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ELASTIC SILICON-FILM-BASED NANOSHELLS: FORMATION, PROPERTIES, AND APPLICATIONS

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UDC 538

Controllable formation and properties of solid single-crystal micro- and nanoshells of various shapes (tubes and spirals, vertically positioned rings and cylinders, and bent and trough-shaped cantilevers) are briefly reviewed, and new results are given. The shells and complicated structures of prescribed size and shape are formed with the use of elastic energy of initial strained SiGe/Si *films of nanometer thickness and methods of highly selective and directed detachment of the films from the silicon substrates. It is experimentally demonstrated that the diameters of the fabricated* SiGe/Si *nanotubes are several times smaller than the values predicted by the continuum elasticity theory. The properties of the shells made of semiconductor and hybrid (metal–semiconductor and metal–dielectric–semiconductor) films and their applications in micro- and nanoscale electrical engineering are discussed.*

Key words: *elastic stresses and strain, thin films, silicon, nanotechnology.*

INTRODUCTION

Elastic deformation of massive solids is well studied and is used in applied mechanics. The present paper describes methods of formation and properties of elastic micro- and nanoshells. Shell formation is based on the use of elastic deformation in ultrathin films detached from the substrate. Methods of epitaxial growth of single-crystal thin films from versatile materials on one substrate have been well developed. It is important that the grown film inherits the parameters of the crystal lattice of the massive substrate. Therefore, if the lattice constant of the grown material is greater than that of the substrate, the film becomes compressed. For instance, the strain of compression in a thin InAs film grown on a GaAs substrate is 7.2% because of the mismatch of the lattice parameters [1].

The idea of using the tremendous internal elastic energy of strained bilayer InGaAs/GaAs films to form micro- and nanoshells was first proposed and verified in [2, 3]. The essence of the method is controllable rolling of strained InGaAs/GaAs films being detached from the GaAs substrate into precision nanotubes with a minimum diameter of 2 nm. It was shown that nanotubes made of single-crystal, elastically strained InGaAs/GaAs films down to 6 Å thick possess significant mechanical strength [2, 3] and interesting mechanical and quantum properties [4–6]. The proposed method of using elastic stresses of thin films is one of the promising ways of solving the key problem in nanotechnology: Creation of precision nanostructures [7–9].

The majority of semiconductor devices fabricated in the world are based on silicon. Silicon is used in microchips, navigation systems, digital TV, cellular phones, solar power engineering, and microelectromechanical systems (MEMS). Unique properties of silicon, on one hand, and dynamic development of the technology of silicon-based integrated circuits (IC) and MEMS toward minimization of their elements, on the other hand, make the problem of obtaining precision silicon three-dimensional micro- and nanostructures rather important. Activities on creation of three-dimensional micro- and nanostructures on the basis of strained SiGe/Si films and investigations of their mechanical, electrical, and structural properties are briefly described in the present review.

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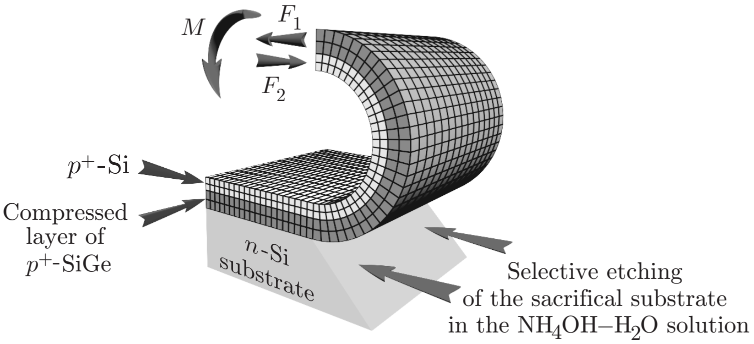

Fig. 1. Rolling of an elastically strained bilayer p^+-SiGe/Si film into a tube during its detachment from the substrate.

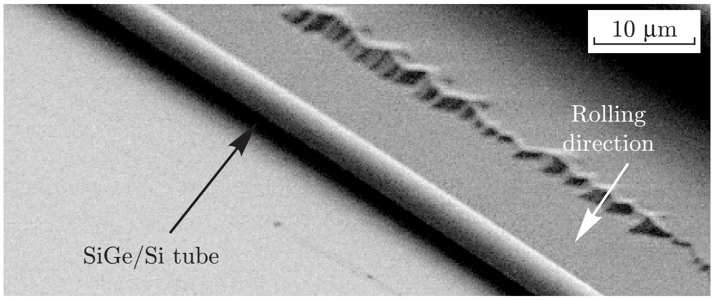

Fig. 2. SEM image of the tube 4 μm in diameter obtained from the $Si_{0.7}Ge_{0.3}$/Si (20/25 nm) film.

1. METHOD OF FORMATION OF SiGe/Si MICRO- AND NANOTUBES

Let us consider the main principles of the method developed for forming SiGe/Si tubes [10]. A single-crystal, elastically strained $Si_{1-x}Ge_x$/Si film is first grown on a silicon substrate by the method of molecular-beam epitaxy (MBE); the germanium–silicon layer of this film is compressed, and the upper silicon layer remains in an unstrained state. Elastic compression strain in the $Si_{1-x}Ge_x$ solid alloy increases with increasing content x of germanium and reaches a limiting value of -4%. The thickness of the $Si_{1-x}Ge_x$ layer should not exceed the critical value at which plastic deformation begins and dislocations start to form. Note that the MBE technology allows one to control the thickness of the grown semiconductor films of a prescribed composition with accuracy to one atomic layer. In turn, controlling the thickness and mechanical stresses in single-crystal epitaxial films ensures the precision of micro- and nanoshells made of this films. After that, a pattern is formed on the epitaxial structure by methods of optical (or electron) lithography; by means of liquid or plasma etching (removal), this pattern is transferred to the substrate surface, which results in opening of windows in the epitaxial structure down to the silicon substrate.

