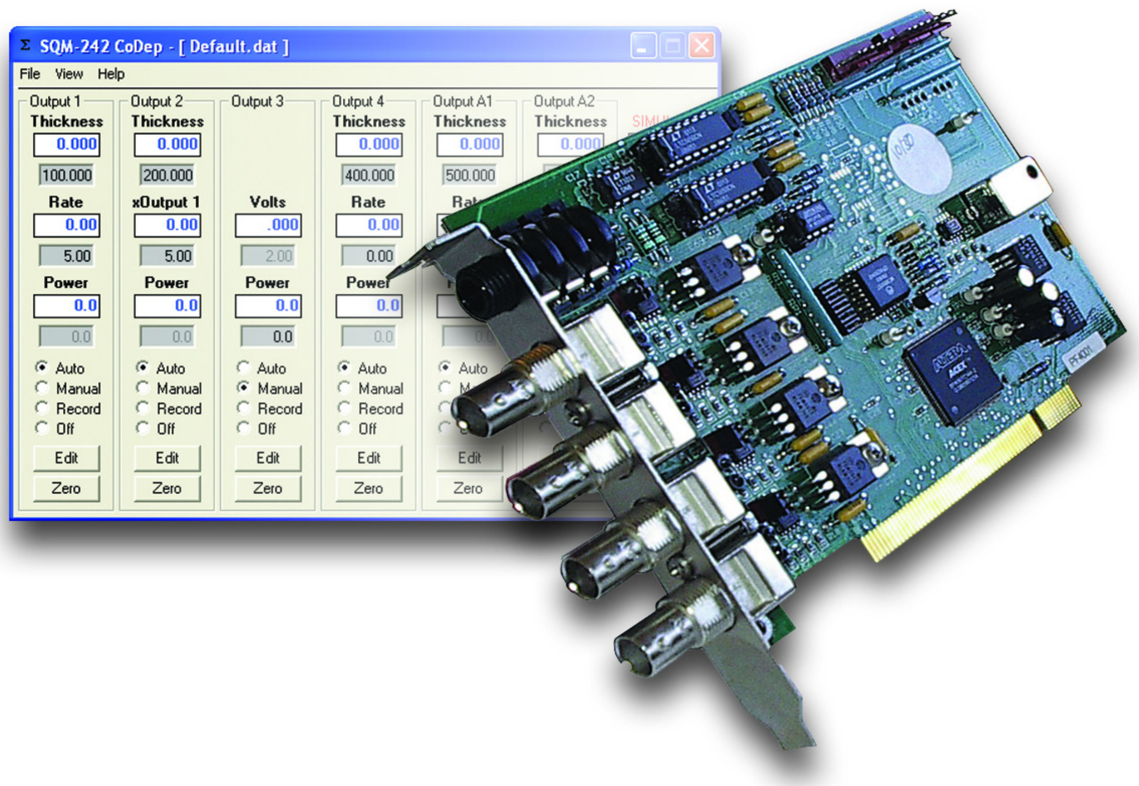
O P E R A T I N G   M A N U A L



SQM-242™

Thin Film Deposition Controller

IPN 074-549-P1A

INFICON

O P E R A T I N G   M A N U A L

SQM-242™

Thin Film Deposition Controller

IPN 074-549-P1A

INFICON Instruments for Intelligent Control®

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DECLARATION
OF
CONFORMITY

This is to certify that this equipment, designed and manufactured by:

INFICON Inc.
Two Technology Place
East Syracuse, NY 13057
USA

meets the essential safety requirements of the European Union and is placed on the market accordingly. It has been constructed in accordance with good engineering practice in safety matters in force in the Community and does not endanger the safety of persons, domestic animals or property when properly installed and maintained and used in applications for which it was made.

Equipment Description: SQM-242 (including all options)

Applicable Directives:
2006/95/EC (LVD)
2004/108/EC (General EMC)
2002/95/EC (RoHS)

Applicable Standards:

Safety:	EN 61010-1:2001
Emissions:	EN 61326-1:1997/A1: 1998/A2: 2001 (Radiated & Conducted Emissions) Class A: Emissions per Table 3 (EMC – Measurement, Control & Laboratory Equipment)
Immunity:	EN 61326-1:1997/A1: 1998/A2: 2001 (General EMC) Class A: Immunity per Table A1 (EMC – Measurement, Control & Laboratory Equipment)
RoHS:	Fully compliant

CE Implementation Date: July 2003 (Updated February 2011)

Authorized Representative: Steve Schill

Thin Film Business Line Manager
INFICON Inc.

ANY QUESTIONS RELATIVE TO THIS DECLARATION OR TO THE SAFETY OF INFICON'S PRODUCTS SHOULD BE DIRECTED, IN WRITING, TO THE AUTHORIZED REPRESENTATIVE AT THE ABOVE ADDRESS.

Warranty

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NOTE: These instructions do not provide for every contingency that may arise in connection with the installation, operation or maintenance of this equipment. Should you require further assistance, please contact INFICON.

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Appendix A

Material Table

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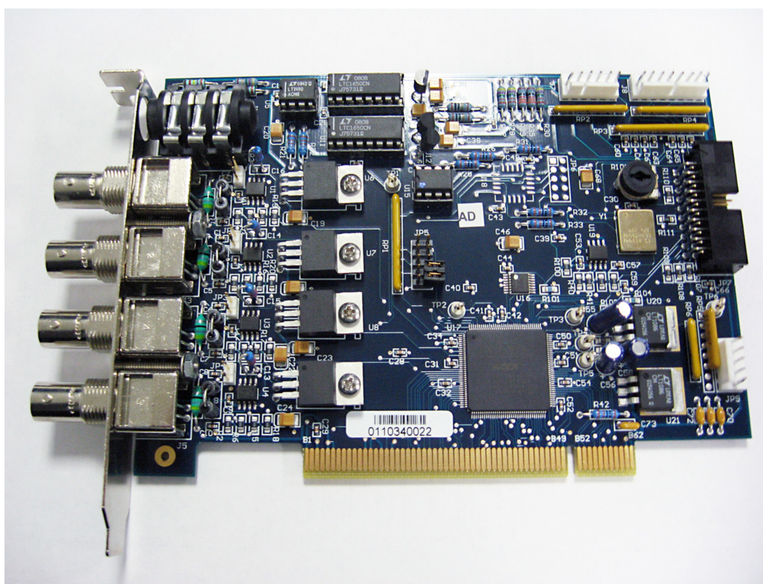
Chapter 1
Introduction

1.1 Introduction

The SQM-242 Card is a powerful thin film deposition controller on a PCI card. Significant features include:

- Measure four 1 MHz to 10 MHz quartz crystal sensors simultaneously.
- Controls two deposition source supplies simultaneously (co-deposition).
- Install multiple cards for up to 24 sensors and 12 control outputs.
- Measure four +/- 10 V analog inputs with optional (SAM-242) piggyback card.
- Installs in any PC running Windows® 98/2000/ME/XP/7-32-bit with a vacant PCI slot.
- Interfaces to your program with Windows DLL and ActiveX® interfaces.
- Sample Visual Basic® and LabVIEW™ programs with source code are included.

Figure 1-1 SQM-242 Deposition Control Card



The sample software included with SQM-242 card allows you to:

- Co-deposit up to six materials, using up to eight sensors.
- Use analog inputs to control heaters, gas flow, and other process variables.
- Use outputs for recording rate, thickness, power, or voltage.
- Save film setup parameters and deposition data to disk.
- Simulate deposition for developing and testing film setups.

The optional SQS-242 software allows multi-layer deposition recipes, graphics, flexible PLC-based digital I/O and RS-232/Ethernet external control.

The SQM-242 card is a PID loop process controller designed for use primarily in physical vapor deposition. The SQM-242 card monitors and/or controls the rate and thickness of thin film depositions. The SQM-242 reads frequency from an in-vacuum 1 to 10 MHz quartz crystal driven by a small external oscillator module. The oscillator module uses the in-vacuum crystal as the feedback element of an IC oscillator circuit to amplify the crystal signal to about 0.75 volts peak to peak. The SQM-242 card supplies 5 V (dc) to the oscillator module, and reads the module's frequency output signal on a single BNC cable. On the SQM-242, a 200 MHz reference oscillator sets a known measurement period. By counting the input transitions during the measurement period, a frequency is calculated.

Deposition rate and thickness are inferred from the frequency change induced by mass added to a quartz crystal. This technique positions sensors in the path between, or to the side of, the target substrate and the source of vaporized material. The sensor incorporates an exposed oscillating quartz crystal whose frequency decreases as material accumulates. The change in frequency provides information to determine rate and thickness and to continually control the evaporation power source. With user supplied time, thickness and power limits and with desired rates and material characteristics, the SQM-242 card is capable of automatically controlling the process in a precise and repeatable manner. User interaction is accomplished via the front panel or serial communications and consists of selection or entry of parameters to define the process.

When reading this SQM-242 Manual, please pay particular attention to the NOTES, CAUTIONS, and WARNINGS found throughout the text. The Notes, Cautions, and Warnings are defined in section 1.2.1 on page 1-3.

1.1.1 Related Manuals

Sensors are covered in separate manuals. PDF files of these manuals are contained in the 074-5000-G1 CD, part of the Ship Kit.

- 074-154 - Bakeable Sensor
- 074-156 - Front Load Sensor, Single/Dual
- 074-157 - Sputtering Sensor
- 147-800 - Cool Drawer Sensor, Single/Dual

1.2 Instrument Safety

1.2.1 Definition of Notes, Cautions and Warnings

When using this manual, please pay attention to the NOTES, CAUTIONS and WARNINGS found throughout. For the purposes of this manual they are defined as follows:

NOTE: Pertinent information that is useful in achieving maximum instrument efficiency when followed.

CAUTION

Failure to heed these messages could result in damage to the instrument.

WARNING

Failure to heed these messages could result in personal injury.

WARNING - Risk Of Electric Shock

Dangerous voltages are present which could result in personal injury.

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1.2.2 General Safety Information

WARNING - Risk Of Electric Shock

The SQM-242/SAM-242 card(s) do not have any user serviceable components.

Dangerous voltages may be present whenever the PC is on or external input/relay connectors are present.

Refer all maintenance to technically qualified personnel.

WARNING - Risk Of Electric Shock

This instrument contains delicate circuitry which is susceptible to transient voltages/static.

Refer all maintenance to technically qualified personnel

WARNING

Failure to operate the SQM-242 card(s) in the manner intended by INFICON can circumvent the safety protection provided by the instrument and may result in personal injury.

1.3 How To Contact Customer Support

Worldwide support information regarding:

- Technical Support, to contact an applications engineer with questions regarding INFICON products and applications, or
- Sales and Customer Service, to contact the INFICON Sales office nearest you, or
- Repair Service, to contact the INFICON Service Center nearest you,

is available at www.inficon.com.

When you contact Customer Support, please have the following information readily available:

- The firmware version displayed at power-up for your instrument and software version if you are calling about the optional applications software.
- A description of your problem.
- An explanation of any corrective action that you may have already attempted.
- The exact wording of any error messages that you have received.

To contact Customer Support, see Support at www.inficon.com.

1.3.1 Returning Your Instrument to INFICON

Do not return any component of your instrument to INFICON without first speaking with a Customer Support Representative. You must obtain a Return Material Authorization (RMA) number from the Customer Support Representative.

If you deliver a package to INFICON without an RMA number, your package will be held and you will be contacted. This will result in delays in servicing your instrument.

Prior to being given an RMA number, you may be required to complete a Declaration Of Contamination (DOC) form. DOC forms must be approved by INFICON before an RMA number is issued. INFICON may require that the instrument be sent to a designated decontamination facility, not to the factory.

Before returning your instrument, create a record of all user-entered parameters so they may be re-entered, if required.

1.4 Specifications

1.4.1 SQM-242 Measurement

Crystal Frequency	1.0 MHz to 10.0 MHz
Frequency Resolution	0.06 Hz @ 6 MHz
Reference Frequency Accuracy	0.002%
Reference Frequency Stability	±2 ppm (0-50°C)
Thickness & Rate Resolution	0.027 Å, 0.044 Å/s @ 2 readings/s, material density = 2.7 gm/cc
Thickness Accuracy	dependent on process conditions, especially sensor location, material stress, temperature and density
Measurement Technique	Active Oscillation
Number of Sensor	4

1.4.2 SAM-242 Inputs

Number of inputs	4, non-isolated
Connectors	BNC
Input Range	0 to ± 10 V (dc)
Input Impedance	20 kΩ
Resolution	15 bit (plus sign)

1.4.3 SQM-242/SAM-242 Outputs

Number of inputs	2, non-isolated
Connectors	1/4" Dual Phone Jack
Output Voltage	0 to ±10 V (dc)
Source Impedance	1 kΩ
Resolution	15 bit (plus sign)

1.4.4 Setup Parameters

Material Density	0.4 to 99.99 gm/cc
Z-Ratio	0.50 to 25.00
Sensor Tooling	0 to 399%
Full Scale Voltage	0 to ±10 V

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Power . . . . 0 to 100%

Slew Rate . . . . 0 to 100%/s

P Term . . . . 0 to 9999

I Term . . . . 0 to 99.9 s

D Term . . . . 0 to 99.9 s

Rate . . . . 0 to 999.9 s

Final Thickness . . . . 0 to 999.9 Å

Mode . . . . Normal or Simulate

Output Control . . . . PID or Manual

Sensor/Output map . . . . Any sensor can control any output

Analog/Output Map (SAM-242) . . . . Any analog input can control any output

Measurement Period . . . . 0.1 to 2 s

1.4.5 External Communications (SQS-242 only)

Serial Port. RS-232C

Baud Rates. 9,600; 19,200; 38,400;

Ethernet TCP/IP Port . . . . Static address, DHCP not supported.

1.4.6 Computer Requirements

Processor . . . . 1 GHz Pentium IV or comparable

RAM . . . . 256 MB RAM

Memory . . . . 30 MB hard disk space

Operating System. . . . . Windows 98/ ME/ NT/ 2000 SP4/ XP SP2/ 7 32-Bit

Comm Port . . . . PCI Slot, Serial or USB for PLC I/O communications (SQS-242 only)

1.4.7 General Specifications

SQM-242 Card Type . . . . PCI (32 bit, 5V, 33MHz)

SQM-242 Max. Cards/Computer . . . 6

SAM-242 Card Typer . . . . Slave to SQM-242 (ribbon cable)

SAM-242 Max. Cards/Computer . . . 1

Power Consumption . . . . 5 W Max

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1.4.8 Operating Environment

Usage . . . . Indoor only

Temperature . . . . 0 to 50°C (32-122°F)

Humidity . . . . 0 to 80% RH. @ 31°C, non-condensing

Altitude . . . . 0 to 2000 m

Installation (Overvoltage) . . . . Category II

Measurement Category II

Pollution Degree. 2

Equipment Type . . . . Class 1 (grounded type). Suitable for continuous operation

Protection . . . . Not protected against harmful ingress of moisture

1.4.9 Storage Temperature

Storage Temperature . . . . -40 to 70°C (-40 to 158°F)

1.4.10 Warm Up Period

Warm Up Period. . . . . None required;
For maximum stability allow 5 minutes.

1.4.11 Size

Not including user connectors

4.21 in. L x 5.91 in. W
(107 mm L x 150 mm W)

1.4.12 Connector Clearance Requirements

Rear . . . . Less than 4.0 in. (102 mm)

1.4.13 Weight

1 card . . . . 0.2 kg / 0.4 lb.

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1.5 Unpacking and Inspection

1. If the SQM-242 card has not been removed from its packaging, do so now.
2. Carefully examine the card for damage that may have occurred during shipping. This is especially important if you notice obvious rough handling on the outside of the container. *Immediately report any damage to the carrier and to INFICON.*
3. Do not discard the packing materials until you have taken inventory and have at least performed successful installation.
4. Take an inventory of your order by referring to your order invoice and the information contained in section 1.6.
5. To install the card, see Chapter 2, Installation.
6. For additional information or technical assistance, contact INFICON, refer to section 1.3 on page 1-5.

1.6 Parts and Options Overview

1.6.1 Base Configurations

SQM-242 Card 782-SQM-242

SQS-242 Software . . . . .782-SQS-242, Optional

SAM-242 Card . . . . .782-SAM-242, Optional

Technical Manual . . . . .074-549 on 074-5000-G1 CD

1.6.2 Accessories

Each sensor requires an oscillator kit to interface to the controller:

SQM-242 10' Oscillator Kit 782-934-003-10

SQM-242 25' Oscillator Kit 782-934-003-25

SQM-242 50' Oscillator Kit 782-934-003-50

SQM-242 100' Oscillator Kit 782-934-003-99

Above kits consist of oscillator 782-900-010, 6 inch BNC oscillator to feedthrough cable 782-902-011 and BNC controller to oscillator cable 782-902-012-10, 782-902-012-25, 782-902-012-50 or 782-902-012-99. These kits are designed for use with the standard in-vacuum cables ranging in length from 6 inches (15.2 cm) to 36 inches (91.4 cm). The 007-044 standard in-vacuum cable supplied with the front load style sensors are 30.75 inches (78.1 cm) long.

1.6.3 Sensors

Front Load Single Sensor . . . . SL-XXXXX

Front Load Dual Sensor . . . . DL-AXXX

Cool Drawer Single Sensor . . . . CDS-XXFXX

Cool Drawer Dual Sensor . . . . CDD-XFXX

Sputtering Sensor. 750-618-G1

Front Load UHV Bakeable Sensor . . . . BK-AXF

NOTE: All shuttered sensors require a feedthrough with an air line and a pneumatic shutter actuator control valve.

Pneumatic Shutter Actuator Control Valve 750-420-G1

NOTE: Multi-crystal (rotary) sensors should not be used with the SQM-242

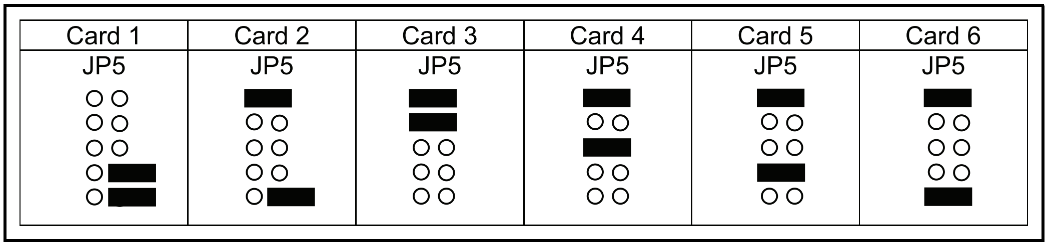
NOTE: Consult individual sensor manuals for part muber configurations.

Chapter 2
Installation

2.1 SQM-242 Card Installation

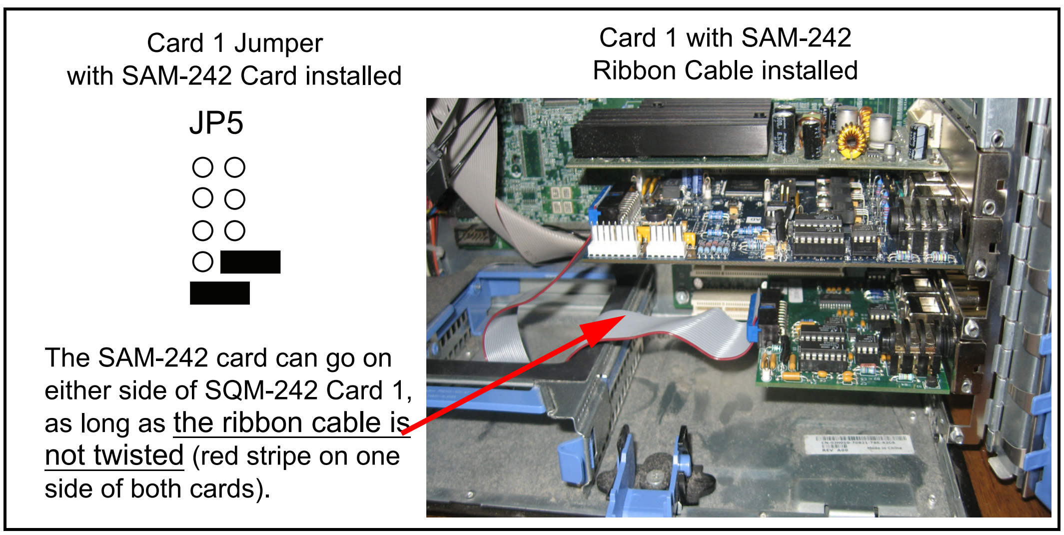
Jumper each SQM-242 card before installation as shown in Figure 2-1.

Figure 2-1 Jumper Configurations



If you are installing a SAM-242 analog piggyback card, it must be connected to Card 1. Set the Card 1 jumper as shown in Figure 2-2 when the optional SAM-242 card is used.

Figure 2-2 SAM-242 Card Installation



Once each card is jumpered:

1. Turn off the computer, unplug the power cord, and remove the computer cover.
2. Locate an empty PCI slot and remove the screw holding the blank bracket for the slot. Remove the blank bracket.
3. With the card's gold contacts down, place it above the PCI slot with the BNC connectors on the card extending through the back of the computer. Press down on the card to seat it into the connector. Repeat with each card.
4. Replace the screw at the top of the card bracket to secure the card. Replace the cover on the computer and plug in the power cord.

2.2 SQM-242 Driver Installation

1. Turn on the computer and start Windows. Windows will find new hardware and prompt to Install Device Drivers.
2. If you are prompted for the location of the Device Drivers, insert the INFICON CD-ROM and direct Windows to D:\SQM242 Card\SQM242_V100_DRIVERS (assuming D is your CD drive).
3. When driver installation is complete, you may be prompted to restart your computer.
4. Check the README.txt file in the \SQM242 Card\SQM242_V100_DRIVERS folder of the INFICON CD-ROM for additional steps that are specific to your version of Windows.
5. Verify that the card was installed properly in Device Manager. Right-click on My Computer, then left-clicking on Properties. Click on the Device Manager tab (Hardware tab in Windows 2000 or XP, then Device Manager). You should see Sigma Instruments listed, with the SQM-242 cards in the sub folder.

If the card is not listed (or has a red x or yellow exclamation point), repeat the installation procedures above carefully.

NOTE: Occasionally it may be necessary to completely uninstall and reinstall a card. Highlight the improperly installed card in Device Manager and press <Delete>. Next, run the "clean" program in the \SQM242 Card\SQM242_V100_DRIVERS folder of the INFICON CD-ROM. Reboot the computer, then follow the steps above carefully.

2.3 Software Installation

SQM-242 Card programs are also on the INFICON CD-ROM. Insert the CD-ROM, click the Windows Start button, and then select Run. Type D:\SQM242 Card\Setup.exe and click OK.

Accept the default installation prompts. When installation completes, you may be prompted to restart your computer. This installer will install three programs: SQM-242 CoDep, SQM-242 Monitor, and SQM-242 Multi.

