# EFAB: Batch Production of Functional, Fully-Dense Metal Parts with Micron-Scale Features

Adam Cohen, Gang Zhang [1], Fan-Gang Tseng, Florian Mansfeld [1], Uri Frodis, Peter Will
USC/Information Sciences Institute, 4676 Admiralty Way, Marina del Rey, CA 90292

## Abstract

EFAB (Electrochemical FABrication) is a new SFF process with the potential to economically fabricate prototypes or mass production quantities of functional, mesoscale-microscale parts and mechanisms. EFAB generates an entire layer simultaneously—versus serially, as with most SFF. Based on electrodeposition, EFAB allows ultra-thin layers (2-10 microns, or even submicron) that minimize stairsteps, and generates a net-shape, fully-dense metal structure that can be homogeneous and isotropic. Minimum feature width is approximately 25 microns, and can be reduced further. EFAB can be used to manufacture micromachines and microelectromechanical systems (MEMS), offering significant advantages over current processes: e.g., true 3-D geometry, IC compatibility, low capital investment, and process automation.

## Background

Microfabrication. During the last decade, there has been extensive worldwide R&D in the field of micromachining/microfabrication. There is much interest in replacing macroscopic devices with micromachines and microelectromechanical systems (MEMS) to reduce size, weight, and cost while often increasing reliability and performance. There is also a desire to create devices offering entirely new capabilities not possible to implement macroscopically (e.g., surgical instruments, mechanical high-resolution displays).

Current microfabrication approaches generally fall into three categories [1]: Bulk micromachining removes material selectively from regions of a substrate (sacrificing precious chip "real estate" and producing very simple shapes); surface micromachining (Fig. 1) deposits thin structural layers and sacrificial layers onto a substrate using semiconductor-type processing; and LIGA generates 2.5-D "extrusions" (Fig. 1) by molding polymers in metal tooling electroplated into apertures in synchrotron-exposed photoresist. All these approaches produce simple geometries (e.g., 1-5 different cross sections), are not standardized or particularly generic (usually requiring a custom process for each new device), and require many manual steps (each using specialized equipment). Moreover, they usually do not permit integrated circuitry to be part of the device, involve large numbers of process variables (often requiring multiple iterations to perfect), are very costly (in facilities, capital equipment, labor, and materials), and involve long lead times.

As a manufacturing paradigm, Solid Freeform Fabrication can potentially overcome the shortcomings of current microfabrication approaches. SFF can offer arbitrary 3-D geometry; short lead times; fully-automated, unattended processing; a single, self-contained machine that produces a huge variety of products; device cost that is largely independent of complexity; high repeatability (few processing variables); and easy device design (few manufacturing constraints). Indeed, in the micro- and mesoscopic

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[1] University of Southern California, Department of Materials Science & Engineering

(between micro and macro) domain, where there are no existing generic fabrication technologies (such as milling and casting that we take for granted in the macroscopic world), many devices are made with great difficulty or not at all. Here SFF can go far beyond its usual role as a tool to increase speed and reduce cost, becoming instead a tool that makes possible for the first time the manufacture of a entire class of new products.

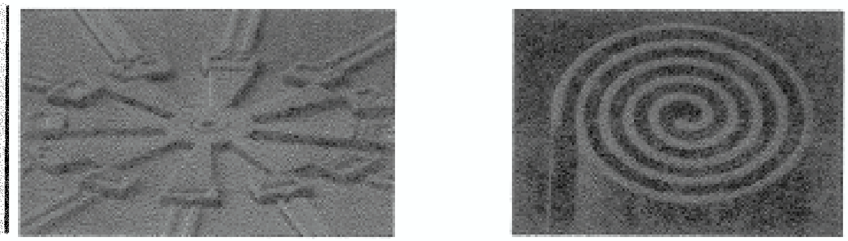

Fig. 1. Typical devices produced by surface micromachining (left) and LIGA (right).

Unfortunately, most SFF processes, intended as they are for producing macroscopic parts, normally cannot produce features less than 50-100 μm wide, or layers less than 50-150 μm thick. Moreover, virtually all SFF processes generate a layer serially (one volume element at a time), so are too slow and costly for quantity production. Nor do materials often allow functional use, due to intrinsic properties or porosity. Some processes are not net-shape, requiring support structures which must be explicitly designed and removed from each device. For example, microstereolithography [2], while succeeding in generating small features and layers, is limited in throughput, produces parts from photopolymer, and requires supports.

