Anodic Bonding For X-Ray Optics

Authors: Erik Burt, K.D. Finkelstein

Abstract

Analyzer crystals are specialized mirrors used to reflect and focus x-ray emissions onto a detector in certain kinds of x-ray spectrometers. This will be a discussion of the feasibility and methodology of creating analyzer optics for x-ray diffraction equipment by means of anodic bonding. The primary focus was on creating repeatable bonds between Schott Borofloat®33 borosilicate glass and polished silicon wafers with specific surface normal crystal orientations. In order to achieve this, we created a safe enclosure to contain the process, and then heated glass and silicon together before applying a voltage. [1]. In order to determine process tolerances, we bonded both recycled, previously manufactured analyzers and fresh glass samples. Bonding was achieved, and it appears that process tolerances may be broader than indicated by Verbeni et al [2].

Introduction

The Dual Array Valence Emission Spectrometer (DAVES) uses five spherically curved analyzer crystals to focus sample emissions onto the detector. These analyzers are shaped to suit specific experimental conditions and expected emission angles, therefore their construction is an ongoing aspect of equipment operation as Prior to this project, analyzers were constructed by epoxy gluing silicon wafers to ground glass substrates. This method was time consuming, expensive, and frequently produced poor results. Dr. Verbeni, working on similar equipment at the European Synchrotron Research Facility, successfully used an electrochemical method called anodic bonding to create analyzer crystals. Extrapolating from his success, and using the wealth of data available on the anodic bonding process from decades of use in semiconductor and MEMS manufacturing, a process was designed and made safe for use at CHESS. (See Appendix A for manufacturing process safety procedure)

Overview of Anodic Bonding

Anodic bonding is an electrochemical bonding process in which a glass substrate and a silicon film or wafer are heated to the point where the ions within the substrate become mobile and can migrate under an applied electric field[1]. This point varies for different formulations of glass, but usually occurs around 200-250C.

By stacking the glass and silicon together, heating to the critical temperature, and applying a voltage across the stack, it is possible to separate these ions, drawing the sodium towards the ground electrode at the bottom of the stack, while the oxygen is drawn to the interface between the silicon and glass. There, the oxygen bonds readily with the silicon, provided that the two surfaces are sufficiently flat and clean. Minimal pressure is required as the electrostatic attraction between the surfaces will cause a “zippering” effect, spreading from one or a few points of contact. The voltage applied can vary widely, depending on multiple factors including thickness of material, desired bond strength, and material composition.

The resulting silicon dioxide bonding layer is strong and conforms perfectly to the surface of the glass, whether flat or spherically curved. It is also relatively inert and stable at room temperature, and provides durable resistance to the mechanical stress from the bent wafer.

See Figure 1 in Appendix B for complete parts list and schematic view of process setup.

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Developing Bonding Parameters

In reviewing the literature on anodic bonding, it became clear that the success of the process hinged on a few key parameters: cleanliness of the bonding surfaces, temperature of the substrate, voltage applied, and the duration of each phase of the process. Substrate geometry was not considered a relevant parameter, as the radius of curvature for spherical analyzers is always either 85cm or 100cm, as determined by the operational needs of DAVES. Substrate composition is determined by the requirement that it closely match the thermal behavior of the silicon wafer, in order to minimize thermal stress. Due to equivalence of equipment and materials, Verbeni's parameters were used as a starting point, with modifications as noted to suit requirements at CHESS.

To ensure cleanliness, we removed particulates and organics from the raw materials using a multistep process of solvent application and ultrasonic cleaning. Furthermore, the process took place within an Air Science Purair FLOW laminar flow cabinet, and the work area and equipment were thoroughly cleaned under the hood prior to use. (See the Appendix A for detailed descriptions of the cleaning process.)

The glass currently used for DAVES' analyzers has a thermal expansion coefficient that is well matched to silicon, with a wide temperature range within which thermal stress in the bond between wafer and substrate is minimized. As a result, heating parameters were determined solely based on equipment limitations. Maximum stack temperature achievable with the current configuration appears to be ~350C.

Voltage parameters were determined by safety concerns stemming from a review of available literature, which indicated that spontaneous arcing between electrodes might occur at potential exceeding 800V[1]. This parameter value has reliably and repeatedly produced satisfactory results, though it may prove desirable to find and use lower voltages in the future. Properly trimming the Kapton foil to avoid arcing is a painstaking process, and reducing voltage would allow for greater tolerance in overhang and therefore faster preparation and manufacturing turnaround.

The final process parameter is time, or rather timing. However, this parameter is easily determined experimentally, due to the nature of the bonding reaction and the equipment used. The Ortec power supply has a dual function meter (voltage and current), and a "bleed off" safety feature for current, the combination of which allow for easy measurement of current flow within the process stack. Ion migration within the glass causes current flow, which means that completion of the bonding process can be quantitatively determined by graphing current in the stack circuit vs time to determine when ions have stopped flowing into the bond, represented by the graph approaching a horizontal asymptote. This triggers the cessation of heat. Next, as the temperature of the substrate drops below the critical point, current drops to a constant minimum value indicating that ion migration has ceased and that voltage can now be disengaged.

