

# **Micro and Nano Electro Mechanical Systems (MEMS-NEMS)**

## **Theory & Fabrication**

### **ME 487**



## **Project 1 Lab Manual**

Dr. Glennys Mensing

Cleanroom Laboratory Teaching Assistants:

Papia Sultana

ChangHee Son

Siyuan Huang

MNMS Research Engineer

Joe Maduzia

**Spring 2022**

<b>INTRODUCTION .....</b>	<b>3</b>
I. CLEANROOM INFORMATION .....	3
II. LAB SAFETY .....	3
III. CHEMICAL SAFETY .....	5
<b>WEEK 1 CLEANROOM INTRODUCTION.....</b>	<b>8</b>
1.1 GOWNING PROCEDURE .....	8
1.2 EQUIPMENT INFORMATION .....	10
1.3 STANDARD WAFER CLEANING PROCEDURE .....	11
<b>WEEK 2 PHOTOLITHOGRAPHY .....</b>	<b>13</b>
2.1 PROJECT 1 OVERVIEW .....	13
2.2 PROCESS REVIEW .....	14
2.3 SPINCOATING PHOTORESIST .....	14
2.4 PHOTORESIST DEVELOPMENT .....	14
<b>WEEK 3 NICR DEPOSITION AND LIFTOFF .....</b>	<b>16</b>
3.1 PROCESS REVIEW .....	16
3.2 LIFT-OFF PROCEDURE .....	17
4.1 PROCESS REVIEW .....	20
4.2 MASK ALIGNMENT .....	21
<b>WEEK 5 BACKSIDE PHOTOLITHOGRAPHY, NITRIDE ETCH, PROTEK APPLICATION, AND KOH WET ETCH .....</b>	<b>22</b>
5.1 PROCESS REVIEW .....	23
5.2 KOH ETCHING .....	23
<b>WEEK 6 MEASUREMENTS AND PACKAGING .....</b>	<b>24</b>
6.1 PROCESS REVIEW .....	24
6.2 PACKAGING .....	24
<b>WEEK 7 TESTING .....</b>	<b>27</b>
7.1 PROCESS REVIEW .....	27
7.2 TEST DEVICES .....	27
<b>PROJECT 1 OVERVIEW .....</b>	<b>29</b>

# Introduction

This lab manual represents countless hours of many people over the years. It combines basic cleanroom information for the MNMS cleanroom, process procedures for each week, general processing information, and an overview of Project 1.

## I. Cleanroom Information

The Micro-Nano Mechanical Systems (MNMS) Laboratory is a 3800 sq. ft suite of labs and related support rooms, including 2 cleanroom laboratories for research in the design and fabrication of small-scale mechanical systems. The MNMS laboratory has class 100 and 1000 cleanrooms for the microfabrication, inspection, and testing of devices. The lab supports research and instruction in the general area of micro- and nano-electro-mechanical systems (MEMS & NEMS), and nano-chemical-electrical-mechanical-manufacturing systems (Nano-CEMMS).

### Cleanroom Access

Access to the cleanroom is restricted to authorized facility users and their supervised guests. Physical entry and exit of the Cleanroom (213) and the Prep Room (202A) are controlled by card reader locks and your university ID card.

## II. Lab Safety

If an emergency situation arises, call 9-911. A procedure for making 9-911 calls is posted by the cleanroom telephones. The procedure and the materials for treating an HF burn are located in the large plastic container beneath the cleaner bench in the yellow side of the cleanroom. YOU MUST WEAR SAFETY GLASSES AT ALL TIMES WHEN USING CHEMICALS. There are chemical hoods in the lab dedicated to particular processes. There are hoods for solvents, acids, bases, ultrasonic cleaning, and spinning photoresist.

Personal protection equipment (PPE) including black nitrile acid gloves, aprons, face shields, and goggles are located on the wall next to the cleaner hood (see Figure 1.1).

Certain chemicals are provided by the MNMS Cleanroom:

Acetone	Isopropyl Alcohol	Methanol	Chrome Etchant	Aluminum Etchant
Buffered HF (BOE)	Hydrofluoric Acid (49%)	Hydrochloric Acid	SPR 220, KMPR Photoresist*	AP 8000 Adhesion Promoter
AZ400K Developer	AZ917 MIF Developer	AZ400T Stripper	Microposit 1165 Stripper	SU 8 Developer

\*Photoresist is stored in the refrigerator in the cleanroom.



Figure 1.1 Safety and personal protection equipment are shown.

Chemicals, not supplied by the MNMS Cleanroom, may be brought into the lab after a MNMS Laboratory Chemical Usage and Storage Request Form is completed, signed, and approved. An MSDS is required for approval. Upon approval, a label will be issued that must be placed on the container prior to bringing it into the cleanroom. Label placement on the container should not obscure the manufacturer's labeling. This label contains the following information: owner's name, owner's e-mail, advisor's name, advisor's e-mail, chemical name, NFPA rating, date, and the assigned storage location in the cleanroom.

MSDS sheets are kept in a binder in both the gown room and the prep room. Electronic MSDS information can be found at the DRS website:

<http://www.drs.illinois.edu/msds/>

Empty chemical bottles should be thoroughly flushed at least three times, caps disposed of in the trash, and the bottles placed in the chase next to the west entrance of the Cleanroom (near the mask aligner).

Users are required to supply their own glassware. Processes in the hood should be clearly labeled with chemical, owner, date, and status of process. Do not leave unlabeled chemicals in the hoods or the sinks. Abandoned glassware will be moved to the "public" shelf or disposed of in the appropriate container.

### Chemical Disposal

Dispose of solvents and dilute hydrofluoric acid in the appropriate waste containers. DO NOT PUT SOLVENTS OR HYDROFLUORIC ACID DOWN THE DRAINS. Small amounts of other acids and bases may go down the drain with copious amounts of water.

### Cleanroom Usage

Please keep the facility tidy and clean. Each person is responsible for the cleanliness of the lab. Dispose of sharp objects such as needles, razor blades, and contaminated glass in the "sharps" containers. Put broken or unusable silicon wafers in the red silicon reclaim bin over by the STS DRIE. A central vacuum system can be used for cleanup of tiny pieces and dust. Plug the hose into the wall connection and vacuum. There are several vacuum sites throughout the facility, including the prep room and the chase. Each user is responsible for maintaining their storage tub.

### **III. Chemical Safety**

#### Acid Handling and Safety

The MNMS cleanroom uses a variety of chemicals, some of which are acids. These chemicals are used for a variety of micro processing applications. It is important to respect these chemicals and employ proper and safe methods for their usage. In the process steps for Project 2, we will be using Buffered HF. The buffering salt used is Ammonium Fluoride ( $\text{NH}_4\text{F}$ ). Please review the MSDS sheets for both HF and  $\text{NH}_4\text{F}$  before coming to the laboratory.

#### Personal Protection Equipment

Below is a list of personal protection equipment (PPE) necessary to use while handling acids. See Figure 1.1 for a description of this equipment.

- A. Safety glasses should be worn at all times.
- B. White Nitrile gloves should be worn at all times.
  - a. Double glove for personal protection when using chemicals
  - b. Handle gloves from the inside to prevent contamination of the outside
  - c. Be conscious of what the gloves contact (do not scratch face, etc.)
  - d. Change when contaminated
  - e. White nitrile gloves are not a primary personal protection from chemicals, but for protection of the substrate and to prevent organic and alkali ion contamination from skin
- C. Acid Apron
  - a. Protection from splashes
  - b. Protection from accidents
- D. Face Shield
  - a. Protection from splashes
  - b. Protection from accidents
- E. Black acid gloves
  - a. Must be worn when working with acids or bases
  - b. Primary personal protection for most acids and bases
  - c. Punch-through time >4 hours for most acids and bases
  - d. Inspect and rinse with DI water before using
  - e. Inspect and rinse with DI water after using
  - f. Nitric acid and solvents will deteriorate the gloves
  - g. If there are any cracks, tears, or perforations present, replace with a new set and notify cleanroom staff
  - h. Turn on the water with white nitrile gloved hands before putting on the acid gloves.
  - i. Do not touch nitrogen gun and DI spray gun with acid gloves
  - j. Handle from the inside - assume that acid is present if they are wet
  - k. Be conscious of where your hands are at all times while wearing the gloves

NOTE: Never touch anything in the fume hood or anywhere else in the laboratory except the specified containers while wearing the black acid gloves. Be aware that you might contaminate surfaces with dangerous chemicals that others will be using without those gloves. An explanation for each such surface will be given during your laboratory section.

## Hydrofluoric (HF) acid Safety Protocol

**SEEK MEDICAL HELP! HF BURNS REQUIRE PROMPT MEDICAL TREATMENT!** The fluorine ion reacts with the calcium in human tissue and requires special medical treatment. These burns cannot simply be washed off.

### Skin Contamination:

- A. Call for help immediately. If you are the person who has been contaminated, have someone in the lab call 9-911 immediately. Relevant 9-911 emergency response information is displayed above the phone.
- B. Remove contaminated clothing immediately.
- C. Decontaminate by washing with copious amounts of water. Flush the affected areas using the safety shower for a minimum of 5 minutes.
- D. Apply Calcium Gluconate gel liberally to the affected area. The HF Treatment Kit is located in a plastic storage box under the cleaner hood on the yellow side of the cleanroom. If the contamination is limited to the fingers, immerse the fingers in a liquid antacid (Equate or Mylanta) after applying the Calcium Gluconate gel.
- E. Place ice packs on the affected area. This will retard the diffusion of the fluoride ion further into the skin. To activate the cold pack, hold the pack upright and squeeze the side of the pouch so that the liquid breaks. Shake the pack vigorously for 10 seconds until ice cold. Place the ice pack in a zip lock bag and apply to the contaminated area.
- F. Await Emergency Medical Personnel.