To run the any software program, click Start, then Program, then Sigma Instruments and select the program.

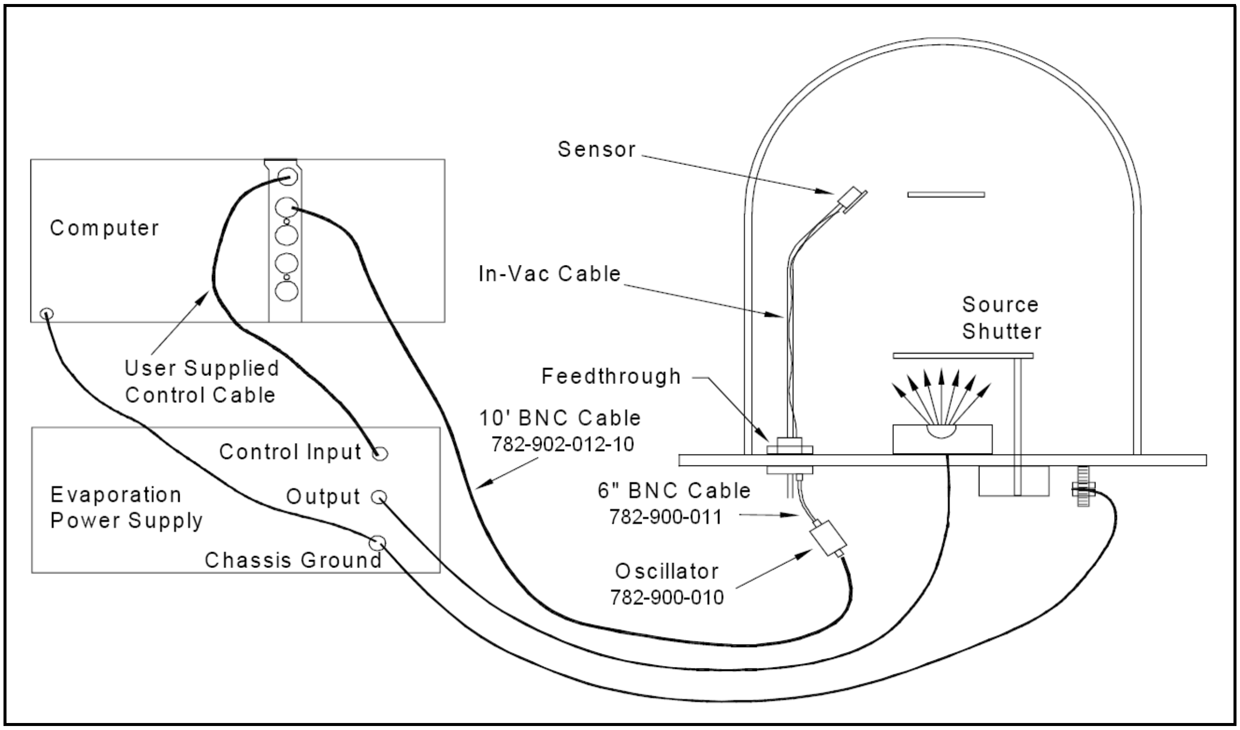
To verify the SQM-242 cards are properly installed, start SQM-242 CoDep. Select the View menu, then Card Setup. If the card revision for each installed card is greater than 0.00, then it is installed properly.

NOTE: If the version is shown as 0.00, then reinstall the Windows drivers as explained in section 2.2. Pay particular attention to any Windows version specific instructions in the README file.

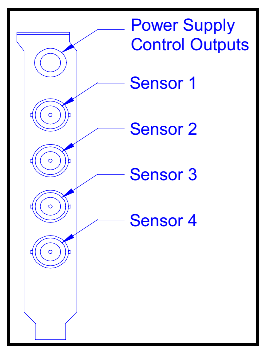
2.4 SQM-242 Card Connections

The control output and sensor input connectors to the SQM-242 card are shown below. Refer to this drawing in the subsequent hookup instructions.

Figure 2-3 SQM-242 Setup



Sensor Connections



A BNC cable connects the SQM-242 sensor input to the "instrument" connector on the remote oscillator. The maximum length is 50 feet (15 meters).

To ensure proper operation of the SQM-242, use oscillators manufactured by INFICON [PN 782-900-010].

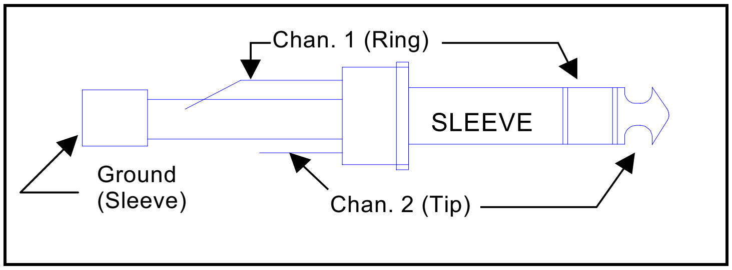
The connection from the remote oscillator "feedthru" connector to the vacuum chamber feedthrough is made using a short 6 inch (15 cm) cable with BNC male to female connectors [PN 782-902-011]. Inside the vacuum chamber, your in-vac cable must be no longer than 36 inches (91.4 cm). It connects from the feed-through to the crystal sensor.

NOTE: The SQM-242 will not work with INFICON ModeLock oscillators.

Output Connections

The SQM-242 output connection is via a 1/4" Stereo Phone Jack. A standard 1/4" Stereo Phone Plug is shown below (with outer collar removed to show the contacts). Output 1 is on the ring, Output 2 is on the tip, and a common ground is on the sleeve.

Figure 2-4 1/4" Stereo Phone Jack



Connect the SQM-242 output to your evaporation power supply, recorder, or other equipment as described in the equipment's operating manual.

CAUTION

Special care must be taken in connecting the SQM-242 card output to the input connector of your equipment. Failure to understand and follow the equipment manufacturer's instructions can result in damage to the equipment and/or SQM-242 card.

The SQM-242 output is 0 to +/- 10 V (dc). See section 3.3 of this manual for instructions on setting the SQM-242 output Full Scale level to match your power supply. If your equipment needs a 4-20 mA control signal, you must obtain a voltage-to-current converter.

NOTE: If you are using the SQM-242 as a monitor only, no output connection is needed.

Ground Connection

The chassis of all control components should be tied to a common earth ground using a low resistance cable. This is particularly important in high noise E-Beam systems.

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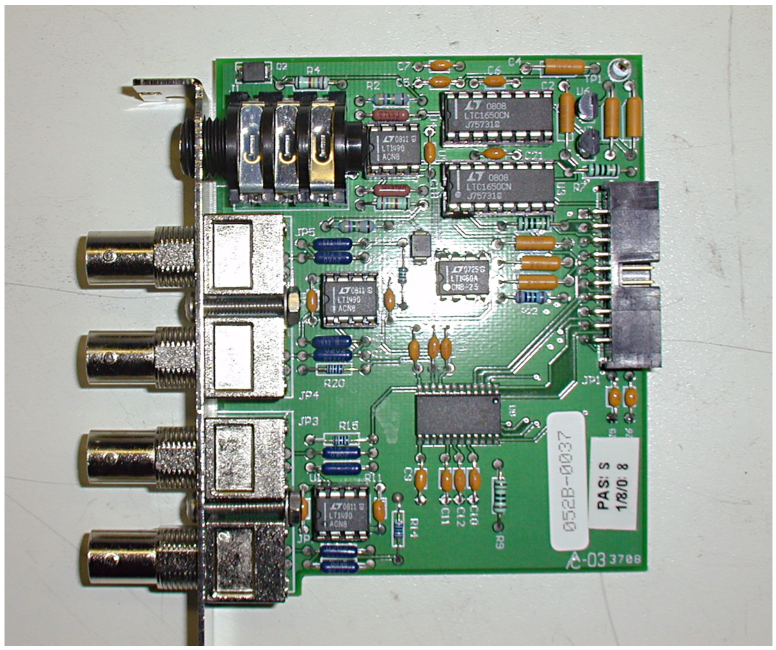
2.5 SAM-242 Card Connections

The input and output and connectors on the SAM-242 card are identical to those on the SQM-242 card.

Figure 2-5 SAM-242 Card



Input Connections

BNC cables connect the SAM-242 input to the signals to be measured. The SAM-242 accepts input voltages within +/- 10 V (dc).

NOTE: You can not connect sensors to these inputs.

CAUTION

The BNC connector shield of each SAM-242 input is connected to a common analog ground. Input signals to the SAM-242 must be within +/-10 V (dc) and share a common ground. Failure to observe this constraint can result in damage to your equipment and/or the SAM-242 card,

Output Connection

The SAM-242 outputs are identical to the SQM-242. See the previous section for hookup instructions.

2.6 Digital I/O

The SQM-242 card and SQM-242 software do not support the digital I/O required to automatically open and close shutters, rotate source pockets, etc.

The optional SQS-242 Codeposition software adds this capability to the SQM-242 card. Using an inexpensive PLC, the SQS-242 software provides virtually unlimited digital I/O capabilities.

Contact INFICON for more information on interfacing the SQM-242 card to your system's digital I/O.

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Chapter 3
SQM-242 CoDep

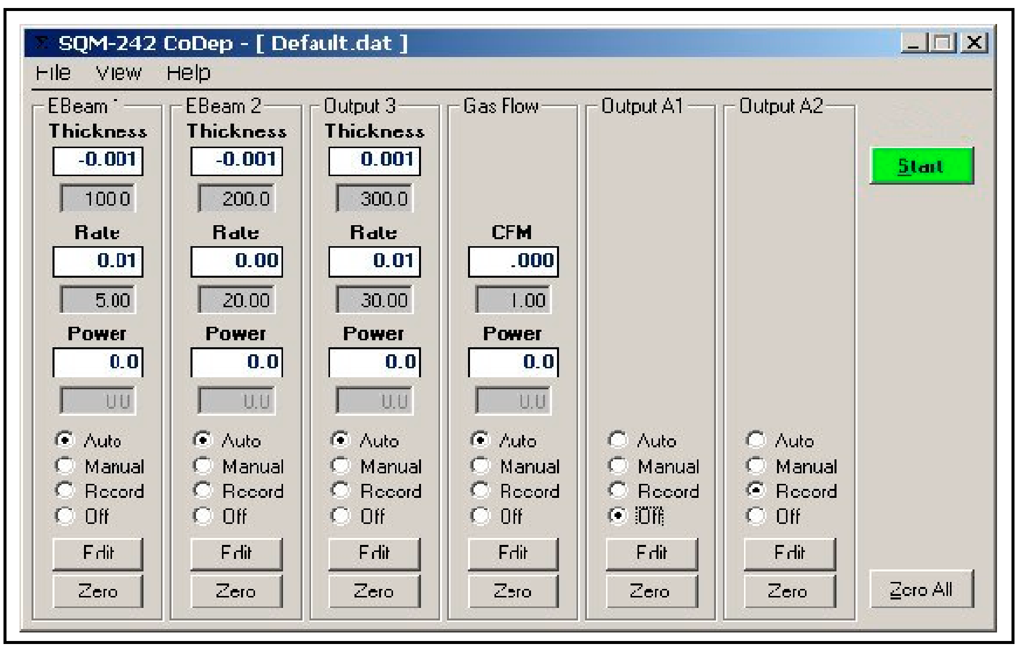
3.1 Introduction

The SQM-242 CoDep program illustrates most of the capabilities of the SQM-242 card. It is intended as a learning tool for new users, and a programming example for interfacing to user applications.

3.2 Main Dialog Box

With no cards installed (or with two SQM-242 cards and an SAM-242 card installed) you will see the dialog box shown in Figure 3-1. The number of "output frames" shown will change depending on the number of cards installed in your system. For example, with only one SQM-242 card installed, the main dialog box shows only two output frames.

Figure 3-1 SQM-242 Codep Main Dialog Box



Each output frame corresponds to a physical output on an SQM-242 card. In Figure 3-1, the first three outputs are each configured to use quartz sensors to measure rate and thickness.

The frame labeled "Gas Flow" is a little different. This output uses an analog input on the SAM-242 card to control backfill gas. The SAM-242 card can use any analog voltage for control. More about this feature later.

Output A1 above is turned off, while Output A2 is used as a recorder output. The output labels are easily edited to provide descriptive names. Dialog boxes within each output frame will change, depending on the function of that output.

Outputs configured for quartz sensor inputs, like the first three in the sample dialog box, display rate and thickness information. The first display is the Thickness Measurement for the material (in kÅ). Immediately below the Thickness Measurement display is the Thickness Setpoint setting. You can edit the Thickness Setpoint at any time. When the Thickness Reading reaches the Thickness Setpoint, the deposition will stop.

NOTE: To adjust a Setpoint, click on the setting and type a new setting. Press <Enter> to send the setting without moving to another field. To move to another field, use the <Tab> key or your mouse. Each time you move to another field, the setting is updated.

Below the thickness displays are the Rate Reading and Rate Setpoint displays (in Å/s). In Auto mode, the SQM-242 control loop continuously adjusts the output power to maintain the deposition Rate Reading at the desired Rate Setpoint.

Below the rate displays are the output Power Reading and manual Power Setpoint. The Power Reading displays the current output power (in % Full Scale). In Manual mode, the Power Setpoint can be edited to manually adjust output power.

The option buttons control the function of each output. As mentioned previously, Auto mode uses a PID control loop to control rate. Manual mode, allows you to manually adjust the output power. That can be useful for material preconditioning or error conditions.

The Record button configures the output as an analog recorder. A recorder output provides a signal that is proportional to thickness, rate, power, or analog voltage. Finally, the Off button sets the output to 0 volts and hides the displays.

Start/Stop . . . . When Start is displayed, starts SQM-242 readings and PID output control. When Stop is displayed, stops readings and sets the power outputs to zero. When Stop is displayed, a Hold button is also visible.

Hold/Resume . . . . Clicking Hold sets all output power levels to zero, and changes the button legend to Resume. Clicking Resume continues deposition without zeroing thickness.

Zero All . . . . Sets all material (i.e., output) thickness readings to zero.

Zero . . . . Sets the selected material thickness reading to zero.

Edit . . . . Displays a dialog box with additional settings for an output.

3.3 Edit: Auto/Manual Mode

When Edit is clicked while Auto or Manual mode is selected, a dialog box is displayed which contains additional output control settings.

NOTE: The type of dialog box displayed depends on whether the output is configured as a control output (Auto/Manual/Off), or as a Recorder output. See the next section for information on recorder outputs.

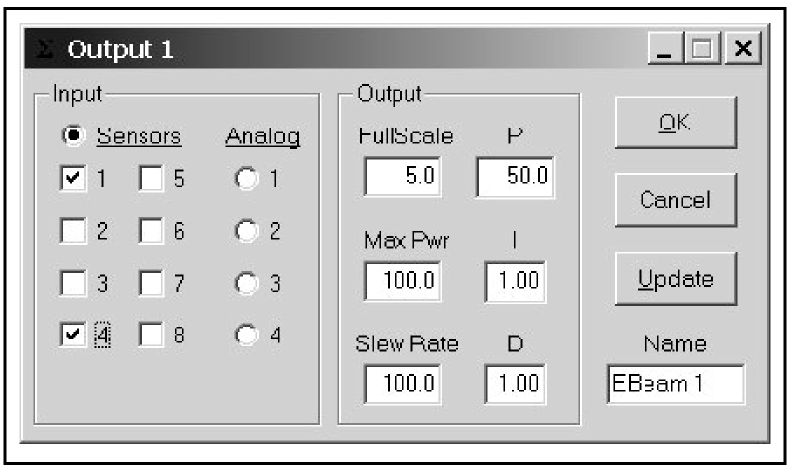
These controls are common to most dialog boxes in the program:

OK . . . . Saves the settings in the dialog box, sends them to the SQM-242 card, and closes the dialog box.

Cancel . . . . Closes the dialog box without saving the settings or sending them to the SQM-242 card.

Update . . . . Saves the settings in the dialog box, sends them to the SQM-242 card, but does not close the dialog box.

Figure 3-2 Output Edit Dialog Box



Input. . . . . Selects the sensor(s) or analog input used as an input to the output's PID control loop.

Click Sensors to configure the loop for quartz sensor inputs. If more than one sensor is selected, their averaged rate and thickness readings are used by the PID control loop and displayed on the main dialog box.

If an analog input is selected, quartz sensors are disabled. Only a single analog input can be selected. Analog inputs extend deposition control to non-quartz sensor inputs.

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Perhaps you want to control a backfill gas during deposition. You can use an analog input to measure pressure from a manometer, and the control output to drive a gas flow valve. You can still use one or more quartz sensors to measure and control deposition of your EBeam or thermal power supply.

In another example, you might want to control deposition rate by controlling temperature. You can assign an analog input to a control output measure and control temperate, then use a quartz sensor as a final thickness setpoint monitor.

If you select a sensor or analog input that is already assigned to another output, an error message will be displayed when you try to update the configuration. You will have the choice of abandoning the change, or overriding the previous configuration. Your choice could leave a control output with no inputs. In that case, output power is fixed at 0%.

NOTE: The sensor or analog input selected does not have to be on the same SQM-242 or SAM-242 card as the control output.

Full Scale . . . . The output voltage that corresponds to 100% output power. Full scale values to +/-10 volts are possible. The full scale output voltage is a function of your power supply input specifications.

Max Power . . . . The maximum output power allowed for an output, in percent of full power. This limits the maximum % of Full Scale voltage that will be sent to the source supply.

NOTE: In Simulate mode at least 55% power is required to simulate deposition. This simulates a minimum power that might be required to vaporize a material.

Slew Rate . . . . The maximum % Full Scale power change, per second, allowed on an output during PID control.

P Term . . . . The proportional term sets the gain of the control loop. High gains yield more responsive, but potentially unstable, loops. Try a value of 25, then gradually increase/decrease the value to respond as desired to step changes in the rate setpoint.

I Term . . . . The integral term controls the time constant of the loop. A small I term, say .5 to 1 seconds, will smooth the response and minimize overshoot to step changes.

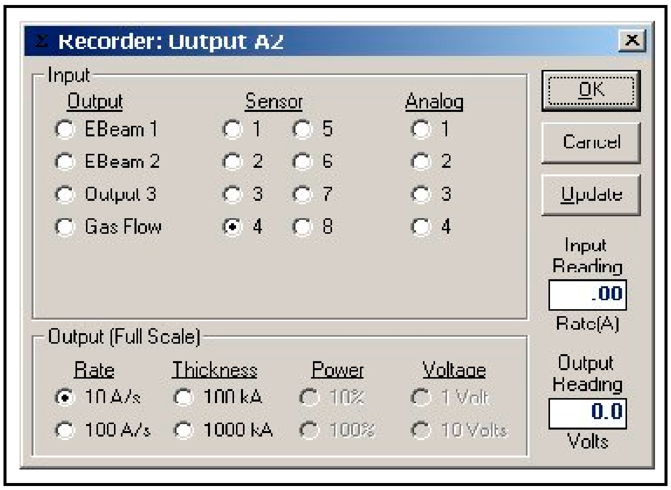
D Term . . . . The derivative term causes the loop to respond quickly to changes. Use 0 or a very small value to avoid oscillations.

Name . . . . It may be helpful to give an output a more meaningful name—perhaps the material being deposited or the evaporation supply being controlled.

3.4 Edit: Recorder Mode

When Recorder mode is selected for an output, the output is not controlled by the PID loop. Instead, the output supplies a voltage that is proportional to an input value.

Figure 3-3 Recorder Edit Dialog Box



Input. . . . . Selects the sensor, analog input, or control output that is being measured. Only one input can be selected.

Output . . . . The recorder output voltage can vary from 0 V to +/-10 V. Output (Full Scale) establishes the measured value on the Input that will generate a Full Scale (+/-10 V) output. In the sample above, a measured rate of 10 Å/s will generate a 10 V recorder output. If you select 1000 kÅ, then a measured thickness of 1000 kÅ will generate a 10 V output to the recorder.

Input Reading . . . . Displays the measured value of the selected input. The units of the input reading are determined by the type of measurement (rate, thickness, power, or voltage) selected for the recorder output.

Output Reading . . . . The output voltage currently supplied to the recorder by the recorder output.

3.5 File Menu

Open . . . . Selects a setup (.DAT) file to be used for thin film deposition.

Save As . . . . Saves the current setup to disk. It can replace the information in the current file or be saved under a different name. Multiple setups can be saved as different files. This is convenient for storing different configurations, materials, rates, etcetera.

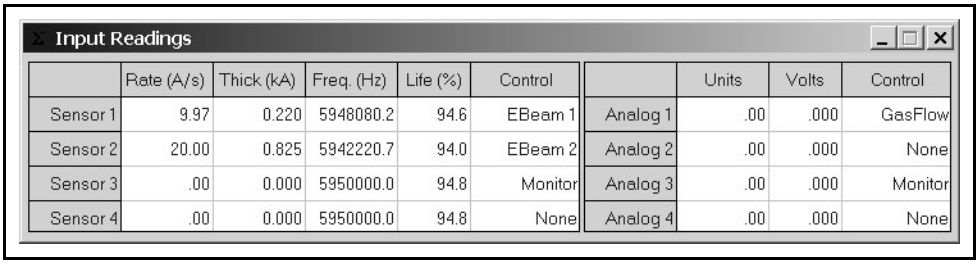
Exit. . . . . Exits the SQM-242 program. Before closing the program, you are prompted to save changes. Select Yes to overwrite the current setup (.DAT) file, no to abandon any changes, or Cancel to return to the program.

3.6 View Menu

3.6.1 View Menu: Readings

Selecting the View menu, then Readings, displays a grid of all sensor and analog inputs. It also provides a convenient place to view the overall input/output configuration of your system. See Figure 3-4.

Figure 3-4 Input Readings



	Rate (A/s)	Thick (kA)	Freq. (Hz)	Life (%)	Control		Units	Volts	Control
Sensor 1	9.97	0.220	5948080.2	94.6	EBeam 1	Analog 1	.00	.000	GasFlow
Sensor 2	20.00	0.825	5942220.7	94.0	EBeam 2	Analog 2	.00	.000	None
Sensor 3	.00	0.000	5950000.0	94.8	Monitor	Analog 3	.00	.000	Monitor
Sensor 4	.00	0.000	5950000.0	94.8	None	Analog 4	.00	.000	None

Unlike the main dialog box, which may show the average of several sensors assigned to an output, this dialog box displays raw input readings. The size of the grid is adjusted to display only the components installed in your system.

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In the sensor grid, the Life column displays the % life remaining for each sensor, based on the sensor Min/Max values entered in the Setup dialog box.

In the analog input grid, two readings are displayed. Volts shows the measured voltage on the analog input, while Units displays the reading in the units displayed on the main dialog box (i.e., CFM). The next section explains how to define analog input units.

