A THERMAL ACTUATOR DESIGN USING TORSIONAL LOADING TO ACHIEVE OUT-OF-PLANE MOTION AND FORCE TRANSMISSION

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ABSTRACT

Thermal actuation is a regularity in MEMS devices, however much of the progress has been in demonstrating planar motion. This paper derives a mechanical way to achieve out-of-plane deflections using simple mechanical beams and basic thermal expansion techniques. Tip deflections were optimized over a range of voltages and varying actuator base geometry. By uniformly directing four torque-bars, possible deflections of 9 μm were calculated without shear failure for a maximum voltage of 15 volts. At constant voltage, deflections decreased to half of maximum for a base thickness of 10 μm. The force transmitted at the deflecting lever arms tip was calculated in the milli-Newton range.

1. INTRODUCTION

Thermal actuators have been used in a wide range of applications such as in microrelays, sensors, assembly systems, optical positioning and switching devices, and grippers [1-7]. The sensitive loading capacity, strength, and traveling range of microactuators has limited out-of-plane actuation growth [1]. Failure to observe key principles in MEMS, the understanding of material mechanics and electrical/thermal properties, has caused several MEMS devices to fail due to insufficient collaboration between mechanical and electrical engineers. Designs usually fall short of meeting both electrical and mechanical functional requirements, and thus, efficient out-of-plane actuators have not become readily available.

MEMS devices can easily become out-of-plane actuators by taking advantage of basic principles of material mechanics. Much is already understood about stresses, bending, and torsion, and so planar actuators can easily actuate out-of-plane without external assistance, but by exploiting thermal expansion forces [2,3,5], to induce twisting motions. By concentrating stresses to pinpointed locations, an engineer can manipulate actuator arrays to deflect in any specified direction. The most prominent factors in limiting the feasibility and performance of these actuators are their geometrical design and physical properties [3,6,7].

Designs of previous thermal actuators achieved actuation by bending and buckling of structures [2,4,6,7,8]. Micron deflections can be achieved by utilizing variable beam cross sections, which concentrate current densities to induce resistance (Joule) heating [6,7]. Coupling multiple actuators in parallel to form arrays can more than double actuator displacement. Bimorph actuators observe slightly larger displacements in maximizing effects due to different thermal coefficients of expansion (TCE) [3,5,9,10]. In-plane and out-of-plane bimorph thermal actuators of single-crystal-silicon and aluminum have been demonstrated to rotate out-of-plane, under limited power input, but it was observed that continual increases in voltage decreased the total rotation angle [3]. Deflections have ranged from 0.5 to 16 μm out-of-plane depending highly on the geometric configuration of the actuator [5]. Residual stresses can also initially buckle actuators out-of-plane, however the precise controllability and exact positioning out-of-plane of the actuator poses a problem [10]. Torsional actuation out-of-plane has been developed using electrostatic comb drives resulting in micron deflections [1,4,8], though a maximum angle of twist of 20-degrees was observed before shear failure under a load of 25 volts [4].

The proposals goal was to develop test structures that achieved larger deflections, angles of twist, and transmitted forces than previous designs, particularly, to show that by guiding torques using thermal expansion, out-of-plane actuators are not limited by geometry and strength requirements.

2. PROPOSED ACTUATOR DESIGN

a) Design Process- To fabricate the polysilicon thermal actuator, a deep reactive ion etch (DRIE) bulk surface micromachining process will be used because high-aspect ratio needed for the various beams [9]. The simplicity of the multiple beam configuration is shown in **Figure 1**. The design does not have complex geometries and only consists of rectangular beams.