*NOTE: The MSDS sheets for HF and Calcium Gluconate gel, as well as this procedure sheet and medications should be transported with the contaminated person to the medical facility.*

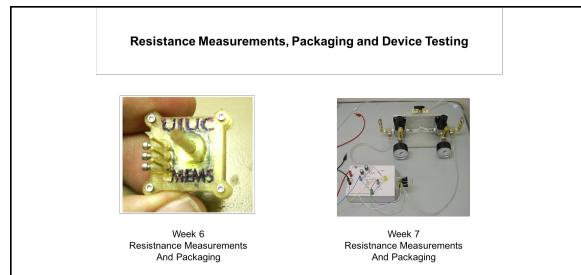
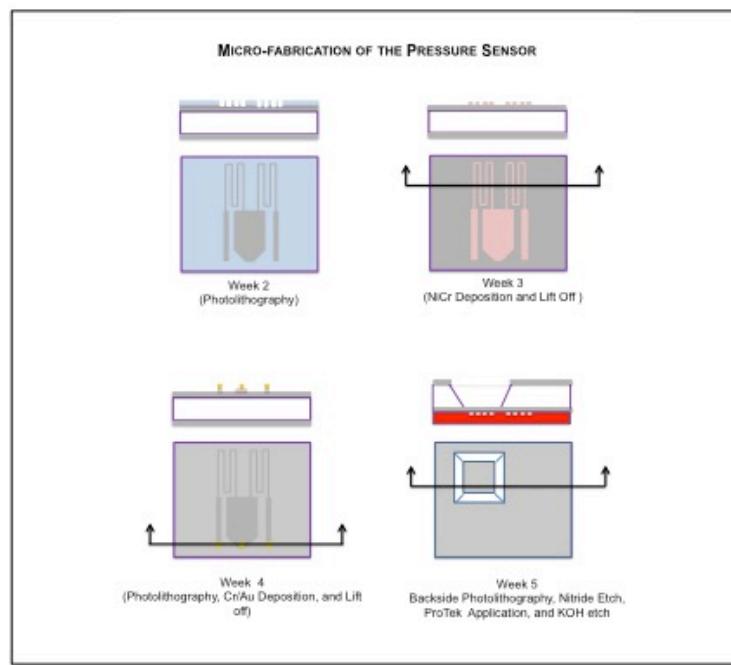
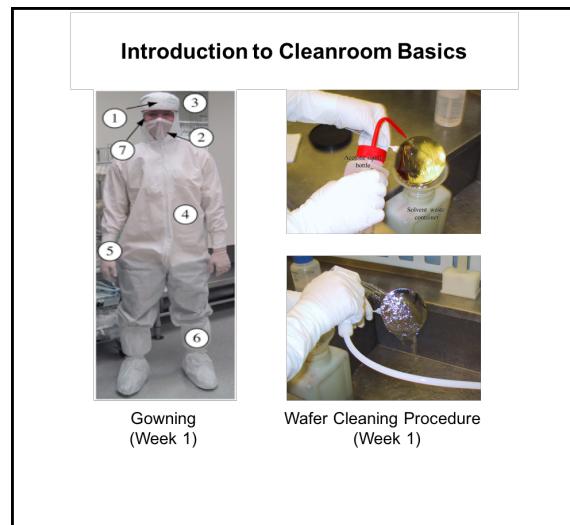
### Eye Contamination:

Chemical burns, particularly those involving the cornea, are considered emergencies. **IT IS VERY IMPORTANT TO RECEIVE MEDICAL TREATMENT AS QUICKLY AS POSSIBLE!**

- A. Call for help immediately. If you are the person who has been contaminated, have someone in the lab call 9-911 immediately. Relevant 9-911 emergency response information is displayed above the phone.
- B. Hold the eye-lid open and flush the affected eye (or both eyes) for a minimum of 15 minutes using the eyewash.
- C. Place ice packs on the affected eye. This will retard the diffusion of the chemical into the eye. Do not use oily drops, ointment, or HF skin burn treatments. To activate the cold pack, hold the pack upright and squeeze side of pouch, so that the liquid breaks. Shake the pack vigorously for 10 seconds until ice cold. Place the ice pack in a zip lock bag and apply to the eyes.
- D. Await Emergency Medical Personnel.

For additional chemical safety, please see the MNMS Cleanroom Chemical Hygiene Plan.

# Project 1 –Overview



# Week 1 Cleanroom Introduction

## Summary

- 1.1 Gowning procedure
- 1.2 Equipment information
- 1.3 Standard wafer cleaning procedure

## 1.1 Gowning Procedure

Leave all personal items such as coats and backpacks in the hallway lockers. You may safeguard your items in the hallway lockers with your own lock. Remove your lock when you exit the facility. Hallway lockers are not for long-term storage.

**Do not bring incompatible materials such as pencils, books, manuals, and especially paper or cardboard.** Bring as little as possible into the cleanroom. Use only cleanroom paper and pens (provided). Samples enter the cleanroom via the pass through. Transferring items from other facilities should be done in airtight containers. When passing samples from other facilities into the MNMS cleanroom, the samples should enter the cleanroom but not the airtight container. All items entering the cleanroom must be blown off with nitrogen prior to entry (Nitrogen Blow-off Station is located next to the pass through).

Observe if the light is flashing above the 213 entry door, and do not enter until the light has stopped flashing. Allow people to exit the pass through room into either the gownroom or the hallway to avoid congestion inside the pass through room. Put on the blue booties provided on top of the pass-through, step on the tacky mat, and swipe in to access the gownroom. All card holders should card in independently. Tailgating is not permitted. Make sure the hallway door is closed before you open the gownroom door. Do not have any two doors open at the same time. Garment hangers with names are assigned to frequent users of the facility. Garments should be replaced after 40 hours of use or if soiled. Garments that are soiled should be placed in the laundry bin while those that are damaged should be given to cleanroom staff. Replace compromised garments immediately. New garment supplies are available in the wire bins in the gowning room.

### Entering the Cleanroom

You must be properly gowned up to enter the cleanroom. Please see the gowning sequence for the proper order of gowning in figure 1.2. After gowning up, you may enter the air shower. It will run for approximately 20 seconds, and you should move around to remove as much dust as possible. When the light in the air shower flashes, you can enter the cleanroom.

When entering the cleanroom, please familiarize yourself with the location of the safety shower, eye wash, fire alarm, and fire extinguisher (see Figure 1.1).

### Gowning sequence:

1. Don blue bouffant, making sure to contain all hair in the bouffant.
2. Don face veil, making sure to cover all facial hair.
3. Don hood, making sure all hair is kept inside the bouffant. Use the mirrors to check that you are covered.
4. Don the coveralls and make sure the hood flaps are beneath the coveralls. Make sure that your gown does not drag on the floor. Use the mirrors to check that you are completely tucked in. You can use the thumb loops if they help in keeping the cuffs of the suit inside the gloves.
5. Don white nitrile gloves and pull the glove cuffs over the coverall sleeves.
6. Don the white Tyvek boots and make sure to pull them over the outside of the coverall.
7. Don safety glasses. (see Figure 1.2)



Figure 1.2 Gown-up procedure

### Exiting the Cleanroom

Check that all doors in the gowning room are closed before you open the door to the gown room. Do not leave any door to the cleanroom or gowning room open to talk to other users. Phones are available for communication between the hallways, prep room, and the cleanroom. Walk on the tacky mats to remove particles from boot soles. Gowning apparel should be removed in the opposite order than it was put on. Gloves, bouffants, veils, and compromised booties should be thrown in the trash container. Dirty gowns should be put in the blue laundry bin.

## 1.2 Equipment Information

The MNMS lab trains users on equipment with staff personnel. Each piece of equipment has a designated trainer to train users and oversee its usage. Proper training is required for all equipment in this facility. Some of the equipment in the cleanroom can be reserved by visiting the cleanroom website ([www-s.mechse.uiuc.edu/cleanroom](http://www-s.mechse.uiuc.edu/cleanroom)).

The cleanroom has a range of state-of-the-art equipment including:

- ❖ STS Pegasus ICP-DRIE etching system
- ❖ PlasmaTherm ICP-DRIE etching system
- ❖ Two Oxygen / Argon RF RIE systems
- ❖ Electron Visions (EVG420 and EVG 620) double-sided aligner
- ❖ MJB3 Suss aligner
- ❖ Flood exposure (402 nm exposure wavelength)
- ❖ EVG wafer bonding system
- ❖ 4-stack multi-zone tube-furnace system
- ❖ High speed spinner housed in a laminar flow fume hood
- ❖ Laminar flow spinner bench with two spinners
- ❖ Multiple chemical fume hoods (acid, base, solvent, cleaner, and hot plate)
- ❖ Confocal 8 gun DC sputtering system
- ❖ 4-pocket e-beam evaporator
- ❖ Molecular Vapor Deposition (MVD) system
- ❖ High-temperature furnace (max temperature is 2200 °C)
- ❖ Vacuum oven
- ❖ Vacuum annealer
- ❖ Programmable curing oven
- ❖ Goniometer
- ❖ Supercritical Dryer
- ❖ Glove box
- ❖ Ultrasonic cleaner
- ❖ Micro-mechanical probe station with Labview and a complete set of electronics instrumentation for precise IV measurements
- ❖ MX-50 Olympus wafer inspection optical microscope as well as a stereoscope and a Axiovert microscope
- ❖ An infrared imaging microscope
- ❖ Profilometer

In addition to the cleanroom laboratories, the MNMS laboratory has a preparation room for lapping, ultrasonic milling, dicing, and sample preparation. A chemical fume hood is also available. Use ceramic top hot plates for liquids. The preset temperatures for the aluminum top hot plates in the spinner hood are 60°C and 110°C. If you change a preset value of the spinner programs or the aligner, please restore to default program parameters.

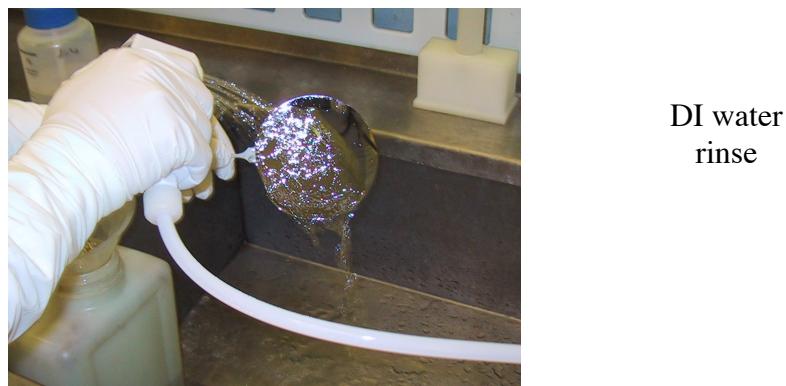
## 1.3 Standard Wafer Cleaning Procedure

It will be necessary to clean a wafer several times during the wafer processing operation. The standard cleaning process consists of an acetone rinse, an isopropanol (IPA) rinse, a deionized water (DI) rinse, an IPA rinse, and a nitrogen blow dry. Besides acetone and isopropanol, other solvents can be used. After a wafer is blown dry with nitrogen, a hot plate dehydration bake can be used to evaporate off any remaining liquid or a standard O<sub>2</sub> descum. The standard clean method is primarily to remove light organics (generated from humans, chemicals, etc.). Abrasion with a lint free polyester wipe may also be necessary to remove foreign particles. The process sheet will specify the type of cleaning process to be used.

Before attempting to clean the wafer, verify that the squirt bottles you will need are full or have sufficient chemical amounts. The acetone wash is conducted in the solvent hood. Before using the squirt bottle, verify that you have acetone. Start the cleaning procedure by spraying the wafer with acetone from the acetone squirt bottle. Thoroughly rinse both sides of the wafer into the solvent collection bottle.



The acetone wash is immediately followed by an isopropanol rinse (into the solvent bottle) and a deionized water rinse (into the sink). The last isopropanol rinse is conducted in the same manner as the acetone rinse.



The deionized water rinse is conducted in the sink basin. If deionized water is used, rinse both sides of the wafer with isopropanol before blowing the wafer dry with nitrogen. Doing this over a wipe and blowing at an angle will avoid potentially blowing the wafer in to the sink.

