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# Control System Implementation for Grating-Element Positioning and Modulation of the Polychromator

by

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submitted to the Department of Electrical Engineering and Computer Science  
in partial fulfillment of the requirements for the degrees of

Bachelor of Science in Electrical Science and Engineering  
and Master of Engineering in Electrical Engineering and Computer Science

at the Massachusetts Institute of Technology

May 22, 1998

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**Abstract**

The Polychromator is a MEMS-based optical diffraction grating with a large number of individually controllable micromirror grating elements which can be electrically programmed to reproduce spectral features of many target chemical species. This thesis reports on the implementation of the control system used to actuate the polychromator. The polychromator design and the test electronics used are described in detail. A model to simulate the actuation of a grating-element is developed in order to obtain a voltage-displacement relationship. The implementation for static displacement and modulation are discussed. The problems encountered, future work possibilities, and the conclusions are presented.

Thesis Supervisor: Stephen Senturia

Title: Barton L. Weller Professor,

Department of Electrical Engineering and Computer Science

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# **Chapter 1. Introduction**

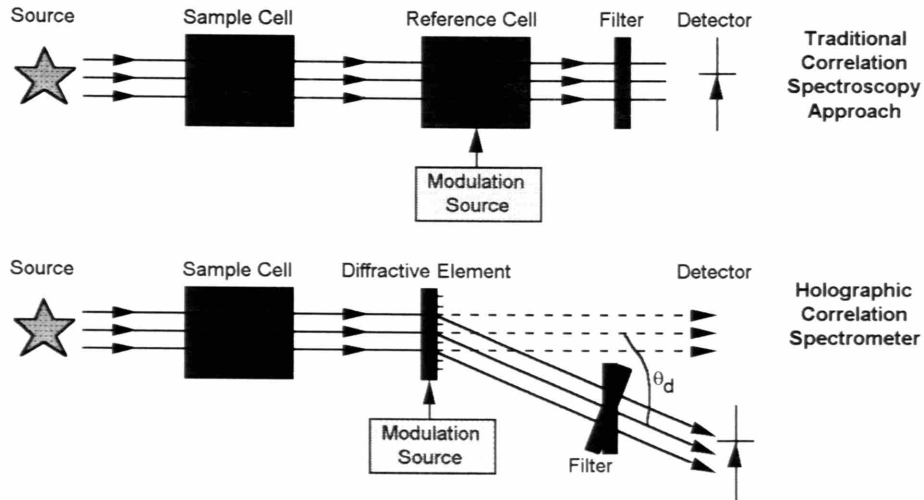
## **1.1 Thesis Outline**

The goals of this work are presented by the way of the thesis outline. This chapter along with providing the motivation for this project, discusses the method chosen to control and actuate the polychromator in order to produce the desired behavior.

Chapter 2 begins with a description of the polychromator, and the test electronics chosen to drive the polychromator chip. In Chapter 3, we first discuss how the polychromator and the electronics interface with each other. Second, we develop the simulation model for the grating-element actuation and create a voltage-displacement relationship. Finally, we discuss how the static displacement and modulation strategies are implemented. Chapter 4 contains a discussion of some of the problem areas found while performing tests on the grating-elements. It also outlines future areas of investigation in order to achieve better understanding of the polychromator actuation. Finally, a summary of all the work done is presented.

## **1.2 Motivation**

Traditional correlation spectroscopy requires the use of a reference cell in order to analyze a sample material. The process of using the reference cell can be cumbersome since we need to replace the cell every time we want to look for a new material in our sample. Also if we are looking for labile species, the handling of the reference cell becomes a very important issue. Instead, we can use a form of holographic correlation spectroscopy to use the benefits of correlation spectroscopy but obtain much greater advantages (Figure 1).



**Figure 1.** Comparison between traditional correlation spectroscopy using a reference cell to analyze material and holographic correlation spectroscopy using a MEMS-device as a programmable optical filter.

We replace our reference cell with a MEMS-based diffractive element, called the polychromator, which allows us to control its optical characteristic by electrostatic actuation. The diffractive element reduces the overall size of the spectrometer system and eliminates the need for a reference cell. This method leads to the development of a miniature, electronically programmable remote chemical detection system for field use.

### 1.3 Problem Statement

The problem addressed in this thesis is to create the control program for the analog driver to permit static displacement and modulation of each grating-element, demonstrate the system with interferometric profilometry, and verify the robustness of the system by comparing the repeatability and accuracy from element to element and die to die.

## **Chapter 2. Background**

### **2.0 Overview**

This section describes the polychromator concept and how the actuation of each grating-element is achieved. Also, the operation of the test electronics used to drive the polychromator is explained.

### **2.1 Polychromator**

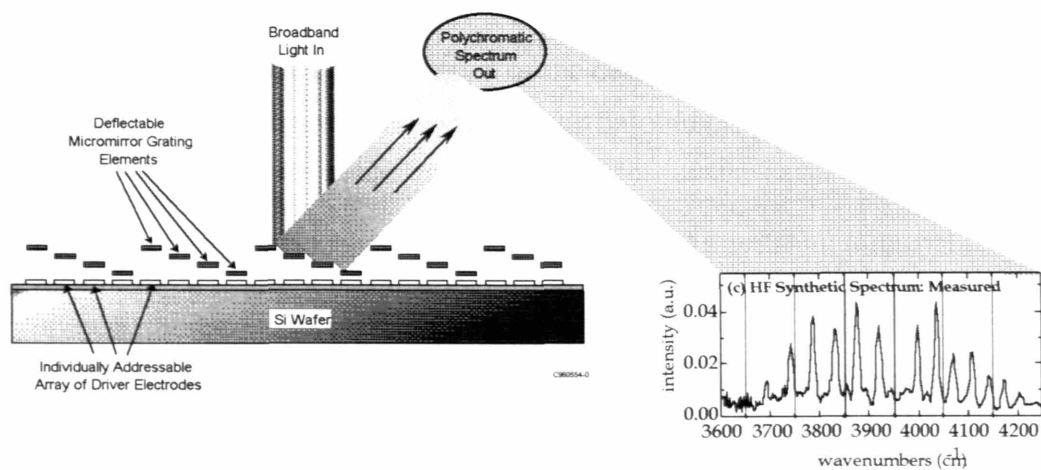
#### **2.1.0 Overview**

The Polychromator is a MEMS-based optical diffraction grating with a large number of individually controllable micromirror grating-elements which can be electrically programmed to reproduce spectral features of many target chemical species[1,2]. The synthetic spectra and the displacement profile producing such spectra can be computer generated in advance. This allows for a very easy and flexible programmable system.

#### **2.1.1 Concept**

Correlation spectroscopy has advantages for chemical sensing and analysis because of its mechanical and optical simplicity, and its high selectivity [1]. In correlation spectroscopy, the cross-correlation of the spectra of a reference cell containing a target compound and that of an unknown is obtained over a range containing multiple spectral lines.

This new MEMS device consists of a linear array of perhaps several thousand elastically supported micromirror grating-elements, with the displacement of each element independently controlled by electrostatic actuation. This device is called a *polychromator* grating, and is shown schematically in Figures 2 and 6 [1, 2]. When illuminated with broad-band white light, the polychromator can be programmed and electrically controlled to produce a spectrum containing selected lines, or reproduce spectral features of any target molecule or combination of molecules.

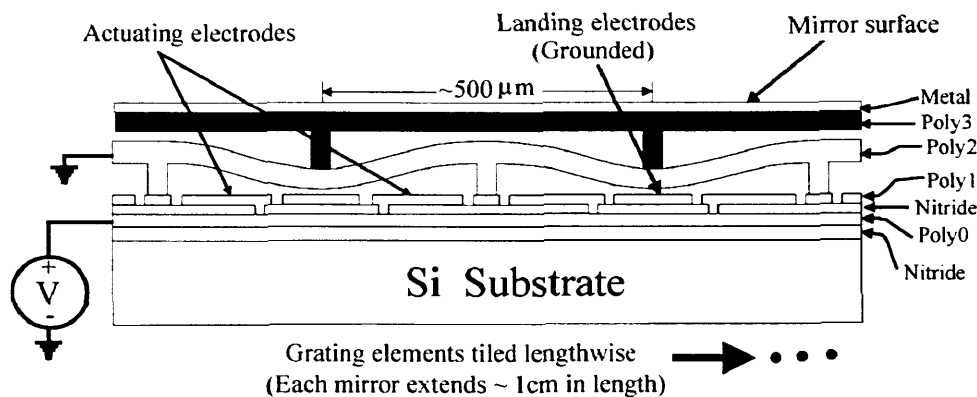


**Figure 2.** Cross section of the Polychromator showing deflected micromirror elements and driver electrodes. The output polychromatic spectrum can be designed to reproduce that of a species of interest, HF in this example [3].

The advantages of combining correlation spectroscopy with the polychromator provide the breakthrough capability of electronic programmability, while eliminating the troublesome reference cell. This permits one system to rapidly search for many species, including examination of labile species, such as reaction intermediates, highly corrosive species, and acutely toxic substances.