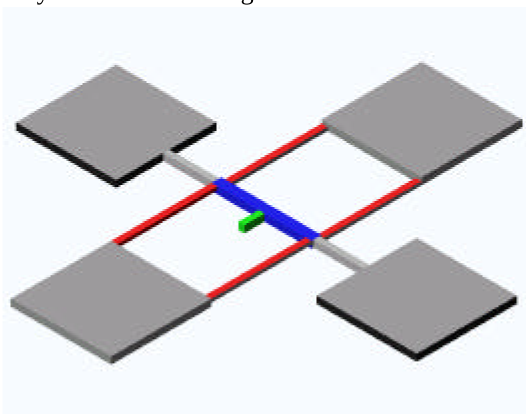

Figure 1. The proposed thermal actuator model. The four large squares represent anchors, the two grey beams are the support beams, the four red beams are the torque-bars, the blue element is the base, and the green bar is the deflecting lever arm.

Limitations of the design include actuator compactness and allowable shear stress between support beams and the base. Depending on necessity and intentions, the actuator can take form in many different ways. Thus, the designer can alternate and change parameters to better suit his needs. This overall size limitation is up to the discretion of the working engineer. However, the more prominent concern resides in the connection feasibility between the base and support beams. The torque-bars can provide sufficient forces to rotate out-of-plane, but at the same time the shear force induced could tear the support beams from the base. Undesired overetching could also result in failure just as easily. In this case, theoretically possible designs could fail due to the shear force exerted at the reduced contact area between the base and the support beams. To prevent such failures, dimensional factors of safety should be added to designs at the expense of limiting the maximum achievable deflection pattern.

b) Sample Calculations- Voltage applied to the torque-bars will stimulate resistance. Equating the electrical and thermal circuits, a temperature gradient is calculated.

$$\dot{Q}_{elec} = V^2 / R, \text{ where } R = rL_{torque} / A_{torque}$$

$$\dot{Q}_{cond} = kA_{torque} * \Delta T / L_{torque}$$

Where
V = 15 volts, the applied voltage
ρ = 1250 μΩ-m, the resistivity of silicon [13]
k= 150 W/m-K, the thermal conductivity of silicon [13]
ΔT = the temperature gradient
L_{torque}= 50 μm, the length of the toque-bar
A_{torque} = 16 μm^2, the cross sectional area of the torque-bar

$$\dot{Q}_{elec} = \dot{Q}_{cond} \Rightarrow \Delta T = V^2 / r * k = 1200K$$

Calculating the induced thermal torque of a single torque-bar,

$$T = F_{exp} L_{eff} = sA_{torque} L_{eff} = EeA_{torque} L_{eff}$$

Where

$e = g\Delta T = 2.76 * 10^{-3}$ = the thermal strain

for g = 2.3 μK-1, TCE silicon
E = 150 GPa, the Young's modulus of silicon
L_{eff} = 0.5 μm, the torque lever arm

$$\Rightarrow T = 3.3 \text{ nN-m}$$

The torque calculations use geometries representative of the torque-bars, while the polar moment of inertia calculated in the angle of twist equation below is that of the base and not the torque-bars. Using four torque bars, the total angle of twist, f, in radians [13],

$$f = \sum \frac{TL}{bJG} = 0.37 \text{, [21 degrees]}$$

Where
T = 3.3 nN-m, the torque of a single torque-bar
L = 150 μm, the half length of the base
b = 0.141, the torque shape coefficient
J = $6.25 * 10^{-22}$ m^4, the polar moment of inertia of the actuator base
G = 61.48 GPa, the shear modulus for the silicon
A deflecting lever arm of 25 μm results in an out-of-plane deflection of 9 μm. The maximum shear stress between the support beams and base can be found by the following relationship [13],

$$t = \sum \frac{T}{a(J/b)} = 0.51 \text{GPa}$$

Where
α = 0.208, the shear shape coefficient
b = 5 μm, the base thickness
It should be noted that throughout the simulation the base width and thickness were equal magnitude.

