7th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 14–18, 1999 NT.20p

Free-standing GeSi/Si micro- and nanotubes

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Abstract. Micro- and nanotubes, as well as free-standing flexible helical microcoils have been fabricated for the first time from strained Ge_xSi_{1-x}/Si bilayers. The scrolling process used for the formation of the nanoobjects proceed in a self-forming manner due to the action of interatomic forces inside the highly strained layers. The obtained tube diameter varied from 1.5 μm to 90 nm depending on the value of lattice mismatch and on the thickness of GeSi/Si bilayer.

Introduction

Nanostructure formation is the forefront of semiconductor science and technology. However, using any traditional fabrication methods (electron or ion beam lithography), it remains difficult to fabricate even planar structures smaller than 10 nm. Fabrication procedures for three-dimensional (3D) nanostructures are far less advanced. However, new interesting physical properties and phenomena can be expected in such structures.

Recently, several new concept of making 3D nanostructures (nanotubes, flexible helical nanocoils, cylindrical quantum well and arrays of nanotubes) have been proposed and realized [1–3]. The concept are based on the possibility of self-scrolling of highly strained InGaAs/GaAs heterolayers (being debonded from substrate) in tube shape scrolls. It has been shown that the rolled up layers get close together, thus forming perfectly bonded tubes walls. The tube diameter could be precisely controlled in the range from 4 μm to 3 nm, depending on the value of lattice mismatch ($\Delta a/a$) and on the thickness d of InGaAs/GaAs bilayer (max $\Delta a/a \approx 7.2\%$) [4].

Results and discussion

We present here 3D micro- and nanostructures fabricated from strained GeSi/Si bilayers using the scrolling process. The use of Ge_xSi_{1-x}/Si heterostructures for the above process (max $\Delta a/a \approx 4\%$, the smallest expected tube diameter ($\sim$ 8 nm) has much potential since: (a) it offers a possibility to obtain conducting tubes with ultra-thin walls (the doping level of Si can be brought up to $\approx 10^{20}$ cm^{-3}, and, in addition, some part of Si layer or even the whole layer can be replaced with $NiSi_2$ or $CoSi_2$ layers having metallic conductivity), (b) the 3D structures fabrication technology matches well the Si-based integration technology.

In the initial pseudomorphic structure, the Ge_xSi_{1-x} layer is compressed. After debonding of the bilayer resulting from lateral undercutting etch of Si substrate through windows on the epilayer side, the interatomic forces (F_1 and F_2—Fig. 1) will act to increase the interatomic distance in the compressed Ge_xSi_{1-x} layer, which tends to bend the bilayer.

The problem of realization of the selective etching was solved by using the well-known chemical-etch stop effect of heavily boron-doped Si ($p^+ \approx 10^{20}$ cm^{-3}). In the case of Ge_xSi_{1-x} films, the effect was even more pronounced, since addition of Ge into Si results in a considerable decrease of the etch rate V [5]. The selective etchant used in this work (selectivity factor $\delta = V_p/V_{p^+} \approx 10^3$) was shown to permit scrolling up of a GeSi/Si in a

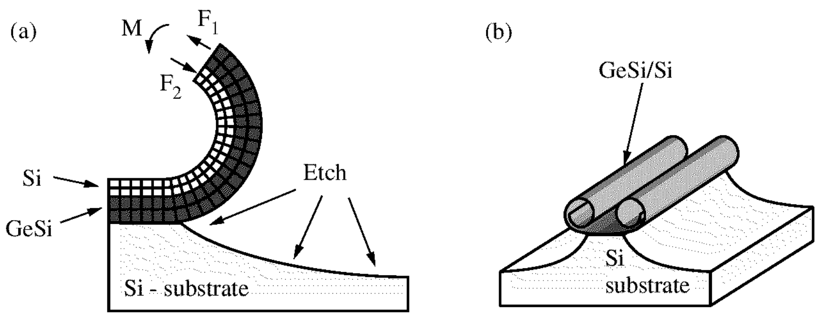

Fig. 1. Schematic illustration of the proposed tube formation technology. (a) Strain-induced bending of the GeSi/Si bilayer after freeing it from bonding with substrate. (b) Self-scrolling of bilayer during removal of substrate. The forces F_1 and F_2 are oppositely directed, and they give rise to a moment of forces M, which tends to bend the bilayer.