Electrodeposition for SFF. If an SFF process could be developed based on selective electrodeposition of material, it might be used for micro- and meso-fabrication, overcoming the limitations of existing microfabrication and SFF processes. Electrodeposition is a tremendously important manufacturing process used to finish metal parts (in the case of electroplating), and also to manufacture metal parts by depositing metal over molds (in the case of electroforming). Electrodeposition takes place in an electrochemical cell consisting of two electrodes, an anode and a cathode (i.e., workpiece or mold) and an electrolyte. Compared with the additive approaches used by most SFF processes, electrodeposition is fundamentally different. The material is "grain-less", deposited one atomic layer at a time (vs. particle-by-particle or drop-by-drop); and the solid produced can have desirable material properties, since it is fully-dense and relatively homogeneous and isotropic (e.g., inter-layer junctions can be avoided). Moreover, material may be deposited over an entire layer (e.g., hundreds or thousands of parts) simultaneously.

An earlier approach to SFF by electrodeposition, invented at MIT, arranged for deposition to occur preferentially in a localized region due to high current density near a sharpened anode that is moved in a 3-D path [3]. However, even using multiple anodes, this process seems too slow for mass production, is unable to easily create parts with overhangs (since it lacks a support material), and suffers from imprecisely-defined features. More conventional approaches to selective electrodeposition, apparently never attempted for use in SFF, are "brush plating", in which electrolyte is applied locally to a substrate; and "laser-enhanced plating", in which the plating rate is locally accelerated by heating. These processes too are essentially serial and therefore slow, and have difficulty producing very small, well-defined features.

The standard approach to high-precision selective electrodeposition—used in the manufacture of PC boards and read-write heads—is known as "through-mask plating". Through-mask plating can be used to deposit features 1 μm or smaller. With this method, the substrate is prepared, photoresist is applied, the resist is UV exposed and developed, the substrate is plated through apertures in the insulating resist, and the resist is finally stripped. This entire process involves a total of up to nine separate steps, the use of several different machines (often located in a cleanroom), and multiple liquids. Automation would lead to a machine of great complexity and high cost. Furthermore, total cycle time is large, so repeating these steps hundreds or thousands of times to fabricate a 3-D part would be impractical.

## Instant Masking

A new method of achieving selective electrodeposition is therefore necessary for a viable SFF process. We have devised such a method, which we call "Instant Masking". As with through-mask plating, Instant Masking uses photolithographically-patterned masks, and deposits material simultaneously over the entire layer (which may consist of a batch of discrete devices). Yet unlike through-mask plating, Instant Masking allows the photolithographic process to be performed completely *separate* from the part-building process, and allows *all* of the masks to be generated simultaneously *prior to* part generation, rather than *during* part generation (again and again for every layer). This separation also makes possible a simple, low-cost, automated, self-contained machine that builds devices, while the photolithographic steps can be handled in a traditional cleanroom (e.g., with masks provided by a service bureau).