## 2.1.2 Actuation

The Polychromator depends on accurate positioning and modulation of each micromirror grating element in order to produce the desired synthetic spectrum. The grating-element actuation method chosen is a combination of electrode and mirror-element design called “leveraged-bending”, shown in Figure 3[7]. Electrodes are placed beneath only about 1/3 of the element, specifically positioned towards the supports. As long as the element itself is bending dominated rather than stress dominated (requiring stress below about 10 MPa in our baseline case), then the bending produced by electrostatic actuation near the supports is leveraged into full travel of the center of the element, without encountering pull-in.



**Figure 3.** Basic grating element design showing two-level structure. The lower structural layer (Poly2) is deflected by electrostatic forces through leveraged bending, while the upper (Poly3) layer with the mirror surface remains flat [3].

Modeling of the grating-element voltage-displacement characteristics provides a first-order calibration of mirror movement, to support both grating positioning and modulation. Models of grating-elements are already done but full calibration of the calculated characteristics awaits experimental confirmation from the first test parts. The

characteristics of the grating-elements are experimentally calculated using the MIT developed in-situ material test procedure (M-Test), a method for measuring residual stress and elastic modulus of thin-film structures [4, 5].

### 2.1.3 Layout and Interface

The polychromator contains 128 controllable elements each requiring high voltages in order for Poly2 to travel down the whole gap between Poly2 and the grounding pad. The actual gratings contain 640-1024 total lines arranged in groups of 128 (Figure 7). In order to apply a voltage to each of the grating-elements, the grating array die is packaged on a 145-pin PGA (Figure 8), and connected by 132 bond pads (128 actuation voltages + 4 ground pads). See Appendix F for package information.

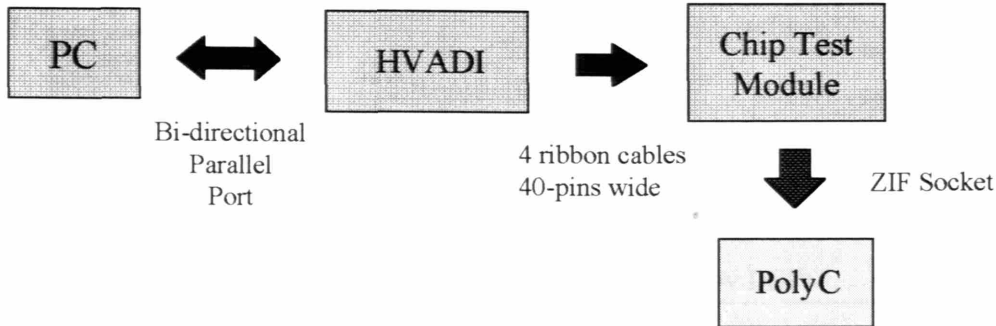
## **2.2 Analog Driver**

### 2.2.0 Overview

The electronic programmability of the polychromator requires the development of a control system in order to operate and control the behavior of each grating-element. The control electronics is composed of two main pieces of hardware: a high voltage analog driver instrument (HVADI) and a personal computer (Figure 4).

## Control Electronics

- 128-channel (Digital Designs & Systems) analog driver
  - controlled by computer
- Dell PentiumII-300 MHz PC

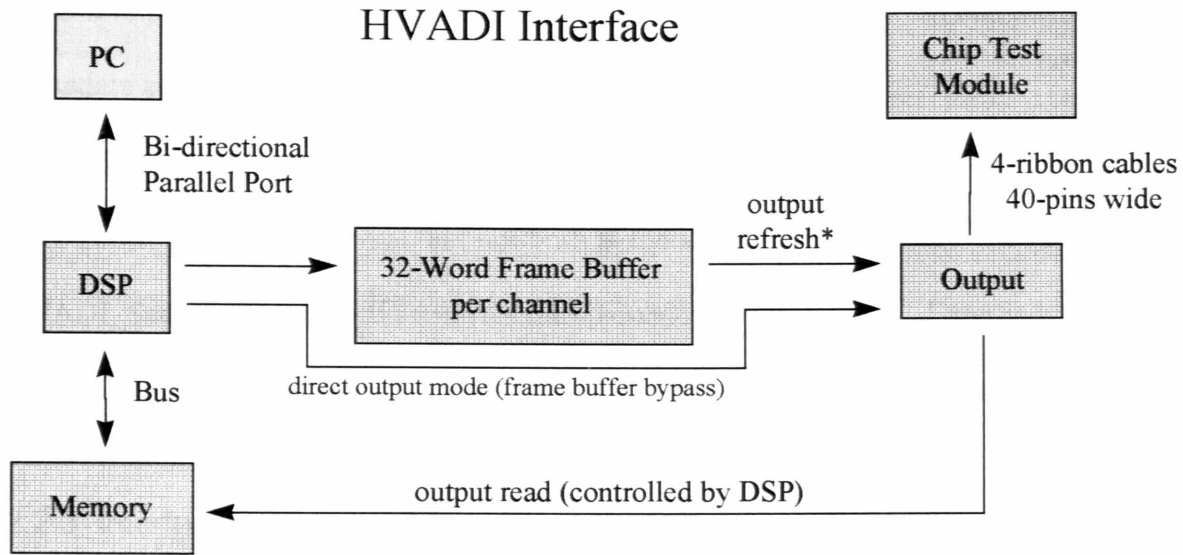


**Figure 4.** Control electronics setup used to drive the polychromator (PolyC).

The test electronics (Figure 9) is composed of a 128-channel programmable high voltage analog driver (being purchased from Digital Designs & Systems), with a range of 0 to 150 V, a 32-word frame buffer for each channel (permitting modulation up to 1 kHz), and a voltage feedback to permit device monitoring.

### 2.2.1 Description

The purpose of the test electronics is to supply a high voltage capability and a frame buffer that allows sets of voltages to be stored in memory. The hardware is controlled by its own DSP processor that communicates with the PC through the parallel port. The PC passes the instructions to the DSP, gives the desired output voltages, and reads the actual output voltages.



\* The output refresh operation is controlled by a trigger event, either internal (DSP) or external (source input).

**Figure 5.** Schematic representation of the internal interface of the HVADI hardware describing how the information passes from the computer to the output stage.

### 2.2.2 Operation

The instrument has several modes of operation: single frame mode, loop frame mode, continuous frame mode, and direct output mode. In the single frame mode, only one frame is used to control the output voltage (requires the PC to send a new frame in order to update the output). In the loop frame mode, a series of frames are passed to the buffer and the HVADI cycles through the frames until it is interrupted (no information required from PC once all frames in cycle are in the buffer). The continuous frame mode requires the PC to continuously send frames to the buffer in order to update the output (the information in the buffer is stored as fast as the PC can send it). An update will only occur when the buffers receive a new frame. Finally, the direct output mode bypasses the

buffer completely passing the desired voltages directly to the output. In this mode there is no update and the buffer is not used.

The speed of the output update is controlled by the trigger source which can be set to be either internal or external, but not both at the same time. Internally, the function HVADI\_SetFrequency(Hertz) controls the frequency of the updates. Externally, the updates are controlled by using a series of pulses, each pulse triggering one update event.

### 2.2.3 Interface

The HVADI hardware interfaces with two parts: the PC and the Chip Test Module (see Figure 10). The computer is connected through a bi-directional parallel cable and the Chip Test Module (Figure 11) through 4 ribbon-cables, each 40-pins wide. The correct interface between the polychromator and the Chip Test Module is to be determined and documented (see Section 3.1).

## **Chapter 3. Simulations and Design**

### **3.0 Overview**

This section outlines the procedures taken to produce the grating-element voltage-displacement characteristics, the grating-element positioning strategy, and the modulation strategies chosen to produce spectral modulation.

### **3.1 Interface**

#### **3.1.0 Overview**

One of the most simple but easily overlooked problems is the interface between any two systems. If the communication between the systems is not mapped correctly, the overall system will not work correctly even if the control strategies are accurate.

Therefore, it is necessary to verify that the analog driver and the polychromator “speak the same language”.

#### **3.1.1 Grating-element mapping**

The polychromator grating, as described previously, is packaged using a 145-pin PGA chip to provide a rigid connection to the control electronics. This chip is inserted into the chip test module of the HVADI hardware (Figure 12), gold strip in the package points away from the jumpers in the module. There are two steps required to verify the proper interface. The first is the channel map of the HVADI to the chip test module and the second is the layout map of the PGA package, the pins in the back to the corresponding bond pads in the polychromator grating.

In order to map the chip test module, an identifying signature was produced for every channel and then that signature was located in the module. The signature corresponds to the base 2 representation of the channel number, i.e. signature 1001011 for channel 75 (Figure 13). Note that the channel number for the HVADI run from 0 to 127, therefore channel 0 corresponds to grating-element #1. The package layout was provided by Honeywell and the grating layout by E. S. Hung.

### 3.1.2 Results

A table map was created using the identification of the signatures in the chip test module (Appendix C). This table was then compared to the package layout, and subsequently, to the bond pad connections of the polychromator grating. The interface connections were verified and only one error was identified. A bond pad connection had been misplaced which shifted the HVADI channel – grating-element mapping. The error was corrected for future packaging of grating arrays.

## 3.2 Simulation

### 3.2.0 Overview

Accurate and efficient models are necessary to produce a repeatable and accurate actuation behavior. Modeling of the grating-element voltage-displacement characteristics provides a first-order calibration of mirror movement, to support both grating positioning and modulation.