The strained SiGe/Si films can be detached from the substrate by highly selective (10^4) etching of the silicon substrate (Fig. 1). To prevent etching of the strained SiGe/Si film, we used the effect of retardation of chemical etching on silicon layers heavily doped by boron [11]. As a selective etchant, we used an aqueous solution of ammonia, which etches low-doped silicon 10^4 times faster than highly doped layers of Si and SiGe with the boron concentration $p^+ = 10^{20}$ cm^{-3} [12, 13]. When the substrate–film bonds are broken, the elastically strained bilayer p^+-SiGe/Si film is bent by the action of the force moment M generated by the oppositely directed forces of interatomic interaction in the film F_1 and F_2 and rolls up into a tube (Fig. 1). The number of coils in the tube is defined by the distance from the edge of the lithographic mesastructure at which the film is detached from the substrate. During bending in free-standing multilayer films, relaxation and redistribution of internal elastic stresses between the layers occur so that the value of strain in each layer becomes lower than the value in the initial flat layer with the maximum stress.

Figure 2 shows the image of a SiGe/Si tube 4 μm in diameter, which was obtained by a scanning electron microscope (SEM). The diameter of free-standing tubes D is proportional to the thickness $d_1 + d_2$ of the bilayer

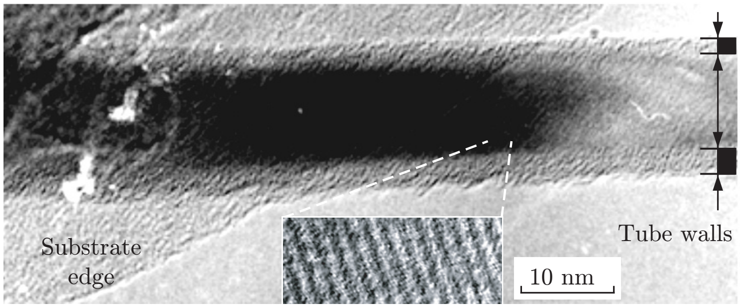

Fig. 3. HRTEM image of a nanotube (inner diameter 10 nm) protruding outside the substrate edge, which was obtained from a $Si_{0.2}Ge_{0.8}/Si/Si_{0.8}Ge_{0.2}$ (1/1/0.5 nm) film, and zoomed-in fragment of the nanotube.

SiGe/Si film and inversely proportional to the mismatch $\Delta a/a$ of the lattice constants of SiGe and Si; according to the continuum elasticity theory, its value can be estimated by the formula [14]

$$D \approx \frac{1}{3\Delta a/a} \frac{(d_1 + d_2)^3}{d_1 d_2}.$$

A more general expression for calculating the tube diameter and the bending radius of three-dimensional structures was derived in [15].

SiGe/Si tubes with diameters of 20 μm to 10 nm were formed in experiments [10]. Figure 3 shows the image of a single-crystal nanotube with a record-beating small inner diameter of 10 nm, which was obtained by the method of high-resolution transmission electron microscopy (HRTEM). The zoomed-in fragment in Fig. 3 displays $\{111\}$ atomic planes with an interplane distance of 3.1 Å. A further decrease in thickness of the rolled bilayer film to several monolayers and optimization of the process of selective etching of the sacrificial substrate (layer) can be expected to ensure formation of SiGe/Si nanotubes with inner diameters smaller than 5 nm. Rolling of strained SiGe/Si films 7.0 to 2.5 nm thick is found to form nanotubes with diameters of 100 to 10 nm. These values are 3 to 10 times smaller than those predicted by the continuum elasticity theory, whereas the diameters (20.0 to 0.6 μm) of nanotubes formed from p^+-SiGe/Si films 9–140 nm thick differ from the computed values by less than 5%. A change in elastic constants for nanometer-thick SiGe/Si films does not lead to a drastic decrease in the computed value of the nanotube diameter. Nanotube diameters significantly smaller than the predicted value were previously observed in rolling of ultrathin InGaAs/GaAs films whose thickness comprised several monolayers [2]. Some theoretical papers were published [15–18], where particular properties of nanoshells based on strained thin films were considered, such as flexural rigidity and dependence of the curvature of the structure on film thickness and elastic constants. It was demonstrated that rolling of strained semiconductor films whose thickness equals several monolayers is significantly affected by surface energy [17] and surface reconstruction [18]. With allowance for these factors, the numerical values of the nanotube diameters are 30% lower than the values predicted by the classical elasticity theory.

2. USE OF ANISOTROPY OF CHEMICAL AND ELASTIC PROPERTIES OF Si FOR FORMATION OF STRUCTURES WITH COMPLICATED THREE-DIMENSIONAL CONFIGURATIONS

2.1. Method of Directional Rolling of Films Based on the Use of Anisotropy of Silicon Etching. A specific feature of etching of low-doped single-crystal silicon in ammonia is a strong dependence of etching velocity on crystallographic orientation [12]. Golod et al. [19] proposed and implemented a method of directional rolling of strained SiGe/Si films into three-dimensional micro- and nanostructures, which is based on the use of anisotropy of lateral etching of the substrate (or sacrificial layer) of silicon in an aqueous solution of ammonia. It was found in experiments that the highest anisotropy of velocities of lateral etching of silicon in aqueous solutions of ammonia is reached on the surface with the orientation (110): $V_{110} : V_{100} : V_{111} = 10 : 4.8 : 1$.

