Empty-space-in-silicon technique for fabricating a silicon-on-nothing structure

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(Received 27 June 2000; accepted for publication 12 September 2000)

A promising technique to form the silicon-on-nothing structure is presented as an alternative to the silicon-on-insulator structure. A large plate-shaped empty space in silicon (ESS) below the surface of the silicon substrate can be fabricated by connecting the spherical empty spaces, which are formed by surface migration of Si on the patterned Si substrate. The ESS technique has the potential to change the microprocess for the fabrication of large-scale integrated circuits and it can be applied to various manufacturing technologies. © 2000 American Institute of Physics.

Silicon-on-insulator (SOI) structure is one of the most attractive candidates for metal–oxide–semiconductor devices for low-power and high-speed applications, because by using this structure it is easy to reduce a coupling capacitance. However, specific substrates, such as separating devices for low-power and high-speed applications, because by using this structure it is easy to reduce a coupling capacitance. However, specific substrates, such as separation by ion implantation of oxygen, epitaxial layer transfer, have to be prepared before the device fabrication. Fabrication of large-scale integrated circuits (LSI) on these substrates brings results in a high cost. Moreover, it is difficult to obtain the silicon layer with defect-free crystalline quality due to the ion-implantation damage or the defects occur during the epitaxial growth step. Recently, an air-gap transistor, which has a void under the transistor region, has been proposed as one of the ideal structure of SOI, because the dielectric constant at the region below the transistors could be 1 with this structure. However, the proposed process sequences were too complicated for fabrication of LSI, because the air gap was formed by the etching step after device fabrication. Thus, it is difficult to enlarge the void region. To overcome these issues, we developed a new simple process for the formation of the empty space in silicon (ESS).

This letter presents a promising technique for the formation of large-scale ESS, based on the microstructure transformation of silicon (MSTS) technique, which had been developed by Sato et al. By applying the MSTS technique to the ingeniously patterned substrates, large plate-shaped empty spaces can be fabricated below the surface of the silicon substrate. In this letter, the concept of ESS and the procedure for forming ESS are presented, in which a self-organizing surface-migration phenomenon is utilized. Controllability in formation of ESS and the crystallinity of the silicon-on-nothing (SON) layer are also described.

The schematic illustrations of self-organizing sequences for the formation of ESS having three typical structures are shown in Figs. 1(a), 1(b), and 1(c): (a) sphere, (b) pipe, and (c) plate. The patterned silicon substrates were annealed in a deoxidizing ambient, such as a hydrogen ambient, with the result that the self-organizing surface migration of silicon occurs in such a way that the surface energy is minimized. In our experiment, deep trenches were formed as an initial shape on the substrate. Due to this initial shape, the trench was transformed to the spherical empty spaces, as is the case of the spheroidization of rods. Formation of spherical empty space started at the bottom of the deep trench because the radius of the curvature is the smallest at the bottom. Thus, in the case of the isolated trenches as shown in Fig. 1(a), each trench broke up to a spherical empty space or spaces, the size and the number of which depend on the depth and the radius of trench. When trenches were formed in a row, the grown empty spaces at the bottom of each trench were combined with one another as shown in Fig. 1(b). As a result, a pipe-shape empty space was formed, which was parallel to the surface of the substrate. Furthermore, plate empty space could also be fabricated by applying this technique to the trenches formed in a lattice. Spherical empty spaces at the bottom of every trench were combined and they were transformed to a plate-shaped empty space.

Details of the formation of ESS with various shapes were clarified by the scanning electron microscopy (SEM) observations as shown in Figs. 2–4. Formation of spherical empty space from a deep trench is shown in Fig. 2. Figures 2(a) and 2(b) show the SEM images of the initial and the final shape of the trench. Rectangular trenches with the size

![FIG. 1. Schematic illustration of self-organizing sequences for the formation of ESS having three typical structures: (a) sphere, (b) pipe, and (c) plate.](image-url)
of $0.25 \mu m \times 0.55 \mu m$ having the depth of $2.3 \mu m$ were formed in $p$-type (001) Si substrates with the resistivity of 4–6 $\Omega$ cm as shown in Fig. 2(a). These trenches were formed by the reactive ion etching method through the SiO$_2$ mask. This mask was removed prior to the annealing process for the ESS formation. The sample shown in Fig. 2(a) was annealed in hydrogen ambient at 1100 $^\circ$C for 10 min under the pressure of 10 Torr. The rectangular trench transformed to the cylindrical shape at the first step of the annealing$^8$.$^9$ The SEM image after the hydrogen annealing shown in Fig. 2(b) clearly demonstrates the formation of a spherical empty space.

