Study of the time response of 4H-SiC Schottky junctions for radiation high speed detection

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1 Introduction

In the last ten years, most of the research activity on Silicon Carbide (SiC) radiation detectors has been concentrated to their technological development and to the verification of their performance in radiation detection and spectroscopy [1]. The wide bandgap of 4H-SiC polytype (3.2 eV) allows to realize Schottky junctions with ultra-low reverse current densities ($< 1\,\mathrm{pA/cm^2}$ at room temperature) and so ultra-low noise radiation detectors can be manufactured [2, 3]. Other interesting physical properties of the 4H-SiC polytype are the high saturation velocities of electrons and holes, equal to 220 μm/ns (experimental [4]) and about 100 μm/ns (Monte Carlo simulation [5, 6]), respectively (two times higher than in silicon) and the high breakdown field of 2 MV/cm (almost 6 times higher than in Silicon). These last properties allow SiC detectors to operate at high electric fields, even close to the carrier saturation velocity regime so that very fast charge collection time can be obtained. Recently SiC detectors have been employed in analyzing the radiation emitted by plasma generated by hitting targets of different materials by means of high power lasers (TW); the detectors operate in time-of-flight configurations, in which the high speed response is crucial for detecting different particles and determine their energies with high resolution [7]. A typical signal measured from a SiC detector exposed to a laser-generated plasma radiation is show in figure 1, in which the signal due only to X-ray component only is shown. The detector current is sent to a 50 Ω resistor where the voltage signal is sampled with a fast digital oscilloscope. Pulses as high as tens of volts with rise time close to one nanosecond have been observed. Originally these detectors have been designed for X-ray spectroscopy and so have not been intentionally optimized for ultra-fast response. Differently, the speed of a time of flight detector is crucial and appropriate design criteria must be derived. At this aim, we have studied the response of SiC detectors to ionizing radiation detection by developing a one-dimension simulator to calculate the current signal delivered by a SiC detector exposed to high energy photons. The signal is calculated considering the carrier velocity-field inside the semiconductor and the contributions of electrons and hole are determined separately, so disentangling the fast and slow components of the current pulse.

The study of the effects of the semiconductor doping level (N_D) and of different applied reverse voltage allow to identify the criteria for the design of a detector with optimized timing performance for particular photon or particle energies. The time response has been studied at various bias

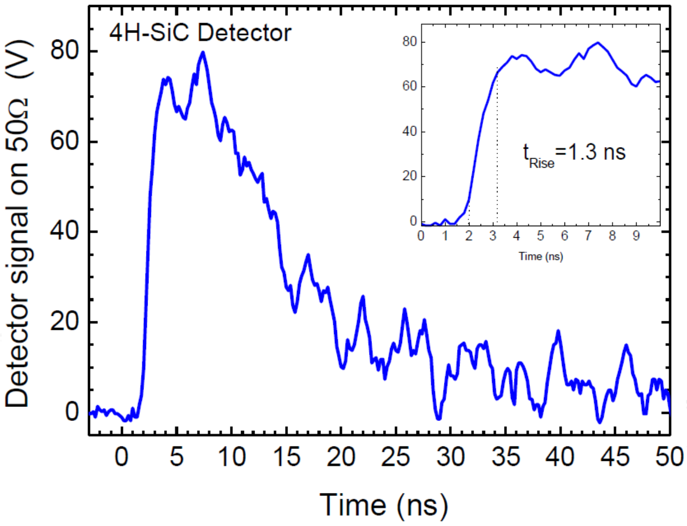

Figure 1. Experimental signal from SiC detector in laser generated plasma experiment.

voltages and different generation points of electron-hole pairs. The simulated signals have been compared with some experimental results finding a good agreement.

2 Theoretical basis

A schematics of the SiC detector for the simulations is shown in figure 2 (a). The detector is supposed to be a Schottky (or pn) junction reverse biased at $V = +V_{\mathrm{BIAS}}$ applied at the ohmic contact, while the current signal is sent to a 50 Ω resistor connected at the Schottky (rectifying) electrode. The semiconductor thickness is L and the depleted region is W_D thick. The photon is supposed to interact with the semiconductor by photoelectric effect at the coordinate $x = X_G$ within the depleted region, generating a total electric charge Q_o given by

