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High efficiency 4H-SiC Schottky UV-photodiodes using self-aligned semitransparent contacts

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Abstract

In this work, we report on 4H-SiC vertical Schottky UV-photodiodes, with a novel “semitransparent” electrode, using self-aligned Ni_2Si interdigit contacts, that allow operation in the pinch-off regime of the directly exposed optically active area. This improves short wavelength detector sensitivity with respect to conventional semitransparent Schottky UV detectors which use thin metal films.

Computer simulations of the electric field distribution were used to optimise the device’s front electrode geometry, maximising the pinch-off surface effect.

The detector dark current was about 200 pA at −50 V thanks to the high Schottky barrier of the Ni_2Si on the 4H-SiC (1.66 eV). Under illumination with radiation at 254 nm, an increase of the current of more than two orders of magnitude is observed, resulting in 78% *internal* quantum efficiency. The vertical photodiodes showed an ultraviolet–visible rejection ratio of about 10^4 and a current responsivity factor of 1.8 higher than a conventional planar metal–semiconductor–metal interdigit structure.

Keywords: 4H-SiC; UV Schottky photodiode

1. Introduction

The detection of ultraviolet (UV) radiation has received great interest in the last years, particularly for those applications, such as dermatology, UV-astrophysics, aero-spatial and

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environmental applications, where insensitivity to the visible component of the light ("visible blindness") is required. Wide band gap materials are excellent candidates for UV "visible blind" detection. Among these materials, silicon carbide (SiC) is the one having the highest maturity in terms of crystalline quality for large area electronic device fabrication.

In the last decade, some works reported *p–i–n* UV-detectors on SiC with promising UV performance [1] and ultraviolet–visible rejection ratio of about 100 [2]. However, in order to improve the sensitivity at short wavelengths, Schottky diodes are preferred to *p–i–n* diodes, since carrier generation occurs in the space-charge region with a high built-in electric field [3]. Other important advantages of Schottky diodes with respect to *p–n* junctions are faster electrical response and simpler fabrication processes.

Schottky-type SiC UV-photodiodes reported in the literature use "semitransparent" thin metal layers ($<$20 nm) [4–7] of Ni, Au or Pt [8,9] as the Schottky barrier layer, but show a relatively low sensitivity at 250 nm with 37% quantum efficiency (*QE*), arising from the low penetration depth of the UV radiation into the metal [10,11]. According to Yan et al. [5], the detector quantum efficiency can be improved by further reducing the thickness of the semitransparent film. However, the uniformity of an ultra-thin Schottky barrier can become a difficult concern and can also be a detrimental factor for the mechanical and thermal stability of the contact.

UV direct exposure of the optically active area (OAA) of the detector may be an alternative to improve sensitivity at short wavelengths. In this context, planar *p–i–n* structures, with the intrinsic region directly exposed to radiation [12], and interdigit structures are promising solutions. Chiou [13] proposed metal–semiconductor–metal (MSM) 4H-SiC photodiodes, using Ni/ITO interdigit Schottky contacts. These planar detectors allowed an improvement of short wavelength sensitivity with respect to *p–i–n* photodiodes, but showed a maximum *internal QE* of about 33% at 310 nm [13].

In this work, we report on vertical Schottky-type UV-detectors on 4H-SiC based on the pinch-off [14] surface effect, achieved using self-aligned Ni_2Si interdigit "semitransparent" contacts. Our detectors showed an *internal QE* of 78% at 254 nm. Moreover, the proposed structure exhibited sensitivity higher than that of a conventional planar interdigit MSM device of the same area.

2. Experimental details

Schottky photodiodes were fabricated on a 5.8 μm thick *n*-type 4H-SiC epitaxial layer, with a doping concentration of 2.7×10^{15} cm^{-3}, grown by ETC S.r.l. on a hot wall horizontal reactor (ACiS M8 by LPE) onto a heavily doped substrate.

Ohmic contacts on the wafer back side were formed by evaporating a 200 nm thick Ni film, followed by a rapid thermal annealing (RTA) at 950 °C. Schottky contacts on the front side of the sample were obtained by defining self-aligned nickel silicide (Ni_2Si) micrometric interdigit structures. Vertical photodiodes with Ni_2Si metal stripes of width 4.8 μm and two different distances, i.e. 5.4 μm and 11.4 μm, were defined by combining standard optical lithography and selective metal etch. RTA was used for the formation of Ni_2Si, thus improving the uniformity of the Schottky barrier, as reported elsewhere [15]. The total area of the diode was 1 mm^2 in both cases, while the area directly exposed to the radiation, i.e. the "open area", was 0.37 mm^2 and 0.43 mm^2, respectively.

