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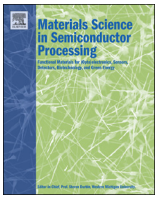

Reversibility of surface damage induced in SiC detectors by low intensity laser plasma

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ABSTRACT

SiC detectors based on Schottky diodes with an interdigit or a thin continuous front electrode are employed for the characterization of plasma generated by low intensity (10^{10} W/cm^2) laser were photons, electrons and keV ions are produced. The exposure to plasma induces the formation on the detector surface of debris and/or micrometric clusters of the target material whose concentration increases with the number of laser shots, leading to the formation of nanometric film after long exposure time. The presence of this deposit strongly modifies the electrical characteristics, the optical response and ion detection properties of the detectors. In particular, we monitored the current-voltage characteristics of SiC devices and we observed an increase of the leakage current, a decrease of the Schottky barrier height and a reduction of the photon detection efficiency in the UV region, by increasing the number of plasma shots. The modification in the electrical and optical properties have been observed after a high number of laser shots, and a simple cleaning procedure allows to remove the surface deposit and, in the case of the continuous front electrode device, to restore the initial electro-optical device performances. The differences related to geometry of the front electrode are discussed.

1. Introduction

Silicon Carbide (SiC) is a semiconductor material suitable for many applications, ranging from nuclear detection to the development of high power electronic devices working at high temperatures and frequencies [1,2]. The wide bad-gap, the radiation hardness and the chemical inertness make this semiconductor suitable for the realization of radiation detectors working in presence of visible and infrared light and/or in harsh conditions such as high radiation background, high temperature and corrosive environments [3,4]. SiC detectors based on Schottky diodes and on p-n junctions have been largely employed for the monitoring of X-rays, neutrons, alpha particles and electrons obtaining high charge collection efficiency, high energy resolution, fast response and high signal-to-noise ratio [5,6].

Indeed, particular attention has been devoted to the 4H-SiC based UV-photon detectors for the detection of the ultraviolet sunlight component, for environmental and health care applications and UV index determination [7,8]. 4H-SiC detectors are in fact particularly suitable for this application, due to their low dark current, high quantum efficiency in all the UV range and excellent visible blindness [9].

Furthermore the relevant properties of SiC detectors allowed also to monitor the ionizing radiation emitted from laser generated plasmas [10,11], permitting measurements of X-ray, fast electrons and ions emitted during the short life of the pulsed laser plasma on a nanosecond or femtosecond scale. In this field, SiC devices found large application, thanks to their intrinsic blindness to the visible light emitted by the pulsed laser and to the visible component of the laser generated plasma itself. In these applications, SiC devices are used in Time of Flight (TOF) configuration, as this technique allows the simultaneous detection of the photons peak (practically at time zero) and of the peaks related to electrons and ions emitted from laser plasma (at times related to their energies and to the path); moreover the accurate determination of the radiation energies, of the ion charge states and of the plasma temperature was demonstrated [12].

In our recent works, we have shown [13] that SiC detectors Schottky type, with two different front-electrode geometries allow to monitor ions in a wide range of energies from a few keV to 10 MeV: detectors with a continuous front-electrode (200 nm thick continuous front electrode) and a thick detection region (about 80 µm thickness or more) are able to detect the high energy plasma ions generated by high intensity (10^{16} W/cm^2) *ns* pulsed laser. Instead SiC devices with a thin (semitransparent, about 20 nm thick) (indicated as M-SiC in the rest of

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the paper) or an interdigit front-electrode (indicated as I-SiC) can be employed to detect soft X, DUV, UV and low energies plasma ions (1–30 keV) emitted by low intensity (10^{10} W/cm^2) laser and, in some cases, accelerated by a suitable system [14,15].

Although SiC detectors are very suitable for laser plasma characterization, their use in application is limited by the damage produced during long-time exposure to plasma. In particular, the overall damage is given by a bulk component consisting of implanted ions and of defects created in the detector active area, due to the ion energy loss inside the device and of a surface component due to the debris, and clusters generated by the plasma at the device surface [16].

In the present paper we report on the impact of the surface damage produced in both type of detectors (M-SiC and I-SiC) after plasma exposure on the electro-optical characteristics of the devices. The surface damage was preliminary monitored by optical microscopy imaging and its effects on the detectors performance were evaluated through detailed electrical (I-V characteristics) and optical (responsivity spectra) measurements carried out on samples exposed to laser generated plasma for different run times. A physical-chemical cleaning procedure of the surface was implemented to investigate the restoring of the initial detector performances. The influence of the different electrode device geometry is investigated.

2. Material and methods

Schottky type 4H-SiC based detectors with two different front electrode structures, were used for this work. They were fabricated at STMicroelectronics-Catania R&D facilities in collaboration with CNR-IMM.