$$Q_o = qN = q\frac{E_{\mathrm{ph}}}{\varepsilon_{\mathrm{SiC}}}\,. \tag{2.1}$$

Where q is elementary charge, N is the number of generated electron-hole pairs, E_{ph} is the photon energy and $\varepsilon_{\mathrm{SiC}} = 7.8\,\mathrm{eV}$ is the electron-hole pair generation energy [2]. The electrons and holes move toward the anode (ohmic contact) and cathode (Schottky contact) with velocities v_e and v_h, respectively. The velocities are function of the coordinate x because of the electric field and mobility distributions $E_{\mathrm{field}}(x)$, $\mu_{e(h)}\ (x)$

$$v_{e(h)} = f(\mu_{e(h)}, E_{\mathrm{field}}(x))\,. \tag{2.2}$$

For a Schottky junction, the electric field intensity can be written as:

$$E_{\mathrm{field}}(x) \approx \frac{qN_D}{\epsilon_S}(W_D - x)\,. \tag{2.3}$$

In which the depth W_D of the depletion layer is given by

$$W_D = \sqrt{\epsilon_s\frac{(V_{\mathrm{BIAS}} - (kT/q))}{qN_D}}\,. \tag{2.4}$$

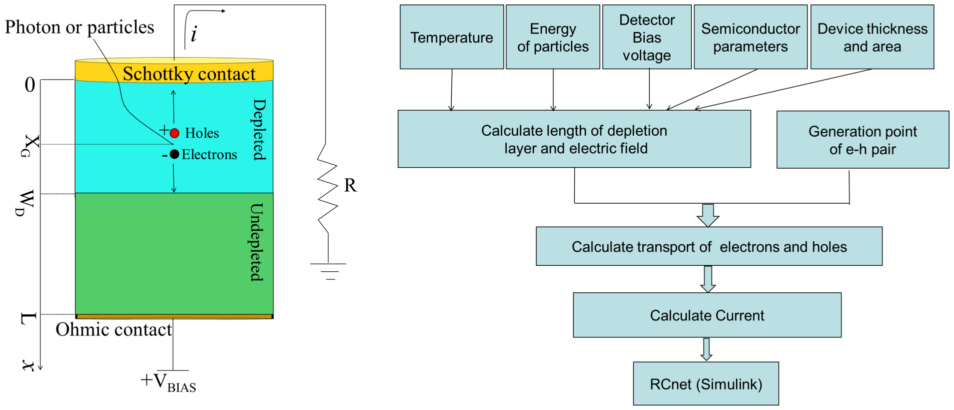

Figure 2. (a) simplified model of SiC detector performance, (b) Flow chart of the Simulator.

Where the ϵ_S, k, T are semiconductor dielectric constant, Boltzman constant and the absolute temperature, respectively.

The current $i(t)$ produced by the movement of electron-hole pairs in the semiconductor can be calculated as [8, 9]:

$$i = -q\left\{v_e\left(\frac{\partial E_{\text{field}}}{\partial V}\right) + v_h\left(\frac{\partial E_{\text{field}}}{\partial V}\right)\right\}. \tag{2.5}$$

Where $A_{\text{field}}/\partial V$ is the derivative of electric field with respect to potential. If no carriers trapping is considered, the induced charge given by integrating (2.5) must equals to the generated charge given by (2.1).

A simulator has been written in Matlab based on this mathematical model; the flow chart of the simulator is shown in figure 2(b). All parameters, like temperature (T), photon energy (E), bias voltage (V_{BIAS}), thickness (L) and active area (A) of the detector can be arbitrarily set, the carrier velocities and mobility as function of the electric field has been assumed accordingly to ref. [4, 5, 10, 11].

3 Case study and simulation results

For the case study we have chosen the parameter values of one of our detector used in some experiments with plasma radiation. The detector is a 5 mm^2 Nichel/4H-SiC Schottky junction with a SiC region thickness $L = 115\,\mu$m and a residual n-doping concentration of $N_D = 5\times 10^{13}\,\text{cm}^{-3}$. The detector response — in terms of current signal and of voltage signal across a 50 Ω — has been simulated assuming $N = 10^9$ electron-hole pairs generated at the given coordinate $x = X_G$ within the active volume at time $t = 0$.

