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## Lateral epitaxial growth of germanium on silicon oxide

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We have developed a method using local oxidation on silicon to create nanoscale silicon seeds for the lateral epitaxial overgrowth of germanium on silicon oxide. The germanium growth starts selectively from silicon seed lines, proceeds by wetting the SiO<sub>2</sub> layer and coalesces without formation of grain boundary. Analysis by high resolution transmission electron microscopy have shown that Ge layers grown above silicon oxide are perfectly monocrystalline and are free of defect. The only detected defects are situated at the Ge/Si interface. Geometrical phase analyses of the microscopy images have shown that the Ge layer is fully relaxed and homogeneous. © 2008 American Institute of Physics. [DOI: 10.1063/1.2963363]

Germanium used as a high mobility channel, presents a strong interest for fully depleted metal oxide semiconductor field effect transistors to be developed in the next complementary metal oxide semiconductor technology generation (22 nm and below).<sup>1</sup> Currently germanium on insulator-(GeOI) structures are fabricated in the form of plain wafers by bonding techniques such as etch back or SMARTCUT,<sup>2</sup> or by Ge condensation.<sup>3</sup> In this paper, we propose the lateral epitaxial growth (LEG) of germanium on a SiO<sub>2</sub> layer formed by oxidation of a standard silicon wafer as an alternative to these techniques.<sup>4</sup> Such a local approach have the advantage of enabling easily the manufacturing of Ge- and Si-based devices at the same level on the wafer, and, from the material point of view, can be effective for defect density reduction, thanks to the low dimensions of the LEG crystals.<sup>5</sup>

It is well known that the main difficulty for growing germanium on silicon stems from a mismatch of 4.2% between the two crystal lattices, what results, on plain wafers, in the emission of misfit dislocations as soon as the growing film exceeds a critical thickness standing in the order of 1 nm.<sup>6</sup> When starting from seeds of limited diameter, a growing mismatched crystal is free of accommodating its lattice in a three-dimensional volume, which opens the possibility of dislocation-free growth. Previous calculations<sup>7</sup> have shown that for a given mismatch, the critical film thickness strongly depends on the seed radius and tends to the infinite below a critical radius value, which would be close to 20 nm for a mismatch of 4.2%. The validity of this approach has been demonstrated with the growth of dislocation-free Ge on silicon covered with a very thin SiO<sub>2</sub> film.<sup>8,9</sup>

We have developed a method to create nanoscale silicon seeds for lateral epitaxial of Ge on silicon oxide by using local oxidation of silicon (LOCOS) within a silicon nitride pattern mask. To realize the LOCOS, a silicon nitride film (~50 nm thick) is deposited on *p*-type Si(001) substrates by plasma enhanced chemical vapor deposition (PECVD) and patterned by conventional deep UV lithography (248 nm)

and reactive ion etching. Silicon nitride patterns consisting of 0.3–10 μm wide lines oriented along the ⟨110⟩ direction are made. A wet oxidation at 1050 °C is then performed in order to grow a ~100 nm thick silicon oxide layer through the nitride mask. At this oxidation temperature, flat {111} interfaces between silicon oxide and Si are formed close to the bird's beaks, as shown in Ref. 10. The oxide layer is then partially etched using a hydrofluoric (HF) acid solution to partially free the {111} facets from SiO<sub>2</sub>, in order to create lateral nucleation seeds for the Ge growth. The growth of Ge on Si surface close to the (111) orientation is of special interest, since in this orientation the misfit dislocations can glide along (111) planes.<sup>11</sup> It is worth noting that the width of the seeds and the thickness of the SiO<sub>2</sub> layer can be easily and precisely adjusted by controlling the thermal oxidation time and the etching time in HF solution. Figure 1(a) shows a cross sectional scanning electron microscopy (SEM) image of a linear silicon seed formed between Si<sub>3</sub>N<sub>4</sub> and SiO<sub>2</sub>. The width of the seed line is inferior to 50 nm. The SiO<sub>2</sub> layer thickness is around 50 nm, and as expected, the surface orientation of the Si seed is close to (111).

The epitaxial growth of Ge on the so formed patterns is carried out in an ultrahigh vacuum chemical vapor deposition (UHV CVD) reactor with a base pressure of  $2 \times 10^{-10}$  Torr using germane (GeH<sub>4</sub>) diluted at 10% in H<sub>2</sub>. As growth of Ge from GeH<sub>4</sub> is naturally selective on Si versus silicon oxide, the growth conditions are chosen to avoid polycrystalline Ge deposition on the nitride mask. The growth temperature is set up at 600 °C under a total pressure of  $1 \times 10^{-2}$  Torr, while the growth time varies between 1 and 2 h.

