Lattice scale inspection of semiconductor interfaces via non-destructive camera-less 3D T-ray imaging

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Introduction

Interfaces play critical roles in all semiconductor fabrication processes and on the electronic properties of semiconductors. Especially, devices involving plurality of interfaces is now of paramount importance. As such the interfaces have been a subject of intensive studies. However, effective characterization of interfaces is complicated because of inherent unknowns involved. For example, consider the case outlined in Fig. 1 where two layers of materials have been deposited on a silicon substrate (Si). The silicon wafer is known to be well characterized. The material properties of Layer-1 (L1) and Llayer-2 (L2) may also be known by themselves; but deposition involves transforming a solid material in to vapor or liquid phase and then back into solid by the deposition process. As a result, the deposited materials' lattice will/may suffer from imperfections and defects such as stacking fault and dislocations. Based on such imperfections, different types of interfaces may be defined. The system outlined in Fig. 1, may/will produce unknowns such as the lattice structure of Layer-1 and Layer-2, the interface between Layer-1/Layer-2, and the interface between Layer-1/silicon substrate. Only known entity in Fig. 1 is the silicon lattice; however, the deposition process still may influence the top surface of the substrate and thus the silicon lattice may suffer from defect formation and/or some rearrangement of the surface atoms. Quantification of such interfaces at the lattice scale is a huge challenge by the current state of the art; especially, a non-destructive inspection of the deposited layers and interfaces that requires interrogation across the depth.

Petroff [1] attempted to define the interface as the region between two single crystalline semiconductors L1 and L2 that differs in physical properties such as crystallographic and/or electronic than those of the bulk of L1 and L2, or L1 and substrate (Fig. 1). Four types of interfaces in III–V semiconductors were discussed based on the degree of lattice parameter mismatch between L1 and L2. For the first type (type-1), which may be termed as the "misfit dislocation" type, the magnitude of the misfit strain at the interface determines whether the interface lattice accommodates the misfit elastically or plastically. The second type of interface (type-2) is formed between two semiconductors with almost identical lattice parameters. This is generally the case of homojunctions in III–V semiconductors with L1 and L2 doped with different elements. Here, the misfit strain is small such that the interface is completely accommodated elastically by the lattice. The point defects and impurities may get trapped within the interface, which could be driven from the bulk by the high temperature. In the absence of such defects, this type of interface, which may be termed as "similar-lattice" type interface, would be closer to a perfect lattice, but a critical characterization is needed to quantify the presence of any inclusions and/or stacking faults. Important device properties such as degradation behavior or photoluminescence efficiency may be affected by the defect formation at this type of interfaces. The third type of interface (type-3) may be called a "rough-surface" interface that is formed between two crystals with rough surfaces. Here, the interface between the two solids, L1 and L2, is not sharp due to the fact that either both the surfaces were rough, or one rough and another smooth surface formed the interface. In addition to the types of defects mentioned in the previous two types of interfaces above, the surface roughness also influences the electronic properties and defect distribution. A fourth type of interface (type-4) may exist in which diffusion of some of the elements of L1 and L2 has taken place into each other. During the diffusion process, new interface phases may be formed by means of a solid solution, or the interface chemical composition may vary in a non-abrupt fashion from that of L1 to that of L2. Control over interface-diffusion processes is, of course, of essential technological importance for devices where sharp interfaces or ultrathin layers are required. Yet a fifth type of interface (type-5) may also form that may be called as a low mismatch compound semiconductor heterointerface, which in principle, will be similar to the type-2 interface except for a sharply defined boundary along different directions. Thus, it is easily recognized that precise techniques for analyzing different types of interfaces are essential for successful device functionality.

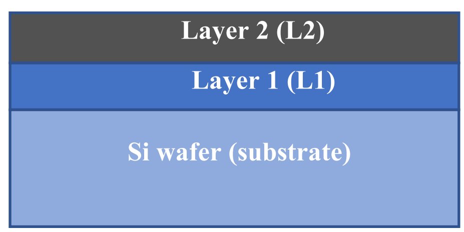

Fig. 1. Sample configuration example involving three layers and 2 interfaces. More layers and interfaces are also common.

Up until now, the only way to characterize the interfaces was by X-ray techniques and transmission electron microscope (TEM) [1–3]. X-ray diffraction produce high precision data but averaged over macroscopic distances;

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thus, missing the very local information. Consequently, extraction of precise interfacial information is not obvious. TEM requires high vacuum, high energy electron beam for penetrating the sample, and a laborious sample preparation where the samples must be polished to thin enough for electron transparency. It is suspected that the high energy electron beam may impart enough energy to perturb the lattice structure, thus, introducing some kind of distortion while the actual device's intrinsic information is important for determining the device performance. TEM also focusses on a very small region (area) of a sample, hence missing the perspectives of the overall sample.

