Solution for a Modular Die-Level Anodic Bonder

by

Christopher Joseph Khan

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Signature of Author..
Department of Mechanical Engineering
May 10, 2004

Certified by..
Alexander H. Slocum
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by..
Ernest G. Cravalho
Chairman, Undergraduate Thesis Committee

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Abstract

Anodic bonding is a common way to package silicon with Pyrex. The anodic bonding process requires high temperature, voltage, and moderate pressure to occur. Often, there are also expectations of alignment of features for things such as power or material delivery. The following thesis proposes a design for a die-level anodic bonding apparatus. It consists of a separate module to meet each requirement; a module for heating, aligning, and applying force. The apparatus is capable of heating the MEMS device to over 400°C, applying more than 1000V across the device, applying greater than 4MPa of pressure, and aligning to within 0.5μm in two directions to create an accurately aligned anodic bond. The apparatus met all of these functional requirements and is modular enough to easily be configured for many other die-level anodic bonding situations.

Thesis Advisor: Alexander H. Slocum
Title: Professor of Mechanical Engineering

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List of Figures

List of Tables

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1 Introduction

1.1 MEMS

In the last decade, the move toward smaller technologies has been intensified and the integration of electrical and mechanical systems has become much more refined. As a result, microelectromechanical systems have become a standard in sensing and control. Most MEMS devices alone are too fragile and small to be used alone in most systems, however. As MEMS move towards smaller scales, their accessibility decreases resulting in a need for an intermediate interface. The need for packaging arises from these interface and implementation issues. Packaging takes care of interfacing issues such as power delivery, material delivery for measurement or control, and heat sinking for the high-power consuming devices.

1.2 Packaging

One method of packaging that is widely used is bonding a Pyrex piece to the MEMS device. This type of bonding is called anodic bonding. The anodic bond is created under conditions of approximately 1000V across the bond, 350°C, and 4MPa. Sodium ions will then quickly migrate from the Pyrex to the interface between the Pyrex and the silicon creating a strong electrostatic bond. After this sodium displacement, oxygen atoms slowly migrate from the Pyrex to the interface and create a permanent silicon dioxide bond. These conditions must be sustained for a short period of time, on the order of one minute, for the bonding process to complete.

1.3 Purpose

The purpose of this project is to design an apparatus that can carry out this bonding procedure with a particular MEMS device and Pyrex packaging piece. The MEMS device being bonded is 800μm thick and 1.5mm square with a 500μm Pyrex layer and a 300μm silicon layer. There are four holes for fluid inlet and outlet, which are the features that need to be aligned. Part of the design scope includes some versatility to allow different types of packaging and silicon combinations. To facilitate the versatility the apparatus will be very modular, small, and portable so that it may be used in a variety of settings without being obtrusive. Modular parts may be easily changed to accommodate bonding circumstances with very different characteristics. In the following paper, I will list the criteria that the design must meet, a method for meeting these criteria, an elaboration on the specific implementation of this design, a performance analysis of the apparatus, and suggestions for future improvements on the apparatus.

2 Design Criteria

2.1 Primary Requirements

Because the apparatus is designed for use with a particular MEMS device, the apparatus will be constrained in several respects such as dimensions, bonding conditions, and alignment characteristics. The features of this particular device include dimensions of 15mm×15mm×0.8mm, four alignment holes approximately 1mm inward from the midpoint of each edge, a 300μm silicon layer, and a 500μm Pyrex layer. The packaging for the MEMS device also imposes constraints on the system with its dimensions of 0.5in×0.5in×1in and its alignment holes matching the ones on the silicon. The environmental bonding conditions inherent to the process constrain the design, but are somewhat flexible and are based on the MEMS device being bonded. The environmental variables must fall within broad ranges, such as a temperature between 350°C and 500°C. This is inherent to anodic bonding, but it is quite a broad range. This MEMS device requires an alignment of approximately 0.5μm in both directions parallel to the bonding plane in order to align the fluid inlet and outlet holes. There must also be angular alignment of approximately 0.5 milliradians. This alignment must hold during the pressure application and bonding process. The pressure application for a MEMS device with this area requires a maximum of 1000N of force to bond. The conditions that the bond is being formed under require up to 1000V of potential. To get good conduction throughout the silicon, the conductors must line the entire exposed area of silicon between the thin layer of Pyrex and the Pyrex packaging. The conductors must also cover the entire projected area of the MEMS device on the opposite side of the packaging. Once the pieces are aligned they must be brought to a temperature of 350°C for the bonding process to catalyze.

2.2 Secondary Requirements

The rest of the design criteria are not necessary for operation, but increase the ease of operation dramatically. First, the alignment must be able to be confirmed visually during and after alignment and force application. Visual alignment is the most reliable and versatile method. Second, heating should be controlled electronically with a temperature controller in order to precisely control heating. This means a thermocouple, heater, and temperature controller must be integrated into the system. None of these constraints are seriously imposing on the design so they are treated as primary functional requirements.

3 Implementation

3.1 Design strategy

There are essentially three different smaller processes within the entire anodic bonding process. The first is the alignment of the MEMS device and the packaging. The second is the application of the bonding force on the MEMS and packaging. The third is the heating and actual bonding of the MEMS and packaging. Taking a modular approach to this design would suggest using three separate modules for each of these tasks. Effort can now be focused on each of the three individual modules without concern for the whole. The MEMS device must sit below the Pyrex packaging resting on the lowest stage.