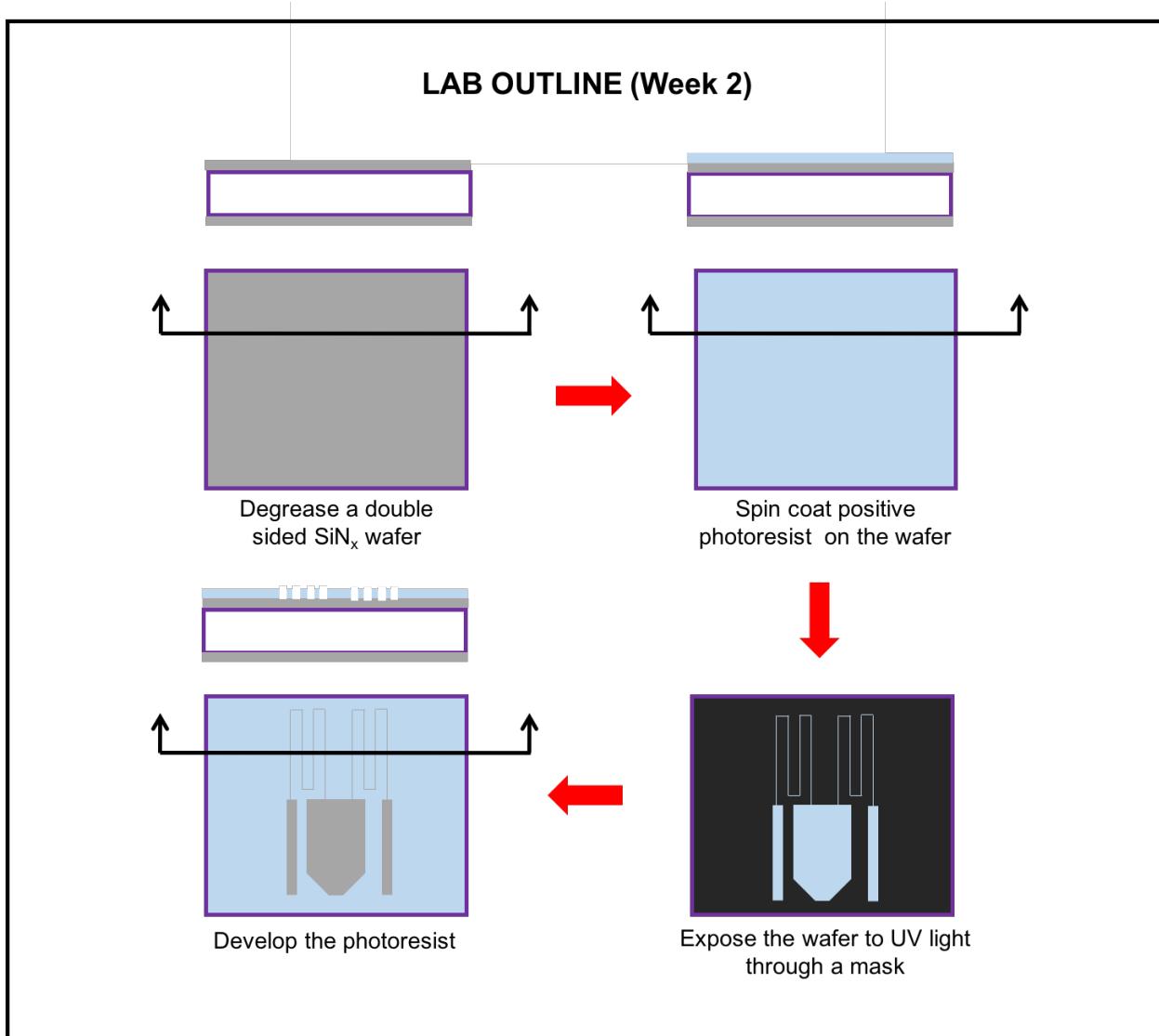
N2 dry



N<sub>2</sub> Spray gun

Removal of any remaining liquids can be accomplished by using the hot plate or descum.

## Week 2 Photolithography



### 2.1 Project 1 Overview

The purpose of Project 1 is to learn fabrication techniques and to fabricate a micro-machined pressure sensor from silicon nitride (SiN) wafers. The design of the pressure sensor utilizes the principle of pressure strained diaphragms. When a pressure differential is placed across a thin diaphragm, it will deflect and strain. The strain is measured using thin-film resistance sensors, which are placed on the diaphragm. When strained, the resistance changes proportionally to the strain, which can be measured using electronics (see additional information in the Project 1 Summary at the end of this document).

## 2.2 Process Review

- 1) Clean wafer (Acetone, IPA, DI, IPA, N2 dry), also called degreasing the wafer
- 2) Descum wafer in O<sub>2</sub> plasma (1min at 100 W)
- 3) Spin coat AP-8000 (~8 drops) adhesion promoter (recipe#3, 3000rpm, 30sec)
- 4) Spin coat wafer with SPR 220 (recipe #3, 3000rpm, 30sec)
- 5) Soft bake on Al ring for 2 minutes at 60°C and 1 minute at 110°C
- 6) Expose mask #1 using EVG 620, 200mJ/cm<sup>2</sup> dose
- 7) Develop in AZ400K developer (5:1 / DI:Developer) 2-3 minutes
- 8) DI quench then rinse with low pressure DI, N<sub>2</sub> dry
- 9) Check with microscope for developing result

## 2.3 Spincoating Photoresist

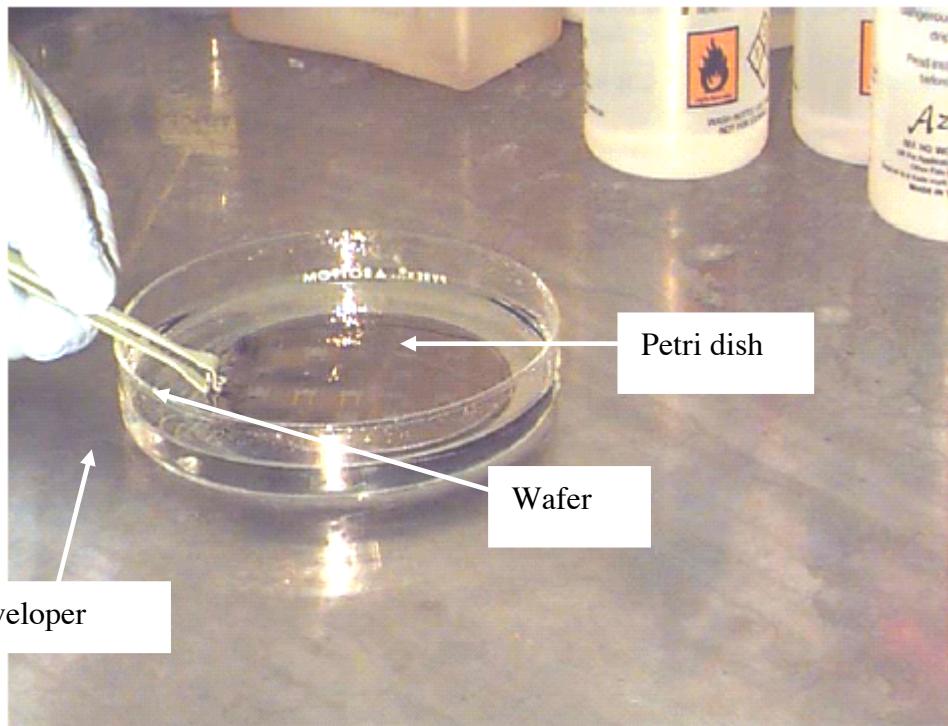
Each formulation of photoresist has documented spin speeds to obtain the desired thickness. In order to determine the correct spin speed, please see the documentation that came with the photoresist. This week, we will be using SPR 220 (a positive tone photoresist), recipe #3 (3000rpm and 30sec). After cleaning the wafer and a descum, use the spinner procedure indicated to complete the coating of the wafer.

## 2.4 Photoresist Development

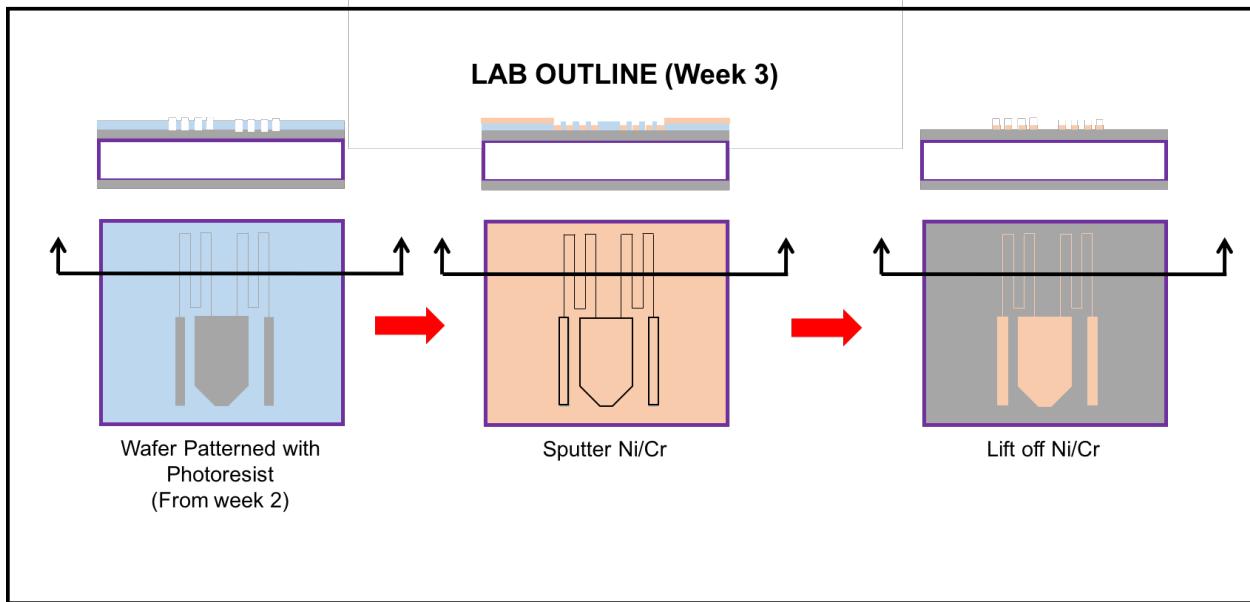
The purpose of photoresist developing is to remove the photoresist that was exposed to the ultraviolet light during the Mask Aligner operation. For a positive photoresist, the ultraviolet light chemically breaks down the bonds in the polymer, allowing a specific type of developer to remove the exposed photoresist. Solution proportions are specified in the process sheet. Use a graduated cylinder to measure out the volume of the developer and place the contents in a Petri dish.

Swirl the wafer around in the developer solution until the photoresist is removed from the exposed areas. The photoresist patterns on the wafer should be clear and sharp. Use the microscope to verify the conditions of the patterns. Prior to using the microscope or completing the process step, rinse the wafer with copious amounts DI water to remove all of the developer. Failure to remove all of the developer will allow the photoresist removal process to continue. If the wafer has not been in the developer long enough, there will be photoresist left in the exposed areas and the pattern edges will be fuzzy. If the wafer has been in the developer too long, the developer will undercut the pattern and your pattern will be distorted.