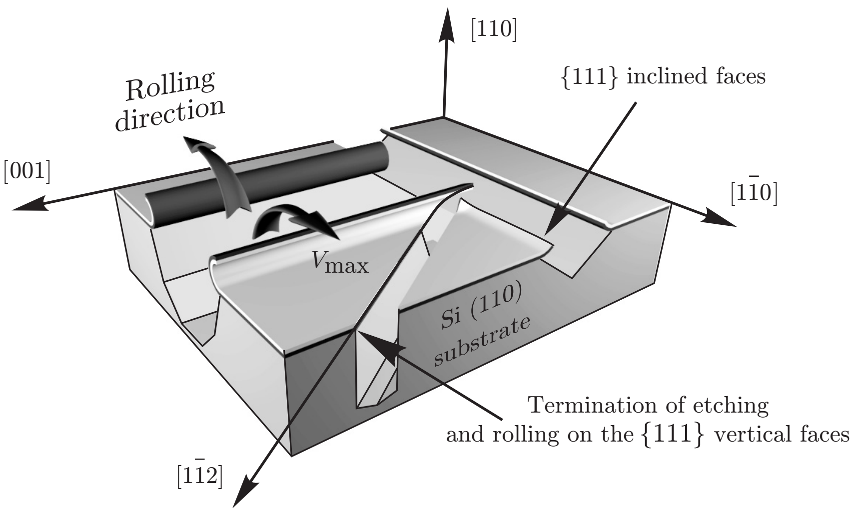

Fig. 4. Etching of the Si (110) substrate and directional rolling of the strained film ($V_{\max}/V_{111} = 10$).

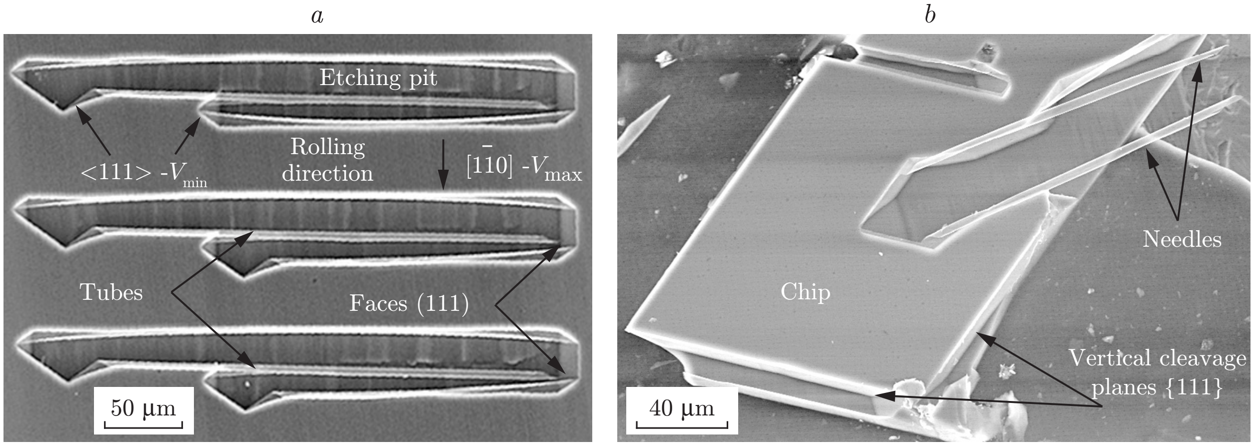

Fig. 5. SEM images of an array of free-standing (suspended) SiGe tubes attached to the substrate by the left ends (a) and a chip with tubes–needles protruding outside the chip edges (b) (tube diameter 4.6 μm; thickness of the $\mathrm{Si_{0.6}Ge_{0.4}/Si_{0.9}Ge_{0.1}}$ film 40 nm).

Figure 4 shows a schematic three-dimensional model of rolling of a SiGe/Si film at the edges of long narrow windows oriented in three crystallographic directions. Stable rolling of the strained SiGe/Si film in the direction of the maximum velocity $V_{[1\bar{1}0]}$ of lateral etching of the substrate in an aqueous solution of ammonia is illustrated. The process of rolling of the strained film can be retarded on those edges of the lithographic figure on which {111} vertical stop faces are formed. As the etching velocity on the {111} vertical faces being formed is substantially lower than that in any other direction, the velocity of lateral etching of the substrate under the film is significantly reduced; hence, rolling of the structured strained film on these edges is significantly retarded.

The efficiency of the method is demonstrated by the example of controllable directional rolling of long narrow strips of a $\mathrm{Si_{0.6}Ge_{0.4}/Si_{0.9}Ge_{0.1}}$ film on a (110) silicon substrate into free-standing microtubes–needles (Fig. 5a) with one end attached to the substrate. Termination of chemical etching on densely packed atomic planes allows one not only to reach directional rolling of the film but also to create through windows and stress concentrators in the Si (110) substrate for chipping out individual chips precisely along the vertical cleavage planes {111}. This approach was used to fabricate chips with tubes–needles protruding outside the chip edges (Fig. 5b). Based on free-standing p^+-SiGe/Si tubes protruding outside the substrate edge, one can create various devices, such as microchannels for fluids, microneedles, or tubular cantilevers.