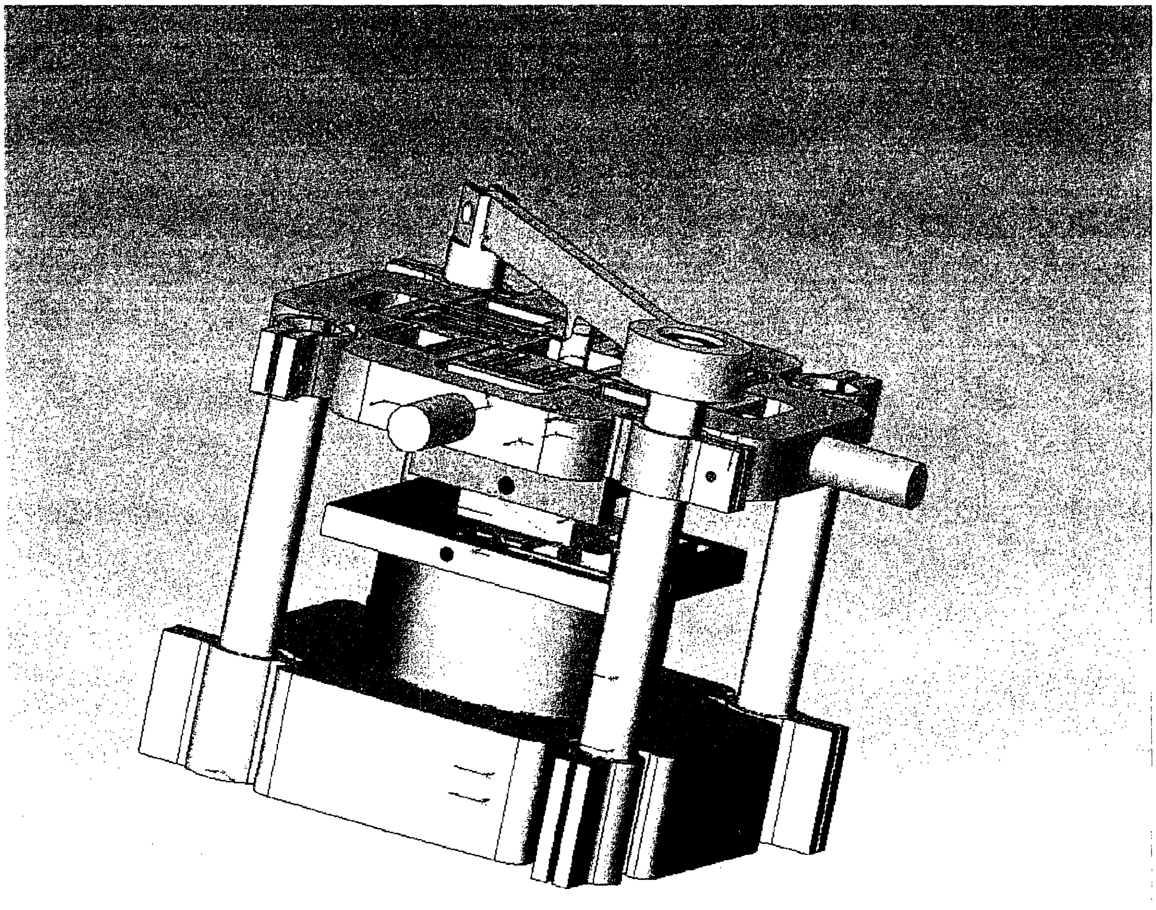

Figure 3.1 Proposed design to meet all functional requirements.

If the silicon were above the Pyrex it would not be constrained from below because the bond face must be clear, nor would it be constrained from the top because gravity will not aid in constraint, nor would there be visual access. All that is left to constrain are the sides of the silicon, which are far to thin for reliable constraint. The only reasonable possibility is the MEMS device sits on the lowest stage. This lowest stage must therefore be the heating stage to ensure excellent heat flow to the bond surface. The MEMS device is far less resistant to heat flow than the Pyrex packaging. The second stage should then be the alignment stage if the force is to come from above the Pyrex packaging. That leaves the force application stage for the top.

3.2 Heating/Constraining Assembly

The heating stage is a fairly straightforward design (figure 3.2). The assembly must hold a heater and thermocouple, support the silicon and make conducting contact from the edges, and leak as little heat as possible. This heat leak is prevented by encasing the heater in a thermally insulating material. Because insulating materials that can withstand high temperatures are typically more expensive or hard to machine, the insulating piece is fairly small and is held by an aluminum base. The heater sits in the insulator and is bonded to the heat shield with a metal-filled epoxy to ensure excellent heat conduction to the MEMS device. The heat shield is machined smooth on the top and bottom for the same reason. The heat shield has a blind hole on the bottom to bring the thermocouple as close to the MEMS device as possible for accurate temperature measurement and is held in place with a metal-filled epoxy for good thermal conduction as well. For conductions to the silicon, a copper flexure approximately four times the dimension of the MEMS device is used to hold it in place. Razor blades attach to the flexures to contact the edges of the MEMS device. The copper flexure fixes one blade, allows one blade to rotate, and allows two blades to rotate and displace for precise edge alignment of the blades and the silicon. The entire base assembly thus far sits on a hollow ceramic stand to electrically and thermally insulate the apparatus from the surface it sits on.