See Appendix B for graphical illustrations of stack temperature and current over time

Results and Next Steps

Anodic bonding has been shown to be a fast and effective method of creating new spherical analyzer crystals for the DAVES system. Repeated bonds were formed using fragmentary wafers and recycled substrates, with varying degrees of quality and completeness.

The results of these initial tests were used to tune recipe parameters, and the poor quality of input materials must be taken into account when considering output quality. More important is that the process appears to have very high yield, even taking poor input quality into account.

The final test was performed using a fresh wafer and substrate of standard .5 inch thickness and 85cm radius of curvature, and it appears to have been a complete success. This final manufactured analyzer shows good visual conformity and apparent strength. However, a thorough characterization of the bond has yet to be completed. Shape of the bonded crystal surface will be tested both using an optical laser setup, and by comparing performance in the DAVES system to known analyzers. Bond strength could be tested by attempting to pull the analyzer apart at the interface using a specially constructed load frame. This is not considered a high priority, though further testing may be required if the lifetime of the new analyzers proves shorter than previous generations.

Though not crucial for production of quality analyzers, additional work could be done in establishing minima for process parameters. It is noteworthy that the voltage parameter is substantially less (700V-3200V) than in Verbeni's work, as is the time required for the bonding process (minutes vs hours). This defies expectations, as Arrhenius' equation suggests that the inverse should be true. Materials and equipment used in both procedures appear to be equivalent, so this discrepancy should be explored at some point.

Another area of interest is assessing the suitability of this method for the construction of toroidal analyzer crystals. Toroidal analyzers would use a similar process, but pose additional challenges including press tool design and wafer flexibility. Such analyzers would improve focus spot shape of the DAVES system when working at Bragg angles well below 90 degrees.

Bibliography

1. "The Creation of an Anodic Bonding Device Setup and Characterization of the Bond Interface Through the use of the Plaza Test"; Thesis, California Polytechnic State University, San Luis Obispo, CA; Timothy Michael McCrone; February 21, 2011
2. "Advances in crystal analyzers for inelastic X-ray scattering"; Journal of Physics and Chemistry of Solids 66 (2005) 2299–2305; R. Verbeni *, M. Kocsis, S. Huotari, M. Krisch, G. Monaco, F. Sette, G. Vanko
3. Schott Borofloat®33 datasheet, available online.
http://www.us.schott.com/borofloat/english/download/index.html
This was used to find temperature parameters and electrical properties.

Acknowledgements

I would like to thank the CHESS Safety Committee and the Machine Shop technicians John Kopsa and Jerry Houghton for their feedback in the process of designing the safety enclosure and developing the SOP.

This work is based upon research conducted at the Cornell High Energy Synchrotron Source (CHESS) which is supported by the National Science Foundation under award DMR-1332208

STANDARD OPERATING PROCEDURES
FOR
Si-GLASS ANODIC BONDING

1. PROCESS OVERVIEW: ANODIC BONDING

The process of anodic bonding involves high voltage at low current, temperatures up to 350C, and possible solvent cleaning of parts in an environment separate from where bonding is done. Proper handling of the materials and procedures involved will reduce or eliminate risk of personal injury or property damage. The steps and information outlined below must be followed while using anodic bonding to produce lenses. Consult your supervisor or Ken Finkelstein before modifying these steps or instrument specific lab procedures.

The steps outlined below address general safety concerns while setting up and operating anodic bonding equipment. You must make sure that the equipment and lab specific operational procedures used are in accordance with this document. Necessary changes should be submitted in written form with the help of the Principal Investigator and verified by the CHESS safety committee and incorporated into this SOP to be followed.

All procedures described herein should be conducted with standard PPE, including but not limited to safety glasses and nitrile gloves. Wherever possible, operations should take place within a single work area as described below. This will ensure user safety, as well as production quality.

2. HAZARDOUS CHEMICALS/CLASS OF HAZARDOUS CHEMICALS

FLAMMABLE LIQUIDS: Ethanol or isopropyl alcohol, Acetone

3. PERSONAL PROTECTIVE EQUIPMENT

EYE PROTECTION: Safety Goggles, Face Shield if desired.
PROTECTIVE CLOTHING: Apron or Lab coat and appropriate chemical resistant gloves, and heat resistant gloves. Closed-toe shoes.

Solvents are handled inside fume hood although wipes moistened with alcohol can be used in laminar flow hood discussed below.

4. ENGINEERING / VENTILATION CONTROL

Process should be conducted within a HEPA-filtered, laminar-flow clean hood to minimize particulates that will interfere with the bonding process.

Use and handling of acetone for purposes of precleaning wafers and substrates must take place under an appropriate fume hood, located in CHESS chemistry room.

Ensure all heat generating equipment has over temperature shut off device installed.

Ensure all electrical equipment is properly grounded with appropriate breakers/fuses.

5. SPECIAL HANDLING PROCEDURES AND STORAGE REQUIREMENTS

Display and follow the CLASSE/Wilson lab general safety procedures, as well as process-specific procedures for the chemicals and equipment used.