### 3.2.1 Polychromator model

For our model, we follow the example set forth by E. S. Hung and S. D. Senturia [7]. Since the upper mirror beam does not affect actuation to first order, the grating element is modeled by considering just the lower beam. The 2D equilibrium equation for an elastic beam with the electrostatic force is given by:

$$EI \frac{\partial^4 z}{\partial x^4} - S(z) \frac{\partial^2 z}{\partial x^2} = F_{elec} \quad (1)$$

where  $x$  is the distance along the beam,  $z(x)$  is the gap height,  $E$  is the elastic modulus,  $I = wh^3 / 12$  is the moment of inertia,  $w$  is the beam width,  $h$  is the beam thickness,  $S(z)$  is the force in the beam due to stress (see Eq. (3)), and  $F_{elec}$  is the electrostatic force per unit length. Neglecting fringing fields and crosstalk between elements, we approximate:

$$F_{elec} = -\frac{\epsilon_o a(x) V^2}{2x^2} \quad (2)$$

where  $a(x)$  represents the shape of the actuation electrode, and  $V$  is the applied voltage. The  $S(z)$  terms contains two contributions, one from the residual stress left in the beam after processing, and one from a nonlinear “strain-stiffening” effect due to the stretching of the beam as it deforms.  $S(z)$  is modeled as follows:

$$S(z) = hw[\sigma_o(1 - \nu) + E \frac{\Delta L}{L}] \quad (3)$$

where  $\sigma_o$  is the biaxial residual stress,  $\nu$  is the Poisson ratio,  $\Delta L$  is the elongation in the length of the beam due to deformation, and  $L$  is the length of the beam. The beam equation is simulated using finite difference code.

### 3.2.2 Voltage-Displacement Relationship

In order to actuate the polychromator grating, we need to obtain a translation table between grating-element displacement and voltage. This relationship allows conversion of a specific displacement profile into the corresponding voltage profile that will produce the desired behavior.

The model used for the polychromator obtains the grating-element displacement that corresponds to a specific electrostatic voltage applied to the electrode. A reverse lookup procedure is used to iterate over the simulation and find the electrostatic voltage that corresponds to a specific displacement. Two translation tables were produced: one with 16 discrete positions for DC positioning and another with displacement in steps of  $0.01\mu\text{m}$  for more refined positioning and accurate modulation.

### 3.2.3 Results

The results of our reverse lookup calculations are stored in an output text file [Appendix D]. The translation file contains the parameters used to produce the file, a brief description of its contents, and the translation table. The table is composed of two columns: the first is the displacement in  $\mu\text{m}$ , and the second is the required voltage. The displacement column corresponds to the distance away from the relaxed position instead of the gap distance. This allows the polychromator grating to be modified without having to change the interpreting software.

### 3.2.4 Calibration

Models of grating-element displacement versus voltage were obtained to a first degree, but full calibration of the calculated characteristics awaits experimental confirmation from the first test parts. The characteristics of the grating elements are experimentally calculated with the use of the M-Test procedure [4, 5].

There are two effects that were not modeled using our finite-difference code that could produce significant changes in element behavior. First, crosstalk between grating-elements can produce a more complex actuation behavior since the displacement of a specific grating-element would depend on the adjacent grating-elements. Second, more complex models that take into account support compliance, exact geometry, and extracted material properties should be used in order to produce more accurate characteristics.

## **3.3 Positioning**

### 3.3.0 Overview

In order to observe the desired actuation displacement, the control system for the polychromator must be able to convert a specific displacement profile into a corresponding voltage profile that will produce the desired displacement. The translation process requires accurate grating-element to voltage-displacement characteristics to produce repeatable and accurate actuation of the polychromator.

### 3.3.1 Static displacement

For the simplest model, we assume that all channels observe the same voltage-displacement relationship. In this case, all that is required is to take a specific

displacement profile, convert it into a voltage profile which in turn is passed to the HVADI hardware, and then actuates the polychromator. If it turns out that not all the grating-elements observe the same relationship, we can use several relationships at the same time and reference each element accordingly when the conversion is desired.

### 3.3.2 Implementation

The conversion process from displacement to voltage is done by means of a table lookup (see Appendix D). One of the main reasons for using a text file to hold the voltage-displacement relationship is that we can either create the file from a simulation or enter the data from actual measurements. In the case that a specific displacement is not found in our table, an interpolation is done using the closest values in the table by giving more weight to the higher displacement (the electrostatic force is directly related to the square of the applied voltage). In order to test the conversion from displacement to voltage, we can use the modulation implementation with only one state (see next section for details).

In order to calibrate and test static displacement on individual or groups of grating-elements, we can use a program developed in conjunction with E. S. Hung that allows the user to apply DC voltages to the grating-elements in four different modes: same voltage to all channels, voltage to a specified channel, voltage to odd-numbered channels, and voltages to even-numbered channels (channels not specified receive 0 volts). There is also a fifth mode under consideration in order to enter displacements profiles by adding the functionality of the modulation scheme (see next section). The legend explaining the modes of operation can be found below.

HVADI support library Version 1.01. [Apr 5 1998 21:44:34]  
DC Grating Testing (Interactive Single Frame Mode)

Press the following keys at any time:

Channel selection:

- m:Select all channels (default)
- c:Select output channel (0-127)
- o:Select odd channels.
- e:Select even channels.

Voltage manipulation:

- z:output voltage -1V, x:voltage +1V
- a:output voltage -10V, s:voltage +10V

Measure all channels:

- p:Print ADC values
- r:Print resistance values (in MOhm)
- q:Terminate program
- ?:Print this menu

In the case where more than one voltage-displacement relationship exist, we can add more columns to our lookup table file (see Appendix D) and then use another table to map each channel to the corresponding relationship.

### **3.4 Modulation**

#### 3.4.0 Overview

The polychromator spectrometer system uses a correlation detection scheme in order to determine the presence of a target species. To use this detection scheme, we need to implement a modulation behavior that shifts the target spectra and produce a high-selectivity only of the species in study.

#### 3.4.1 Strategies

The modulation strategy that was chosen uses a first-derivative detection scheme proposed by Mike Sinclair (Sandia). This method uses a two state-switching modulation

scheme where two output target spectra are used for a specific target species and the difference in the output signal is used to determine the presence of the species. In addition, a second-derivative detection scheme (three states) was proposed by S. D. Senturia which might give even better results. It is possible that with our current design we don't have enough actuation lines to take full advantage of this method and that will need to be determined.

### 3.4.2 Implementation

In order to allow the most flexibility to the system, both derivative schemes were implemented. The information required by the control system, namely the different displacement profiles that compose the required derivative scheme, was implemented as a text file to keep the inputs and the control program separate.

The text file contains a brief description of its function and a table with the corresponding states for the derivative scheme (Appendix E). In order to distinguish between the first-derivative and second-derivative scheme, the input file requires the following identifying line “%n” where n is the number of states (n=2 for first-derivative, n=4 for second-derivative). The columns in the file are mirror #, state a1 and state a2 for first-derivative, followed by state a1 and state a3 for second derivative.

The control system reads all the states from the input file and keeps it in memory until another input file is desired, or the system is exited. The program translates each displacement state profile into a voltage profile and passes it to the frame-buffer in the HVADI.

### 3.4.3 Results

The results of the modulation scheme are very promising and allow great flexibility in the programming of the control system. Two output modulations are shown in Figures 14 and 15. This modulation method allows many different patterns to be used to test the grating. An example with two grating-elements is shown in Figure 16. We apply a “follow the leader” state switching where both lines start at the same position and only one line changes at a time. Line1 and 2 start at P1, Line2 changes to P2, Line1 changes to P2, Line2 changes to P1 and the cycle repeats. If we observe this test under an interference microscope, we can determine if both channels have the same voltage-displacement relationship by comparing the number of fringes when both channels have the same applied voltage.

## **Chapter 4. Discussion and Conclusions**

### **4.0 Overview**

This section discusses some of the problems encountered with grating-element actuation, and presents possible explanations and areas of further study to eliminate the problems. It is followed by a discussion of suggested areas of investigation that will provide a better understanding of the grating-element actuation and a more accurate control of the polychromator. The chapter concludes with a summary of the work done for this thesis.

### **4.1 Problems**

#### **4.1.1 Shorting**

In many of the beams that were tested, there was a “shorting” behavior that did not allow the grating-elements to travel the full gap. Initially, these gratings would deflect downwards as expected with increasing voltage. As the applied voltage reached around 40-50 volts (in most cases), the resistance between the actuation and ground pads suddenly dropped by a factor of 10 or more. Most of the voltage drop occurred between the interconnects and the test resistor (used to measure current drawn), effectively reducing the voltage between the actuation electrode and the rest of the grating. This “shorting” behavior caused the grating-element to pop back up to an undeflected position.

A lot of testing was done in order to determine the cause of the “shorting” behavior. With some destructive testing, E. S. Hung was able to identify the mechanism behind this strange behavior. The layout of the layers below Poly2 cause a ditch to be

formed between grating-element which causes a larger height of Poly2 in this area during its deposition (Figure 17). When Poly2 is patterned and etched, the extra height causes a small stringer to be left behind that will cause a great deal of problems during the actuation of the gratings (Figure 18).

