# A NOVEL FABRICATION METHOD FOR 3-D MICROSTRUCTURES USING SURFACE-ACTIVATED BONDING OF THIN FILMS


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## ABSTRACT

We propose a novel fabrication method for 3-D microstructures using surface-activated bonding (SAB) of thin films. This method is a kind of layer manufacturing technique for metallic or dielectric microstructures with an accuracy of sub-micrometers. In our method called FORMULA (Formation of μ-structures by lamination), all sliced patterns for microstructures are first formed on a donor substrate by photolithography, then they are transferred and laminated onto a target substrate using SAB. Because one transfer process requires only several minutes, the throughput of ten layers per hour is possible. Aluminum patterns were successfully transferred and laminated on the target substrate to construct various microstructures.


## INTRODUCTION

Recently, various fabrication technologies have been developed to obtain real 3-D microstructures. Laser microfabrication technology utilizing stereolithography of photopolymers has been considerably improved, especially its accuracy, by using two-photon-absorption [1]. In spite of the fine resolution and its low equipment demand, a structural material is restricted to a resin. Other promising technology is EFAB (Electrochemical Fabrication) [2], which can be used to fabricate metallic microstructures using a combination of instant masking, metal plating, and planarization. However, this method has room for improvement in the minimum feature size and the throughput of layers per hour.

We propose a novel fabrication method for 3-D microstructures using SAB [3] of thin films at room temperature. It is a kind of layer manufacturing method, as well as a structure-transfer method, and differs from other layer manufacturing methods by virtue of being a thin film process and from other structure-transfer methods [4] by virtue of using SAB. Furthermore, this method does not require an additional process for transfer: such as a releasing process of structures by sacrificial etching, formation of tethers that sustain released structures, or formation of bumps for bonding. In this paper, the principle of this new method, the prepared bonding equipment, and the first experimental results are described.

## PRINCIPLE OF FORMULA

The principle of FORMULA is shown in Figure 1. The process consists of photolithographic steps and the following lamination steps.

(I) A structural material is deposited on the donor substrate.

(II) All pieces of the sliced pattern for 3-D microstructure are photolithographically patterned.

(III) The donor substrate is loaded into the vacuum chamber and set opposite to the target substrate. Then the surfaces of both substrates are cleaned by irradiation of a fast atom beam (FAB).

(IV) After positioning of the substrates, they are mated and the first pattern is strongly bonded to the target substrate by SAB. This bonding process is performed at room temperature.

(V) On separation of the substrates, this pattern is transferred from the donor substrate onto the target substrate.

(VI) Steps (III) through (V) are repeated for multiple layers with layer-by-layer positioning. Finally, a 3-D microstructure is constructed on the target substrate as a laminated structure of stacked patterned thin films.

It is an essential that a low-adhesion layer is coated on the donor substrate prior to the deposition of thin film, in order to reduce the adhesion strength.

The LSI process easily enables an accurate size of slice patterns in the order of sub-micrometers. Alignment