Inspect all equipment for defects before setting them up. Pay particular attention to oxidation or discoloration of electrodes. Electrodes may need to be resurfaced or replaced periodically.

Label all solvents according to CLASSE/CU EH&S guidelines. Store the flammables in the approved flammable storage cabinets whenever they are not being used.
Use secondary containment carriers whenever transporting hazardous material outside of the lab. Use due care and caution when moving hazardous materials.

If precleaning of parts is necessary to remove organic material, use a two-step process (acetone followed by alcohol). Apply solvents under the appropriate fume hood in the chemistry room, then package and transport clean parts to the work area.

Avoid particulate contamination wherever possible. Prepare the work area by thoroughly cleaning with lint-free cleaning cloth each time you set up. Avoid bringing potential contaminants into the work area.

Inspect silicon wafers and glass substrates for defects before use. Report defects to PI.

6. SPILL AND ACCIDENT PROCEDURES

Keep a 5-gallon universal spill kit nearby, which can be used for small incidental spills.

Keep an approved fire extinguisher nearby, in case of electrical/chemical fire.

For large spills/fires- isolate the spill if possible/activate fire alarm, evacuate area, keep people away, and call for help:

EH&S (8 AM - 5 PM) - (607) (25)5-8200
CU Dispatch (24 HOURS) - Dial 911 OR (607) 255-1111 when using outside line or cell phone.

7. WASTE DISPOSAL

Collect any solvent waste generated by this process in appropriate container. Containers are provided in the chemical rooms. Follow established procedure for notifying CLASSE operations staff if the waste containers need to be changed.

PARTICULARLY HAZARDOUS SUBSTANCES ONLY

8. APPROVAL REQUIRED

N/A

9. DECONTAMINATION PROCEDURES

N/A

10. DESIGNATED AREA

N/A

11. DEATAILED EQUIPMENT LIST

Hotplate
DC voltage source with Multimeter
Metalized Kapton film
Convex glass "pressing" tool
Thermocouple
Laminar flow hood with safety doors and sensing hardware installed
Ultrasonic/UV bath
Acetone and alcohol wash bottles
Kimwipes

12. DETAILED DESCRIPTION OF PROCESS

1) Wipe down work area with lint-free cloth. Activate laminar flow hood (clean hood) in work area, and leave running while preparing materials.
2) Test proper operation of safety circuit, ensuring that voltage source cannot be engaged with doors open. Report any failure of the safety circuit immediately and do not operate until repairs have been made.
3) Inspect and, if necessary, degrease silicon wafers and glass substrates.
    a. Degreasing with acetone should be performed in CHESS chemistry room fume hood. Materials requiring this step should be wrapped in clean paper and plastic before transport between chemistry room and the work area.
    b. After cleaning, materials previously degreased can be wiped down with alcohol wipes under clean hood in the work area.
4) Concave glass substrate can be cleaned with UV/sonic cleaner, using recommended settings from manufacturer. Wipe with alcohol to remove moisture, dry quickly, and combine parts as soon as possible, to avoid any contamination of

the contact surfaces. These operations can be performed within the laminar flow hood.

5) Place aluminum ground electrode on hotplate, then glass plate with concave surface up, then silicon wafer, then positive Kapton foil electrode with metalized side against the silicon, then convex tool. Top with weight sufficient to press silicon wafer to convex shape.
6) Kapton foil should overhang wafer surface slightly to allow electrical connection to positive HV supply, but not so far as to contact hot plate or ground. Use trim tool to size both aluminum and Kapton electrodes.
7) Attach voltage source to electrodes, making sure ground is connected to the bottom electrode. HV power source includes volt/current meter.
8) Attach thermocouple. Perform final alignment check, ensuring that silicon wafer is centered over glass parts
9) Close personnel safety doors after ensuring hotplate and lens bonding assembly is grounded.
10) Activate the hotplate. Monitor temperature and adjust as necessary to ensure temperature is at desired setting between RT and 350 degrees C.
11) When substrate reaches desired temperature, apply voltage initially up to 400V DC. Voltage may need to be adjusted upwards, but should never exceed 800V.
12) Monitor current flow, adjusting voltage as necessary to keep peak current no higher than 2.5 milliAmps. As bonding occurs, current will approach a very small value. Once the rate of change has slowed to approximately 0.01 mA per 2 minutes, heater can be turned off.
13) Continue to monitor current until it reaches zero. At this point, voltage should be turned off. Do not attempt to remove lens until the apparatus has fully cooled.
14) Inspect the lens for adequate bonding. The back of the lens should be smooth and silver. Bubbles, spots of rainbow or other color indicate improper bonding. Wrap lens in paper and label appropriately.
15) Return all equipment to designated storage. If necessary, discard Kapton foil as non-hazardous waste. Unplug all electrical equipment, and turn off laminar flow hood. Leave the area as you would like to find it.

