6.777J/2.732J Design and Fabrication of Microelectromechanical Devices
Spring Term 2007

Solution to Problem Set 1 (12 pts)

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Problem 2.6 (4pts): Dynamics with Matlab and Simulink

(a) From the transfer function,

$$H(s) = \frac{Y_1(s)}{X(s)} = \frac{1}{s^2 + 2s + 4}$$

we have,

$$s^2 Y_1(s) + 2sY_1(s) + 4Y_1(s) = X(s)$$

Taking the inverse Laplace transform, the time domain expression becomes:

$$\ddot{y}_1(t) + 2\dot{y}_1(t) + 4y_1(t) = x(t),$$

with initial values $y_1(0) = \dot{y}_1(0) = 0$.

Defining the two state variables to be $y_1(t)$ and $y_2(t) = \dot{y}_1(t)$, we can write

$$\begin{cases} \dot{y}_1(t) = y_2 \\ \dot{y}_2(t) = -4y_1(t) - 2y_2(t) + x(t) \end{cases}$$

The system is subjected to a step input $x(t) = u(t)$, which can be expressed as:

$$u(t) = \begin{cases} 0 & x \le 0 \\ 1 & x > 0 \end{cases}$$

We can create an ode function called `fnc` as follows:

```
function dy = fnc(t,y)
dy = zeros (2,1)        % create a column vector of all zeros
                        % to define the [y1; y2] array
dy(1) = y(2) ;         % then define the state derivatives
dy(2) = -4*y(1) - 2*y(2) + 1;
```

Matlab command ode45 can be used to integrate these equations for a time interval of 10 seconds:

```
[T,Y] = ode45(@fnc,[0 10],[0 0]);
```

Figure 1 shows the system response of $y_1(t)$, which corresponds to an underdamped 2nd-order system (overshoot, oscillation, etc..). Alternatively, we can integrate using ode23. The difference between ode23 and ode45 is the algorithm: ode23 uses a lower order algorithm and is more efficient for a coarse estimate. In this simple case, there is not much difference using either algorithm. But whenever you use numerical methods, it is wise to choose the integration parameters (tolerance, for example) to ensure an accurate representation of the system and a practically acceptable computation time.

The full MATLAB script for the problem is posted at the end of the solution. Note that the program fnc.m (which defines the function fnc) and the program p2_6a.m must be in the same directory when p2_6a.m is called.

(b) Using tf object

H=tf(1,[1 2 4])

we create the transfer function corresponding to $\frac{1}{s^2+2s+4}$, by including the coefficients of the powers of s, as arrays in descending order (of the powers), for the numerator and denominator respectively.

Then we use the MATLAB commands

step(H)
bode(H)

to plot the step response of the above transfer function and its Bode plot. The step response is the same as Figure 1; the bode plot is shown in Figure 2.

(c) Using SIMULINK

The system can also be represented using a Simulink block diagram as shown in Figure 3 (here using the transfer function formulation). The resulting plot is again similar to that in Figure 1.