The total transmitted force at the tip of the actuators deflecting lever arm, thus is

$$F_{trans} = (\sum T / L_{lever}) \cos f = 490 mN$$

3. TEST STRUCTURES

Shown in **Figure 1**, the polysilicon actuators positions four torque-bars at the edges of the base, two being flush with the bottom surface and two flush to the top surface. Alternative connection designs of the torque-bars utilizing larger L_{eff} values would provide larger torques, resulting in a direct increase in the angle of twist, though for simplicity this model was considered. The support beams were designed to have a thickness equal to the base, however a width of only two-thirds to allow easier twisting, while still providing ample support. The torque provided by the actuator can be altered by two other methods as well: by simply adding more torque-bars to the design or by applying a pre-etch doping step to increase the actuators sensitivity to thermal gradients. To ensure a uniform doping profile, high temperature diffusion in situ (during deposition) would be used to add more charge carriers [11]. Careful consideration must be taken when doping and applying high voltages to the torque-bars to prevent plasticity and even liquidification. Increasing the length of the deflecting lever arm, while preserving the angle of twist, f, would further increase deflections, however the transmitted perpendicular force would decrease.

Multiple test structures were examined for varying base thicknesses and widths, over a range of voltage inputs to examine the overall effects and trends using MATLAB.

5. PREDICTED RESULTS

The following graphs describe the overall trends in out-of-plane deflection, angle of twist, the maximum shear stress incident to the support beam and base, and the total transmitted force.

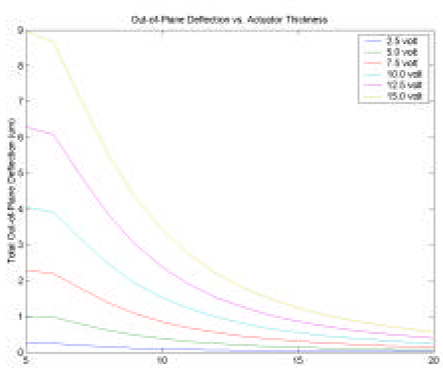

Figure 2. Out-of-plane deflections for varying base thickness and input voltage.

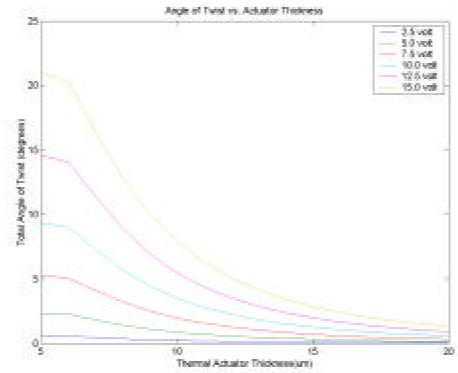

Figure 3. Angles of twist for varying base thickness and input voltage.

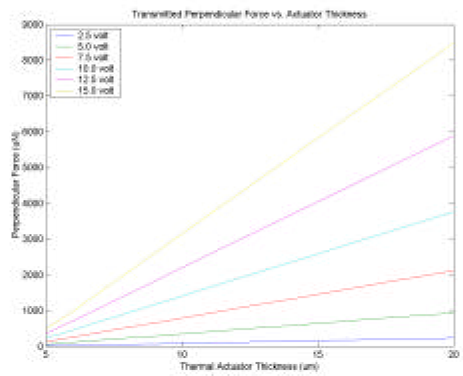

Figure 4. The transmitted perpendicular force for varying base thickness and input voltage.

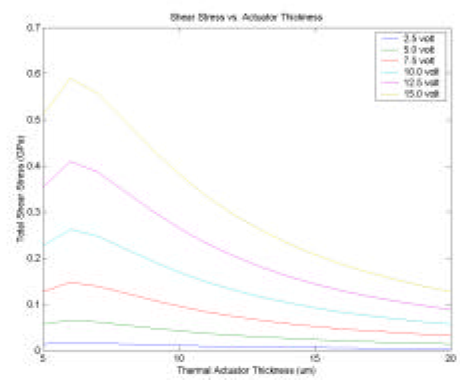

Figure 5. The total maximum shear stress for varying base thickness and input voltage.