STANDARD OPERATING PROCEDURES
FOR
LAMINAR FLOW HOOD CLEANING

1. PROCESS OVERVIEW:

Successful anodic bonding requires extremely clean surfaces. The primary sources of contamination are organics from handling (finger oils, skin, tool oil transfers, etc.) and particulates from contact and from the air. Establishing a standard for cleaning and preparation of the bonding materials will ensure that contamination is minimized and production is maximized.

Consult your Principal Investigator or Ken Finkelstein before modifying these steps or instrument specific lab procedures. Necessary changes should be submitted in written form with the help of the Principal Investigator and verified by EH&S/CLASSE safety and incorporated into this SOP to be followed at all times.

All procedures described herein should be conducted with standard PPE, including but not limited to safety glasses and nitrile gloves. Wherever possible, operations should be take place within a single work area as described below. This will ensure user safety, as well as production quality.

2. HAZARDOUS CHEMICALS/CLASS OF HAZARDOUS CHEMICALS

FLAMMABLE LIQUIDS: Ethanol

3. PERSONAL PROTECTIVE EQUIPMENT

EYE PROTECTION: Safety Goggles
PROTECTIVE CLOTHING: Apron or Lab coat and appropriate chemical resistant gloves, and heat resistant gloves. Closed-toe shoes. Tyvec sleeves or lint-free clothing(i.e. no wool, flannel, etc.)

4. ENGINEERING / VENTILATION CONTROL

Process should be conducted within a HEPA-filtered, laminar-flow clean hood. This will provide ventilation for any fumes, as well as reducing particulates that will interfere with the bonding process.

Ensure that all heat generating equipment is turned off and cool before attempting to clean.

Ensure that all electrical equipment is properly grounded with appropriate breakers/fuses.

5. SPECIAL HANDLING PROCEDURES AND STORAGE REQUIREMENTS

Display and follow the CLASSE/Wilson lab general safety procedures, as well as process-specific procedures for the chemicals and equipment used.

Inspect all equipment for defects before setting them up in the experiment. Pay particular attention to oxidation or discoloration of surfaces. This may indicate areas where past cleaning has been insufficient, or areas that require additional cleaning before use. Report defective equipment or serious discoloration/oxidation to supervisor.

Avoid bringing potential contaminants into the work area. The only things in the flow hood should be the tools and equipment used in the bonding process. This also maximizes airflow.

Label all solvents according to CLASSE/CU EH&S guidelines. Store the flammables in the approved flammable storage cabinets whenever they are not being used.

6. SPILL AND ACCIDENT PROCEDURES

Keep an approved fire extinguisher nearby, in case of minor electrical/chemical fire.

In case of fire, activate fire alarm, evacuate area, keep people away, and call for help:

EH&S (8 AM - 5 PM) - (607) (25)5-8200
CU Dispatch (24 HOURS) - Dial 911 OR (607) 255-1111 when using outside line or cell phone.

7. WASTE DISPOSAL

No hazardous waste should be generated in the normal application of this SOP. If waste is accidentally generated notify supervisor and CLASSE safety committee, and work with them to complete accident reporting and investigation.

PARTICULARLY HAZARDOUS SUBSTANCES ONLY

8. APPROVAL REQUIRED

N/A

9. DECONTAMINATION PROCEDURES

N/A

10. DESIGNATED AREA

Wilson Lab Room 317(Vacuum Lab)

11. DETAILED EQUIPMENT LIST

Laminar flow hood
Isopropyl Alcohol
Lint-free wipes

12. DETAILED DESCRIPTION OF PROCESS

1) Inspect hood and equipment prior to use. If you have not used the area for some time, inspect electrical connections and filters and have any defects repaired or replaced. Otherwise, simply ensure that all equipment is in good order and at hand before proceeding with cleaning.
2) Before doing any work inside the hood, turn it on. Constant airflow will help remove dust and particulates in the air as you clean the surfaces. Don gloves, apron and Tyvec sleeves. If you have friable hair or dandruff, consider a paper cap.
3) Using alcohol on KimWipes or similar lint-free cloth, wipe down all moveable equipment inside the work area. This includes all wires and supports, and the underside of all equipment.
4) Using alcohol on KimWipes or similar lint-free cloth, wipe down the and benchtop and inside of the flow hood from top to bottom and back to front. Don't forget the ceiling and underneath the hotplate. This step is especially important if the work area has been unused for some time, as dust and contamination may have had time to settle. The alcohol should be sufficient to remove whatever light oils and off-gassed materials may be present.
5) Repeat steps 3 and 4 with a dry lint-free cloth.
6) Leave the flow hood running until you have mated the bonding surfaces. Once the full stack is assembled, you can turn off the airflow to facilitate heating.
7) If particulate contamination begins to be problematic, examine the work area and surrounding room for recent changes. Consider testing air quality with the HAL-HPC600 or similar device. See Chris Whiting ccw63@cornell.edu for training. Manual available online from manufacturer.

STANDARD OPERATING PROCEDURES
FOR
OPTICS BONDING MATERIALS CLEANING

1. PROCESS OVERVIEW

Successful anodic bonding requires extremely clean surfaces. The primary sources of contamination are organics from handling (finger oils, skin, tool oil transfers, etc.) and particulates from contact and from the air. Establishing a standard for cleaning and preparation of the work area will ensure that contamination is minimized and production is maximized.

