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In-line monitoring of strain distribution using high resolution X-ray Reciprocal space mapping into 20 nm SiGe pMOS

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ABSTRACT

Together with the downscaling comes the introduction of new materials, such as strained SiGe, in order to boost the transistor performances. For an effective deployment it requires the implementation of methods capable to monitor the strain directly in the process lines. High Resolution X-Ray Diffraction has played a critical role in industry for thin films metrology purpose and have the potential to extend its capability to the strain characterization in the transistors. The latest industrial instruments provide fast and automatic measurement capabilities. This enables the use of Reciprocal Space Mapping (RSM), a key feature for strain characterization, as a monitoring method. To do so, automatic data extraction of RSMs is of course mandatory, so preliminary work performed on RSM treatment will be introduced in this paper. So far these studies have been carried out on nanostructures representative of transistor technologies and reveal innovative and conclusive results.

1. Introduction

Strain engineering is one of the key areas of development of the advanced transistor technology. Introduction of strain induced by the growth of new materials such as SiGe, for pMOS transistor, onto a silicon substrate, enhanced the transistor performance by impacting the transistor mobility [1]. As a result the ability to monitor the strain directly on the production line is of high interest.

High Resolution X Ray Diffraction (HRXRD) is commonplace in semiconductor industry as it provides a highly sensitive and non-destructive technique for semiconductor materials characterization. Used to monitor materials and support process development on thin-films [2] it requires to extend its application to 3D structures such as transistors. This represents a real challenge since the strain field in transistors is highly heterogeneous [3]. However, the standard procedure, simple scans in reciprocal space (rocking curve) [4,5], is of limited interest in the case of non-uniformly strained structures. On the contrary, Reciprocal Space Mapping (RSM) allows a deeper understanding of the strain field, imaging the crystallographic state of the structure [6]. The use of RSMs has proven by many times its capability to accurately depicts the strain field of transistor structure [7,8]. Several case studies have been already performed to explore the level of information that could be provided by such technique, through direct analysis [9], simulation based on analytical models [10] or finite element models (FEM) [11,12]. One step further is its implementation in a manufacturing line, for both strain engineering and metrology, providing key information on the evolution of strain field throughout the different process steps.

At the same time, dedicated metrology tools are now available for the acquisition of RSMs directly on the production wafer [13]. They provide a small-spot size, compatible with metrology structures, together with an advanced linear detector, enabling the fast acquisition of RSMs. RSMs contain a number of important parameters, such as the geometry, the in-plane and out-of-plane strain, nonetheless, the link between the strain field into nanostructures and the measured diffraction pattern is not straightforward, so that innovative and yet automated analysis is required.

The methodology used to investigate the strain distribution into complex nanostructures using RSMs is at the moment restrained to punctual analysis [14]. In this paper we will explore the evolution of the strain field using a set of RSMs collected at the first steps of the elaboration of Raised Source/Drain, in pMOS-like transistors. At this end two automatic and accurate methodologies have been developed. The first one uses a direct analysis of the RSMs without any modeling and allows for a fast monitoring of strain field into the transistor during processing. The second one is a database method build on a large set of

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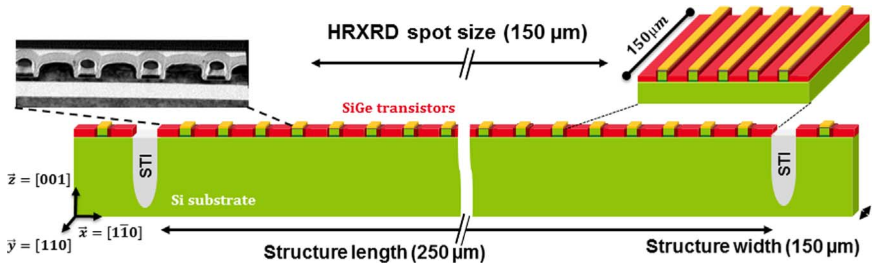

Fig. 1. Schematic of a metrology structure, separated by shallow trench isolation (STI).

finite element modeling (FEM). It allows a fine description of the strain field into the structure. Both are fully automated. These both advances pave the way for a fully automated strain analysis during in-line processing.

2. Material

This study is performed on 150×250 µm^2 metrology structures, embedded on 300 mm production wafers (Fig. 1). The MOSFET transistors are periodically repeated within the gate length direction, so that it creates lines grating. The studied lines are composed of pMOS transistors (20 nm gate length, 108 nm gate pitch) depicted by 30 nm thick $Si_{0.76}Ge_{0.24}$ epitaxial Source/Drain deposited on (001) bulk silicon. The sources and drains, selectively grown between gates exhibit (111) stacking faults at the top edges and the channel direction is the (110) crystallographic direction (Fig. 2).