6. DISCUSSION AND CONCLUSIONS

The plots of the out-of-plane deflection and angle of twist, shown in **Figures 2** and **3**, are represented as inverse logarithmic function of base thickness. These graphs indicate, for a constant voltage, deflections reduce to under half of its maximum when a thickness of 10 µm is reached. Therefore, to preserve total deflections, it is best to keep the width of the base small, yet in doing so the total force transmitted is significantly minimized as seen in **Figure 4**. The actuators deflections also increases linearly with base length, and so longer beams could be beneficial, however, the possibility of buckling, failure by stiction, loss in overall strength and stiffness, and possible bowing could further reduce total transmitted force.

For minimal base thickness, the total shear stress exposed to the support beams increases, shown in **Figure 5**, and then dramatically decreases similar to the deflection and angle of twist curves. This phenomenon results from the competing components, L_{eff} and base thickness. The effective torque lever arm increases linearly and for small values this dominates over the base thickness that is proportional to the inverse third power. Once the maximum shear stress in the actuator was attained for 6 μm base thickness, the base thickness, then dominated L_{eff}.

This paper has reviewed a simple technique that achieves out-of-plane actuation with high transmittal force for applied voltages. Above all, in-plane thermal expansion laws can direct out-of-plane displacements and forces. The limiting factors of the design happens to be the shear stress at the attachment points of the support beams and the geometrical dimensions of the base design. Previous designs indicated that shearing occurs at 8.5 GPa [1], which for these structures was preserved.

8. ACNOWLEDGEMENTS

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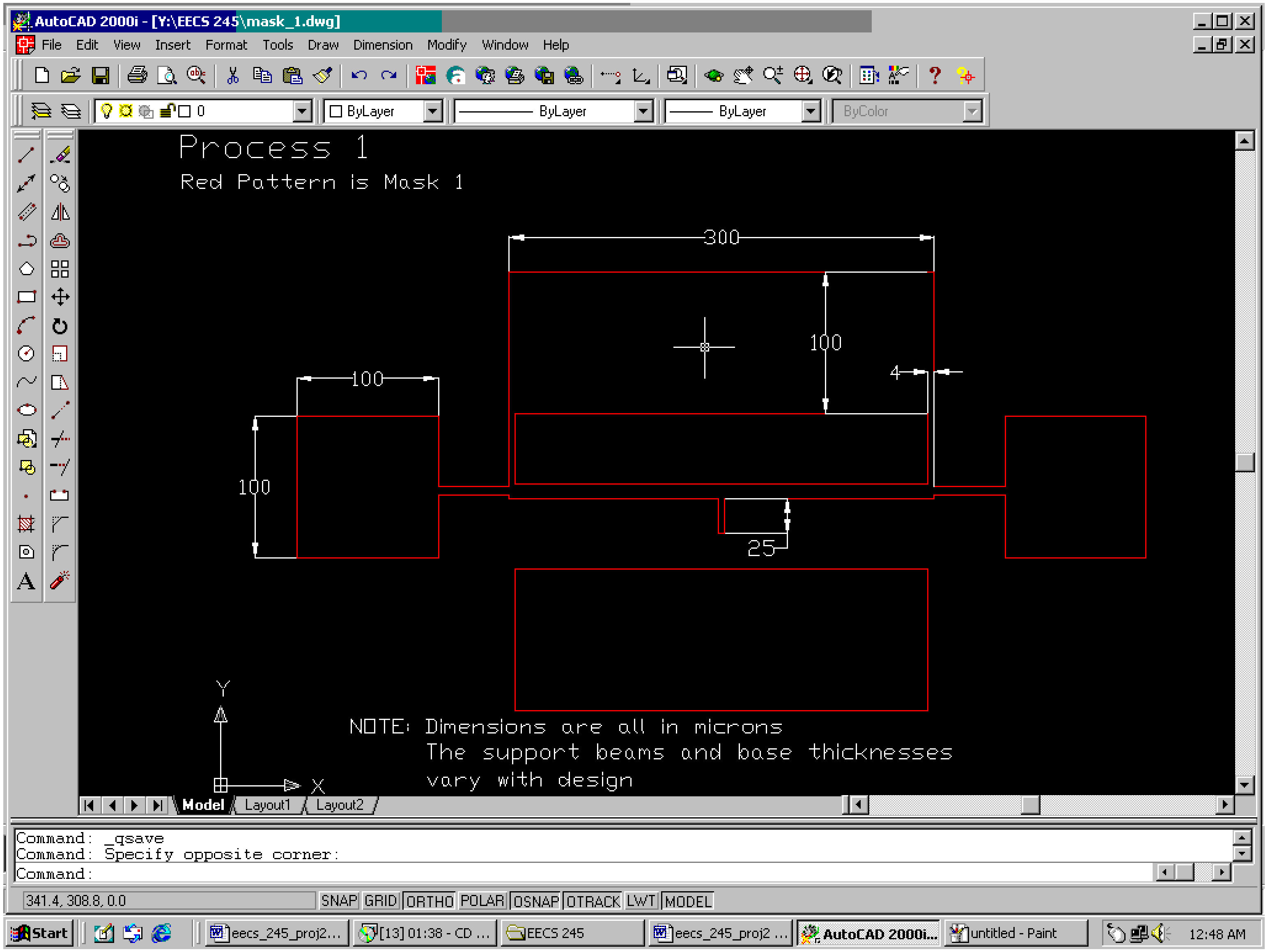
FINAL LAYOUT