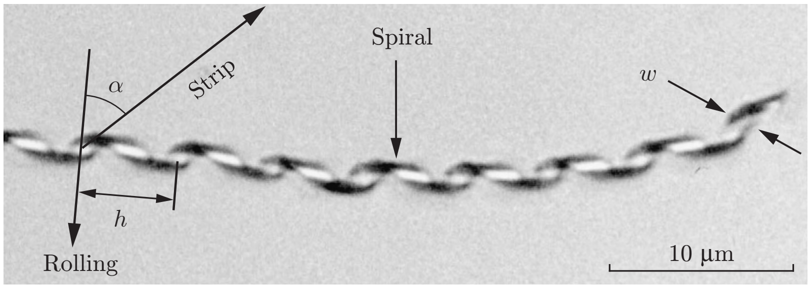

Fig. 6. Photograph of a microspiral 1.8 μm in diameter formed from a $Si_{0.6}Ge_{0.4}$/Si (10/20 nm) film; the distance between the coils is $h = 5.23$ μm, the width of the film strip is $w = 1.3$ μm, and the angle between the initial strip and the rolling direction is $\alpha = 48^\circ$.

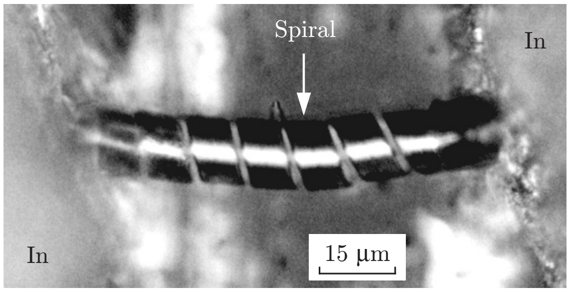

Fig. 7. Photograph of a $Si_{0.6}Ge_{0.4}$/Si microspiral (40/100 nm) 13 μm in diameter with contacts (In) on a sapphire substrate (the measured resistance of the spiral is 10 kΩ).

2.2. Spirals. The use of anisotropy of mechanical properties of strained semiconductor films allows one to form not only tubes but also other three-dimensional structures. In particular, three-dimensional spirals are formed from narrow strips of strained InGaAs/GaAs [2] and SiGe/Si films (Figs. 6 and 7) [10] aligned at a certain angle with respect to the rolling direction with a minimum rigidity ($E_{\min}$ is the minimum value of Young's modulus in the substrate plane) during their detachment from the substrate. Such a shape of the object ensures the minimum energy of elastic strains in the film [2]. Though the anisotropy of Young's modulus on the (100) silicon surface is only 23%, it is sufficient for stable formation of three-dimensional spirals. The distance between the spiral coils $h = \pi D \tan \alpha$ is determined by the misalignment angle α between the strip of the SiGe/Si film and the rolling direction (see Fig. 6). It was found [10] that tubes and spirals with diameters from 100 nm to 13 μm (see Fig. 7) are conducting, and the measured resistance is consistent with parameters of the bulk material. It was shown that SiGe/Si spirals with a small pitch can elastically bend at angles greater than 90° and significantly extend in the lengthwise direction [10]. Such flexible conducting three-dimensional spirals can be used to fabricate inductance coils, probes for surface-probe microscopes, movable joints, and elements of MEMS sensors and actuators and robots.

Anisotropy of elastic properties of single-crystal SiGe/Si films combined with directional rolling provides the basis for fabricating ordered arrays of spirals. Figures 8a and 8b show the SEM images of the arrays of two-coil SiGe/Si/Cr spirals formed on silicon substrates with crystallographic directions (100) and (110), respectively. To form such ordered arrays of spirals, we had to solve the problem of uncontrollable etching of the sacrificial silicon substrate at the strip edges and ensure a controllable process of strained film rolling in a prescribed direction, beginning from the strip edges. To solve this problem, we decided to align the initial long narrow strips of the strained film in directions along which {111} stop surfaces are formed during etching in an aqueous solution of ammonia. In this case, the strained film starts to roll at the ends of the strips and proceeds in the directions of the greatest velocity of lateral etching of the sacrificial silicon substrate, which are simultaneously the directions of low rigidity in single-crystal bilayer SiGe/Si films. For (100) and (110) silicon substrates, the strips of the strained film should be oriented in the directions $\langle 110 \rangle$ and $\langle 112 \rangle$, respectively (Fig. 8). Note that the method of controllable

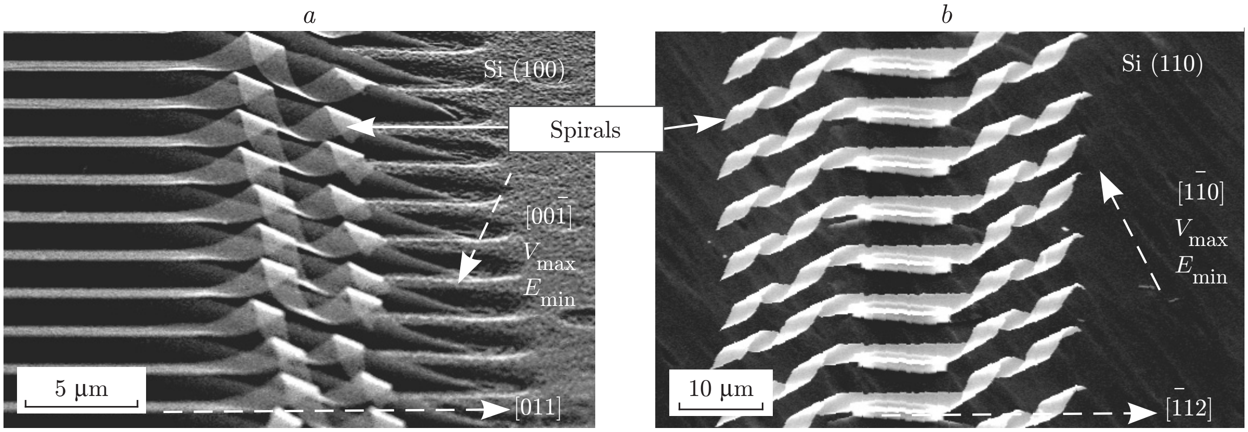

Fig. 8. SEM images (at an angle to the surface) of arrays of microspirals obtained from $Si_{0.6}Ge_{0.4}$/Si/Cr (2.6/4/30 nm) (a) and $Si_{0.6}Ge_{0.4}$/Si/Cr (10/7/20 nm) films (b) on substrates with crystallographic directions (100) and (110), respectively.

directional rolling of strained SiGe/Si films into three-dimensional structures is based on anisotropy of elastic and chemical properties of materials themselves. As the indicated properties of silicon are retained for films up to several nanometers thick, three-dimensional objects can be scaled to nanodimensions.