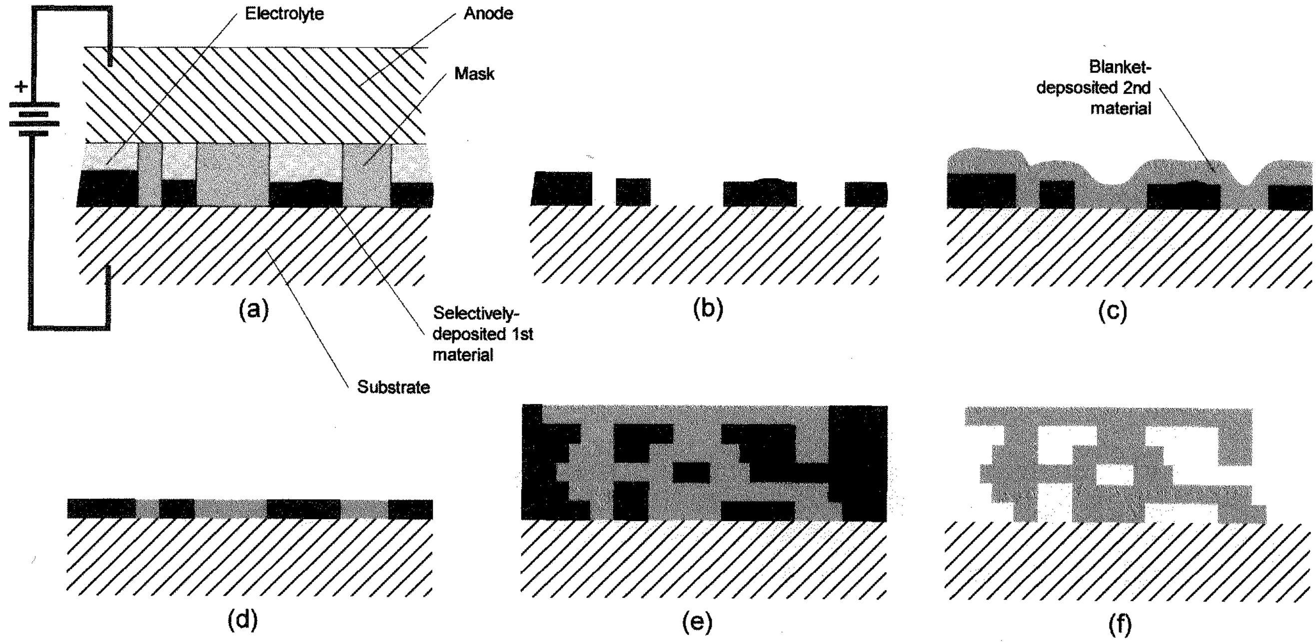

Fig. 2. Stages in the EFAB process.

Instant Masking selectively deposits material onto a substrate (or previous layer) by simply mating a patterned mask against the substrate, depositing material through apertures in the mask, and then un-mating the mask. Since the mask may be topologically complex (e.g., consist of isolated "islands" of masking material), it must be attached to a support structure, which in our current implementation is simply the anode of the electrodeposition cell. This configuration is shown in Fig. 2 (a).

## EFAB

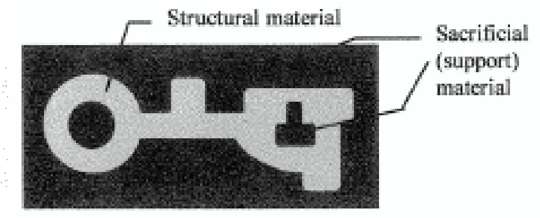

Fig. 3. Plan view of a layer in the EFAB process.

We call the new SFF process we are developing—based on selective electrodeposition using Instant Masking—EFAB (Electrochemical FABrication). A completed layer in EFAB consists of both structural and sacrificial material, as shown in Fig. 3. The block of sacrificial material in which EFAB-built devices are temporarily embedded serves the same purpose as sacrificial material used in SFF processes such as those of Cubital and Sanders Design: mechanical support of structural material. This eliminates most restrictions on device geometry, allowing the structural material on a layer to overhang—and even be disconnected from—that of the previous layer. Such geometrical freedom also makes possible monolithically-fabricated "assemblies" of discrete, interconnected parts (as with Cubital's Geneva mechanism demonstrated in the early '90s). This is a necessity for micro- and mesoscopic devices, for which actual assembly is generally not possible. Furthermore, the placement of the sacrificial material, and its ultimate removal in an automated, batch process, is not device-specific (avoiding the need for explicit support design).

In our current implementation, the process consists of the following steps, repeated on every layer: 1) selectively deposit first material; 2) blanket deposit second material; 3) lap. The process flow is shown in Fig. 2. In Fig. 2 (a), the first material is selectively deposited onto a substrate, producing the (incomplete) layer shown in Fig. 2 (b). In Fig. 2 (c), the second material has been blanket-deposited over this, contacting the substrate in those regions not plated with the first material. Then, as in Fig. 2 (d), the entire two-material layer has been lapped to achieve precise thickness and planarity. After repetition of this process for all layers, the structure shown in Fig. 2 (e) is etched to yield the desired device (Fig. 2 (f)).

While some implementations of EFAB could selectively deposit both structural and sacrificial materials using Instant Masking, we are currently employing lapping in the process for several reasons: 1) it allows the use of blanket deposition of one material, thus requiring only half the masks, and bypassing any alignment of these masks to those used for the other material; 2) neither material needs to be deposited with an extremely uniform thickness to achieve high accuracy and good masking; 3) layer thickness—and thus Z accuracy—can be precisely controlled.