Consult your Principal Investigator or Ken Finkelstein before modifying these steps or instrument specific lab procedures. Necessary changes should be submitted in written form with the help of the Principal Investigator and verified by EH&S/CLASSE safety and incorporated into this SOP to be followed at all times.

All procedures described herein should be conducted with standard PPE, including but not limited to safety glasses and nitrile gloves. Wherever possible, operations should be take place within a single work area as described below. This will ensure user safety, as well as production quality.

2. HAZARDOUS CHEMICALS/CLASS OF HAZARDOUS CHEMICALS

FLAMMABLE LIQUIDS: Ethanol or isopropyl alcohol, Acetone

3. PERSONAL PROTECTIVE EQUIPMENT

EYE PROTECTION: Safety Goggles, Face Shield if desired.
PROTECTIVE CLOTHING: Apron or Lab coat and appropriate chemical resistant gloves, and heat resistant gloves. Closed-toe shoes.

Solvents are handled inside fume hood although wipes moistened with alcohol will be used in laminar flow hood discussed below.

4. ENGINEERING / VENTILATION CONTROL

Process should be conducted under an appropriate fume hood, located in CHESS chemistry room.

Ensure that all processes are conducted on a clean layer of UHF foil. This will prevent contamination from previous users of the fume hood.

Ensure that fume hood is functioning and splash guards are lowered.

5. SPECIAL HANDLING PROCEDURES AND STORAGE REQUIREMENTS

Display and follow the CLASSE/Wilson lab general safety procedures, as well as process-specific procedures for the chemicals and equipment used.

Label all solvents according to CLASSE/CU EH&S guidelines. Store the flammables in the approved flammable storage cabinets whenever they are not being used.

Use secondary containment carriers whenever transporting hazardous material outside of the lab. Use due care and caution when moving hazardous materials.

Use a two-step process (acetone followed by alcohol). Apply solvents under the appropriate fume hood in the chemistry room, then package and transport clean parts to the work area for alcohol wipe.

Avoid particulate contamination wherever possible. Prepare the fume hood by wiping benchtop with a damp disposable towel. Do all work over a clean sheet of UHF foil.

Avoid bringing potential contaminants into the work area by ensuring that other experiments are not occupying the space.

Inspect silicon wafers and glass substrates for defects before use. Report defects to PI.

6. SPILL AND ACCIDENT PROCEDURES

Keep a 5-gallon universal spill kit nearby, which can be used for small incidental spills.

Keep an approved fire extinguisher nearby, in case of electrical/chemical fire.

For large spills/fires- isolate the spill if possible/activate fire alarm, evacuate area, keep people away, and call for help:

EH&S (8 AM - 5 PM) - (607) (25)5-8200
CU Dispatch (24 HOURS) - Dial 911 OR (607) 255-1111 when using outside line or cell phone.

7. WASTE DISPOSAL

Collect any solvent waste generated by this process in appropriate container. Containers are provided in the chemical rooms. Follow established procedure for notifying CLASSE operations staff if the waste containers need to be changed.