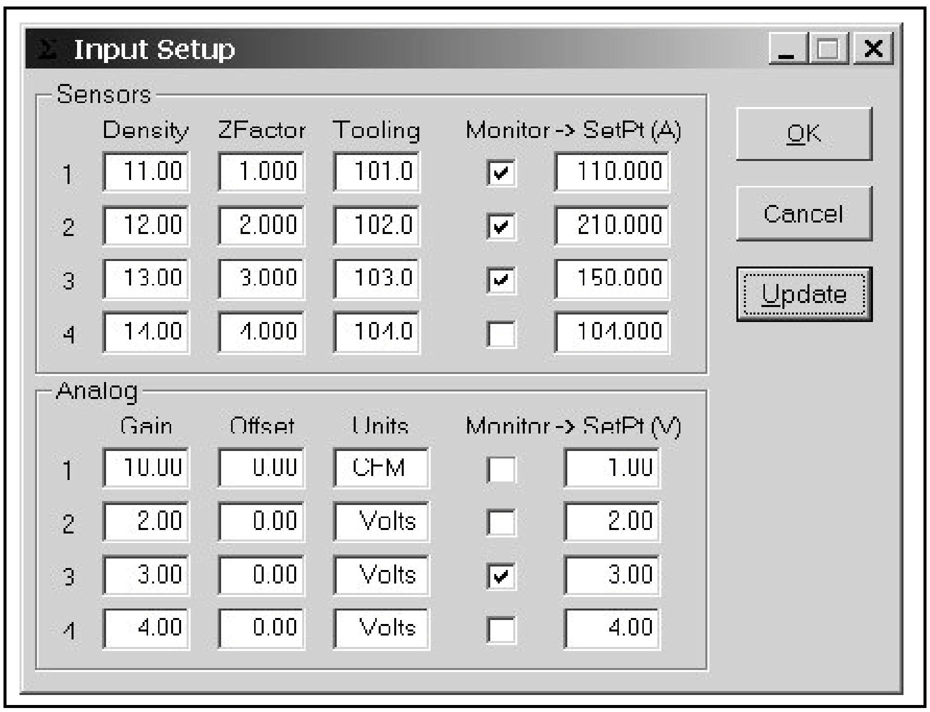
The last column shows the function assigned to each input-output control, setpoint monitor, or unassigned. If an input is assigned to a control loop, that output is listed. An input assigned as a setpoint monitor (see the next section) shows Monitor. If an input is assigned as both a control input and a setpoint monitor, only the control function is listed. Unassigned inputs show None.

3.6.2 View Menu: Input Setup

The Input Setup dialog box configures each input on the SQM-242 and SAM-242 cards. See Figure 3-5.

Inputs are numbered consecutively, starting with Card 1 (Sensors 1 to 4), then Card 2 (Sensors 5 to 8), etcetera. The SAM-242 analog input card is shown as Analog 1 to 4.

Figure 3-5 Input Setup Dialog Box



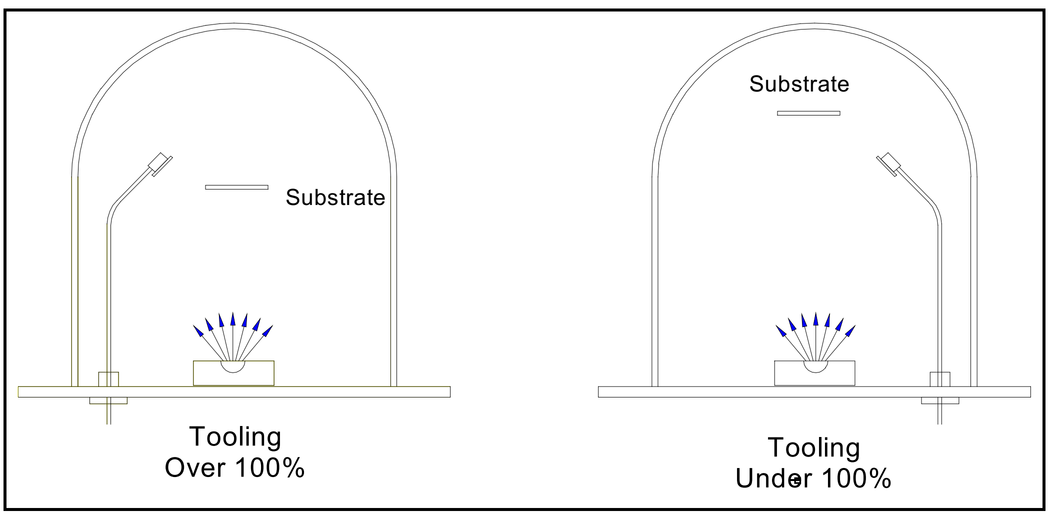
Sensors Frame . . . . Settings in this frame control a sensor's calculation of rate and thickness. They also allow a sensor to be assigned as a Final Thickness monitor, independent of any output control assignment.

Density . . . . The density of the material measured by this quartz sensor, in grams per cubic centimeter. Material density can be found in Table A-1 and numerous handbooks.

Z-Ratio. . . . . Z-Ratio compensates for the mechanical stress a material causes to the quartz crystal. Z-Ratio has an effect only during the last 70% of crystal life. If you cannot find the Z-Ratio of a material, set the value to 1 and change crystals when the crystal Life approaches 70%. See Table A-1 for known values of some materials.

Tooling . . . . Adjusts for measured deposition rates that differ from the actual substrate deposition rate. If the sensor sees only 50% of the substrate rate, set the value to 200. This multiplies the sensor reading by 2. Use Figure 3-6 as a general guard for approximating tooling factor.

Figure 3-6 Tooling Factor Approximation



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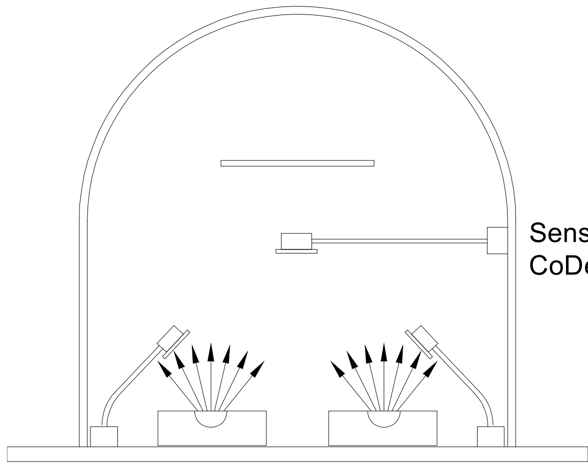
Monitor . . . . Monitor sensors halt deposition when their Thickness setpoint is reached.

Figure 3-7 Sensor Setup



Often sensors are configured to tightly control the deposition rate of a material, such as Sensor 1 & 2 above. However, you might also use a monitor sensor near the substrate, to more accurately monitor the final thickness of the co-deposited material.

Setpoint. . . . . The material thickness (in kÅ) measured by a monitor sensor that will halt deposition.

Analog . . . . The SAM-242 analog input card measures DC voltages in the +/-10 volt range. These voltages may represent temperature, flow, or any other process variable. The analog frame allows you to modify the display to show values in the desired units, using a linear (y = mx + b) transformation.

Assume you have a temperature transmitter that sends 0 V at 0°C and 10 V at 100°C. You want to control temperature to 200°F (it's an example!). Set the analog input Gain to 18, Offset to 32, and Units to Deg F (F = 9/5C + 32). The SQM-242 will display setpoints and measurements associated with the analog input in degrees F.

To leave the analog input display in Volts, set Gain = 1 and Offset = 0.

Gain . . . . The gain term for transforming voltage to measured units. This is the m term in y = mx + b.

Offset. . . . . The offset term for transforming voltage to measured units. This is the b term in y = mx + b.

Units . . . . The units that you wish to display for the analog input.

Monitor . . . . An analog input can also act as a monitor to stop deposition. For example, an analog signal from an optical monitor could stop deposition when a certain voltage is reached. A voltage input from a pressure transducer might also prevent deposition until a certain vacuum is reached.

Setpoint. . . . . The voltage measured by a monitor input that will halt deposition. Analog setpoints are entered in Volts, not calculated units!

3.6.3 View Menu: Card Setup

This dialog controls the most basic functions of the SQM-242 card. It also provides useful installation and troubleshooting information.

Simulate . . . . Normally the SQM-242 card uses the quartz crystals as inputs for controlling the source outputs. The SAM-242 card uses analog input voltages for control. Simulate mode simulates these inputs. No SQM-242 or SAM-242 card needs to be installed for the simulate mode.

Card 1, Card 2, Analog. . . . . Shows the firmware revision of each installed card. A value of 0.00 indicates that the card is not seen by the software, and is probably not installed properly in Windows. See Chapter 7, Troubleshooting and Maintenance.

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Frequency . . . . The frequency values for the quartz crystal sensors used as inputs to the SQM-242. Sensor readings outside the Max/Min values cause a crystal fail error. Values 1 MHz to 10 MHz are permitted, but 6 MHz crystals are most common.

Min/Max values are also used to calculate the % Life remaining on the sensor dialog box. For 6 MHz crystals, set the Max value to the highest possible new crystal frequency (typically 6.1 MHz). Set the Initial frequency to the nominal new crystal frequency (6 MHz). Set Min Frequency to the lowest useable crystal frequency (typically 5 MHz). Keep in mind that some materials cause premature crystal failure.

Period . . . . Sets the measurement period between 0.2 seconds (5 readings per second) and 2 seconds. A longer period gives higher reading accuracy, especially in low rate applications.

Filter. . . . . Sets the number of readings used in the reading filter. A low setting gives rapid response to process changes, high settings give smoother readings.

Log to File . . . . Enables data logging to disk. Enter a filename without path to save data in the application directory. Enter a full path to save data in another directory. Data is saved in comma delimited format easily imported import into any spreadsheet.

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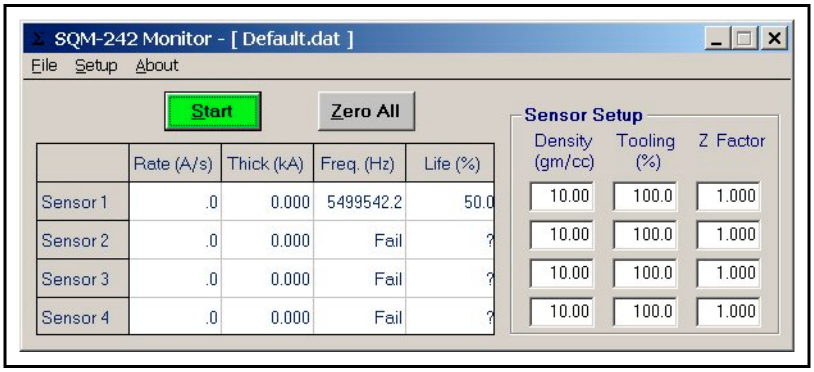
Chapter 4
SQM-242 Monitor

4.1 Introduction

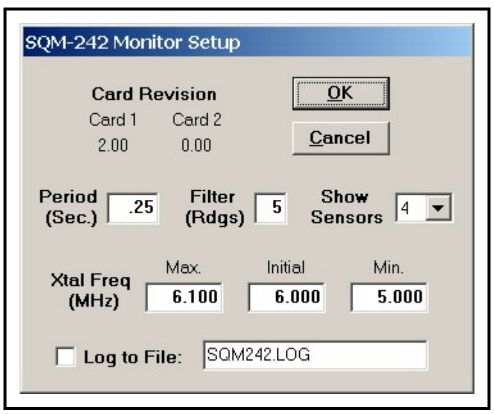
The SQM-242 Monitor program is a version of SQM-242 CoDep that has been streamlined for monitor-only applications. With SQM-242 Monitor you enter sensor Density, Tooling, and Z-Ratio (Z-Factor) parameters, then click Start to begin taking readings.

Figure 4-1 SQM-242 Monitor Main Dialog Box



Since this is a monitor-only program, there are no settings for output control. The Setup dialog box contains only monitor-related functions. Simulate mode is not available because it would provide no additional information.

Figure 4-2 Monitor Setup Dialog Box



Capabilities to save setup parameters and log data to the hard disk are identical to those of SQM-242 CoDep.

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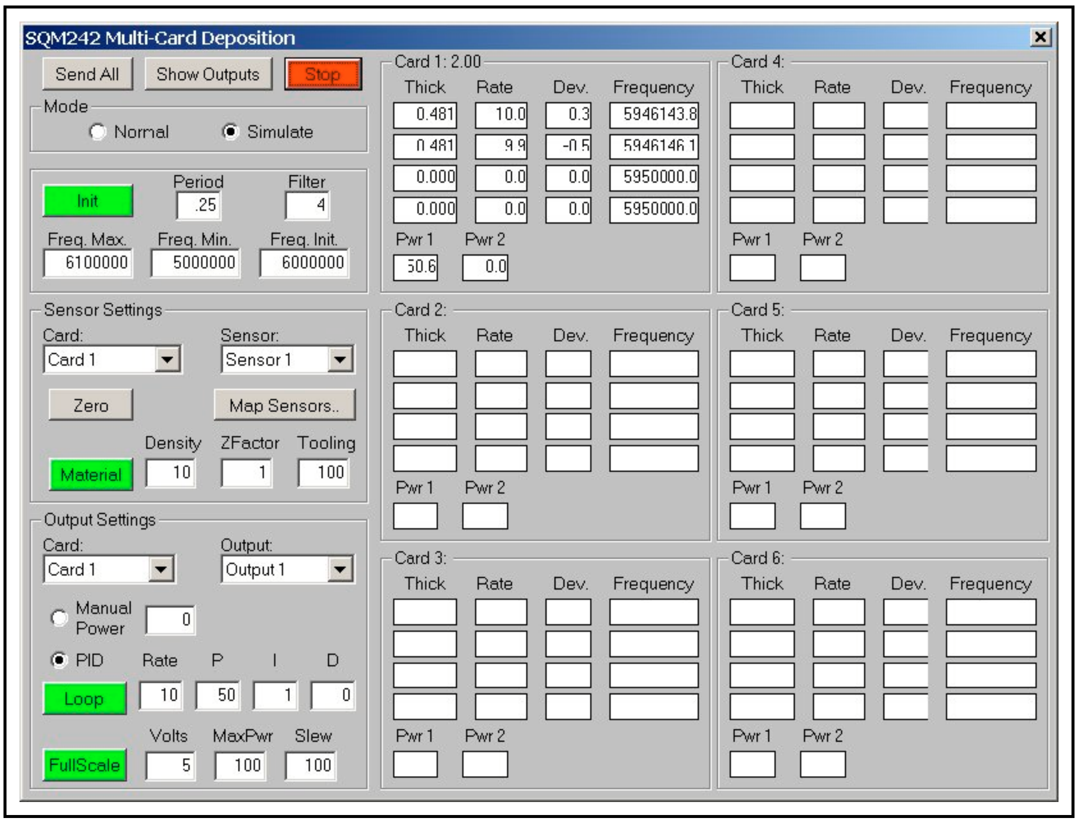
Chapter 5
SQM-242 Multi

5.1 Introduction

The SQM-242 Multi program extends the capabilities of the SQM-242 CoDep program to include up to six SQM-242 cards. With the SQM-242 Multi program, you can monitor up to twenty four sensors and control up to 12 source outputs.

Figure 5-1 SQM-242 Multi Main Dialog Box



On startup, the program displays the firmware revision of each card that is properly installed. If an SQM-242 is installed, but no revision (e.g., Card 1: 2.00) is displayed, then consult the card installation section of this manual (refer to section 2.1, SQM-242 Card Installation, on page 2-1).

Operation of the SQM-242 Multi program is very similar to SQM-242 CoDep. Refer to the previous chapter for descriptions of the parameter settings and readings text boxes (refer to Chapter 3, SQM-242 CoDep).

5.2 Operation

Send All . . . . Sends all of the stored parameters to the SQM-242 card(s) in preparation for a Read command. Normally you will click Send All to initialize the card, then make individual Sensor and Output setting changes as needed. Current settings are stored in an INI file in the application directory on exit from the program.

Show Sensors / Show Outputs . . . Toggles the card reading area between displaying individual sensor readings, and the average of all sensors assigned to an output.

Read/Stop . . . . Starts and stops the SQM-242 card(s) from measuring and controlling deposition. When the card is stopped, all outputs are set to zero.

Mode . . . . Alternates between reading sensors and simulating sensor readings. Simulate mode is useful for training purposes, since no sensors (or even an SQM-242 card!) need to be installed.

In Simulate mode, sensors will not indicate a rate reading until the output power reaches at least 50%. Also, we introduce some noise into the readings in Simulate to better mimic an actual deposition process.

Init . . . . Enter card initialization values, then press the Init button to send the values to the SQM-242 card(s). This must be done before sending any other settings. The values will be saved on exit from the program.

Zero . . . . Sets the thickness reading of the selected sensor to zero. You can select a specific sensor to zero all sensors on a card, or all sensors on all cards using the Card/Sensor dropdown boxes. First select the sensor to be zeroed, then click Zero.

Map Sensors . . . . Assigns each sensor to an output. If a sensor is assigned to Monitor, then it displays rate and thickness, but does not contribute to the control of any output to rate setpoint. If a single sensor is assigned to an output, and the output mode is set to PID, then that sensor serves as the "measured rate" input to the PID loop. If multiple sensors are assigned to an output, then the average of all assigned sensors is used as the "Measured rate" input to the PID loop. If multiple sensors are assigned to an output and a sensor fails, it is automatically excluded from the average.

Material . . . . Sends the Density, Z-Ratio (Z-Factor), and Tooling parameters to the selected sensor(s).

Manual/PID . . . . Sets the output mode for the selected output(s). In PID mode, output power is controlled by the output Loop settings, to achieve the desired Rate setpoint.

In Manual Power mode, output power is fixed at the Power setting. To change the output power in ManPwr mode, enter a new Power value then click Set Power. Alternates Sends the Density, Z-Ratio and Tooling parameters to the selected sensor(s).

Loop. . . . . Sends the PID and rate setpoint parameters to the SQM-242 card(s).

FullScale . . . . Sends the Full Scale Volts, Maximum Power, and Slew Rate parameters to the SQM-242 card(s).

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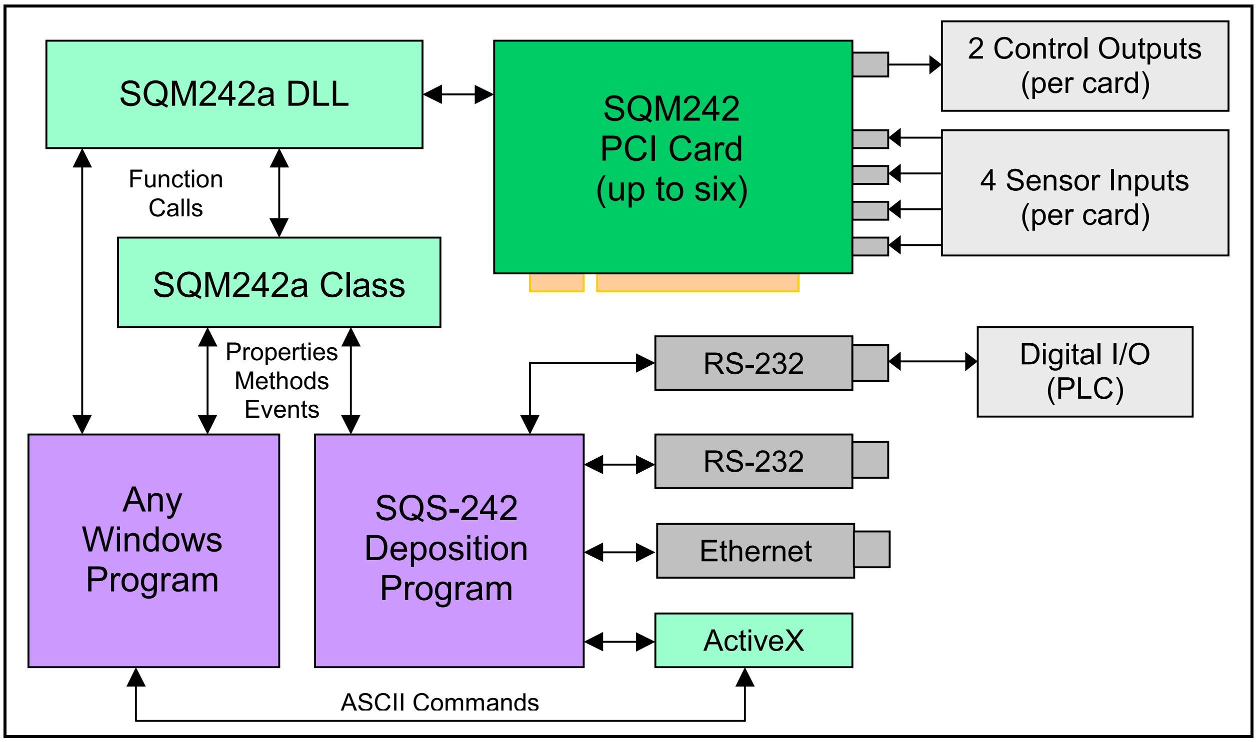
Chapter 6
Communications

6.1 Introduction

The diagram below illustrates basic concepts for interfacing to the SQM-242 card.

Figure 6-1 Communications Diagram



Communications with the SQM-242 card are through a 32 bit DLL, SQM242a.DLL, placed in the Windows system directory. This is a standard DLL, which does not require registration.

A description of each DLL function is listed later in this Chapter. The Visual Basic, C, and LabVIEW programs on the CDROM demonstrate the syntax for calling the DLL.

You can also use the optional SQS-242 deposition control program as the user interface. This program provides multi-layer processes, graphing, data logging, and digital I/O. It can be controlled from your application by sending just a few ASCII text commands. This is an excellent option if you have an application that already communicates with a stand alone deposition controller via RS-232. Contact INFICON for more information regarding the optional SQS-242 deposition control program.

If you have the SQS-242 deposition control program, first run the SQS-242 program, then start the SQS242 Comm program, and go to the Utility tab. Select ActiveX, then Version, and click Send. You will see the Version 3.XX response from the SQS-242 program (including header and checksum characters). The same ASCII commands are used to control the SQS-242 program from a different computer via RS-232 or Ethernet.

6.2 DLL Functions

In the function descriptions below, "long" indicates a 32 bit integer, "double" indicates a double precision real. Array parameters require a pointer to the first element of the array (standard C calling convention).

NOTE: These function definitions are for SQM242A.DLL, which supports up to 6 SQM-242 cards and the SAM-242 card. Contact INFICON for information on interfacing to the older SQM242.DLL.

`Sif142Startup2 (long Mode, long CardStatus (0 to 7))`

Loads the DLL and initializes the card. Must be called with Mode=0 before any other function. The card status parameter is an array that returns card installation status information

Mode . . . . -1 unloads the DLL, any other value loads the DLL.

CardStatus(0) . . . . DLL and card installation status. Values >900 are errors.