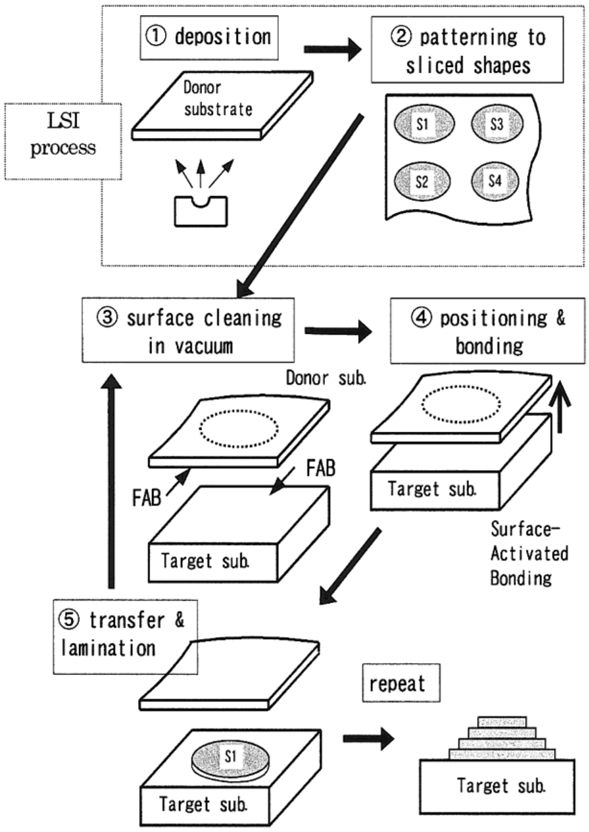


**Figure 1. Principle of FORMULA method**

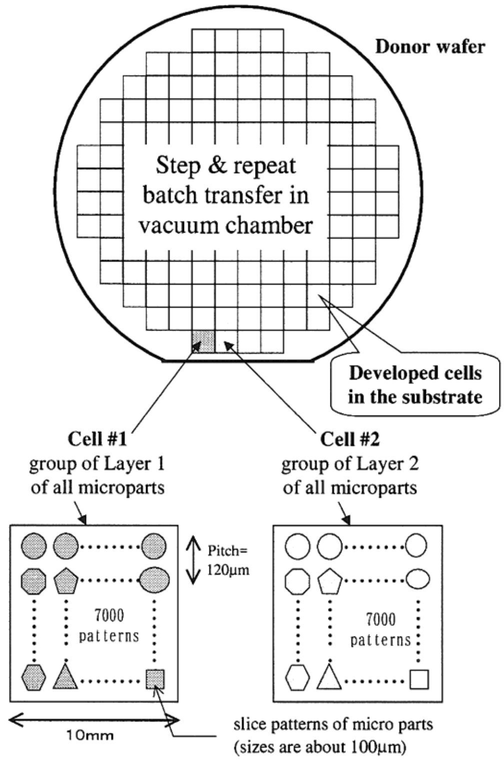


**Figure 2. Floor plan for batch fabrication of many microstructures**

accuracy between layers can also be obtained to better than sub-micrometer order using an accurate stage that is commonly applied in a stepper. Owing to spatially separating the locations of pattern formation and lamination, the formation of the upper layer does not damage the lower layer as in stereolithography. Although a new problem of gluing thin films arises in the lamination process, it is solved in SAB by bonding the films directly and strongly without thermal distortion or degradation of accuracy due to inserting an intermediate layer. Furthermore, FORMULA can be used to fabricate microstructures of any material that can be bonded by SAB.

Figure 2 shows an example of a floor plan for the batch fabrication of many microstructures using cell-by-cell transfer of sliced patterns. We define a "cell" which includes all sliced patterns in one layer separated from all other sliced patterns of many microstructures. The sliced patterns of all microstructures are allocated in the same manner in all cells, and the cells are developed two-dimensionally on the donor substrate. Then, all sliced patterns in a cell are bonded and transferred to the target substrate at the same time. This sequence resembles a step-and-repeat exposure process of a stepper in a conventional LSI process. In the example shown in Figure 2, thousands of multilayered (>100) microstructures can be fabricated at the same time. Note that all sliced patterns can be prepared in the only one photolithographic process and the lamination can be consecutively carried out in the chamber.

This process is suitable essentially for wafer-to-wafer transfers but mainly cell-level transfers are first considered for initial process development.

## EXPERIMENTAL

FORMULA is verified experimentally by demonstrating the batch transfer of thin film patterns by SAB and lamination of these patterns onto the target substrate. Because SAB has been applied to bulk materials such as Si wafers [5] up to now, there is concern as to whether or not thin film can be bonded by this method and transferred to another substrate without any damage. It is also of concerned whether or not repeating this transfer process can form a microstructure.

Figure 3 shows the experimental specimens. The donor substrate is an n-type Si wafer and initially spin-coated by commercial polyimide. This layer is important in this technology to control the adhesion strength of thin film patterns. A 0.5μm-thick pure aluminum film is deposited on this substrate by DC sputtering at room temperature. This film is wet-etched using photomask A or B. Photomask A is a

