Recent results with epitaxial SiC Schottky diodes particle detectors

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Abstract--**Schottky detectors based on a 4H-SiC epitaxial n-type layer deposited onto a 4H-SiC n^+ type substrate have been tested as particle detectors. The charge collection efficiency (CCE) has been tested by means of a 0.1mCi ^{90}Sr β-source and with 5.48 MeV α-particles from ^{241}Am. The response of the SiC devices, investigated over a range of thickness up to 22μm, is characterised by 100% charge collection efficiency. The charge signal is stable and reproducible, with no evidence of priming or polarization effects, probably due to the high crystalline quality of the epitaxial layer.**

I. Introduction

Due to the limited radiation hardness of silicon [1], wide band-gap semiconductors as diamond and silicon carbide have been recently proposed as potential alternatives for semiconductor-based on-line dosimeters in clinical radiotherapy [2,3] and as position particle detectors in high energy physics experiments[4]. The limited radiation hardness of silicon presents a drawback in standard on-line dosimeters used in radiotherapy, as the Si dosimeter sensitivity strongly depends on the accumulated dose [5]. For this reason, Si devices must be frequently recalibrated, typically every 25-30Gy [6]. To investigate the potential of SiC devices as possible alternative to Si dosimeters, some of the authors have recently reported a complete characterization of Schottky barrier epitaxial 4H-SiC samples used in on-line configuration under γ-, 6MV-photon, and electron radiation [2,3]. The current response of the devices shows no priming effects during irradiation, as a consequence of the high crystalline quality of the epitaxial layer. A linear response of the radiation-induced collected charge with the dose in the range 0.1-10Gy and a linear trend of the radiation induced current with the dose rate in the range 0.1-10 Gy/min have been observed, with a sensitivity which compares favorably with that of standard on-line dosimeters.

SiC particle detectors for high energy experiments have been recently proposed by the RD50 CERN Collaboration (Geneva) with the main purpose to develop radiation-hard semiconductor detectors to be used in the next generation of LHC (Large Hadron Collider) at CERN [7]. These detectors should withstand fast hadron fluences up to 10^{16}/cm^2 in their operative environment: at such radiation levels, standard pixels and microstrip position sensitive detectors based on Si would not survive. Due to the 3.3eV gap (4H-SiC), the detection properties of SiC should lie between those of Si and diamond: in fact, the average energy per unit length required to produce an e-h pair in this material by a minimum ionizing particle (*mip*) is 51/μm, against values of 36/μm for diamond and 89/μm for Si. Moreover, the wide band gap of SiC will assure a low-leakage current at room temperature, this material should also be characterized by an higher radiation resistance than Si at high fluences and doses. Semi-insulating 300 μm-thick SiC substrates equipped with ohmic contacts in a sandwich geometry have been tested in the past as particle detectors by means of a β ^{90}Sr source [8]. A response of approximately 2000e^- has been measured applying a reverse voltage up to 500V, corresponding to a charge collection distance of approximately 39μm in the semiconductor bulk. Nonetheless, due to polarization effects probably related to trapping processes at deep levels, this signal was found to decay very quickly and irreversibly down to 800e^-. For this undesirable effect, which should be related to the high defect density in the bulk, this material was considered unsuitable for position-sensitive detection. On the contrary, as epitaxial SiC is characterized by a very high crystalline quality, it is potentially an attractive candidate for this application.

The properties of epitaxial 4H-SiC Schottky barriers detectors have been studied in [9] by means of α-particles from an ^{241}Am source: a 100% charge collection efficiency has been measured with such devices, observing no polarization effects. Radiation damage of these devices has been tested with a γ-^{60}Co source and 8.2MeV electron from a linear accelerator up to a dose of 40MRad and with 24GeV/c protons up to a fluence of ≈9×10^{13}cm^{-2}. The effective net doping concentration

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in the space charge region (N_{eff}) was measured by Capacitance Voltage characterization before and after irradiation: N_{eff} was observed to decrease from the initial value of $7.71x10^{15}cm^{-3}$ to $1.39x10^{15}cm^{-3}$ at the highest electron dose of 40 MRad [10]. This result suggests that irradiation generates new traps and/or increases the density of the pre-existing traps. Nonetheless, this effect has a negligible influence on the detector performance: a 100% charge collection efficiency was still observed at room temperature after the highest irradiation electron and gamma dose and the highest proton fluence, and a decrease of the leakage current was observed in the irradiated diodes [11]. These very promising results have encouraged our group to keep forward in the study of SiC devices as position sensitive particle detectors: the work discussed in this paper has been concentrated on the investigation of the charge response of epitaxial 4H-SiC Schottky barriers induced by alpha particles from ^{241}Am and β-particles from a ^{90}Sr-source. This is the first experimental study performed with β-particles with such devices and we believe it is a key-step to determine the feasibility of SiC position-sensitive detectors for high energy physics experiments.