In the figure 3 two examples of the simulated signals on 50 ohm resistive load are shown. The junction is biased at 300 V, the depletion layer width is $W_D = 80\,\mu$m and the maximum electric field is about 75 kV/cm. Two different coordinates of the charge generation point X_G are assumed, close to the cathode $(0.1W_D)$ and in the middle of the depletion region $(0.5W_D)$. The detector junction capacitance has been taken into account in deriving the voltage signal. Risetimes of 340 ps and 710 ps and pulse widths of 0.93 ns and 1.12 ns FWHM have been determined in these particular

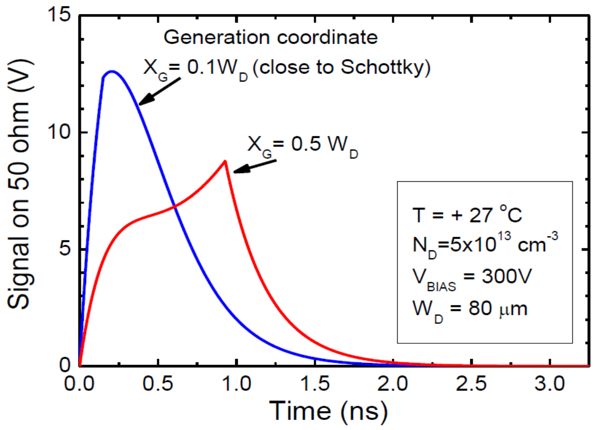

Figure 3. Signals delivered by the SiC detector as simulated for two different generation points.

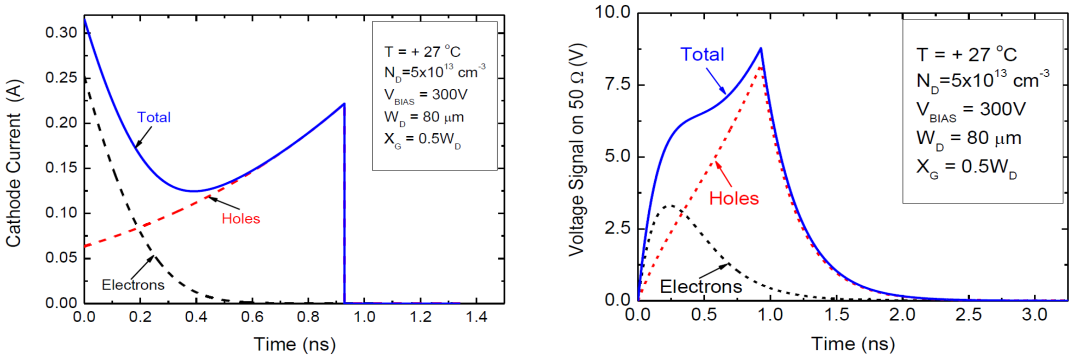

Figure 4. Contribution of electrons and holes to the detector signal in the particular case of $X_G = 0.5W_D$ and $V_{\mathrm{BIAS}} = 300V$. (a) Current signal induced at the Schottky contact (cathode). (b) Voltage signal measured across a 50 Ω resistor connected to the cathode.

cases, showing a significant dependence of pulse risetime, width and amplitude from the charge generation point.

In figure 4 (a) and (b), the signal corresponding to the interaction point $X_G = W_D/2$ is analysed distinguishing the contributions of electrons and holes to the cathode current (figure 4-a) and to the voltage signal at cathode (figure 4-b). In figure 4-a it can be observed that the electron contribution decrease and slows down as the time increases, the opposite is observed for the hole contribution: this is because of the electrons (holes) move in the direction of decreasing (increasing) electric field intensity. The cathode current injected into the RC network constituted by the external load resistance $R = 50\,\Omega$ in parallel with the detector's junction capacitance C_D gives the cathode voltage signal shown in figure 4 -b. It can be observed that in this particular case the signal risetime and duration is mainly given by the hole contribution.

Figure 5 (a) shows the result of simulations of the detector at different bias voltages assuming the same charge generation point within the depletion region at 30 μm from the Schottky contact. Figure 5 (b) shows the corresponding calculated pulse risetime and FWHM. When the bias voltage increases, both the electric field as the depletion layer depth increase. The drift path of the electrons increases but the collection time of the holes decreases: the overall effect as $\mathrm{V_{BIAS}}$ ranges from

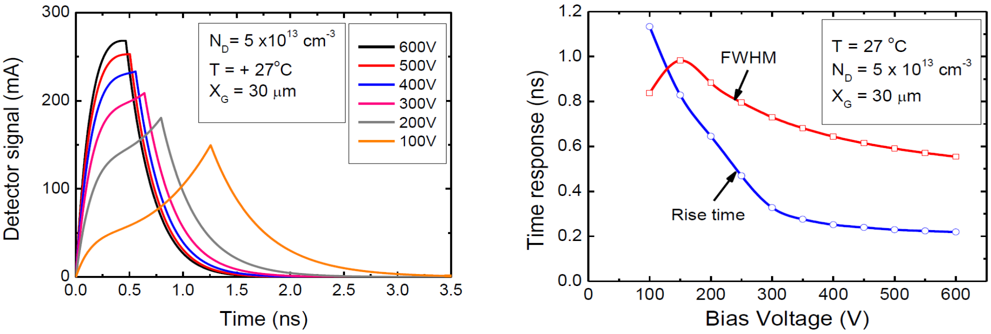

Figure 5. (a) Signals delivered at different bias voltages for the same generation point at $X_G = 30\,\mu$m. (b) Rise time and FWHM of signals of figure 5 (a) as a function of detector bias voltage.