The width of the transistor is much larger than in actual devices in order to get measurable diffracted intensities. This also reduces a complex three-dimensional strain fields into a simpler bi-dimensional one. Assuming that all the transistors are identical, any acquired RSM is representative of a single device. However, by measuring an array of devices, signal-to-noise ratio is improved significantly.

As such structures are embedded in the production wafers, they follow the exact same process than the others. This enables to indirectly follow the strain state of production transistors along the procedure. In this regards fourteen process steps that may impact the strain have been monitored, from the growth of SiGe source/drain to the anneal step prior to silicidation.

On this kind of nanostructures, the strain distribution is much more complex than for full sheet thin-films [3]. Generated by the hetero-epitaxy of SiGe on Si bulk it is modified by relaxation effects, mainly at the free surfaces and at the interfaces between the epitaxial material and its surroundings. As a consequence the strain field is dependent on many factors such as the shape, the size, the pitch and the elastic properties of the materials. Furthermore the complex initial strain, after the growth step, can change during the subsequent process steps. The thermal processes, mask removal and stressors are known to modify this strain state [15,16]. Finally, in our case we are expecting a thickness change and consequently a modification of the strain field at

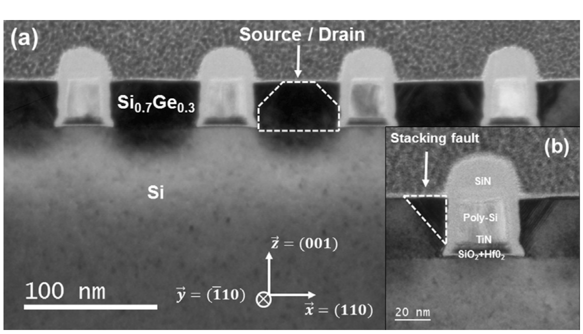

Fig. 2. Bright field transmission electron microscopy (TEM) images of a metrology structure with a large view (a) and zoomed in on the gate (b).

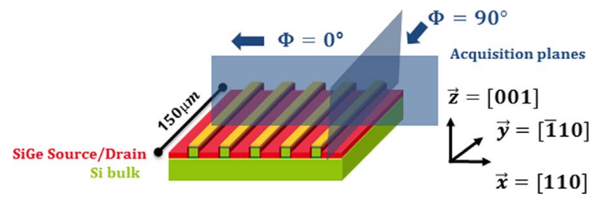

Fig. 3. Schematic of a metrology structure. The measuring orientations (Φ=0° and Φ=90°) and the corresponding crystallographic planes ((110) and ($\bar{1}10$)) are indicated on the schematic.

the final steps due to etching processes.

3. Instrumental setup

RSMs have been measured using a JV7300HR industrial system (Bruker Semiconductor) with two mains features, i) a small spot size with a footprint of 50×100 µm^2 on the sample and ii) a linear detector with an angular aperture of 10°. Symmetrical 004 and asymmetrical (in grazing exit)$\bar{1}\bar{1}5$ RSMs have been acquired for each process step, along (Φ=90°) and perpendicularly (Φ=0°) to the lines grating (Fig. 3). To evaluate the capability of this in-fab HRXRD equipment, prior comparisons have been performed with acquisitions operated at the Advanced Photon Source (APS) synchrotron [17]. This study has demonstrated that the industrial equipment allows acquiring RSMs of high quality with an acquisition time compatible with inline production requirement.

004 RSM depicts the diffraction between crystallographic planes parallel to the sample surface. It allows measuring the inter-reticular D-spacing d^{004}, i.e. the out-of-plane strain. $\bar{1}\bar{1}5$ RSMs capture the diffraction of tilted planes, measuring the inter-reticular D-spacing d^{115}, providing both out-of-plane and in-plane strain features. The in-plane strain variation corresponds to a relaxation of the pseudomorphic condition of the SiGe layer while the out-of-plane strain variation is due to Poisson effect and the relaxation phenomenon. All together they grant information on the whole strain field of the structure, in the diffracting volume. The relative variation of the inter-reticular D-spacing or strain ε in the corresponding j direction is given by:

$$\varepsilon_j = \frac{d_j^{hkl} - d_j^{hkl}|_{ref}}{d_j^{hkl}|_{ref}} \quad (1)$$

In the following, we consider the silicon substrate lattice as a reference, i.e. $d_j^{hkl}|_{ref} = d_i^{Si}$. With this reference, the calculated in plane-strain is related to the silicon structure and appears to be positive whereas the SiGe layer is under a compressive state. For out-of-plane strain, it is always positive but higher than the real strain in the SiGe layer. In order to access the proper SiGe strain field the knowledge of the germanium content is required.

Measurement in the Φ=0° configuration allows acquiring information on the strain field along x and z direction while the Φ=90° configuration images the strain field in the y and z direction. This also means that the first configuration measures periodic finite structure (perpendicular to the lines grating) and the other one an infinite