LAYOUT DESCRIPITIONS THE THERMAL ACTUATOR USING TORSIONAL LOADING TO ACHIEVE OUT-OF-PLANE MOTION AND FORCE TRANSMISSION

To fabricate the polysilicon thermal actuator, a deep reactive ion etch (DRIE) bulk surface micromachining process will be used because high-aspect ratio needed for the various beams.

The fabrication process will be similar to the one presented by Yeh and Jiang [9]. To build the multiple test structures, the SOI wafer will initially will have a 10-20 μm thick silicon layer on top of a 1μm thick buried in oxide depending on the particular test structure to be fabricated. The majority of the etching will happen in the first etch step, under Process 1, as shown in mask descriptions on the following pages. Process 1 will etch entirely down to the oxide sacrificial layer. The general outline of the actuator is etched in this process and in Process 2 the two torque-bars attached to the lower end of the base are developed. This process will slowly etch the silicon layer so as to leave 4 μm layer above the oxide. This etch is critical to ensure the sufficient transmission of torque to the actuator. Process 3 will deposit the final layer of silicon to finalize the structure. However, due to the cavity where the two remaining torque-bars are to be positioned a sacrificial oxide deposition is necessary. Photoresist is used as the mask in all processes.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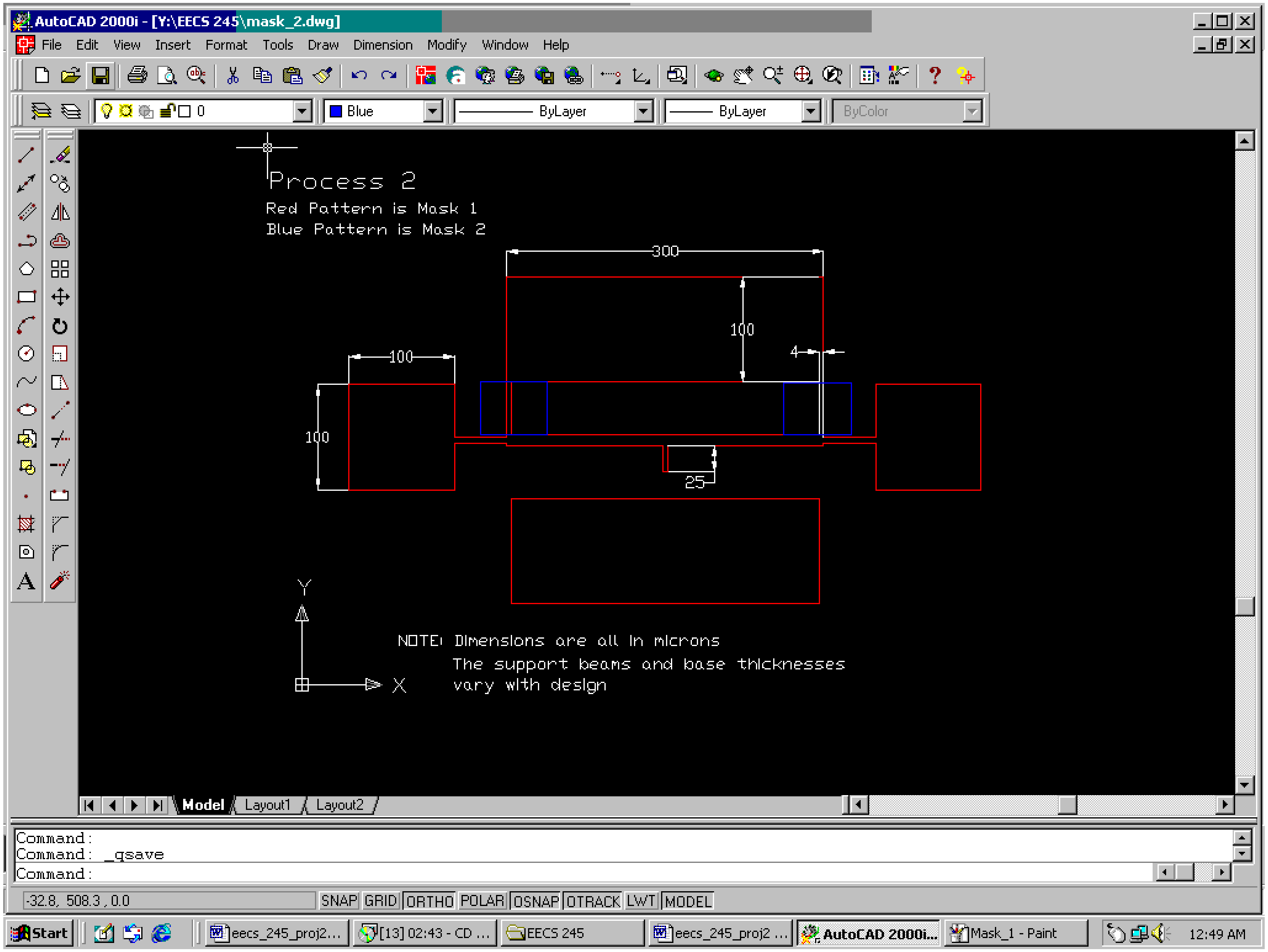
File Edit View Insert Format Tools Draw Dimension Modify Window Help
Process 1
Red Pattern is Mask 1
300
100
4
100
100
25
NOTE: Dimensions are all in microns
The support beams and base thicknesses
vary with design
Model
Layout1
Layout2
Command: _qsave
Command: Specify opposite corner:
Command:
341.4, 308.8, 0.0
SNAP GRID ORTHO POLAR OSNAP OTRACK LWT MODEL
Start
12:48 AM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Process 2
Red Pattern is Mask 1
Blue Pattern is Mask 2