CardStatus (1 to 6) . . . . Firmware revision of card 1 to 6. Zero is no card found.

Card Status(7) . . . . Firmware revision of SAM-242 card.

`Sif142Init (double Xfmax, double Xfmin, double Xinit, double Period)`

Initializes the measurement engine. Should be called before readings are taken.

Xfmax . . . . Maximum crystal frequency (10 MHz Max). Any measurement greater than Xfmax results in a Crystal Failure.

Xfmin . . . . Minimum crystal frequency (1 MHz Min). Any measurement less than Xfmin results in a Crystal Failure.

Xinit . . . . Initial frequency of a new crystal. Usually either 6.00 MHz or 5.00 MHz. Must be between Xfmax and Xfmin.

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Period . . . . Sets the period of the measurement system between 0.1 and 2 Seconds.

Sif142Simulate (long Mode)

Sets the operating mode. Normal mode requires SQM-242 card(s), sensors, and a deposition power supply for proper operation. In simulate mode, no SQM-242 card is needed. The DLL simulates the frequency readings and power output required for PID loop control. Note that in this mode the initial sensor frequency is fixed at 5.95 MHz and at least 50% output power is required to start simulating deposition.

Mode . . . . 1 turns on simulate mode,
0 turns on normal mode.

Sif142StartMeas ()

Starts the card measuring frequency and zeros the sensor thickness reading.

Sif142ZeroSensor (long SensorNum)

Sets a sensor (0 to 23) thickness reading to zero.

Sif142Zero2 (long OutputNum)

Sets a control output (0 to 13) thickness reading to zero by setting each assigned sensor thickness to zero.

Sif142Material (long Sensor, double Density, double Zfact, double Tooling)

Sets up the material-specific parameters for each of the sensors.

Sensor . . . . A bit weighted value of which sensor(s) the parameter is for. For example, to set the sensor two (of 0 to 23) place 100 in the lowest three bits. Send 111 in the lowest three bits to set sensors 0, 1 and 2.

Density . . . . Sets the density of the material. Valid values are from 0.4 to 99.99 gm/cc.

Zfact . . . . Z-Ratio (Z-Factor) of the material. This is a unitless number, and can be found in Appendix A, Material Table. Values are from 0.5 to 25.

Tooling: . . . . Accounts for the difference in deposition rate at the sensor vs. the substrate. Has a range from 0 to 9.99, representing 0 to 999%.

`Sif142GetMaterial (double SensorParams (0 to 23, 0 to 2), double SystemParams (0 to 4)`

Read material parameters: density, Z-Ratio, and tooling (0 to 23, 0 to 2) and system parameters: max freq, min freq, init freq, period, norm/sim (0 to4)

`Sif142FullScale (long Output, double FullScaleVolts, double MaxPwr, double SlewRate)`

Sets the source output operating parameters.

Output . . . . The output these parameters are for, 0 to 13.

FullScaleVolts. . . . . Maximum voltage the output is scaled to. This is the output at 100% power. Values from -10 to +10 are valid.

MaxPwr . . . . Maximum power that the loop is allowed to output, expressed as 0.0 to 1.0 (representing 0% to 100%)

SlewRate: . . . . Maximum rate of change that the output can change, expressed as (Percent of full scale x 0.01 / Second).

`Sif142Auto (long Output)`

Exits manual power control and starts the control loop running on the indicated output channel.

Output . . . . 0-11, indicating the output to place in PID control.

`Sif142Loop2 (double Rate, double P, double I, double D, long Output)`

Sets the control loop parameters for an output. The sensors specified in the Sif142MapSensors function are averaged to provide the input parameters to the PID loop.

Rate . . . . Specifies the rate that we wish to control to, from 0 to 999.9 Angstroms/Second.

P. . . . . Proportional (gain) term of the PID loop. A unitless number from 0 to 9999.

I . . . . Integral term, from 0 to 99.9, expressed in seconds.

D. . . . . Derivative term, from 0 to 99.9, expressed in seconds.

Output . . . . The output (0 to 13) the parameters apply to.

From the user entered PID parameters, and the error history, a power output setting is calculated using:

`Sif142SetPower (long Output, double Power)`

Sets the control voltage value in manual mode. If an output was in Auto mode, turns off PID control and places the output in Manual mode.

Output. . . . . Specifies which output, 0 to 13.

Power . . . . Power is between 0.0 and 1.0, representing 0 to 100% of full scale.

`Sif142MapSensors (long SensLoop(0 to 23))`

An array that associates each sensor (0 to 23) with an output (0 to 13) for PID control. An output value of -1 for a sensor causes the sensor to continue to monitor deposition, but have no effect on output control.

SensLoop () . . . . Array (0 to 23) of sensor to output assignments (0 to 13).

`Sif142MapAnSensors (long AnLoop(0 to 3))`

An array that associates each analog input (0 to 3) with an output (0 to 13) for PID control. An output value of -1 for an input causes the input to continue to monitor voltage, but have no effect on output control.

AnLoop () . . . . Array (0 to 3) of analog input to output assignments (0 to 13).

`Sif142GetReadings (double SensorArray(0 to 23, 0 to 2), double OutputArray (0 to 13))`

Fills two arrays with measurement data. In the second dimension of the SensorArray the elements are Rate (Å/s), Thickness (Å), and Frequency (Hz). Negative frequency values indicate a sensor error. The OutputArray element is output power, 0 to 1.

If a 0 is returned from this function, there are no new readings available. A non zero value means that there is new data, with the returned value indicating the number of readings in the buffer. The buffer is 10 readings long. To flush it, keep reading until there is no new data.

`Sif142GetAnReadings (double AnalogArray(0 to 3), double OutputArray (0 to 13))`

Fills two arrays with measurement data. The AnalogArray is voltage. The OutputArray is filtered power.

If a 0 is returned from this function, there are no new readings available. A non zero value means that there is new data, with the returned value indicating the number of readings in the buffer. The buffer is 10 readings long. To flush it, keep reading until there is no new data.

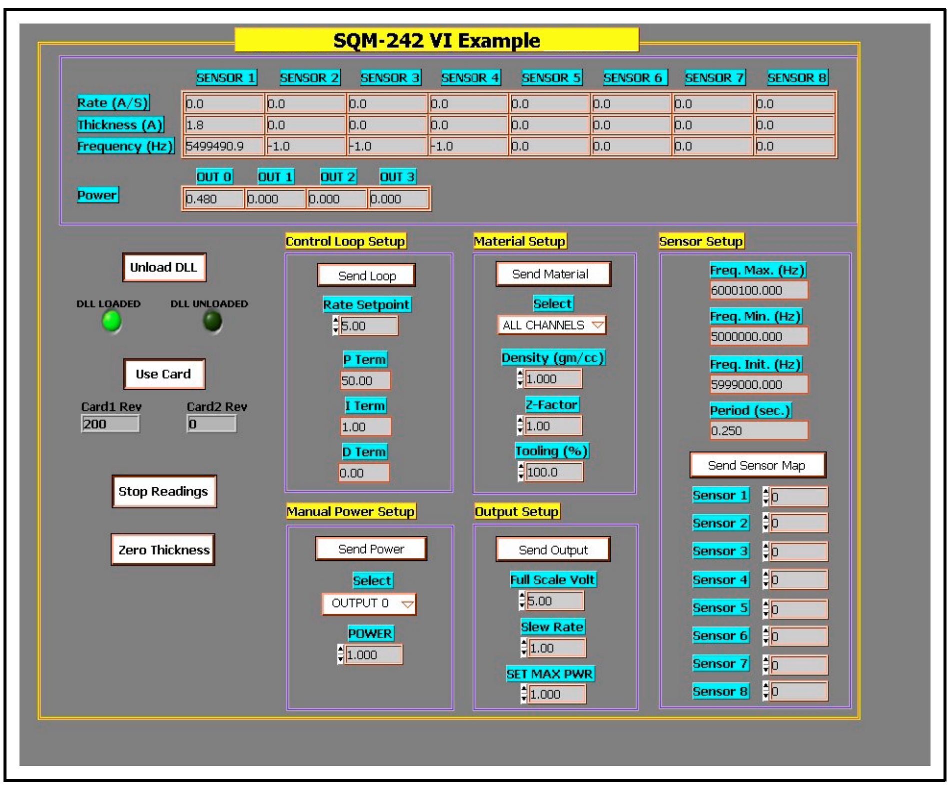
`Sif142GetPower (double PowerArray(0 to 13))`

Fills the array with the current output powers. Unlike the Sif142GetReadings OutputArray, the value is an instantaneous unbuffered value.

6.3 Sample Files

On the INFICON CDROM in D:\SQM242 Card\SQM242_V100_SAMPLES.There are sample interface files for use in C, Visual Basic, or LabVIEW. These files are meant to act as means to aid you in creating your own software and to allow you to interface to SQM-242 card with other devices in your operation.

Figure 6-2 LabVIEW VI Example Main Dialog Box



NOTE: Before using the LabVIEW demo, it may be best to familiarize yourself with operation of the SQM-242 CoDep program.

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To run the LabVIEW demo, click "Load DLL", "Use Card" and then set the Sensor and Output parameters as desired. Click "Start Readings" to display readings. Be sure to click "Unload DLL" before stopping the LabVIEW program. Otherwise, a Windows error will occur, and LabVIEW may shut down. LabVIEW 6 or higher is required.

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Chapter 7
Troubleshooting and Maintenance

7.1 Troubleshooting Guide

If the SQM-242 fails to function as expected, or appears to have diminished performance, the following Symptom/Cause/Remedy charts may be helpful.

CAUTION

The SQM-242/SAM-242 card(s) do not have any user serviceable components.

Refer all maintenance to qualified INFICON personnel.

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7.1.1 Troubleshooting the SQM-242

Table 7-1 General Troubleshooting

SYMPTOM	CAUSE	REMEDY
1. Crystal fail message is always on.	a. Sensor not connected.	a. Verify proper sensor connections.
	b. SQM-242 malfunctioning.	b. If available, insert a known working SQM-242, or other QCM, in place of suspect one; if SQM-242 is confirmed bad, contact INFICON service department.
	c. Defective cable from feedthrough to oscillator.	c. Use an Ohm meter or DMM to check electrical continuity or isolation as appropriate.
	d. Poor electrical contact in the sensor, feedthroughs, or in-vacuum cable.	d. Use an Ohm meter or DMM to check electrical continuity or isolation as appropriate.
	e. Failed crystal/no crystal/defective crystal.	e. Replace crystal with a new INFICON crystal.
	f. Two crystals placed into the crystal holder.	f. Remove one of the crystals.
	g. Frequency of crystal out of range.	g. Verify that the crystal frequency is within the required range, use INFICON crystals. Set the desired range in the software.
2. Noisy signal.	a. Distance from sensor head to the oscillator is longer than 40 in. (101.6 cm).	a. Replace cables to preserve the maximum allowable length.
	b. Mechanical/electric noise sources located near the SQM-242/cables.	b. Reroute cables to reduce noise pickup (1 ft away from high power conducting lines makes a sizable reduction in the amount of noise), keep all ground wires short with large surface area to minimize ground impedance.

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Table 7-1 General Troubleshooting

SYMPTOM	CAUSE	REMEDY
3. Control voltage output does not function properly.	a. DAC board damaged from applying voltage to the control voltage output.	a. Ensure cable connection to the DAC board does not have a potential across the contacts, contact INFICON service department.
	b. Reversed polarity of control voltage relative to that accepted by the source power supply.	b. Verify source output polarity of the DAC and the required input polarity of the source power supply, reconfigure the SQM-242 if necessary.
	c. Improper control cable fabrication.	c.Check for correct cable wiring.
4. Frequency reading is unstable or drifting.	a. Temperature (of the crystal) is changing. An AT-cut crystal frequency may drift as much as 10 Hz/°C.	a. Control the temperature of the chamber. Check watering cooling for flow and temperature. Check source to crystal distance (12" is ideal)./
	b. Humidity (level on the crystal) is changing. Moisture being absorbed or exuded from the crystal surface.	b. Control the humidity of the chamber.
	c. "Unbalanced" or damaged coaxial cable.	c. Check cables for any sign of damage. Replace cable if found. Perform continuity test on cables.

Table 7-1 General Troubleshooting

SYMPTOM	CAUSE	REMEDY
5. Poor rate control.	a. Control loop parameters improperly selected.	a. Test to ensure a stable rate is possible in manual mode. Refer to the instruction manual section on tuning control loop parameters.
	b. Electron beam sweep frequency "beating" with the SQM-242's measurement frequency.	b. Adjust the sweep frequency so it is not a multiple of the SQM-242's measurement frequency.
	c. Inadequate resolution.	c. Low density materials cause little frequency change per angstrom of thickness; hence low resolution. Increase the measurement period.

NOTE: QCM resolution is affected by material density and measurement period. Low density materials cause little frequency change per angstrom of thickness; hence low resolution. Increasing the measurement period significantly increases QCM resolution.Increasing the filter value only increases the display resolution.

Measurement Resolution @ Density = 1 g·cm^{-3}

Measurement Period (sec.)	Frequency Resolution (Hz)	Thickness Resolution (Å)	Rate Resolution (Å/s)	Rate (Å/s) @ Density = 2 (g·cm^{-3})
0.25	0.110	0.16	0.64	0.320
0.50	0.055	0.08	0.16	0.080
1.00	0.028	0.04	0.04	0.020
1.50	0.018	0.03	0.02	0.010
2.00	0.014	0.02	0.01	0.005

7.1.2 Troubleshooting Sensors

NOTE: Many sensor head problems may be diagnosed with a DMM (Digital Multi-Meter). Disconnect the short oscillator cable from the feedthrough and measure the resistance from the center pin to ground. If the reading is less than 10 megohms, the source of the leakage should be found and corrected. Likewise, with the vacuum system open check for center conductor continuity, a reading of more than 1 ohm from the feedthrough to the oscillator indicates a problem. Cleaning contacts or replacing the in-vacuum cable may be required.

NOTE: A somewhat more thorough diagnosis may be performed with the optional Crystal Sensor Emulator, 760-601-G1. See section 7.3 on page 7-16 for a discussion of its use and diagnostic capabilities.A more detailed troubleshooting guide is shipped with the sensor. Refer to that manual for more detailed information in some cases.

Table 7-2 Troubleshooting Sensors

SYMPTOM	CAUSE	REMEDY
1. Large jumps of thickness reading during deposition.	a. Mode hopping.	a. Mode hopping is a byproduct of active oscillation with a heavily damped crystal. Temperature stabilization is key in diminishing this. Replace the crystal.
	b. Stress causes film to peel from crystal surface.	b. Replace crystal or use high performance RunSaver™ crystal; consult factory.
	c. Particulate or "spatter" from molten source striking crystal.	c. Thermally condition the source thoroughly before deposition, use a shutter to protect the crystal during source conditioning.
	d. Material build up, scratches or foreign particles on the crystal holder seating surface (improper crystal seating.)	d. Clean and polish the crystal seating surface on the crystal holder.
	e. Small pieces of material fell on crystal (for crystal facing up sputtering situation.)	e. Check the crystal surface and blow it off with clean air.
	f. Small pieces of magnetic material being attracted by the sensor magnet and contacting the crystal (sputtering sensor head.)	f. Check the sensor cover's aperture and remove any foreign material that may be restricting full crystal coverage.

Table 7-2 Troubleshooting Sensors

SYMPTOM	CAUSE	REMEDY
2. Crystal ceases to oscillate during deposition before it reaches the end of its normal life.	a. Crystal struck by particulate or spatter from molten source.	a. Thermally condition the source thoroughly before deposition, use a shutter to protect the crystal during source conditioning.
	b. Material on crystal holder partially masking crystal cover aperture.	b. Clean crystal holder.
	c. Existence of electrical short or open condition.	c.Using an ohm meter or DMM, check for electrical continuity in the sensor cable, connector, contact springs, connecting wire inside sensor, and feedthroughs.
	d. Thermally induced electrical short or open condition.	d. See 2C above.
NOTE: Crystal life is highly dependent on process conditions of rate, power radiated from source, location, material, and residual gas composition.		
3. Crystal does not oscillate or oscillates intermittently (both in vacuum and in air.)	a. Intermittent or poor electrical contact (contacts oxidized.)	a. Use an Ohm meter or DVM to check electrical continuity, clean contacts.
	b. Leaf springs have lost retentivity (ceramic retainer, center insulator.)	b. Carefully bend leaves to approx. 45°.on ceramic retainer and 60° inside the sensor head.
	c. RF interference from sputtering power supply.	c. Verify earth ground, use ground strap adequate for RF ground, change location of the computer and cabling away from RF power lines.
	d. Cables not connected, or connected to wrong sensor input.	d. Verify proper connections, and inputs relative to programmed sensor parameter.

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Table 7-2 Troubleshooting Sensors

SYMPTOM	CAUSE	REMEDY
4. Crystal oscillates in vacuum but stops oscillation after open to air.	a. Crystal was near the end of its life; opening to air causes film oxidation which increases film stress.	a. Replace crystal.
	b. Excessive moisture accumulates on the crystal.	b. Turn off cooling water to sensor prior to venting, flow warm water through sensor while chamber is open.
5. Thermal instability: large changes in thickness reading during source warm-up (usually causes thickness reading to decrease) and after the termination of deposition (usually causes thickness reading to increase.)	a. Inadequate cooling water/cooling water temperature too high.	a. Check cooling water flow rate, be certain that cooling water temperature is less than 30°C; refer to appropriate sensor manual.
	b. Excessive heat input to the crystal.	b. If heat is due to radiation from the evaporation source, move sensor further away from source and use silver crystals for better thermal stability; install radiation shield.
	c. Crystal not seated properly in holder.	c. Clean or polish the crystal seating surface on the crystal holder.
	d. Crystal heating caused by high energy electron flux (often found in RF sputtering.)	d. Use a sputtering sensor head.
	e. Poor thermal transfer (Bakeable.)	f. Use Al or Au foil washer between crystal holder and sensor body.

Table 7-2 Troubleshooting Sensors

SYMPTOM	CAUSE	REMEDY
6. Poor thickness reproducibility.	a. Variable source flux distribution.	a. Move sensor to a more central location to reliably sample evaporant, ensure constant relative pool height of melt, avoid tunneling into the melt.
	b. Sweep, dither, or position where the electron beam strikes the melt has been changed since the last deposition.	b. Maintain consistent source distribution by maintaining consistent sweep frequencies, sweep amplitude and electron beam position settings.
	c. Material does not adhere to the crystal.	c. Make certain the crystal surface is clean; avoid touching crystal with fingers, make use of an intermediate adhesion layer.
	d. Cyclic change in rate.	d. Make certain source's sweep frequency is not "beating" with the SQM-242 measurement frequency.
7. Large drift in thickness (greater than 200 Å for a density of 5.00 g/cc) after termination of sputtering.	a. Crystal heating due to poor thermal contact.	a. Clean or polish the crystal seating surface on the crystal holder.
	b.External magnetic field interfering with the sensor's magnetic field (sputtering sensor.)	b.Rotate sensor magnet to proper orientation with external magnetic field, refer to the sputtering sensor manual IPN 074-157.
	c. Sensor magnet cracked or demagnetized (sputtering sensor.)	c. Check sensor magnetic field strength, the maximum field at the center of the aperture should be 700 gauss or greater.

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7.1.3 Troubleshooting Computer Communications

Table 7-3 Troubleshooting Computer Communications

SYMPTOM	CAUSE	REMEDY
1. Communications cannot be established between the host computer and the SQM-242.	a. Card not found by software.	a. Card not jumpered properly.
	b. Driver not installed properly.	b. Confirm the operating system is an accepted OS. If autorun driver install feature does not work, the driver can be installed from the device manager manually.
	c. Driver not communicating.	c. Previous installation attempts can cause comm issues. Perform the SQM242 clean.exe procedure.

NOTE: To perform this procedure, you do not need to uninstall the SQM-242 software, or any other INFICON software. Be sure you are logged on with administrator privileges. You will need the SQM242clean software to perfom this procedure.

If you previously tried to install the card, but it did not work:

1. In Control Panel remove/uninstall any SQM-242 cards.
2. Run the "clean" program (SQM-242 clean.exe).
3. Search in Regedit for any occurrences of WINDRVR or WINDRIVER.
4. If any are found, delete them. If you can't, you need higher privileges.
5. Search in \Windows\Inf\OEM*.INF files for “Sigma” and delete any that are found.
6. Restart the computer and follow the next steps for a clean install.
7. Install the card and start the computer. You should get a "New Hardware Found" message.
8. If not, the card is defective, or not installed or jumpered properly.
9. When prompted for a driver, point windows to the INFICON CD-ROM.
10. Windows should find the SQM-242 Card driver and install it.
11. Restart the computer and verify that SQM-242 card(s) are shown in Control Panel.

(Steps 12-15 are not always needed, but it doesn't hurt).

12. Select Start, Run, type WDREGINS, click OK.
13. A DOS window will flash very briefly. Restart the computer.
14. If prompted for a WINDRVR driver, point Windows to the CDROM drivers again.
15. Restart the computer and load the SQM-242 software.

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7.2 Replacing the Crystal

CAUTION

Always use clean nylon lab gloves and plastic tweezers for handling the crystal (to avoid contamination which may lead to poor adhesion of the film to the electrode).

Do not rotate the ceramic retainer assembly after it is seated (as this will scratch the crystal electrode and cause poor contact).

Do not use excessive force when handling the ceramic retainer assembly since breakage may occur.

NOTE: Certain materials, especially dielectrics, may not adhere strongly to the crystal surface and may cause erratic readings.