II. Experimental Procedures

We have investigated two Schottky diodes (A and B), fabricated from two different 4H-SiC epitaxial wafers, purchased from CREE research, consisting in a n-type, 4H-SiC epitaxial layer grown on a n^+-type substrate of 4H-SiC 360μm thick, with a nitrogen doping of $6.8x10^{18}cm^{-3}$. A n^+-type buffer layer, 1μm thick, lies between the epitaxial layer and the substrate. The as-received SiC wafers have been subjected to an accurate solvent clean. A Ti/Au thin film has been evaporated onto the backside of the wafer and annealed under vacuum at 500°C for 60 s, to form a large area low-resistance ohmic contact. Then the wafer has been patterned using standard photolithography and immediately before the deposition of the Schottky contact it has been de-oxidised using an Ar-ion etch. Lift-off has been used to pattern the circular Au (1000Å) contacts onto samples A and B (2mm and 1.42mm diameter respectively). The wafers have then been cut into square samples using a diamond saw.

To determine the effective net doping N_{eff} and the total active thickness of the epitaxial layer *d* in the two samples, capacitance versus reverse voltage characteristics have been measured with a HP 4284A connected to a probe station in the range 0-600V, using the whole range of frequency of the test signal (100Hz-1MHz).

The detector performance has been tested with 5.48-MeV α particles from an ^{241}Am source placed in vacuum (~1Pa). The charge collection efficiency (CCE) was obtained by normalizing the pulse height with respect to the response of a Si p-n junction detector.

The charge collection efficiency to beta particles has been investigated by means of a 0.1mCi ^{90}Sr β-source. The experimental set-up is characterised by a low-noise read out based on an Amptek255 shaper-preamplifier. The shaping time is 2μs, and the series noise is linearly proportional to the capacitance load with the function ENC=388+5.7e$^-$/pF, the gain is 219 e$^-$/mV. The pulse height spectrum giving the charge response of the SiC detector when exposed to the ^{90}Sr β-source has been measured as a function of the reverse voltage in the range 0-250V. At each reverse voltage, we have evaluated the signal mean value of the distribution and, separately, the electronic noise contribution to the signal. The charge collection efficiency has been obtained by subtraction of the mean noise distribution to the mean of the signal distribution.

III. Experimental Results

The leakage current of the epitaxial SiC Schottky diodes placed in the sample-holder of the CCE experimental set-up (in air and darkness), is of the order of ≈10-100pA in the voltage range used in this study: this gives a negligible parallel noise contribution to the total noise in the charge collection efficiency measurements. The C-V characteristics have been measured at room temperature, in air: they are shown in figure 2. The effective doping concentration N_{eff} and the maximum active thickness in the epitaxial layer W, evaluated by C-V analysis, resulted: N_{effA}~$5.7x10^{14}cm^{-3}$, d_A=20.3μm, N_{effB}~$6.1x10^{14}cm^{-3}$, d_B =20.8μm. The full depletion voltages evaluated from C-V measurements are respectively ~230V and ~250V for A and B samples.

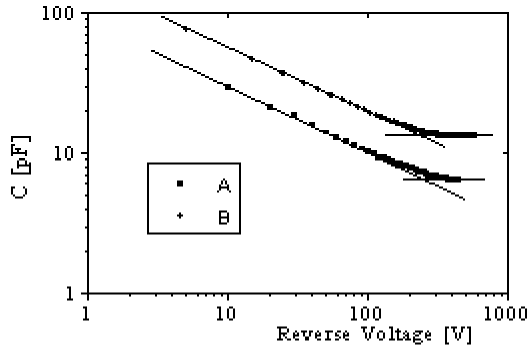
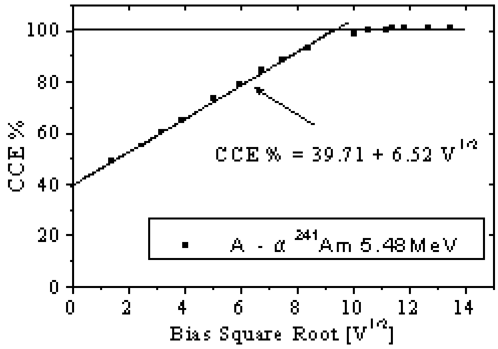


Fig. 1. C-V characteristics for samples A and B measured with a 100KHz test signal frequency. The C-V curves are independent of the test signal frequency in the range 100Hz-1MHz.

