

Using of self-formed semiconductor micro- and nanotubes as a precise etch mask

V. Ya. Prinz, A. V. Chehovskiy and L. A. Nenasheva

Institute of Semiconductor Physics RAS SB, 630090 Novosibirsk, Russia

Abstract. Concepts of making precise etch mask using self-formed tubes have been proposed and realized. The InGaAs/GaAs mask-tubes diameter have been precisely controlled in the range from 4 μm to 8 nm. Using reactive ion etching and these mask-tubes, a mesa-structure and a groove on the GaAs substrate were fabricated.

Realization of recent physical concepts in quantum effect devices as well as in single-electron and atom/molecular switching devices requires further development of nanolithography and nanofabrication methods.

It is required not only to obtain nano- and atomic-scale patterning of semiconductor and metal films, but also to build up device elements with perfectly straight and sharp edges, free of roughness and having precisely controlled sizes.

Despite the extensive use of resist lithography in nanofabrication, it remain difficult to fabricate structures smaller than 10 nm using conventional optical or electron beam technologies, all the more it is impossible to fabricate structures with sharp and straight edges. Self-forming processes for making resistless mask are now proposed as an alternative way to overcome this barrier.

Recently [1–4], self-formed semiconductor nanotubes have been fabricated, and the possibility of precise control over their parameters has been shown. The fabrication process is based on the possibility of self scrolling of highly strained InGaAs/GaAs heterolayers (being debonded from substrate) in a tube shaped scroll. It has been shown that the scrolled up layers get close together, thus forming perfectly bonded tube walls. The tube diameter D is determined by the bilayer thickness d and by the mismatch of lattice parameters $\frac{\Delta a}{a}$ (i.e., by the composition of the InGaAs solution used): $D = \frac{4}{3} \times \frac{d \times a}{\Delta a}$. The InGaAs/GaAs tubes with the tube diameter D as small as 3 nm and length over then 1 mm may be produced. Fabrication of highly ordered arrays of nanotubes was also rendered possible.

Here we introduce a nanofabrication technique, which is based on the use of self formed nanotubes as an etch mask for fabricating high-precision mesa-structures (for example, a bar or a wire of a lateral width determined by the tube diameter).

The following properties of the tubes are important for using them as masks:

1. Ultra-small sizes of the objects, which fall into the nanometer scale range and are highly reproducible.
2. Smooth and straight edges of the scrolled tubes.
3. Possibility of fixing the tubes at a preset place of the structure.
4. Hardness of the tubes to plasma etching.
5. Possibility of formation of tube arrays (using a multi-layered structure).
6. Possibility of successive transformation of sizes (step-by-step pass-over from micro to nanometer scale range along two coordinates using a multi-layered structure).

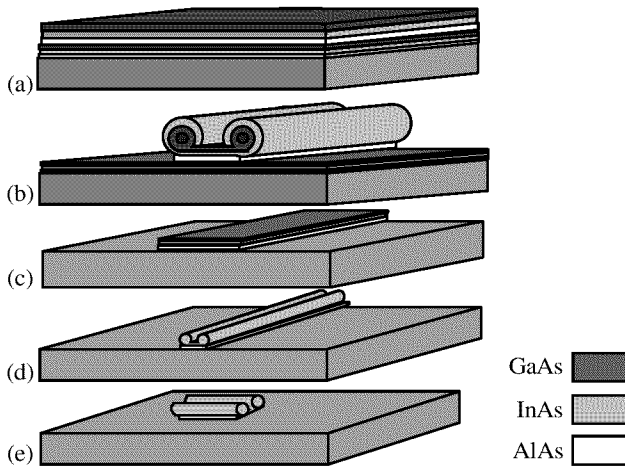


Fig. 1. (a) Initial structure involving thick and thin GaAs/InGaAs/AlAs layers grown on a GaAs substrate; (b) doubled tubes produced using selective wet etching of the thick AlAs layer; (c) mesa-structure produced by reactive ion etching and tube removing by selective etching of thick AlAs; (d) scrolling of the thin GaAs/InGaAs layer contained in the mesa-structure in a tube during AlAs thin layer selective wet etching; (e) the same as (d), with the exception that another direction of scrolling gives ring-shaped tubes.

Let us consider the characteristics of tubes in more detail on the example of formation of mesa-structure. Figure 1 exemplifies steps of transformation from micro- to nano-sizes of self-scrolling tubes. The result of this steps is nanotubes situated in designated place of substrate. This nanotubes were obtained by using wet etching and reactive ion etching only. The double tubes is used as a mask for patterning the underlying layers at reactive ion etching. The most important here is the possibility of etching the structure without causing damages to the tubes. This possibility stems from the following two points:

- the outer layer of the tubes is the InGaAs one. During reactive ion etching of GaAs with CCl_2F_2 — or $\text{SiCl}_4/\text{SF}_6$ -based etchers the tubes are not damaged because InGaAs/GaAs selectivity of etching is more than 1000 [4].
- In order to destroy the tube, it is required to etch through all the layers forming the multi-coil tube, while the total number of coils closing together can be as high as 40.