**Caution: If a photoresist coated wafer is left in the developer solution for a long enough period of time, all of the photoresist will be removed.**



## Week 3 NiCr Deposition and Liftoff



### Summary

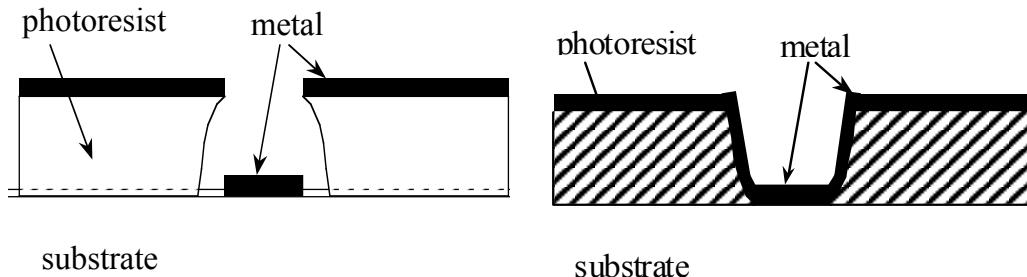
#### 3.1 Process Review

#### 3.2 Liftoff

### 3.1 Process Review

- 1) Descum 1 min at 100W O<sub>2</sub>
- 2) Sputter NiCr for 4 min at 400 W (~500 Å)
- 3) Liftoff NiCr in 1165 PR stripper in ultrasound for at least 10 minutes. Do not let dry and move immediately to next step.
- 4) Acetone bath in ultrasound for 2 minutes, IPA bath in ultrasound for 2 minutes and DI rinse.  
(Wipe w/ alpha wipe and acetone to remove any remaining particles.)
- 5) Check with microscope and make sure there are no remaining particles
- 6) Measure NiCr height, width, and spacing

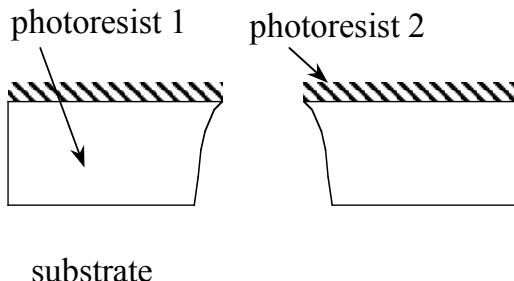
### 3.2 Lift-Off Procedure



**Figure 3.1.** Lift-off patterning of metal thin film. The proper way (left), improper (right).

Lift-off is a process used to pattern metal thin-films when a proper wet etchant or dry etching chemistry is not available. Lift-off takes advantage of the fact that the step coverage of most metal thin-film deposition methods (except via CVD and electroplating) is quite limited, so that the metal cannot overcoat steep or undercut steps. Figure 3.1 illustrates the lift-off process. A "negative" mask, i.e., patterned photoresist, is fabricated before the metal deposition and the edges of the mask are undercut, allowing discontinuous metal regions on the substrate and on the mask. The "sacrificial" photoresist is then dissolved away by using a solvent such as acetone or photoresist stripper (1165, NMP, or trade name), "lifting-off" the unwanted metal. A short oxygen plasma descumming is usually preferred before the metal deposition to make sure that the substrate surface is free from residual photoresist to obtain good adhesion between the metal and substrate.

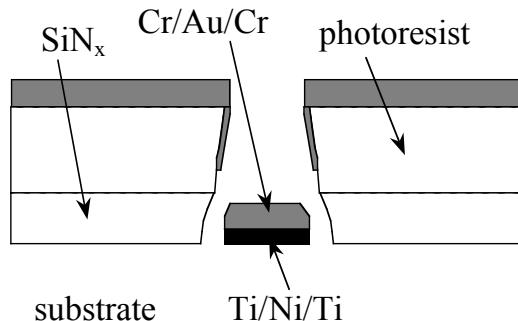
How easy the lift-off process is depends on the "undercut" photoresist profile, the thickness of metal deposited, the step coverage with different metal deposition methods used (evaporation has worst step coverage thus is most suitable for lift-off), migration and ductility of the metal film. The left side of Figure 3.1 shows the proper way for the PR to shadow the deposited metal on the substrate, allowing liftoff of the metal on top of the PR. The right side shows what happens if the PR slopes outward, allowing the metal to form attachments between the substrate and top of the PR, thereby preventing clean liftoff from occurring. Relatively thick ductile metal films such as Au and Cu are usually more difficult to lift-off than thin and brittle films, since even very thin side wall films (nm) can form effective attachments.



**Figure 3.2.** Double layer photoresist for obtaining good lift-off profile.

In order to obtain good undercut profile for lift-off, a simple method soaks a positive photoresist with chlorobenzene before development to harden the top layer ( $\sim 1000 \text{ \AA}$ ) in unexposed areas so that with slight over development, an undercut profile is created. A more delicate way uses a double layer or a trilayer of photoresist. A double layer photoresist undercut

profile is shown in Figure 3.2. Two layers of photoresist are spun and exposed. With two developers 1 and 2 that selectively develop photoresist 1 and 2 respectively, a more controllable undercut profile can be created.

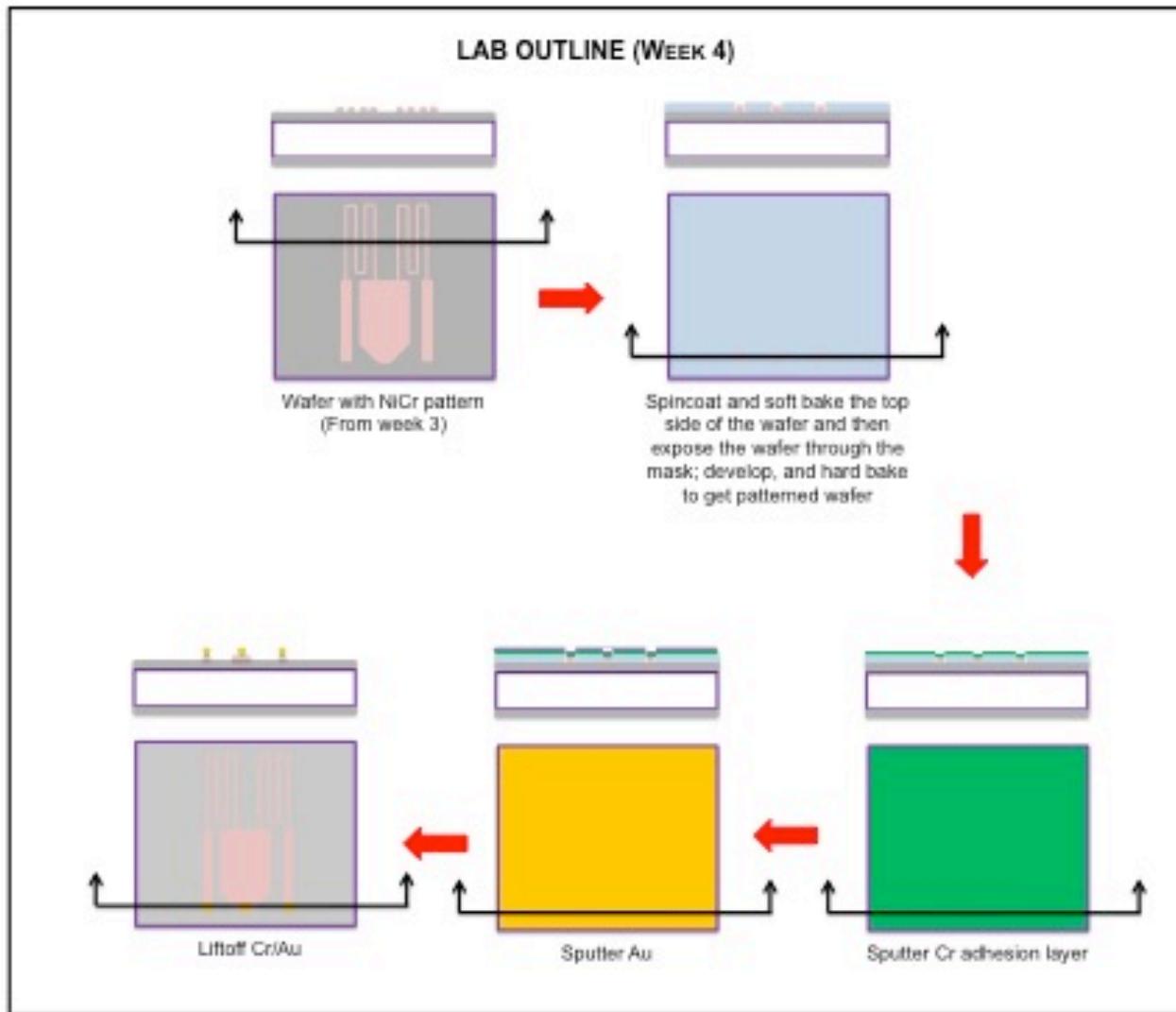


**Figure 3.3.** A  $\text{SiN}_x$  assisted lift-off method used for thick Au deposition.

For very challenging lift-off of thick ductile films, such as 3000 Å Cr/Au/Cr on 1000 Å of Ti/Ni/Ti, additional steps may need to be taken to achieve good liftoff, since Ni is very tough and Au is very ductile. Figure 3.3 shows a method that uses a layer of  $\text{SiN}_x$  (~ 5000 Å) deposited on the substrate. A PECVD  $\text{SiN}_x$  is patterned with photolithography using AZ5214 EIR photoresist. After that, a low power  $\text{CF}_4$  RF plasma is employed to etch  $\text{SiN}_x$  with significant isotropy, so that an undercut profile is created in the  $\text{SiN}_x$  and photoresist. With this process, these thick, tough, ductile metal layers can be removed because of the undercut profile and the increase of the step height as shown in Figure 3.3. The thickness of  $\text{SiN}_x$  can be tailored to accommodate the thickness of the metal film that needs to be patterned with lift-off.

In addition to using these techniques, using thicker photoresists, such as AZ4620 or AZ4920, can also help to affect good liftoff properties, even if the sidewalls are vertical, rather than undercut, simply put since the sidewall is higher, making sidewall deposition difficult. Moreover, any deposition technique that reduces sidewall deposition will improve liftoff.

## Week 4 Photolithography, Cr/Au Deposition, and Lift-off



### Summary

#### 4.1 Process review

#### 4.2 Mask alignment

## 4.1 Process Review

- 1) Degrease the wafer (acetone, IPA, DI, IPA, N2 dry)
- 2) Descum 1 min at 100W O<sub>2</sub>
- 3) Spin coat top side of wafer with AP8000 adhesion promoter (recipe#3, 3000rpm, 30sec)
- 4) Spin coat top side of wafer with SPR 220 (recipe #3, 3000rpm, 30sec)
- 5) Soft bake on Al ring 2 minutes at 60°C and 1 minute at 110°C
- 6) Expose mask #2 (12 sec exposure) using EVG 620, 200mJ/cm<sup>2</sup> dose
- 7) Develop in AZ400K developer (5:1 DI : Developer, 100ml DI) about 1-2 minutes
- 8) DI quench then rinse with low pressure DI, N<sub>2</sub> dry
- 9) Check with microscope for developing result
- 10) Hard bake 30 sec at 110°C
- 11) Descum 1 min at 100W O<sub>2</sub>
- 12) Sputter Cr for 30 seconds at 300 W (50 Å)
- 13) Sputter Au for 3 minutes at 300 W (500 Å)
- 14) Liftoff in 1165 PR stripper in ultrasound for 5-10 minutes, DI rinse, then transfer (don't let dry).
- 15) Acetone bath in ultrasound for 2 minutes, IPA bath in ultrasound for 2 minutes, N<sub>2</sub> blow.
- 16) Check with microscope and make sure there are no remaining particles. (wipe if necessary)

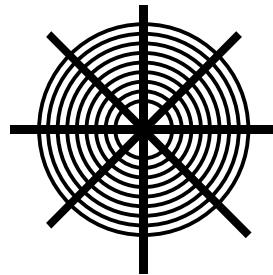
### Review Previous Procedures

This week's lab will focus on combining all the processing learned in the previous labs including degreasing a wafer (Week 1), spincoating photoresist (Week 2), mask alignment (Week 2), sputtering (Week 3), and liftoff (Week 3). Please review these previous sections.

