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Electron diffraction with ten nanometer beam size for strain analysis of nanodevices

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A method to perform nanobeam diffraction (NBD) in a transmission electron microscope with high spatial resolution and low convergence angle is proposed. It is based on the use of a properly fabricated condenser aperture of 1 μm in diameter, which allows an electron beam about 10 nm in size to be focused on the sample, with a convergence angle in the 0.1 mrad range. Examples of NBD patterns taken in an untilted ⟨110⟩ cross section of a silicon device are shown. Their quality is adequate for spot position determination and hence to obtain, in principle, quantitative strain information. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3003581]

The control of lattice strain has become one of the most crucial issues in the present 65 nm generation of complementary metal-oxide semiconductor (CMOS) devices for application to memories for computers and mobile phones (nanoelectronics); it influences the electron and hole mobility in a transistor channel. The determination of the strain tensor in the active area of the present and future Si technology nodes requires techniques with a nanometer scale spatial resolution. The only solution can be presently given by transmission electron microscopy (TEM) techniques such as electron diffraction,[1–3] high resolution electron microscopy.[4] and, very recently, electron holography.[5] In particular the convergent-beam electron diffraction (CBED) technique, which can probe the local lattice deformation in crystals in a point-to-point mode with a 1 nm spot size and a sensitivity of about 10^{-4}, is presently of widespread use.[3] Quantitative strain analysis is possible and is accomplished by comparing the experimental patterns with those computed for a large number of different cell parameters, according to the kinematical theory of electron diffraction. Although the possibility of two-dimensional strain mapping in the active region of the ⟨110⟩ cross-sectioned shallow trench isolation (STI) structures has been demonstrated, this method has two main drawbacks: (i) the sample must be tilted by a few degrees off the ⟨110⟩ (horizontal) zone axis to avoid dynamical interactions in the CBED patterns, what results in the worsening of the spatial resolution along an axis, and (ii) the HOLZ line must be sharp enough to accurately fit the experimental to the calculated patterns. This sharpness is not generally found in regions of the nanodevice close to the surface, where high strain gradients are likely to occur, resulting in HOLZ line splitting. In this case, a model of displacement field in the analyzed region must be assumed to obtain strain information from the investigated area.[6–9]

To overcome these difficulties, in particular, when analyzing sample volumes with high strain gradients along the electron beam direction, the nanobeam electron diffraction (NBD) method, which uses a nanometer-sized parallel beam, has been recently proposed.[10–12] In this technique, a small probe with reduced convergence angles is directed to the sample producing diffraction patterns with sharp spots similar to those of conventional selected area electron diffraction. A key advantage of NBD is that the sample can remain aligned along the ⟨110⟩ zone axis to which micro- and nanoelectronic devices are aligned. Strain quantification can be obtained from a comparison of the sharp diffraction spots between strained and unstrained regions of the sample.

To perform NBD experiments, we have used a FEI Tecnai F20ST TEM, operating at 200 kV. In the scanning TEM (STEM)/nanoprobe conditions used in our previous strain analysis work by CBED (Ref. 3) the spot size is about 1 nm, whereas the convergence angle is about 9 mrad if a 50 μm C2 aperture is used. To get a tiny spot with a much reduced convergence, we have fabricated a 1 μm aperture and used it as a condenser-lens diaphragm.

The fabrication was performed in two steps. First, the aperture of a commercial 20 μm Pt diaphgram was reduced by sputter depositing a bilayer of Al (10-μm-thick) as the adhesion layer, and Au (2.5-μm-thick) as the high-electron stopping power material. This process resulted in an aperture below 1 μm in size, with a fairly irregular shape. As a second step, to obtain a regular circle with the desired diameter, the aperture was bored through by focused ion beam (FIB) milling, scanning a 30 keV, 100 pA, Ga^+ beam over a 1 μm diameter circular pattern. A FEI DB STRATA 235M equipment has been employed. The resulting circular 1 μm hole is shown in Fig. 1 (Ref. 13). This kind of apertures for TEMs are presently not commercially available.