These stringers act like small cantilevers connected to the Poly2 structure. When a voltage is applied to the electrode, these cantilevers bend towards the electrode. At the moment where the stringer comes in contact with the actuation electrode, a “shorting” behavior is exhibited since the Poly2 structure is now at the same potential as the electrode and the grating returns to an undeflected position. In some cases, the stringer becomes permanently stuck to the electrode, and prevents using that particular grating-element. In order to eliminate the presence of these stringers, longer etch times are being used during the manufacturing process.

#### 4.1.2 Crosstalk

Another behavior that was noticed during the actuation of some gratings was a considerable crosstalk effect between grating-elements. As voltage was applied to one line, the line next to it deflects partially. Even if the electrode of the next line was grounded, there was still some crosstalk between the elements. In our simulation model, we assumed that adjacent elements did not affect each other but it may turn out that our assumption was wrong.

There are a few reasons that might be causing this crosstalk effect. First, our infamous stringers which may cause undesired connections between adjacent elements. Second, a leakage current through the nitride layer which may cause a voltage in the

adjacent electrode or ground pad. Finally, a fringing field between the actuation electrode and the adjacent grating-elements could cause undesired effects.

## **4.2 Future Work**

There are a four main areas of investigation that will lead to a better understanding of the grating-element actuation and a more accurate control system for the polychromator. First, obtaining a more accurate simulation model of the polychromator is necessary in order to produce a more accurate voltage-displacement relationship. The first step in obtaining a better model is to calibrate the characteristics of the grating-elements using the M-Test procedure [4,5]. Another step is to use a more complex model that takes into account the presence of the adjacent grating-elements in order to understand the effect of the neighboring electrostatic forces. This step is very important since we noticed considerable crosstalk effects between the elements, and the source could not be easily identified.

Second, exhaustive interferometric measurements using both the WYKO optical profilometer and the interference microscope (fringe counting) are needed in order to assess the accuracy of our model and get a more specific voltage-displacement relationship. Third, it is important to understand the dynamic response of the grating-elements in order to determine how the elements will react to changes in the actuation voltage. The natural mechanical frequency can cause ringing effects of the grating-element position which will produce disturbances in the output spectra. Finally, it is necessary to verify the repeatability and accuracy of each grating-element. It is important to determine if different grating-elements exhibit different voltage-displacement relationships in order to calibrate

the voltage-displacement table. It is also important to determine if there is any charge accumulation in the grounding electrode or if there is any leakage current through the nitride layer which will cause time-dependent electrostatic forces.

The continuing investigation of these areas is vital to assure that the polychromator exhibits a predictable and accurate actuation behavior. This characterization will ensure that the optical performance of the device will be consistent and that no calibration would be required for each manufactured device.

### **4.3 Conclusions**

The control system implementation for the polychromator is presented. The static displacement and modulation strategies were designed to be as modular as possible using input files to address all the information required: voltage-displacement relationship and displacement profiles. This allows us to modify our design without having to make changes to our implementation and reproduce our input files with simulated or measured values. The control system implemented will make it very easy to integrate the detection and analysis system that is being developed at Sandia National Laboratories.

As part of this thesis, areas of further study are identified wherever possible in order to achieve better understanding of the grating-elements actuation and the accurate control of the system in order to produce accurate spectral features. The polychromator concept will considerably change the way chemical detection is performed at present, both as a spectrometer system and as remote sensing equipment for field use. The control system implemented will provide the tools necessary for the actuation of the polychromator.

## References:

- [1] “Synthetic spectra: A Tool for Correlation Spectroscopy,” M.B. Sinclair, M.A. Butler, A.J. Ricco, and S.D. Senturia, *Applied Optics* 36, pg. 3342–3348 (May 20, 1997)
- [2] “Synthetic Infrared Spectra,” M.B. Sinclair, M.A. Butler, S.H. Kravitz, W.J. Zubrzycki, and A.J. Ricco, *Optics Letters* 22, pg.1036–1038 (July 1, 1997)
- [3] G. B. Hocker, et. al., Polychromator Semiannual Report, Contract Number N66001-97-C-8620, January 1998.
- [4] P. M. Osterberg, and S. D. Senturia, “M-Test: a Test Chip for MEMS Material Property Measurements Using Electrostatically Actuated Test Structures”, *Journal of Microelectromechanical Systems*, June 1997, Vol. 6, No. 2, pp. 107-118.
- [5] Raj K. Gupta, “Electrostatic Pull-In Test Structure Design for in-situ Mechanical Property Measurements of Microelectromechanical Systems (MEMS)”, Ph.D., June 1997, MIT.
- [6] Elmer S. Hung, “Positioning, control, and dynamics of electrostatic actuators for use in optical and RF systems”, Ph.D., August 1998, MIT.
- [7] “Leverage Bending for Full-Gap Positioning with Electrostatic Actuation,” Elmer S. Hung, and S. D. Senturia, to be presented.

## Appendix A: Figures

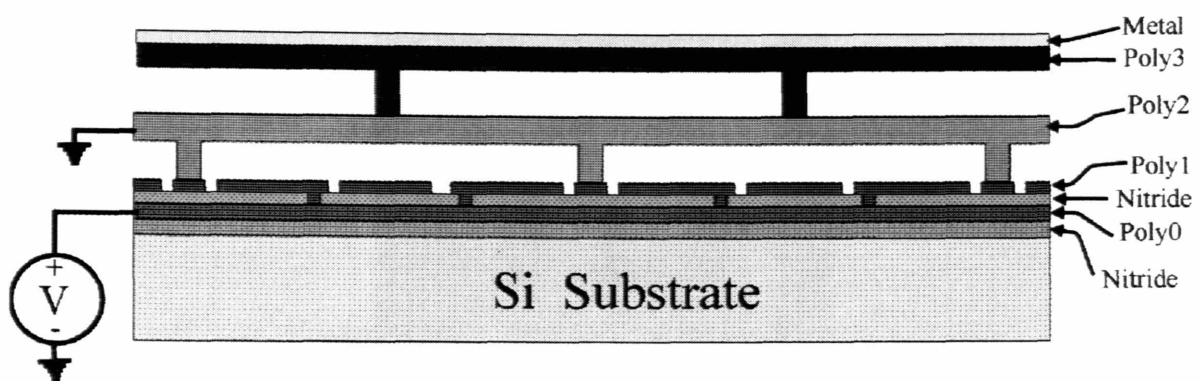


Figure 6. Basic grating element design showing two-level structure at rest (no voltage applied between Poly1 and Poly2).