2.3. Complicated Structures. Micro- and nanomechanical devices consist not only of tubes but also of objects of more complicated three-dimensional configurations, which form the basis for transmission devices and mechanisms, gears, hinges, and flexible beams. Development of the approach of simultaneous usage of anisotropy of elastic and chemical properties of SiGe and Si films made it possible to fabricate even more complicated three-dimensional objects and structures based on these objects, such as vertically located rings and cylinders (Fig. 9) or criss-cross tubes. Prinz et al. [20] were the pioneers to demonstrate that it is possible to fabricate vertical SiGe/Si rings (with the walls perpendicular to the substrate surface), to precisely position these rings, encapsulate them into a resist (polymer film), and attach to the substrate. Owing to the high accuracy of obtaining epitaxial layers and high selectivity of substrate etching accompanied by detachment of the strained SiGe/Si film, the rings have smooth walls with a precision thickness. Grützmacher et al. [21] proposed to use a ring with smooth vertical walls to form a conducting channel of a double-gate transistor similar to FinFET transistors [22]. It can be expected that the surface scatter of electrons in such a smooth-walled thin-film channel will be less intense; hence, the response time of the transistor will decrease and the energy consumed by the device will be lower.

The technological issues of formation of two-dimensional arrays of rings with vertical walls lying on the substrate were considered in [23]; it was proposed to use these rings as a mold in nano-imprint lithography, which is a technology that allows creating nano-sized imprints in polymer films applied onto a semiconductor substrate. Such narrow rings of nanometer thickness, which can sustain compressive stresses along their axis, can pierce thin polymer films and, thus, create clear-cut patterns in these films. The first stage implies that L-shaped windows providing access for the etchant to a low-doped sacrificial layer are opened in the initial heterostructure by means of electron lithography and plasma-chemical etching. This procedure produces a mesastructure in the form of a narrow strip of the strained film with one end being “free” and the other end being attached to the ambient SiGe/Si film. Then, there follows selective etching of the sacrificial layer, which favors rapid detachment of the narrow strip of the strained film from the substrate and rolling of the film into a ring (Fig. 9b). Further etching removes the sacrificial layer under the strained film adjacent to the “rectangular” window. Under the action of elastic forces, the film detached from the substrate bends and put the ring askew (Fig. 9c). At the moment the ring walls occupy the vertical position with respect to the substrate, the etching process is terminated. Figure 9d shows the SEM image of an ordered array of vertical rings formed by the procedure described above. The first experiments with the use of substrates with vertical rings as a mold were performed on a laboratory setup for imprint lithography at the Paul Scherrer Institut (Switzerland). After the mold was held up (Fig. 9e), the rings were found to detach from the mold surface and to remain encapsulated in the polymethylmethacrylate (PMMA) film. The reason is

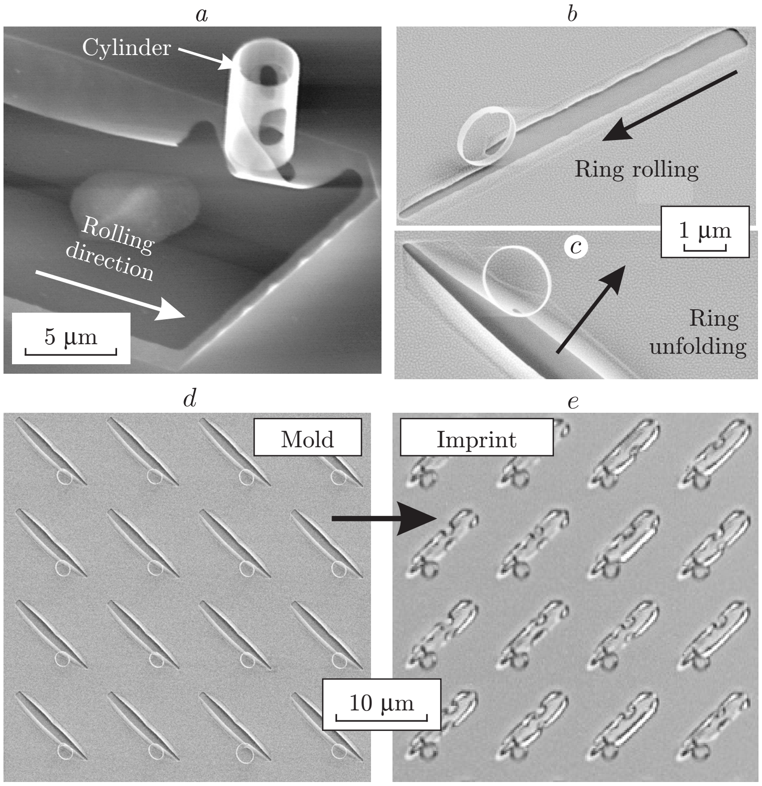

Fig. 9. SEM images: (a) vertically positioned cylinder (the angle with the substrate plane is ≈ 60°) obtained from a $Si_{0.6}Ge_{0.4}/Si_{0.9}Ge_{0.1}$ (20/20 nm) film grown on a (110) Si substrate; (b–e) imprint lithography with the use of a mold in the form of an array of vertical rings on a (100) Si substrate: rolling of a strip of a $Si_{0.7}Ge_{0.3}/Si$ (10/10 nm) film into a ring (b), laying the ring askew (c), mold (ordered array of vertical rings) (d), and imprint in the PMMA film with the SiGe/Si rings detached from the mold (e).