Planar MSM structures were also fabricated in the same wafer and quantitatively compared to the proposed vertical device, as explained later in the text.

In this work, we present a device layout that does not include passivation and/or chemical/mechanical protection layers. However, as frequently proposed in the literature, due to its high optical transmittance in the UV range, SiO_2 passivation layers of appropriate thickness can be be used as anti-reflecting coating [1,3] and as chemical protection to further improve the device performance.

The electrical and optical response of the devices was evaluated using a CVI Inc. Hg line pencil lamp and interferential filters selecting the wavelengths of 254, 313, 334, 365 and 405 nm with a bandwidth of about 10 nm. The power density of the incident radiation was determined by the response of a commercial calibrated UV-detector. Photocurrent–voltage I_{ph}–V characteristics of the photodiodes were acquired by using a Keithley 236 source meter unit.

3. Device design and simulations

It is known that a reverse biased Schottky diode can operate as a photodetector provided that the Schottky contact allows the transmission of a significant fraction of the incident radiation. In particular, the optically active device area is correlated to the junction depleted region W in the semiconductor [1,3]. Neglecting diffusion effects with respect to electrical drift, carriers generated by UV absorption are collected at the device electrodes only for distances $<W$. We define the OAA of the photodiode as the region of width W around the reverse biased electrodes. Computer simulations of the electric field distribution were performed by the Dessis-ISE software [16,17] using a set of calibrated transport parameters for 4H-SiC, based on the comparison between simulation and experimental data on the material performed over the past years. Schottky boundary conditions were applied at the surface contacts, using the experimental values of the barrier height and of the Richardson constant. The calculated value of the depletion width at the radiation exposed surface indicated that W_s was lower than the depletion depth W in the vertical direction and that it was about 0.9 μm at 0 V, 1.3 μm at −6 V and 2.7 μm at −24 V. In the grey scale image of Fig. 1, the electrical field distribution on a cross section view of a simulated structure is shown: the reverse bias is −24 V and the electrode spacing is 5.4 μm. As clearly visible in the figure, the depleted regions under contiguous electrodes merge at a reverse bias in the range −20 V, −25 V (pinch-off voltage).

4. Results and discussion

Firstly, diodes with 5.4 μm spaced stripes were characterized. The electrical uniformity of the interdigit Ni_2Si Schottky contacts were tested and, from current–voltage (I–V) characteristics, a barrier height of 1.66 ± 0.02 eV and an ideality factor n of 1.04 ± 0.01 were determined, in agreement with the values obtained for standard unpatterned contacts [18].

The electro-optical characterisation of the photodiodes was carried out by photocurrent–voltage I_{ph}–V measurements. A relevant increase of the current under illumination at 254 nm is clearly visible in the I_{ph}–V characteristics depicted in Fig. 2. The value of the leakage current, measured in dark conditions, was ∼1 pA at −1 V (measured with the lock-in amplification method) and below 200 pA up to a reverse bias of −50 V. The increase in the photocurrent with the applied reverse bias can be ascribed to the increase of the OAA correlated to the junction depleted region. When the applied voltage reaches the pinch-off value, the OAA is coincident with the “open area” and a further increase of the reverse bias does not change the optically active area. As clearly visible in Fig. 2, the value of the photocurrent I_{ph} almost saturates at 53 nA above −20 V, due to the pinch-off of the 5.4 μm spaced Schottky stripes.