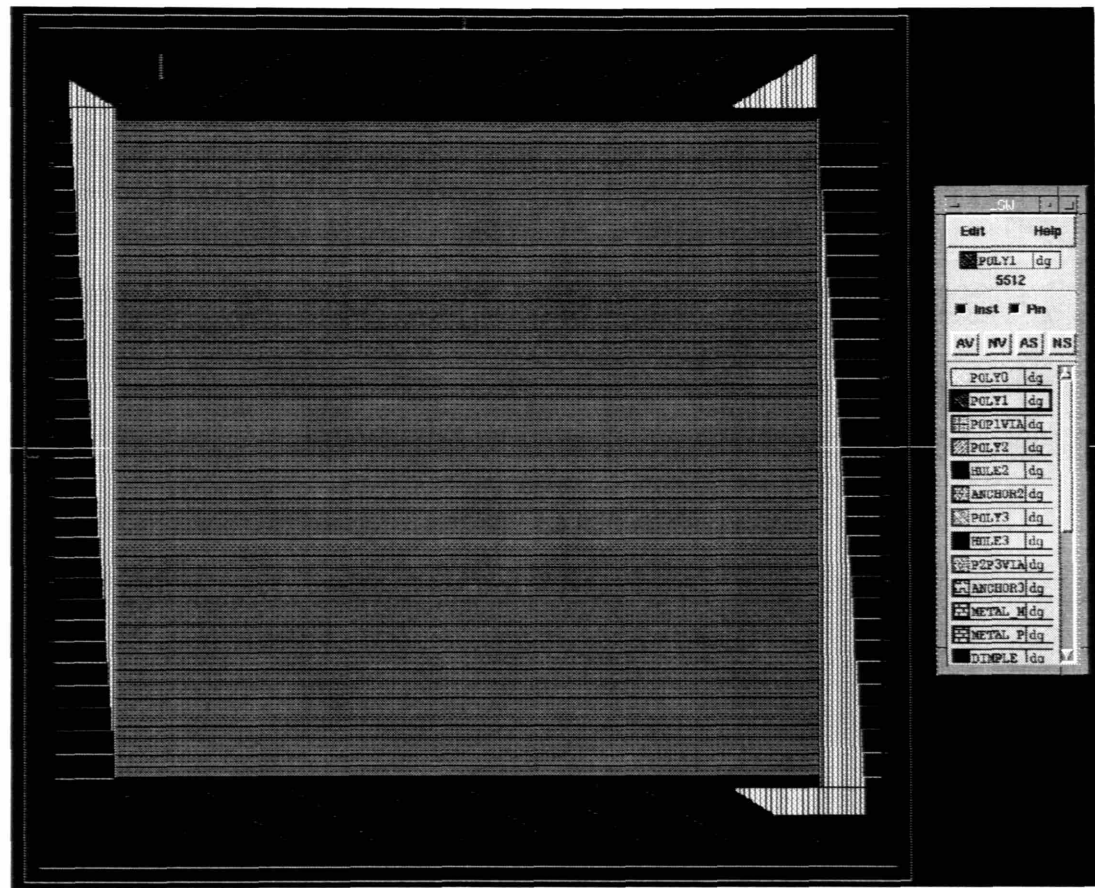
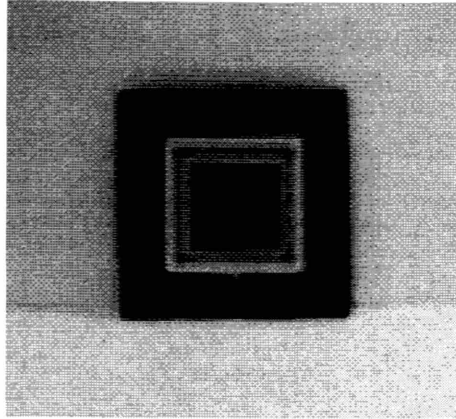
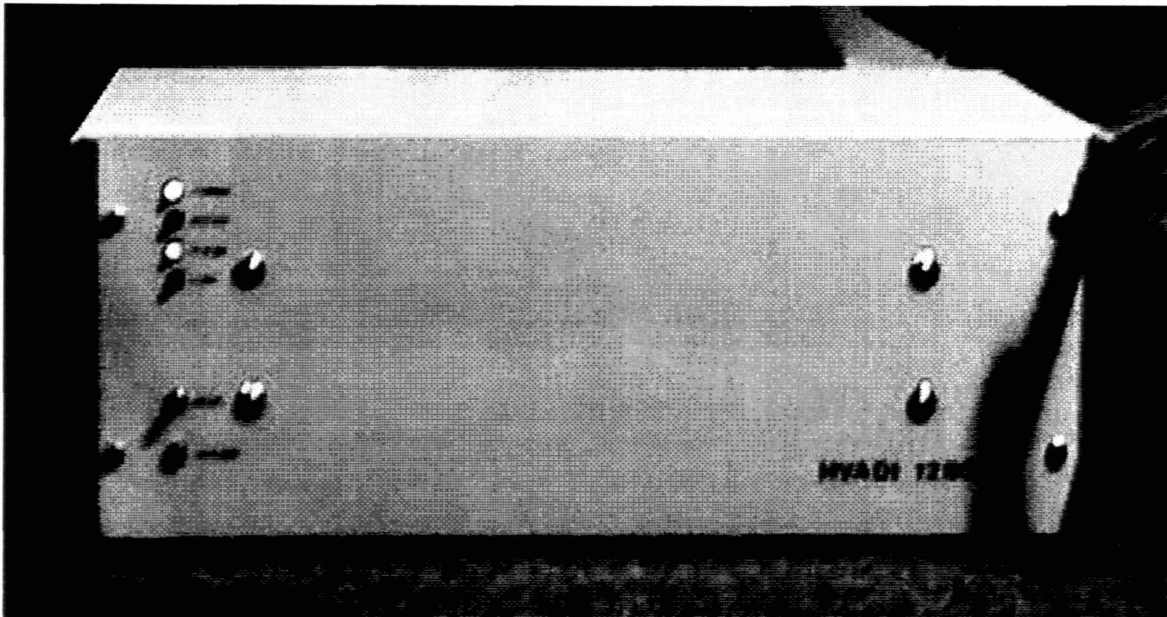


Figure 7. Large grating at the wafer-level.



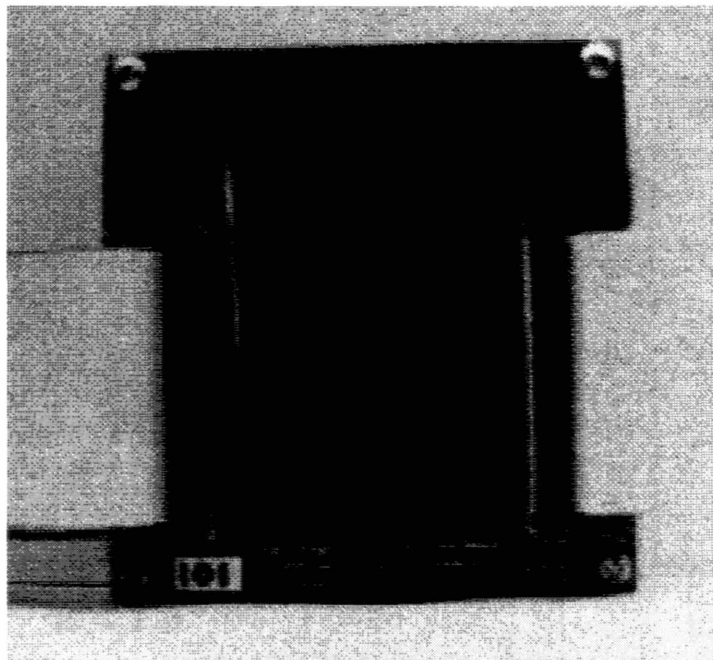
**Figure 8.** Large grating in 145-pin PGA package.



**Figure 9.** Front view of the high voltage analog driver instrument (HVADI).



**Figure 10.** Back view of the HVADI, showing connections for the 4 ribbon cables and the parallel port.



**Figure 11.** Chip Test Module.

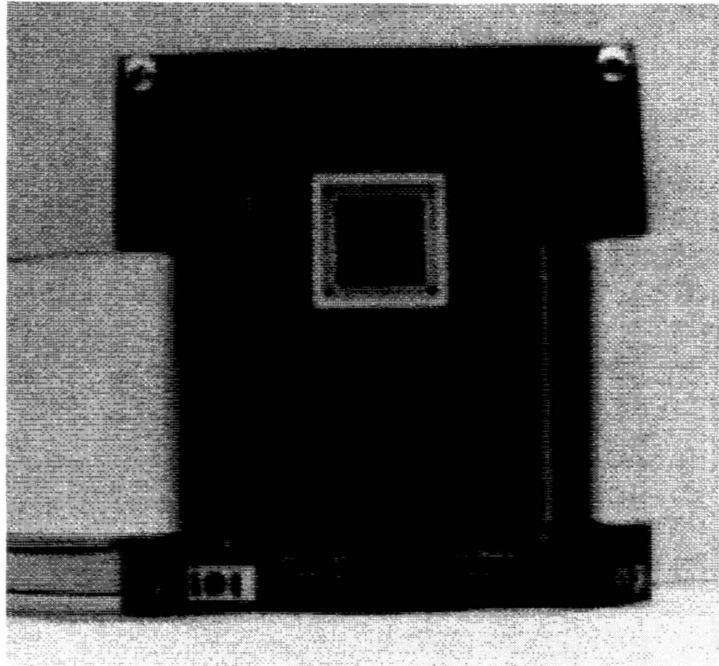


Figure 12. Chip Test Module with the Polychromator inserted.

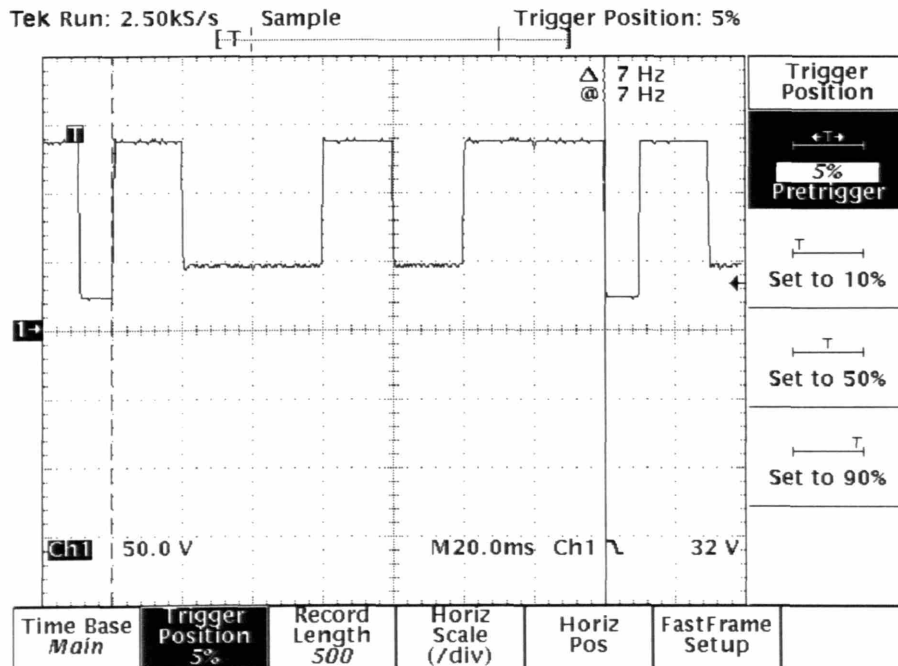


Figure 13. Voltage signature for HVADI channel 75. Note that high is equal to 150 volts, low is equal to 50 volts and the starting mark is equal to 25.