All SFF processes require software to generate cross sectional layer geometry from 3-D CAD geometry. With EFAB, one or more high-resolution (e.g., +/- 1 μm) photomasks must be prepared which include the geometry of all the cross sections of the device. For now, we generate mask files using layout editor software; however, we are developing custom software which will import .STL files and export a 2-D photomask file in a format accepted by commercial photomask-making equipment.

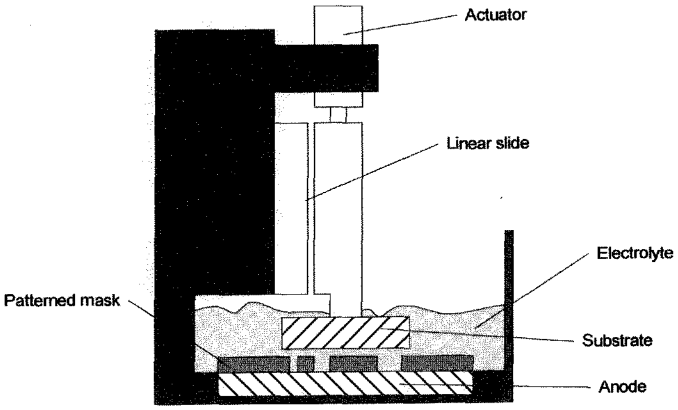

Fig. 4. Schematic of first-generation EFAB machine.

## Experimental

Materials. EFAB can be used to form structures from any electrodepositable metal, with the only constraint being that the accompanying sacrificial metal can be selectively removed (e.g., by chemical etching) after the layers are formed. Nickel and copper form a desirable material system, with copper as the sacrificial material, and it is this system that we have focused on thus far. Nickel has good strength, temperature, and corrosion resistance, and its magnetic properties are useful in electromagnetic devices. Meanwhile, copper can be selectively etched with respect to nickel. We employed commercially-available electrolytes (i.e., plating baths) such as acid copper, cyanide copper, pyrophosphate copper, Watts bath, and nickel sulfamate.

First-generation machine. We constructed the machine shown schematically in Fig. 4 to allow us to investigate the Instant Masking process. This machine uses an interchangeable copper anode, which forms the floor of a plating tank. The substrate, a nickel disk, is pressed against the mask from above using a linear slide and actuator.

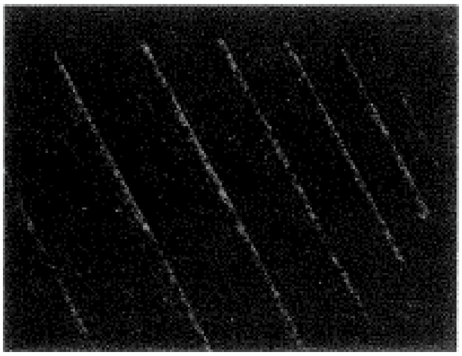

Fig. 5. Patterned mask on anode.

Mask. As shown in Fig. 5, the mask consists of a thin layer of material patterned with the desired features on a flat metal disk. This particular mask incorporates several resolution test patterns, in which the smallest bar is 12 μm wide and the largest is 200 μm wide.

Experiments were performed to determine suitable masking conditions with the goal of eliminating "flash" (extraneous deposits).

Second-generation machine. We constructed the machine shown schematically in Fig. 6, to allow fabrication of multi-layer, 3-D parts. The machine consists of several subsystems: the first includes a metal substrate onto which the layers are deposited, a linear slide to move the substrate up and down, an actuator, and an indicator to monitor lapping progress. Another subsystem includes a patterned anode (with multiple masks, one of which is shown in Fig. 7), precision X and Y stages, and a tank to contain the electrolyte. A third subsystem includes an anode and an electrolyte tank.