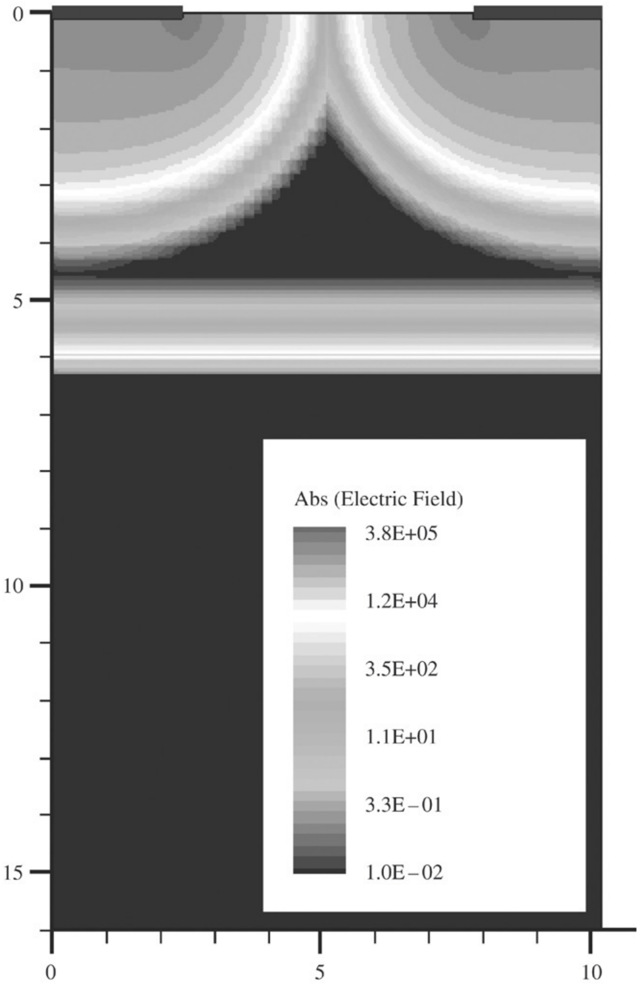

Fig. 1. Grey scale image of the simulated structure at −24 V reverse bias showing the intensity of the electric field on a cross section view. The distance between contiguous metal stripes is 5.4 μm. Points with the same grey intensity are at the same electric field intensity. The image shows the pinch-off of the depleted region under contiguous front electrodes.

A figure of merit of the photodetector is the *quantum efficiency (QE)*, that can be expressed as $\mathrm{QE} \cong \frac{1.24\times R}{\lambda}$, where R is the *responsivity* and λ is the *wavelength* expressed in microns [19]. In order to extract the *internal QE*, the *internal R* of our detectors was determined as the ratio of the photocurrent I_{ph} and of the incident radiation power, i.e. $R = \frac{I_{\mathrm{ph}}}{E_e A}$, where E_e is the incident irradiance (optical incident power per unit area) and A is the detector optically active area. The value of R was determined for the reverse bias of −20 V, i.e. in the pinch-off regime, with the OAA coincident with the "open area" directly exposed to radiation. The values of the *internal QE* are summarized in Fig. 3. It is worth nothing that the detector sensitivity increases with decreasing wavelength and, between the investigated wavelengths, reaches its maximum of 78% at 254 nm corresponding to a maximum *internal R* of 160 mA/W. Considering the total device area (1 mm^2), an *external QE* of 29% is obtained. Hence, the operation in the surface pinch-off

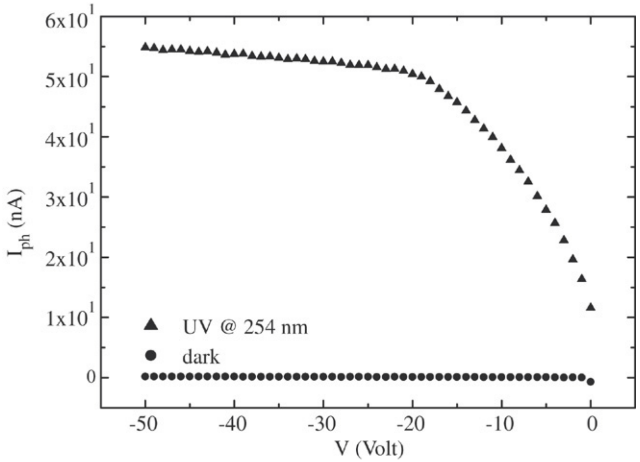

Fig. 2. Photocurrent of vertical 4H-SiC interdigit Schottky photodiode (with 5.4 μm spaced metal strips) as a function of the reverse bias, under dark conditions and under illumination at 254 nm.

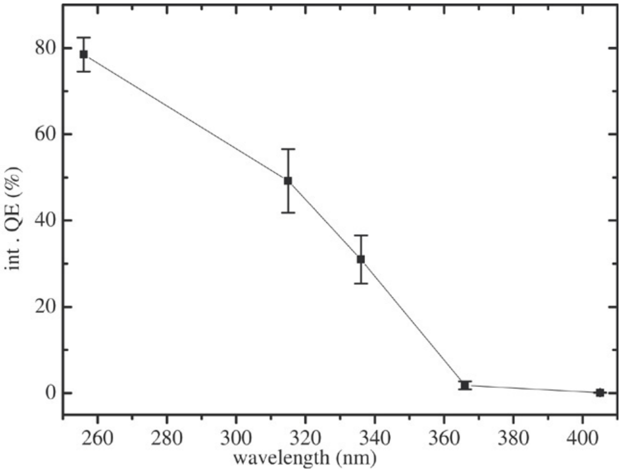

Fig. 3. Internal *QE* values versus wavelength of the vertical 4H-SiC Schottky UV-detectors at a 20 V reverse bias. The maximum in the internal *QE*, 78% is reached at 254 nm.