In Fig. 2(a) is reported a TEM image of the aperture, obtained in nanoprobe mode, defocusing the C2 lens so to get the most parallel beam. From the profile in Fig. 2(b) a full width at half maximum (FWHM) size of less than 12 nm is measured. This compares favorably with the 50 nm spot used by Gao *et al.*[11] and is about the same reported by Usuda *et al.*[10] To evaluate the beam convergence angle, a ⟨110⟩ cross section of a bare silicon wafer has been used. By measuring the FWHM diameter of the tiny central spot (ϕ) and the distance of the various diffracted spots from the transmitted beam (D_i), a mean value of the α convergence angle ϕ can be obtained through the equation $\alpha=(\phi/D)\theta_i$, where θ_I is the Bragg angle of a reflection i. It is found a value $\alpha=0.14$ mrad, which is adequate to perform accurate determi-

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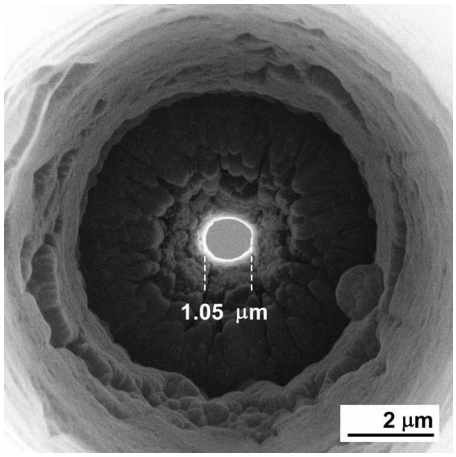

FIG. 1. Scanning electron microscopy image of the 1 μm aperture, used as a C2 aperture in the Tecnai F20 microscope. The circular hole has been obtained by FIB milling the commercial 20 μm Pt aperture, after deposition of the Al/Au bilayer.

nations of the position of the diffraction spots in the NBD patterns. Moreover, reducing convergence below 1 mrad reduces in parallel the dynamical effects due the presence of HOLZ lines.

It should be noted that in Tecnai TEMs a further operating mode is offered (STEM/microprobe) to obtain fine spots with smaller convergence than in STEM/nanoprobe. However, the convergence angle is more than a factor of 2 higher than that obtained by our method.

In Fig. 3(a) is reported a dark-field STEM image obtained with a high-angle annular detector of a cross section of a STI, fabricated according to the current 65 nm CMOS technology node. For CBED experiments, a 50 μm C2 aperture has been used, to have a sufficient number of HOLZ lines in the central disk of the pattern; moreover, the sample has been tilted to the ⟨340⟩ zone axis, i.e., by 8° off the vertical ⟨110⟩ axis of the cross section.[3] Figures 3(b) and 3(c) show CBED patterns taken focusing a 1 nm spot on the points labeled T and B of the electrically active silicon region of Fig. 3(a), respectively. They correspond to areas close either to the wafer surface or to the underlying (undeformed) silicon substrate. The sharp HOLZ line pattern in Fig. 3(c) (point B, negligible strain) becomes split in Fig. 3(b), due to the vertical large strain gradient[6–8] present in silicon regions close to the top T of the structure. Moreover, subsidiary (intermediate) fringes are generated between the two main HOLZ lines. As mentioned above, strain quantification becomes difficult in this case, because the HOLZ bandwidth, the intermediate fringe number and intensity, as

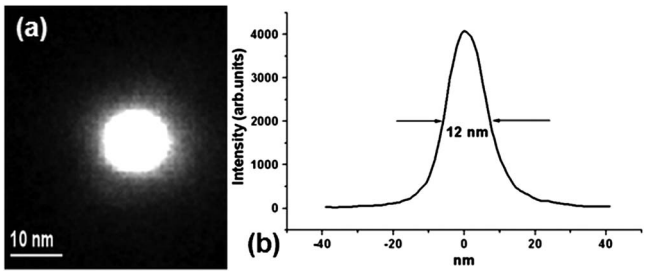

FIG. 2. (a) TEM image of the 1 μm C2 aperture, taken in nanoprobe mode, with a parallel beam; (b) profile of the spot in (a), which exhibits a FWHM=12 nm.