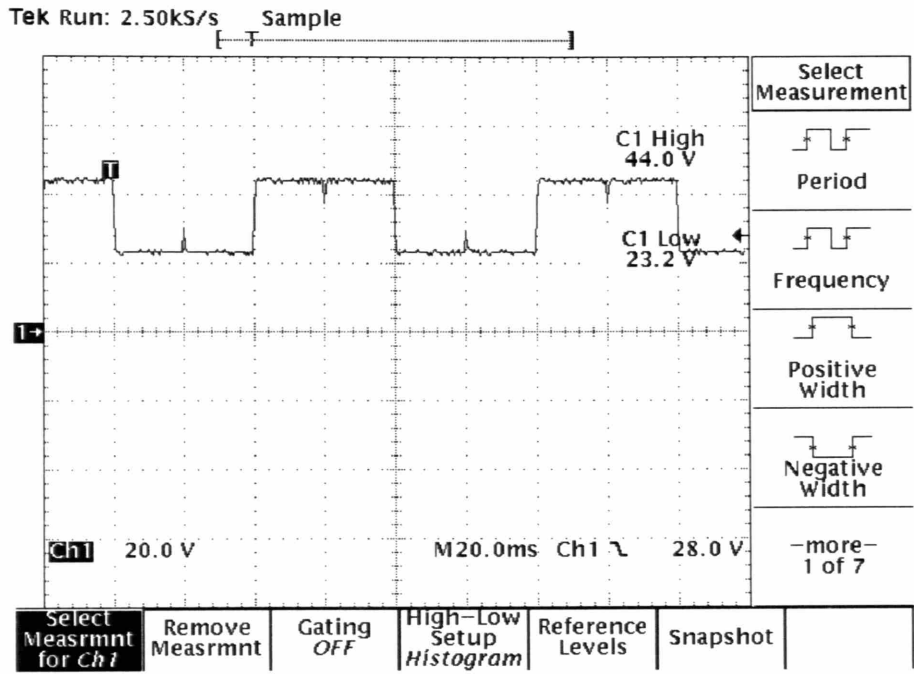


Figure 14. Output voltage waveforms for a first derivative scheme (two states).

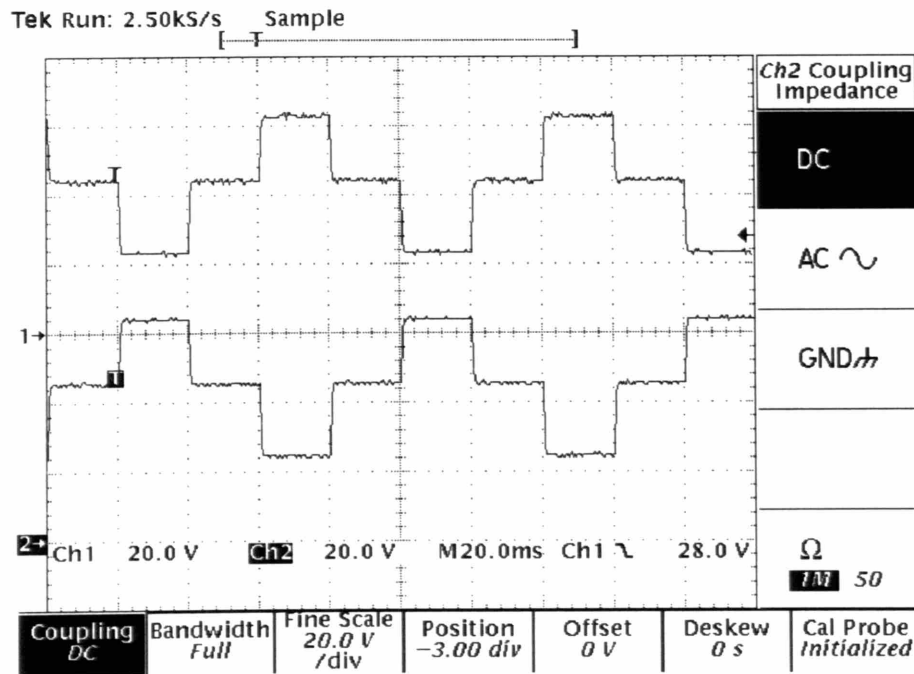


Figure 15. Output voltage waveforms for a second derivative scheme (three states).

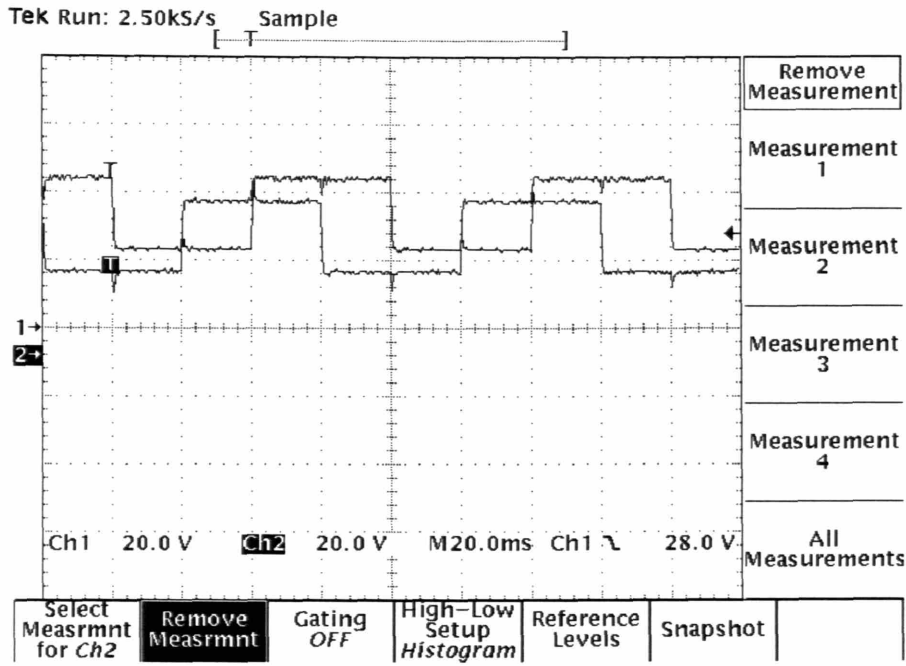


Figure 16. Output voltage waveforms for “follow the leader” state switching. Note that channel 2 is offset from the x-axis in order to observe both channels simultaneously.

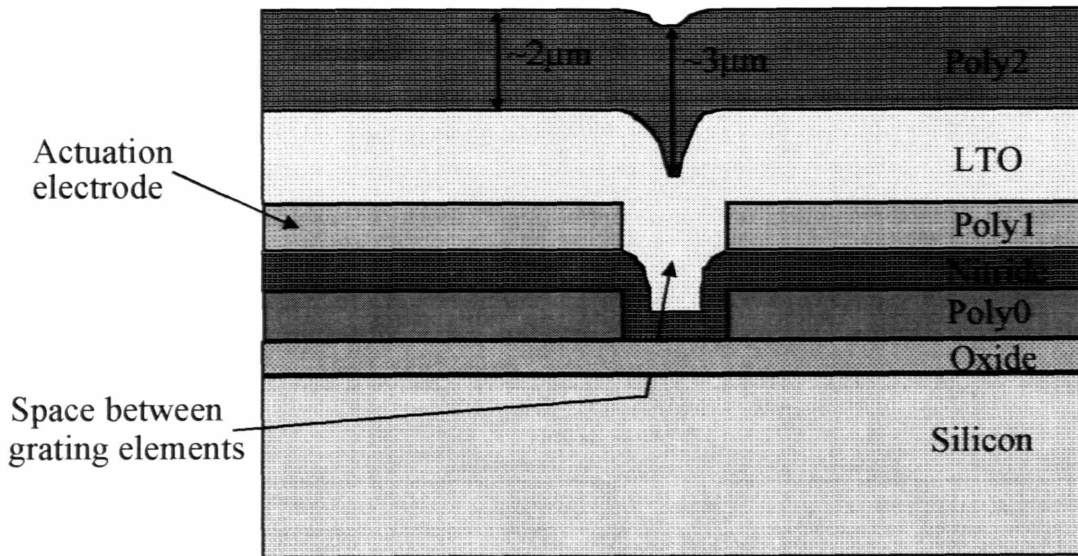
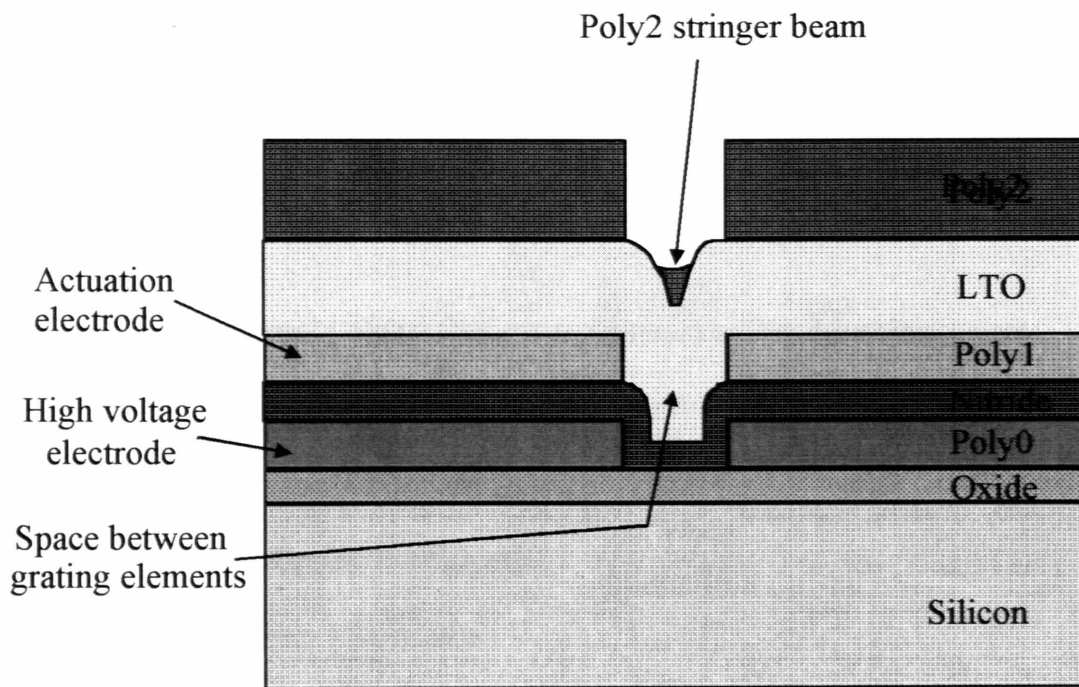


Figure 17. Cross section of two grating elements after deposition of Poly2.



