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Stress evaluation on hetero-epitaxial 3C-SiC film on (100) Si substrates

R. Anzalone[1,*], M. Camarda[1], C. Locke[2], J. Carballo[2], N. Piluso[1], G. D'Arrigo[1], A. Severino[1], A.A. Volinsky[3], S.E. Saddow[2,4] and F. La Via[1]

[1]IMM-CNR, sezione di Catania, Stradale Primosole 50, 95121, Catania, Italy

[2]Dept. of Electrical Eng., Univ. of South Florida, Tampa, FL 33620, USA

[3]Dept. of Mechanical Eng., Univ. of South Florida Tampa, Florida 33620, USA

[4]Dept. of Molecular Pharmacology and Physiology, University of South Florida, Tampa, FL 33620, USA

[*]Corresponding author: ruggero.anzalone@imm.cnr.it

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Abstract. SiC is a candidate material for micro- and nano-electromechanical systems (MEMS and NEMS). In order to understand the impact that the growth rate has on the residual stress of CVD-grown 3C-SiC hetero-epitaxial films on Si substrates, growth experiments were performed and the resulting stress was evaluated. The film thickness was held constant at ~2.5 μm independent of the growth rate so as to allow for direct comparison of films as a function of the growth rate. Supported by profilometry, Raman and micro-machined free-standing structures, this study shows that the growth rate is a fundamental parameter for the low-defect and the low-stress hetero-epitaxial growth process of 3C-SiC on Si substrates.

Introduction

Silicon Carbide (SiC) has long been recognized as an excellent material for high-power, high-frequency and high-temperature electronics due its outstanding electrical and thermal properties. SiC is now receiving added attention for its potential application in micro- and nano-electromechanical systems (MEMS and NEMS) due to its exceptional electrical, mechanical and chemical properties as compared with silicon (Si), which is currently the leading material in these technology areas.

Among the polytypes of SiC, cubic SiC (i.e., 3C-SiC) possesses unique properties, such as high electron drift velocity, which are more suitable for high-frequency power devices [1]. However, the most important property of 3C–SiC is that it can be grown on large diameter Si substrates, offering the possibility for low-cost batch processing, making SiC more attractive for sensors and device applications [2].

Unfortunately, due to high residual stresses (which normally arise during the growth process), the use of hetero-epitaxial 3C-SiC for Si-based MEMS fabrication techniques has been somewhat limited. The residual strain/stress field in a thin film determines the final wafer bow, which has important implications with regard to the processing, the epitaxial quality and the film's properties [3-4]. Therefore, it is necessary to reduce and control the residual stress in 3C-SiC films for high performance MEMS devices.

Experimental

For a better understanding of the impact that the growth rate has on the residual stress, wafer bow and film crystallinity of LPCVD-grown 3C-SiC heteroepitaxial films, three 3C-SiC films of the same thickness were grown at three different deposition rates on individual 50 mm diameter (100) Si wafers. A high-quality 3C-SiC epitaxial multi-step growth process was used to reduce the defect density and to improve the crystalline quality [5]. The process was adopted to grow three 3C-SiC films on (100) Si substrates, with a growth rate of 2.45, 3.21, 4 μm/h, respectively. The film thickness, measured with a FT-IR (Fourier Transform InfraRed) system at the wafer centre, is 2.4 μm, for all the samples grown.

Results and Discussion

The sample profile [z(x)] was observed from surface profiler measurements along the <110> direction (orthogonal to the wafer flat). The film profiles are shown in Fig. 1 for the three growth rates; the asymmetry of the measured data is due to the slight wafer tilt. From this analysis all three films are under compressive stress. The stress (σ) was calculated using a modified Stoney's equation that takes into account the elastic relation of the film to wafer bending [6]:

$$\sigma = \frac{M_{film}h}{\Delta R}\left(\frac{1+4mn+6mn^2 4mn^3+m^2n^4}{6mn(1+n)}\right), \quad (1)$$

where $m=M_{film}/M_{sub}$ are the biaxial modulus $(M=E/(1-\upsilon))$ of the film and substrate and $n=t/h$, with t and h the individual thicknesses of the substrate and film, respectively.