Another important point is the possibility of selective removal of AlAs layer by using HF acid etchant which does not attack GaAs and InGaAs layers [5]. It makes possible to obtain tubes, accomplish all technological operations and then remove it out.

It was shown that having a multilayer structure (Fig. 1(a)) containing of a few strained InGaAs/GaAs bilayers separated with sacrificial AlAs layers; one can first fabricate tubes from the upper layer (Fig. 1(b)), then, using them as a mask for reactive ion etching form a pattern on underlayer (Fig. 1(c)), and, finally, scroll up a tube from this layer (Fig. 1(d),(e)). It is possible to choose the proper direction of the scrolling process and fabricate either long tubes (Fig. 1(d)) or ring-shaped tubes (Fig. 1(e)).

We propose to use the self-formation process for successive scaling down of lithographic pattern. By way of example, let us consider a strip of width L formed lithographically from strained bilayer film. After having been freed from bonding with substrate, the strip scrolls

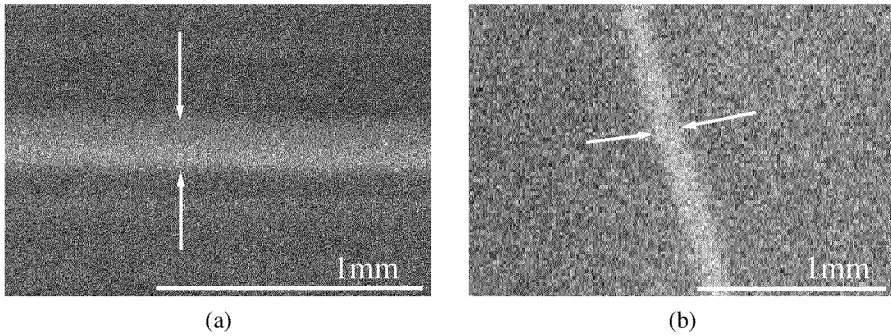


Fig. 2. (a) The electron microscope image of mesa-structure. The mesa-structure has 300 nm of width and 50 nm of height, (microscope electron beam was directed obliquely); (b) the electron microscope image of groove. The groove has 100 nm of width and 10 nm of depth.

up in a tube of diameter D . Since $L = D \times \pi \times n$, where n is the number of coils, the lateral size the planar structure clearly transforms in an “apparent” (for instance, for ion etching) size D . The scaling factor is $\pi \times n$. In our case, n might be as high as 40, which permitted reduction of the scale by a factor of 100. By successive repetition of the procedure, one can pass over from micro- to nanoscale range. For example, if we have a multi-layered structure containing a few strained bilayer films, which can be successively debonded from substrate, we can pass over from a strip of width L in the upper layer to a tube of diameter $L_1 = \frac{L}{\pi \times n}$ which will serve next as a mask for the formation of a strip of width L_2 in the underlying layer in order to subsequently transform the strip of width L in tube of diameter $L \ll L_1 \ll L_2$, and so on.

The experimental ion reactive etching was performed in a parallel plate capacitance plasma system at a 13.56 MHz frequency. High frequency power of 0.1 W/cm^2 density was supplied to the electrode where samples was situated. The second electrode was the chamber of the reactor. The reactive gases flowed through the chamber from its top uniformly in the time during the whole course of the etching, their pressure being maintained around 5 Pa.

Figure 2(a) shows the obtained GaAs mesa-structure. This mesa-structure was fabricated on the GaAs substrate using reactive ion etching in a $\text{CCl}_2\text{F}_2/\text{O}_2$ gas mixture and in other reactive gases. The tube lying on the GaAs substrate surface was used as a precise etch mask (this tube of 300 nm diameter was fabricated using a $\text{GaAs}(4\text{ML})/\text{In}_{0.4}\text{Ga}_{0.6}\text{As}(6\text{ML})$ bilayer). After the tube was removed from substrate, the mesa-structures became opened. This mesa-structure had a width 300 nm and a height 50 nm. The edges of the mesa-structure are straight and sharp.

Figure 2(b) shows the groove obtained on a GaAs substrate. The initial structure consisted of an upper $\text{GaAs}(2\text{ML})/\text{In}_{0.65}\text{Ga}_{0.35}\text{As}(2\text{ML})$ bilayer, an AlAs (10ML) sacrificial layer and a GaAs substrate. The scratch of width less than 50 nm was made on the surface of the structure and the HF-based etchant could penetrate to the AlAs layer through this scratch. A part of AlAs layer was only etched out because of little time of the etching. As a result, two tubes (20 nm in diameter) have been self-scrolled from that part of $\text{GaAs}(2\text{ML})/\text{In}_{0.65}\text{Ga}_{0.35}\text{As}(2\text{ML})$ bilayer which had not AlAs underneath. The tubes lied parallel to the scratch and the scratch was between the tubes. Afterwards, a “window” to the GaAs substrate was opened. Then some part of the substrate behind the “window”

was etched out using selective reactive ion etching of GaAs and the creating of groove was finished.

Authors have a circumstantial evidences that tubes of 8 nm in diameter may be used as masks too. In the future, the proposed techniques may be used in combination with the commercial solid-state technology.

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