This paper describes a non-contact, non-destructive technique via high resolution, camera-less, terahertz radiation (T-ray) imaging for critical investigation of semiconductor interfaces along with practical examples. Here all measurements are done under ambient conditions without requiring any sample preparation. Several types of interfaces are exemplified. To our knowledge, the results reported in this paper are the first attempt where different types of interfaces are identified via nondestructive, camera-less T-ray imaging route.

Experimental

Details of the terahertz camera-less imaging technique and instrumentation has been described elsewhere [4–6]. Fig. 2 exhibits an example of mounting and scanning a 200 mm wafer. T-ray imaging was performed using a terahertz nanoscanning spectrometer and 3D imager (TNS3DI, Applied Research & Photonics, Harrisburg, PA). Samples were mounted one at a time on the nanoscanner. Automated positioning of the T-ray beam on the sample was performed by built-in software of the TNS3DI. The samples are raster scanned over a given volume and the captured reflected intensity matrix, termed as the Beer-Lambert Reflection (BLR) matrix, was used for image generation and analysis [5–6]. All samples were mounted in the vertical orientation. Measurements were carried out with the front-end software of the TNS3DI. For the 3D (volume) image generation, each sample was scanned over a user-selected three-dimensional space. That is, first a line-scan was conducted on the X-axis on the X-Y plane; then the line-scan was repeated to cover the whole X-Y plane for a single surface. The T-ray was then focused on a plane below the surface by programmatically adjusting the Z-stage by a user-defined increment of depth and the surface scan was then repeated for the entire sub-surface. This procedure is repeated until the whole volume was scanned and the reflected intensity of the entire volume were stored in the BLR matrix. The matrix was then subjected to an algorithm for generating the image of the volume [5]. A mounted 200 mm wafer is shown as an example of sample configuration (Fig. 2). The wafer remains stationary while the probe is used to scan either the whole wafer or a small volume as decided by the user. A 5 µm × 5 µm × 5 µm volume was scanned for the present work. Successive zooming of this image was conducted by the supplied image analysis software that allowed choose any space within the measured volume to zoom in. The results are summarized below.

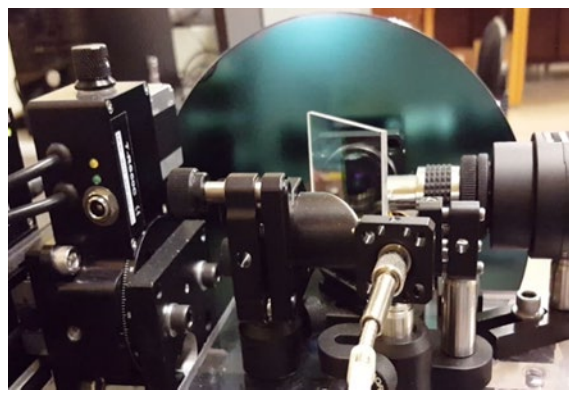

Fig. 2. A whole wafer scanner. A 200 mm silicon wafer is mounted that remains stationary. The scanner is capable of scanning over a small volume or the entire wafer.

Results

Fig. 3 displays a 3D image of (5 µm)^3 volume of the sample under investigation. Sequential zooming was conducted in order to inspect the features. Fig. 4(a) displays a (1 µm)^3 volume image and 4(b) shows a further zoomed in image over (200 nm)^3. Both of these images show the layer formation across the thickness (Z-axis).

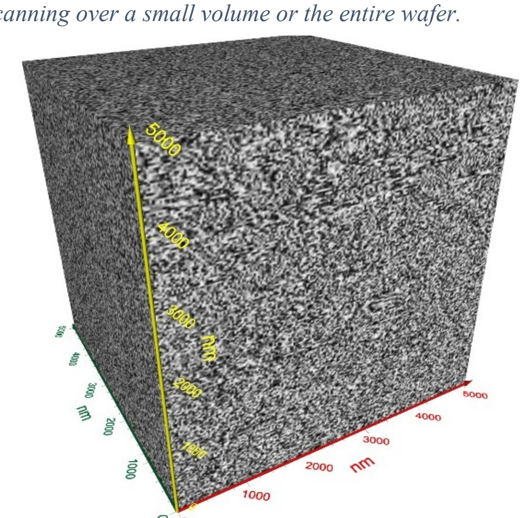

Fig. 3. 3D image (5µm)^3 volume of a segment of the top layer.