ESS with various shapes could be successfully fabricated by combining the earlier-mentioned empty spheres. Formation of pipe-shaped ESS is shown in Fig. 3. Six trenches were arranged in a line, as shown in the SEM image in Fig. 3(a). The size of each trench was $0.25 \mu m \times 0.55 \mu m$ and the depth was $2.3 \mu m$. The distance between the neighboring trenches (distance between the centers of each trench) was $0.58 \mu m$, which was shorter than the diameter of the spherical empty space formed at the bottom of each deep trench. Thus, the spherical ESSs were combined with one another and transformed to the pipe-shaped ESS, as shown in Fig. 3(b).

Formation of plate-shaped ESS was experimentally demonstrated as shown in Fig. 4. By arranging the trenches in a lattice, the spherical empty spaces were connected to one another and they were transformed to a large and thin plate-shaped ESS. The initial shape of each trench was similar to that shown in Fig. 2(a). The number of the trenches was

![FIG. 2. SEM images of the initial and the final shape of the trench due to the hydrogen annealing. (a) Initial shape of the rectangular trenches was $0.25 \mu m \times 0.55 \mu m$ with the depth of $2.3 \mu m$. (b) The trenches were transformed to an empty sphere due to the hydrogen annealing at 1100 $^\circ$C for 10 min at 10 Torr.

![FIG. 3. SEM image showing pipe-shaped ESS. (a) Six trenches were arranged in a line. The size of each trench was $0.25 \mu m \times 0.55 \mu m$ and the depth was $2.3 \mu m$. (b) Pipe-shaped empty space was formed as a result of the connection of the six trenches due to the hydrogen annealing at 1100 $^\circ$C for 10 min at 10 Torr.

![FIG. 4. SEM image of the plate-shaped ESS with the area of $180 \mu m \times 1500 \mu m$ and the thickness of $0.7 \mu m$. A uniform SON layer having the thickness of $0.7 \mu m$ was formed on the ESS. The cross section of the initial trench was $0.29 \mu m \times 0.43 \mu m$ with the depth of $2.4 \mu m$. The number of trenches was $1.1 \times 10^6$.](image-url)
The thickness was 2.4 m and the thickness was 0.7 m. A uniform SON layer having the thickness of 0.7 μm was formed on the ESS.

The thickness as well as the area of the SON layer and the plate-shaped ESS can be controlled. The area is same as that of the total region where trenches have been formed. The thickness can be estimated based on the size of each spherical ESS and the density of trenches. According to the surface-diffusion-dominated breakup model, the radius of the spherical ESS (R_s) and the distance between each sphere (λ) can be expressed as R_s = 1.88 R_R and λ = 8.89 R_R, respectively, where R_R and L are the radius and the length of initial trench, assuming that the initial shape is a cylindrical rod. Thus, using the latter relation, the number of the spherical ESS formed from a deep trench can be forecasted based on the initial trench depth. The case shown in Fig. 2 is for the condition where the number of the formed spherical ESS is one.

In order to combine the spherical empty spaces with one another, the distance between the neighboring trenches are thus smaller than 3.76 R_R (= 2 R_s). By changing the distance (d) between trenches, the radius of the pipe and the thickness of the plate can be controlled, systematically. The radius of the plate-shaped ESS is evaluated to be R_P = (8.89 R_R^3/d)^{1/2}. The thickness of the plate-shaped ESS is evaluated to be t = 27.9 R_R^3/d^2. These evaluations were verified by the experimental results shown in Figs. 3 and 4.

The crystalline quality of the SON layer was found to be comparable to that of the bulk silicon, which is the most important requirement for device application. No detectable stress was observed on the SON layer with Raman measurement. No defect was observed even in the SON layer by transmission electron microscopy observation. Moreover, the flatness of the wide area of the surface of the migrated region was confirmed to have the same roughness as the initial substrate even in the trench area. During the ESS process, transformation is performed solely by the surface migration of silicon atoms. Thus, no stress and defects could be formed. The surface tends to be flattened as reported previously in the case of the hydrogen and ultrahigh vacuum annealing. The high density of the trenches facilitates flattening of the SON region, because the wavelength of the sinusoidal structure on the Si substrate was less than 1 μm, which was much shorter than the reported length. These results assure the wide applicability to LSI of the SON structure fabricated by the ESS process.

In conclusion, the ESS technique for the formation of SON structure was presented. Empty spaces of various shapes, such as plate, sphere, and pipe, could be formed, due to the hydrogen annealing of the patterned silicon substrate. The ESS technique is the promising device-applicable technique for the formation of SON structure having a good crystallinity. Moreover, the ESS technique is applicable to a wide range of manufacturing.

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