The values of Young's modulus (E) along the <100> axis and Poisson's ratio (υ) were taken to be 130 GPa and 0.279 for silicon [10] and 379 GPa and 0.44 for silicon carbide, respectively [7]. Average film and substrate thicknesses were measured by weighing the wafer before and after the growth. ΔR is the change in radius of curvature determined from $(\Delta R)=(1/R_2)-(1/R_1)$, where R_1 is the radius of curvature of the substrate prior to film deposition, while, R_2 is the radius of curvature after the film is deposited.

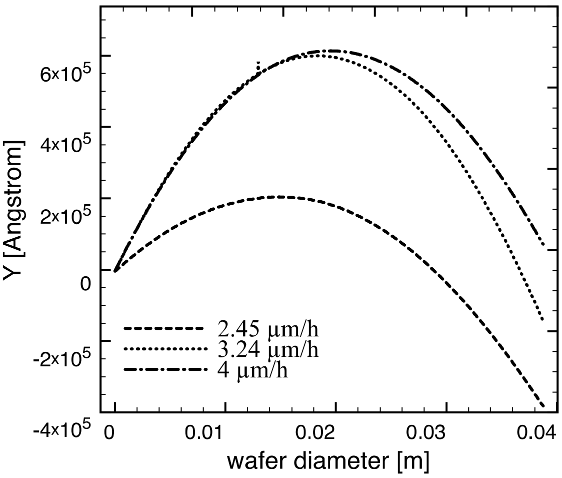

Fig. 1. Wafer profile for the three different growth rate values.

The curvature K of the samples $[d^2z/dx^2]$ (not shown), can be calculated directly from the deformation profile $z(x)$ and gives information about the strain in the sample. The calculated curvature values are -0.08, -0.15 and -0.26 m^{-1} for the films grown at 2.45, 3.21, 4.00 μm/h, respectively. From these values it is possible to observe that the wafer curvature (the inverse of the curvature radius) decreases with decreasing growth rate. From the measured sample curvature, one can determine the average residual stress within the layer using Eq. 1.

The calculated stress increases with growth rate, from 0.31 GPa to 0.89 GPa for 3C-SiC films grown at 2.45 and 4.00 μm/h, respectively, (Fig. 2). From Stoney's equation a lower stress value corresponds to a lower growth rate, with all films under compressive stress.

The crystalline quality was also measured by Raman spectroscopy using an HR800 integrated system by Horiba Jobin Yvon in a back-scattering configuration. The excitation wavelength is supplied by a He-Ne laser at 632.8 nm. The Full Width at Half Maximum (FWHM) values of the TO vibration mode of 8.57 cm^{-1}, 9.01 cm^{-1} and 9.24 cm^{-1} were found for 3C-SiC films grown at 2.45, 3.21, and 4.00 μm/h, respectively (not shown). From the TO Raman mode peaks it is clear that the growth rate is strictly related to the growth parameters, with an evident increase in the film quality (in terms of the defect density) with the decreasing of growth rate. In Figure 3 is shown the TO and LO Raman shift for the three different growth rates. From this analysis it is possible to observe that the stress nature is tensile and the sample growth at 2.45 μm/h is farther from the theoretical stress free value (dotted line) than the other samples; thus the 2.45 micron/h sample is the *most stressed* one. This result is totally at odds with the stress calculated with the Stoney's equation and with the curvature measurement that shows a film under compressive stress.