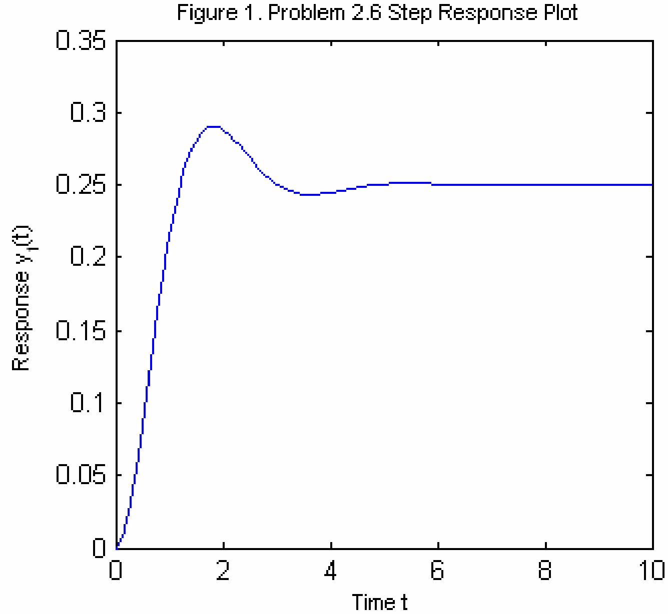


Figure 1. Problem 2.6 Step Response Plot

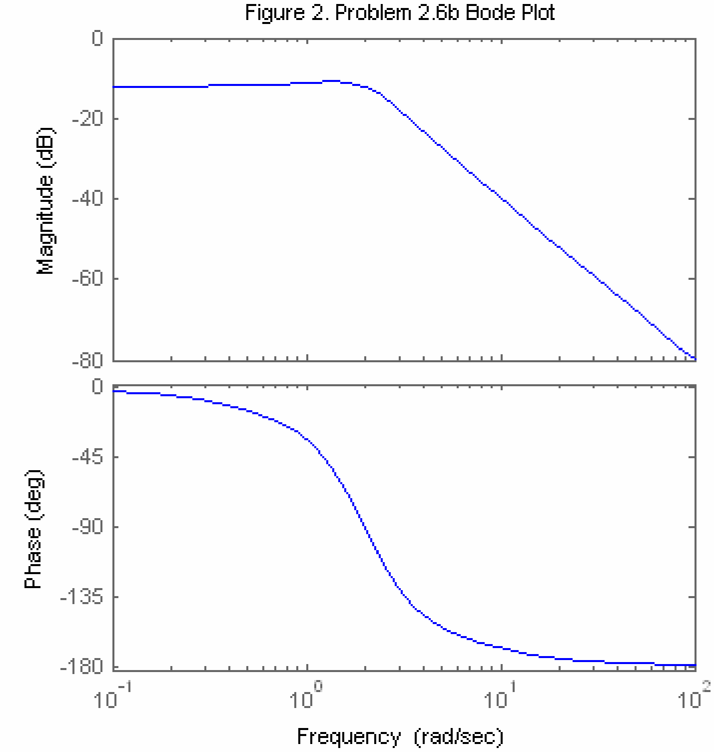
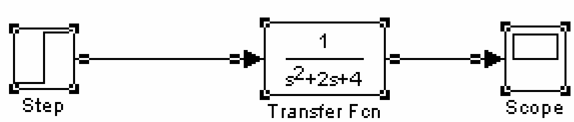


Figure 2. Problem 2.6b Bode Plot

Figure 3. Simulink model for Problem 2.6c



Problem 3.8 (2 pts): KOH etched diaphragm

Figure 4 shows the desired diaphragm features on a (100) silicon wafer. The mask feature size a can be expressed as a function of wafer thickness t_w, diaphragm thickness t_d, diaphragm dimension d and the intersection angle θ between {111} and {100} planes:

$$a = d + 2(t_w - t_d)\cot\theta \tag{1}$$

Substituting the numbers, we get $a = 1079.7\mu m$.

If the pattern is misaligned by $\theta = 1°$, the actual size of the KOH pit will be $a(\cos\theta + \sin\theta)$ and hence the edge length variation will be

$$\Delta a = a(\cos\theta + \sin\theta - 1) = 18.7\ \mu m \tag{2}$$

This in turn translates to the edge-length variation for the diaphragm Δd.

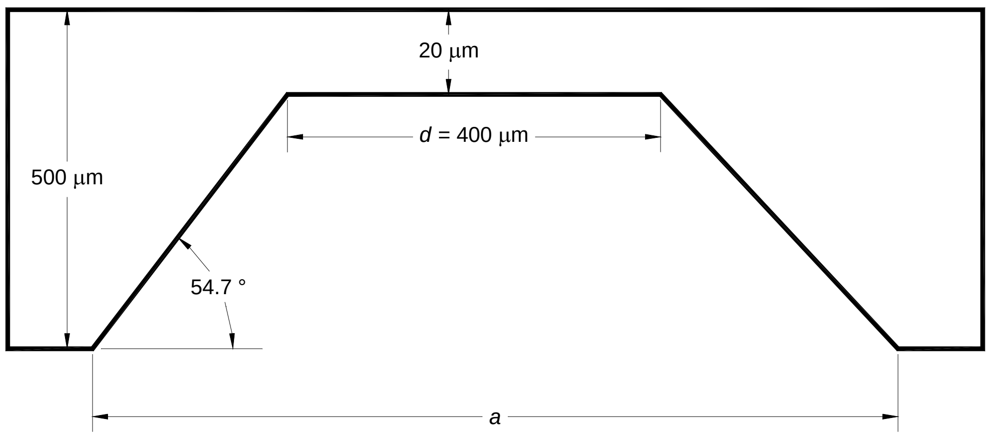


Figure 4. Cross section of a (100) silicon wafer placed in an anisotropic etchant.