insufficient mechanical strength of the free narrow strip of the SiGe/Si film, which forms the ring, at the place of its attachment to the remaining portion of the strained bilayer film on the substrate. It is possible to fix the vertical rings on the mold and, thus, avoid deformation and detachment of rings during imprint lithography, for example, by using an additional resist layer applied onto the initial mold [20]. A decrease in thickness of the rolled strained film to 3–4 nm offers prospects for fabricating molds on the basis of vertical rings of submicron diameter with atomically-smooth precision walls.

3. FABRICATION OF THREE-DIMENSIONAL HYBRID STRUCTURES ON THE BASIS OF METAL–SEMICONDUCTOR AND METAL–DIELECTRIC–SEMICONDUCTOR FILMS

As in the planar IC technology, fabrication of functional devices based on three-dimensional structures requires not only semiconductor strained films but also more sophisticated multilayer hybrid structures including layers of metals, dielectrics, piezoelectrics, etc. This allows a significant extension of the area of applicability of three-dimensional thin-film structures in microelectromechanics and micro- and nanoelectronics. For instance, the use of piezoelectrics makes it possible to bend mechanical beams and generate their oscillations, and current-conducting metal strips provide power for electromechanical and electronic devices. In addition, this problem is important because of requirements of the rapidly developing technology of “flexible electronics” [24, 25] aimed at design of integrated circuits, electronic paper, displays and photodetectors, electronic skin and implants, capable of bending and sustaining considerable mechanical strains.

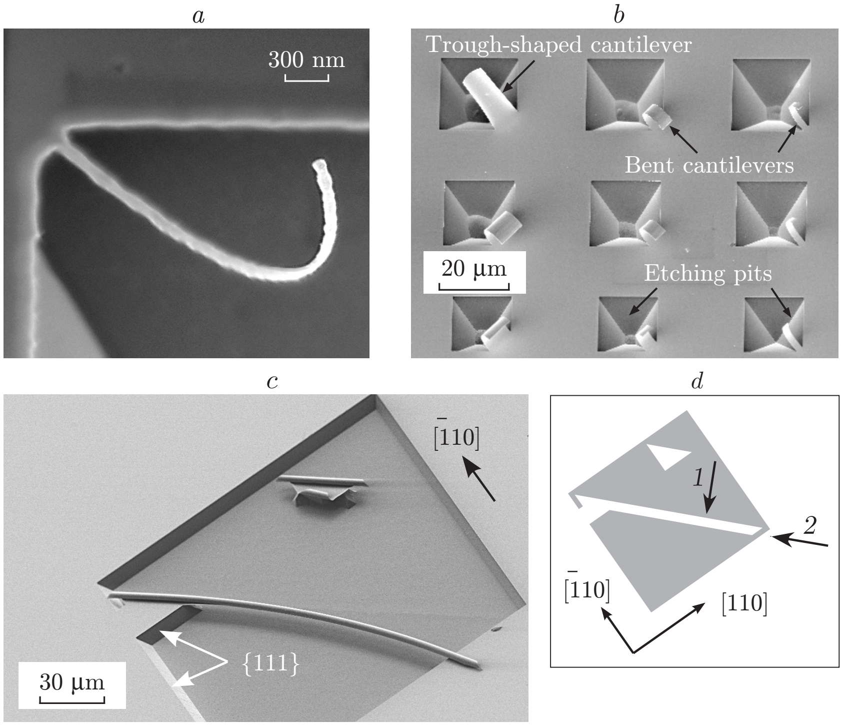

Fig. 10. SEM images of three-dimensional metal–semiconductor SiGe/Si/Cr microstructures: (a, b) bent cantilevers $Si_{0.8}Ge_{0.2}$/Si/Cr (12/50/20 nm) with a bending radius of 3.2 μm in different scales; (c) suspended free-standing tube $Si_{0.6}Ge_{0.4}$/Si/Cr (20/20/20 nm) 210 μm long and 3.5 μm in diameter; (d) schematic of the initial mesastructure designed for free-standing tube formation (arrow 1 shows the rolling direction of the white figure and arrow 2 shows the direction in which the rolling process is suppressed by formation of the stop face {111}).