The growth process is monitored *in situ* by reflection high energy electron diffraction (RHEED). The RHEED diagrams recorded during growth show only spotty and streaky patterns, no polycrystalline signature (rings) being detected, which indicates clearly a monocrystalline growth. Figure 1 shows cross sectional SEM images illustrating different stages of Ge lateral growth from the Si seeds. The Ge growth is selective, it starts from the Si seeds, as shown on Fig. 1(b), and proceeds laterally by "wetting" the SiO<sub>2</sub> layer following

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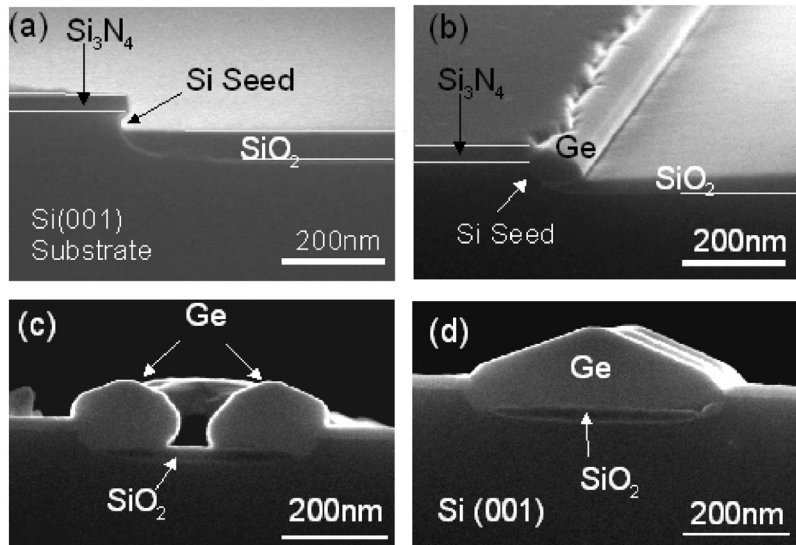


FIG. 1. Cross sectional SEM images of a linear Si seed oriented along the  $\langle 110 \rangle$  direction (a) and of Ge crystals grown from the Si seeds at different deposition times: 1 h (b), 1 h and 45 min (c), and 2 h (d).

an angle close to  $125^\circ$ . This angle corresponds to  $\{11-1\}$  facet, while the LEG Ge crystals exhibit  $\{113\}$  and  $\{111\}$  facets in their upper part [Fig. 1(c)]. Coalescence of Ge crystals from adjacent seeds takes place for longer deposition time and leads to rooflike structures delimited by  $\{113\}$  and  $\{111\}$  facets [Fig. 1(d)], as currently observed for selective epitaxial growth of Ge layers.<sup>12</sup> The orientation of the seed patterns appears to be an essential parameter. The Ge crystals grows straight and parallel to the seed lines when these latter are oriented along the  $\langle 110 \rangle$  direction, as seen in Fig. 1(b). In the  $\langle 110 \rangle$  orientation, stable Ge facets can be formed.<sup>13</sup> When seed lines are disoriented with respect to the  $\langle 110 \rangle$  direction, the Ge growth is more irregular, facet formation becomes unfavorable for lateral growth. This results in the formation of separated faceted crystals along the seeds, as shown in Fig. 2.

To better study the Ge structures, transmission electron microscopy (TEM) analysis is carried out on cross sectional specimens in a Cs-corrected Tecnai F20 installed at CEMES-CNRS. As a first step, weak beam dark field analysis<sup>14</sup> (WBDF) is used to investigate the presence of extended defects in the Ge crystals. Figure 3(a) is a WBDF image of a coalesced germanium crystal taken in a  $g=220$ , ( $g, -2g$ )

condition. No defect is visible in the inner part of the structure while the contrast zones found at the two Si/Ge interfaces confirm the presence of defects due to the misfit between bulk silicon and germanium. Moreover several plane view TEM analysis show that the joining of two fronts result in defect-free interface. This means that the Ge crystals have evolved from a growth shape to an equilibrium shape during the coalescence, with a reorganization of the material that leads to a new grain-boundary-free Ge crystal.

These results are compatible with the hypothesis that LEG Ge consists in fully relaxed single crystals free of bulk defects. High Resolution TEM analysis (HRTEM) is carried out on the same specimen [Figs. 3(b) and 3(c)]. The recorded images confirm that as grown Ge is fully crystalline. In addition, HRTEM images obtained in the Si/Ge interface region [Fig. 3(c)] indicate the presence of stacking faults and

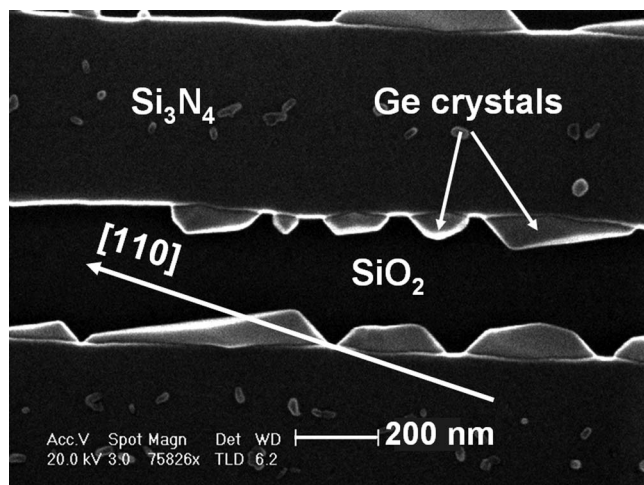


FIG. 2. Ge crystals grown from linear seeds disoriented by  $22^\circ$  from the  $\langle 110 \rangle$  direction.