If the sensitivity S of a pressure sensor varies as the inverse fourth power of the diaphragm edge length d, i.e.

$$S \propto d^{-4}$$

then the percentage variation attributed to variations in wafer thickness is:

$$\%\frac{\Delta S}{S} \propto 4d^{-1} \cdot \Delta d \cdot 100\% \tag{3}$$
$$= 18.7\%$$

Problem 4.15 (2 pts): Crayon engineering: Debug and recreate a process and mask set for a pressure-sensing silicon diaphragm

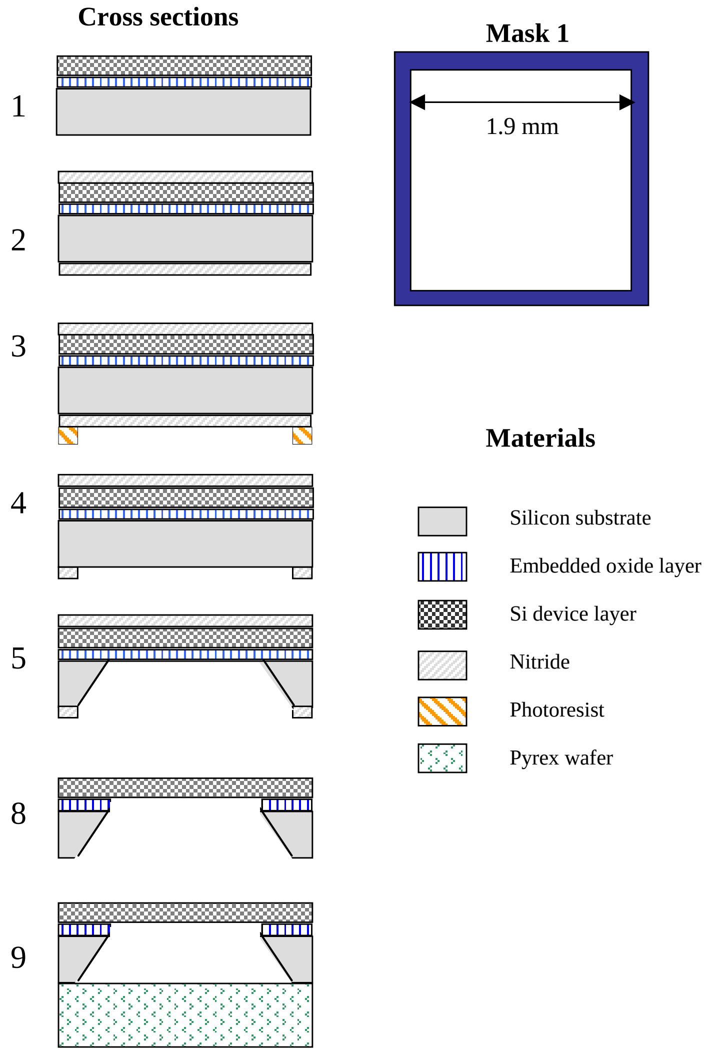
Proposed process step	Error
1. Start with a double-side-polished n-type silicon wafer.	
2. Perform photolithography using 1-μm-thick positive photoresist to define the diaphragm area	Must precede with a clean (RCA or piranha)
3. Deep-reactive-ion etch the silicon to form the diaphragm; ash resist.	1 μm of PR is very thin when used as a mask in DRIE. In other words, since the selectivity of DRIE to silicon over PR is ~ 50:1, etching though ~ 500μm of Si would require more than 10μm of PR. Also, DRIE would lead to a non-uniform membrane thickness with variations on the order of the required thickness (15 μm). This will make the device function improperly if fabricated at all.
4. Anodically bond the silicon wafer to a pyrex wafer	Must precede with wafer cleaning