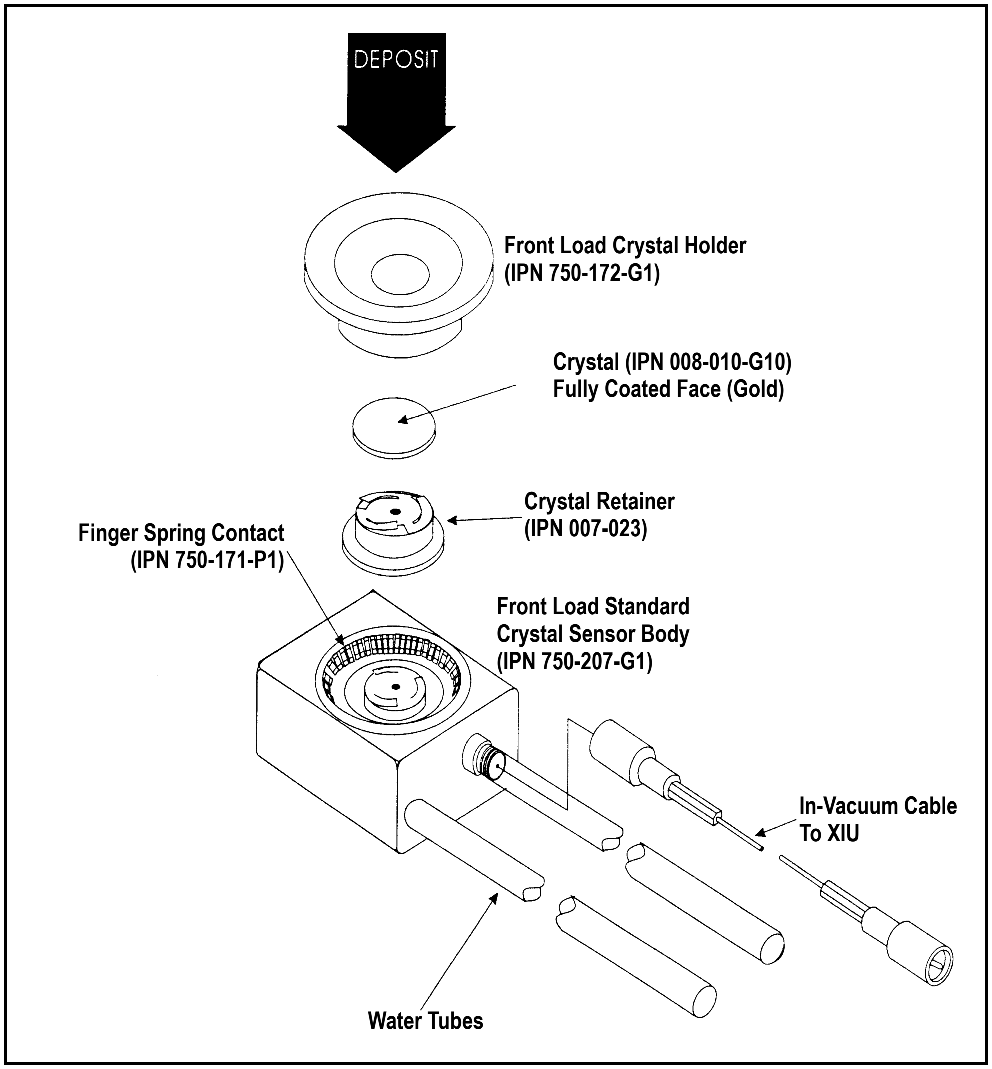
NOTE: Thick deposits of some materials, such as SiO, Si, and Ni will normally peel off the crystal when it is exposed to air, as a result of changes in film stress caused by gas absorption. When you observe peeling, replace the crystals.

7.2.1 Front Load

Follow the procedure below to replace the crystal in the Front Load sensor: (see Figure 7-1)

1. Gripping the crystal holder with your fingers, pull it straight out of the sensor body.
2. Gently pry the crystal retainer from the holder (or use the Crystal Snatcher; see Figure 7-6 on page 7-15).
3. Turn the retainer over and the crystal will drop out.
4. Install a new crystal, with the patterned electrode face up.
5. Push the retainer back into the holder and replace the holder in the sensor body.

Figure 7-1 Front Load Crystal Sensor (Exploded)



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7.2.2 Cool Drawer

Follow the procedure below to replace the crystal in a Next Generation Cool Drawer™ sensor:

1. Using your thumb and index fingers, gently squeeze the sides of the retainer at the mid section then lift it up, away from the drawer, as shown in Figure 7-2.
2. Hold the drawer by the handle and turn it upside down to remove the spent crystal.
3. Install a new crystal in the drawer. Observe its orientation. The pattern electrode should face upward as shown in Figure 7-3.

4 Hold the retainer by its sides. Align its orientation notch with the drawer then gently and evenly push the retainer down until it snaps firmly into the drawer. see Figure 7-3. Never push down (or pull up) on the contact spring, doing so may permanently damage it.

5 Inspect the whole assembly. The retainer should be even and engage the drawer at all four corners.

Figure 7-2 Cool Drawer - removing the crystal

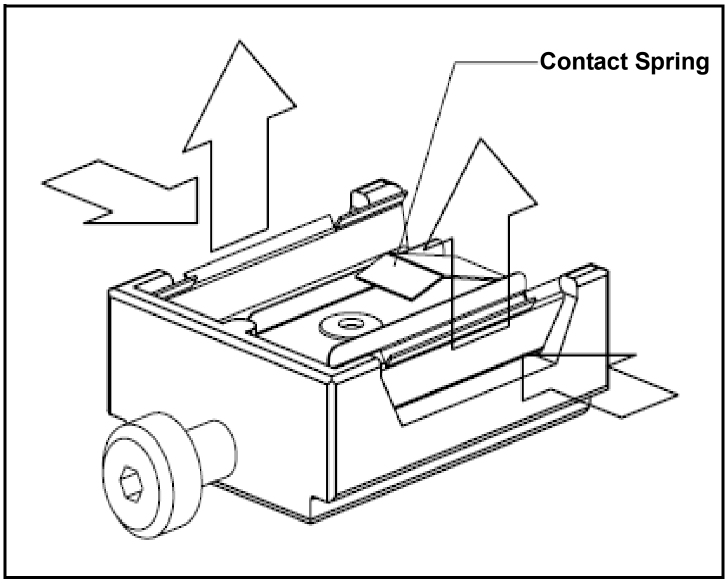
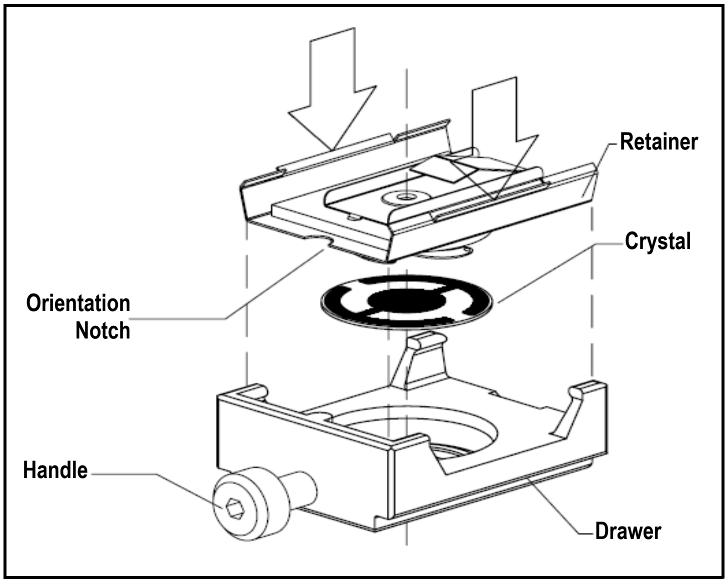


Figure 7-3 Cool Drawer - replacing the crystal



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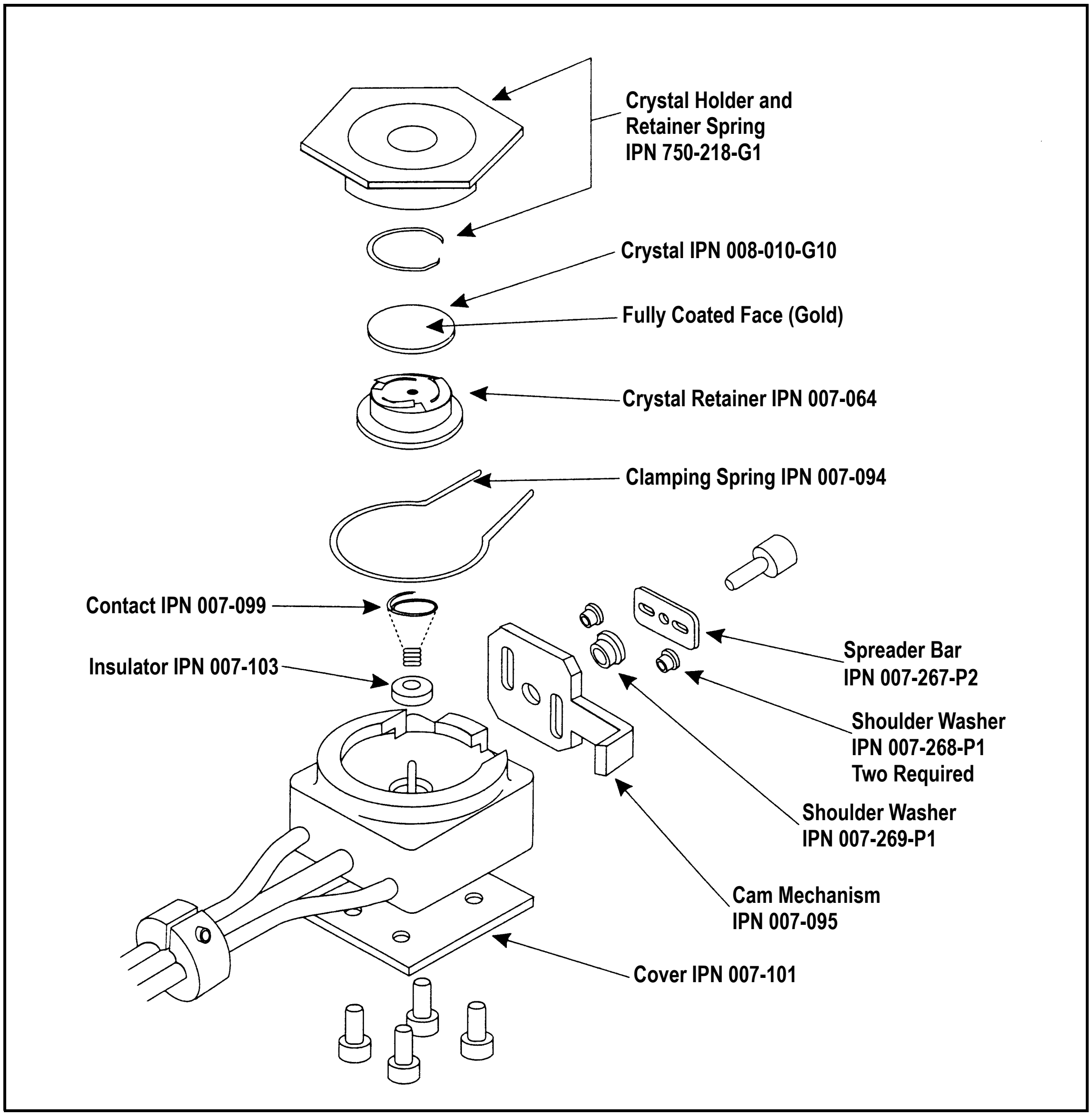
7.2.3 Bakeable Sensor

For the Bakeable sensor, the procedure is the same as the Front Load sensor except that you must first unlock the cam assembly by flipping it up. Once the crystal has been replaced, place a flat edge of the holder flush with the cam mechanism and lock it in place with the cam. See Figure 7-4.

Figure 7-4 Bakeable Crystal Sensor



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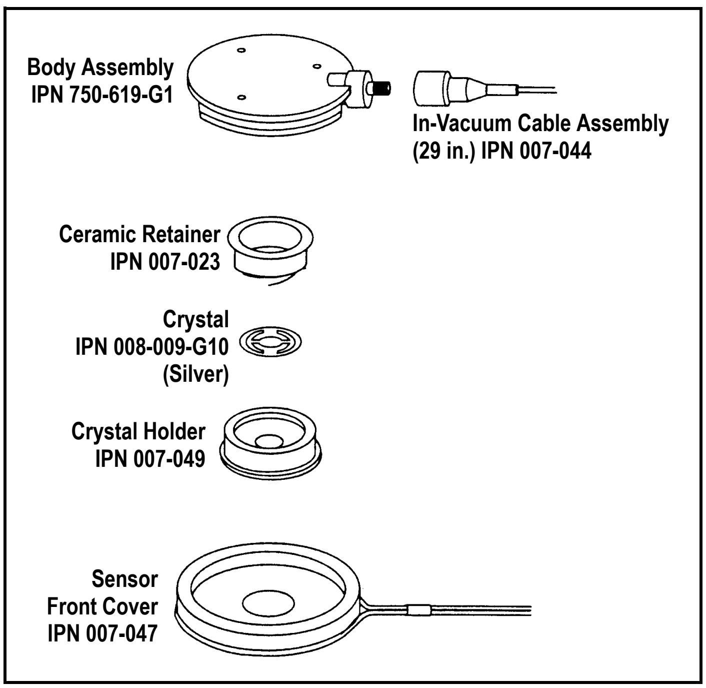
7.2.4 Sputtering Sensor

Observe the general precautions for replacing crystals and follow the instructions below to replace the crystal in a sputtering sensor.

1. Grip the body assembly with your fingers and pull it straight out to separate it from the water-cooled front cover. (You may have to disconnect the sensor cable in order to separate the parts.) See Figure 7-5.
2. Pull the crystal holder straight out from the front of the body assembly.
3. Remove the ceramic retainer from the crystal holder by pulling it straight out with the crystal snatcher (see section 7.2.5 on page 7-15).
4. Turn the crystal holder over so that the crystal drops out.
5. Install a new crystal into the crystal holder with the patterned electrode facing the back and contacting the leaf springs on the ceramic retainer.
6. Put the ceramic retainer back into the crystal holder and put the holder into the body assembly of the sensor.
7. Align the position of the body assembly so that the connector matches with the notch on the front cover of the sensor. Snap the two parts together. Reconnect the sensor cable if it has been disconnected.

Figure 7-5 Sputtering Crystal Sensor



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7.2.5 Crystal Snatcher

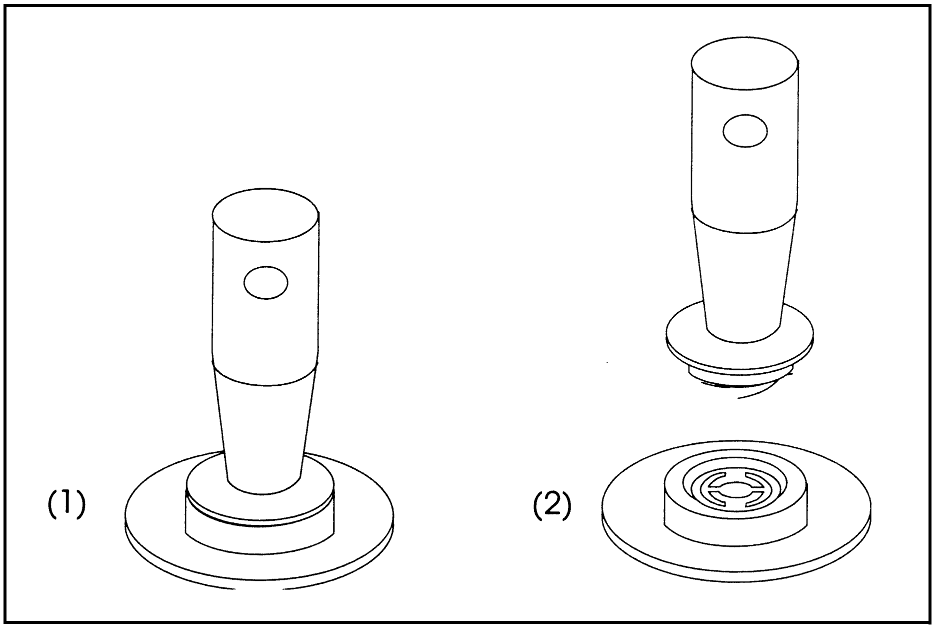
Use the crystal snatcher, supplied with the sensor, as follows:

1 Insert crystal snatcher into ceramic retainer (1) and apply a small amount of pressure. This locks the retainer to the snatcher and allows the retainer to be pulled straight out (2). See Figure 7-6.

2 Reinsert the retainer into the holder after the crystal has been replaced.

3 Release the crystal snatcher with a slight side-to-side motion.

Figure 7-6 Use of the Crystal Snatcher



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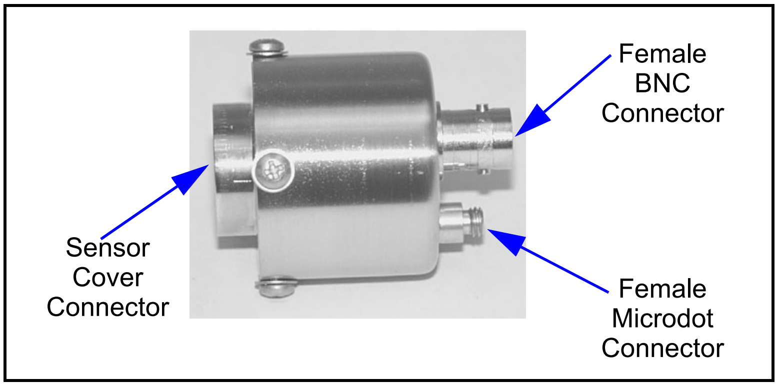
7.3 Crystal Sensor Emulator IPN 760-601-G2

NOTE: 760-601-G2 is fully compatible with all Thin Film Deposition Controllers.

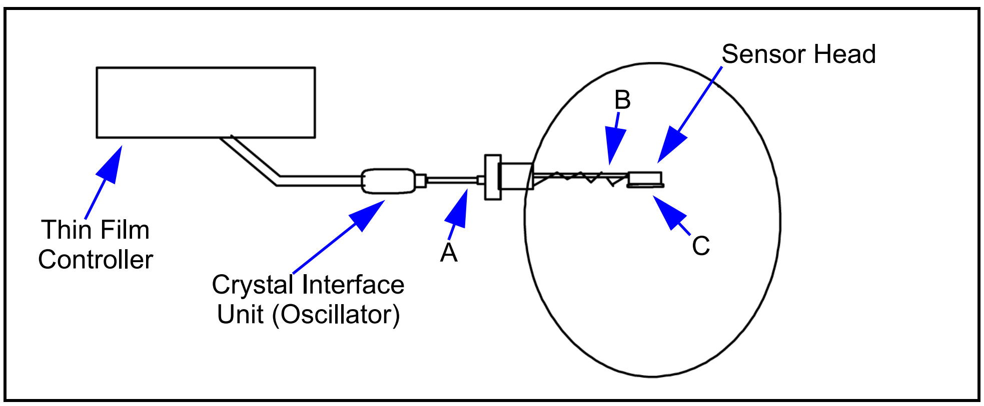
The Crystal Sensor Emulator option is used in conjunction with the Thin Film Deposition Controller to rapidly diagnose problems with the Deposition Controller's measurement system. See Figure 7-7.

Figure 7-7 Crystal Sensor Emulator



The Crystal Sensor Emulator may be attached at various points in the measurement system, from the oscillator to the sensor head. It provides a known good monitor crystal with known good electrical connections. Using the emulator and the controller in a systematic manner provides a fast means of isolating measurement system, cable, or sensor problems. See Figure 7-8.

Figure 7-8 Crystal Sensor Emulator Attachment Points



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CAUTION

This product is designed as a diagnostic tool, and is not intended for use in vacuum. Do not leave the Crystal Sensor Emulator installed in the vacuum system during processing.

7.3.1 Diagnostic Procedures

The following diagnostic procedures employ the Crystal Sensor Emulator to analyze a constant Crystal Fail message. The symptom is a Crystal Fail message that is displayed by the SQM-242 software even after the monitor crystal has been replaced with a new good monitor crystal.

7.3.1.1 Measurement System Diagnostic Procedure

1. Refer to Figure 7-8 on page 7-16. Remove the six-inch BNC cable from the Feed-Through at point A.
2. Connect the Crystal Sensor Emulator to the 6 inch BNC cable at Point A.
    - If the Crystal Fail message disappears after approximately five seconds, the measurement system is working properly. Re-install the six-inch BNC cable to the Feed-Through. Go to section 7.3.1.2.
    - If the Crystal Fail message remains, continue at step 3.
3. Disconnect the six-inch BNC cable from the Oscillator and from the Emulator.
4. Visually inspect the six-inch BNC cable to verify that the center pins are seated properly.
5. Use an Ohm meter to verify the electrical connections on the six-inch BNC cable.
    - There must be continuity (<0.2 ohms after accounting for resistance of ohmmeter leads) between the center pins.
    - There must be isolation (>10 megohms) between the center pins and the connector shield.
    - There must be continuity between the connector shields.

    Replace the six-inch BNC cable if it is found to be defective and repeat Step 2 of this procedure.
6. If the six-inch BNC cable is not defective, re-connect the six-inch cable to the oscillator and to the Crystal Sensor Emulator. If the Crystal Fail message remains, contact INFICON.

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7.3.1.2 Feed-Through Or In-Vacuum Cable Diagnostic Procedure

1. Refer to Figure 7-8 on page 7-16. Remove the In-Vacuum cable from the Sensor Head at point B.
2. Connect the Crystal Sensor Emulator to the In-Vacuum cable.
   - If the Crystal Fail message disappears after approximately five seconds, the Feed-Through and In-Vacuum Cable are working properly. Re-install the In-Vacuum cable to the Sensor Head. Go to section section 7.3.1.3 on page 7-19.
   - If the Crystal Fail message remains, continue at step 3.
3. Disconnect the In-Vacuum cable from the Feed-Through and the Emulator. Disconnect the six-inch BNC cable from the Feed-Through.
4. Using an Ohm Meter, verify electrical continuity from the BNC center pin on the Feed-Through to the Microdot center pin on the Feed-Through. A typical value would be less than 0.2 ohms.
5. Verify electrical isolation of the center pin on the Feed-Through from the electrical ground (Feed-Through body). A typical value would be in excess of 10 megohms.

If the Feed-Through is found to be defective, replace the Feed-Through, re-attach the BNC and In-Vacuum cables, and repeat this procedure starting at Step 2, otherwise continue at step 6.

6. Verify electrical continuity from center pin to center pin on the In-Vacuum cable.
7. Verify that the center pin of the In-Vacuum cable is electrically isolated from the In-Vacuum cable shield.

If the In-Vacuum cable is found to be defective, replace the In-Vacuum cable. Re-attach the BNC and In-Vacuum cables, and repeat this procedure starting at Step 2, otherwise continue at step 8.

8. Connect the In-Vacuum Cable to the Feed-Through.
9. Verify electrical continuity from the center pin on the BNC connector of the Feed-Through to the center pin on the un-terminated end of the In-Vacuum cable.
10. Verify electrical isolation from the center pin to electrical ground (Feed-Through body).

If the Feed-Through/In-Vacuum cable system is found to be defective, look for defective electrical contacts at the Feed-Through to In-Vacuum cable connection. Repair or replace the Feed-Through as necessary. Re-attach the BNC and In-Vacuum cables and repeat this procedure starting at step 2. Otherwise, continue at step 11.

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11 Connect the six-inch BNC cable to the Feed-Through and disconnect it from the oscillator.

12 Verify electrical continuity from the center pin of the Microdot connector on the Feed-Through to the un-terminated end of the six-inch BNC cable.

13 Verify electrical isolation from the center pin to electrical ground (Feed-Through body).

If the Feed-Through/six-inch BNC cable system is found to be defective, look for defective contacts at the Feed-Through to BNC cable connection. Repair or replace the Feed-Through as necessary, re-attach the BNC cable to the XIU and In-Vacuum cable to the Crystal head and repeat this procedure starting at step 2.