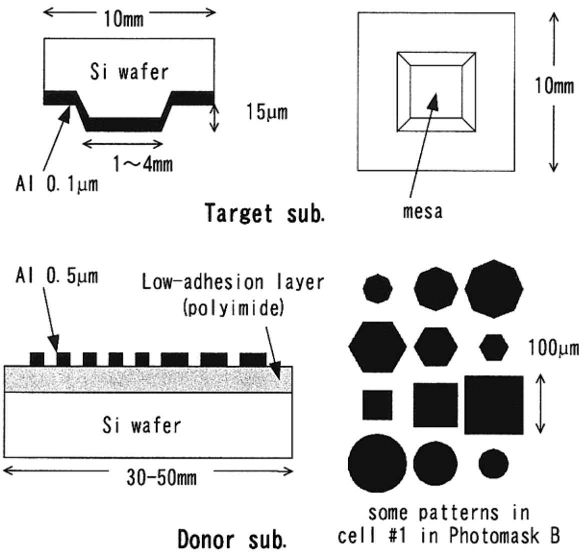


**Figure 3. Specimens**

simple pattern consisting of four kinds of arrays of square patterns. Photomask B realizes batch fabrication of the microstructures shown in Figure 2. This includes cylinders, cones, pyramids, and other geometry. The target substrate is an n-type (100) Si wafer which has a mesa-like structure to avoid the influence of the dicing edge [5]. The structure is prepared by photolithography and KOH anisotropic etching using thermal oxide as an etching mask. This substrate is coated with 0.1μm-thick aluminum to achieve Al-to-Al direct bonding. These specimens are cut before the bonding process because of the restriction of the bonding apparatus described below.

Figure 4 shows a schematic view of the bonding equipment. This consists of an electrically controlled lower stage with high-resolution (50nm) encoders, a manually driven upper stage, two FAB sources, and a high-vacuum system. The lower stage comprises piezoelectric-driven x-y-θ stages that have the maximum motion range of 25mm and an electrostatic chuck to attach a donor substrate. A target substrate is glued to the upper stage via an adapter.

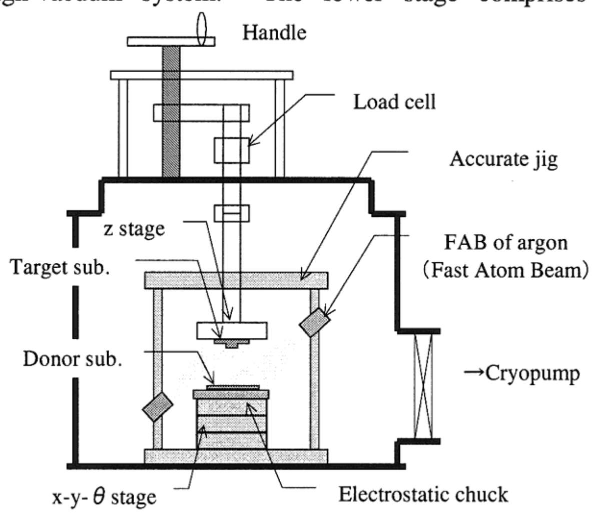


**Figure 4. Schematic view of bonding equipment**

The lamination sequence is described in Figure 5. After the substrates are set on the stages, a microscope is installed in the chamber. While viewing the donor substrate, the θ-stage is adjusted to the position where the direction of the cell array is exactly the same as that of x-y stages. Then cell #1 of the donor substrate is aligned just below the mesa on the target substrate using x-y stages. The chamber is evacuated after the microscope is removed. The backpressure is not as good as that in the ultrahigh-vacuum system, which is used in the literature [5]. For surface cleaning of the specimens by FAB, approximately 0.1 Pa of argon gas is introduced into the chamber. The beam incident angle is 45°, and applied voltage is between 1 and 2kV. Immediately (<30sec) after surface cleaning, the upper stage is driven down to mate the substrates, resulting in SAB of thin film patterns on the donor substrate and the mesa on the target substrate. Then, the upper stage is raised, and thin film patterns are transferred onto the mesa. After the transfer, x-y stages move in increments of the cell pitch that is defined in the floor plan. It is noted that there is no face-to-face alignment between layers in this lamination process. The transfer process is repeated for multilayers.

