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Photovoltaic Behavior of V_2O_5/4H-SiC Schottky Diodes for Cryogenic Applications

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ABSTRACT The photovoltaic behavior of (divanadioum pentoxide)/(4H polytype silicon carbide) Schottky diodes under ultraviolet illumination and down to 28K is investigated. In addition to their high stability, by using the thermionic model the analysis allows to confirm the predictability of performances at cryogenic temperatures, such as the high light/dark current ratio and the dependence of the photocurrent and open circuit voltage on material parameters. Because of the low-annealing temperature, this structure is shown to be a good candidate for solar-blind photodetectors in the UV spectral range of spatial and terrestrial cryogenic applications.

INDEX TERMS 4H-SiC device, photodiodes, photovoltaic effects, Schottky diodes, silicon compound.

I. INTRODUCTION

Silicon Carbide has been one of the first semiconducting material employed in optoelectronics. Already in 1907 electroluminescence has been observed on silicon carbide ("carborundum") as active material in a cat's whisker detector configuration [1] and it is also used for blue light emitting diodes (LEDs) [2]. However, due to the development of much more efficient LEDs based on InGaN [3] and on ZnTe/ZnS superlattices [4], SiC lost its role as standard blue emitter, but some niche applications for SiC emitters remain; recently, a SiC single photon emitter has been successfully implemented [5] with interesting applications for quantum communication and quantum cryptography.

Nowadays, on the photoreceiver side of optoelectronics, SiC plays an important role as absorber material for solar-blind photodetectors [6] in the UV spectral range and in harsh environments, thanks to its wide bandgap and its hardness to highly ionized radiations [7]. Though a variety of 4H-SiC-based UV detectors are available today, such as, Metal-Semiconductor-Metal [6], p-i-n [8] and avalanche gain [9] photodetectors, new materials to be used in conjunction with 4H-SiC are being proposed, as AlN-SiC photodetectors [10]. All these devices require either a high annealing temperature for contact formation, i.e., at least *1173K* to get a good Schottky contact [11], or expensive process steps to fabricate the photo-active region as occurs for p-i-n [12] and AlN-SiC [10] diodes.

Recently, it has been shown that the evaporation of thin V_2O_5 films on *4H-SiC* represents an interesting alternative for realizing Schottky SiC diodes [13] with a low temperature annealing process, i.e., *723K*. In this paper, electro-optical analysis of V_2O_5/*4H-SiC* Schottky diodes in the range *28-300K* show photovoltaic behavior, justifying their use as SiC based UV-blind photodetectors at low temperatures.

II. EXPERIMENTAL SAMPLES

V_2O_5/*n-4H-SiC* Schottky diodes, with the cross-section shown in Fig. 1, are the same used in [13]. The epilayer is $5\mu m$-thick and $8.8\cdot 10^{15} \pm 2.2 \cdot 10^{15} cm^{-3}$-doped, grown on <0001> *4°* off-axis Si-face n^+ 4H-SiC $350\mu m$-thick and $21m\Omega cm$ substrate. Firstly, *Ni* ohmic back contact has been thermally evaporated and annealed at *1273K*, then V_2O_5 (99.99% powered Sigma-Aldrich) layer has been deposited *5nm*-thick, with a dot shape of *1mm* diameter, and annealed at *723K* in Nitrogen ambient for *10min* along with a $500\mu m-$dot and *100nm*-thick Aluminum film used as anode. Diode contact area is $S=1.96\cdot 10^{-3} cm^2$.

Device characterization is performed in a Janis Research Inc. cryo-system from *28K* to *300K* using HP4155B Semiconductor Parameters Analyzer and an Agilent

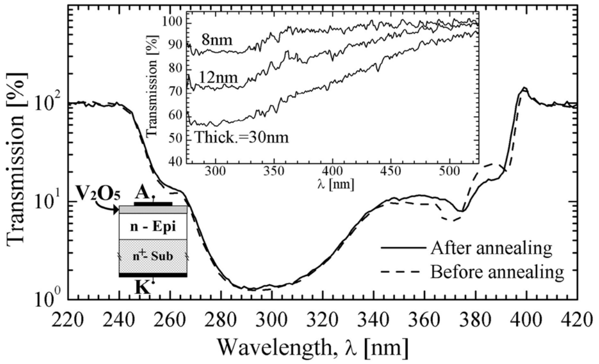

FIGURE 1. **Transmission spectra of *5nm-V_2O_5/4H-SiC* after and before annealing at *723K*. In the inset, the transmission of *V_2O_5*/glass at different thicknesses.**