7.3.1.3 Sensor Head Or Monitor Crystal Diagnostic Procedure

NOTE: The procedure is for use with front load style sensor heads.

1 Remove the Crystal Cover from the Sensor Head.

2 Refer to Figure 7-7 on page 7-16. Connect the Crystal Sensor Emulator to the Sensor Head at Point C. Note that this only works on a Front Load style sensor head.

- If the Crystal Fail message disappears after approximately 5 seconds the Sensor Head is operating properly. Re-insert the Crystal Cover into the Sensor Head.
- If the Crystal Fail message remains, continue at step 3.

3 Disconnect the In-Vacuum cable from the Sensor Head and the Feed-Through. Remove the Crystal Sensor Emulator from the Sensor Head.

4 Using an Ohm meter, verify the electrical connections on the Sensor Head.

- Verify there is electrical continuity from the center pin contact on the Microdot connector on the Sensor Head to the leaf spring contact in the Sensor Head. Take care not to apply to much pressure on the center pin of the microdot connector as it may become damaged.
- There must be electrical isolation between the center pin of the Microdot connector and the Sensor Head body.

If the Sensor Head is found to be defective, contact INFICON to have the Sensor Head repaired.

5 Connect the In-Vacuum Cable to the Sensor Head.

- Verify there is continuity (<0.2 ohm) from the leaf spring contact in the Sensor Head to the center pin on the un-terminated end of the In-Vacuum cable.
- Verify there is isolation (>10 megohm) between the leaf spring contact and the In-Vacuum cable shield.

If the Sensor Head or the In-Vacuum cable system is found to be defective, look for defective contacts at the In-Vacuum cable to Sensor Head connection, repair or replace the Sensor Head as necessary. Re-attach the In-Vacuum cable to the Feed-Through and repeat this procedure starting at step 2.

6 Ensure that the leaf springs in the Sensor Head and those in the ceramic retainer are bent to an angle of approximately 60 degrees and 45 degrees from flat, respectively.

7.3.1.4 System Diagnostics Pass But Crystal Fail Message Remains

If the system is operating properly yet the Crystal Fail message is still displayed, perform the following tasks.

1 On the Ceramic Retainer verify that the center rivet is secure. Repair or replace the ceramic retainer as necessary.

2 Inspect the inside of the Crystal Holder for build-up of material. Clean or replace the Crystal Holder as necessary.

After verifying the Sensor Head contacts, the Sensor Head/In-Vacuum cable connection and the ceramic retainer contacts, re-assemble the system. If the Crystal Fail message remains, replace the monitor crystal with a new monitor crystal. Verify that the monitor crystal works properly by inserting it into a known good measurement system. If you continue to experience problems, contact INFICON.

7.3.2 Sensor Cover Connection

The Crystal Sensor Emulator can be used to verify the measurement system for INFICON Thin Film Deposition Controllers and Monitors.

However, the Crystal Sensor Emulator's Sensor Cover Connector is compatible with some sensor heads, and is incompatible with others. This is discussed in the following sections.

7.3.2.1 Compatible Sensor Heads

The Sensor Cover Connection will fit the sensor heads shown in Table 7-4.

Table 7-4 Compatible Sensor Heads

Sensor Head	Part Number
Front Load Single Sensor Head	SL-XXXXX
Front Load Dual Sensor Head	DL-AEXX

7.3.2.2 Incompatible Sensor Heads

The Sensor Heads for which the Crystal Sensor Emulator's Sensor Cover Connector will not fit are shown in Table 7-5.

Table 7-5 Incompatible Sensor Heads

Sensor Head	Part Number
Front Load UHV Bakeable Sensor Head	BK-AXX
Cool Drawer Single Sensor Head	CDS-XXXXX
Sputtering Sensor Head	750-618-G1
CrystalSix Sensor Head	750-446-G1
Cool Drawer Dual Sensor Head	CDD-XXXX
Crystal12 Sensor Head	XL12-XXXXXX
RSH-600 Sensor Head	15320X-XX

NOTE: The Crystal Sensor Emulator’s Sensor Cover will not fit the crystal holder opening of the older style INFICON transducers that have the soldered finger springs.

7.3.3 Emulator Specifications

Dimensions

1.58 in. diameter x 1.79 in.
(40.13 mm diameter x 45.47 mm)

Temperature Range

0 to 50^{o}C

Frequency

760-601-G2: 5.5 MHz ± 1 ppm at room temperature

Materials

304 Stainless Steel, Nylon, Teflon®, brass. Some internal components contain zinc, tin, and lead.

Chapter 8
Calibration

8.1 Importance of Density, Tooling and Z-Ratio

The quartz crystal microbalance is capable of precisely measuring the mass added to the face of the oscillating quartz crystal sensor. The SQM-242's knowledge of the density of this added material allows conversion of the mass information into thickness. In some instances, where highest accuracy is required, it is necessary to make a density calibration as outlined in section 8.2.

Because the flow of material from a deposition is not uniform, it is necessary to account for the different amount of material flow onto the sensor compared to the substrates. This factor is accounted for in the tooling parameter in material grid. The tooling factor can be experimentally established by following the guidelines in section 8.3 on page 8-2.

If the Z-Ratio is not known, it could be estimated from the procedures outlined in section 8.4 on page 8-2.

8.2 Determining Density

NOTE: The bulk density values retrieved from Table A-1 are sufficiently accurate for most applications.

Follow the steps below to determine density value.

1. Place a substrate (with proper masking for film thickness measurement) adjacent to the sensor, so that the same thickness will be accumulated on the crystal and substrate.
2. Set density to the bulk value of the film material or to an approximate value.
3. Set Z-Ratio to 1.000 and tooling to 100%.
4. Place a new crystal in the sensor and make a short deposition (1000-5000 Å).
5. After deposition, remove the test substrate and measure the film thickness with either a multiple beam interferometer or a stylus-type profilometer.
6. Determine the new density value with equation [1]:

$$\text{Density}(g/cm^3) = D_1\left(\frac{T_x}{T_m}\right) \qquad [1]$$

where:

D_1 = Initial density setting

T_x = Thickness reading on SQM-242

T_m = Measured thickness

7 A quick check of the calculated density may be made by programming the SQM-242 with the new density value and observing that the displayed thickness is equal to the measured thickness, provided that the SQM-242's thickness has not been zeroed between the test deposition and entering the calculated density.

NOTE: Slight adjustment of density may be necessary in order to achieve $T_x = T_m$.

8.3 Determining Tooling

1 Place a test substrate in the system's substrate holder.

2 Make a short deposition and determine actual thickness.

3 Calculate tooling from the relationship shown in equation [2]:

$$\text{Tooling (\%)} = TF_i\left(\frac{T_m}{T_x}\right) \quad [2]$$

where

T_m = Actual thickness at substrate holder

T_x = Thickness reading in the SQM-242 software

TF_i = Initial tooling factor

4 Round off percent tooling to the nearest 0.1%.

5 When entering this new value for tooling into the program, T_m will equal T_x if calculations are done properly.

NOTE: It is recommended that a minimum of three separate evaporations be made when calibrating tooling. Variations in source distribution and other system factors will contribute to slight thickness variations. An average value tooling factor should be used for final calibrations.

8.4 Laboratory Determination of Z-Ratio

A list of Z-values for materials commonly used are available in Table A-1. For other materials, Z can be calculated from the following formula:

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$$Z = \left(\frac{d_q \mu_q}{d_f \mu_f}\right)^{\frac{1}{2}} \quad [3]$$

$$Z = 9.378 \times 10^5 (d_f \mu_f)^{-\frac{1}{2}} \quad [4]$$

where:

d_f = density (g/cm^3) of deposited film

μ_f = shear modulus (dynes/cm2) of deposited film

d_q = density of quartz (crystal) (2.649 gm/cm^3)

μ_q = shear modulus of quartz (crystal) (3.32 x 10^{11} dynes/cm^2)

The densities and shear moduli of many materials can be found in a number of handbooks.

Laboratory results indicate that Z-values of materials in thin-film form are very close to the bulk values. However, for high stress producing materials, Z-values of thin films are slightly smaller than those of the bulk materials. For applications that require more precise calibration, the following direct method is suggested:

1. Establish the correct density value as described in section 8.2 on page 8-1.
2. Install a new crystal and record its starting frequency, F_{co}. The starting frequency will be displayed on the main dialog box.
3. Make a deposition on a test substrate such that the percent crystal life display will read approximately 50%, or near the end of crystal life for the particular material, whichever is smaller.
4. Stop the deposition and record the ending crystal frequency F_c.
5. Remove the test substrate and measure the film thickness with either a multiple beam interferometer or a stylus-type profilometer.
6. Using the density value from step 1 and the recorded values for F_{co} and F_c, adjust the Z-Ratio value in thickness equation [5] to bring the calculated thickness value into agreement with the actual thickness. If the calculated value of thickness is greater than the actual thickness, increase the Z-Ratio value. If the calculated value of thickness is less than the actual thickness, decrease the Z-Ratio value.

$$T_f = \frac{Z_q \times 10^4}{2\pi z p}\left\{\left(\frac{1}{F_{co}}\right)ATan\left(zTan\left(\frac{\pi F_{co}}{F_q}\right)\right) - \left(\frac{1}{F_c}\right)ATan\left(zTan\left(\frac{\pi F_c}{F_q}\right)\right)\right\} \quad [5]$$

where:

T_f = thickness of deposited film (kÅ)

F_{co} = starting frequency of the sensor crystal (Hz)

F_c = Final frequency of the sensor crystal (Hz)

F_q = Nominal blank frequency = 6045000 (Hz)

z = Z-ratio of deposited film material

Z_q = Specific acoustic impedance of quartz = 8765000 (MKS units)

p = density of deposited film (g/cc)

For multiple layer deposition (for example, two layers), the Z-value used for the second layer is determined by the relative thickness of the two layers. For most applications the following three rules will provide reasonable accuracies:

- If the thickness of layer 1 is large compared to layer 2, use material 1 Z-value for both layers.
- If the thickness of layer 1 is thin compared to layer 2, use material 2 Z-value for both layers.
- If the thickness of both layers is similar, use a value for Z-Ratio which is the weighted average of the two Z values for deposition of layer 2 and subsequent layers.

8.5 Tuning the Control Loop

The function of the control loop parameters is to match the instrument's reaction to an error (between the measured deposition rate and the desired rate) to the time related characteristics of the deposition source and its power supply. There are three adjustable parameters; **P**(proportional), **I**(integral) and **D**(derivative) used to accomplish this. It is convenient to think of sources as falling into two categories "fast" or "slow". The tuning parameters are affected by source level, rate, sweep range or beam density, tooling and source condition.

NOTE: If you do not know if the source is fast or slow, it is straight forward to measure the delay. Using manual power, establish a rate and allow it to become steady. Increase the source power a few percent (~5% if possible). Allow the source to again stabilize. If the delay time is greater than 1 second characterize the source as "slow". Typically, thermal evaporation sources are considered "slow" and E-beam sources are considered "fast."

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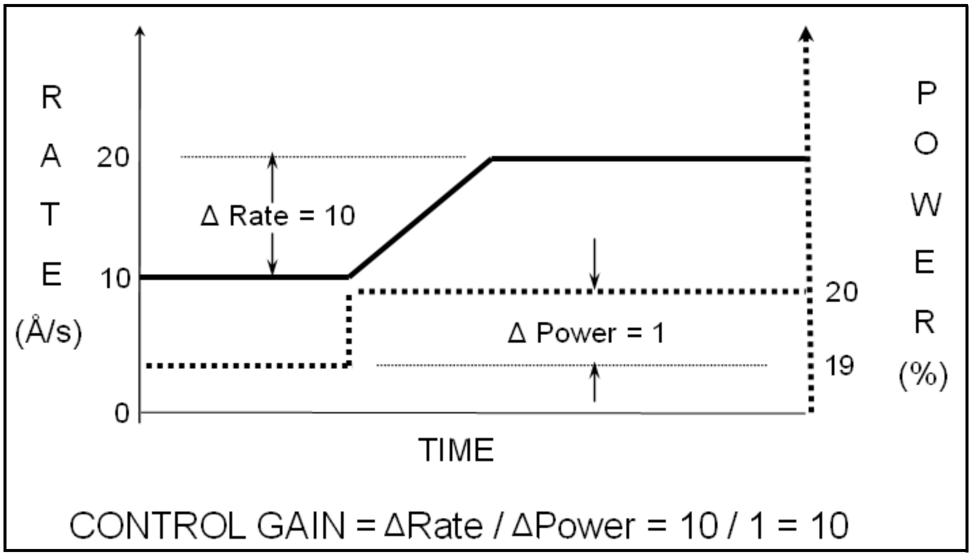
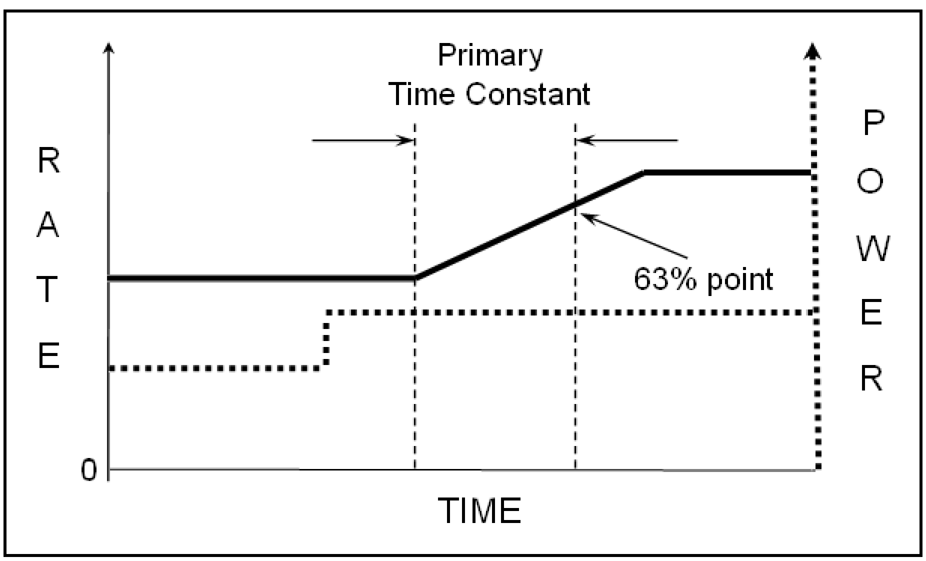
The proportional gain(P) parameter sets the rate at which the control voltage changes in response to an error signal (see Figure 8-1). Any error in the rate causes the source control voltage to ramp to a new value. When the source control voltage increases or decreases to the correct value, the value required to achieve the desired rate, the error goes to zero and the output remains constant.

Figure 8-1 Proportional Gain



The integral time constant(I) is defined as the time difference between the actual start of a change in rate and the time at which 63% of the rate step is achieved (see Figure 8-2.) It instructs the controller on how much attention to pay to the schedule of the thickness profile. If we don't care what happened in the past and we want zero rate error right now, we don't want any Integral feedback. To accomplish that we set the integral time constant to its maximum value, which tells the controller to ignore any past error unless it lasts for a very long time.

Figure 8-2 Time Constant



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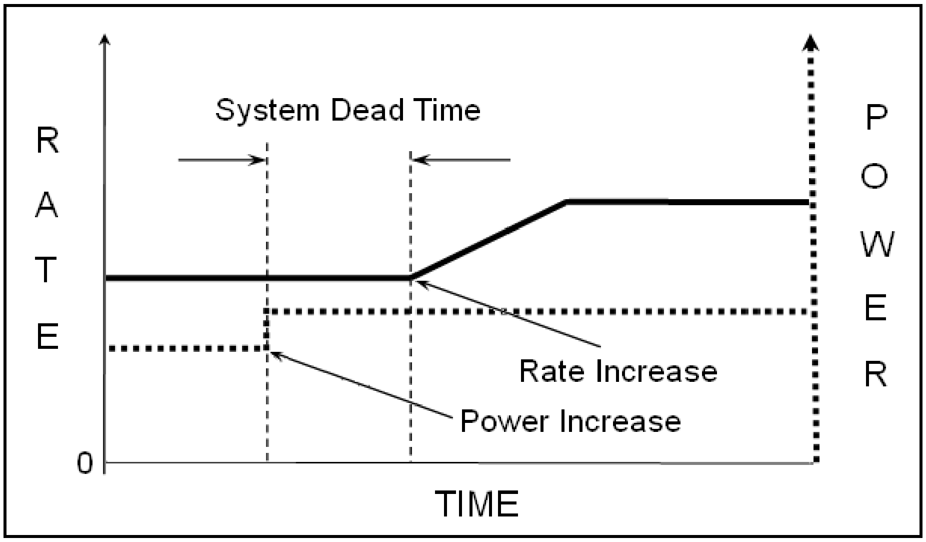
The derivative time constant(D) is utilized to compensate for slow responding sources such as boats and induction heated sources. This value is defined as the time difference between a change in % power and the start of an actual change in rate (see Figure 8-3.) The Derivative Time constant instructs the controller on how much attention to pay to the rate of change of a error. A value of zero tells the controller to ignore the rate of change of the error. A large value tells the controller that the source is slow and it is going to be hard to get it going and hard to stop it. So if the rate starts to fall off, give it power, or if the target is quickly approaching, begin to decrease the power.

Figure 8-3 Dead Time



8.5.1 Fast Source

In general, fast sources are: all electron beam types (unless a hearth liner is used), some very small filament sources and sputtering sources. If the source response has been characterized as "FAST", as suggested in the NOTES in section 8.5, a integrating type control loop should be established.
With fast sources, the I and D terms can typically be set to 0.1. If satisfactory control cannot be established using only P, the source is probably not a "fast" source. The response of a system with too little controller gain (its P value is too large) is characterized as over damped as shown in Figure 8-4. Decrease the P value until the system oscillates as is shown by the under damped curve. Proper control is established by an intermediate value that approximates the critically damped curve.

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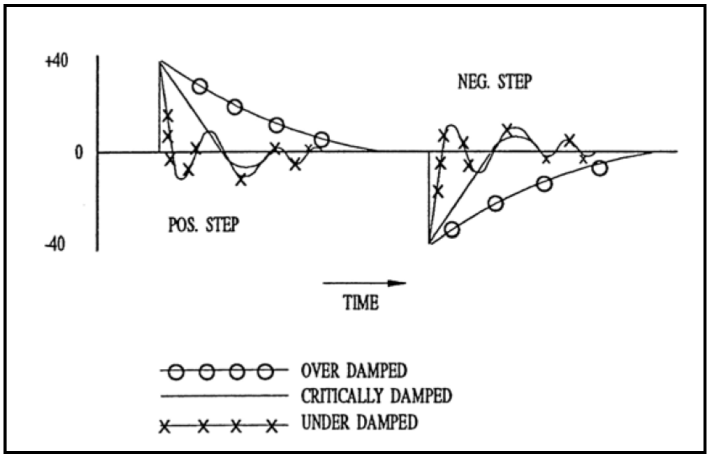
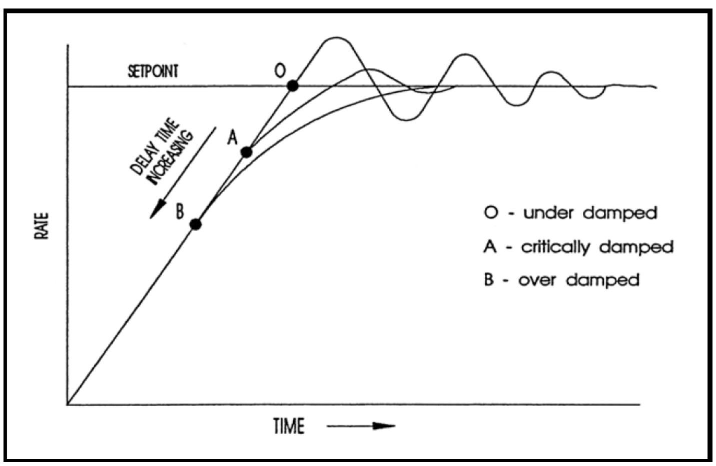
Figure 8-4 Example of Over Damped Curve



8.5.2 Slow Source

A slow source, for the purpose of this discussion, is a deposition source that has more than a one second delay (lag) between the control voltage change (into the source's power supply) and the measurement system's ability to sense that change has taken place. In very slow systems such as large filament boats, the P term may have to be set low to maintain stability where the rate smoothly levels off but remains below the target value. In this case, you will need to adjust the integral time constant. This parameter works in reverse meaning the smaller the value the larger the effect. So, slightly decrease this parameter then watch the rate graph. The rate should ramp up to the target without overshoot. If the ramp takes too long then slowly decrease the Integral Time again and repeat these steps until you are satisfied with the control. Most thermal sources are slow sources. For slow sources, the D term is more involved. As illustrated in Figure 8-5, the derivative time constant (D) is the time delay between a change in the source's power setting and a noticeable change in deposition rate.

Figure 8-5 Example of Delay Setting



8.5.3 Loop Tuning Procedure

NOTE: Please keep in mind, control loop tuning is a trial and error process and there is no "best" procedure to accomplish this task.

1. **Set System Parameters**: In the SQM-242 Co-dep software, set a Period of 0.25 seconds as a good starting point. Set Tooling parameters to 100% for now. Initially set the Rate Filter to 1.00 (no filter) to see the noise of the system. Simulate should be OFF. Keep in mind that Simulate mode is a tool for testing process layers. It is not likely to match the control response of your vacuum system.

2. **Create a One-Layer Test Process**: In View >> Input setup, input the Z-Ratio and density of the material you are depositing. On the main dialog box, set the desired rate and leave the other parameters at their default values.

3. **Test the Setup**: Set the power to manual mode, then press Start. Slowly increase the power to 10%, and verify that your power supply output is about 10% of full scale. Continue to increase power until a rate near your desired rate is achieved. Again, verify that the power supply output agrees with the SQM-242 Power (%) reading. If the readings don't agree, check your wiring and verify that the Edit>>Output menu, Full Scale voltage agrees with your power supply's input specifications. Log the data for a few minutes. Plot the data, if the system has significant short term noise at a fixed power (maybe >10%), the control loop will be very difficult to adjust, especially at low rates. It is better to eliminate the source of the noise before attempting to set the PID values.

4. **Select a Filter Alpha**: On the View >> Card Setup menu, slowly decrease the filter Alpha from 1to a lower value until the rate display noise is minimized. If you set Alpha too low, the display will lag the true system response and may hide significant problems. A value of 0.5 equally weights the current reading and the previous filtered readings.

5. **Determine Open Loop Gain**: Record the Power reading at the desired rate as PWR_{DR}. Slowly lower the power until the Rate (Å/s) reading is just at (or near) zero. Record the zero rate Power reading as PWR_{0R}.