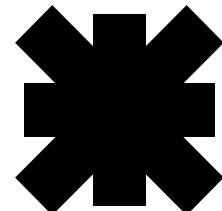
## 4.2 Mask Alignment

The purpose of alignment is to insure that the series of masks for a project are all aligned to the same position on the wafer. The alignment marks are used as the reference point for all future masks. The alignment marks for these projects are all the same and shown on the right. Since they are the same, once the wafer alignment marks completely fills the mask alignment marks, the mask to wafer alignment is complete. To accomplish bottom alignment, computer generated alignment cross-hairs are used to record the mask alignment mark positions before the wafer is inserted. Once the wafer is inserted, the computer generates an image on the backside of the wafer directly below where the mask alignment marks were detected.

There are two alignment marks per mask and the aligner has top microscopes used for top alignment (front side); two bottom microscopes used for bottom (backside) alignment.

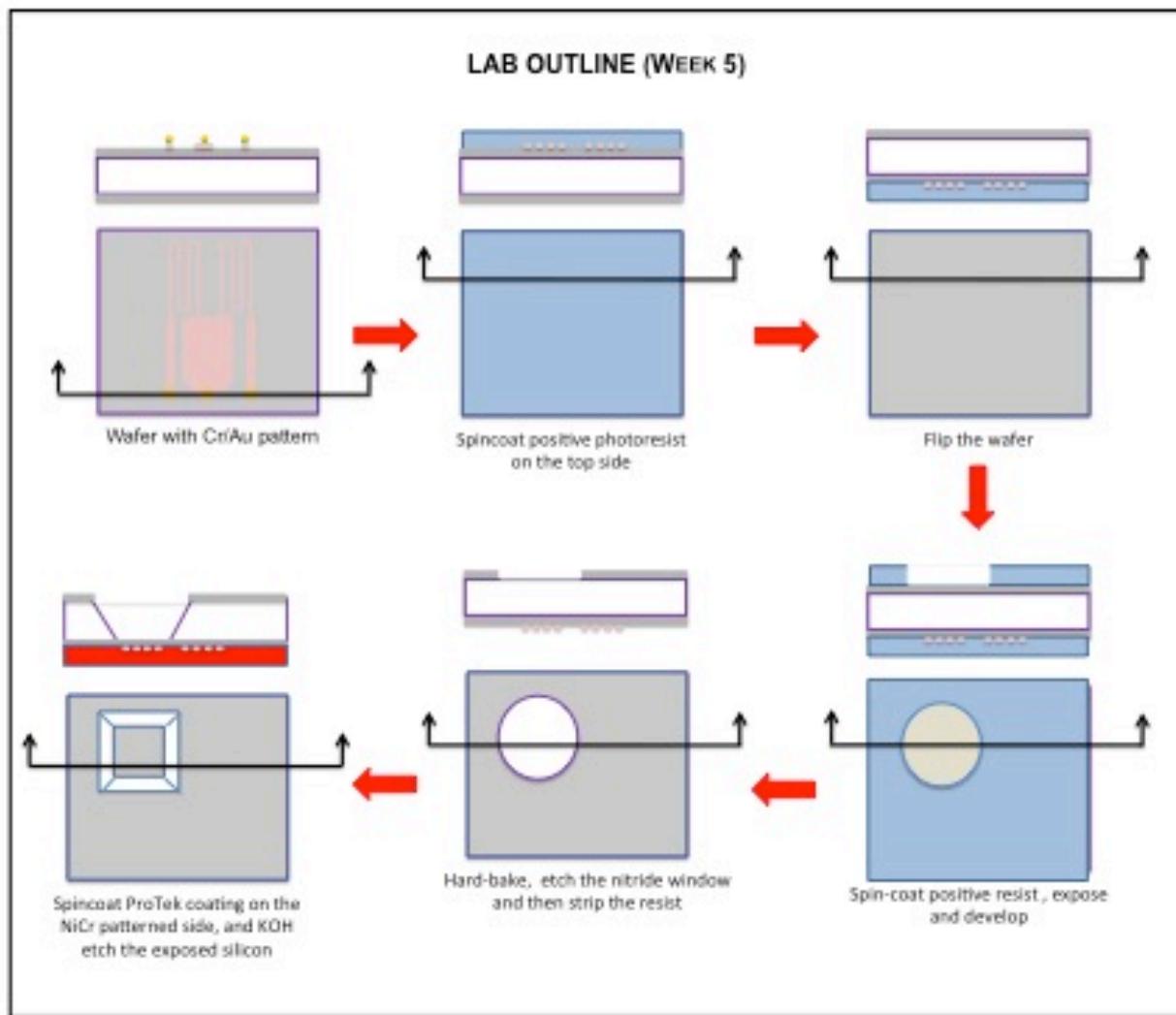


Aligning mark



Magnified view of  
center after  
alignment

# Week 5 Backside Photolithography, Nitride Etch, ProTEK Application, and KOH Wet Etch



## Summary

### 5.1 Process review

### 5.2 KOH Etching

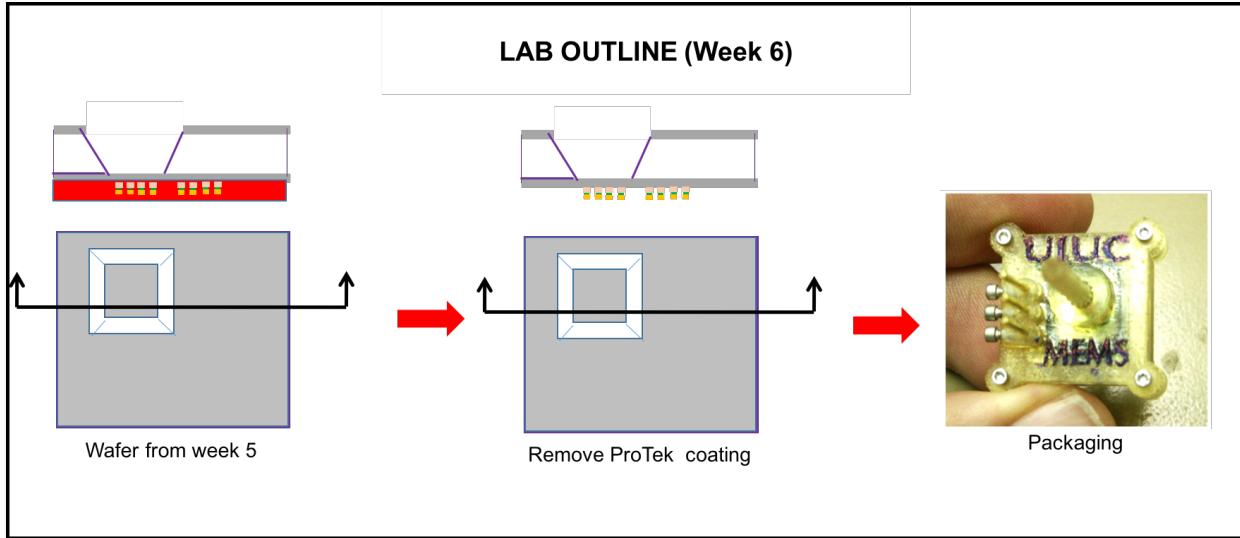
## 5.1 Process Review

- 1) Degrease the wafer (acetone, IPA, DI, IPA, N<sub>2</sub> dry)
- 2) Spin coat top side of wafer with SPR 220 (recipe #3, 3000rpm, 30sec)
- 3) Soft bake on Al ring 2 minutes at 60°C and 1 minute at 110°C
- 4) O<sub>2</sub> de-scum bottom side in RIE for 1 minute at 100 W
- 5) Spin coat bottom of wafer with AP8000 adhesion promoter (recipe#3, 3000rpm, 30sec)
- 6) Spin coat bottom side of wafer with SPR 220 (recipe #3, 3000rpm, 30sec)
- 7) Soft bake on Al ring 2 minutes at 60°C and 1 minute at 110°C
- 8) Expose mask #3 using EVG 620, 200mJ/cm<sup>2</sup> dose
- 9) Develop in AZ 400 K developer (5:1 of DI:Developer, 100ml DI) 1-2 minutes
- 10) DI quench then rinse with low pressure DI, N<sub>2</sub> dry
- 11) Inspect under the microscope
- 12) Hard bake on hotplate at 110°C for 2 minutes with heat shield
- 13) Etch backside nitride windows in RIE-AXIC with etch recipe “nitride” (15 minutes etch time)
- 14) Strip PR in 1165 stripper in ultrasound for 5 minutes (make sure gold side is up), DI quench
- 15) Degrease the wafer (acetone, IPA, DI, IPA, N<sub>2</sub> dry)
- 16) O<sub>2</sub> de-scum in RIE for 1 minute at 100 W only if needed
- 17) Spin coat top of wafer with ProTEK Primer (recipe #8, 1500 rpm for 30 seconds)
- 18) Bake at 205°C for 60 seconds
- 19) Spin coat top of wafer with ProTEK Protective Coating (recipe #9, 1500 rpm for 60 sec)
- 20) Bake at 140°C for two minutes and then at 205°C for one minute
- 21) Load wafer in KOH and put into 30% KOH solution (1400mls of 45% KOH and 700 mls DI), set hotplate to 120°C and bath should be 63°C, set stir-plate at 180RPM, and etch for 24 hrs

## 5.2 KOH Etching

- 1) Verify that KOH solution is at proper temperature (63°C) and that the hotplate is set accordingly.
- 2) Verify that the cooling water for the KOH bath lid is on. (This is to prevent the solution from evaporating away. Vapors will condense on lid and drip back into bath.)
- 3) Rinse wafer holding jig well with DI water.
- 4) Place wafer in jig with wafer flat down.
- 5) Place wafer jig into KOH etch bath with stir bar in center (180 rpm)
- 6) Set timer for 24 hours but watch progress and remove when all windows are open.