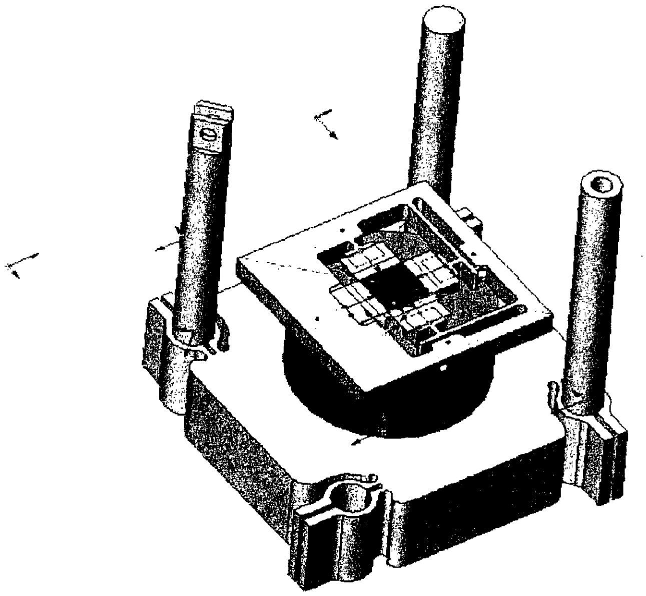

Figure 3.2 The base and heating assembly.

3.3 Aligning/Constraining Assembly

The second stage is the alignment stage and is almost purely a flexure (figure 3.3). It consists of an aluminum flexure approximately ten times the dimension of the MEMS device, a steel flexure approximately the same dimensions, and an aluminum block with a graphite conductor to constrain and conduct to the Pyrex packaging. The aluminum flexure is designed to displace in the plane of the bond approximately +/-1.6mm in orthogonal directions independently. The flexures are driven by micrometers with 0.5μm resolution. The steel flexure moves in the direction perpendicular to the bond surface in order to move the Pyrex packaging into contact with the MEMS device after alignment has been achieved. It is able to displace approximately 1-2mm. The steel flexure connects the aluminum flexure to the aluminum block, which holds the Pyrex packaging in place with a pair of spring plungers. The force it is held with is enough to also hold up the graphite piece, which acts as the other conductor for the anodic bonding process. The graphite covers the entire projected area of the bond surface and is compressed between the Pyrex and the aluminum block during the force application.

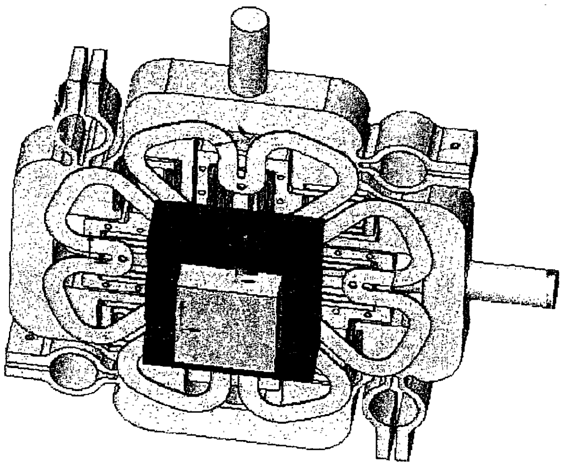

Figure 3.3 The alignment/conducting assembly

3.4 Force Application Assembly

The third stage consists of essentially a lever arm. The fulcrum is at one corner of the apparatus and the force application to the rod is at the opposing corner. This configuration allows area around the middle of the lever and the center of the apparatus to be clear for viewing access to the alignment holes. The center of the lever exerts a force on a rod, which exerts a force on the aluminum block holding the Pyrex packaging. The force provided at the corner of the apparatus is delivered through a series of

Belleville disc springs. The disc springs allow high force with small travel. The displacement of the springs is a direct approximate measurement of the force being applied to the bond surface used for controlled force application.

4 Specific Implementation Details

4.1 Isolating Materials

Although the default material for the apparatus is aluminum because of its availability and machinability, there are many material requirements that aluminum does not satisfy. For example, to prevent a short between the high and low voltage, some material must be electrically isolative. It is convenient that the block holding the heater is thermally isolative because hat piece may now act as both insulators leaving fewer restrictions on the rest of the design and materials. For cost considerations, alumina silicate is used to make this insulator. The dielectric constant is approximately $4000^{V}/_{mm}$ and the thermal conductivity is approximately $1.5^{W}/_{m\cdot K}$, which is similar to the Pyrex on the other side of the silicon. The apparatus sits on a base constructed of this electrically isolative material. Unfortunately, ceramic materials usually must be machined with special tooling. The alumina silicate is somewhat abrasive and requires carbide tooling if machined extensively.