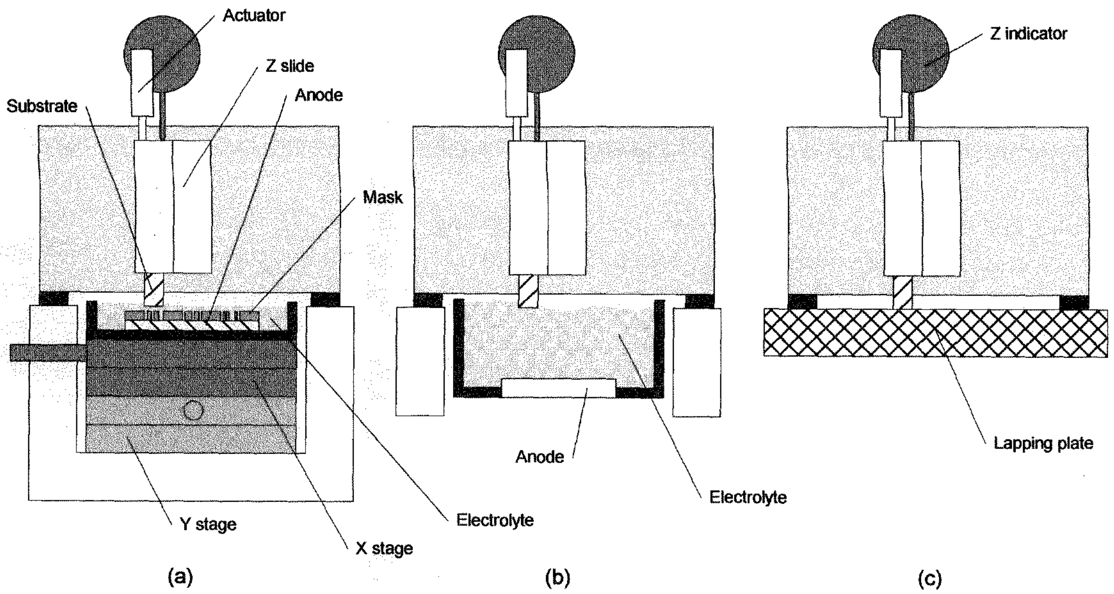

Fig. 6. Schematic of second-generation EFAB machine.

The steps required to make a part are as follows:

1. Lap the substrate to establish a reference/starting plane.
2. Position the anode to place the mask for the current layer below the substrate (Fig. 6(a)), then mate the substrate with the mask and selectively deposit several μm of the first material.
3. Deposit several μm of the second material over the first material (Fig. 6(b)).
4. Lap the deposited layer (Fig. 6(c)) until the final desired thickness is reached.
5. Repeat steps 2-4 for remaining layers of the part.
6. Immerse the deposited material in an etchant to remove the sacrificial material.

Cu etching. The ability to remove sacrificial material from narrow and long channels is a potential limitation on part geometry. We artificially created such geometry in advance of having EFAB'd test parts by embedding Cu wires of various diameters in epoxy with only their ends exposed, and immersing these in a commercial Cu etchant. We also immersed Ni wire in the etchant to see if there was any significant effect on Ni.

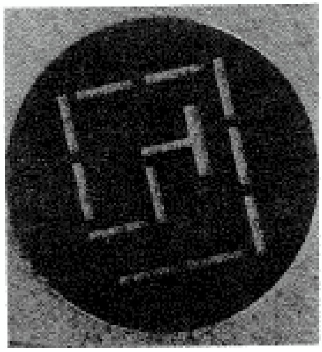

Fig. 7. Mask for selectively depositing sacrificial material on a part layer: the circle is 1.3 mm diameter.

## Results

Instant Masking. Using the first-generation machine, we were able to obtain excellent definition of the plated deposit: the edges of the deposit were sharp and there was virtually no flash. This is shown in Fig. 9 (traces of electrolyte remain on the substrate in this picture). Rectangular bars down to about 25 μm width were well defined, although 12-μm bars showed some definition problems.

Cu etching. We observed a reasonable etch rate of the epoxy-embedded Cu wires (200-300 μm/hr), and found that this varied little over a wire diameter range of 40-200 μm. No significant size change of the Ni wire was observed.

Other performance issues. We have not as yet evaluated layer thickness accuracy, mask registration accuracy, residual stress, or material properties (though we expect these to be similar to commercial electroformed Ni).

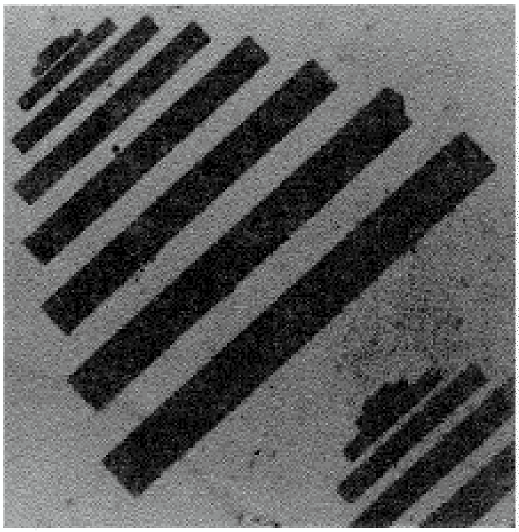

Fig. 8. Deposit produced using Instant Masking using first-generation machine and the mask shown in Fig. 5.