6. **Determine Open Loop Response Time**: Calculate 1/3 of your desired rate ($RATE_{1/3}$), and 2/3 of the desired rate ($RATE_{2/3}$) for this layer. Slowly increase the power until Rate (Å/s) matches $RATE_{1/3}$. Get ready to record the loop's response to an input change. Quickly adjust Power (%) to PWR_{DR}. Measure the time for the Rate (Å/s) reading to reach $RATE_{2/3}$. You may want to do this several times to get an average response time. Twice the measured time is the step response time, $TIME_{SR}$. $TIME_{SR}$ is typically 0.2 to 1 second for E-Beam evaporation, 5 to 20 seconds for thermal evaporation.

7. **Set PID Values**: Set the power to zero. In the Edit>>Output menu set P=25, I= $TIME_{SR}$, D=0. Set Max. Pwr to ~20% higher than PWR_{DR}. Exit the output menu and select Auto to move to Auto (PID control) mode and observe the Power graph. The power should rise from 0%, and stabilize near PWR_{DR} with

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little ringing or overshoot. If there is more than about 10% overshoot, lower the P Term. If the time to reach PWR_{DR} is very slow, increase the P Term. A lower I Term will increase response time, a higher value will eliminate ringing and setpoint deviations. Unless you have a very slow source, It is unlikely you will need any D Term. If you do have a slow source you will need to determine the response time from when you adjust power to when a change in rate occurrs.

Continue to adjust P & I values, alternating between Manual Power 0% and Auto mode until steady-state response is smooth and the step response is reasonably controlled. You don’t need to totally eliminate ringing during this step if the steady-state response is smooth; preconditioning will minimize step changes. Typical I values for thermal systems are 4 to 10; Ebeam I values are 0.5 to 2. It’s impossible to predict P values, but it is best to select the lowest value that provides adequate rate control.

Ebeam systems may require additional steps to limit the control loop’s response during arcing. First, be sure Max. & Min. power are set to limit the output to reasonable values for this material and rate. Slew Rate can further limit too-aggressive power changes. Remember that slew rate is % of full scale per second. At rates below 10 Å/s, a slew rate of 1-2% per second is common. Finally, decreasing the filter Alpha will limit the PID response to occasional large noise spikes, such as from arcing.

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Chapter 9
Measurement and Control Theory

9.1 Basics

The Quartz Crystal deposition Monitor, or QCM, utilizes the piezoelectric sensitivity of a quartz monitor crystal to added mass. The QCM uses this mass sensitivity to control the deposition rate and final thickness of a vacuum deposition. When a voltage is applied across the faces of a properly shaped piezoelectric crystal, the crystal is distorted and changes shape in proportion to the applied voltage. At certain discrete frequencies of applied voltage, a condition of very sharp electro-mechanical resonance is encountered. When mass is added to the face of a resonating quartz crystal, the frequency of these resonances are reduced. This change in frequency is very repeatable and is precisely understood for specific oscillating modes of quartz. This heuristically easy to understand phenomenon is the basis of an indispensable measurement and process control tool that can easily detect the addition of less than an atomic layer of an adhered foreign material.

In the late 1950's it was noted by Sauerbrey[1,2] and Lostis[3] that the change in frequency, DF = F_q-F_c, of a quartz crystal with coated (or composite) and uncoated frequencies, F_c and F_q respectively, is related to the change in mass from the added material, M_f , as follows:

$$\frac{M_f}{M_q} = \frac{(\Delta F)}{F_q} \qquad [6]$$

where M_q is the mass of the uncoated quartz crystal. Simple substitutions lead to the equation that was used with the first "frequency measurement" instruments:

$$T_f = \frac{K(\Delta F)}{d_f} \qquad [7]$$

where the film thickness, T_f, is proportional (through K) to the frequency change, DF, and inversely proportional to the density of the film, d_f. The constant, K = $N_{at}d_q/F_q^2$; where d_q (= 2.649 gm/cm^3) is the density of single crystal quartz and N_{at} (=166100 Hz cm) is the frequency constant of AT cut quartz. A crystal with a starting frequency of 6.0 MHz will display a reduction of its frequency by 2.27 Hz when 1 angstrom of Aluminum (density of 2.77 gm/cm^3) is added to its surface. In this manner the thickness of a rigid adlayer is inferred from the precise measurement of the crystal's frequency shift. The quantitative knowledge of this

1.G. Z. Sauerbrey, Phys. Verhand .8, 193 (1957)
2.G. Z. Sauerbrey, Z. Phys. 155,206 (1959)
3.P. Lostis, Rev. Opt. 38,1 (1959)

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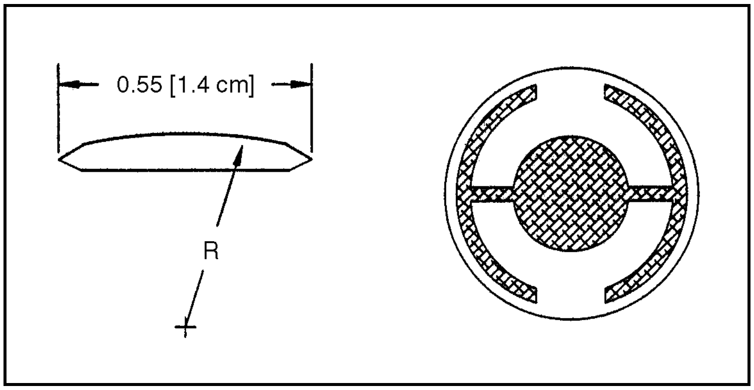
effect provides a means of determining how much material is being deposited on a substrate in a vacuum system, a measurement that was not convenient or practical prior to this understanding.

9.1.1 Monitor Crystals

No matter how sophisticated the electronics surrounding it, the essential device of the deposition monitor is the quartz crystal. The quartz crystal shown in Figure 9-1 has a frequency response spectrum that is schematically shown in Figure 9-2. The ordinate represents the magnitude of response, or current flow of the crystal, at the specified frequency.

Figure 9-1 Quartz Resonator



The lowest frequency response is primarily a “thickness shear” mode that is called the fundamental. The characteristic movement of the thickness shear mode is for displacement to take place parallel to the major monitor crystal faces. In other words, the faces are displacement antinodes as shown in Figure 9-3. The responses located slightly higher in frequency are called anharmonics; they are a combination of the thickness shear and thickness twist modes. The response at about three times the frequency of the fundamental is called the third quasiharmonic. There are also a series of anharmonics slightly higher in frequency associated with the quasiharmonic.

The monitor crystal design depicted in Figure 9-1 is the result of several significant improvements from the square crystals with fully electroded plane parallel faces that were first used. The first improvement was to use circular crystals. This increased symmetry greatly reduced the number of allowed vibrational modes. The second set of improvements was to contour one face of the crystal and to reduce the size of the exciting electrode. These improvements have the effect of trapping the acoustic energy. Reducing the electrode diameter limits the excitation to the central area. Contouring dissipates the energy of the traveling acoustic wave before it reaches the edge of the crystal. Energy is not reflected back to the center where it can interfere with other newly launched waves, essentially making a small crystal appear to behave as though it is infinite in extent. With the crystal’s vibrations restricted to the center, it is practical to clamp the outer edges of the crystal to a holder and not produce any undesirable effects. Contouring also

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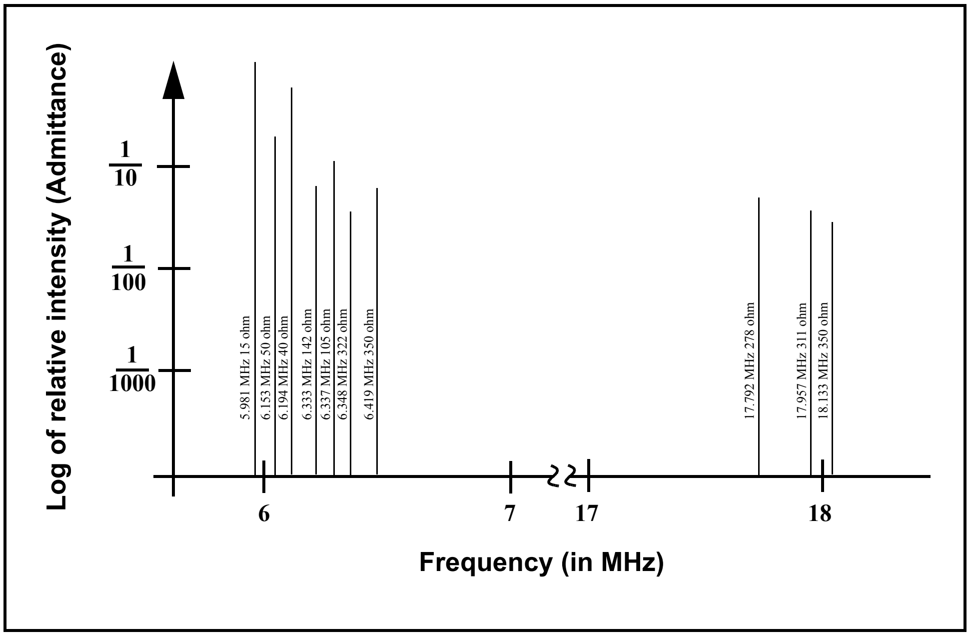
reduces the intensity of response of the generally unwanted anharmonic modes; hence, the potential for an oscillator to sustain an unwanted oscillation is substantially reduced.

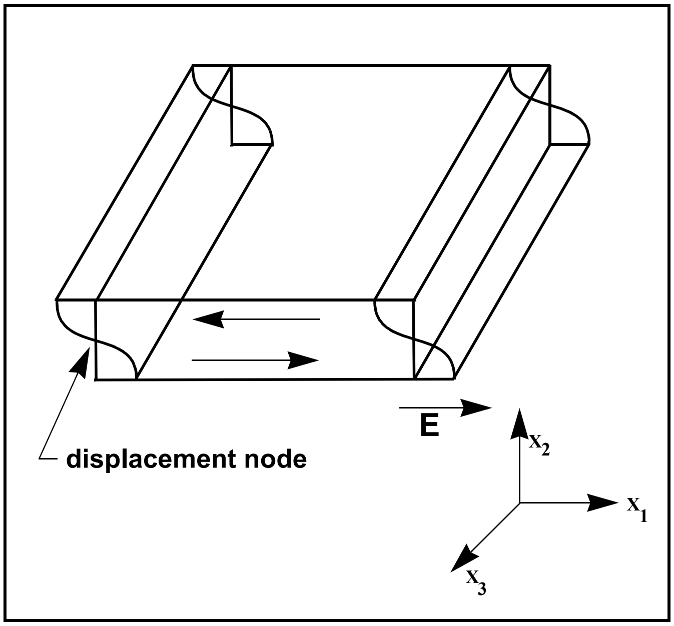
Figure 9-2 Frequency Response Spectrum



The use of an adhesion layer has improved the electrode-to-quartz bonding, reducing “rate spikes” caused by micro-tears between the electrode and the quartz as film stress rises. These micro-tears leave portions of the deposited film unattached and therefore unable to participate in the oscillation. These free portions are no longer detected and the wrong thickness consequently inferred.

The “AT” resonator is usually chosen for deposition monitoring because at room temperature it can be made to exhibit a very small frequency change due to temperature changes. Since there is presently no way to separate the frequency change caused by added mass (which is negative) or even the frequency changes caused by temperature gradients across the crystal or film induced stresses, it is essential to minimize these temperature-induced changes. It is only in this way that small changes in mass can be measured accurately.

Figure 9-3 Thickness Shear Displacement



9.1.2 Period Measurement Technique

Although instruments using equation [7] were very useful, it was soon noted they had a very limited range of accuracy, typically holding accuracy for DF less than 0.02 F_q. In 1961 it was recognized by Behrndt[4] that:

$$\frac{M_f}{M_q} = \frac{(T_c - T_q)}{T_q} = \frac{(\Delta F)}{F_c} \qquad [8]$$

where T_c and Tq are the periods of oscillation of the crystal with film (composite) and the bare crystal respectively. The period measurement technique was the outgrowth of two factors; first, the digital implementation of time measurement, and second, the recognition of the mathematically rigorous formulation of the proportionality between the crystal's thickness, l_q, and the period of oscillation, $T_q = 1/F_q$. Electronically the period measurement technique uses a second crystal oscillator, or reference oscillator, not affected by the deposition and usually much higher in frequency than the monitor crystal. This reference oscillator is used to generate small precision time intervals which are used to determine the oscillation period of the monitor crystal. This is done by using two pulse accumulators. The first is used to accumulate a fixed number of cycles, m, of the monitor crystal. The second is turned on at the same time and accumulates cycles from the reference oscillator until m counts are accumulated in the first. Since the frequency of the reference is stable and known, the time to accumulate the m counts is known to an accuracy equal to ± $2/F_r$ where F_r is the reference oscillator's frequency. The

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4.K. H. Behrndt, J. Vac. Sci. Technol. 8, 622 (1961) monitor crystal's period is $(n/F_r)/m$ where n is the number of counts in the second accumulator. The precision of the measurement is determined by the speed of the reference clock and the length of the gate time (which is set by the size of m). Increasing one or both of these leads to improved measurement precision.

Having a high frequency reference oscillator is important for rapid measurements (which require short gating times), low deposition rates and low density materials. All of these require high time precision to resolve the small, mass induced frequency shifts between measurements. When the change of a monitor crystal's frequency between measurements is small, that is, on the same order of size as the measurement precision, it is not possible to establish quality rate control. The uncertainty of the measurement injects more noise into the control loop, which can be counteracted only by longer time constants. Long time constants cause the correction of rate errors to be very slow, resulting in relatively long term deviations from the desired rate. These deviations may not be important for some simple films, but can cause unacceptable errors in the production of critical films such as optical filters or very thin layered superlattices grown at low rates. In many cases the desired properties of these films can be lost if the layer to layer reproducibility exceeds one, or two, percent. Ultimately, the practical stability and frequency of the reference oscillator limits the precision of measurement for conventional instrumentation.

9.1.3 Z-match Technique

After learning of fundamental work by Miller and Bolef [5], which rigorously treated the resonating quartz and deposited film system as a one-dimensional continuous acoustic resonator, Lu and Lewis[6] developed the simplifying Z-Match® equation in 1972. Advances in electronics taking place at the same time, namely the micro-processor, made it practical to solve the Z-match equation in "real-time". Most deposition process controllers/monitors sold today use this sophisticated equation that takes into account the acoustic properties of the resonating quartz and film system as shown in equation [9].

$$T_f = \left(\frac{N_{at} d_q}{\pi d_f F_c Z}\right) \arctan\left(Z \tan\left[\frac{\pi(F_q - F_c)}{F_q}\right]\right) \quad [9]$$

where $Z=(d_q u_q/d_f u_f)^{1/2}$ is the acoustic impedance ratio and u_q and u_f are the shear moduli of the quartz and film, respectively. Finally, there was a fundamental understanding of the frequency-to-thickness conversion that could yield theoretically correct results in a time frame that was practical for process control. To achieve this new level of accuracy requires only that the user enter an additional material parameter, Z, for the film being deposited. This equation has been tested

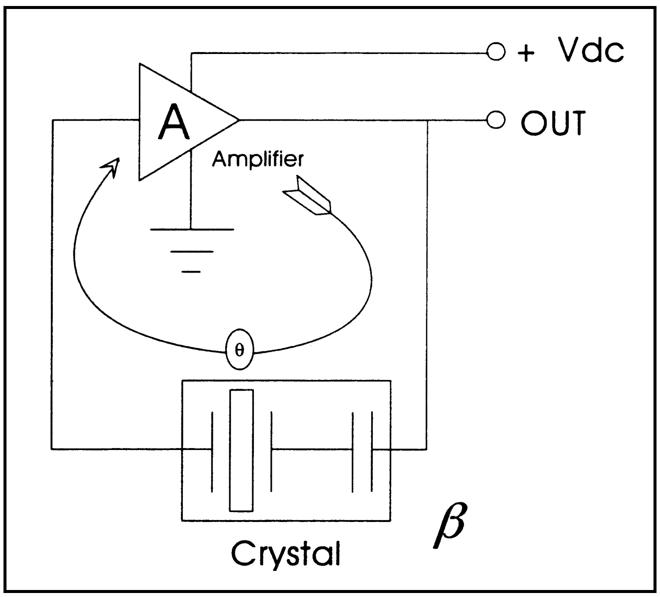
5.J. G. Miller and D. I. Bolef, J. Appl. Phys. 39, 5815, 4589 (1968)
6.C. Lu and O. Lewis, J Appl. Phys. 43, 4385 (1972)

for a number of materials, and has been found to be valid for frequency shifts equivalent to $F_f = 0.4F_q$. Keep in mind that equation [7] was valid to only $0.02F_q$ and equation [8] was valid only to $\sim 0.05F_q$.

9.1.4 Active Oscillator

The SQM-242 relies on the use of an active oscillator circuit, Specifically the type schematically shown in Figure 9-4. This circuit actively keeps the crystal in resonance, so that any type of period or frequency measurement may be made. In this type of circuit, oscillation is sustained as long as the gain provided by the amplifiers is sufficient to offset losses in the crystal and circuit and the crystal can provide the required phase shift. The basic crystal oscillator's stability is derived from the rapid change of phase for a small change in the crystal's frequency near the series resonance point, as shown in Figure 9-6 on page 9-7.

Figure 9-4 Active Oscillator Circuit



The active oscillator circuit is designed so the crystal is required to produce a phase shift of 0 degrees, which allows it to operate at the series resonance point. Long- and short-term frequency stabilities are a property of crystal oscillators because very small frequency changes are needed to sustain the phase shift required for oscillation. Frequency stability is provided by the quartz crystal even though there are long term changes in electrical component values caused by temperature or aging or short-term noise-induced phase jitter.

As mass is added to a crystal, its electrical characteristics change. Figure 9-5 on page 9-7 is the same plot as Figure 9-6 overlaid with the response of a heavily loaded crystal.

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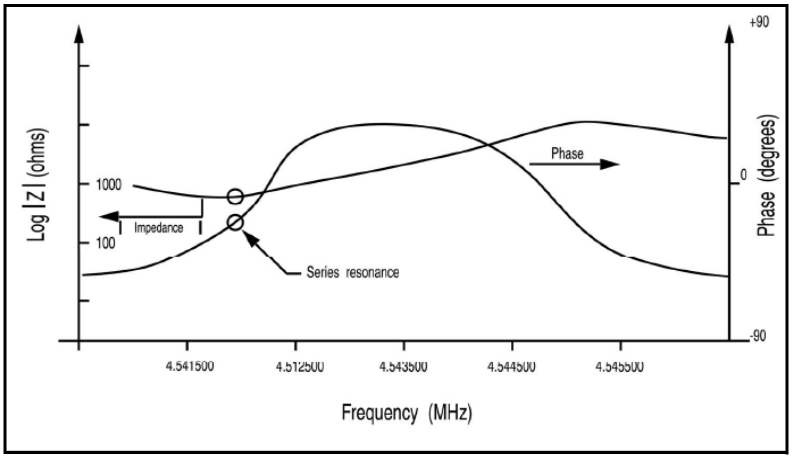
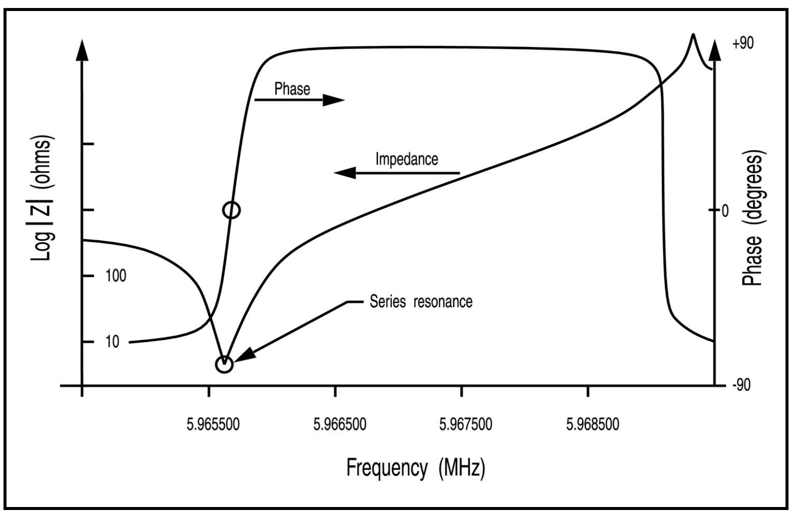
Figure 9-5 Heavily Loaded Crystal



The crystal has lost the steep slope displayed in Figure 9-6. Because the phase slope is less steep, any noise in the oscillator circuit translates into a greater frequency shift than that which would be produced with a new crystal. In the extreme, the basic phase/frequency shape is not preserved and the crystal is not able to provide a full 90 degrees of phase shift.

Figure 9-6 Crystal Frequency Near Series Resonance Point



The impedance, |Z|, is also noted to rise to an extremely high value. When this happens it is often more favorable for the oscillator to resonate at one of the anharmonic frequencies. This condition is sometimes short lived, with the oscillator switching between the fundamental and anharmonic modes, or it may continue to oscillate at the anharmonic. This condition is known as mode hopping and in addition to annoying rate noise can also lead to false termination of the film because of the apparent frequency change. It is important to note that the SQM-242 will frequently continue to operate under these conditions; in fact there is no way to tell this has happened except that the film's thickness is suddenly apparently thinner by an amount equivalent to the frequency difference between the fundamental and the anharmonic that is sustaining the oscillation.

9.1.5 Control Loop Theory

The instrumental advances in measurement speed, precision and reliability would not be complete without a means of translating this improved information into improved process control. For a deposition process, this means keeping the deposition rate as close as possible to the desired rate. The purpose of a control loop is to take the information flow from the measurement system and to make power corrections that are appropriate to the characteristics of the particular evaporation source. When properly operating, the control system translates small errors in the controlled parameter, or rate, into the appropriate corrections in the manipulated parameter, power. The controller's ability to quickly and accurately measure and then react appropriately to the small changes keeps the process from deviating very far from the set point.

The controller model most commonly chosen for converting error into action is called PID. In the PID, P stands for proportional, I stands for integral and D stands for derivative action. Certain aspects of this model will be examined in detail a little further on. The responsiveness of an evaporation source can be found by repetitively observing the system response to a disturbance under a particular set of controller settings. After observing the response, improved controller parameters are estimated and then tried again until satisfactory control is obtained. Control, when it is finally optimized, essentially matches the parameters of the controller model to the characteristics of the evaporation source.

Techniques for calculating optimum source control parameters can be classified by the type of data used for tuning. They fall into basically three categories:

- Closed Loop Methods
- Open Loop Methods
- Frequency Response Methods

Of these categories, the open loop methods are considered superior. They are considered superior because of the ease with which the necessary experimental data can be obtained and because of the elimination (to a large extent) of trial and error when the technique is applied. The important response characteristics are determined as shown in Figure 9-7.