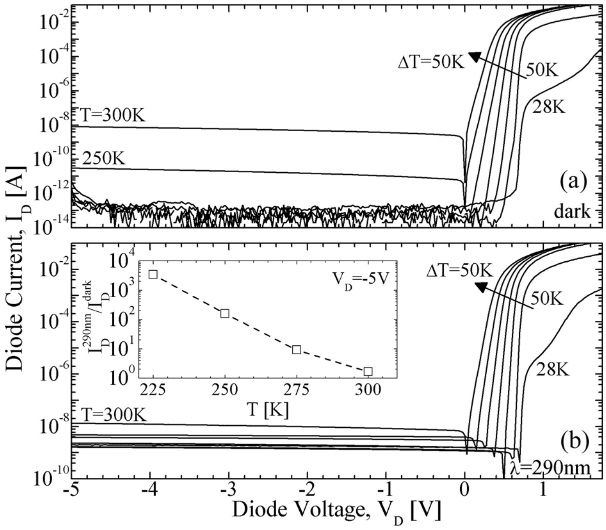

FIGURE 2. ***I_D–V_D* characteristics a) in dark and b) under UV illumination *λ=290nm* at various *T*. In the inset of b) the ratio *I_D^{290nm}/I_D^{dark}*.**

E4980a LCR meter at *1MHz* for I_D–V_D and C_D–V_D measurements, respectively. Optical measurements have been performed by using a LOT-qd MSH-150 monochromator system with a resolution of *0.3nm* and a 150W Xe arc lamp, having an optical power density of $140\mu W/cm^2$ at $\lambda = 290nm$. The exposed surface of samples is limited to *2mm*-diameter dot by means of a shadow mask concentric with the anode metal.

III. DISCUSSION

Transmission spectra of *V_2O_5/4H-SiC* structure, measured before and after the annealing process, and of *V_2O_5* deposited with different thickness on a *7059* Corner glass are reported in Fig. 1. Measurements have been made by using a Stanford Research Systems SR830 lock-in amplifier with an United Detector Technology Inc. PIN-10 Si-photodiode, for the range of *350–550nm,* and a Roithner Lasertechnik EPD-365-0-0.9 GaP-photodiode for the range *245–400nm*. As shown from the inset, the optical transmission spectra of the *V_2O_5*-glass increases with the film thinning and reaches about *90%* at λ=*300nm* for the *8nm*-film. Using these data to obtain the Tauc plot in the form of $(\alpha h\upsilon)^{1/2}$, the optical bandgap results *2.38eV*, which agrees with those reported in [14]. *V_2O_5/4H–SiC* structures realized with *5nm-V_2O_5* film show the main absorption in the range *240-400nm*, being the lower limit given from *GaP* photodiode, and a slightly difference in the range *340-400 nm* for the annealing process at *723K* [13].

I_D–V_D curves of *V_2O_5/4H–SiC* structures measured in the range *28-300K* under dark and illumination conditions are shown in Fig. 2(a) and (b), respectively. The behavior of curves in Fig. 2(a) can be described by thermionic model [15] as in [13]:

$$I_D = I_S\left(e^{\frac{V_D}{\eta V_T}}-1\right) = SR^{**}T^2 e^{-\frac{\Phi_{BN}-\Delta\Phi}{V_T}}\left(e^{\frac{V_D}{\eta V_T}}-1\right) \tag{1}$$

where R^{**}=$146Acm^{-2}K^{-2}$ is the Richardson constant, Φ_{BN}=*0.8eV* the Barrier Height, η=*1.027* the ideality factor at *300K*, $\Delta\Phi = \sqrt{qE_M/(4\pi\varepsilon)} + \alpha_{DIP}E_M$ the barrier lowering due to the image force and the static dipole effects, E_M the maximum electric field at the junction, q the electron charge, ε the *4H-SiC* dielectric permittivity and V_T the thermal voltage. In particular, at *T=300K* the *V_2O_5/4H-SiC* diode reverse current, I_D^{dark}, can be justified with α_{DIP}=*1.15nm* [13] and, as shown in Fig. 2(a), goes out from resolution of measurement set-up below *200K*. Further, it is several orders of magnitude lower than the photo-current I_D^{290nm} generated with λ=*290nm*. Observing the inset of Fig. 2(b), the ratio I_D^{290nm}/I_D^{dark} increases from *1.6* to *3400* when the temperature decreases from *300K* to *225K* at V_D=−*5V*.