Fig. 5 displays the front face (2D) image of the 3D image in Fig. 4(b), where, layers, interfaces, lattice imperfection, and regions of nanograin formation are visible. Here the layer demarcations are clearly visible; the layer thicknesses and lattice distances may also be measured at selected places from this image. The interface between Layer-1 and Layer-2 is a likely example of type-3 interface or rough surface interface, which is also the case between Layer-2 and Layer-3, as well as between Layer-4 and Layer-5. However, the interface between Layer-2 and Layer-3 could also be a type-4 or

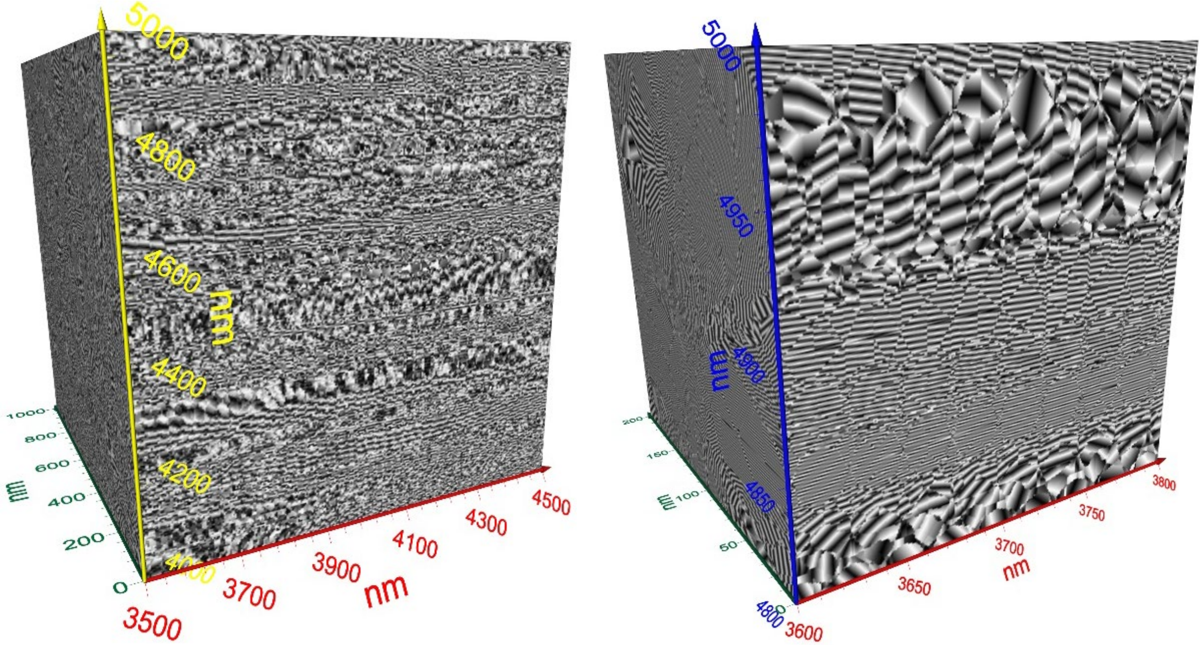

Fig. 4. Zoomed in high resolution images. (a) 1 µm × 1 µm × 1 µm. (b) 200 nm × 200 nm × 200 nm.

