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Defect characterization of 4H-SiC wafers for power electronic device applications

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Abstract
Silicon carbide is a semiconductor of choice for the fabrication of high-power, high-temperature and high-frequency electronic devices.

Nevertheless, such a material still presents many problems as regards the crystallographic quality and the presence of defects, which influence the device performance.

We have investigated 4H-SiC wafers and 4H-SiC epitaxial layers by microscopy and structural techniques in order to obtain information about the defect morphology. The goal of this analysis will be to correlate them with the electrical properties of SiC for power electronic device applications.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Silicon carbide is a wide-band-gap semiconductor, interesting because of its physical properties such as high breakdown field, high saturated drift velocity and high thermal conductivity [1], which has been intensively studied in the last few years. The above-mentioned properties make SiC a semiconductor of choice for electronic applications in which high temperature, high voltage, high frequency and/or high power are involved.

Despite the high potentiality of this material, SiC technology at the moment shows some limitations and requires further study if we are to obtain electronic devices with the same quality standards as in the Si technology. Indeed, the reliability of SiC-based devices is strictly correlated with the defects present in the crystalline structure.

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We have focused our investigation on 4H-SiC wafers and on 4H-SiC epitaxial layers in order to determine in both situations the different types of defect. A preliminary investigation has been performed by optical microscopy and scanning electron microscopy with the aim of finding evidence of the defect morphology on a large scale. A deeper insight into the defect type has been obtained by atomic force microscopy (AFM), the profilometer technique and micro-Raman spectroscopy. Different types of defect such as micropipes, comets, super-dislocations and etch pits have been characterized by finding particular physical fingerprints.

This investigation is aimed at correlating the defects and the electrical properties of SiC for power electronic device applications.

2. Experimental method

All the 4H-SiC wafers and 4H-SiC epitaxial layers investigated were supplied by CREE Research Inc. The characteristics of the substrates were as follows: n-type ($N_D = 2 \times 10^{19}$ cm^{-3}), two-inch diameter, 8° off-axis, selected micropipe density (16–30 cm^{-2}), silicon face. The characteristics of the epitaxial samples were: n-type 7 μm thick epitaxial layers ($N_D = 4 \times 10^{15}$ cm^{-3}).

The investigations of the samples were performed by optical microscopy, surface profilometry, scanning electron microscopy and AFM with the aim of finding evidence of the defect morphology and their qualitative surface densities. In optical densitometry the defect density is determined by optical bright-field microscopy (NIKON microscope, with magnification up to 2000×).

We reconstructed the defect map of the wafer analysed and we reported the most significant ones in a detailed series of photographs. By using a surface profiler (TENCOR P-10), scanning electron microscope (CAMBRIGE STEREOSCAN 90) and atomic force microscope (DME DS 95-200), each defect morphology was carefully reconstructed.

Structural characterization was performed by Raman spectroscopy, which represents a powerful technique for the characterization of SiC, because it is non-destructive and requires no special preparation of samples. The parameters of the Raman signal such as intensity, width, peak frequency and polarization of Raman bands provide fruitful information on the crystal quality. Phonon Raman scattering has already been studied for various polytypes. Moreover, microprobe techniques are the most advantageous inside the microscopic portion of the sample investigated, allowing analysis of an epilayer without any mask effect from the substrate.

The micro-Raman system used in this work is a Renishaw system equipped with an argon laser with the excitation line at 514.5 nm and a cooled CCD camera as a detector. The other most important features are: spectral resolution 3 cm^{-1}, spatial resolution 1 μm, depth of field 2 μm in the confocal configuration.

3. Results

The investigation by optical microscopy and scanning electron microscopy showed mainly the presence of five different types of defect: *micropipes*, *etch pits*, *super-dislocations*, *planar defects* (triangular or polygonal) and *comets* [2, 3].

All wafers investigated, bulk wafers or wafers with epitaxial layers, present high concentrations of micropipes, but only bulk wafers show planar defects.

Top views of some defects on epitaxial layers are shown in figures 1 and 2, obtained by means of optical microscopy and scanning electron microscopy.

The investigation by surface profilometer shows that for super-dislocations similar to those represented in figure 1 there is a difference in height of up to 400 nm.