The first type of detector (I-SiC) was fabricated on an *n-type* 4H-SiC epitaxial layer, 4 µm thick with a 10^{14} cm^{-3} N dopant concentration grown onto an *n-type* heavily doped substrate. The ohmic contact on the sample back side was formed by sputtering of a 200 nm thick nickel film, followed by a rapid annealing at 1000 °C in N_2 ambient. The Schottky contact on the device front side was obtained by sputtering of a 100 nm Ni thick film, with an interdigit geometry obtained combining standard optical lithography and highly selective metal etch. A rapid thermal processing at 700 °C in N_2 ambient was used for the treatment of the front Schottky barrier and the Ni_2Si formation [17]. Standard TiNiAu and AlSiCu multilayers were used, respectively, for the back and front metal contacts. Tested devices have a square geometry, a total area of about 8 mm^2 and an area of about 5.6 mm^2 directly exposed to the impinging radiation (70% of fill factor being the single Ni_2Si strip width of about 3 µm and the distance between contiguous front metal stripes of about 7 µm). The second type of detector (M-SiC) was fabricated on a 25 µm thick epitaxial layer with a 10^{14} cm^{-3} N dopant concentration always grown onto a heavily n-doped substrate. The ohmic contact on the sample back was formed in similar way to that used for the I-SiC devices just described. The Schottky contacts on the device front side was formed instead by a continuous electrode obtained by sputter deposition of a 10 nm thick film of Ni followed by a rapid annealing at 700 °C in N_2 ambient producing the formation of about 20 nm thick Ni_2Si. The M-SiC devices have an area of 330 × 330 µm^2, are planar and laterally defined by the front metal contact, patterned through standard optical lithography and highly selective metal etch. An AlSiCu multilayer was used for the front contact pad.

The diodes were exposed to plasma produced by a Nd:YAG laser operating at 1064 nm wavelength, with a 9 ns pulse duration, 400 mJ laser energy and 10^{10} W/cm^2 pulse intensity. A bulk tantalum (Ta) target was irradiated with laser at 45° incidence angle and the generated plasma, emitted mainly orthogonally to the target surface, expanded towards the detector, placed at about 15 cm of distance from the target. The irradiations were performed in vacuum at a pressure of 10^{-6} mbar. At the used laser intensity, being the fluence about 80 J/cm^2, previous investigations demonstrated that the produced Ta plasma contains different charge states, from Ta^{+} up to Ta^{6+} with a kinetic energy of about 250 eV per charge state. Then, the maximum ion energy is of about 1.5 keV and the plasma temperature is of about 33 eV [18].

Both types of detectors were exposed to the plasma during different exposition runs in order to produce a controlled aging effect. The detectors were placed at a short distance (≈ 15 cm) from the target in order to enhance (accelerate) the aging effect. Generally, in fact, detectors operating in TOF configuration are placed at longer distances, of about 50–100 cm in order to resolve ions with different energy. In standard flying distance conditions, the effects of plasma exposure could be observable only after a larger number of irradiation shots, with respect to the experiment described in this work.

The I-V characteristics of the diodes were measured in dark condition and at room temperature by using a Source Meter Unit - Keithley 2636B.

The optical characterization was performed by using a wide spectrum and low flux Xenon lamp, a CVI/Digikrom DK240 monochromator, a 100 µm diameter core optical fiber provided with focusing system and a commercial Ophir-Optronics power meter, used to calibrate the apparatus.

After the electrical and optical characterization, all the detectors (as they were, stuck on the board used in the plasma apparatus) were subjected to a cleaning procedure in H_2O_2 (concentration 30%) followed by a rinsing step in H_2O and a drying step under N_2 flow. The H_2O_2 cleaning process was chosen to oxidize and then remove the Tantalum deposit (micrometric cluster or very thin film layer) from the surface of the detectors accumulated during the plasma exposure. This cleaning procedure could be applicable for all the thin metallic deposits that can be oxidized in H_2O_2, such as for example Al, Ti and Cu. Opportune cleaning procedure, selective with respect to the substrate, can be studied for different plasma targets and then for different debris deposited on the detectors surface.

The detectors surface was inspected (by optical microscopy) and the electro-optical performances of the devices were measured again after the cleaning procedure with the same techniques yet described. Moreover the cleaning procedure was also performed on virgin (i.e. un-irradiated) devices in order to exclude effects of the cleaning procedure itself on the detectors performances.

3. Results and discussions

3.1. Electrical characterization

The exposure of SiC detectors to laser generated plasma induces the formation of a surface damage, as evidenced by the optical microscopy images reported in Fig. 1, relative to the top surface of M-SiC (upper part of the figure) and I-SiC (lower part of the figure) detectors after different number of laser shots (respectively 1000, 5000 and 10,000 from the left to the right side of the figure, respectively). Before plasma irradiation, detectors exhibit clean surface (not shown in figure), while after plasma exposure the surface results covered by debris (of Ta from the plasma target) consisting of micrometric clusters. The increase of the number plasma cycles, implies an increase in the density of such clusters resulting at the end in the coverage of the device surface by a thin continuous Ta film, as can be deduced by the brightness of the surface observable at microscope in the case of the 10,000 shots (see Fig. 1 right side).

The presence of Ta clusters and of a thin Ta layer on the detector surface influences considerably the electrical characteristics of the devices, as observable in Fig. 2, showing the I-V characteristics of detectors before and after plasma aging. The leakage current of the I-SiC detector (Fig. 2a) is very low before aging (about 2×10^{-11} A up to -10 V). After 500 plasma shots the leakage increases of more than three orders of magnitude and further continues to increase with the number of plasma shots. Similar results are obtained for the M-SiC (Fig. 2b), where the leakage current is lower than 10^{-11} A in un-irradiated