PARTICULARLY HAZARDOUS SUBSTANCES ONLY

8. APPROVAL REQUIRED

N/A

9. DECONTAMINATION PROCEDURES

N/A

10. DESIGNATED AREA

N/A

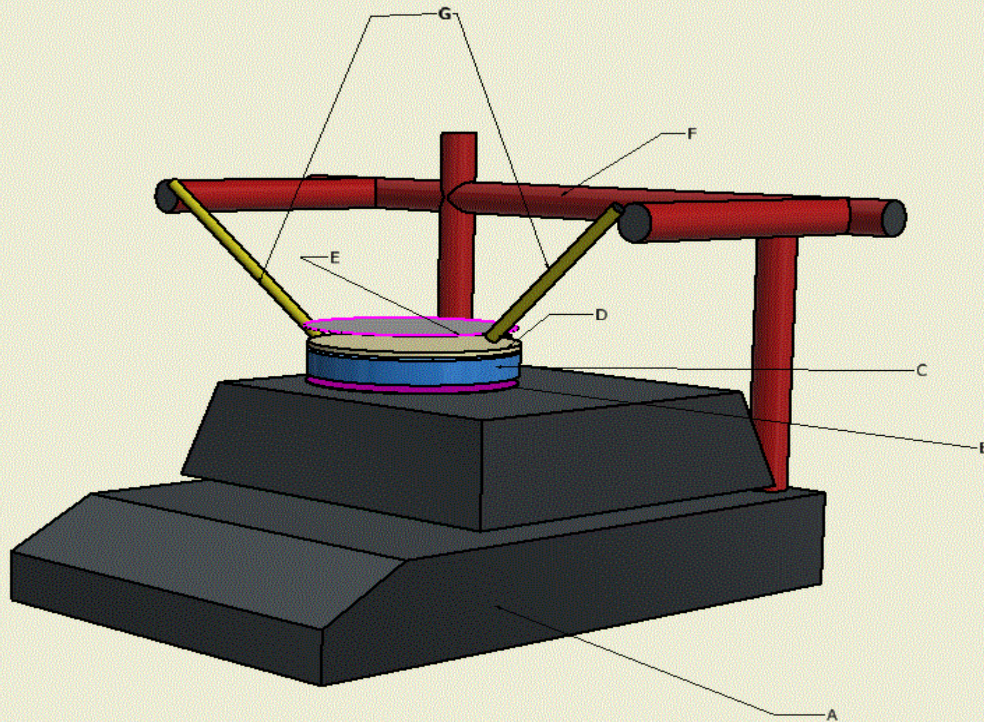
11. DEATAILED EQUIPMENT LIST

UHF foil
Ultrasonic cleaning bath
Acetone and alcohol wash bottles
Kimwipes

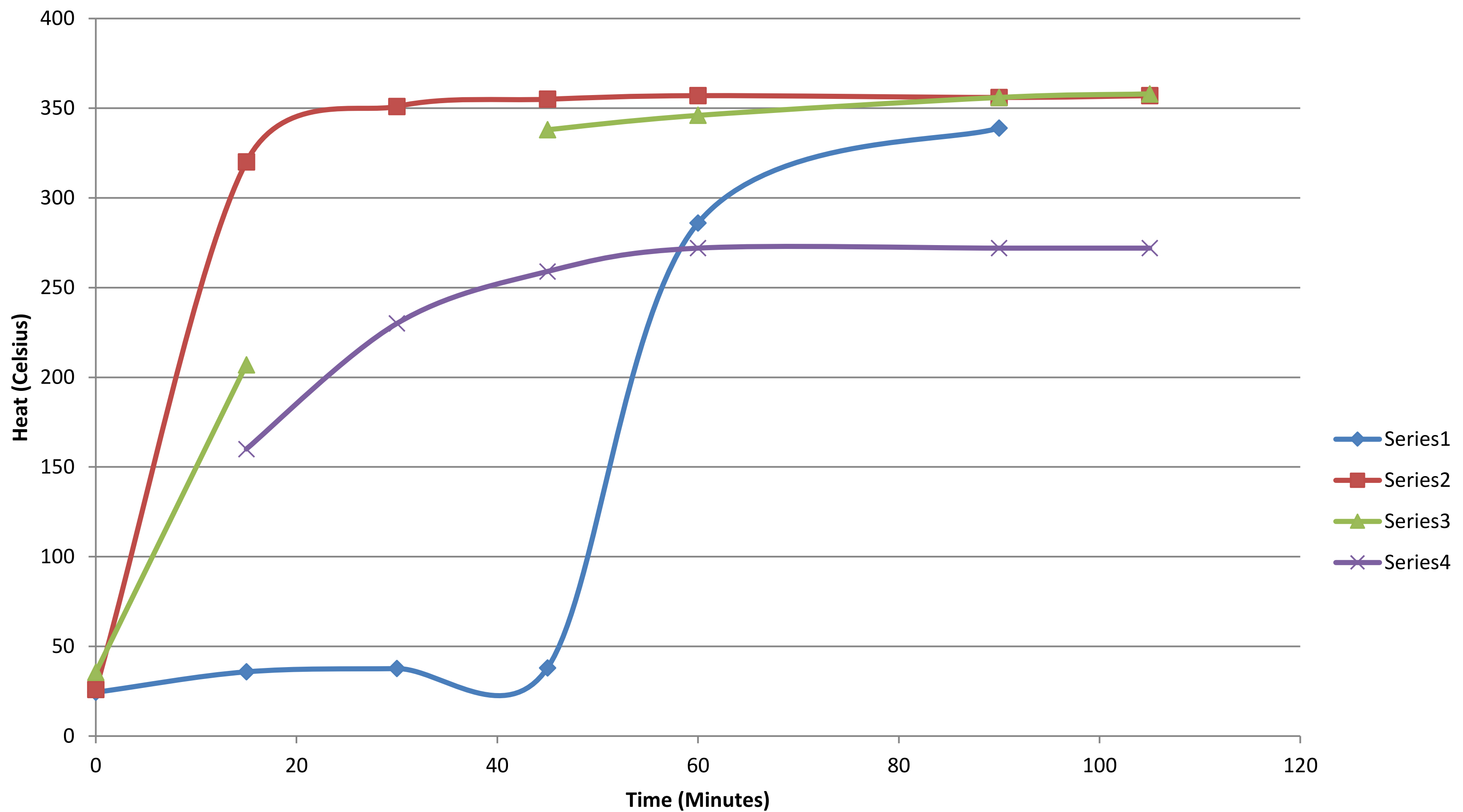
12. DETAILED DESCRIPTION OF PROCESS

1) Wipe down work area with damp disposable towel. Check fume hood and ultrasonic bath for proper operation and safety.
2) Empty bath, wipe interior, and refill with fresh deionized water.
3) Inspect silicon wafers and glass substrates. Good bonding requires good materials. Scratches, chips, and inclusions should be reported to your supervisor.
4) Wipe down substrate and wafer with acetone on Kimwipes. Use firm circular motions. Remember to thoroughly clean both faces and the circumference.
5) Place substrate and matched wafer in ultrasonic bath for a 60 minute cycle at 60C and start. It is not necessary to monitor the process.
6) When cycle is complete, don fresh gloves and lay down a clean sheet of UHF foil to work on.
7) Remove bonding materials and pat dry with lint-free wipes.
8) Lay down a second sheet of foil and some large clean paper sheets. Double wrap each piece. This means wrapping with one sheet with the folds on top, then flipping the piece and wrapping again.
9) Fold the second sheet of foil around the wrapped bonding materials. Transport to work area.
10) When work area is fully prepared, unwrap materials, wipe bonding surface with alcohol on Kimwipes, and assemble stack without delay.