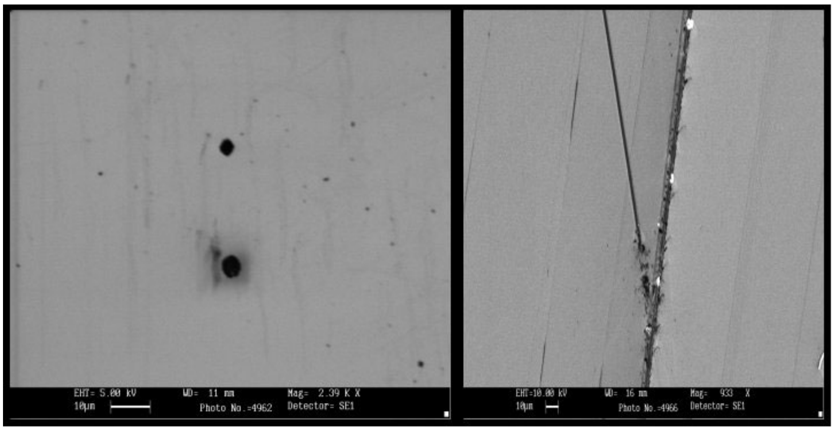

Figure 1. Photographs of typical micropipes (left side) and super-dislocations (right side) provided by scanning electron microscopy.

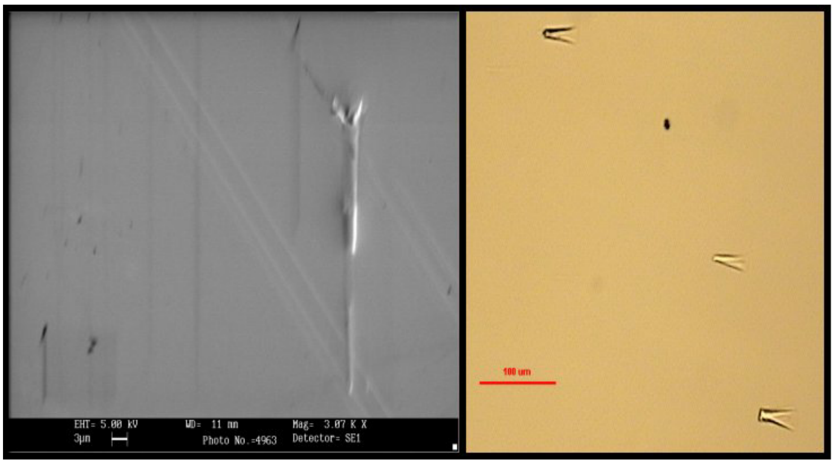

Figure 2. Photographs of comets—optical (right side) and scanning electron microscopy images (left side).

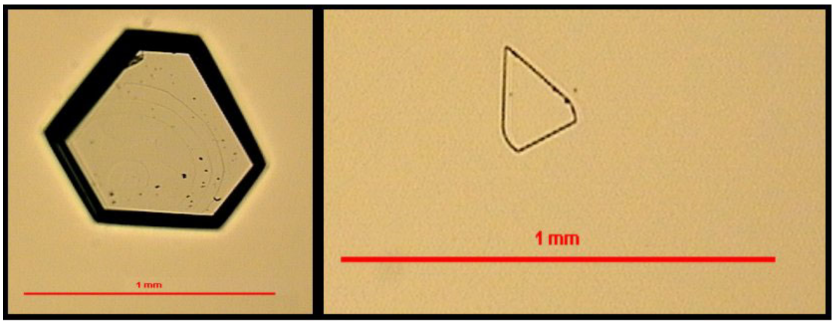

Figure 3. Planar defect images obtained by optical microscopy.

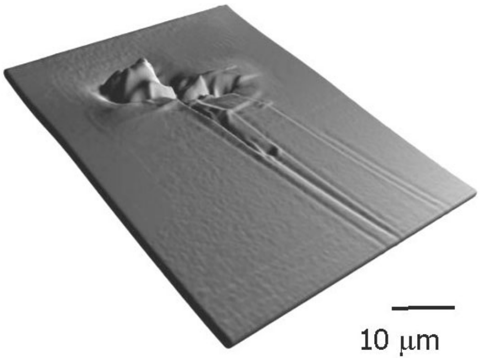

Figure 4. Comet reconstruction by AFM.