4.2 Conducting Materials

The counterparts to these isolative materials are the conductive parts used to minimize resistance in the bonding process. The graphite piece that is forced against the Pyrex packaging and the copper flexure are both very highly conductive materials. The current must run through the steel razor blades, unfortunately, which is the most resistive component in that loop other than the Pyrex. For thermal conductivity, an aluminum heat shield is used as the support for the silicon. The heater is attached to the heater with an aluminum-filled epoxy as is the thermocouple. There are no other considerations for electrical or thermal conductivity in the design or materials beyond what has been said. All other design and material selections are purely mechanical.

4.3 Flexures

The flexure designed for motion in the bonding plane is much more complicated, but is not one that must be created from scratch. The design is based on Shorya Awtar's, a graduate student in the lab, Ph.D. thesis[1] (figure 4.1). Beyond the borrowed design, arms are incorporated to allow angular adjustment and clamps to align it with the four posts that the base aligns with (figure 4.2). The angular adjustment is done out of plane so as not to interfere with the rest of the design. For ease of use, the clamps are operated with standard wing nuts. Supports are also added to allow high-resolution micrometer positioning. To take advantage of the full range of the flexures, supports are on both sides of each direction. The micrometers have a range greater than the range of the flexures and have a resolution of less than 1um. The micrometers used are the Newport HR-6 high-resolution locking micrometers. They are ideal for size, price, precision, and availability.

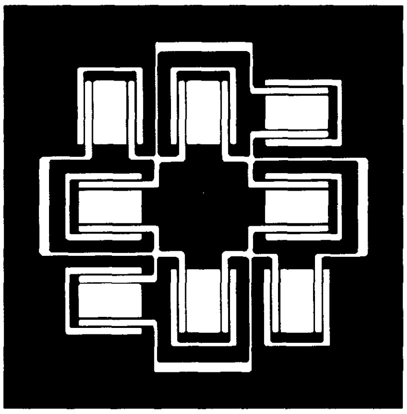

Figure 4.1 Dr. Awtar's flexure design.

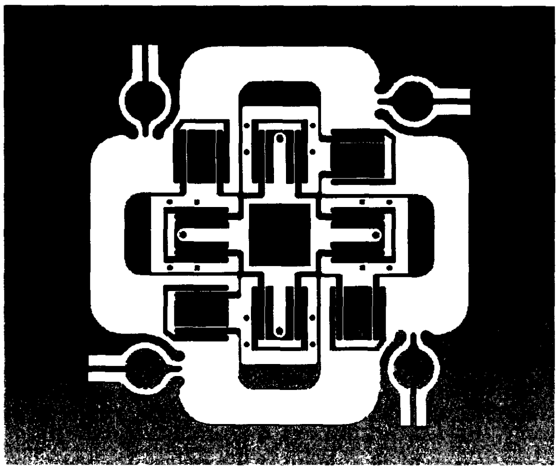

Figure 4.2 Flexure design modified for anodic bonding implementation.

The flexure for moving the Pyrex packaging perpendicular to the bonding plane is much easier to drive because there are no precise motions required. This part should be kept to a minimum dimension in the direction of its travel and to the dimensions of the apparatus in the bonding plane. Spring steel is an idea candidate for such a task. The shape of the flexure is essentially the perimeter of a four-leaf clover. With a flexure path length of nearly 100mm and a thickness of approximately 0.5mm, it is suitable for less than 3mm of travel. The conducting flexure is designed to have the least performance. If all went

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[1] Awtar, Shorya, "Synthesis and Analysis of Parallel Kinematic XY Flexure Mechanism", Ph.D. thesis, MIT Dept. of Mech. Eng., January 2004

perfectly, it would not deflect at all. To make up for misalignment between the razor blades and the silicon, the conducting flexure rotates three of the blades and displaces two, leaving a fully constrained system.

4.4 Modularity/Interfaces

Interfaces in modular systems are often designed for ease of engagement and disengagement. In this system, there are several interfaces that are inherently constrained in the axial direction. The constraint is part interference, which is basically the stacking of parts. Therefore, radial constraining is the main concern. Pins may be used instead of screws to constrain radially because they require less manufacturing and are easily engaged and disengaged. Spring plungers are used to engage the Pyrex packaging and constrain the Pyrex in both the radial and the axial directions. Some parts must be constrained in the axial direction, such as the axial flexures, the aluminum block, and the razor blades. This may not explicitly suggest the use of screws, but it justifies their use in this modular system. Epoxy is the lower extreme of modularity. It is permanently constrains the system to the use of those parts, but it is necessary for the attachment of the heater and the thermocouple to the heat shield because both require high thermal conductivity for high temperatures and accurate sensing. Metal-filled epoxy is used to withstand the high temperatures. The epoxy is also used to attach the ceramic insulating base to the aluminum base. Since the base is made of alumina silicate, which is very brittle, the epoxy is used to prevent it from being disassembled and reassembled, which would cause erosion of the ceramic.

5 Performance

5.1 Bonding

The bond between the silicon and the Pyrex is probably the only sure thing with this apparatus. Given clean surfaces between the two, they will bond at high temperature, pressure, and voltage almost certainly. They bonded on the first attempt with the apparatus. The bond was almost instantaneous. The temperature easily reached 400°C and the pressure easily reached approximately 2MPa. The conditions were so favorable that the power supply did not even reach 1000V. The bond took place before it could reach that voltage. The most difficult part of the operation was getting the silicon in place. If it does not quite line up with the razor blades, shim stock must be use to get it to the right height. There was some maneuvering required, but nothing preventing a successful test.

