detection[4]) only a high sensitivity and short switching-on time are necessary. 4*H*-SiC interdigit vertical photodiodes with high external quantum efficiency were previously demonstrated exploiting the surface "pinch-off" effect.[5] The fundamental aspect of these Schottky photodetectors is the direct exposure to radiation of the optically active area (OAA).

The oxidation process is a crucial topic in SiC technology since it results in the formation of a large density of carrier traps located at the SiO_2/SiC interface. These carrier traps are named near interface traps and, generally, are slow states.[6–9] In the case of UV photodetectors, due to its high optical transmittance in the UV range, silicon oxide (SiO_2) is frequently proposed as antireflecting coating, passivation, and/or chemical protection layer.[1,2] However, the influence of a thermal oxidation on the response of SiC UV photodetectors was not extensively reported to date.

In this letter, the performances of an interdigit 4*H*-SiC Schottky UV detector were studied in the presence of a thermal protective SiO_2 layer, grown on the SiC exposed area. A large improvement of the optical response was observed, revealing a photocurrent gain effect. From the static and dynamic electro-optical responses, the gain effect was attributed to the presence of charge traps at the oxide/semiconductor interface. Their recovery time was estimated from photocurrent fall-time measurements. A physical interpretation of the observed phenomenon is also proposed.

Schottky-type UV photodiodes were fabricated on *n*-type 4*H*-SiC epitaxial layers, 5.8 μm thick with 2.7×10^{15} cm^{-3} residual dopant concentration, grown by ETC S.r.l. onto a heavily doped 4*H*-SiC substrate. A large area Ohmic contact on the sample backside was formed by evaporation of a 200 nm Ni film, followed by an annealing at 950 °C. Interdigit Schottky contacts, Ni stripes (6 μm wide and 4.5 μm spaced), were fabricated on the wafer frontside. An optimized thermal process was performed to induce the formation of Ni_2Si stripes and to improve the uniformity of the Schottky barrier.[10,11] The total diode area was 1.44 mm^2, while the area directly exposed to radiation was estimated 38% of the total device area. In some devices, a thin silicon oxide layer was thermally grown onto the "open area," i.e., between the metal Ni_2Si stripes of the front electrode. Several low temperature oxidation processes were performed producing in any case similar results. Here, we report about oxidation at 600 °C in O_2 for 1 h. The thickness of the SiO_2 layer was 2 nm, as measured by atomic force microscopy performed on an opportunely prepared sample.[12] A not-in-scale schematic cross view of the fabricated device with superficial oxide is shown in the inset of Fig. 1.

The response of the detectors was evaluated using a Hg (low vapor pressure) lamp and interferential filters. The incident optical irradiance was determined using a commercial UV detector. The dynamic electro-optical performances were studied modulating the optical beam by means of a mechanical shutter. This modulation system allowed us to monitor photocurrent transient effects slower than the switching time of the shutter (about 1 s). Current-voltage *I-V* characteristics were measured using a Keithley 236 source measure unit.

First, the device currents were measured as a function of the reverse bias, both in the dark condition I_{dark} and under

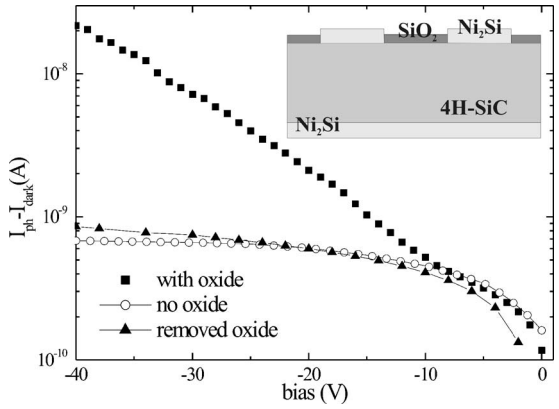

FIG. 1. Optical response vs the applied bias of "with oxide", "no oxide", and "removed oxide" samples. In the inset: schematic cross view of a "with oxide" diode.

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UV illumination I_{ph}. The optical response, i.e., the difference ($\Delta I = I_{ph} - I_{dark}$), of the different samples is reported in Fig. 1 for an incident wavelength of 256 nm and an optical irradiance of 1.2 $\mu W/cm^2$. The devices with the covering oxide layer are referred in the following as "with oxide" diodes, while those without the oxide layer as "no oxide" diodes. A third group of devices, named "removed oxide" diodes, is "with oxide" devices, in which the oxide was removed by chemical wet etching.

As can be clearly seen in Fig. 1 a relevant change occurs when the oxide layer is present. At low biases the photocurrent has a similar trend as in the case of the "no oxide" diode, while a significant increase of the optical response can be observed above a "threshold" bias V_g (see Fig. 1). Referring the optical responses of our diodes at −25 V (pinch-off regime, see Ref. 5) to the response of a commercial detector (for an optical irradiance of 1.2 $\mu W/cm^2$ at a wavelength of 256 nm), internal quantum efficiency (QE) values of 200% and 55% were obtained for the "with oxide" and "no oxide" diodes, respectively. An internal QE higher than unity for the device with oxide indicates that an internal gain is involved.