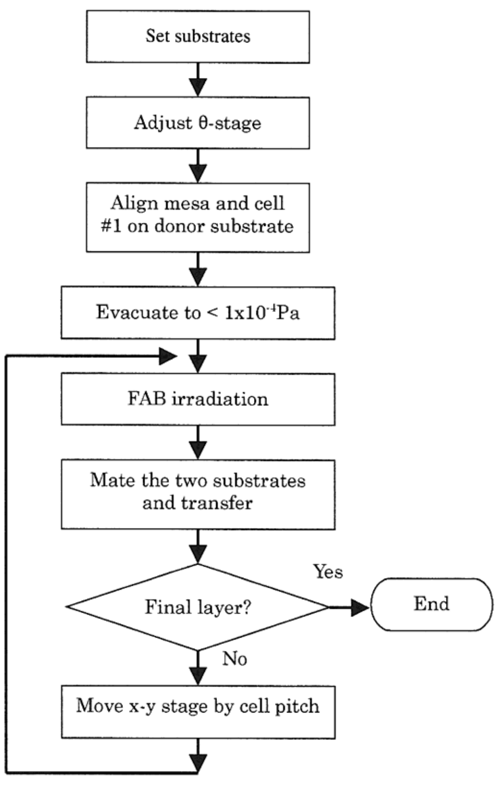


**Figure 5. Flowchart of lamination process**

## RESULTS AND DISCUSSION

### Single-layer transfer

Figure 6 shows a single-layer transfer process of thin film patterns. Al film is patterned into thousands of 8x8μm squares using photomask A. The etching depth of Al film with 10min of FAB irradiation is about 8nm under the condition of 1.5kV applied voltage and 15mA plasma current. The bonding load is $30kg/mm^2$ and holding time is 10min. Batch transfer of 3,600 Al patterns onto a 1x1mm square mesa is successfully demonstrated. There is no observable mistransfer or torn pattern in the mesa area. Thickness remains the same before and after transfer, as long as measured by Alpha-Step ®. Although the thickness of the thin film is set at 0.5μm in this experiment, it can be arbitrarily determined in the film deposition step in the range of 0.1μm to a few micrometers.

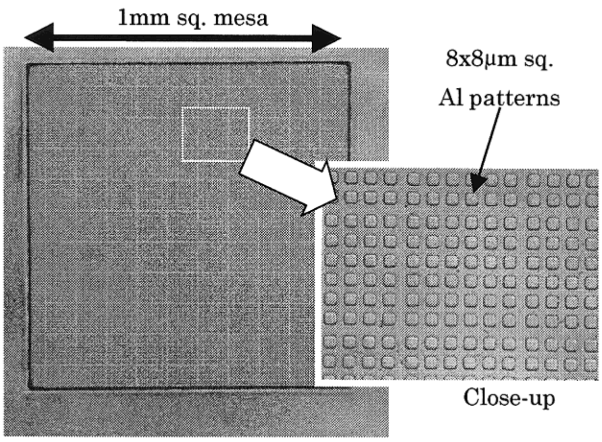


**Figure 6. Micrograph of transferred patterns**

The bonding strength of the transferred Al pattern has been measured preliminarily using a simple microscratch tester. We found that the strength was the same as the adhesion strength of sputtered aluminum on the glass substrate which is assumed to be in the order of $10^7$Pa. It was also confirmed that the transferred patterns can endure the Ni electroplating process and a reversal mold can be obtained.

### Multilevel lamination

Figure 7 shows a multilayer lamination of thin film patterns. Al film is patterned by photomask B, which includes 58 types of microstructures in a 1x1mm square. Each microstructure is sliced into 25 layers, and a cell corresponding to each layer is allocated in a 2-D array at a 1mm pitch. The transfer and lamination process is repeated nine times. The bonding conditions are 5min of FAB irradiation and 5min of holding. These times can be shortened to less than 5min by increasing the plasma current and minimizing the holding time.

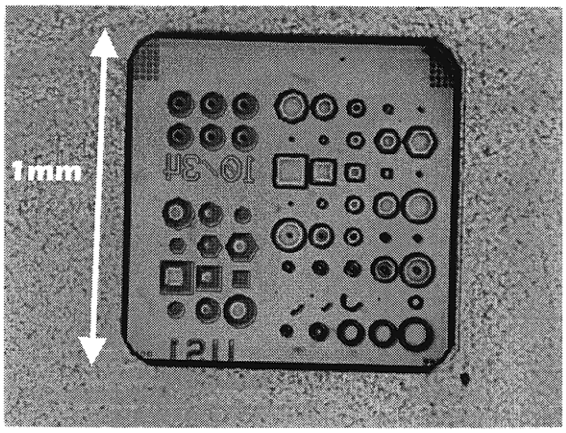


**Figure 7. Micrograph of nine-layered structures**

Figure 8 is a SEM micrograph of truncated octagonal pyramids. The diameters of the base are 100, 75, and 50μm from forefront to back respectively. These structures are designed so that the upper layer is smaller in radius by 3μm than the lower layer. Figure 9 is an AFM image of the structure. It is clear that thin film patterns are transferred and laminated to form 3-D