**Figure 18.** Cross section of two grating elements right after Poly2 is patterned.

## **Appendix B: Test equipment**

The following is a list of the test equipment used to perform the research described in this thesis.

1. 128-channel (Digital Designs & Systems) analog driver instrument
2. Dell PentiumII-300MHz PC
3. Tencor P-10 Surface Profilometer
4. WYKO Optical Profilometer
5. Interference Microscope
6. Tektronix TDS 540B

## Appendix C: Chip Test Module channel map

The following table showing the HVADI channel mapping on the Chip Test Module where the polychromator package is inserted.

Channel map for HVADI  
Chip Test Module (handle on right)

	A	B	C	D	E	F	G	H	J	K	L	M	N	P	R
15	GND	93	89	88	86	82	81	78	76	75	72	69	67	64	GND
14	96	GND	92	90	87	84	83	77	73	71	68	65	GND	GND	61
13	99	GND	95	94	91	85	80	79	74	70	66	GND	63	60	57
12	101	97	GND	/	/	/	/	/	/	/	/	62	62	58	56
11	104	100	98	/	/	/	/	/	/	/	/	59	59	55	54
10	107	103	102	/	/	/	/	/	/	/	/	/	53	52	50
9	108	105	106	/	/	/	/	/	/	/	/	/	48	51	49
8	110	109	111	/	/	/	/	/	/	/	/	/	47	45	46
7	113	115	112	/	/	/	/	/	/	/	/	/	42	41	44
6	114	116	117	/	/	/	/	/	/	/	/	/	38	39	43
5	118	119	123	/	/	/	/	/	/	/	/	/	34	36	40
4	120	122	126	/	/	/	/	/	/	/	/	/	GND	33	37
3	121	124	127	GND	2	6	10	15	16	21	27	30	31	GND	35
2	125	GND	GND	1	4	7	9	13	19	20	23	26	28	GND	32
1	GND	0	3	5	8	11	12	14	17	18	22	24	25	29	GND

## Appendix D: Sample voltage-displacement file

This is sample input file used to describe the voltage-displacement relationship.

The lines starting with \* are used to describe the function of the file. The columns in the table are the displacement in  $\mu\text{m}$  and its corresponding actuation voltage.

\* Polychromator displacement vs. voltage profile

\* for 16 preset positions

\* Displacement Voltage

0.0	0.0
0.125	19.0754
0.25	26.9818
0.375	33.3068
0.5	39.0139
0.625	44.4648
0.75	49.7988
0.875	55.0771
1.0	60.2886
1.125	65.3999
1.25	70.3553
1.375	75.0656
1.5	79.442
1.625	83.384
1.75	86.7609
1.875	89.4307

## Appendix E: Sample modulation file

This is sample input file used to describe the modulation states. The lines starting with \* are used to describe the function of the file. The %4 indicates the number of displacements columns (states) in the table. The columns in the file are mirror #, state a1 and state a2 for first-derivative, followed by state a1 and state a3 for second derivative.

```
* Sample modulation profile for material
* 2nd derivative method (distances in microns)
* Mirror# Pos#1 Pos#2 Pos#3 Pos#4
%4
1 .75 .25 .75 1.25
2 .75 1.25 .75 .25
3 .75 .25 .75 1.25
4 .75 1.25 .75 .25
5 .75 .25 .75 1.25
6 .75 1.25 .75 .25
:
:
:
121 .75 .25 .75 1.25
122 .75 1.25 .75 .25
123 .75 .25 .75 1.25
124 .75 1.25 .75 .25
125 .75 .25 .75 1.25
126 .75 1.25 .75 .25
127 .75 .25 .75 1.25
128 .75 1.25 .75 .25
```

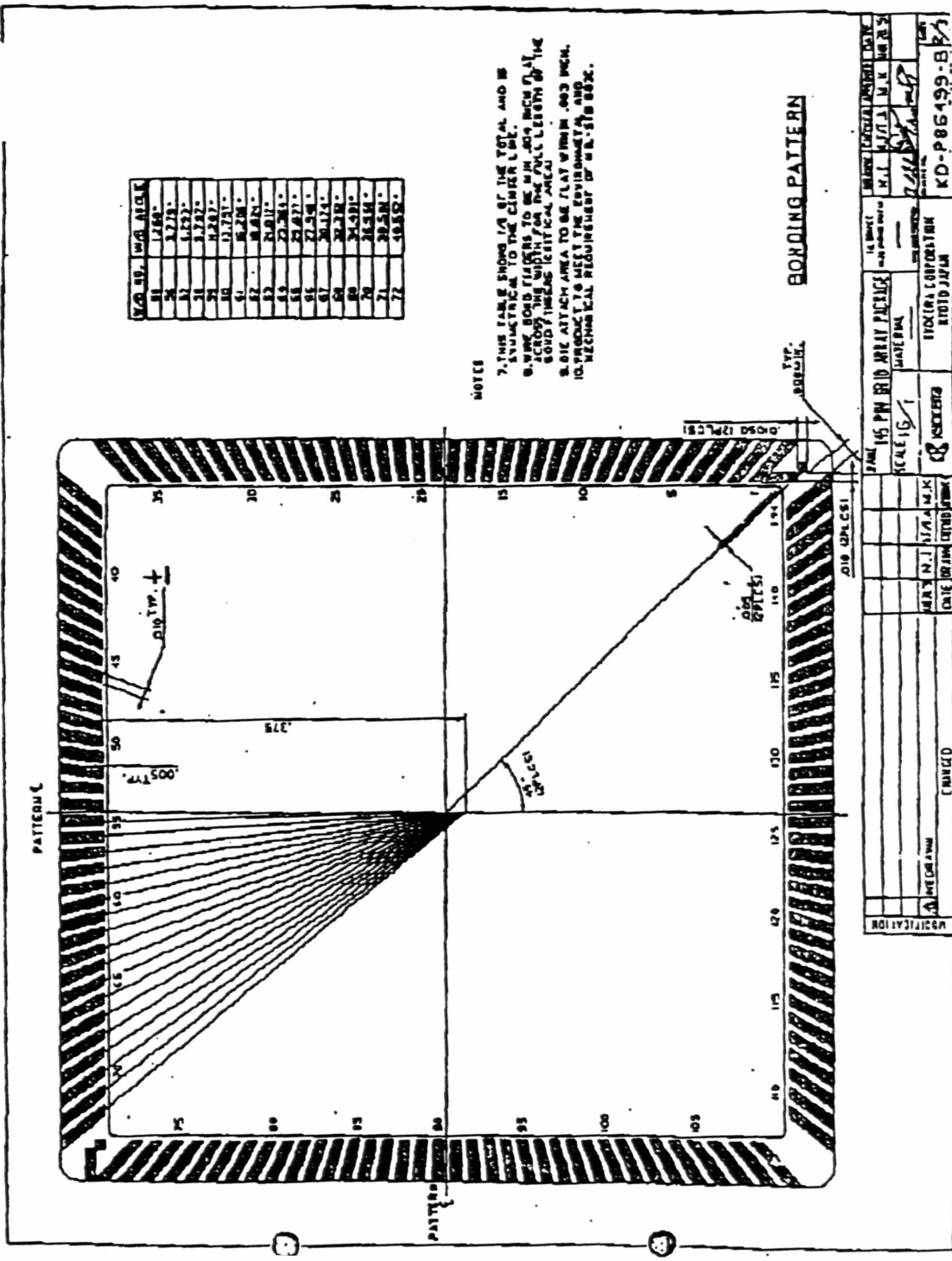


WIRE BOND PAD / CONNECTOR PIN INTERCONNECTION PLAN

W/B NO.	PIN NO.	W/B NO.	PIN NO.	W/B NO.	PIN NO.	W/B NO.	PIN NO.	W/B NO.	PIN NO.
1	D3	27	M1	53	R8	79	L14	105	D13
2	C2	28	M1	54	M8	80	M15	106	C13
3	B1	29	M2	55	M9	81	M13	107	B11
4	D2	30	L3	56	R9	82	K14	108	A15
5	E3	31	M2	57	R10	83	L15	109	C12
6	C1	32	P1	58	P9	84	J14	110	B13
7	E2	33	M3	59	P10	85	J13	111	A14
8	D1	34	M3	60	M10	86	K15	112	B12
9	F3	35	P2	61	R11	87	J15	113	C11
10	F2	36	R1	62	P11	88	M14	114	A13
11	E1	37	M4	63	R12	89	M15	115	B11
12	G2	38	P3	64	R13	90	M13	116	A12
13	G3	39	R2	65	P12	91	G13	117	C10
14	F1	40	P4	66	M11	92	G15	118	B10
15	G1	41	M5	67	P13	93	F15	119	A11
16	M2	42	R3	68	R14	94	G14	120	B9
17	H1	43	P5	69	M12	95	F14	121	C9
18	M3	44	R4	70	M13	96	F13	122	A10
19	J3	45	M6	71	P14	97	E15	123	A9
20	J1	46	P6	72	R15	98	E14	124	B8
21	K1	47	M5	73	M13	99	D15	125	A8
22	J2	48	P7	74	M14	100	C15	126	C8
23	K2	49	M7	75	P15	101	D14	127	C7
24	K3	50	R6	76	M14	102	E13	128	A7
25	L1	51	R7	77	L13	103	C14	129	A6
26	L2	52	P8	78	M15	104	B15	130	B7

NOTES  
 1. PIN IS EXTRA PIN USED FOR ORIENTATION  
 AND IS CONNECTED TO GND.  
 2. ALL LEADS MUST MEET THE LEAD INTEGRITY  
 CRITERIA MIL-STD-883C METHOD 2005.4.