regime, proposed for our detectors, allows an improvement of the electro-optical performance with respect to previously published interdigit diodes (planar MSM), that had a maximum *R* of 70 mA/W at 310 nm and an *internal QE* of about 33% [13]. Even operating in a photovoltaic mode, a similar trend was observed in the proposed devices, with a maximum *internal QE* and *R* of 20% and 37 mA/W, respectively, measured at 254 nm @ 0 V bias.

The degree of "visible blindness" of the photodiode, described by the ultraviolet–visible rejection ratio and obtained in our case by the ratio between the optical sensitivity at 254 nm and at 405 nm, is 1.5×10^3 in photovoltaic mode (0 V) and $>7 \times 10^3$ in the pinch-off regime (−20 V). These results confirm that the Schottky structure is to be preferred to the *p–i–n* photodiode that has an ultraviolet–visible rejection ratio <200 [20,13].

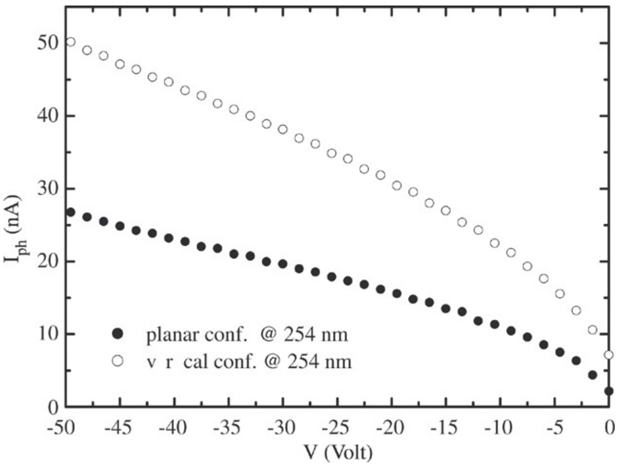

Fig. 4. Comparison of the photocurrent of vertical 4H-SiC Schottky UV-detectors and planar MSM detectors (with 11.4 μm spaced metal stripes), under illumination at 254 nm. The response of the vertical detector is a factor of 1.8 higher than that of the planar MSM structure.

The optical response of the photodiodes was only tested at room temperature. However, the electrical current–voltage characterization of the devices, performed in the temperature range 25–200 °C, showed an increase of only a factor 1.5 of the dark current at −30 V, at a temperature as high as 200 °C. This result suggests that also the optical response should be substantially stable in a wide temperature range.

The electro-optical performances of the proposed vertical interdigit photodiodes were compared with that of MSM detectors fabricated on the same wafer. In order to have a quantitative comparison, the MSM detectors were operated in two electrical configurations. In the *vertical* configuration the two front electrodes are short circuited and polarized with respect to the ohmic contact on the back-side, thus creating a vertical Schottky diode. Instead, in the *planar* (MSM) configuration the back ohmic contact is floating and the polarisation is applied between the two front electrodes. As an example, in Fig. 4 we report the I_{ph}–V characteristics of diodes with 11.4 μm spaced stripes, operated in the vertical and the planar configurations, for an irradiation wavelength of 254 nm. The values of the dark current were similar in the two configurations (∼200 pA at −50 V) and were not shown in the figure.

The optical response of the vertical photodiodes is about a factor of 1.8 higher than that of the conventional MSM structure, as confirmed by the electrical simulation of the two different electrical configurations. In fact, before the pinch-off regime, in the vertical device the depleted region, i.e. the optically active area, is about two times larger than in the MSM planar structure [21].

5. Conclusions

High sensitivity 4H-SiC vertical interdigit photodiodes were demonstrated exploiting the surface pinch-off effect of the directly exposed OAA. Computer simulations of the electric field distribution in the vertical structure with 5.4 μm spaced metal stripes gave a pinch-off reverse voltage of about −20 V, −25 V, in agreement with the electro-optical measurements. In the pinch-off regime, the detectors showed a maximum *internal QE* of 78% and an *internal R* of 160 mA/W at 254 nm, with an ultraviolet–visible rejection ratio $>7 \times 10^3$. The responsivity of the proposed photodiodes is a factor of 1.8 higher than that of a conventional planar MSM structure.

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