In general, it is not possible to characterize all processes exactly; some approximation must be applied. The most common is to assume that the dynamic characteristics of the process can be represented by a first-order lag plus a dead time. The Laplace transform for this model (conversion to the s domain) is approximated as:

$$\frac{\text{Output}}{\text{Input}} = \frac{K_p \exp(-Ls)}{T_1 s + 1} \qquad [10]$$

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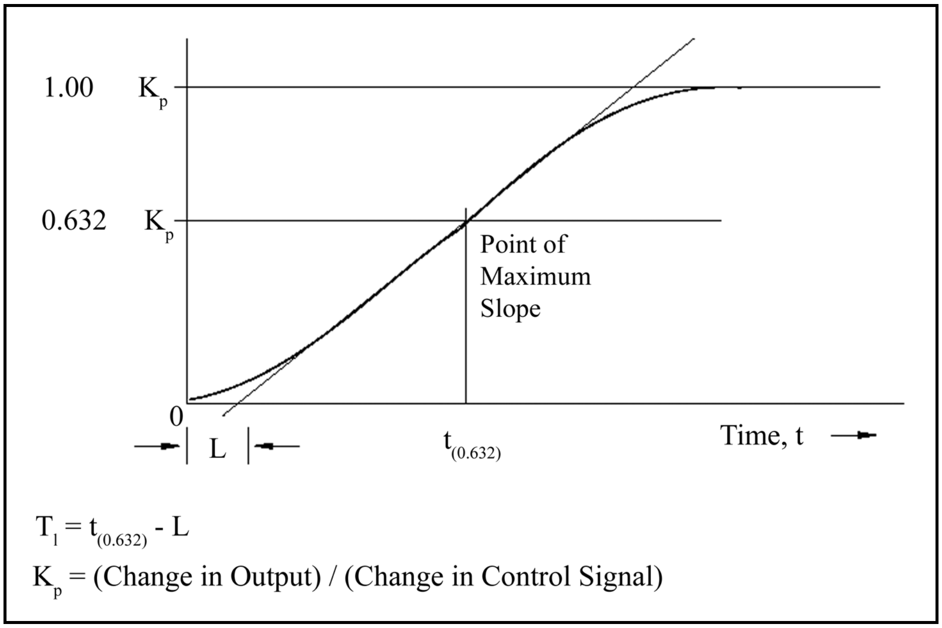
Three parameters are determined from the process reaction curve. They are the steady state gain, K_p, the dead time, L, and the time constant, T_1. Several methods have been proposed to extract the required parameters from the system response as graphed in Figure 9-7. These are: a one point fit at 63.2% of the transition (one time constant); a two point exponential fit; and a weighted least-square-exponential fit. From the above information a process is sufficiently characterized so that a controller algorithm may be customized.

Figure 9-7 Response of Process To An Open Loop Step Change (At t=0 Control Signal is Increased)



A controller model used extensively is the PID type, shown in Laplace form in equation [11].

$$M(s) = K_c\left(1 + \frac{1}{T_i s} + T_d s\right)Es \qquad [11]$$

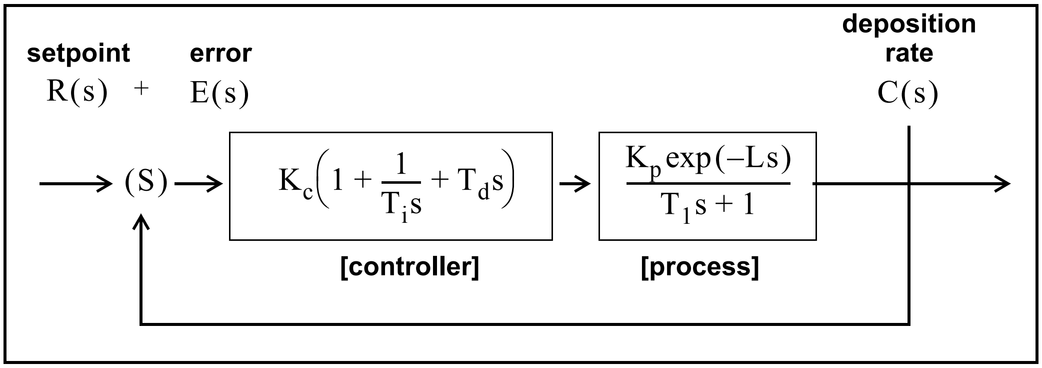
Where

- M(s) = manipulated variable or power
- K_c = controller gain (the proportional term)
- T_i = integral time
- T_d = derivative time
- E(s) = process error

Figure 9-8 represents the controller algorithm and a process with first order lag plus a dead time. The process block implicitly includes the dynamics of the measuring devices and the final control elements, in our case the evaporator power supply.

R(s) represents the rate setpoint. The feedback mechanism is the error generated by the difference between the measured deposition rate, C(s), and the rate set point, R(s).

Figure 9-8 PID Controller Block Diagram



The key to using any control system is to choose the proper values of K_c, T_d and T_i. Optimum control is a somewhat subjective quantity as noted by the presence of several mathematical definitions as shown below.

The Integral of the Squared Error (ISE) is a commonly proposed criterion of performance for control systems.

It can be described as:

$$ISE = \int e^2(t)dt \quad [12]$$

where error = e = setpoint minus the measured rate. The ISE measure is relatively insensitive to small errors, but large errors contribute heavily to the value of the integral. Consequently, using ISE as a criterion of performance will result in responses with small overshoots but long settling times, since small errors occurring late in time contribute little to the integral.

The Integral of the Absolute Value of the error (IAE) has been frequently proposed as a criterion of performance:

$$IAE = \int |e(t)|dt \quad [13]$$

This criterion is more sensitive to small errors, but less sensitive to large errors, than ISE.

Graham and Lathrop[7] introduced the Integral of Time multiplied by the Absolute Error (ITAE) as an alternate criterion of performance:

$$ITAE = \int t|e(t)|dt \quad [14]$$

7.Graham, D., and Lanthrop, R.C., “The Synthesis of Optimum Transient Response: Criteria and Standard Forms, Transactions IEEE, vol. 72 pt. II, November 1953.

ITAE is insensitive to the initial and somewhat unavoidable errors, but it will weight heavily any errors occurring late in time. Optimum responses defined by ITAE will consequently show short total response times and larger overshoots than with either of the other criteria. It has been found that this criteria is generally most useful for deposition process control.

The most satisfactory performance criterion for deposition controllers is the ITAE. There will be overshoot, but the response time is quick, and the settling time is short. For all of the above integral performance criteria, controller tuning relations have been developed to minimize the associated errors. Using manually entered or experimentally determined process response coefficients, ideal PID controller coefficients can be readily calculated for the ITAE criteria as shown below.

$$K_c = (1.36/K_p)(L/T_1)^{-0.947} \quad [15]$$

$$T_i = (1.19T_1)(L/T_1)^{0.738} \quad [16]$$

$$T_d = (0.381T_1)(L/T_1)^{0.995} \quad [17]$$

For slow systems, in order to help avoid controller windup (windup is the rapid increase in control signal before the system has the chance to respond to the changed signal), the time period between manipulated variable (control voltage) changes is lengthened. This allows the system to respond to the previous controller setting change, and aggressive controller settings can be used. A secondary advantage is that immunity to process noise is increased since the data used for control is now comprised of multiple readings instead of a single rate measurement, taking advantage of the mass integrating nature of the quartz crystal.

With process systems that respond quickly (short time constant) and with little to no measurable dead time, the PID controller often has difficulty with the deposition process noise (beam sweep, fast thermal shorts of melt to crucible, etc.). In these situations a control algorithm used successfully is an integral/reset type of controller. This type of controller will always integrate the error, driving the system towards zero error. This technique works well when there is little or no dead time. If this technique is used on a process with measurable lag or dead time, then the control loop will tend to be oscillatory due to the control loop over-compensating the control signal before the system has a chance to respond.

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Appendix A
Material Table

A.1 Introduction

The following Table A-1 represents the density and Z-ratio for various materials. The list is alphabetical by chemical formula.

CAUTION

Some of these materials are toxic. Please consult the material safety data sheet and safety instructions before use.

An * is used to indicate that a Z-ratio has not been established for a given material. A value of 1.000 is defaulted in these situations. Density is given in g·cm^{-3}.

Table A-1 Material Table

Formula	Density	Z-Ratio	Material Name
Ag	10.500	0.529	Silver
AgBr	6.470	1.180	Silver Bromide
AgCl	5.560	1.320	Silver Chloride
Al	2.700	1.080	Aluminum
Al_2O_3	3.970	0.336	Aluminum Oxide
Al_4C_3	2.360	*1.000	Aluminum Carbide
AlF_3	3.070	*1.000	Aluminum Fluoride
AlN	3.260	*1.000	Aluminum Nitride
AlSb	4.360	0.743	Aluminum Antimonide
As	5.730	0.966	Arsenic
As_2Se_3	4.750	*1.000	Arsenic Selenide
Au	19.300	0.381	Gold
B	2.370	0.389	Boron
B_20_3	1.820	*1.000	Boron Oxide
B_4C	2.370	*1.000	Boron Carbide
BN	1.860	*1.000	Boron Nitride
Ba	3.500	2.100	Barium
BaF_2	4.886	0.793	Barium Fluoride

Table A-1 Material Table (continued)

Formula	Density	Z-Ratio	Material Name
BaN_2O_6	3.244	1.261	Barium Nitrate
BaO	5.720	*1.000	Barium Oxide
$BaTiO_3$	5.999	0.464	Barium Titanate (Tetr)
$BaTiO_3$	6.035	0.412	Barium Titanate (Cubic)
Be	1.850	0.543	Beryllium
BeF_2	1.990	*1.000	Beryllium Fluoride
BeO	3.010	*1.000	Beryllium Oxide
Bi	9.800	0.790	Bismuth
Bi_2O_3	8.900	*1.000	Bismuth Oxide
Bi_2S_3	7.390	*1.000	Bismuth Trisulphide
Bi_2Se_3	6.820	*1.000	Bismuth Selenide
Bi_2Te_3	7.700	*1.000	Bismuth Telluride
BiF_3	5.320	*1.000	Bismuth Fluoride
C	2.250	3.260	Carbon (Graphite)
C	3.520	0.220	Carbon (Diamond)
C_8H_8	1.100	*1.000	Parlyene (Union Carbide)
Ca	1.550	2.620	Calcium
CaF_2	3.180	0.775	Calcium Fluoride
CaO	3.350	*1.000	Calcium Oxide
$CaO\text{-}SiO_2$	2.900	*1.000	Calcium Silicate (3)
$CaSO_4$	2.962	0.955	Calcium Sulfate
$CaTiO_3$	4.100	*1.000	Calcium Titanate
$CaWO_4$	6.060	*1.000	Calcium Tungstate
Cd	8.640	0.682	Cadmium
CdF_2	6.640	*1.000	Cadmium Fluoride
CdO	8.150	*1.000	Cadmium Oxide
CdS	4.830	1.020	Cadmium Sulfide
CdSe	5.810	*1.000	Cadmium Selenide
CdTe	6.200	0.980	Cadmium Telluride
Ce	6.780	*1.000	Cerium
CeF_3	6.160	*1.000	Cerium (III) Fluoride
CeO_2	7.130	*1.000	Cerium (IV) Dioxide
Co	8.900	0.343	Cobalt

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Table A-1 Material Table (continued)

Formula	Density	Z-Ratio	Material Name
CoO	6.440	0.412	Cobalt Oxide
Cr	7.200	0.305	Chromium
Cr_2O_3	5.210	*1.000	Chromium (III) Oxide
Cr_3C_2	6.680	*1.000	Chromium Carbide
CrB	6.170	*1.000	Chromium Boride
Cs	1.870	*1.000	Cesium
Cs_2SO_4	4.243	1.212	Cesium Sulfate
CsBr	4.456	1.410	Cesium Bromide
CsCl	3.988	1.399	Cesium Chloride
CsI	4.516	1.542	Cesium Iodide
Cu	8.930	0.437	Copper
Cu_2O	6.000	*1.000	Copper Oxide
Cu_2S	5.600	0.690	Copper (I) Sulfide (Alpha)
Cu_2S	5.800	0.670	Copper (I) Sulfide (Beta)
CuS	4.600	0.820	Copper (II) Sulfide
Dy	8.550	0.600	Dysprosium
DY_2O_3	7.810	*1.000	Dysprosium Oxide
Er	9.050	0.740	Erbium
Er_2O_3	8.640	*1.000	Erbium Oxide
Eu	5.260	*1.000	Europium
EuF_2	6.500	*1.000	Europium Fluoride
Fe	7.860	0.349	Iron
Fe_2O_3	5.240	*1.000	Iron Oxide
FeO	5.700	*1.000	Iron Oxide
FeS	4.840	*1.000	Iron Sulphide
Ga	5.930	0.593	Gallium
Ga_2O_3	5.880	*1.000	Gallium Oxide (B)
GaAs	5.310	1.590	Gallium Arsenide
GaN	6.100	*1.000	Gallium Nitride
GaP	4.100	*1.000	Gallium Phosphide
GaSb	5.600	*1.000	Gallium Antimonide
Gd	7.890	0.670	Gadolinium
Gd_2O_3	7.410	*1.000	Gadolinium Oxide

Table A-1 Material Table (continued)

Formula	Density	Z-Ratio	Material Name
Ge	5.350	0.516	Germanium
Ge_3N_2	5.200	*1.000	Germanium Nitride
GeO_2	6.240	*1.000	Germanium Oxide
GeTe	6.200	*1.000	Germanium Telluride
Hf	13.090	0.360	Hafnium
HfB_2	10.500	*1.000	Hafnium Boride
HfC	12.200	*1.000	Hafnium Carbide
HfN	13.800	*1.000	Hafnium Nitride
HfO_2	9.680	*1.000	Hafnium Oxide
$HfSi_2$	7.200	*1.000	Hafnium Silicide
Hg	13.460	0.740	Mercury
Ho	8.800	0.580	Holminum
Ho_2O_3	8.410	*1.000	Holminum Oxide
In	7.300	0.841	Indium
In_2O_3	7.180	*1.000	Indiurn Sesquioxide
In_2Se_3	5.700	*1.000	Indium Selenide
In_2Te_3	5.800	*1.000	Indium Telluride
InAs	5.700	*1.000	Indium Arsenide
InP	4.800	*1.000	Indium Phosphide
InSb	5.760	0.769	Indium Antimonide
Ir	22.400	0.129	Iridium
K	0.860	10.189	Potassium
KBr	2.750	1.893	Potassium Bromide
KCl	1.980	2.050	Potassium Chloride
KF	2.480	*1.000	Potassium Fluoride
KI	3.128	2.077	Potassium Iodide
La	6.170	0.920	Lanthanum
La_2O_3	6.510	*1.000	Lanthanum Oxide
LaB_6	2.610	*1.000	Lanthanurn Boride
LaF_3	5.940	*1.000	Lanthanum Fluoride
Li	0.530	5.900	Lithium
LiBr	3.470	1.230	Lithium Bromide
LiF	2.638	0.778	Lithium Fluoride

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Table A-1 Material Table (continued)

Formula	Density	Z-Ratio	Material Name
$LiNbO_3$	4.700	0.463	Lithium Niobate
Lu	9.840	*1.000	Lutetium
Mg	1.740	1.610	Magnesium
$MgAl_2O_4$	3.600	*1.000	Magnesium Aluminate
$MgAl_2O_6$	8.000	*1.000	Spinel
MgF_2	3.180	0.637	Magnesium Fluoride
MgO	3.580	0.411	Magnesium Oxide
Mn	7.200	0.377	Manganese
MnO	5.390	0.467	Manganese Oxide
MnS	3.990	0.940	Manganese (II) Sulfide
Mo	10.200	0.257	Molybdenum
Mo_2C	9.180	*1.000	Molybdenum Carbide
MoB_2	7.120	*1.000	Molybdenum Boride
MoO_3	4.700	*1.000	Molybdenum Trioxdide
MoS_2	4.800	*1.000	Molybdenum Disulfide
Na	0.970	4.800	Sodium
Na_3AlF_6	2.900	*1.000	Cryolite
$Na_5Al_3F_{14}$	2.900	*1.000	Chiolite
NaBr	3.200	*1.000	Sodium Bromide
NaCl	2.170	1.570	Sodium Chloride
$NaClO_3$	2.164	1.565	Sodium Chlorate
NaF	2.558	1.645	Sodium Fluoride
$NaNO_3$	2.270	1.194	Sodium Nitrate
Nb	8.578	0.492	Niobium (Columbium)
Nb_2O_3	7.500	*1.000	Niobium Trioxide
Nb_2O_5	4.470	*1.000	Niobium (V) Oxide
NbB_2	6.970	*1.000	Niobium Boride
NbC	7.820	*1.000	Niobium Carbide
NbN	8.400	*1.000	Niobium Nitride
Nd	7.000	*1.000	Neodynium
Nd_2O_3	7.240	*1.000	Neodynium Oxide
NdF_3	6.506	*1.000	Neodynium Fluoride
Ni	8.910	0.331	Nickel

Table A-1 Material Table (continued)

Formula	Density	Z-Ratio	Material Name
NiCr	8.500	*1.000	Nichrome
NiCrFe	8.500	*1.000	Inconel
NiFe	8.700	*1.000	Permalloy
NiFeMo	8.900	*1.000	Supermalloy
NiO	7.450	*1.000	Nickel Oxide
P_3N_5	2.510	*1.000	Phosphorus Nitride
Pb	11.300	1.130	Lead
$PbCl_2$	5.850	*1.000	Lead Chloride
PbF_2	8.240	0.661	Lead Fluoride
PbO	9.530	*1.000	Lead Oxide
PbS	7.500	0.566	Lead Sulfide
PbSe	8.100	*1.000	Lead Selenide
$PbSnO_3$	8.100	*1.000	Lead Stannate
PbTe	8.160	0.651	Lead Telluride
Pd	12.038	0.357	Palladium
PdO	8.310	*1.000	Palladium Oxide
Po	9.400	*1.000	Polonium
Pr	6.780	*1.000	Praseodymium
Pr_2O_3	6.880	*1.000	Praseodymium Oxide
Pt	21.400	0.245	Platinum
PtO_2	10.200	*1.000	Platinum Oxide
Ra	5.000	*1.000	Radium
Rb	1.530	2.540	Rubidium
RbI	3.550	*1.000	Rubidiurn Iodide
Re	21.040	0.150	Rhenium
Rh	12.410	0.210	Rhodium
Ru	12.362	0.182	Ruthenium
S_8	2.070	2.290	Sulphur
Sb	6.620	0.768	Antimony
Sb_2O_3	5.200	*1.000	Antimony Trioxide
Sb_2S_3	4.640	*1.000	Antimony Trisulfide
Sc	3.000	0.910	Scandium
Sc_2O_3	3.860	*1.000	Scandium Oxide

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Table A-1 Material Table (continued)

Formula	Density	Z-Ratio	Material Name
Se	4.810	0.864	Selenium
Si	2.320	0.712	Silicon
Si_3N_4	3.440	*1.000	Silicon Nitride
SiC	3.220	*1.000	Silicon Carbide
SiO	2.130	0.870	Silicon (II) Oxide
SiO_2	2.648	1.000	Silicon Dioxide
Sm	7.540	0.890	Samarium
Sm_2O_3	7.430	*1.000	Samarium Oxide
Sn	7.300	0.724	Tin
SnO_2	6.950	*1.000	Tin Oxide
SnS	5.080	*1.000	Tin Sulfide
SnSe	6.180	*1.000	Tin Selenide
SnTe	6.440	*1.000	Tin Telluride
Sr	2.600	*1.000	Strontium
SrF_2	4.277	0.727	Strontium Fluroide
SrO	4.990	0.517	Strontium Oxide
Ta	16.600	0.262	Tantalum
Ta_2O_5	8.200	0.300	Tantalum (V) Oxide
TaB_2	11.150	*1.000	Tantalum Boride
TaC	13.900	*1.000	Tantalum Carbide
TaN	16.300	*1.000	Tantalum Nitride
Tb	8.270	0.660	Terbium
Tc	11.500	*1.000	Technetium
Te	6.250	0.900	Tellurium
TeO_2	5.990	0.862	Tellurium Oxide
Th	11.694	0.484	Thorium
ThF_4	6.320	*1.000	Thorium.(IV) Fluoride
ThO_2	9.860	0.284	Thorium Dioxide
$ThOF_2$	9.100	*1.000	Thorium Oxyfluoride
Ti	4.500	0.628	Titanium
Ti_20_3	4.600	*1.000	Titanium Sesquioxide
TiB_2	4.500	*1.000	Titanium Boride
TiC	4.930	*1.000	Titanium Carbide

Table A-1 Material Table (continued)

Formula	Density	Z-Ratio	Material Name
TiN	5.430	*1.000	Titanium Nitride
TiO	4.900	*1.000	Titanium Oxide
TiO_2	4.260	0.400	Titanium (IV) Oxide
TI	11.850	1.550	Thallium
TIBr	7.560	*1.000	Thallium Bromide
TICI	7.000	*1.000	Thallium Chloride
TII	7.090	*1.000	Thalliurn Iodide (B)
U	19.050	0.238	Uranium
U_3O_8	8.300	*1.000	Tri Uranium Octoxide
U_4O_9	10.969	0.348	Uranium Oxide
UO_2	10.970	0.286	Uranium Dioxide
V	5.960	0.530	Vanadium
V_2O_5	3.360	*1.000	Vanadium Pentoxide
VB_2	5.100	*1.000	Vanadium Boride
VC	5.770	*1.000	Vanadium Carbide
VN	6.130	*1.000	Vanadium Nitride
VO_2	4.340	*1.000	Vanadium Dioxide
W	19.300	0.163	Tungsten
WB_2	10.770	*1.000	Tungsten Boride
WC	15.600	0.151	Tungsten Carbide
WO_3	7.160	*1.000	Tungsten Trioxide
WS_2	7.500	*1.000	Tungsten Disulphide
WSi_2	9.400	*1.000	Tungsten Silicide
Y	4.340	0.835	Yttrium
Y_20_3	5.010	*1.000	Yttrium Oxide
Yb	6.980	1.130	Ytterbium
Yb_2O_3	9.170	*1.000	Ytterbium Oxide
Zn	7.040	0.514	Zinc
Zn_3Sb_2	6.300	*1.000	Zinc Antimonide
ZnF_2	4.950	*1.000	Zinc Fluoride
ZnO	5.610	0.556	Zinc Oxide
ZnS	4.090	0.775	Zinc Sulfide
ZnSe	5.260	0.722	Zinc Selenide

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Table A-1 Material Table (continued)

Formula	Density	Z-Ratio	Material Name
ZnTe	6.340	0.770	Zinc Telluride
Zr	6.490	0.600	Zirconium
ZrB_2	6.080	*1.000	Zirconium Boride
ZrC	6.730	0.264	Zirconium Carbide
ZrN	7.090	*1.000	Zirconium Nitride
ZrO_2	5.600	*1.000	Zirconium Oxide

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