# Week 6 Measurements and Packaging



## Summary

### 6.1 Process review

### 6.2 Packaging

## 6.1 Process Review

- 1) Group A
- 2) Remove ProTEK coating in 1165 (~5 minute) bath followed by acetone/IPA rinse/N2
- 3) Test resistance measurements on probe station
- 4) Prep package devices (prep room)
- 5) Group B
- 6) Prep package devices (prep room)
- 7) Remove ProTEK coating in 1165 (~5 minute) bath followed by acetone/IPA rinse/N2
- 8) Perform profile measurements using profilometer

## 6.2 Packaging

Students will do on-wafer testing of their micro fabricated pressure sensor. These tests include resistance measurements and profile measurements. The packages will also be prepared this week but the device will not be assembled until next week.

### **6.2A Resistance testing**

- a. We use the 4-probe station to test the resistance of the pressure sensor. The data will be entered into a large spreadsheet for everyone to utilize at the end of the project for data analysis.

### **6.2B Profile testing**

- a. The profilometer will be used to test the profile of your NiCr wires. For every die, you need to get the height of the resistance strip, the width of the strip, and the gap between the strips. Both the sensing and reference resistance are needed for testing, however the sensing area is extremely vulnerable once it is on top of the nitride membrane. Using the provided sketch of the wafer, note the number for each die, test every usable die, and record all the needed data.

### **6.2C Package preparation**

- a. The packages for our pressure transducers were fabricated using a stereo lithography apparatus (SLA). If you would like to read more about this process, information is available at <http://www.arpotech.com.au/slahelp.htm>. Although this process can create pieces to quite good mechanical tolerances, additional preparation must be done on the packages. Since this work involves a lot of particle generation, it will be completed in the sample preparation room.
- b. The screw holes that are used to hold the two halves of the package together as well as hold the 3 pogo pins in place must be tapped and threaded. These include the four holes at the corners of the bottom half of the package and the 3 holes that go into the side of the contact pin holes. When tapping the thread, it is important not to damage the surrounding plastic by trying to force the tap in too rapidly. Therefore, the best method to tap is to alternate between two clockwise turns and one counterclockwise turn. After every couple of turns, completely remove the tap and clear the plastic particles out of the cutting threads. Continue until the thread is cut all the way through. It is important not to force the tap through the hole but rather let it cut and pull itself through.
- c. The package must also be inspected for any defects or burrs. These are especially critical on the inside of the package where the die will sit as well as the grooves for the o-rings. Remove any burrs found on these surfaces carefully, using a razor blade or x-acto knife.
- d. Finally insert the two o-rings into the grooves as well as the three pogo pins and the seven screws.

### **6.2D Packaging and testing the sensor**

- a. Place the die on the bottom half of the package, take great care to make sure that the electrical contacts are facing up, and the top is placed with the side of the gold contact pads aligned with the pogo pin holes so the electrodes can be in contact with the pogo pins as they are inserted through the holes. Screw the four screws at the corners of the package evenly.
- b. Insert the pogo pins into the holes, hold them down with one finger, and tighten them by screws. If you push the pogo pin too hard when tightening them, it might break the die and your device will not work. Push down slightly and tighten them. If you do not push them when tightening, they might not contact well enough and the device will not work. Make sure

the pogo is in contact with the die and the die is not broken. Measuring resistance between the 3 pogo can do this.

# **Week 7 Testing**

## Summary

### 7.1 Process Review

### 7.2 Test devices

## **7.1 Process Review**

- 1) Load devices into packages by placing into bottom packager first
  - a) Ensure the Cr/Au pads align with the gold pogo pins
  - b) Make sure to use 2 o-rings
  - c) Make sure to align notch in top and bottom of the RP package
- 2) Load device into test jig
- 3) Connect pressure tubing (forward tube should be on the backside)
- 4) Make electrical connections ( $R_{\text{sensor}}$  should be the furthest to the right)
- 5) Balance the Wheatstone Bridge
- 6) Incrementally pressurize the forward side (and/or back side) of the membrane by opening the valve and record the current at each increment until membrane failure occurs
- 7) Close the valve
- 8) Release the pressure in the line
- 9) Load next sample
- 10) Discuss project report

## **7.2 Test Devices**

- A. Load packaged devices into test jig (see figure 7.1) with pogo pins facing to the left
- B. Connect pressure tubing - forward tube should be on the front side
- C. Make electrical connections to  $R_{\text{sensor}}$ , ground and  $R_{\text{reference}}$  -  $R_{\text{sensor}}$  should be on top
- D. Turn power on
- E. Balance the Wheatstone bridge using first the coarse and then the fine potentiometers, the bridge is balanced when there is zero current
- F. Verify that the both the forward and reverse line valves are closed on the pressure apparatus
- G. Incrementally pressurize the forward side (and/or back side) of the membrane by opening the valve and record the current at each increment until membrane failure occurs

- H. Close the valve
- I. Release the pressure in the line
- J. Load next sample and repeat
- K. Discuss project report

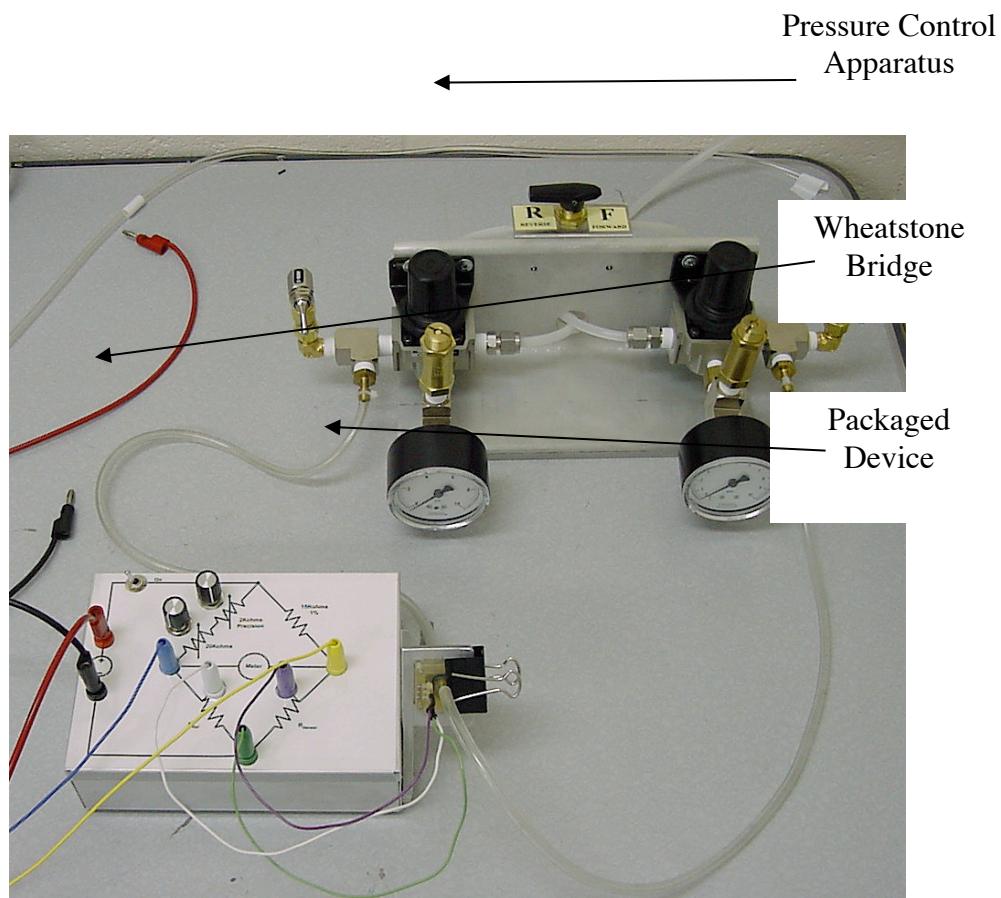


Figure 7.1 Testing setup for Project 1.

# Project 1 Overview

Write-up by: Prof. Mark Shannon

The sensors are fabricated using low-pressure chemical vapor deposited (LPCVD) amorphous silicon nitride ( $\text{SiN}_x$ ) on single crystal Si wafers. The  $\text{SiN}_x$  layer will be patterned, and partially removed with reactive ion etching (RIE), to form a "window" exposing the Si beneath it. The exposed Si will then be anisotropically wet etched away in a potassium hydroxide (KOH) solution, until a membrane of  $\text{SiN}_x$  on the other side of the wafer remains. This membrane forms the diaphragm that is strained under an applied differential pressure. The strain is measured by nickel chromium (NiCr) thin-film strain gages that are sputtered and patterned on the  $\text{SiN}_x$  diaphragm.

The microfabricated sensors of various sizes and pressure ranges will then be packaged and tested. The results will be compared to theory, and a report will be written that will address the sources of errors (both systematic and random), and how the individual fabrication processes affected the measured results.

Micromachined pressure sensors work on a simple principle. A pressure difference across a diaphragm causes it to deflect and become mechanically displaced and/or strained. Various displacement and/or strain detection methods are employed: capacitive, resistive, piezoelectric, piezoresistive, resonant beam, Hall effect, magnetoresistive, optical, etc. One of the earliest, simplest, and effective methods is to put a strain gage on the diaphragm to measure the strain induced by the pressure. To design and fabricate the sensor, we need to understand how the diaphragm deflects under pressure, how a strain gage converts the strain to an electrical signal, and how the signal is processed to reduce noise.

The bulk micromachined pressure sensors we are considering all have the same form, as shown by the cross section view in Figure 1. The diaphragm is much thinner than the substrate wafer, and essentially is constrained from moving at the edges. A strain gage is bonded to the diaphragm. The bulk micromachined cavity is enclosed, so that a pressure differential can be applied across the diaphragm. A review of various pressure sensors is given in Madou in pgs. 631-636.

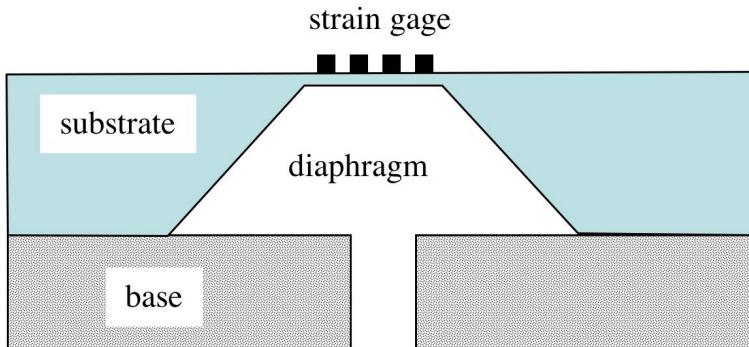


Figure 1.