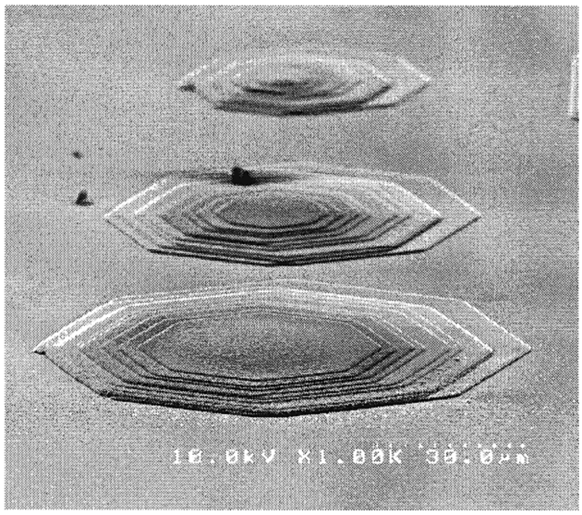

**Figure 8. SEM micrograph of truncated octagonal pyramids**

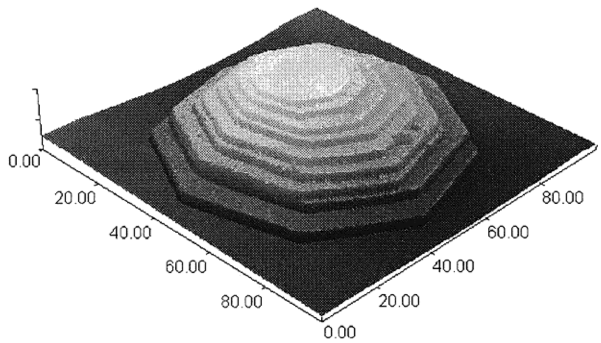


**Figure 9. AFM image of truncated octagonal pyramid**

microstructures. However, a slight misalignment of about 3μm between layers is observed. This is due to vibration of the equipment and insufficient lateral stiffness of the z stage. We believe this misalignment can be reduced to less than 1μm by isolating the chamber from the pump and by changing the z stage to a very stiff linear motion stage, even if there is no face-to-face alignment system.

**Surface roughness**

Figure 10 shows the surface roughness of Al patterns before and after the transfer. The average roughness (Ra) is calculated from the AFM linear profile data. Surface roughness reflects the grain of aluminum which depends on the deposition conditions. We have found that surface roughness is considerably improved after the transfer. This is because the side facing "up" after the transfer was originally formed on polyimide which has a very smooth surface owing to spin coating. The transfer process in our method is just like peeling from the low-adhesion layer, so there is no damage on the released structure due, for example, to sacrificial etching in other transfer methods [4]. When this structure is used especially in optical applications, this improvement of surface roughness is advantageous because the surface has low scattering loss.

Although the Al pattern with rough surface of Ra>10nm was transferred in this experiment, the surface of the thin film pattern should preferably be smooth, since it has been reported that surface roughness of bonding interface is important in SAB for strong bonding [6]. The optimization of the deposition or CMP (Chemical Mechanical Polishing) after deposition is considered a good approach to obtain a smooth surface.

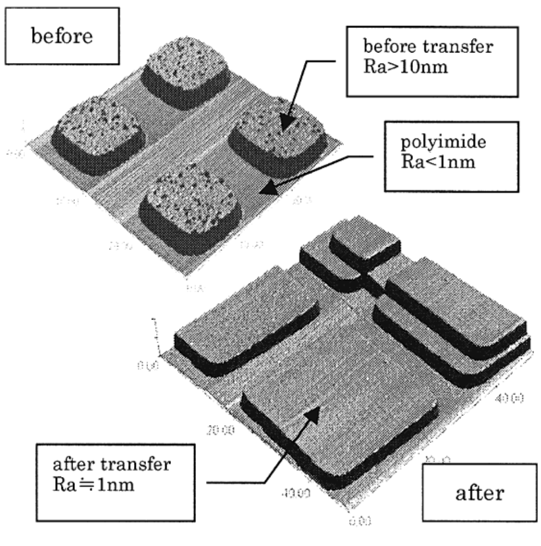


**Figure 10. AFM images of Al patterns before and after transfer**

## APPLICATIONS

Using FORMULA technology, batch fabrication of 3-D microstructures such as gears and fluidic parts can be realized. This technology can be applied to various materials that can be patterned by photolithography and bonded by SAB, such as Si, $SiO_2$, Pt and $LiNbO_3$ [7] as well as Al. Multilevel diffractive optics and a computer-generated hologram are also considered suitable applications. A multistep structure with sub-micrometer height can be fabricated easily because step height can be exactly set by the deposition of thin films.