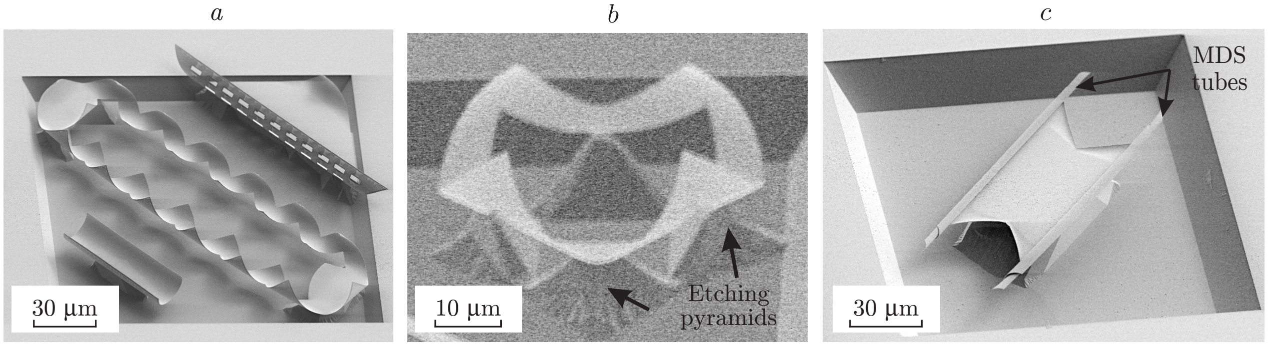

Fig. 11. SEM images of three-dimensional SiGe/Si/Si_3N_4/Cr MDS microstructures: (a, b) $Si_{0.6}Ge_{0.4}$/Si/Si_3N_4/Cr (20/20/75/20 nm) structures with the bending radius of 8 μm in different scales; (c) two suspended $Si_{0.6}Ge_{0.4}$/Si/Si_3N_4/Cr (10/10/10/18 nm) tubes 3.8 μm in diameter.

Methods for fabrication of free-standing three-dimensional microstructures from strained metal–semiconductor SiGe/Si/Cr and metal–dielectric–semiconductor (MDS) SiGe/Si/Si_3N_4/Cr films were developed in [26, 27]. The choice of the metal layer (Cr) and dielectric layer (Si_3N_4) was motivated, first, by the high chemical stability of these materials to the aqueous solution of ammonia used for etching the silicon substrate and, second, by considerable internal mechanical tensile stresses, which favor the rolling of hybrid films. The studies showed that hybrid SiGe/Si/Cr films can be used to fabricate three-dimensional structures of different types and shapes: submicron bent (Fig. 10a) and trough-shaped cantilevers (Fig. 10b), rings, tubes (Fig. 10c), and spirals (see Fig. 8). Criteria for formation of bent and trough-shaped cantilevers on the basis of strained films were identified. If strips with the width smaller than half of the bending radius ($w < R/2$) are rolled, stable formation of bent cantilevers is observed, because of the low value of flexural rigidity of the film in the cross section of the narrow strip. To form trough-shaped cantilevers of a prescribed size from strips of the strained film, two conditions must be satisfied: 1) the width of the strips has to be equal to or greater than the bending radius ($w \geqslant R$); 2) the length of the strips must be greater than their width ($L > w$). Figure 11 shows the three-dimensional SiGe/Si/Si_3N_4/Cr MDS structures of different configurations formed with the use of plasma-enhanced chemical vapor deposition (PECVD) (Fig. 11a and b) and high-temperature low-pressure chemical vapor deposition (LPCVD) (Fig. 11c) silicon nitride. The three-dimensional MDS structures obtained are attached to small pyramids (pedestals) formed by anisotropic selective etching of the substrate and are located at a significant distance from the substrate surface. This is clearly seen in the zoomed-in image of the SiGe/Si/Si_3N_4/Cr structure in the form of a "crown" (Fig. 11b). Such a three-dimensional geometry is expected to reduce the influence of the substrate on the operational characteristics of devices based on free hybrid films by analogy with planar capacitance and inductance elements whose detachment from the substrate increases their figure of merit (Q-factor) [28]. The studies identified conditions for obtaining Si_3N_4 and Cr layers that ensure internal elastic tensile stresses (the strain reaches 0.3–2.0%) necessary for formation of micro- and nanoshells. For chromium films 20 nm thick obtained by thermovacuum vaporization and for PECVD silicon-nitride films 75 nm thick, the elastic strains were found to be $\varepsilon_{\mathrm{Cr}} = 1\%$ and $\varepsilon_{\mathrm{Si_3N_4}} = 0.38\%$. If technological conditions of metal and dielectric application onto the SiGe/Si film are satisfied, it is possible to precisely control the value of internal mechanical stresses in these layers, which allows controlling the bending radius of three-dimensional hybrid structures. From the viewpoint of the technology of fabricating semiconductor devices, it is important that semiconductor SiGe/Si heterostructures remain strained after application of LPCVD silicon nitride during more than 2 h at a temperature of 650–800°C. Tubes of an identical diameter are formed from the initial SiGe/Si structures and from these structures after high-temperature processing. This means that SiGe/Si films can sustain long-time high-temperature processing with no relaxation of mechanical stresses and without intermixing of the germanium–silicon solid solution with the neighboring layers.

We have experimentally demonstrated that the diameter of hybrid tubes can be controlled by varying the thicknesses of the metal and dielectric layers, by applying additional high-temperature annealing, which alters the mechanical stresses in Si_3N_4 and Cr layers, and using selective removal of individual layers. A method of transformation of three-dimensional metal–semiconductor structures with the use of selective dry plasma etching was described in [26, 27]. The chromium layer was selectively removed in the $Cl_2 + CO_2$ plasma from the surface of bent SiGe/Si/Cr beams (Fig. 12a), which initiated their transformation into SiGe/Si rings (Fig. 12b). In another test, addition of sulphur hexafluoride ($Cl_2 + CO_2 + SF_6$) made it possible to remove Cr and SiGe layers from the surface of hybrid beams (Fig. 12c) and to form almost flat silicon beams (Fig. 12d). Note that dry etching methods have an important advantage over etching by liquids, because the former require no additional drying of samples, which can lead to capillary sticking of thin-film three-dimensional structures.