## Diaphragm Theory

The goal of diaphragm theory is to predict the deflection and thus strain of a diaphragm as a function of pressure, shape, size, and boundary conditions of the diaphragm, as well as the material properties. With the deflection known for a given diaphragm and pressure, then the strain gage and signal processing can be designed to give the measurable output. The fabrication methods to achieve the designed parameters can then be evaluated. A good source for the analysis is Timoshenko and Woinowski-Krieger, *Theory of Plates and Shells 2nd Ed.*

## Small Deflection Theory

Standard elementary methods to predict the deflection of a plate under various loadings assume very small deflections, such that the total deflection is much less than the thickness of the plate ( $w \ll h$ ). While limiting, small deflection theory provides a good starting point for the analysis. The governing equation for the deflection,  $w$ , of an elemental strip for an Euler-Bernoulli beam plate is

$$D \frac{d^2 w}{dx^2} - S w = \frac{q}{2} x (x - l) - M_o, \quad D = \frac{E h^3}{12(1-\nu^2)} \quad (1)$$

where  $S$  is the axial load,  $M_o$  are the edge moments, and  $q$  is an applied distributed load per unit area, or pressure.  $S$  and  $M_o$  arise from the reactions at the edges, which are assumed to be held rigid and unmoving by the surrounding wafer, i.e. fixed.  $E$  is Young's modulus,  $\nu$  is Poisson's ratio,  $h$  is the plate thickness, and  $l$  is its length. The boundary conditions after applying symmetry are

$$\frac{dw}{dx} = 0 \text{ at } x=0, \frac{l}{2}, \quad w=0 \text{ at } x=0 \quad (2)$$

The solution for the maximum deflection at  $x = l/2$  for rectangular plates takes the form

$$w_{\max}(x = l/2) = \frac{ql^4}{384D} f(u), \quad u^2 = \frac{S}{D} \frac{l^2}{4}, \quad , \quad (3)$$

where  $f$  is a transcendental function. Since  $S$  is not known a priori, the solution for  $w$  must be solved iteratively. However, eqn. (3) shows that for small deflections ( $w \ll h$ ) that the deflection is proportional to the pressure, to the fourth power for its length, and inversely to the cubic power for its thickness. Therefore, the plate size can easily be adjusted to linearly scale different pressure ranges.

For plates that are fixed along all sides, various methods can be employed to determine the solutions for given geometries. Circular diaphragms are first considered due to their simplicity, then rectangular geometry, since it is a common shape given by anisotropic wet etching methods.

### Circular Diaphragm

A uniformly loaded circular diaphragm of diameter,  $d$ , with fixed edges has a maximum deflection at the center for the small deflection case of

$$w_c(r=0) = \frac{q(d/2)^4}{64D} \approx 0.00098 \frac{qd^4}{D} \quad . \quad (4)$$

The radial strain,  $\varepsilon_r$ , for the small deflection is,

$$\varepsilon_r = \left( \frac{q(d/2)^3}{64D} + \frac{1}{\tan(\Phi)} \right) \Phi - 1, \quad \Phi = \pi - 2 \arctan \left( \frac{64D}{q(d/2)^3} \right) \quad . \quad (5)$$

To the first order,  $\varepsilon_r$  is linear with  $q$ , since small deflections were assumed to find (4) initially.

### Rectangular Diaphragm

Approximate solutions have been found for uniformly loaded rectangular diaphragm with fixed edges. The a maximum deflection at the center of a rectangle  $a$  by  $b$ , as showed in figure 2, is

$$w_c(x, y = 0) \approx 0.00260 \frac{qa^4}{D}, b/a \rightarrow \infty. \quad (6)$$

For a square diaphragm,

$$w_c(x, y = 0) \approx 0.00126 \frac{qa^4}{D}, b/a = 1. \quad (7)$$

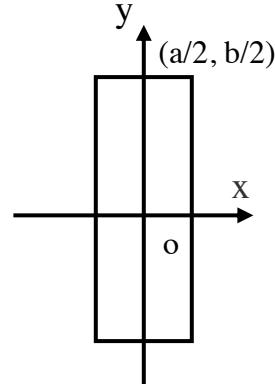


Figure 2

which is 1.28 times larger than a circular diaphragm with  $d = a$ . For equal area diaphragms, the center deflection of the circular diaphragm is  $0.00158 qa^4/D$ , or 1.25 times larger than the square. The discrepancies are due to the fact that square and rectangular diaphragms have more than one radius of curvature for  $b/a$  finite, compared to the single curvature of the circular case. Thus, the deflection and strain profiles are more complicated for rectangular diaphragms. A simple expression for strain as in (5) is not forthcoming, although to the first order it is still proportional to the pressure. Strain gages, therefore, are calibrated to give an accurate pressure/strain response. However, for design purposes, (6) & (7) and the form of (5) adjusted for the appropriate constant can be used to estimate the radial strain.

### Large Deflection Theory

Complicating the analysis a little further, the deflections for thin-film diaphragms can easily extend past the small deflection assumption, which begins to give significant errors by  $w > 0.5 h$ . For  $1 \mu\text{m}$  diaphragms over 1 mm square and larger areas, deflections of  $10 \mu\text{m}$  are commonly achieved. Large deflection plate theory starts with an assumed deflection profile and uses a strain energy formulation to predict the deflection profile. Some results of interest follow.

### Circular Diaphragm

A uniformly loaded circular diaphragm of diameter,  $d$ , with fixed edges is assumed to have a deflection profile as

$$w(r) = w_c \left( 1 - \frac{r^2}{(d/2)^2} \right), \quad (8)$$

with the center deflection determined from the theory as

$$w_c(r=0) = \frac{q(d/2)^4}{64D} \frac{1}{1+0.488 \frac{w_c^2}{h^2}} \quad . \quad (9)$$

The last term comes from the effect of stretching the diaphragm due to the deflection, which acts to stiffen the diaphragm. The deflection is no longer proportional to the pressure. As  $w_c$  becomes much larger than  $h$ , the solution changes dramatically from the small deflection case. For really large deflections, (9) is no longer applicable, and exact theory must be used. However, the numerical results of exact theory show a similar roll-off in  $w$  with  $q$ .

For very large deflections, another theory can provide very useful results. In the limit of  $w_c \gg h$ , if we assume that incompressible deformation of the diaphragm takes place such that  $v$  approaches 1/2, then (9) reduces to the result that given by membrane theory. Membrane theory assumes incompressible deformation, and that bending moments due not occur within the plate. For this case, the center deflection is given by

$$w_c = 0.662(d/2)^3 \sqrt[3]{\frac{qd}{2Eh}} \quad . \quad (10)$$

The deflection is now proportional to the cube root of the pressure, and inversely to the cube root of the thickness, rather than the inverse cube, both of which are much weaker dependence than for the small deflection case. It is also only slightly greater than proportional to the diameter.

### Rectangular Diaphragm

Rectangular diaphragms in large deflections add a considerable level of complexity to finding a closed form solution, such as that given in (9) for circular ones. As such, numerical solutions and evaluations of the equations are required to approximate the deflections. The essence, however, is similar to circular diaphragms. The solution begins basically proportional to the pressure as in (6) & (7) and ends similar to the membrane theory of (10). Careful calibration is a must in practice to achieve accurate results.

All these results show that large deflections of the diaphragm should be avoided in the design, if our only concern is diaphragm theory. However, the strain must be converted via a gage to an output signal. As will be seen, for very small strains, the signal to noise ratio of strain gages places a lower limit on the deflection needed to accurately measure the pressure.

### Strain Gage Theory

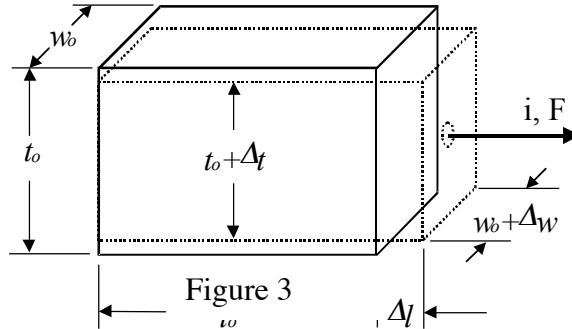
#### Materials

Most strain gages work by changing an electrical output (some give a photoelastic output). Three main types of response are: (i) change in resistance with strain, (ii) change in piezoelectric voltage, and (iii) piezoresistive output. Other types of material responses also can be utilized, but are beyond the scope of this lab. Pure metals create resistive type gages, piezoelectric materials such as zinc oxide and PZT can be integrated with conductors to form pure piezoelectric gages, and doped polysilicon is commonly used for piezoresistive gages.

## Resistive Theory

Resistive-type strain gages operate under a simple principle. Stretching, or straining, an electrical conductor changes its length and cross-sectional area. As the length and cross-sectional area changes, the resistance to current flow changes. Consider an element being stretched as shown in Figure 3. A current,  $i$ , flows in the same direction as the applied force,  $F$ , that is stretching the element. The resistance of the element can be expressed from the definition as

$$R = \frac{\rho_e l}{t w} = \frac{\rho_e (l_o + \Delta l)}{(t_o + \Delta t)(w_o + \Delta w)} = \frac{\rho_e l_o}{t_o w_o} \frac{(1 + \Delta l / l_o)}{(1 + \Delta t / t_o)(1 + \Delta w / w_o)}, \quad (11)$$



where  $\rho_e$  is the electrical resistivity of the material. If we assume that the material is isotropic and is *uniaxially* strained (not the actual condition), and that  $\rho_e$  does not change with strain (not a good assumption for large strains, but basically true for the small strains being considered), then with the axial strain  $\Delta l / l_o = \varepsilon$ ,  $\Delta t / t_o = \Delta w / w_o = -\nu\varepsilon$ , the resistance can now be written

$$R = \frac{\rho_e l_o}{t_o w_o} \frac{(1 + \varepsilon)}{(1 - \nu\varepsilon)^2} = R_o \frac{(1 + \varepsilon)}{(1 - 2\nu\varepsilon + \nu^2\varepsilon^2)}, \quad (12)$$

where  $R_o$  is the initial resistance of the element. Note that  $\Delta w / w_o \approx -\nu\varepsilon$  is assumed for the sensor element. This assumption can lead to a small error, since for bonded thin-films, it is the strain of the substrate that dominates the change in  $w$ , not that of the sensor material.

If we are to look at the change in voltage across the element after it is strained, if we keep the current flow,  $i$ , constant through the element regardless of the strain, then

$$\Delta V = V - V_o = i_o R_o \frac{(1 + \varepsilon) - (1 - 2\nu\varepsilon + \nu^2\varepsilon^2)}{(1 - 2\nu\varepsilon + \nu^2\varepsilon^2)} = i_o R_o \varepsilon \frac{1 + 2\nu - \nu^2\varepsilon}{(1 - 2\nu\varepsilon + \nu^2\varepsilon^2)}. \quad (13)$$

While eqn. (13) is general and shows that the voltage changes non-linearly with strain, a much simpler form can now be found. Since the strain imposed must be small (even for the large deflection case the *strain* is still small), then for  $\nu < 1$  and  $\varepsilon \ll 1$ , (13) becomes

$$\Delta V = i_o R_o (1 + 2\nu) \varepsilon = i_o \frac{\rho_e l_o}{t_o w_o} (1 + 2\nu) \varepsilon. \quad (14)$$

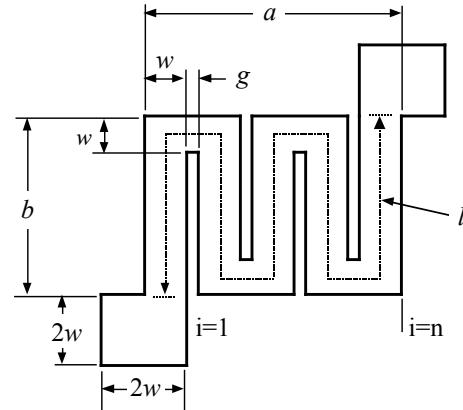
Eqn. (14) shows that the change in voltage is linear with the strain. It also shows the variables that the designer can manipulate to increase the signal. To maximize the  $\Delta V$  for a given strain (i.e. signal), we can attempt to maximize the path length over the cross-sectional area ( $l/t w$ ), and find

a material with a high resistivity. But keep in mind that as resistance increases, so does the self-heating, or the  $i^2 R$  dissipation. The main issue is the heating per unit volume, given by

$$q''' = i_o^2 \frac{\rho_e}{t_o^2 w_o^2}, \quad (15)$$

which is independent of the path length. Hence, increasing  $l$  is a no-penalty method of increasing signal. Eqn. (15) also shows that to keep the heating constant with increasing resistivity, the current needs only to decrease by the square root. Thus, increasing  $\rho_e$  while keeping heating constant, increases  $\Delta V$  only by the square root of the increase. Decreasing cross-sectional area, while looking appealing in (14) requires a one for one reduction in current, given by (15). But other factors come into play. As the thickness,  $t_o$ , decreases below a particular size, the effective resistivity increases, which again helps slightly. Other issues are interference between thermal expansion, changes in resistance due to temperature of the gage. A thin-film bonded to the substrate also takes on the mechanical properties of the substrate. So the ideal material would have the same mechanical properties of the substrate, zero changes in resistance with change in temperature (i.e.  $\alpha = 0$  in  $R_o(1 + \alpha\Delta T)$ ), and high resistivity. Each of these factors needs to be considered when interpreting the signal output.