5.2 Alignment

The precision of the alignment is a function of three things; the mechanism, the sensing, and the driving. The mechanism of flexures allows for a perfectly continuous deflection at this scale. The sensing is through an optical confirmation of alignment and is dependent on the optical system. The resolution of the entire system can only be as good as the resolution of the optical system. The driving of the system is fairly continuous with the exception of slight hysteresis. The resolution must then be defined by the resolution or magnification of the optical system and the continuousness of the input to the micrometers. The micrometers have a reactive force proportional to their rotational velocity so it is quite easy to drive them continuously. The viscous-like effect makes the operation of the micrometers very smooth. The degradations are in microns so it would be fairly easy to get better than 0.5μm resolution. The microscope that was used could not get that kind of resolution so 0.5μm is not reasonable. Given a microscope with enough magnification 0.1μm would be a good target for resolution. The angular adjustments are very coarse in comparison. Because the adjustments are done at a distance away from the actual displacement, they can rectify a similar visual misalignment. The adjustments are made approximately 30mm away from the center of the apparatus, whereas the displacement is approximately 7mm away from the center.

6 Conclusion

6.1 Manufacturing

There are few areas of the apparatus that are slightly weak (table 6.1). The largest problem with the apparatus is the manufacturing of three parts; the ceramic heater casing, the conducting razor blades, and the alignment flexure. The heater assembly is made of the brittle aluminum silicate and when the heat shield or flexure pins are slid in and out of the ceramic, it wears fairly quickly. Metal inserts would allow more accurate measurements and less wear. The razor blades were cut when held in a metal piece matching their desired dimensions.

Table 6.1 Problems and recommendations for current and future designs

Problem	Recommendation
Ceramic heater is too brittle	Epoxy metal inserts in for interfaces or use tougher material
Razor blades misshapen	Remake, inspect quality of razor die before use
Alignment flexure blades were too thin and inconsistent	Make sure waterjet cutter is in good condition, or possibly use EDM machine to make the flexure
Conducting flexures not flexible enough	Make length of blade rotation flexure longer
Too many pieces required for force application	Instead of lone rod to deliver force, make attached adjustable rod
Graphite conductor was not constrained well	Account for graphite compression when milling its pocket and supply a vertical force keeping it against the aluminum

There were machine misalignments in the process of making the metal pieces so possibly redoing or refining that process would greatly increase the usability of the apparatus. The alignment flexure was machined on an abrasive water jet cutting machine. The properties of that particular machine did not allow for precise cutting of the flexures, so the blades varied in thickness along their lengths and depths. This variation caused weak blades that broke quite easily.

6.2 Design

The parts of the apparatus that were actually weak in design were the conducting flexures, the force application lever, the aluminum Pyrex constraining piece, and its interface with the graphite. The conducting flexures did not have enough allowance for rotational adjustment of the razor blades, which may not have been necessary if the razor blades had been machined better. It would still be a useful improvement to make constraining the silicon easier. The force application lever needs an accurate length rod to transmit the force to the aluminum Pyrex constraining piece. The lever should include a variable length rod so that it may be more easily used and have fewer loose parts. The Pyrex constraining piece needs a better interface with the graphite. The graphite was unexpectedly light and compliant so the interface needs to allow for compression of the graphite. Also, the aluminum block needs to either provide more support for the graphite or constrain the wire being compressed between it and the aluminum because the force from the wire movement easily moved the graphite out of position.

6.3 Evaluation

The final product was successful. It met all of the functional requirements; alignment and bonding. It looked good and functioned well (figure 6.1). Aside from constraining the silicon, operation was easy and straightforward. If the revisions listed above were made, that would be solved as well. Beyond that, refinement of manufacturing is all that is needed.