An analysis of experimental data obtained on elastic strains in thin metal and dielectric films, which was performed with the use of a formula [15] for determining the bending radius of multilayer strained films showed that a proper choice of the layer thicknesses and stresses yields almost identical diameters of SiGe/Si tubes and hybrid tubes. In other words, application of additional strained layers of the dielectric and metal onto the semiconductor SiGe/Si film will not change the diameter of the tubes being formed. This will allow one to avoid deformation of the walls of longitudinally modulated tubes containing segments with different numbers of layers and coils. Such segments can be found in tubes used as building blocks for cantilevers or transistors possessing source, gate, and drain regions located along the tube. At the same time, it becomes possible to define the diameter of hybrid tubes and to obtain tubes with a locally modulated thickness by using lithography and selective etching of metal layers.

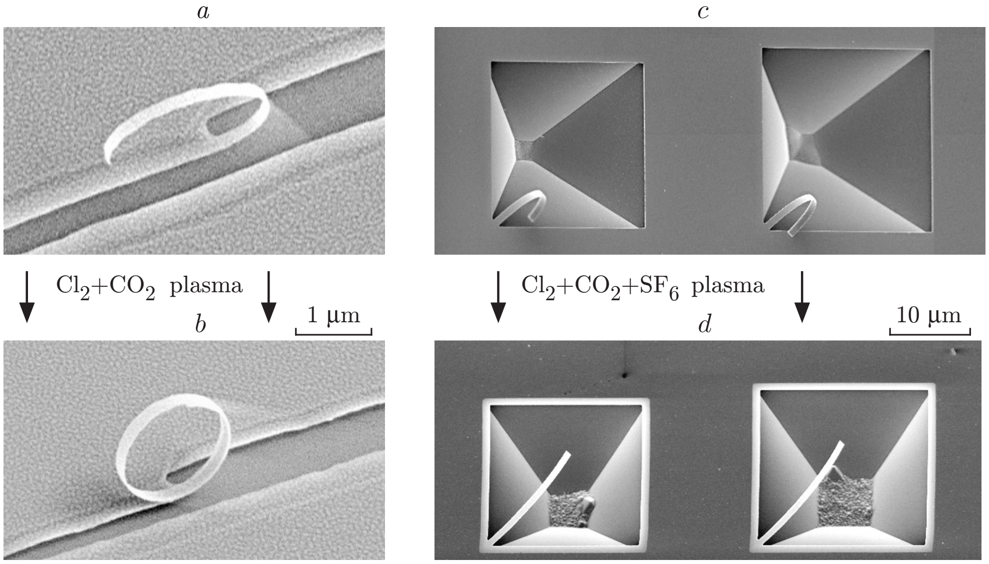

Fig. 12. SEM images: (a) narrow strip of $Si_{0.6}Ge_{0.4}$/Si/Cr (10/10/18 nm) with a bending radius of 1.15 μm; (b) the same strip transformed by selective removal of Cr in the $Cl_2 + CO_2$ plasma into a ring with a bending radius of 0.8 μm; (c) strips of the $Si_{0.6}Ge_{0.4}$/Si/Cr (12/50/20 nm) film with a bending radius of 3.2 μm; (d) "planar" silicon beams obtained from the same strips after removal of Cr and Si layers in the $Cl_2 + CO_2 + SF_6$ plasma.

Note that the possibilities of the method of self-rolling of strained thin films are not limited to Cr and Si_3N_4 only but can be extended to other strained materials possessing sufficient etching selectivity. For instance, metal (Ti/Au) nanotubes and semiconductor–metal (InGaAs/GaAs/Au) microtubes were formed in [29–31]. Fast-response sensors for hot-wire anemometers were created on the basis of InGaAs/GaAs/Au microtubes and tested [30, 31]. Rolling of a semiconductor film with conducting metal streaks [2, 3, 5] automatically resolves the problem of creating ohmic contacts to tubes, which currently hinders the development of the carbon-nanotube technology [32]. The proposed technology for creating three-dimensional hybrid SiGe/Si/Cr and SiGe/Si/Si_3N_4/Cr structures is promising for fabrication of bulk microcapacitors, inductance coils, bolometers, field transistors on tubes, and building blocks for micro- and nanoelectromechanical systems.

CONCLUSIONS

The paper describes methods of fabricating solid (SiGe/Si) and hybrid nanoshells. The methods are based on the use of internal elastic stresses in nanometer-thick films detached from the substrate by highly selective and anisotropic chemical etching. The variety of shapes, high precision of formation of SiGe/Si shells, and compatibility of methods of their formation with the planar technology of fabricating silicon MEMS and IC offer prospects for the use of such shells in microelectromechanics and electronics. Activities aimed at formation, investigation, and application of three-dimensional micro- and nanostructures based on strained (SiGe/Si) and hybrid shells are currently underway in Russia, Germany, Switzerland, Taiwan, Japan, and USA [15–18, 33–40]. Free-standing tubes protruding outside the substrate edge and bent and trough-shaped beams are used to create prototypes of cantilevers for atomic-force microscopes, as well as nanoprobes and micro- and nanoneedles for intracellular injections, and nanoinjectors for ink-jet printers [41–43]. It is planned to use tubes attached on the substrate as nanochannels for fluids in microlaboratories on a chip [42]. Thin-film beams and spirals are suitable for fabricating microelectromechanical mirrors-switches [37], flexible sensors of MEMS, and electrochemical nanosensors [36]. Possible areas of application of semiconductor and hybrid tubes, rings, spirals, and other shells in electronics include nanotransistors, capacitors, inductance coils, and optical resonators for lasers and light-emitting diodes [44–46]. In chemistry, application of nanotubes and shells seems to be promising for creating nanoreactors [47], which will allow controllable chemical synthesis in a closed volume of size commensurable with the light wavelength. The described methods of nanostructuring of elastically strained thin films offer numerous possibilities for creating new three-dimensional nanostructures and devices based on these nanostructures.

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