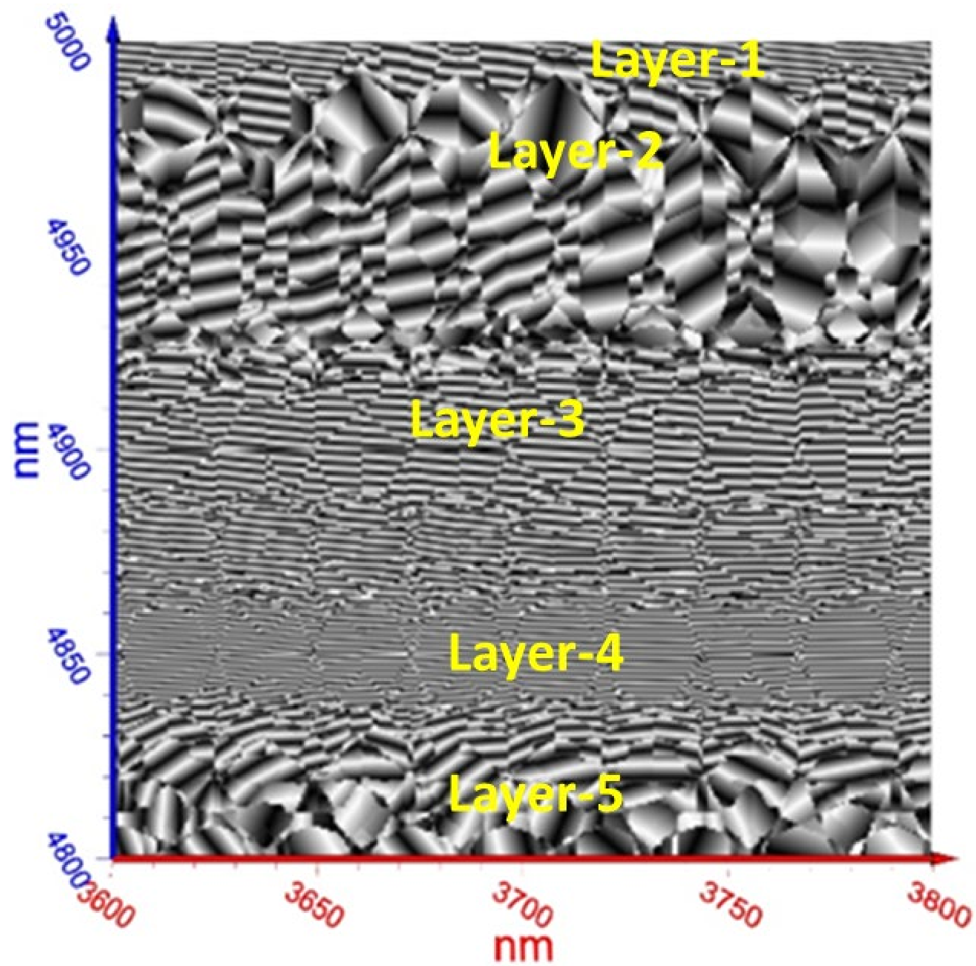

Fig. 5. Zoomed in image over 200 nm × 200 nm of one side of Fig. 4(b). Nanocrystalline grain structures are visible. Sharp interface line runs across between the layers. The layer thicknesses may be measured.

diffusion type interface, where a lack of sharp interface line is visible and some diffusion of materials from both Layer-2 and Layer-3 into each other might have taken place. The interface between Layer-3 and Layer-4 constitutes an example of a type-1 or the misfit-lattice interface.

Fig. 6 displays a 2D image of an interface which qualifies as the type-2 or "identical lattice" interface. The top and the bottom parts of the image (Fig. 6) showing the formation of near identical lattices, however, distorted lattices are visible in the interface region identified by the arrows.

Fig. 7 shows a 2D image (200 nm × 200 nm) of the nanograin structure of a deposited carbon layer. The nanograins are characteristics of an amorphous material such as carbon.

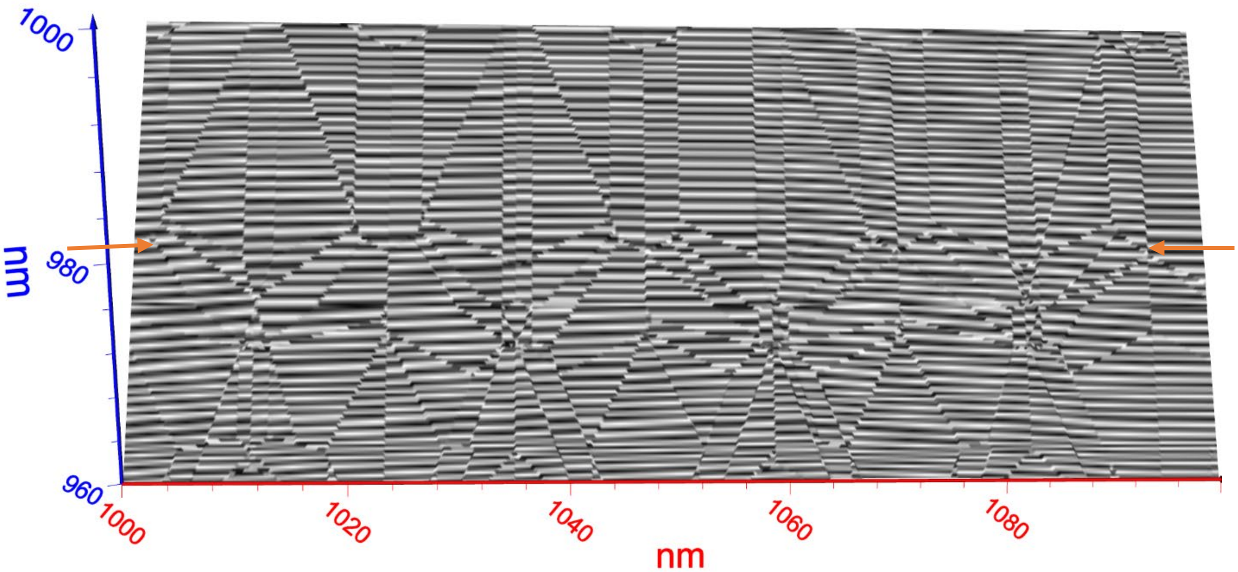

Fig. 6. Interface line (see arrow) runs between two layers of similar lattice.