Corrected process:

1. **Start with double-side polished SOI wafer, device layer 15 μm thick, oxide layer 1μm thick, substrate 500 μm thick. RCA clean.**
2. **Deposit LPCVD nitride, 0.5 μm thick (will coat both sides).**
3. **Spin 1-μm-thick positive photoresist on bottom side and perform photolithography using Mask 1 to the bottom side.**
4. **Dry etch the nitride on the bottom side using CF_4 / H_2 plasma for example. Ash resist .**
5. **KOH etch the silicon from the bottom side using the embedded oxide layer as an etch stop. If the dimensions of Mask 1 were calculated correctly, the resultant profile on the top side must be 1 mm across.**
6. **Piranha clean to remove all resist residue.**
7. **Etch the remaining nitride in 85% phosphoric acid.**
8. **Etch the exposed oxide using BOE for ~10 minutes. RCA clean.**
9. **Anodically bond the patterned SOI wafer to a Pyrex wafer.**

The device cross sections at different steps and the mask needed are shown in Figure 5 below.
The side of the square on the mask is calculated from equation 1 in Problem 3.8 above.

Figure 5: Corrected process flow and mask for a pressure-sensing silicon diaphragm



Problem 4.13 (4 pts): Crayon engineering: Create process and mask set for a DEP trap

Step		Description
Starting Material: Pyrex wafer		4” or 6”; will be used as insulating layer B
1	**Clean**	Piranha
2	**Photolithography**	Using image reversal resist and Mask 1. Thickness of resist at least 1.5 µm (3 times that of the layer to be lifted off). Image reversal (negative) resist necessary for lift off process later on
3	**Deposit Au-Ti bilayer**	E-beam evaporation (good for lift-off to be performed in next step). thickness of gold ~ 0.5 µm, thickness of titanium ~ 100 Å. Ti used as adhesion layer.
4	**Lift-off Au-Ti bilayer**	Acetone. Follow by water rinse.
5	**Clean**	Using Nanostrip. It might be possible to use Piranha however it will eat up some of the Ti layer and might lead to delamination of gold layer.
6	**Deposit silicon oxide**	PECVD, about 10 µm thickness. Will be used as insulating layer A.
7	**Photolithography**	Using image reversal resist and Mask 2. Thickness of resist at least 1.5 µm.
8	**Deposit Au-Ti bilayer**	E-beam evaporation. Thickness of gold ~ 0.5 µm, thickness of titanium ~ 100 Å. Ti used as adhesion layer.
9	**Lift-off Au-Ti bilayer**	Acetone. Follow by water rinse.
10	**Photolithography**	Spin cast positive thick photoresist, prebake; expose MASK 3, develop, postbake
11	**Etch oxide**	Dry etch using CF_4/H_2 plasma. Anisotropic and selective over Si.
12	**Strip resist**	By ashing for example.
13	**Clean**	Using Nanostrip.