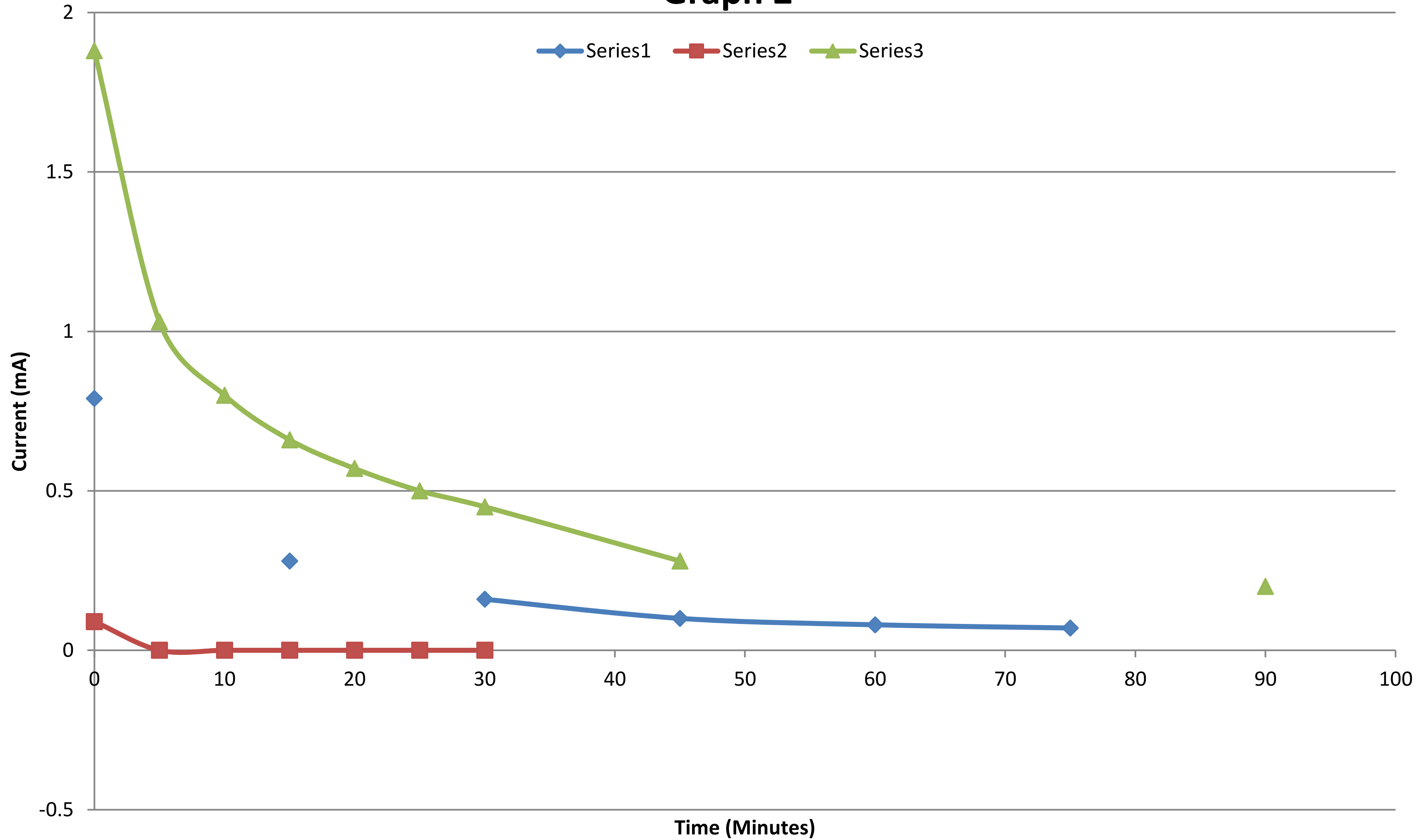
FIGURE 1
Glass substrate is 4inches in diameter
Hotplate is ~8.5x12x4 inches