Furthermore, Figure 11 (next page) shows an advanced idea of FORMULA in which a sacrificial layer is introduced around a structural layer. Both structural and sacrificial layers are transferred and stacked at the same time; finally, the sacrificial layers are selectively etched. The additional process to the principle in Figure 1 is the deposition of the sacrificial layer after patterning of the structural layer, and the following planarization process, such as CMP. This method has good productivity because it requires only one photolithography process including planarization and the cell-by-cell lamination process which takes several minutes per layer. This method is expected to enable the pre-assembled fabrication of complex microparts.

Finally, this method is considered to be convenient for fabricating 3-D photonic crystals [8], [9]. A defect in a lattice can be arbitrarily introduced by the advanced FORMULA method shown in figure 12. A wide variety of dielectric materials can be applied in view of the refractive index.

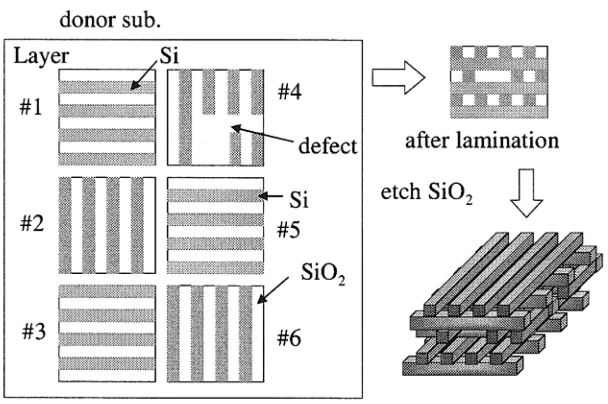


**Figure 12. Fabrication of photonic crystal**

## CONCLUSION

We proposed a novel fabrication method for 3-D microstructures using surface-activated bonding of thin films at room temperature. Batch transfer of aluminum thin film patterns by this method was realized. Batch fabrication of nine-layered various

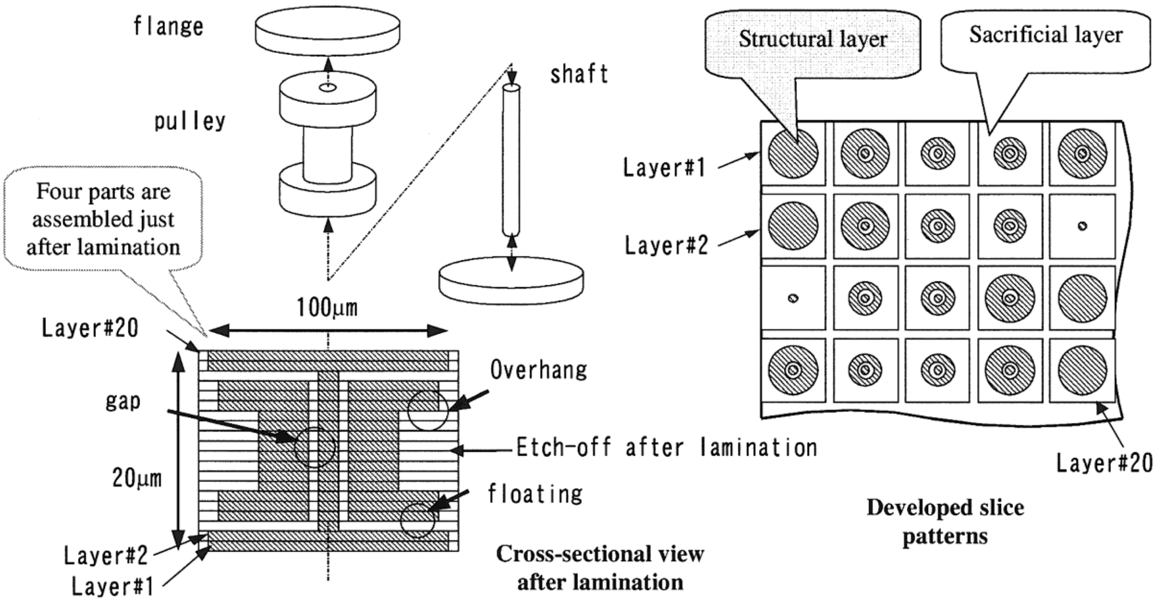


**Figure 11. Advanced FORMULA for pre-assembled fabrication of microparts**

microstructures was successfully demonstrated. This method is promising to fabricate complex microstructures using a variety of materials with the throughput of ten layers per hour.

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