Fabrication of Micro-Chain Mail by Simultaneous, Patterned Electrodeposition on a Plane and Multiple Cylinders**

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Herein we describe a method for forming complex three-dimensional (3D) microstructures by decomposing them into substructures to be patterned on separate substrates, then juxtaposing the patterned substrates, and joining the substructures to form the desired structures. The broad applicability of the method is demonstrated by the fabrication of micro-chain mail, the charm of the structure of which as a target has been noted by others.[1, 2]

We decomposed the chain mail (H) shown in Figure 1 into two sets of curves and lines: one set was patterned onto a plane, and the other set was patterned onto several cylinders. The patterns on these cylinders joined the patterns on the plane, such that two neighboring lines in the center of the pattern on the plane connected to two curves on two neighboring cylinders to form an oval. This oval linked with four other ovals. The partial ovals at the sides of the pattern on the plane were completed similarly. The collection of ovals—connected in this fashion—formed the chain mail.

To fabricate this chain mail, we formed the 2D pattern (Figure 1) in photore sist on a gold-coated glass slide by photolithography, and the remainder of the patterns on cylinders as features in silver by microcontact printing (μCP).[3] The patterns on the cylinders were aligned with those on the plane so that they formed the required template. Isotropic electrodeposition of nickel metal onto areas defined by this template produced the chain mail with links that were continuous and interconnected; the electrodeposition welded the substructures together.[4] Dissolving the substrates released the metal structure; the result was a free-standing, interlinked chain mail with a wire width of about 100 μm (Figure 2).

Forming patterns on separate substrates, and joining these patterns by electrodeposition, can form 3D microstructures with complex topologies and topographies. The smoothness of the connections between the components is determined by the design of these patterns, and by the way the substrates contact each other (here, the cylinders contacted the planar substrate tangentially and the connections are smooth). Microstructures having different topologies and topographies can be generated by using the same procedure: In general, we can make any 3D wire structure that can be laid down in a plane so that all wire crossings occur on vertical lines in the plane; the number of cylinders required equals the number of vertical lines through the crossings.[5]
Experimental Section

The masks for photolithography were produced with a rapid prototyping technique: we designed the patterns with a CAD program; the files containing these designs were sent to a commercial high-resolution printer (5010 dpi) and printed onto transparencies. By UV photolithography, we transferred patterns into negative photoresist (NANO XP SU-8, MicroChem Corp., Newton, MA) on silicon wafers for microcontact printing, and patterns into positive photoresist (Shipley 1813, Micro lithography Chemical Corporation, Newton, MA) on a glass slide coated with a thin layer of gold by ebeam evaporation. The surface of these patterned silicon wafers was made more hydrophobic by exposing them to a vapor of perfluoro-1,1,2,2-tetrahydrooctyltrichlorosilane (United Chemical Technologies, Inc., Bristol, PA) in a vacuum desiccator; poly(dimethylsiloxane) (PDMS) prepolymer (Sylgard 184, Dow Corning, Midland, MI) was cast against the silanized silicon wafers and cured at 60°C for about 3 h, and the elastomeric PDMS replica were peeled from the silicon wafers to be used for microcontact printing. We coated the glass slide with about 1.5 nm of titanium and about 15 nm of gold by ebeam evaporation; the capillaries were mounted on a stage that rotated about two orthogonal axes during the evaporation, and coated with about 50 nm of titanium and about 70 nm of silver. Subsequent wet chemical etching was accomplished by immersing the printed substrates in an aqueous ferri-ferrocyanide bath (0.001 M K₃[Fe(CN)₆], 0.01 M K₄[Fe(CN)₆], 0.1 M Na₂S₂O₃) for about 30 s to remove the underivatized silver. We aligned the patterns on the substrates manually under a microscope.

Received: December 18, 2000 [Z 16298]


Color-Tuned Electroluminescence from Columnar Liquid Crystalline Alkyl Arenecarboxylates**

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Columnar liquid crystals consisting of a polycyclic aromatic core surrounded by flexible side chains combine the good charge-transport properties of aromatic single crystals with the good film-forming properties of viscous liquids. Thus, thin films made of large well-aligned monocristalline domains can be obtained at room temperature after annealing the material in the liquid crystalline state at elevated temperature. The columns generally align perpendicular to the surface. Thus, the direction of maximum charge mobility, which is along the column axis due to the proximity of the aromatic cores of neighboring molecules, is normal to the plane of the film.

Such semiconducting materials may be used in light-emitting diodes, where an organic film or a stack of organic layers is confined between an anode with high work function (usually formed from transparent indium–tin oxide) and a cathode with low work function (for example, Al or Mg). In devices containing only a single organic layer, the fluorescent organic material needs to exhibit both sufficient hole and electron affinity to allow injection of charges of both signs into the organic layer. It is useful to prepare multilayer devices in order to efficiently confine the recombination of charges in such diodes.**

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[**] We are grateful to Nguyen Hau Tinh (Bordeaux), Joachim Wendorff and Jörg Koptitzke (Marburg), and Reinhold Oesterhaus (Paderborn) for their help and advice, and to Bayer AG for a sample of Baytron P.


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