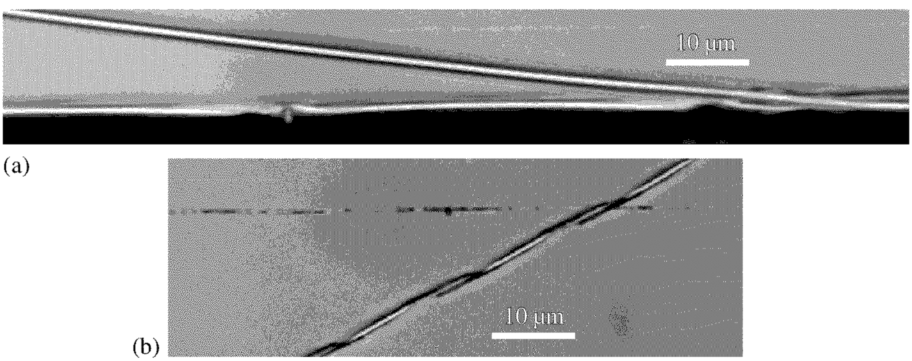

Fig. 2. Photographs of a tube (a) and a helical coil (b) of 1.5 μm in diameter made from a $Ge_{0.4}Si_{0.6}$/Si bilayer. Thicknesses of $Ge_{0.4}Si_{0.6}$ and Si films were 10 and 20 nm, respectively.

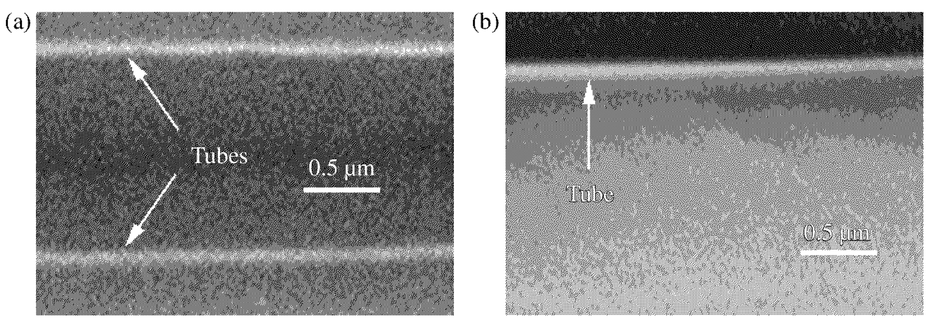

Fig. 3. SEM images of tubes with diameter 90 nm. (a) $Ge_{0.8}Si_{0.2}$/Si bilayer was used. Thicknesses of $Ge_{0.8}Si_{0.2}$ and Si layers were 2 and 5 nm, respectively. (b) $Ge_{0.8}Si_{0.2}$/Si/$Ge_{0.3}Si_{0.7}$ three-layered system was used. Thickness of each layer was 2 nm (the total thickness was 6 nm).

tube, with the thickness of cap silicon layer having been decreased by no more than $\pi D/\delta$, where D is the tube diameter. The latter can be confirmed by the following estimates. Indeed, the length of time required for freeing the bilayer film from bonding with substrate over the distance equal to the scroll circumference can be written down as $t = \pi D/V_{\text{sub}}$, where V_{sub} is the etch rate of substrate. In fact, this duration will be even shorter, since in the cause of etching the scrolling film facilitates the access of etchant towards the substrate. In view of the above, the decrease in the thickness of the cap Si layer will be

$$\Delta d = V_{\text{film}} \cdot t = \frac{V_{\text{sub}}}{\delta} \cdot t = \delta^{-1} \cdot \frac{V_{\text{sub}}}{V_{\text{sub}}} \cdot \pi D = \delta^{-1} \cdot \pi D. \quad (1)$$

In our case this value is less than $10^{-3}\pi D$.

The possibility of formation of Ge_xSi_{1-x}/Si tubes and helical coils with well-defined parameters has been demonstrated on a series of epitaxial structures grown on the MBE "Katun" setup. Using Ge_xSi_{1-x}/Si heterostructures of different thickness, we have fabricated tubes of a preset diameter. Figures 2 and 3 exemplifies a photographs of such tubes and helical coils.

In the last case (Fig. 3(b)), a protective $Ge_{0.3}Si_{0.7}$ cap layer was used. The etch rate of $Ge_{0.3}Si_{0.7}$ is 17 times smaller than that of (100) silicon.

In the future, the proposed technology can be successfully used in combination with the Si technology of ICs.

Acknowledgements

The authors thank A. E. Plotnikov for taking SEM images and O. P. Pchelyakov for interest in the study. The work was supported by the Russian Foundation for Basic Research (Grants 97-02-18479 and 97-02-18408), Russian Program "Physics of Solid State Nanostructures" (Project 98 – 2030) and Russian Program "Promising Technologies and Devices for Micro- and Nanoelectronics" (Project E42).

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