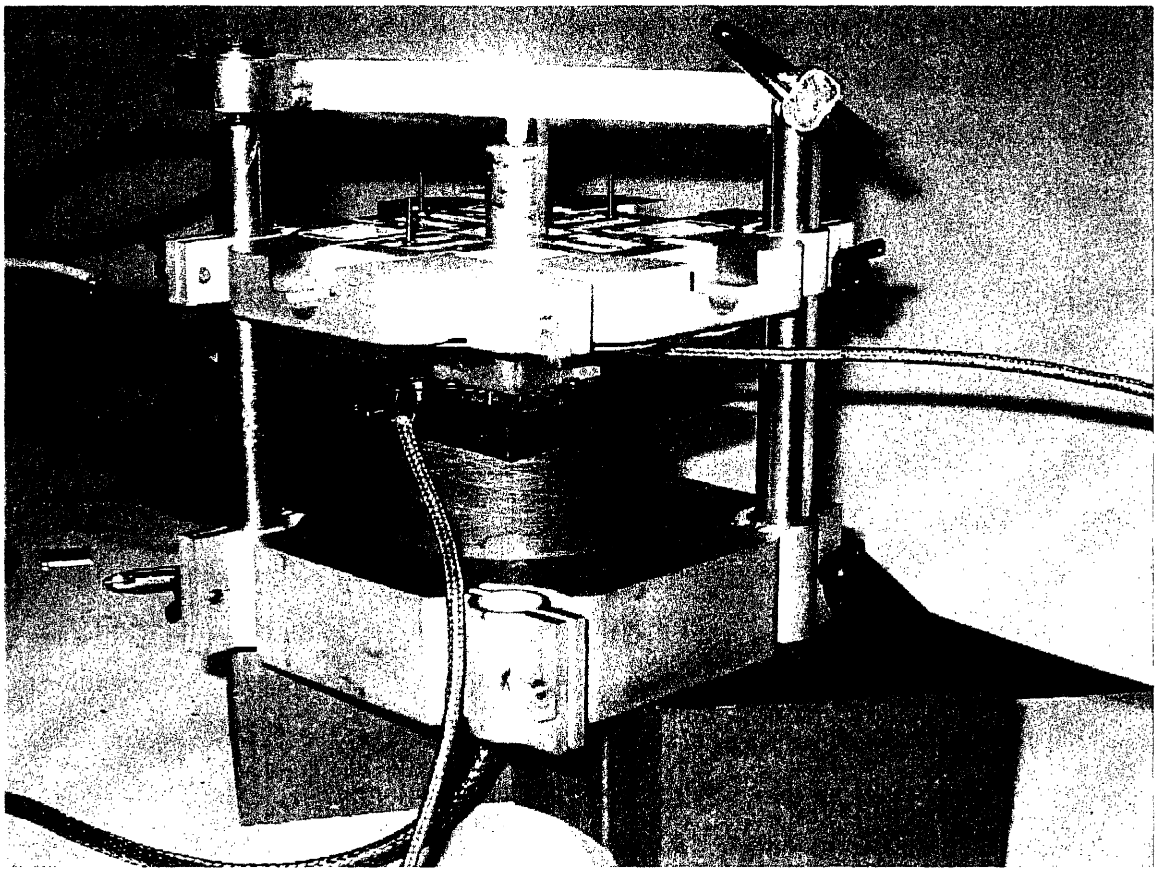
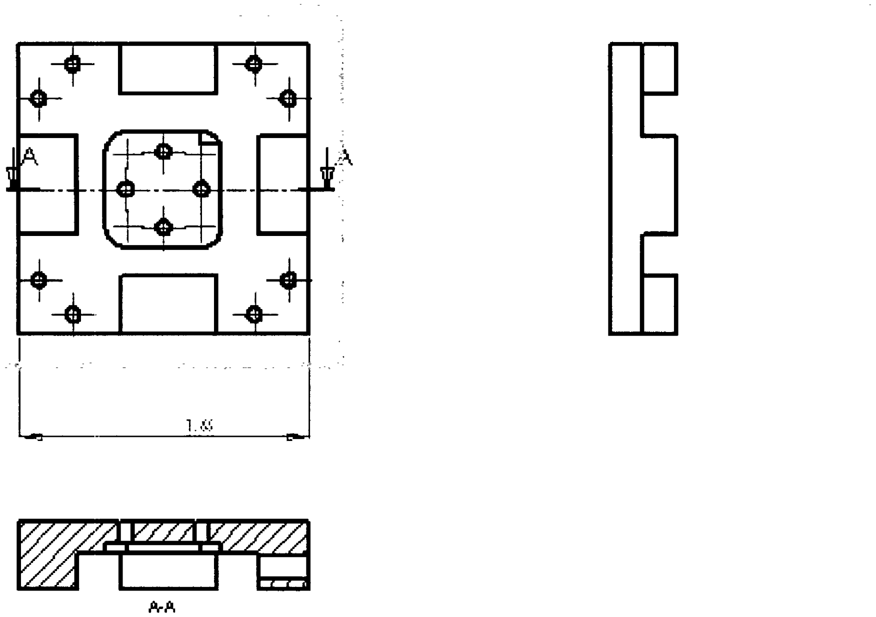
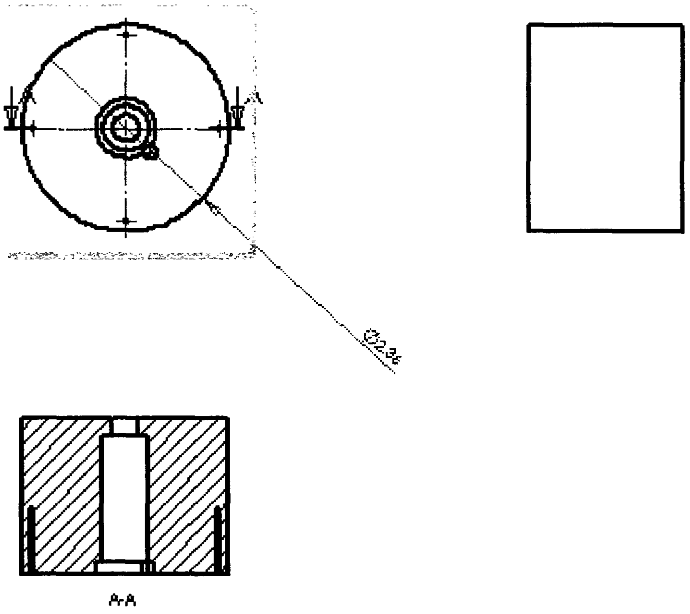


Figure 6.1 Finished anodic bonding apparatus

The modularity of the apparatus is not easily measurable. It would cost roughly $100 in materials to make fixtures for a completely different silicon piece. Some design and assembly would have to be done, but nothing that couldn't be done in a given week. Improvements in the acceptance of the configuration described in this thesis might be a useful change in the apparatus, but would not be worth it if reliability or robustness were sacrificed. As it is, the apparatus works fine.