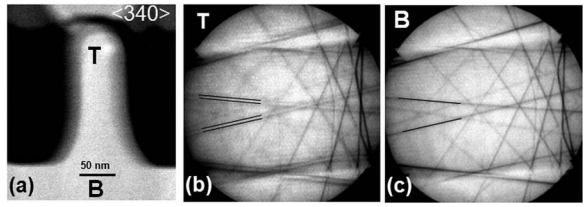

FIG. 3. (a) STEM image of a 65 nm STI structure, taken in the ⟨340⟩ zone axis; [(b) and (c)] CBED patterns corresponding to points T and B, respectively. The HOLZ line splitting is evident in (b), whereas the corresponding lines in (c) are sharp. The black segments have been marked to guide the eye. Spot size: 1 nm.

well as the possible pattern asymmetries depend on the shape of the displacement field, in particular, of its vertical component[7,9] when HOLZ lines split. In Fig. 4(a) is shown an (untilted) ⟨110⟩ STEM image of the same structure of Fig. 4(a), whereas in Figs. 4(b) and 4(c) are shown the NBD patterns, corresponding to the same points T and B. Good quality, circular diffraction spots are visible in the undeformed silicon point, whereas at point T they become elongated in a direction nearly parallel to the ⟨001⟩ direction suggesting that the shape of the displacement field previously found in similar structures[7] also affects NBD patterns.

This finding indicates that, despite the NBD advantage over CBED of being performed at zero tilt angle, thus avoiding tilt superpositioning, it is not always possible to quantify strain by NBD by merely determining lattice parameter variations $\Delta a/a$ from a measurement of the spot position with respect to a pattern taken in an undeformed silicon area.[10–12] In such cases, an approach similar to that used for CBED strain analysis (assuming a displacement field model and comparing simulated and experimental NBD patterns) should be explored. Dynamical simulations are needed to get a reasonable fit; in principle, information about the accuracy and sensitivity of the method could also be extracted wherefrom. This work is now in progress and is beyond the scope of the present letter; it will be the subject of a forthcoming paper. However, practical figures of these two parameters can be deduced from both our experiments and the theory of electron diffraction. A limiting factor of the strain *sensitivity* is given by the size of the charge coupled device camera (1024×1024 in our case), which is often employed to acquire the NBD patterns, as a shift by 1 pixel of a diffraction peak corresponds to a strain of 5×10^{-4}. About *accuracy* the dynamical nature of the analyzed diffracted beams must be taken into account, which results in a not negligible FWHM angular width of the corresponding rocking curves; for instance, for the 111 spots in a silicon NBD pattern (interplanar spacing: $d_{111}=0.3135$ nm, extinction distance at 200 kV

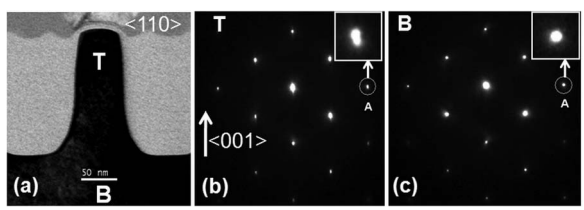

FIG. 4. (a) STEM image of the same structure as in Fig. 4(a), taken in the (untilted) ⟨110⟩ zone axis; [(b) and (c)] NBD patterns taken in points T and B, respectively. C2 aperture: 1 μm; convergence angle: 0.14 mrad. Note the deformation of the (2−2 0) spot close to the surface (T), which is not observed at the bottom (B).

$\xi_{111}=80$ nm) one gets $(d/\xi)_{111}=4\times10^{-3}$. This indicates that both strain accuracy and sensitivity are in a 10^{-3} scale.

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