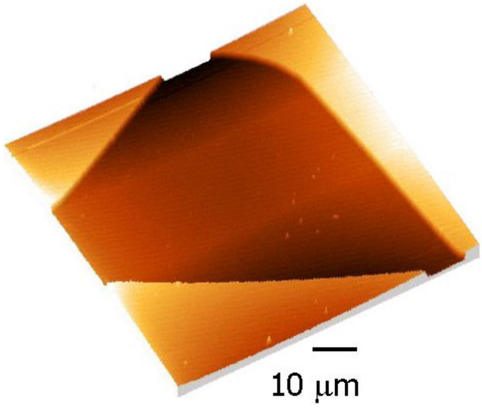

Figure 5. A triangular defect image obtained by AFM.

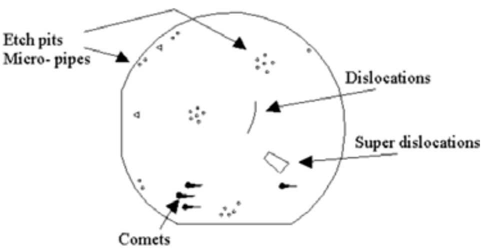

Figure 6. The defect distribution on a 4H-SiC epitaxial layer.

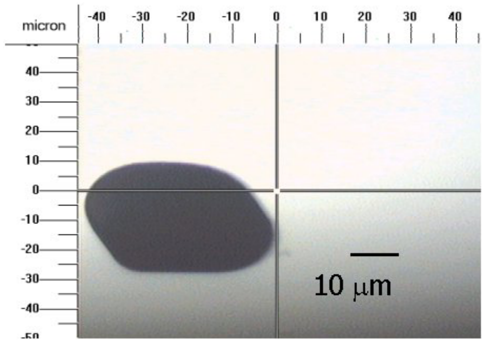

Figure 7. An optical view of a micropipe (1000×).

The results of surface bulk wafer characterization are reported in figure 3, where some planar defects are shown.

AFM reconstruction is very appealing for single-defect investigation. Figures 4 and 5 show examples of comets and triangular planar defects.

At the end of the morphological investigation we realized wafer maps. An example of a map is shown in figure 6.

Structural characterizations have been performed by micro-Raman spectroscopy. The characteristic peaks of 4H polytype are centred at 204 cm^{-1} (FTA, folded transverse acoustic mode), 776 cm^{-1} (FTO, folded transverse optical mode), 796 cm^{-1} (FTO), 964 cm^{-1} (FLO) [4]. The most significant results are the presence of 6H-SiC and 3C-SiC inclusions in 4H-SiC wafers and epilayers. Moreover, by micro-Raman spectroscopy it is possible to obtain a profile of the doping concentration.

Figure 7 shows a micropipe with a diameter of 30 μm in a 4H-SiC wafer with the carrier concentration of $N_D = 2 \times 10^{19}$ cm^{-3}. At the edge of the micropipe, exactly on the marker in figure 7, we obtained different Raman spectra. As is clear from figure 8, there are different peaks related to different polytypes. In particular, we found 3C-SiC inclusions and 6H-SiC inclusions in 4H-SiC bulk.

Also, dislocations in epitaxial layers (see figure 9) show the presence of other polytypes. Micro-Raman investigation, performed on a dislocation (figure 10), shows the presence of 6H-SiC inclusions.

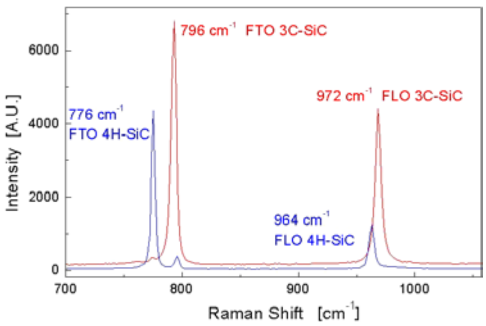

Figure 8. Raman spectra; 3C-SiC inclusions.

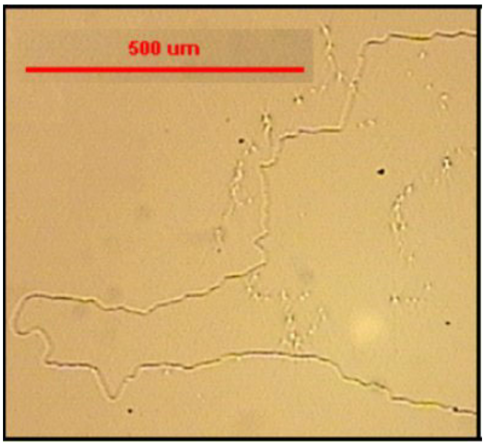

Figure 9. Dislocations in 4H-SiC epilayers.