Appendix

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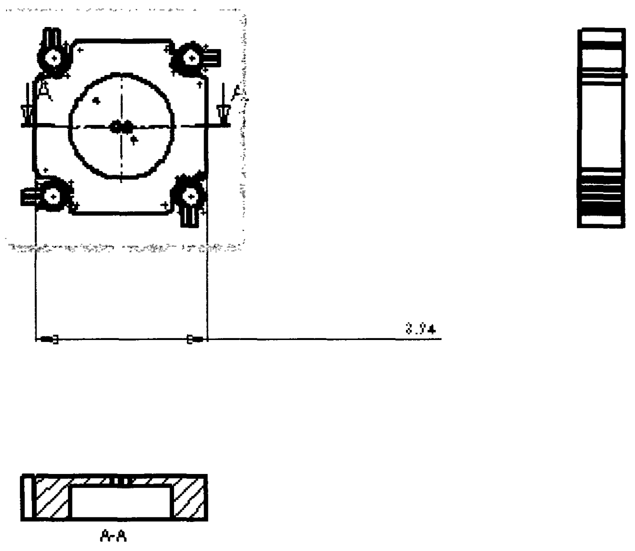
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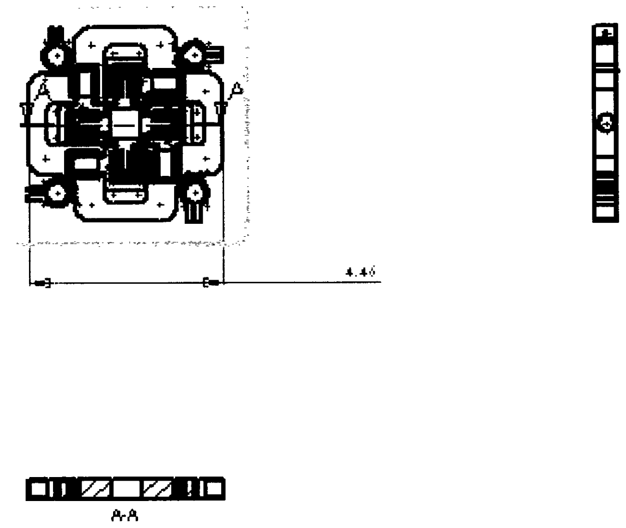
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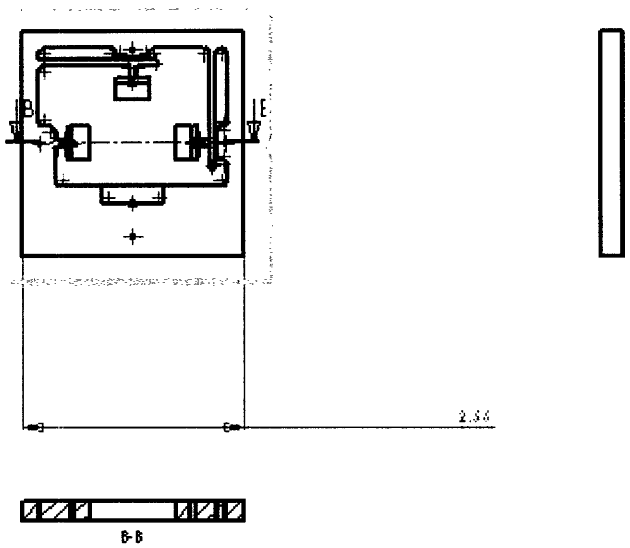
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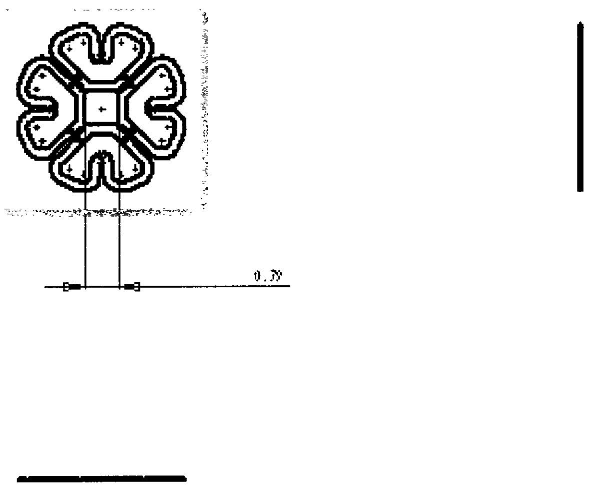
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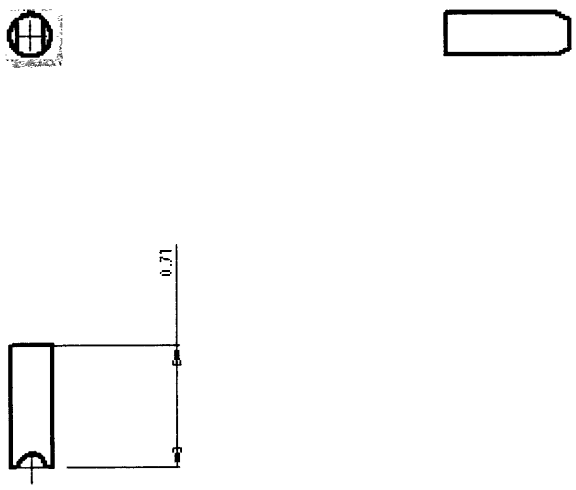
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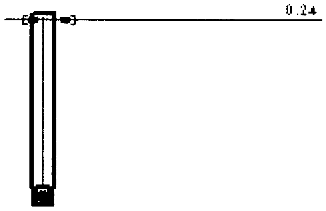