The material often used in standard strain gages is a nickel chrome alloy, NiCr, which is also used for heater elements. NiCr has both a very low thermal coefficient,  $\alpha$ , one of the lowest of all metals, and has a high  $\rho_e$ , one of the highest of all metals, making it nearly ideal.



$a, b$  = length of sides       $n$  = number of serpentines (integer)  
 $g$  = gap thickness       $t$  = thickness (into the page)  
 $l$  = active resistor length       $w$  = width of serpentine

Figure 4

### Strain Gage Design Parameters

Figure 4 shows a general shape of the resistance strain gage sensors, with the important dimensions labeled. The overall design goal is to achieve the highest possible signal for the given area. To do so, the path length,  $l$ , is to be maximized for given side lengths,  $a$  and  $b$ , and minimum gap size,  $g$ . There are two main constraints to maximizing  $l$ . The minimum  $g$  depends on the resolution attainable during the photolithography and patterning process. High-resolution masks yield a considerably smaller  $g$ , on the order of 1 to 2  $\mu\text{m}$ , producing a sensor with a smaller overall area for the same active area. The second main constraint is that the number of serpentine lengths,  $n$ , must be an integer, which limits the value of the width,  $w$ , for a given  $g$ .

In terms of the parameters in Fig. 4, the maximum size of a serpentine sensor is

$$ab = (n(w + g) - g)b = (nw + (n - 1)g)b, \quad (16)$$

excluding contact pads. The active path length,  $l$ , is defined as the total centerline length of the serpentine resistor. For many serpentine passes ( $n > 10$ ), or large aspect ratio ( $l/w > 100$ ), the centerline approximation gives a reasonably accurate estimation of the true active length. However, for few serpentine passes or small aspect ratios, the centerline approximation breaks down, since a larger percentage of the current will flow along the inner corners of the serpentine, rather than along the outer corners. Using the centerline approximation, the active sensor length can be estimated as

$$l \approx nb + (n-1)g . \quad (17)$$

### Signal Processing

How to best extract the strain signal from the gage is a rather large subject that will not be covered here. But some basic concepts are needed to design the device to achieve the needed resolution for a given pressure range.

Strain gages can be run in either a constant current or constant voltage mode, with benefits and trade-offs for both. In constant voltage mode, the current is measured as it changes with resistance. Constant voltage sources are straightforward to implement in a circuit, as are precise current measurement sub-circuits. Constant current mode can be employed, using a current source and reading voltage variations. Variations in power dissipation due to  $i^2R = V^2/R$  heating within the gage itself and the leads due to changes in resistance due to the strains causes errors to occur. Reducing the voltage or current to counter these inherent errors increases the signal to noise ratio. Consider the relative error of the voltage in Eqn. (14), such that

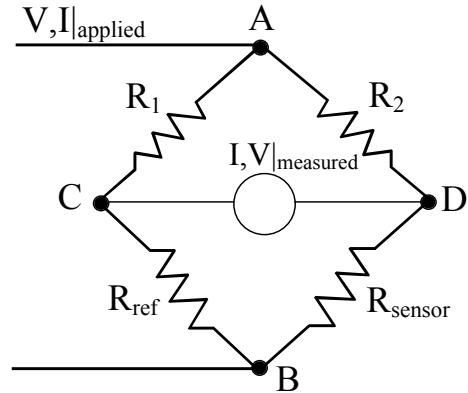


Figure 5

$$\frac{\Delta V \pm \delta_V}{V_o \pm \delta_{V_o}} = (1 + 2\nu)(\varepsilon \pm \delta_\varepsilon) , \text{ and } \varepsilon \pm \delta_\varepsilon = \frac{1}{(1 + 2\nu)} \left( \frac{V \pm \delta_V}{(i_o \pm \delta_i) R_o} - 1 \right) . \quad (18)$$

The right terms show that as  $i_o$  becomes much smaller than its uncertainty  $\delta_i$ , the uncertainty in the pressure-induced strain grows quickly. Conversely, for very small strains, as the signal drops below the uncertainty in voltage readings (usually set by the resolution and noise of the data acquisition system), the voltage reading becomes all noise. The solution to these issues is to design

the deflection to have sufficient strain for a given pressure range, and a current well above the uncertainty in measuring it.

Most often, neither the voltage nor current is directly measured from the strain gage. Instead, to help mitigate various factors, such as variations in temperature, humidity, aging, etc., which would change the output of the sensor, a Wheatstone Bridge configuration is employed. Figure 5 is a diagram of a Wheatstone Bridge, in which two sensors are used: one as the active element,  $R_{\text{sensor}}$ , on the diaphragm and the other as the reference,  $R_{\text{ref}}$ , on the solid substrate.  $R_1$  and  $R_2$  are chosen to (i) maximize the difference change from A to B, and (ii) balance the bridge so at the reference configuration either the potential between C and D is zero, or the current that flows between C and D is zero. Whether or not the circuit is operated with a voltage or current applied between A and B, and whether I or V is measured between C and D depends on several factors. Often, a voltage  $V_{AB}$  is applied, and a current  $I_{CD}$  is measured, in order to keep the potentials the same across  $R_1$  and  $R_2$ , and  $R_{\text{ref}}$  and  $R_{\text{sensor}}$ , so that differences in  $i^2R$  heating between each resistor is minimized, so that these systematic errors are mitigated.

In general, strain gages are noisy and are generally not run with a steady-state current or voltage. Modulating the input source and using either filters or auto-correlation schemes provides relatively straightforward methods for increasing the signal to noise ratio. Millivolt signals for microstrains are easily achieved using these types of signal processing schemes. We will look at both the steady-state and transient output from our pressure sensors for testing.

## Diaphragm Fabrication

### Controlling Diaphragm Thickness

Controlling the diaphragm thickness to have a uniform thickness and smooth surfaces are the prime goals of the etching process used. One of the basic problems is the beginning silicon wafer. Normal silicon wafers are designed for electronics, so that the top surface is very smooth (usually  $< 2 \text{ nm rms}$  roughness) and has very few defects. However, the backside doesn't need to be smooth, nor do the two sides need to be perfectly parallel for the electronic devices to be fabricated. However, the smoothness and parallelism of both sides' matters for bulk etching. Many etching processes tend to follow the initial surfaces, so if they start off rough, they'll remain so, i.e. if the etch rate is uniform as desired, the roughness will be maintained. Therefore, more expensive double-sided polished Si wafers are used for the bulk-etched substrates. The variability in thickness also causes problems. If the final thickness of the diaphragm is determined by timing the etching, even assuming a uniform etch rate, then if the wafer thickness varies, so will the final diaphragm thickness. Wafers are known to vary as little as  $2 \mu\text{m}$  and as much as  $50 \mu\text{m}$  from center to edge. Therefore, often more expensive prime wafers with size control are used for the bulk sensors, particularly for DRIE etch wafers. The situation becomes more complicated when realistic, non-uniform etch processes are considered. Etch rates are frequently slower or faster near the edges of the cavity as the etch depth increases due to side wall and fluid dynamic effects. A great deal of process control has gone into improving uniformity in etch rates. However, the single most used method of controlling diaphragm thickness and surface finish is by using etch stops, which will be presented later.

The sensor is to be fabricated on a  $<100>$  crystalline, double side polished, silicon wafer covered on both sides by  $\sim 1 \mu\text{m}$  of LPCVD silicon nitride. The fabrication process depicted in Fig. 1 begins with double side alignment marks on the wafer followed by an evaporation of 50 nm of NiCr to form the sensor and Cr/Au to form the leads. The backside nitride below the sensor is

to be reactively ion etched (RIE) using a SF<sub>6</sub> plasma, to open a "window" in the Si wafer. The Si window is to be wet anisotropically etched in a 30% KOH solution at 65 °C to form a SiN<sub>x</sub> diaphragm on which the sensors are deposited.

### Etching Techniques

#### Wet etching

The main wet etching techniques that are employed are isotropic (primarily acid etching of glasses and silica), and anisotropic etching of Si with KOH, TMAH, EDP, and N<sub>2</sub>H<sub>4</sub>. The following issues will be considered: etchant concentration and chemistries, temperature and fluid dynamics, mask materials and processing, and etch stops. All these factors will determine the design and performance of the pressure sensor.

#### Dry etching

The main dry etching techniques used are different types of reactive ion processes, RIE, RIBE, CAIBE, ICP-DRIE. We will conduct ICP-DRIE etching of Si, and the major portion of the laboratory is to determine the parameters used for the etching, the mask materials and processing, and etch stops that are possible. The focus will be to understand the process' strong and weak points.

### Growth Techniques

The major growth techniques used for the bulk micromachined pressure sensors include those used in surface micromachined devices, epitaxial silicon layer growth, low temperature and high temperature dry and wet including thermal silicon dioxide for masks, LPCVD oxides and nitrides, PECVD oxides and nitrides, LPCVD poly-silicon, metal evaporation and sputtering, as well as oxide sputtering. We will focus on LPCVD and PECVD oxide and nitride growth for the mask layers, and metal evaporation and sputtering for the strain gage.

### Strain Gage Fabrication

The strain gages are fabricated using a number of processes. As will be detailed in the process sheets, NiCr thin-film serpentine patterns are sputtered onto the SiN<sub>x</sub> surface before the Si wafer is KOH etched. The pattern is made using a liftoff photolithography process. Low resistivity leads made from gold (Au) are then sputtered and patterned on top of the NiCr pattern to complete the strain gage circuit on the wafer.

### Packaging

Once the sensors are completed in wafer form, the individual dies are diced (removed) from the wafer, and are to be packaged in a plastic carrier, as will be detailed, in order to make the electrical contacts, as well as form the inlet and outlet ports to apply the pressure across the diaphragm.