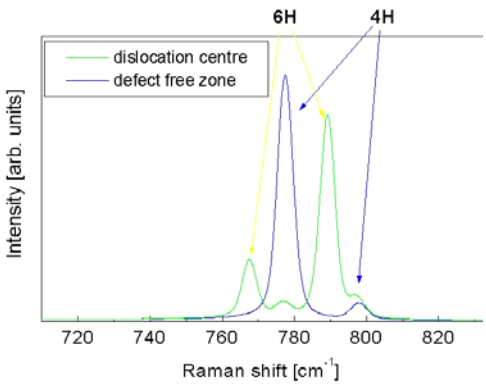

Figure 10. Raman spectra; 6H-SiC inclusions.

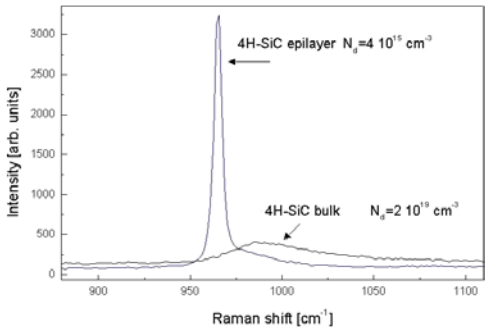

Figure 11. Raman spectra for different doping concentrations.

The Raman measurement can detect coupled modes of LO phonons and plasma oscillations of free carriers whose spectral features depend on the carrier concentration and carrier damping. We have performed measurements on a 4H-SiC bulk wafer and 4H-SiC epilayer in a defect-free zone. In figure 11 the LO phonon peak theoretically centred at 964 cm^{-1} is shown. On increasing the doping level, the peak intensity decreases while the peak width increases. It is worth underlining that with an accurate analysis of the peak intensity and linewidth, a determination of the dopant concentration of the wafer can be carried out and a map realized for dopant concentration larger than a certain threshold [5].

One of the wafers mapped for defect type and position was processed in order to obtain Schottky diodes and to correlate the presence of a single defect with the electrical behaviour of the device.

The devices realized have the structure reported in figure 12.

By means of I–V analysis, diodes with or without defects will be carefully compared in the near future. Preliminary results show that defects such as comets strongly influence the breakdown voltage of the Schottky diodes [6].

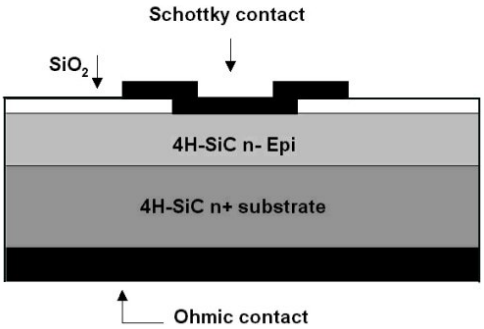

Figure 12. A schematic diagram of a SiC Schottky diode, with a Schottky barrier in titanium.

4. Conclusions

4H-SiC wafers and epitaxial layers were characterized morphologically and structurally. Defects have been highlighted showing the presence of different polytypes (3C-SiC and 6H-SiC) on 4H-SiC.

In order to obtain a correlation between defects and performances of power electronic devices, Ti/4H-SiC Schottky diodes have been realized. A preliminary investigation shows that defects seem mainly to influence reverse breakdown voltage.

References

[1] Harris G L (ed) 1995 *Properties of Silicon Carbide EMIS Datareviews No 13* (London: IEE) and references therein
[2] Sasaki M, Nishino Y, Nakashima S and Harima H 1998 *Mater. Sci. Forum* **264–268** 41–4
[3] Zhou W L, Pirouz P and Powell J A 1998 *Mater. Sci. Forum* **264–268** 417–20
[4] Nakashima S and Harima H 1997 *Phys. Status Solidi* a **162** 39–64
[5] Bourton J C, Sun L, Pophristic M, Luckacs S J, Long F H, Feng Z C and Ferguson I T 1998 *J. Appl. Phys.* **84** 6268–73
[6] Defives D, Noblanc O, Dua C, Brylinski C, Barthula M, Aubry-Fortuna V and Meyer F 1999 *IEEE Trans. Electron Devices* **46**