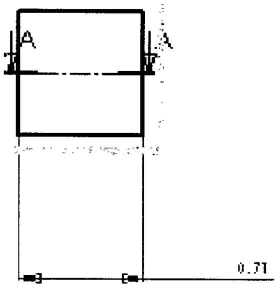

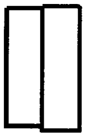

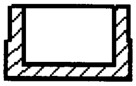

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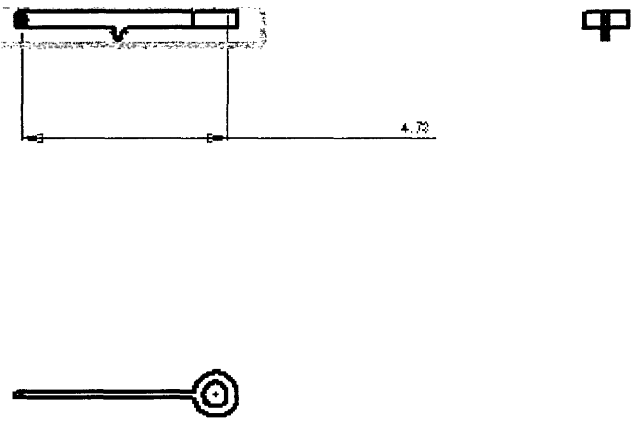
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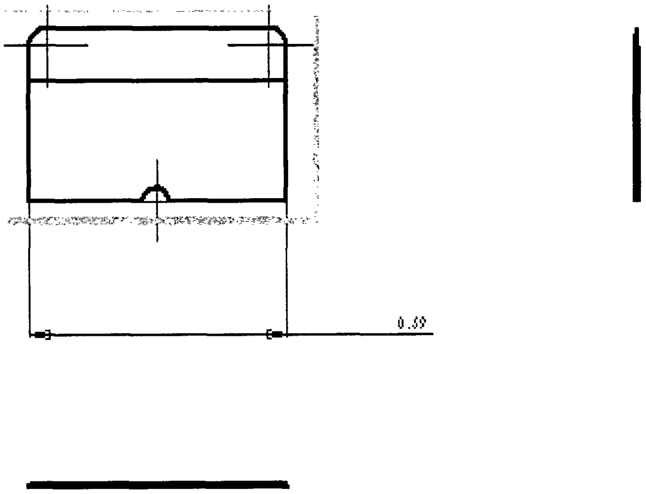
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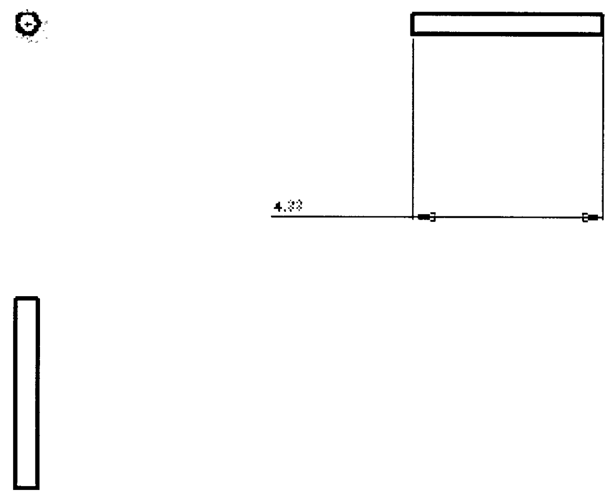
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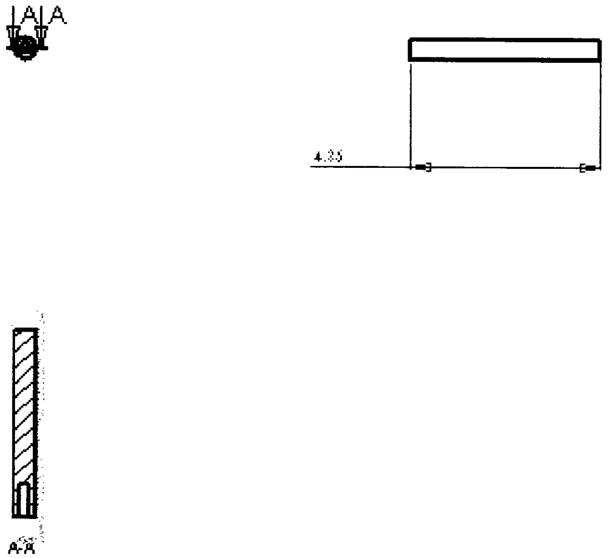
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