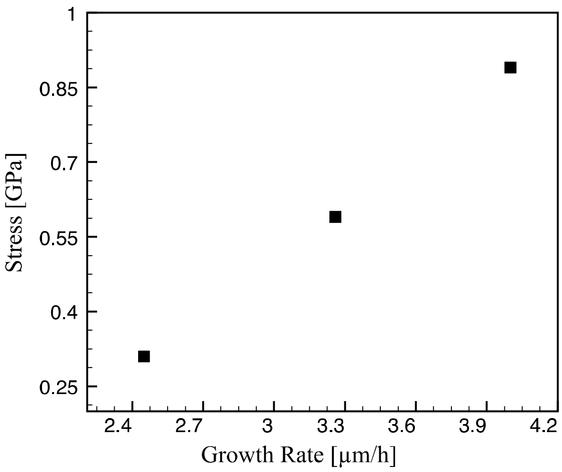

Fig. 2. Residual stress (σ) calculated by the modified Stoney's equation as a function of the growth rate.

To support the Raman analysis, on the three samples we micro-machined different free standing structures as stress probes. The planar rotating probe is a microstructure extremely sensitive as a stress probe, more than the free-standing cantilever, commonly used for stress analysis. In Figure 4 is shown a SEM image of the structure. From the rotation of the central arm it is clear that all the films are under tensile stress (inset, Fig. 4) [8].

As can be seen from the experimental data, there is an inconsistency between confocal Raman and micro-structure rotation, which both indicate a tensile residual film stress, while the convex wafer bow and the Stoney's equation would indicate a film under compressive stress. In order to explain the variation of wafer bow as a function of growth parameters many theories have been presented [9]. To try to understand this apparent disagreement between different experimental data we developed a new theory capable to include the stress field inside the substrate. In particular, we studied a systematic approach to correlate global (wafer-scale) measurements to those obtained by local indicators (as cantilevers or planar rotators) of the strain status. It is assuming that the source of this discrepancy is the initial stress in the substrate, related to the defects in the silicon substrate (voids, among others) [10-11].

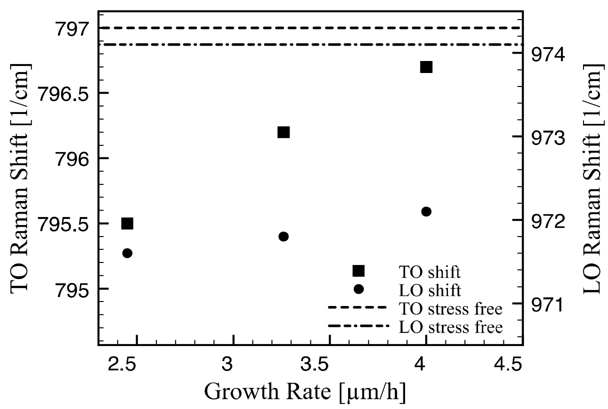

Fig. 3. TO and LO Raman shift as a function of film thickness for different growth rate values.

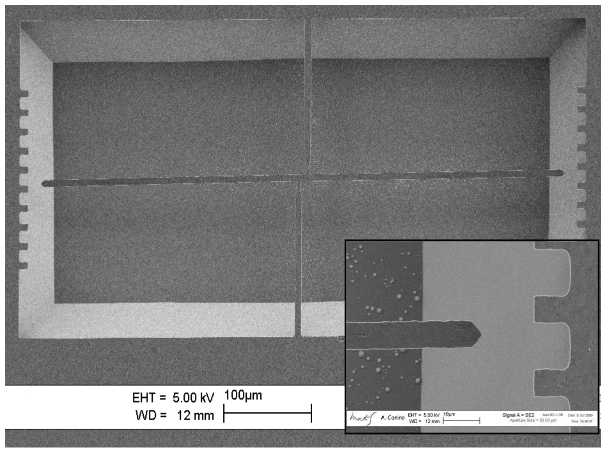

Fig. 4. SEM plan view of planar rotating probe. From the rotation of the main arm (inset) it is possible to observe that the sample is under tensile stress.

Summary

In this work, different residual stress analyses performed by modified Stoney's equation (through optical curvature measurement), Raman shift analysis and free-standing structures were presented. From these measurements was found an apparent disagreement about the nature of the stress. These discrepancies between the experimental data can be explained assuming a strong stress field located in the substrate and related to defects generated in the silicon during the growth process.

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