## EFAB applications

Broadly speaking, EFAB can be used to fabricate microscopic parts, microelectromechanical systems (MEMS), and mesoscopic parts and machines. There is a large and growing market for such devices in such industries as medical, automotive, electronics, and aerospace. Some application examples are:

- Micro- and mesoscopic mechanical machine parts, such as hinges, springs, screws, drive chains, and helical gears;
- Monolithically-manufactured systems such as motors, gearboxes, gas turbines, chemical processors, microsurgical and endoscopic instruments, optical scanners, motion sensors, compressors, pumps, cooling systems, solenoids, and valves;
- Micro- and mesoscopic electrical parts, such as on-chip inductors, transformers, low-loss RF transmission lines, and heat sinks; electronic packaging components, such as interconnects for multichip modules.

In our current program, we plan to use EFAB to produce a functional mesoscopic vibration sensor, shown as a CAD model in Fig. 9.

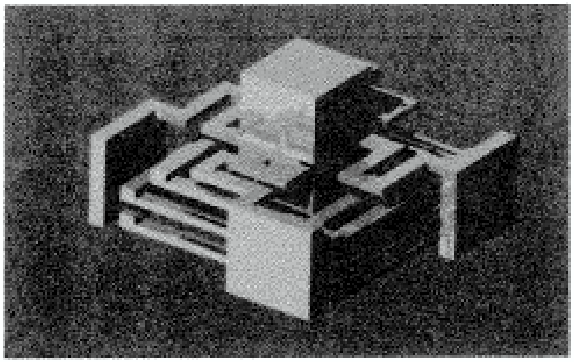

Fig. 9. Preliminary concept of a vibration sensor (overall size 1 x 1 x 0.5 mm)

## EFAB limitations

While well suited for small devices, electrodeposition is too slow (typically 25-100 μm/hr) a deposition process in most cases for the production of macroscopic devices (e.g., larger than 10 mm in height). Fig. 10 suggests a suitable size range for EFAB devices. Furthermore, there is difficulty using electrodeposition to deposit materials of low conductivity. Also, EFAB also requires part-specific tooling (photomasks), thereby adding to cost and not allowing device fabrication to begin instantly after CAD. Finally, device geometries will not be unlimited: removal of sacrificial material will impose some constraints.

## Conclusions

We are developing a new SFF process and machinery based on selective electrodeposition. We have demonstrated that we can selectively deposit features down to about 25 μm in width with good definition, and we are working to produce multi-layer parts. In developing this process, we hope to provide a capable, generic microfabrication process that will allow functional metal micro- and mesoscopic parts and complex systems to be prototyped and mass-produced by a fixed process that is cost-effective and speedy. We are beginning the development of the next generation machine, which will automate most of the procedures which now must be performed manually using the second-generation machine, and will build parts consisting of many layers unattended.

## Acknowledgements

DARPA/DSO, for primary funding under the Mesoscopic Machines Program (William Warren, Program Manager); Herbert Schorr and Ron Ohlander of ISI, for seed funding; Kan Lee and Victor Jordan of USC for parts fabrication; Jeannine DiCamillo of ISI for administrative support; Mark Messner and Myron Browning, for consulting; Tsung-Hsi Hsieh of USC, for lab assistance; Rebecca Jackman of Harvard and Winston Chan of U. Iowa for information on materials processing; Edward Goo of USC, for use of equipment.

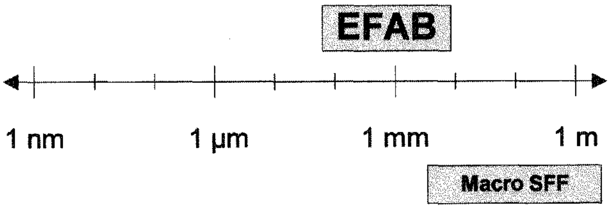

Fig. 10. Possible range of device sizes for EFAB vs. macroscopic SFF.

## References

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[2] See http://dmtwww.epfl.ch/~abertsch/index.html
[3] J. Madden and I. Hunter, Journal of Microelectromechanical Systems, vol. 5, no. 1, p. 26 (1996).