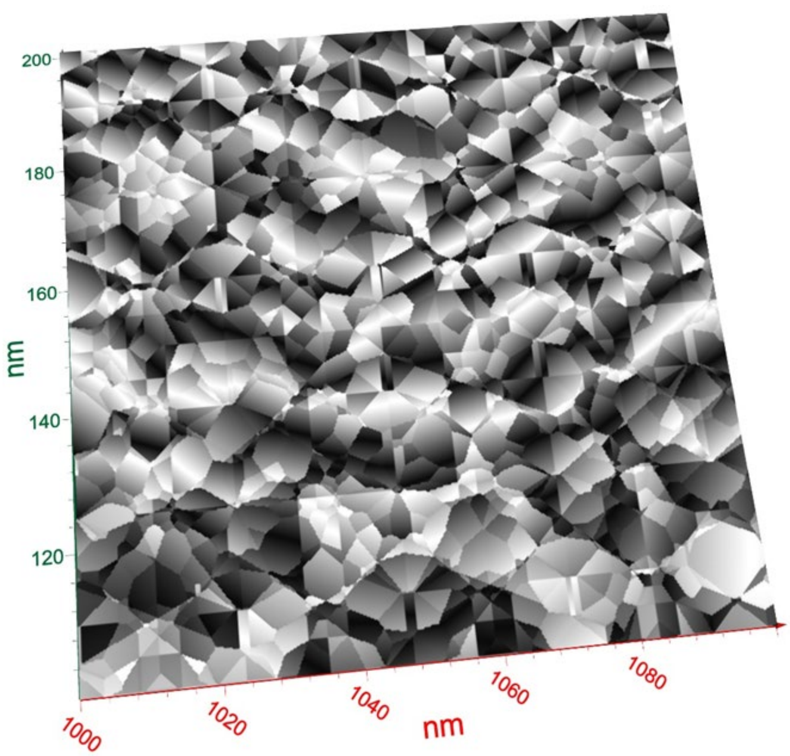

Fig. 7. Nanograins distribution in a deposited carbon layer.

Discussion

A relevant question is, how the non-destructive interface analysis presented in this paper is applicable to semiconductor manufacturing? So, an assessment of the relevance to manufacturing is discussed here. As outlined in the text, semiconductor interfaces determine the functionality of the devices or a lack thereof. For example, a simple (smallest) unit of an IC is a transistor, which is actually a sandwich of an *n*-type and a *p*-type semiconductor, in the sequence of *npn* or *pnp*. Thus, a single transistor involves two interfaces of the n-type and p-type material. More complex devices such as a MOSFET involves more interfaces at the source, drain, and channel. Interfaces are also involved in bonding and adhesion in semiconductors [9] that are not specifically discussed herein but would fall in one of the 5 types of interfaces discussed. In addition, when one material is deposited on another, defects at the interface could also arise in the form of delamination or inclusion.

Thus, the metrology technique and methodology described in this paper are directly related to the semiconductor manufacturing process development. It is also important for non-destructive inspection of devices and post-process failure mode analysis.

Conclusions

We have demonstrated a terahertz camera-less 3D (volume) imaging technique for non-contact and nondestructive investigation of semiconductor interfaces. The lattice image clearly reveals the lattice structure of different layers that may be used for quantification. Different kind of interfaces was discussed with images from real samples that exemplified each kind. In particular, images of misfit-lattice interface (type-1), identical lattice interface (type-2), rough surface interface (type-3), and diffusion type interface (type-4) have been presented. An example of mismatch compound semiconductor heterointerface (type-5) was not available yet. The camera-less imaging technique described herein, thus, constitutes an important tool for semiconductor interface analysis. The technique can be used for interface analysis of polymers [8] or any other materials. The ability for measuring size parameter via lattice resolution imaging is also suitable for quantification of semiconductor layers, features, and other materials system, from zero-dimensional to three-dimensional [5].

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