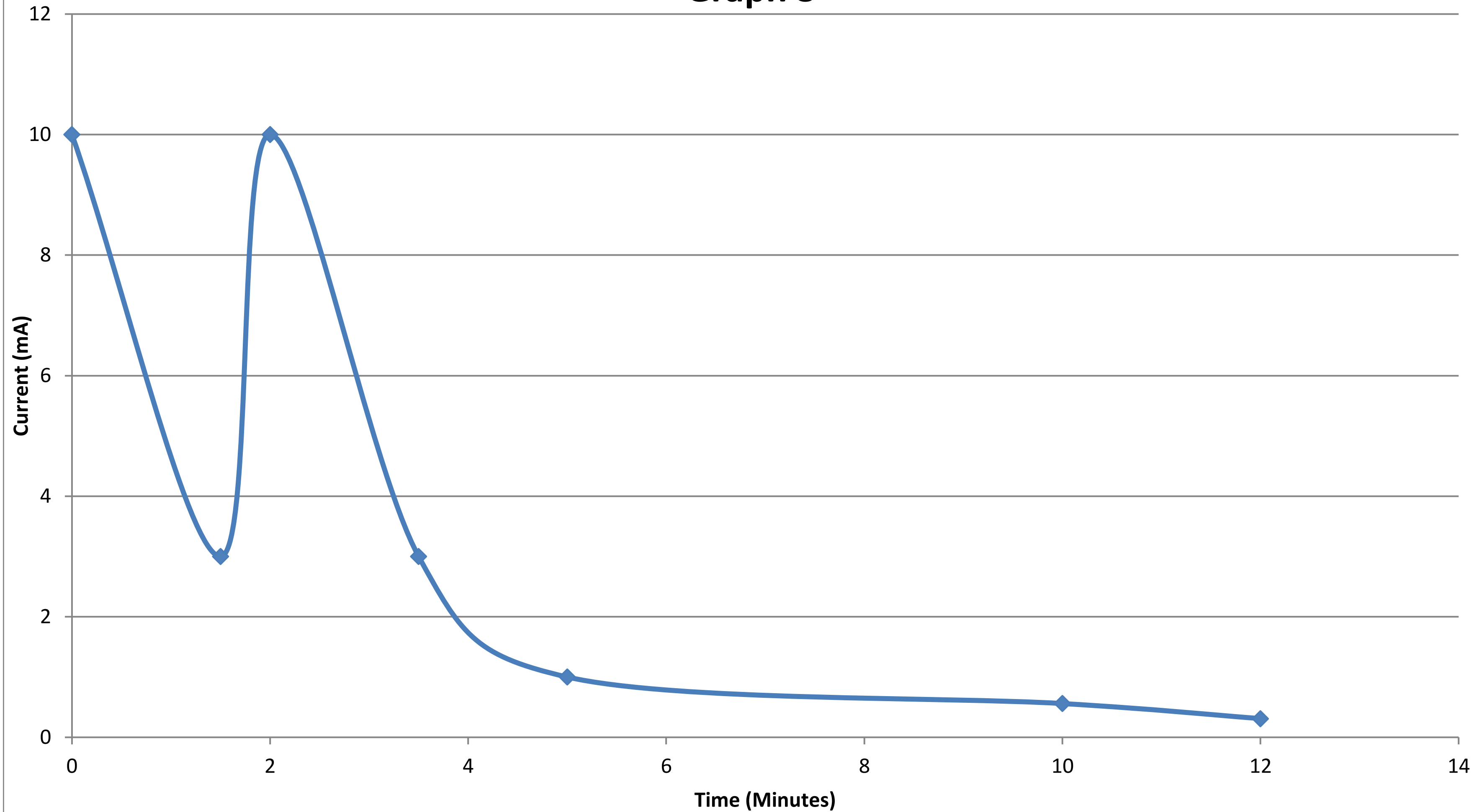
Parts List		
Not shown	Tag	Labelled Parts
Ortec High Voltage power supply	A	IKA CMag HP7 Hotplate
Omega HH501BJK with J-&K-type thermouples	B	Aluminum electrode cut from UHV foil
Macor insulator/press tool	C	Spherically ground Schott Borofloat33 substrate
5lbs metal weight	D	Silicon Wafer(Not to Scale)
	E	Metallized kapton filml electrode
	F	Support frame constructed of thorlabs hex clamps and threaded rods
	G	Spring-loaded high voltage probes



All temperature readings taken with J-type thermocouple, placed within Macor insulating block under press weight. Placement was such that thermocouple read temperature at top surface of process stack. Hotplate set at 500C, laminar flow hood turned off after stack assembled. Potential sources of measurement error or inherent temperature variation not fully explored. Initial readings (45 minutes and prior) in Series 1 taken before thermocouple was placed within Macor, demonstrating the potential error range.



Current change over time for three bonding attempts, corresponding to the first three heats in the previous graph. Voltage from DC power supply set at 800V throughout, and current measured by ammeter on same power supply. Current readings corrected to account for base current of .16mA due to internal resistance of power supply. Gaps in the trendline indicate evolutions in the measurement frequency.



This represents the final bonding attempt of the project, made with a completely new substrate and wafer, corresponding to Series in in Graph 1. Voltage was initially set to 500V, then increased to 800V at 2 minutes . This appears to illustrate that the maximum current during the bonding process is dependent on the clean, bondable surface area of the materials. Previous attempts used flawed materials and fragments, and produced significantly lower currents.