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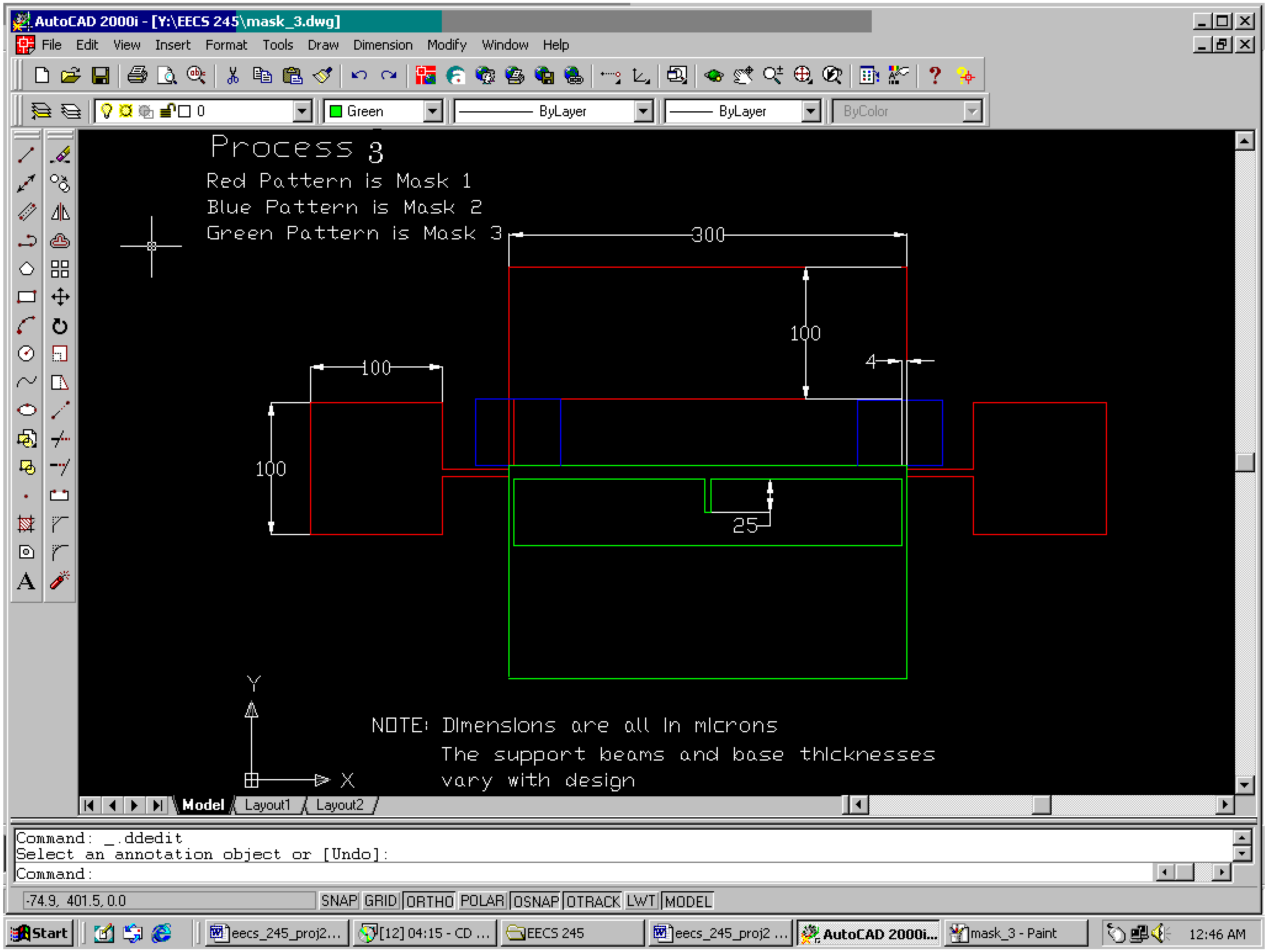
100
4
100
100
25
NOTE: Dimensions are all in microns
The support beams and base thicknesses
vary with design
Command :
Command : _qsave
Command :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File Edit View Insert Format Tools Draw Dimension Modify Window Help
Green
ByLayer
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Process 3
Red Pattern is Mask 1
Blue Pattern is Mask 2
Green Pattern is Mask 3
300
100
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100
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25
Y
X
NOTE: Dimensions are all in microns
The support beams and base thicknesses
vary with design
Model
Layout1
Layout2
Command: _.ddedit
Select an annotation object or [Undo]:
Command:
-74.9, 401.5, 0.0
SNAP GRID ORTHO POLAR OSNAP OTRACK LWT MODEL
Start
eecs_245_proj2...
[12] 04:15 - CD ...
EECS 245
eecs_245_proj2 ...
AutoCAD 2000i...
mask_3 - Paint
12:46 AM