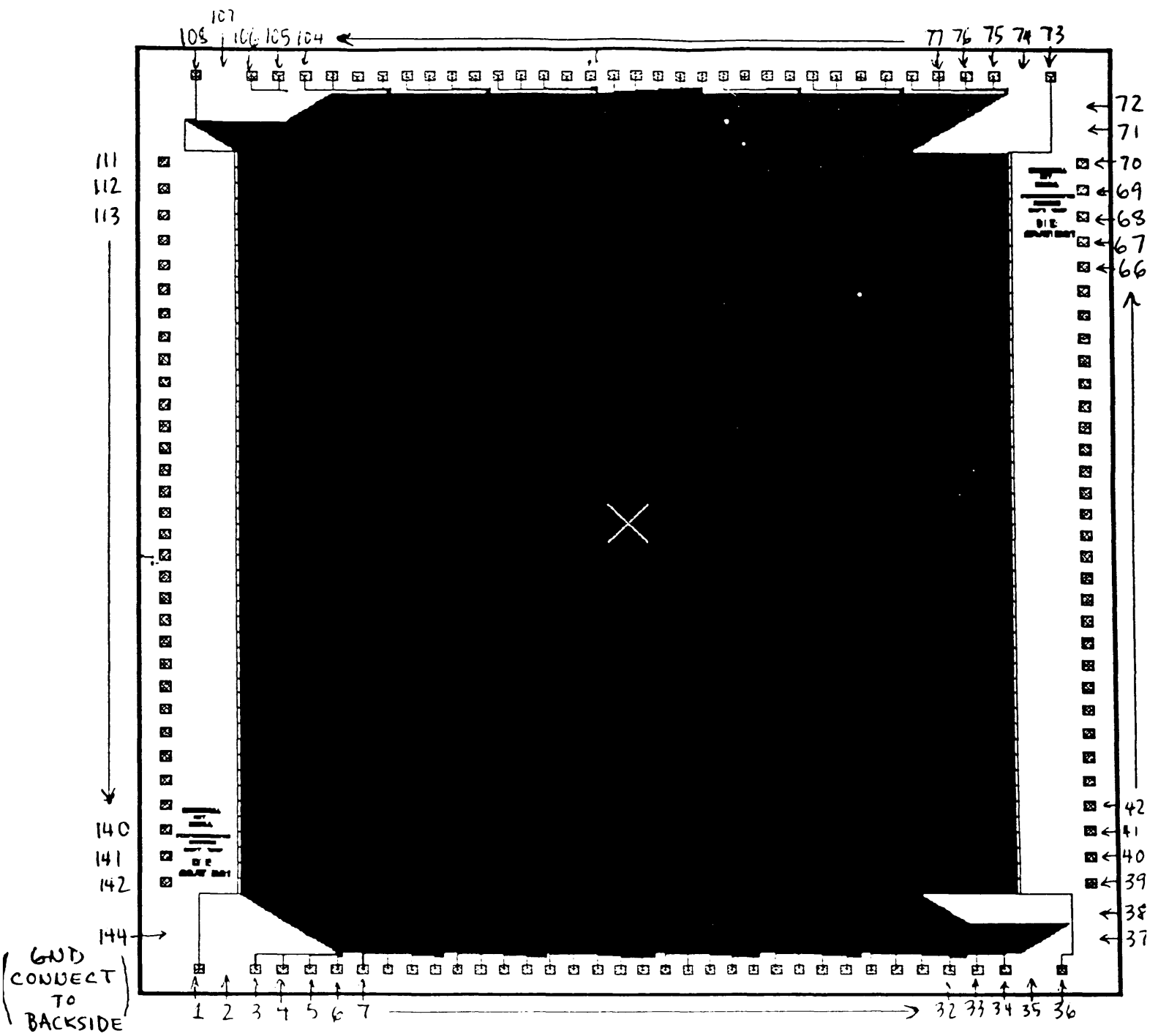
DATE	11/11/11	BY	WJ
REV	1	DATE	11/11/11
DESCRIPTION	WIRE BOND PAD / CONNECTOR PIN INTERCONNECTION PLAN		
DESIGNED BY	WJ		
CHECKED BY	WJ		
APPROVED BY	WJ		
DATE	11/11/11	BY	WJ
REV	1	DATE	11/11/11
DESCRIPTION	WIRE BOND PAD / CONNECTOR PIN INTERCONNECTION PLAN		
DESIGNED BY	WJ		
CHECKED BY	WJ		
APPROVED BY	WJ		



NO.	WD.	WD. AREA
1	1.25	1.56
2	1.50	2.25
3	1.75	3.06
4	2.00	4.00
5	2.25	5.06
6	2.50	6.25
7	2.75	7.56
8	3.00	9.00
9	3.25	10.56
10	3.50	12.25
11	3.75	14.06
12	4.00	16.00
13	4.25	18.06
14	4.50	20.25
15	4.75	22.56
16	5.00	25.00
17	5.25	27.56
18	5.50	30.25
19	5.75	33.06
20	6.00	36.00
21	6.25	39.06
22	6.50	42.25
23	6.75	45.56
24	7.00	49.00
25	7.25	52.56
26	7.50	56.25
27	7.75	60.06
28	8.00	64.00
29	8.25	68.06
30	8.50	72.25
31	8.75	76.56
32	9.00	81.00
33	9.25	85.56
34	9.50	90.25
35	9.75	95.06
36	10.00	100.00
37	10.25	104.56
38	10.50	109.25
39	10.75	114.06
40	11.00	119.00
41	11.25	124.06
42	11.50	129.25
43	11.75	134.56
44	12.00	140.00
45	12.25	145.56
46	12.50	151.25
47	12.75	157.06
48	13.00	163.00
49	13.25	169.06
50	13.50	175.25
51	13.75	181.56
52	14.00	188.00
53	14.25	194.56
54	14.50	201.25
55	14.75	208.06
56	15.00	215.00
57	15.25	222.06
58	15.50	229.25
59	15.75	236.56
60	16.00	244.00
61	16.25	251.56
62	16.50	259.25
63	16.75	267.06
64	17.00	275.00
65	17.25	283.06
66	17.50	291.25
67	17.75	299.56
68	18.00	308.00
69	18.25	316.56
70	18.50	325.25
71	18.75	334.06
72	19.00	343.00
73	19.25	352.06
74	19.50	361.25
75	19.75	370.56
76	20.00	380.00
77	20.25	389.56
78	20.50	399.25
79	20.75	409.06
80	21.00	419.00
81	21.25	429.06
82	21.50	439.25
83	21.75	449.56
84	22.00	460.00
85	22.25	470.56
86	22.50	481.25
87	22.75	492.06
88	23.00	503.00
89	23.25	514.06
90	23.50	525.25
91	23.75	536.56
92	24.00	548.00
93	24.25	559.56
94	24.50	571.25
95	24.75	583.06
96	25.00	595.00
97	25.25	607.06
98	25.50	619.25
99	25.75	631.56
100	26.00	644.00

NOTES  
 1. THIS TABLE SHOWS 1/8" OF THE TOTAL AND IS  
 2. ADJUSTED TO THE CENTER LINE.  
 3. WORK BOND FLATNESS TO BE WITHIN .003 INCH PER  
 4. FOOT OF THE SURFACE.  
 5. THE ATTACH AREA TO BE FLAT WITHIN .003 INCH.  
 6. MECHANICAL REQUIREMENT IS 200,000 PSI.

NO. 15	NO. 15	NO. 15	NO. 15
DATE	DATE	DATE	DATE
BY	BY	BY	BY
CHECKED	CHECKED	CHECKED	CHECKED
APPROVED	APPROVED	APPROVED	APPROVED
SCALE 1/8" = 1"			
TYPE BORING			
KID-P86499-B			



DIE Pad → Package pad # mapping for "GRATINGS" Dies  
 Numbers indicate which package pad # to wirebond to  
 Note that package pad #'s 2, 35, 37-38, 71-72, 74, 107, 109-110, 143  
 are **not** bonded to the die