Fig. 3 shows the *T*–dependency of $\Delta I_D^{290nm} = I_D^{290nm} - I_D^{dark}$ measured at V_D=*0V* and *-5V*, while the inset describes the photocurrent spectrum at V_D=*-5V* for different temperatures. From the curves of Fig. 3 two different behaviors can be clearly distinguished: *i)* for a fixed V_D, the current

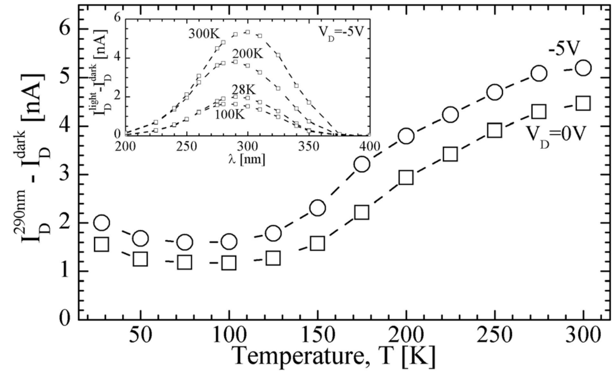

FIGURE 3. ***T*-dependency of the photocurrent for λ=*290nm* at *V_D=0V* and −*5V*. In the inset the spectrum of the photocurrent at various *T* and *V_D=−5V*.**

$\Delta I_D{}^{290nm}$ reduces with T and reaches a minimum value of $1.59nA$ at $75K$ and $V_D=-5V$; *ii)* for a fixed T, the photocurrent increases with the reverse voltage V_D but has a weaker V_D-dependency than that caused from the barrier lowering affecting $I_D{}^{dark}$ given from (1). These behaviors can be explained by estimating the net photocurrent for a reversely biased junction for a given λ [15]:

$$\Delta I_D^{\lambda}(T, V_D) = -q\Phi_0 S\left(1-\frac{e^{-\alpha W_{SC}}}{1+\alpha L_p}\right) - \frac{q p_0 D_p S}{L_p} \qquad (2)$$

where Φ_0 is the incident photo flux per unit area, $W_{SC} = \sqrt{2\varepsilon\left(V_{bi}-V_D-V_T\right)/\left(qN_D^{+}\right)}$ is the space charge width, $L_p = \sqrt{V_T\mu_p\tau_p}$ the hole diffusion length, μ_p the hole mobility, $D_p = V_T\mu_p$ the hole diffusion coefficient, and τ_p the hole lifetime. It is worth to note that (2) is approximated to the first term of r.h.s. due to the very low hole concentration, p_0, value for *4H-SiC* [16]. To evaluate L_p in (2) accordingly to the method [17], in Fig. 4(a) the values of (2), measured under weak absorption ($\lambda=350nm$) and for three T, are plotted as function of $W_{SC}=S\varepsilon/C_D$ obtained from C_D–V_D technique. L_p values are extracted from the intersection of curves with x-axis. Note that W_{SC} value measured at $V_D=0V$ decreases from $0.278\mu m$ to $0.25\mu m$, mainly, for the expected reduction of the built-in voltage, V_{bi}, while $L_P=2.3\mu m$ and $0.806\mu m$ at $300K$ and $100K$, whose T–dependency is mainly due to the carrier recombination through single energy level traps as also shown in [18]. Furthermore, it is interesting to observe that, by using μ_p equal to $117cm^2/V/s$ at $300K$ [19], the hole lifetime results $17ns$, which is consistent with the lifetime values found for this kind of epilayer [20]. In particular, from the above analysis the depth $L_{LIM}=W_{SC}+L_p$ of the photoactive region at $T=300K$ results $2.55\mu m$, which corresponds to an absorption coefficient of $\alpha_{LIM}=1/L_{LIM}=3921cm^{-1}$ and, using the linear dependency of $\alpha^{1/2}-h\nu$ [21], is located at $\lambda_{LIM}=295nm$. This value is confirmed from the curves in the inset of Fig. 3. The results of the previous analysis obtained at various T are reported in Table 1. Using these data in (2) and treating Φ_0 as fitting parameter, in Fig. 4(b) the values of (2) are compared with ΔI_D^{290nm} curves of Fig. 2. Note that the effect of Φ_0 in (2) is limited to shift the curves, whereas their slope depends only on the others parameters. Considering that at $\lambda = 290nm$ the incident photo flux of the optical system is $20.4{\cdot}10^{13}\cdot\ cm^{-2}s^{-1}$, Φ_0 into the semiconductor is reduced of 12.4% at $300K$ and it can be due both to the optical absorption from V_2O_5 as shown in the inset of Fig. 1 and to defects at the surface [17]. Furthermore, the reduction of the photocurrent with the temperature is due to the reduction both of the active optical length [17] and of Φ_0.