The charge collection efficiency of sample A measured with α-particles is shown in fig. 2 as a function of the square root of the voltage.

The linear dependence of the CCE on the square root of the voltage indicates that the charge collection efficiency is increasing linearly with the active thickness of the device. A 100% charge collection efficiency is measured for bias higher than ~80V. A 40% CCE is observed at 0V bias, which corresponds to the contribution due to minority carrier



diffusion from the neutral field region: best fit corresponds to a minority carrier diffusion length L ~7μm.

Fig. 2. Charge collection efficiency of sample A measured with α-particles from ^{241}Am in vacuum, plotted as a function of the square root of the reverse voltage.

The charge collection properties of detector B have been measured by means of the ^{90}Sr β-source set-up in the range 0-250V. At each bias, the signal is stable and reproducible, showing the absence of priming and polarization effects. The charge signal (# electrons) is plotted against the reverse voltage in fig. 3: the collected charge follows the same trend as the C-V characteristics and saturates at approximately 240V, with a maximum value of the collected charge of 1100e$^-$.

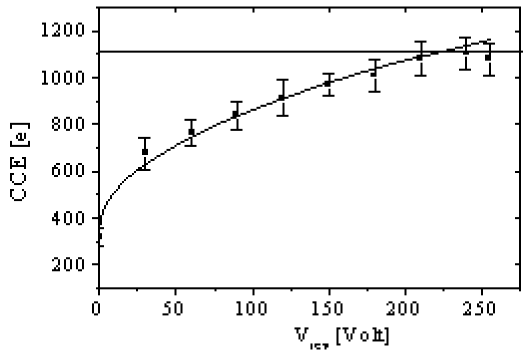


Fig. 3. Charge Collection Efficiency of sample B measured at room temperature with the ^{90}Sr β-source.

To investigate the contribution of the minority diffusion length to the CCE measured with β-particles, we have plotted in fig. 4 the charge collection efficiency as a function of the depletion depth, as determined by C-V analysis. The curve shows clearly a linear trend up to the value of ~18μm.

The experimental data are in good agreement with the theoretical curve, determined considering a charge collection rate of 51e/μm. The contribution to the signal due to the diffusion length of the minority carriers is taken into account, with L~4μm. These results demonstrate that sample B is characterized by a 100% charge collection efficiency with β-particles over the total thickness of the epitaxial layer d.

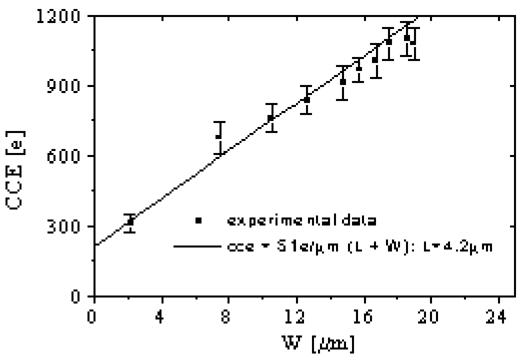


Fig. 4. Charge collection efficiency of sample B to β-particles from ^{90}Sr vs. depletion depth W. The experimental data are in good agreement with the theoretical curve, if a diffusion length of 4.2μm is taken into account.

IV. Conclusions

Two 4H-SiC epitaxial Schottky diodes have been characterized as particle detectors using ^{241}Am α- and ^{90}Sr β-sources. The charge collection properties have been tested during exposure to the β-source with a low read-out system, with shaping time of 2μs and ENC =388+5.7e/pF. I-V and C-V characteristics have been measured to determine the net doping concentration N_{eff} and maximum active thickness *d* of the epitaxial layers. They are of the order of 5-6x10^{14}cm^{-3} and 21μm respectively, with full depletion voltages in the range 230-250V. The two devices show a 100% charge collection efficiency, observed both with α- and β-particles. We measure a 0V bias contribution to the signal corresponding to diffusion lengths of the order of 4-7μm. During the measurement the signal is stable and reproducible, evidencing no priming or polarization effects. This indicates that trapping/detrapping effects at deep levels are negligible, due to the high crystalline quality of the epitaxial layer. Our results demonstrate that epitaxial SiC is a promising material for applications in high energy physics experiments as particle detector. We are now planning to process microstrip and pixels devices with epitaxial 4H-SiC to investigate the feasibility of position sensitive detectors with this material.

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VI. References

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