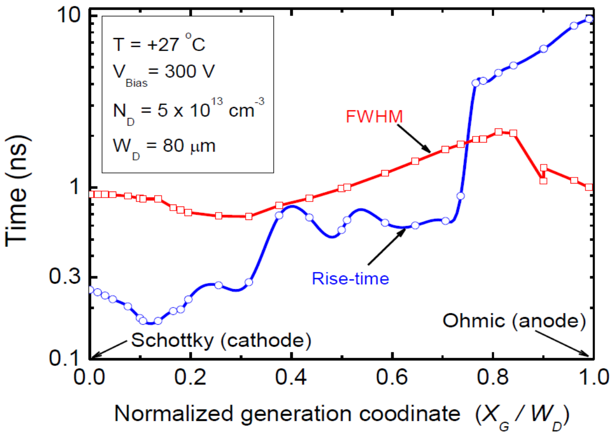

Figure 6. Rise time and FWHM of the voltage signal as function of normalized generation coordinate. The detector bias voltage is 300 V.

100 to 600 Volts is a significant reduction of the risetime from 1.2 ns down to 0.3 ns followed by a saturation effect toward 0.2 ns. It can be observed that the signal FWHM is always in the subnanosecond range and V the full duration of the signal pulse is below 2 ns for bias voltages higher than 300 V.

Figure 6 shows the time response — in terms of pulse risetime and FWHM — as function of normalized generation coordinate at constant bias voltage $V_{\text{BIAS}} = 300$ V. It results that the rise time increases significantly from 0.3 ns up to 10 ns as the generation coordinate X_G moves from Schottky (cathode) to Ohmic (anode) contact, as qualitatively expected because of the increase of the path of the holes and because the charges generated closer to the anode starts from points with weaker electric field.

An example of comparison between simulation and experimental results is shown in figure 7. The detector signal has been acquired during its irradiation with laser-generated plasma and the signal shown is due to X-ray photons. The rise time of 0.7 ns and the FWHM of 1 ns — obtained with the simulator assuming a generation point in the middle of the depletion layer ($X_G = W_D/2$) — well match with what has been observed experimentally.

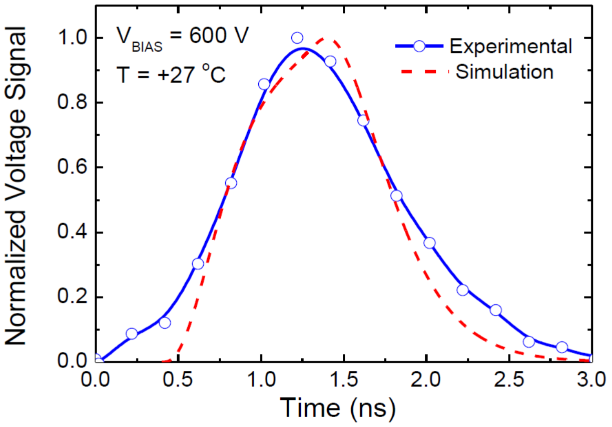

Figure 7. Comparison between experimental result and simulation results. The detector bias voltage is 600 V.

4 Conclusions and future work

A simulator designed for deriving the signals from SiC detectors when irradiated with photons has been presented. Once the semiconductor, geometrical and bias parameters are set, the detector signal is calculated in terms of output current and voltage across a load impedance. The dependence of the detector response — in terms of risetime and pulse width — has been studied as function of the charge generation point and of the detector bias voltage, disentangling the contribution of electrons and holes and taking into account the current integration effect onto the detector capacitance. The simulations explain quantitatively the sub-nanosecond risetime of SiC detectors as observed in experiments with radiation from laser-generated plasma. The designed simulator is a useful tool to predict the device response for different thickness and/or doping of the semiconductor, so aiding the detector design. Future work will be devoted to include in the effect of the series resistance of the undepleted region, not negligible in particular cases, and to extend the simulator capability to predict the detector response to protons and alphas, considering their ionization distribution.

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