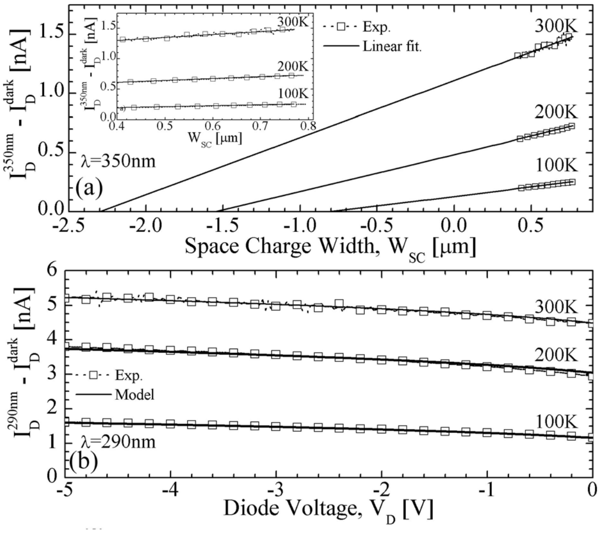

FIGURE 4. **a) $\Delta I_D{}^{350nm}$ vs. W_{SC} curves at $\lambda=350nm$ at different T. In the inset the same plot with shorter scale range. b) Comparisons of $\Delta I_D{}^{290nm}$-V_D curves between measurement data and model results at different T.**

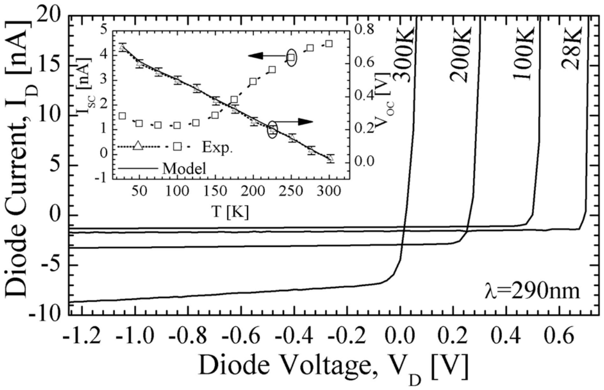

FIGURE 5. **$I_D{}^{290nm}$-V_D curves at various T. In the inset $I_{SC}{}^{290nm}$ and $V_{OC}{}^{290nm}$ vs. T.**

TABLE 1. **Physical parameters extracted from measurements.**

T	$[K]$	100	200	300
$N_D{}^+$	$[10^{15}cm^{-3}]$	9.55	9.57	9.93
V_{bi}	$[V]$	0.691	0.637	0.575
$W_{SC}\|_{VD=0V}$	$[\mu m]$	0.278	0.266	0.25
L_h	$[\mu m]$	0.806	1.55	2.3
α_{LIM}	$[cm^{-1}]$	9225	5506	3921
λ_{LIM}	$[nm]$	264	284	295
Φ_0	$[10^{13}cm^{-2}s^{-1}]$	1.03	2	2.53

Photovoltaic effect of the diode at $\lambda=290nm$ is shown in Fig. 5 from the I_D-V_D curves in linear scale. The short-circuit current, I_{SC}, and the open-circuit voltage, V_{OC}, are reported as function of T in the inset. I_{SC} behaves similarly to the photocurrent in Fig. 3, whereas $V_{OC}\simeq\eta V_T ln(I_{SC}/I_S)$ varies accordingly to the well-known equation [15]. By using the measured data for I_{SC} and by extracting the model parameters from the dark I_D–V_D curves reported in Fig. 2(a), the analytical results accurately describe the experimental data. Finally, it is worth to note that repetitive thermal cycles applied to devices evidence their stable behavior in the whole temperature and illumination ranges.

IV. CONCLUSION

In this paper low temperature behavior under UV–illumination conditions of $V_2O_5/4H\text{–}SiC$ Schottky diodes is reported by showing an high UV-dark current ratio from *250K* to lower temperatures, an open-circuit voltage of *0.7V* down to *28K*. Further, as a relevant parameter for a photodetector, $I_D^{290nm}\big|_{V_D=0V}$ changes from *4.47nA* to *1.16nA* reducing the temperature from *300K* to *100K*. Distinguishing from the traditional *4H-SiC* Schottky technology for the low temperature annealing process (*723K*) and the high device stability, $V_2O_5/4H\text{–}SiC$ structure is shown suitable for solar-blind photodetectors in the UV spectral range.

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