After removing the oxide layer ("removed oxide" diode), the optical response is almost coincident to that of the "no oxide" device (see Fig. 1). This result clearly demonstrates that the presence of oxide is responsible for the observed photocurrent gain effect. Moreover, an improvement of the photoresponse due to an antireflecting effect of the 2 nm thick oxide layer can be ruled out. In fact, to have antireflecting effect the oxide thickness must be in the range of 30–70 nm for wavelengths of 200–400 nm.[13] Furthermore, an antireflecting effect should result in an enhancement of the optical response independently of the bias, in contrast with data shown in Fig. 1.

The photocurrent gain can be discussed in terms of the barrier lowering due to charge traps at the oxide/semiconductor interface. During the operation, the photodiode is reversely polarized and the interdigit front electrode (the anode) is at a negative bias. Traps, located in the interface region between contiguous metal strips, are partially occupied and then positively charged because of the bias. UV irradiation promotes further charge trapping proportionally to the photocurrent. Consequently, negative mirror charges are generated in the semiconductor side. The associated electric field close to the Schottky contact strips locally results in a reduction of the barrier height.[14,15] The local electric field enhancement in the strips edge regions acts on the entire photodiode resulting into an average Schottky barrier lowering with respect to the dark condition. The barrier height in the presence of UV irradiation is then given by $\phi_B = \phi_{B\_dark} - \Delta\phi_B$, where ϕ_{B_dark} is the barrier height in dark condition and $\Delta\phi_B > 0$ is the barrier lowering.

The current of a Schottky photodiode in reverse bias and under illumination is the sum of the thermionic emission term and of the photogeneration current,

$$I_{ph\_ox} = \text{const} \exp\left(\frac{-q(\phi_{B\_dark} - \Delta\phi_B)}{kT}\right) + I_\lambda, \quad (1)$$

where k is the Boltzmann constant, T the temperature, q the electron charge, and being the photogeneration current $I_\lambda = \eta(P_D/h\nu)q$ OAA, where P_D is the optical irradiance, OAA is the optically active area, η is the semiconductor quantum efficiency, and $h\nu$ is the energy of radiation.[5,13]

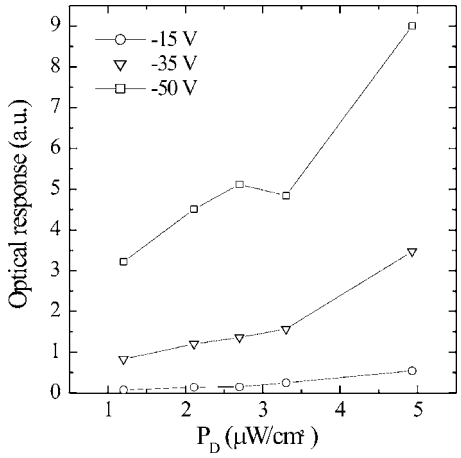

FIG. 2. Optical response vs the incident irradiance of a "with oxide" device for three values of the reverse bias, −15, −35, and −50 V.

The response of the device with oxide is then

$$\Delta I_{ox} = \left(\exp\left(\frac{q\Delta\phi_B}{kT}\right) - 1\right) I_{dark\_ox} + I_\lambda, \quad (2)$$

where the first term of addition is the gain current term. It is interesting to note that a trapped charge density of only 1×10^{10} / cm^2 is sufficient to justify a barrier lowering of 0.3 eV (at −25 V reverse bias).[15,16] Moreover, we mention that both barrier height and the trapped charges are influenced by the applied electric field. In particular, the trapped charges are known to increase with the applied voltage,[17] producing an enhancement in the barrier lowering. The response (see Fig. 2) of the "with oxide" diodes at different incident irradiance values (1.2, 2.1, 2.7, 3.3, and 4.9 $\mu W/cm^2$) and wavelength of 256 nm was measured at different biases in the gain regime (−15, −35, and −50 V). As fixing the bias is equivalent to keep constant the OAA, the nonlinear increase of the optical response with the irradiance P_D shown in Fig. 2 indicates that the gain is dependent on the irradiance. This is due to the increase of the trapped charge density proportionally to the optical irradiance.[18] Furthermore, the trapped charge density increases with the external electric field.[17] Then the optical response increases with the external bias also in the pinch-off regime, as clearly visible in Figs. 1 and 2. It is also important to point out that, similarly to the "no oxide" case, the "with oxide" device exhibits visible blindness, since measurements performed at 400 and 500 nm showed the absence of photocurrent. Then, absorption between levels located in the semiconductor band gap and the conduction band (extrinsic transitions) can be ruled out.[19] Dark current measurements performed in the "with oxide" samples before and after UV illumination (not shown here) evidenced the presence of a persistent photocurrent that can be correlated to the above described slow states.