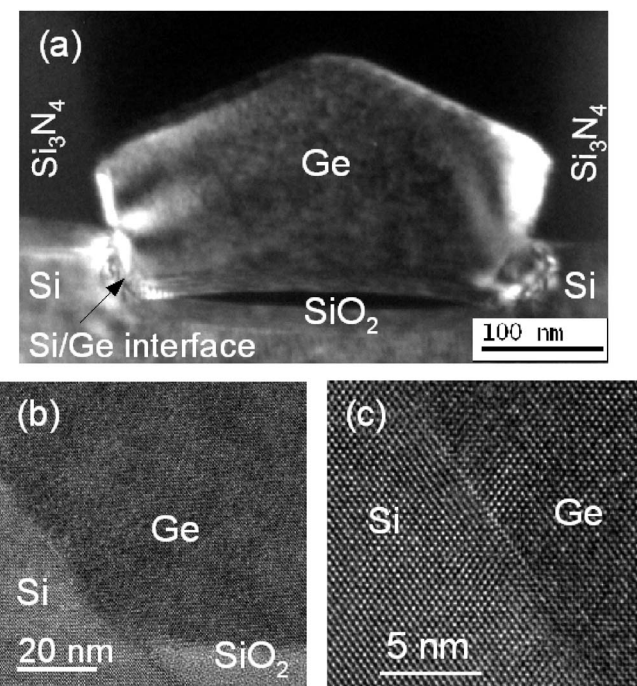


FIG. 3. TEM WBDF images obtained in a  $g=220$ , ( $g, -2g$ ) condition from a Ge crystal (a) and HREM images [(b) and (c)] of the Ge/Si interface.



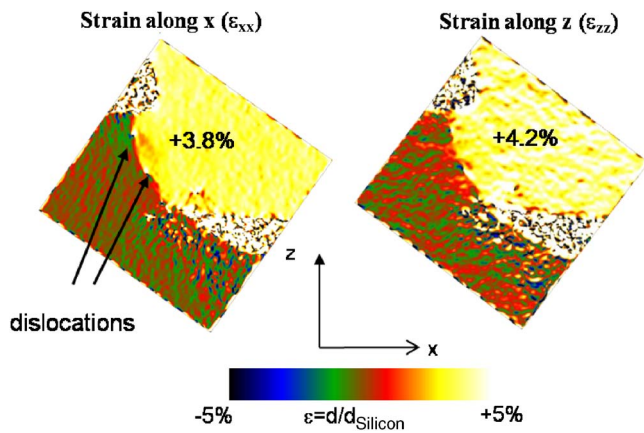


FIG. 4. (Color online) Two-dimensional strain maps of the Germanium seeds measured with reference to the silicon lattice. The strain value for relaxed germanium is  $\varepsilon=4.2\%$

interfacial dislocations at the interface. The defect density appears to be very low at the Ge/Si interfaces. It is possible that the seed morphology (roughness and orientation) helps plastic relaxation. The roughness confines dislocations at interface, and, the (111) Ge/Si interface enables misfit dislocations to glide in the interfacial plane.<sup>11</sup>

In order to evaluate the amount of strain in germanium crystals, geometric phase analysis of HRTEM images is performed.<sup>15,16</sup> The lattice spacing is constant in the silicon layer far from the interface and it is used as the reference. As a consequence the measured strain  $\varepsilon$  is a relative value with respect to an unstrained silicon lattice. In Fig. 4, the strain of the (11-1) and (200) planes are combined to determine the two-dimensional deformation tensor perpendicular to a  $\langle 110 \rangle$  zone axis. Two uniform zones of different constant strain are apparent in the image due to the change in the lattice spacing when passing from the silicon to the germanium region. It can be also observed, in Fig. 4, that the expansion of the Ge lattice with respect to relaxed Silicon is uniform in the (110) and (100) directions and amounts respectively to  $\varepsilon_{xx}=+3.8\%$  and  $\varepsilon_{zz}=+4.2\%$ . From these results we can conclude that the Ge crystal is almost fully relaxed, homogeneous and crystalline.

In conclusion, we have shown that large fully relaxed monocrystalline Ge crystals on  $\text{SiO}_2$  with very low defect

densities can be easily obtained by LEG. A reproducible method based on LOCOS has been developed to create well localized nanoscale apertures through the  $\text{SiO}_2$  layer, that act as seeds for transferring the crystalline order from the Si substrate to the LEG Ge crystals. This local approach could be an attractive alternative to GeOI plain wafer for micro- and optoelectronic applications.

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