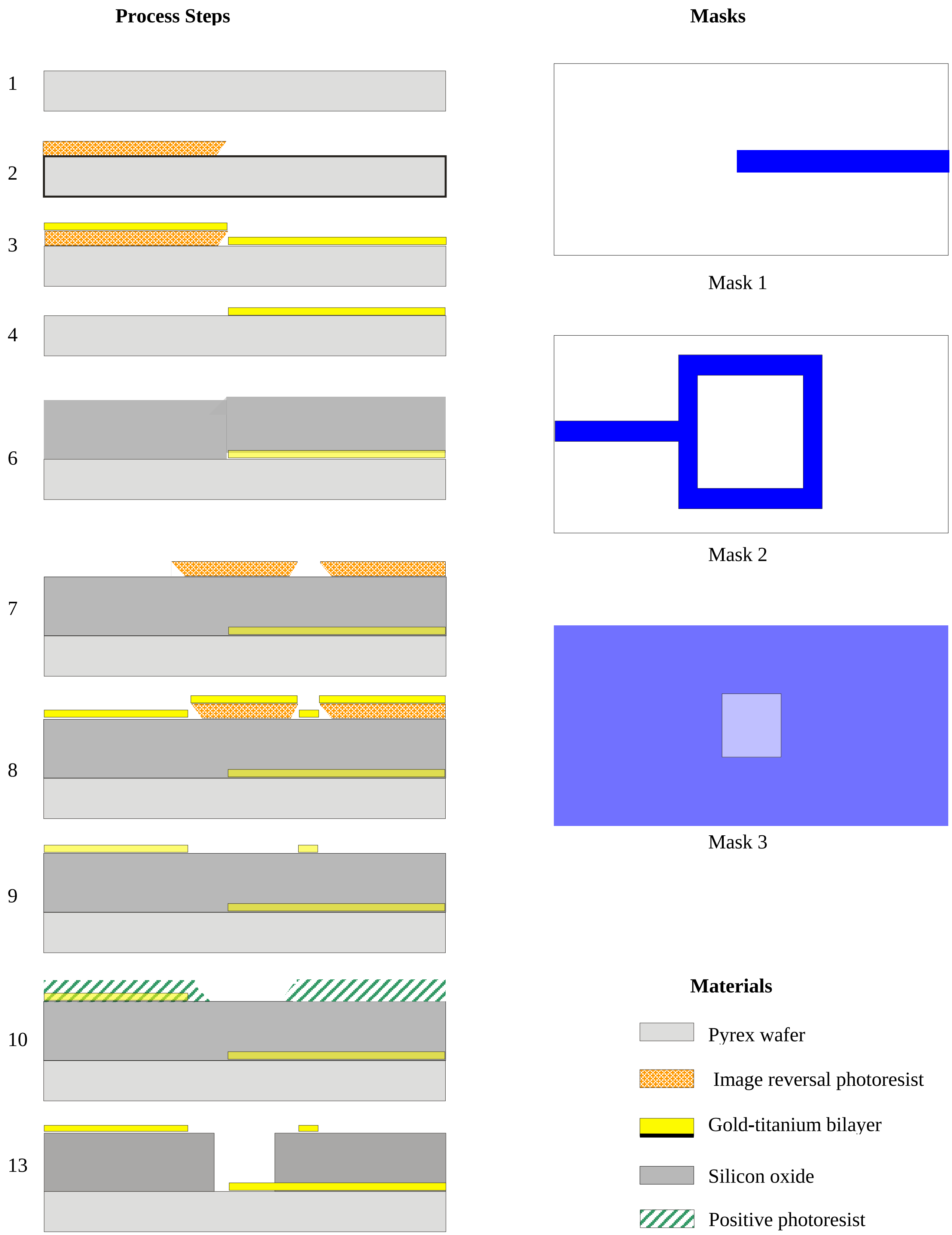


Figure 6: Process flow and mask set for a DEP trap

MATLAB CODE FOR PROBLEM 2.6

```
%-----------------------------fnc.m-----------------------------------------
%Create a function fnc to define the relations between the state
%derivatives and the state variables. fnc is then called using ode45.

function dy = fnc(t,y)
dy = zeros (2,1)        % create a column vector of all zeros
                        % to define the [y1;y2] array
dy(1) = y(2) ;          % then define the state derivatives
dy(2) = -4*y(1) - 2*y(2) + 1;

%----------------------------END OF PROGRAM----------------------------------

%-----------------------------p2_6a.m---------------------------------------
%MATLAB code for Problem 2.6a
%Use the code below to call the defined function fnc and plot the response
%over 10 sec

[T,Y] = ode45(@fnc,[0 10],[0 0]);
plot(T,Y(:,1))
title('Figure 1. Problem 2.6 Step Response Plot');
xlabel('Time t');
ylabel('Response y_1(t)');

%----------------------------END OF PROGRAM----------------------------------

%-----------------------------p2_6b.m---------------------------------------
%MATLAB code for Problem 2.6b

H=tf(1,[1 2 4]);    % Use tf to create the transfer function
step(H)             % Use step to plot the step response
title('Figure 1. Problem 2.6 Step Response Plot');
figure              % Open a new figure
bode(H)             % Use bode to generate the bode plot
title('Figure 2. Problem 2.6b Bode Plot');

%----------------------------END OF PROGRAM----------------------------------
```