When, after irradiation, UV-light is switched off, in the reverse biased photodiode, oxide traps (filled under UV irradiation) release the charges, leading to a recover of initial value of the surface potential (the surface barrier increases again). To monitor the slow current transient component correlated with the charges detrapping, the dynamical performances of the "with oxide" diode were measured using the previously described beam modulation system.

The dynamical response of the photodetector can be described considering the dependence of the surface potential

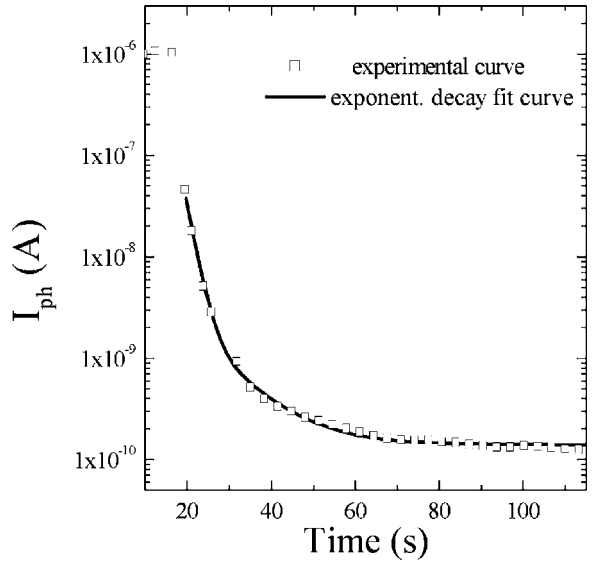

FIG. 3. Photocurrent vs time at a −30 V. A detrapping time of 10 s was extracted by the fit of the experimental data plotted in a semilogarithmic scale: exponential decay fit curve is superimposed to the experimental points.

recovery from the variation of the trapped charge density. As can be easily deduced from Eq. (2), when the optical excitation is halted and $I_\lambda = 0$, the device current decays

$$I_{\text{ph\_ox}}(t) = I_{\text{dark\_ox}} \exp\left(\frac{q\Delta\phi_B(t)}{kT}\right) \tag{3}$$

and the equilibrium current $I_{\text{dark\_ox}}$ is reached after the complete charge release from the traps. We remember that the variation of the trapped charge density ΔQ_{ss} follows an exponential decay with a constant time τ_r. Finally, since the change of the barrier height is proportional to the variation of the trapped charge density, i.e., $\Delta\phi_B(t) \propto \Delta Q_{ss}(t) \propto \exp(-t/\tau_r)$, it is clear from Eq. (3) that the *logarithm* of the photocurrent will decay exponentially with the time constant τ_r.

In Fig. 3 the experimental values of the photocurrent (open square symbols) at a reverse bias of −30 V are reported as a function of the time in a semilogarithmic scale for a "with oxide" device. The exponential decay fit curve (continuous line), obtained with a fall time of $\tau_r = 10$ s, is superimposed to the experimental data. Measurements, done at 256 nm and at different bias in gain regime, were fitted with exponential decay curves, obtaining τ_r ranging from 10 to 19 s. For bias below V_g, i.e., before the onset of the photocurrent gain, the fall time was not resolvable from the switching time of the optical beam.

The current rise from the dark to the illumination condition can be described with similar parameters and physical considerations. Further contributions to the fall and rise current mechanisms are eventually related to the transit time of photocarriers in the depletion region, to the diffusion time outside depletion region, and to the *RC* of the circuit.[13,17,19,20] In our case, due to the detector layout (geometry, epilayer thickness, doping, and crystalline quality) these contributions are expected to be negligible when compared with the characteristic time of the photocurrent decay.

The "no oxide" samples were characterized as reference, but the rise and fall times were shorter than the mechanical shutter switching time. Also the rise current transient of the "with oxide" device was faster than the beam modulation system.

The long fall time affects only the switching-off performance of "with oxide" photodetectors and then it is related to the detrapping of charges.[18] Moreover, also the threshold bias V_g in the gain effect is consistent with the location of the traps at SiO_2/SiC interface. In fact, those traps are involved in the photodetection only above an appropriate reverse bias ($>V_g$), i.e., when the interface region is included in the optically active area.[5]

In conclusion, the effects of an oxide layer, thermally grown on the SiC exposed area, on the optical performances of interdigit 4*H*-SiC Schottky UV photodiodes were studied. A relevant change in the photocurrent was observed and an internal QE higher than unity was measured, involving the presence of an internal gain. This effect was ascribed to the positive charges trapping in the oxide and the negative mirror charges in the semiconductor. The associated electric field enhancement implies a barrier lowering. The proposed mechanism was used to analytically describe the optical response. Dynamical measurements allowed us to determine a time correlated with the oxide detrapping time in the range of 10–19 s.

The photocurrent gain effect demonstrated in our interdigit devices in the presence of a covering oxide layer can enhance the sensitivity of UV detectors for those applications where high sensitivity and short switching-on time are required.

The authors would like to acknowledge S. Libertino and C. Spinella for fruitful discussions and ETC, a LPE group company, for growing the 4*H*-SiC epitaxial wafers.

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