Strain-induced Self-rolling Process
– Functional Semiconductor Micro and Nanotube Arrays

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1. **Description**: This process produces a new class of nanoscale building blocks based on III-V semiconductor tubes created by strain induced self-rolling mechanism from epitaxially grown heterojunction films that have been lithographically patterned and subsequent etching of an underlying sacrificial layer. Depending on the undercut extent, single or multi-wall tubes can be formed. Our research builds on this new nanotechnology paradigm.

Illustration of the strain-induced self-rolling mechanism of semiconductor nanotube formation using GaAs-In$_x$Ga$_{1-x}$As bilayer as an example. The strain in the bilayer generates momentum which drives the rolling action.

Array of GaAs-In$_{10.3}$Ga$_{0.7}$As nanotubes 50 microns (long) X 560 nm (diameter)


The formation approach involves epitaxial growth (bottom-up) which determines the composition and thickness (thus diameter) of the rolling component and lithographic processing (top-down) which controls the length, position and shape of the final structure. Also, if the
strain direction is reversed, when the compressively strained layer is placed on the top, the rolling direction goes downward.

These semiconductor nanotubes (SNT) can be transfer printed to another substrate with their alignment and integrity maintained, creating the potential of new 3-D nanoscale structures for heterogeneous integration.

These micro and nanotubes can be “functionalized” by epitaxially embedding active structures such as quantum wells, quantum dots, and 2D electron gas, as well incorporating polycrystalline and amorphous layers in the tube wall. Further, the basic fabrication concept of strained induced self-rolling, analogous to the Japanese paper folding micro-origami technique, can be used to produce arrays of MEMS/NEMS components based on the use of multiple strained layers sandwiched by sacrificial layers and step by step lithography patterning to sequentially release parts of the structure in desired directions.

2. Dimensional capabilities:
   a. Diameter: min. 3 nm (from monolayer thin films of InAs/GaAs) to several microns have been produced
   b. Length: SNTs as long as 2 mm have been produced but there is no fundamental limit
   c. Wall thickness: depends on misfit strain and thickness of layers

3. Geometric capabilities:
4. Geometric Forms: Tubes, spirals, helical structures and other 3-D structures
5. Materials: Process should apply to all material systems with the two essential components: strained film and sacrificial layer, including Si-Ge, III-V, II-VI semiconductors as well as composite materials with metals and polymers.
6. Speed: this is a parallel process that produces arrays of tubes at the same time. The rolling rate is highly depending on the concentration of the selective etching solution, but it is on the scale of seconds to minutes.
7. Uniqueness:
   1. Simple process can easily be scaled to whole wafers using existing micro-electronic processing technology to produce nearly perfect symmetrical, precisely positioned, cylindrical SNTs with wide range of controlled diameters, lengths and wall thicknesses.
   2. Structures not possible via other processes
   3. A variety of heterojunctions and discrete active structures, such as quantum well, quantum dots and nanowires, as well as chemical and biological layers can be grown and thus embedded in the tube wall for optically, electrically, and biologically active tubes.
4. Compared to conventional Si-based MEMS, the III-V based micro-origami fabrication method has the advantages of self-positioning precision, scalable structures and control of the shape of 3D structure with the atomic precision which is determined by layer thickness and built-in strain.

8. **Competition:** planar structure devices, Si-based MEMS/NEMS and metamaterials

9. **Limitations:**
   1. Finding etching solution for highly selective etching of the sacrificial layers.
   2. Tube diameter is determined by the layer thickness and misfit-strain. The layer thickness and misfit-strain should be designed within the range where the misfit dislocation is not generated.

10. **Demonstrated applications:** micro/nano syringe, micro-fluidic channel, micro/nano actuator, optically pumped microtube resonator and laser.

11. **Potential Applications:**
   1. Next generation of nanoelectronic and photonic devices, and handheld chem/bio sensors
   2. Building blocks for MEMS and NEMS devices
   3. Micro-injection tubes for chem/bio devices
   4. Micro-nozzles for ink-jet printing
   5. Etch mask for nanofabrication
   6. Magnetic conductors using ferromagnetic material filled coils
   7. X-ray waveguides
   8. Microfluidic devices

12. **Current Research Focus:**
   1. Better understanding of the thermal, optical and electrical transport properties of single and arrays of SNTs with and without functionalize tube walls
   2. Nanolasers
   3. Development of other strain-driven 3-D structures
   4. Improved yields during transfer printing

13. **Examples and additional information.**
   1. Fabrication of quantum well SNTs

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**38 nm thick**

GaAs Cap layer (5nm)
AlGaAs barrier layer (10nm)
GaAs QW (55nm)
AlGaAs barrier layer (10nm)
In0.53Ga0.47As strain layer (8nm)
Al0.5Ga0.5As Sacrificial layer (900 nm)
GaAs buffer (100nm)
GaAs sub.

*Z contrast image (JEOL 2200FS)*

GaAs QW SNT epitaxial structure, TEM and SEM images
14. Recent publications:


