Operating Manual

IMM-200

074-733-P1A

INFICON

Two Technology Place

East Syracuse, NY 13057-9714

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1 Disclaimer and Copyrights

Disclaimer

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2 Declaration of Conformity

INFICON

EU DECLARATION OF CONFORMITY

This declaration is issued under the sole responsibility of the manufacturer INFICON. The object of the declaration is to certify that this equipment, designed and manufactured by:

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

is in conformity with the relevant Community harmonization legislation. 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: IMM-200 Thin Film Deposition Monitor

Applicable Directives:
2014/35/EU (LVD)
2014/30/EU (EMC)
2011/65/EU (RoHS)

Applicable Standards:

Safety: EN 61010-1:2010 Safety Requirements for Electrical Equipment For Measurement, Control, and Laboratory Use.
Part 1: General Requirements

Emissions: EN 61326-1:2013 (Radiated & Conducted Emissions)
(EMC – Measurement, Control & Laboratory Equipment)
EN 55011:2009/A1:2010 Group 1, Class A
ICES-001 Issue 4 ISM emissions requirements (Canada)
FCC 47 CFR Part 18 Class A emission requirement (USA)

Immunity: EN 61326-1:2013(General EMC)
Class A: Immunity
(EMC – Measurement, Control & Laboratory Equipment)

RoHS: Fully compliant

CE Implementation Date: February 26, 2020

Authorized Representatives:

Oliver Wyrsch
President, ISS

Hjalmar Bruhns, Ph.D.
VP of R&D, ISS

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.

3 Warranty

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No warranty is made by Seller of any Seller product which has been installed, used or operated contrary to Seller's written instruction manual or which has been subjected to misuse, negligence or accident or has been repaired or altered by anyone other than Seller or which has been used in a manner or for a purpose for which the Seller product was not designed nor against any defects due to plans or instructions supplied to Seller by or for Buyer.

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

4 Introduction and Specifications

Designed for use in vapor deposition processes, IMM-200 is a deposition monitor used to determine the *in situ* deposition rate and thickness of a thin film. Rate and thickness are inferred from the frequency change induced by mass added to an exposed oscillating quartz crystal. This quartz crystal is housed in a sensor body positioned between, or to the side of, the source of vaporized material and the target substrate.

User interaction is accomplished via remote communication and consists of the selection or entry of parameters to define the material and instrument characteristics. A complete QCM system consists of an electronics unit, also called IMM-200, a power supply, a sensor head containing a quartz crystal and software to communicate to IMM-200. This IMM-200 Operating Manual provides user information for installing, programming and operating IMM-200. When reading the Operating Manual, please pay particular attention to the Notes, Cautions, and Warnings found throughout the text. The Notes, Cautions, and Warnings are defined in Definition of Notes, Cautions, Warnings, and Dangers [▸ 12]. You are invited to comment on the usefulness and accuracy of this manual by visiting our website at www.inficon.com.

4.1 Specifications

Measurement

Sensor inputs	One
Measurement frequency range	6.0 MHz (new crystal) to 4.5 MHz
Reference frequency stability	±2 ppm 0–60°C
Frequency resolution	0.0035 Hz per 100 ms
Rate and thickness resolution	0.0042 Å (new crystal); 0.0076 Å (crystal @ 4.5 MHz) over 100 ms sample for an AT cut crystal, material density = 1.0, Z-Ratio = 1.0
Measurement interval	100 ms
Measurement technique	ModeLock

Configuration Parameters

Material name	29 character string
Density	0.40–99.99 g/cm³
Z-Ratio	0.100–9.999
Tooling	10.0–999.9%
Crystal type	AT, BT, SC, and IT crystal cuts supported
Maximum thickness	0.000–9999.9 kÅ
Rate filter time	0.0-30.0 s in 0.1 s increments
AC line frequency	0 = 50 Hz, 1 = 60 Hz

Remote Communications Status

Time stamp	Indicates timestamp tick, updated 10 times per second
Time stamp warning	0 = none, 1 = timestamp at its maximum value
Unit status	0 = unknown/error, 1 = measure, 2 = idle, 100 = reserved, 101 = reserved, 102 = reserved
Frequency	4.5 MHz to 6.0 MHz
Raw rate	Measured rate updated every 100 ms expressed in Å/s
Rate filtered	Raw rate value averaged over the rate filter time updated every 100 ms
Thickness	Calculated thickness expressed in kÅ, updated once every 100 ms
Deposition status	0 = thickness < maximum thickness, 1 = thickness ≥ maximum thickness, 98 = unknown, 99 = not in measure
Activity	0 to 820
Crystal life	0 to 100%
Crystal status	0 = initializing, 1 = good, 2 = marginal, 3 = failure, 98 = unknown, 99 = not in measure
User timer	64 bit unsigned value expressed in µs
Communication status	0 = none, 1 = warning, device not responding, 2 = error, device not responding

Remote Communications Commands

Start/Stop measure	Starts or stops the instrument from measuring frequency
Zero thickness	Zeros the material thickness

	Zero timer	Zeros the user timer
	Zero thickness and timer	Simultaneously zeros both the thickness and the user timer
	Default parameters	Resets all parameter values to their default values
	Store parameters	Stores all parameters to non-volatile memory
	Calculate checksum	Calculates the checksum of all writable, non-volatile parameters currently stored in non-volatile memory
Communications	Communication type	Ethernet, 1 RJ45 jack
	Protocol	P3 Plus
	Cable length	<100 m
LED Indicators	Status	Unit status
Operating Environment	Usage	Indoor only
	Humidity	Up to 85% RH, non-condensing
	Temperature	0–50°C (32–122°F)
	Altitude	Up to 2000 m
	Installation (overvoltage)	Category II per IEC 60664
	Pollution degree	2 per EN 61010
	Storage temperature	-10–60°C (14–140°F)
	Cleaning	Use a mild, nonabrasive cleaner or detergent taking care to prevent the cleaner from entering the unit
Physical Dimensions	Size	222.6 mm (8.76 in.) x 106.1 mm (4.18 in.) x 35.3 mm (1.39 in.)
	Weight	0.48 kg (1.06 lbs.)
Power	Input voltage	24 V (dc)
	Power consumption	12 W
	Fuse	30 V (dc), 2.5 A, internal, self-resetting
	Temporary overvoltages	per CE requirements
	Warm-up period	None required, up to 15 minutes for maximum stability

4.2 Safety

4.2.1 Definition of Notes, Cautions, Warnings, and Dangers

When using this manual, please pay attention to the Notes, Cautions, Warnings, and Dangers found throughout. For the purposes of this manual they are defined as follows:

Pertinent information that is useful in achieving maximum IMM-200 efficiency when followed.

⚠ CAUTION

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

⚠ WARNING

This symbol alerts the user to the presence of important operating and maintenance (servicing) instructions.

⚠ DANGER

Immediate danger, death, or very severe injuries can occur.

⚠ DANGER

Risk of Electric Shock

Dangerous voltages are present which could result in personal injury.

4.2.2 General Safety Information

⚠ CAUTION

Do not use the product in a manner not specified by the manufacturer.

If used in a manner not specified by the manufacturer protection provided by the equipment may be impaired.

⚠ CAUTION

The instrument contains delicate circuitry which is susceptible to transient power line voltages. Disconnect power whenever making any interface connections. Refer all maintenance to qualified personnel.

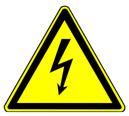
⚠ DANGER

Risk of Electric Shock

There are no user-serviceable components within the IMM-200 case. Potentially lethal voltages are present. Refer all maintenance to qualified personnel.

4.2.3 Earth Ground

When using the optional power supply, IMM-200 is connected to earth ground through a sealed three-core (three-conductor) power cable, which must be plugged into a socket outlet with a protective earth terminal. If an extension cable is used, it must always have three conductors, including a protective earth terminal. If a user supplied power supply is used, the power supply connector must have a shield which is grounded to AC line ground.



⚠ DANGER

Warning of Electrical Shock

Never interrupt the protective earth circuit. Any interruption of the protective earth circuit inside or outside IMM-200 or disconnection of the protective earth terminal may cause dangerous voltages to be present on or inside IMM-200.

This symbol indicates where the protective earth ground is connected inside IMM-200. Never unscrew or loosen this connection.

4.3 How to Contact Us

Worldwide customer support information is available under Support at www.INFICON.com where you can contact:

- a Product Engineer with questions regarding applications for and programming IMM-200
- a Service Engineer with questions regarding troubleshooting, diagnosing or repairing IMM-200
- Sales and Customer Service, to find the INFICON Sales office nearest to you
- Repair Service, to find the INFICON Service Center nearest to you

If you are experiencing a problem with your IMM-200, please have the following information readily available:

- the serial number and IMM-200 software version numbers
- 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 may have received

4.3.1 Returning the Product

Do not return any component of IMM-200 to INFICON without first speaking with a Customer Support Representative. Obtain a Return Material Authorization (RMA) number from the Customer Support Representative. If a package is sent to INFICON without an RMA number, the package will be held and the sender will be contacted. This will result in delays in servicing IMM-200. Prior to being given an RMA number, a Declaration Of Contamination (DOC) form may need to be completed if the product has been exposed to process materials. DOC forms must be approved by INFICON before an RMA number is issued. INFICON may require the product be sent to a designated decontamination facility, not to the factory.

4.4 Unpacking and Inspection

✓ If IMM-200 has not been removed from its shipping container, do so now.

1. Carefully examine IMM-200 for damage that may have occurred during shipping. This is especially important if rough handling on the outside of the container is noticed. Immediately report any damage to the carrier and to INFICON.
   ⇨ Do not discard the packing materials until an inventory has been taken and at least a power-on verification has been performed.
2. Take an inventory of the order by referring to the order invoice.

3 To perform a power-on verification, see Initial Power-On Verification.

4 For additional information or technical assistance, contact INFICON, refer to How to Contact Us [▸ 15].

4.5 Parts and Options Overview

IMM-200 Part Number 785-602-G1

Optional Power Supply Part Numbers The power supplies listed below are rated for an input of 100 to 249 V (ac), 2 A, 50 to 60 Hz with an output of 24 V (dc), 3.34 A, 80 W maximum.

Part Number	Description
961-021-G1	Power supply kit US 120 V
961-021-G2	Power supply kit US with 4.5 m (14.8 ft.) power cord extension
961-021-G3	Power supply kit US with 9.0 m (29.5 ft.) power cord extension
961-021-G4	Power supply kit 230 V
961-021-G5	Power supply kit 230 V with 4.5 m (14.8 ft.) power cord extension
961-021-G6	Power supply kit 230 V with 9.0 m (29.5 ft.) power cord extension
961-021-G7	Power supply kit IL 240 V
961-021-G8	Power supply kit IL with 4.5 m (14.8 ft.) power cord extension
961-021-G9	Power supply kit IL with 9.0 m (29.5 ft.) power cord extension
961-021-G10	Power supply kit UK 240 V
961-021-G11	Power supply kit UK with 4.5 m (14.8 ft.) power cord extension
961-021-G12	Power supply kit UK with 9.0 m (29.5 ft.) power cord extension

Optional Mounting Bracket Part Number 785-201-G1: IMM-200 mounting bracket with four shock absorbing, male-to-female, black neoprene rubber mounting feet.

785-202-G1: IMM-200 mounting bracket with four clean room compatible shock absorbing, female-to-female, stainless steel mounting feet.

Optional Communications Cable Part Number

Part Number	Description
600-1190-P4	Ethernet communication cable, 4.3 m (14.1 ft.)
600-1190-P8	Ethernet communication cable, 7.6 m (24.9 ft.)

Part Number	Description
600-1190-P15	Ethernet communication cable, 15.3 m (50.2 ft.)

4.5.1 Optional Mounting Bracket Kit

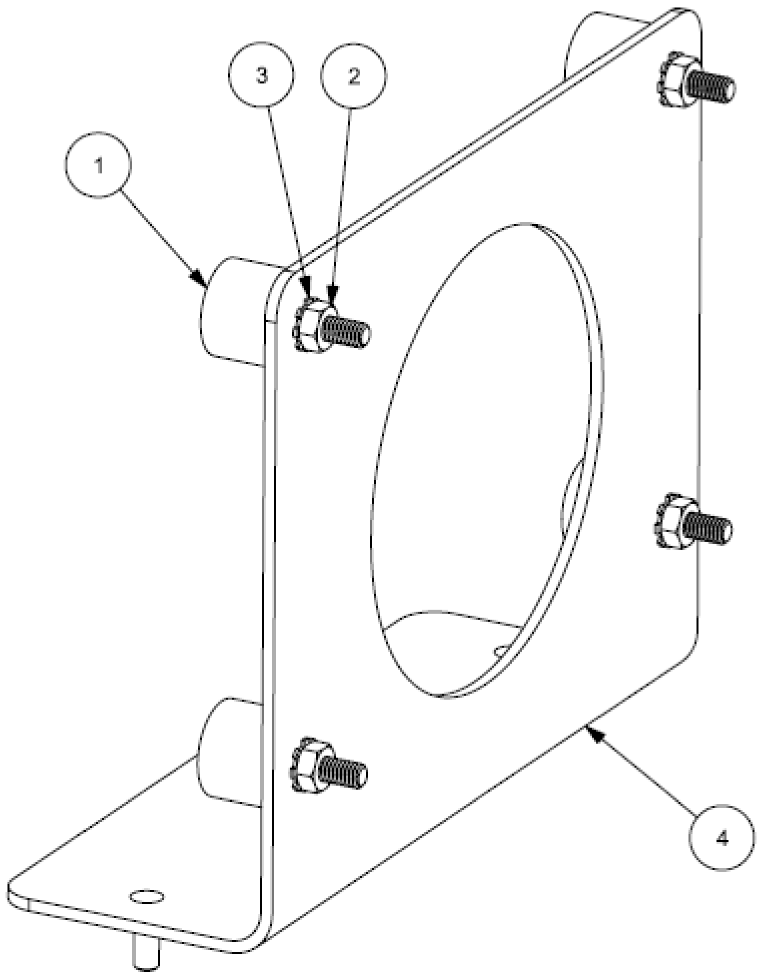
⚠ WARNING

The optional mounting bracket is not intended to be mounted on walls or ceilings.

Injury may occur if the mounting bracket falls from a wall or ceiling onto a person.

In systems with a high amount of vibration, using the optional mounting bracket with vibration isolating mounting feet will greatly reduce any influence vibration has on IMM-200.

The optional mounting bracket with the neoprene mounting feet is shown below (PN 785-201-G1). Item 1 shows the neoprene mounting feet 070-2104, item 2 is a stainless steel M4 hex nut, item 3 is a stainless steel M4 internal lock washer, and item 4 is the mounting bracket.



The mounting bracket may be positioned in any orientation and mounted to any surface, other than a wall or ceiling, able to withstand the combined weight of IMM-200 and the mounting bracket (approximately 0.68 kg (1.5 lbs.)).

NOTICE

When mounting IMM-200 into a fixed position, ensure there is enough room to disconnect the power cord when needed.

PN 070-2104 contains neoprene. If you are mounting IMM-200 and the mounting bracket in a clean room and neoprene is not compatible with your clean room, you can use the mounting bracket with stainless steel shock absorbing mounting feet, PN 785-202-G1.

4.6 Initial Power-On Verification

A preliminary functional check of IMM-200 can be made before installation. It is not necessary to have sensors or communication cables connected to do this.

The green IMM-200 **Status** light is used to identify if the unit is operating correctly, or if there is a failure condition.

Connect 24 V (dc) to the power connector using either one of the power supplies listed in Parts and Options Overview or a user supplied power supply with a power rating indicated by **Power**, in Specifications.

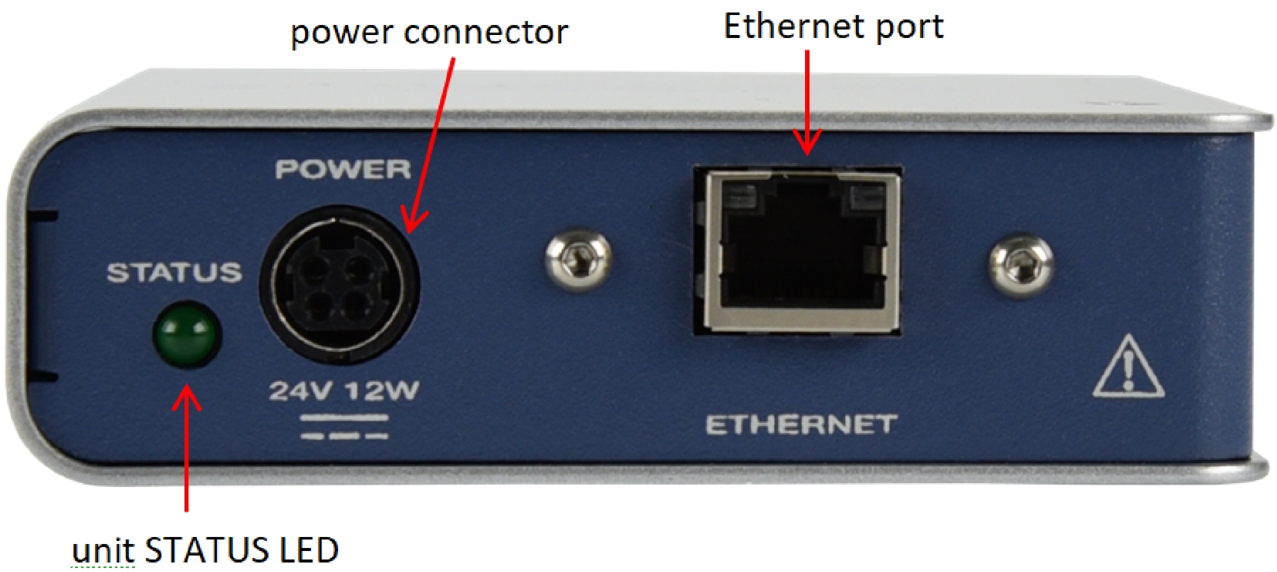
If a user supplied power supply is used, INFICON recommends the power connection to IMM-200 use a Kycon connector, part number KPPX-4P. Pins 3 and 4 carry +24 V (dc), pins 1 and 2 are ground. Whenever a user supplied power supply is used, the connector shield on the 24 V power cable must be connected to the mains protective earth ground terminal through the user supplied power supply.

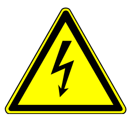
If a good crystal is connected, the **Status** LED illuminates and remains steadily on. This status indicates proper operation of IMM-200. If a good crystal is not connected, the **Status** LED illuminates 1 s on,1 s off, to indicate a crystal fail. IMM-200 is in **Idle** if the **Status** LED flash pattern is 1 s on, 4 s off.

If the **Status** LED has the following flash patterns, please contact INFICON as an error exists. To contact INFICON service, refer to How to Contact Us [▸ 15].

LED State	Description
0.5 s on, 0.2 s off, 0.5 s on, 1 s off	Invalid firmware or POST fail

If the **Status** LED is off, confirm that the proper power is connected to IMM-200. If the proper power is connected but the LED is still off, contact INFICON service.





⚠ WARNING

Do not open the instrument case. There are no user-serviceable components within the instrument case. Dangerous voltages may be present whenever power is present. Refer all maintenance to qualified personnel.

This symbol indicates where the protective earth ground is connected inside IMM-200. Never unscrew or loosen this connection.

5 Installation and Interfaces

Before permanently installing IMM-200, read this entire chapter. Follow the recommendations as closely as possible. INFICON has taken numerous steps to ensure its equipment will operate in a variety of harsh situations. Failure to adhere to these simple practices may adversely affect the performance and longevity of IMM-200.

NOTICE

Use caution when mounting IMM-200 to a fixed position. Ensure there is enough room to disconnect the power cord when needed.

5.1 Avoiding Electrical Interference

Careful consideration of simple electrical guidelines during installation avoids many problems caused by electrical noise. To maintain the required shielding and internal grounding and ensure safe and proper operation, IMM-200 must be operated with all enclosure covers, sub-panels, and braces in place and fully secured with the screws and fasteners provided.

Verifying / Establishing Earth Ground

If ground must be established, the following procedure is recommended:

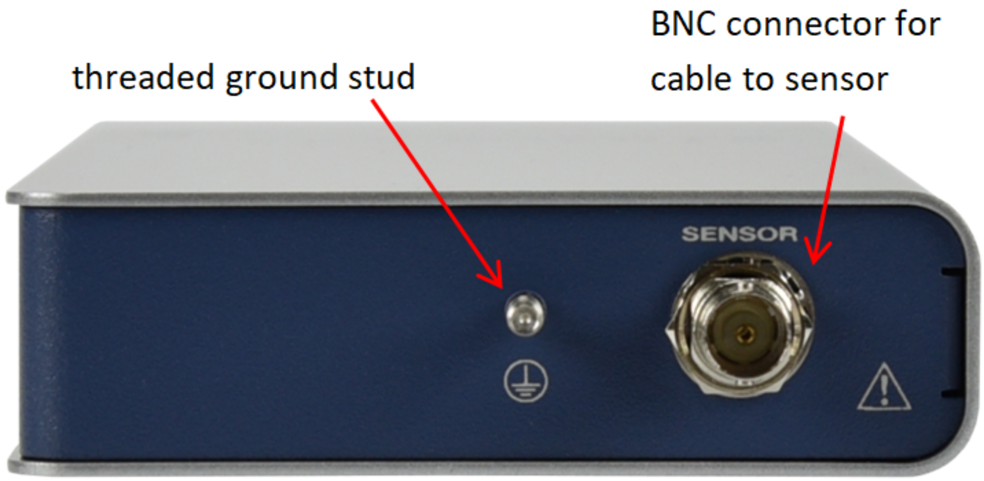
► Where soil conditions allow, drive two ten-foot copper clad steel rods into the ground six feet apart. Pour a copper sulfate or a salt solution around each rod to improve the ground's conduction. A near-zero resistance measurement indicates earth ground is achieved.

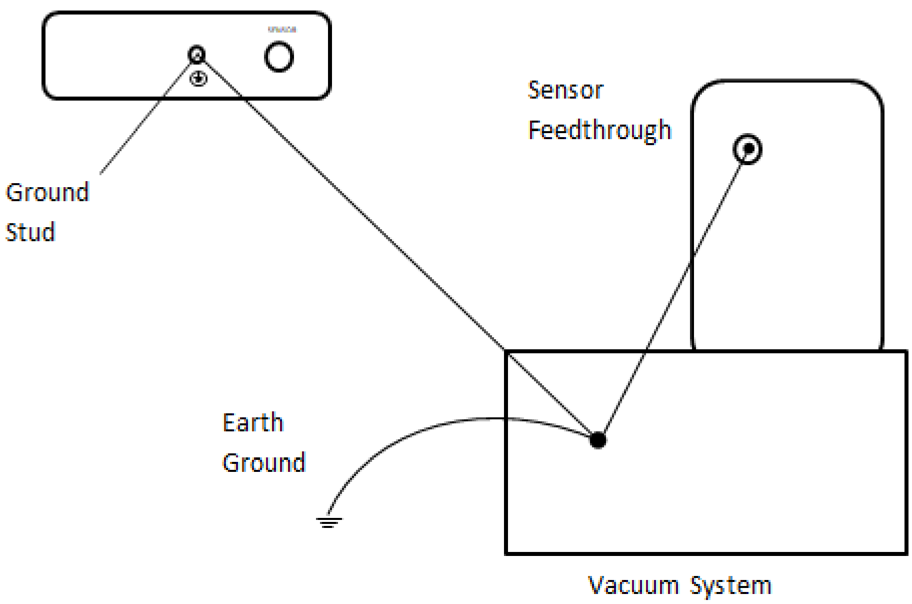
⇨ Keep the connections to this grounding network as short as possible.

Connections to Earth Ground

There are two required earth ground connections:

1. The earth ground connection on IMM-200 is a threaded stud with a hex nut. Connect a ring terminal to the ground strap, allowing a good connection and easy removal and installation. This connection must be made at installation. For best protection against high frequency noise, the length-to-width ratio of the earth conductor should not exceed a ratio of 5:1. The ground strap should connect from IMM-200 to the vacuum system as shown.





2. The instrument is also connected to earth ground through the 24 V power cable. The power supply is in turn connected to earth ground by the sealed three conductor power cable, which must be plugged into a socket outlet with a protective earth ground terminal. Extension cables must always have three conductors including a protective earth terminal.

   Whenever a user supplied power supply is used, the connector shield on the 24 V power cable must be connected to the mains protective earth ground terminal through the user supplied power supply.

⚠ DANGER

Warning of Electrical Shock

Never interrupt the protective earth circuit. Any interruption of the protective earth circuit inside or outside IMM-200 or disconnection of the protective earth terminal may cause dangerous voltages to be present on or inside IMM-200.

This symbol indicates where the protective earth ground is connected inside IMM-200. Never unscrew or loosen this connection.

⚠ CAUTION

An external earth ground connection is required to ensure proper operation, especially in electrical noisy environments.

When used with RF powered sputtering systems, the grounding method may have to be modified to the specific situation. An informative article on the subject of Grounding and RFI Prevention was published by H.D. Alcaide, in “Solid State Technology,” p.117, April, 1982. In many cases, a braided ground strap is sufficient. However, there are cases when a solid copper strap 0.8 mm thick x 25.4 mm wide (0.030 in. x 1 in.) is required because of its lower RF impedance.

Minimizing Noise Pickup from External Cabling

When IMM-200 is fully integrated into a deposition system, there can be many wire connections. Each connection is a potential path for electrical noise to reach the inside of IMM-200. The likelihood of these wires causing a problem can be greatly diminished by adhering to the following guidelines:

- Use shielded coax cable or twisted pairs for all connections.
- Minimize the cable lengths.
- Avoid routing cables near areas that have the potential to generate high levels of interference. For example, large power supplies such as those used for electron beam guns or sputtering sources can be a source of large, rapidly changing electromagnetic fields. Placing cables at a minimum of 30 cm (1 ft.) away from these problem areas can significantly reduce noise pickup.
- Be sure that a good ground system and straps are in place per recommendations Avoiding Electrical Interference [▹ 21].
- Ensure that all IMM-200 covers are in place and tightly secured with the provided fasteners.

Always use shielded cables when making connection to IMM-200 to minimize electrical noise pickup.

See also

Parts and Options Overview [16]

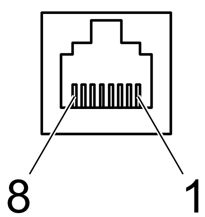
5.2 Connecting the Instrument

For operating IMM-200, interface cables conforming to the Ethernet standard are required.

If a cable is not available, one can be made according to the following instructions:

Cable type: Ethernet shielded patch cable (CAT5e quality or better) with FCC68 connector.

Pin Assignment



Pin	Signal	Description
1	TD+	Transmission data +
2	TD-	Transmission data -
3	RD+	Receive data +
4	nu	Not used
5	nu	Not used
6	RD-	Receive data -
7	nu	Not used
8	nu	Not used

5.3 Indicators and Switches

5.3.1 Status LED

Green LED displays the unit status.

LED State	Description
boot loader flash 1 (0.4 second on, 0.4 second off)	Normal, a valid firmware version is present.
boot loader flash 2 (0.2 second on, 0.2second off)	Old firmware is being overwritten, new firmware has been downloaded and passed the integrity check.
boot loader flash 3 (0.5 second on, .2 second off, .5 second on, 1 second off)	The firmware is invalid.
off	The unit is in diagnostics mode, or the unit has encountered an error, or no power is applied to the device.
flash (1 second on 4 seconds off)	The unit is in idle mode.
blinking (1 second on 1 second off)	The unit is in **Measure** mode and a crystal failure has been detected.
on	The unit is in **Measure** mode or the unit is running normally in boot.

6 Special Features

6.1 Introduction

To enhance its performance and allow easier integration into a system having rotary sensor heads, IMM-200 is equipped with special features. These special features are explained further in the following subsections.

6.2 50 / 60 Hz Line Frequency

The AC Line Frequency configuration parameter is used to minimize measurement system noise by identifying to IMM-200 the mains voltage line frequency. The difference between 50 and 60 Hz line frequency has a small affect on the measurement circuit timing. In most cases this is negligible. However in cases where the material density and deposition rate are very low, setting this parameter value to match the mains voltage line frequency optimizes IMM-200 measurements.

6.3 Start/Stop Measurement

The **Start/Stop Measurement** remote communications command indicates to IMM-200 to either start measuring frequency or to stop measuring frequency. The unit is placed into idle when the stop measurement command is sent. This command is very useful when using a rotary sensor head. Since IMM-200 does not control the indexing of the rotary head, it has no way of knowing when a crystal switch is being performed. Therefore, whenever a crystal switch is done, a crystal fail occurs after breaking electrical contact during the crystal switch.

When the **Stop Measurement** command is activated, IMM-200 stops looking for the crystal signal. The rotary head can then be indexed to the next position without a crystal fail occurring. Once the rotary head is in the next position, the **Start Measurement** command is given and the unit looks for the crystal signal. Once the crystal frequency is acquired, IMM-200 resumes calculating the rate and thickness. The thickness value begins incrementing from the point of the previous crystal's last thickness value. The value used is the one recorded immediately prior to when the **Stop Measurement** command was received by IMM-200.

6.4 Crystal Type

Crystals cut from different crystallographic orientations of quartz can be used with IMM-200. These are referred to as AT, BT, SC, or IT cut crystals. Thickness shear mode waves propagating through these different crystal cuts have different acoustic velocities. Typical Z ratio values commonly found in the literature are normalized for AT-cut quartz crystals.

For proper thickness calculation it is necessary to select the crystal type to match the crystals being used.

AT-Cut Crystals

AT-cut crystals are commonly used as gravimetric sensors to monitor film thickness. These are singly rotated crystals and are less expensive than doubly rotated crystals. Frequency vs. temperature curves for the family of AT-cut crystals have an inversion point near room temperature making them ideal to operate on or around room temperature applications. While the frequency of an AT-cut crystal is sensitive to thermal radiation impulses and acceleration, the atmospheric loading on its quality (Q factor) is less than SC or IT-cut crystals.

BT-Cut crystals

BT-cut crystals have a frequency-temperature characteristic that has a second order polynomial shape without an inversion. These crystals have a stress coefficient that is equal and opposite to the stress coefficient of AT-cut crystals. In other words, a tensile film deposited on BT-cut crystals has a frequency shift in the opposite direction to that of the same film on AT-cut crystals.

IT-Cut Crystals

Like SC-cut crystals, IT-cut crystals are used in OCXOs (oven controlled crystal oscillators) due to their higher frequency temperature inversion point compared with other crystal cuts. IT-cut crystals have a frequency temperature inversion around 75°C. Both the IT-cut family and the SC-cut family are ideal for thin film deposition applications at high temperatures. At higher temperatures, for example 100-300°C, both the IT and SC-cut crystals have a lower temperature coefficient of frequency compared to AT-cut crystals.

SC-Cut Crystals

SC-cut crystals are expensive compared to AT-cut crystals. An SC-cut crystal has an extremely stable resonance frequency. Their frequency-temperature inversion point of approximately 93°C, being close to the oven temperatures, makes them appealing to be used in OCXOs. The resonance frequency of this type of crystal has very good immunity to acceleration. Their acceleration sensitivity is approximately two orders of magnitude less than AT-cut crystals. TCXOs (temperature compensated crystal oscillators) (clocks) almost always have these crystals in their resonator circuits.

6.5 Crystal Life and Starting Frequency

Crystal life is reported as a percentage of the monitor crystal’s frequency shift, relative to the 1.50 MHz frequency shift allowed by IMM-200. This quantity is useful as an indicator of when to change the monitor crystal to safeguard against crystal failures during deposition.

A newly installed crystal has a crystal life between 0 and 5%. In many cases, a brand new quartz crystal does not have a frequency of exactly 5 MHz or 6 MHz due to process variations when producing the crystal. If a new crystal indicates 5% life spent, it means that either the quartz blank is slightly thicker than normal (more mechanical robustness), or the electrode is slightly thicker than normal (better thermal and electrical properties), or both. This additional thickness causes the starting frequency to be lower than the rated value of 5 MHz or 6 MHz. Despite a lower-starting-frequency, the crystal performance is not adversely affected. These lower-starting-frequency crystals have been tested and results indicate that a brand new crystal indicating 3 to 5% life spent is just as good as, if not better than, a crystal indicating 0 to 2% life spent.

As deposited material is added to the crystal, the percent crystal life increases up to a maximum of 100%. It is usually not possible to use a monitor crystal to 100% crystal life. Normally a crystal is changed after a specific amount of crystal life is consumed. Useful crystal life is dependent on the type of material being deposited and the resulting influence of the material on the quartz monitor crystal. For materials that are low stress and rigidly adhere to the crystal, such as copper, at approximately 100% crystal life the inherent quality, (Q), of the monitor crystal degrades to a point where it is difficult to maintain a sharp resonance and the ability to measure the monitor crystal frequency deteriorates. When depositing dielectric or organic materials, the life of a gold, aluminum, or silver quartz monitor crystal is much shorter, as little as 10 to 12% crystal life. This is due to thermal and intrinsic stresses at the quartz-dielectric film interface, which are exacerbated by the poor mechanical strength of the film. Many organic materials deposit as non-rigid films, which cause the crystal Q to fall rapidly. For these materials, the percent of the life of the quartz has very little to do with the monitor crystal failure.

7 Ethernet Communications

7.1 Introduction

IMM-200 uses a Lantronix® XPort Ethernet communications interface for sending parameter values, instrument commands, and status, warning and error messages between IMM-200 and a host computer. INFICON P3Plus communications protocol packets with computed CRC are transferred between the IMM-200 and the Lantronix adapter (8, N, 1, 921600 bps).

7.2 Setting the IP Address

IMM-200 Ethernet settings can be configured using the Lantronix DeviceInstaller Windows application downloadable from: https://www.lantronix.com/products/deviceinstaller/

There are a few ways to set the IP address. All of them are described in the User Guide for the XPort device. https://cdn.lantronix.com/wp-content/uploads/pdf/DeviceInstaller_UG.pdf

If the IP address is already known, type it into the browser. A prompt appears with a login dialog. IMM-200 is shipped with both the username and password unset/empty, so leave them blank and click **OK** to login. The IP address for IMM-200 is under **Network**. Make sure that the IP address for the **Remote Host** (under Channel 1 | Connection) is set to the same subnet as the new IP. It is not used, but the IP must be compatible.

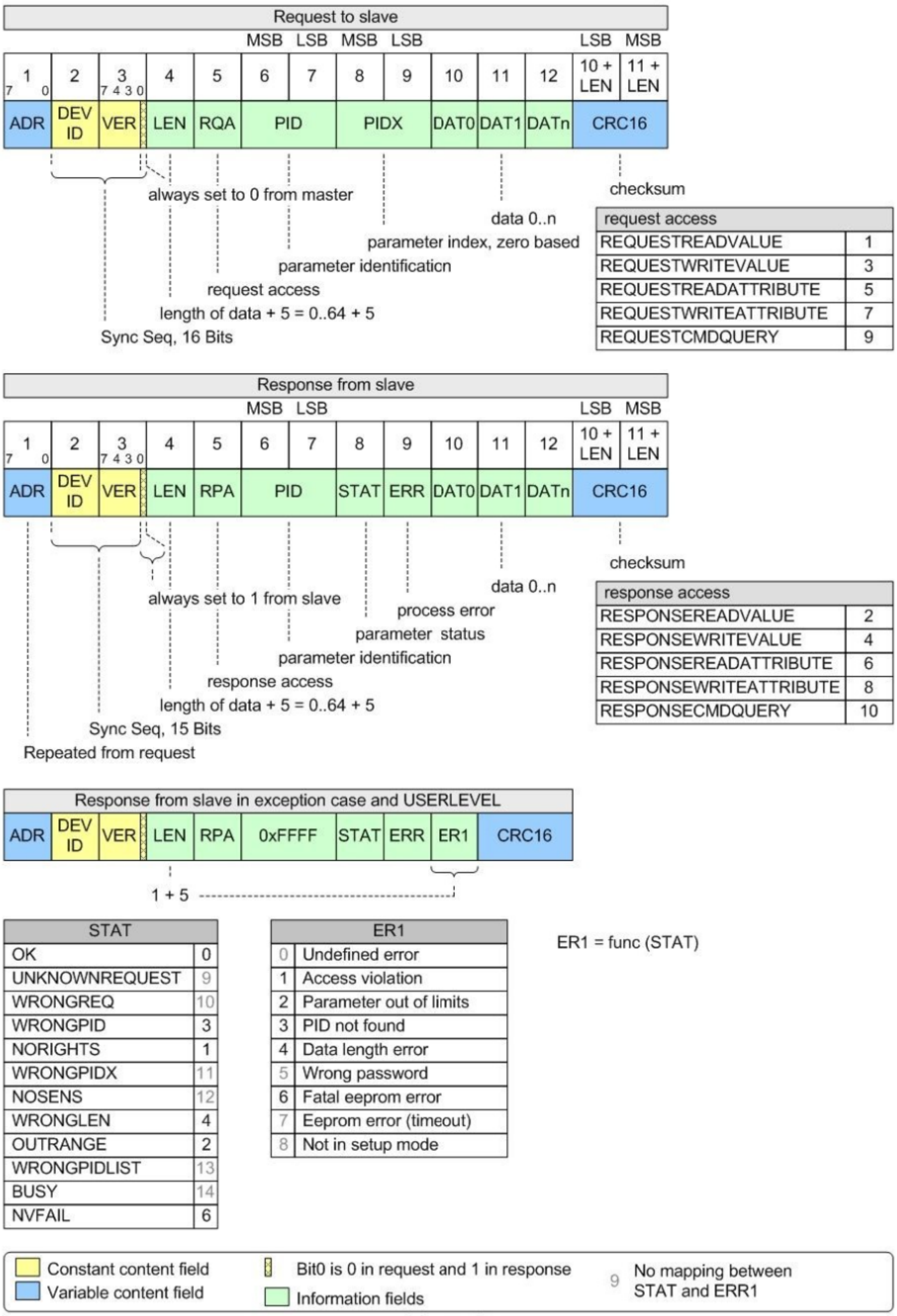
If the IP address is unknown, the easiest way to access the device is to install the Lantronix DeviceInstaller Windows application. It will find all Lantronix devices on the network. From the factory the default configuration of the Ethernet module is set for an IP address of 192.168.1.101 and a subnet mask of 255.255.255.0. The DeviceInstaller may find many Lantronix devices on the network. IMM-200 uses the XPort-05. Once the XPort device to be modified is selected, use the **Web Configuration** from within the app or just use the browser (with the known IP address).

7.3 Protocol

IMM-200 uses the P3Plus (P3P) communication protocol with the following notes:

- ADR byte not evaluated (set to 0)
- ADR byte included in CRC calculation
- DEV ID ignored by slave on **Requests** to slave.

- DEV ID set to 129 (0x81) by slave for all **Responses** from slave
- PIDX ignored (set to 0)



Platform P3Plus

7.4 Example IMM-200 P3P Messages

7.4.1 Request Read Value

Get Material Density

RQA = 1 (Requested Read Value)

PID = 302 (0×012e)

Request (11 bytes):

0000000501012e0000405e

Response (15 bytes):

0081010902012e00003f8000001e06

Density = 1.0

7.4.2 Request Write Value

Set Crystal Cut Type

RQA = 3 (Request Write Value)

PID = 308

DAT0-DAT3 = 0×00000001 (BT cut)

Request (15 bytes):

000000090301340000000000001178a

Response (11 bytes):

00810105040134000735b

7.4.3 Request Read/Write Attribute -Combination Message

Set up request for several PID values to be returned together with the 703 Combination message. The DATA section of the 703 message has the following format:

DAT0 = N (number of PIDs in request -- Byte 10 of Request Write Attribute message)

DAT1-DAT2: 1st PID of request (Bytes 11-12 : MSB-LSB)

DAT3-DAT4: 2nd PID of request

...

DAT(n-1)-DATn: N^{th} PID (n = N*2)

Request the following five values to be returned with a 703

RQA = 7 (Request Write Attribute)	
PID = 703	
DAT0 = 5	
DAT1-DAT2 = 205	Timestamp
DAT3-DAT4 = 230	Crystal Status
DAT5-DAT6 = 233	Activity
DAT7-DAT8 = 234	Crystal % Life
DAT9-DAT10 = 231	Frequency

Request (22 bytes):

000000100702bf00000500cd00e600e900ea00e7d490

Response (11 bytes):

008101050802bf0000c42c

Send 703 Combination message Read Attribute Request for the data

RQA = 5 (Request Read Attribute)

PID = 703

Request (11 bytes):

000000050102bf000028a8

Response (39 bytes):

008101210202bf000000000001392054ec00000000100000065000000104155d21452d
fc79f1969

Timestamp	84054200000
Crystal status	1
Activity	101
Crystal life %	16
Frequency	5720145.29491

crc16 = 26805

7.5 IMM-200 PID List

		Request Access (RQA) / Response Access (RPA)							
	PID	Read Value	Write Value	Read Attr.	Write Attr.	Cmd Query	Data Type	Data Length (Bytes)	Notes
General Device Parameters		1/2	3/4	5/6	7/8	9/10			
Production Number	110	x					string	15	last byte always null
Serial Number	111	x					U32	4	
Product Name	112	x					string	33	last byte always null
Manufacturer Name	113	x					string	20	last byte always null
Manufacturer Model Number	114	x					string	20	last byte always null
Firmware Revision	115	x					string	20	last byte always null
Hardware Revision	116	x					string	15	last byte always null
AC Line Frequency	150	x	x				U32	4	
Sensor/Module Status									
Unit Status	200	x					U32	4	
Timestamp	205	x					U64	8	
User Timer	206	x					U64	8	
Filtered Rate	207	x					F64	8	
Raw Rate	208	x					F64	8	
Thickness	209	x					F64	8	
Deposition Status	220	x					U32	4	
Crystal Status	230	x					U32	4	
Frequency	231	x					F64	8	
Activity	233	x					U32	4	
Crystal % Life	234	x					U32	4	
Crystal Position	235	x					U32	4	
Material Name	301	x	x				string	30	All thirty bytes should be sent (padded with

		Request Access (RQA) / Response Access (RPA)							
	PID	Read Value	Write Value	Read Attr.	Write Attr.	Cmd Query	Data Type	Data Length (Bytes)	Notes
									spaces or null); last byte always set to null
Density	302	x	x				F32	4	
Z-Ratio	303	x	x				F32	4	
Tooling	304	x	x				F32	4	
Maximum Thickness	305	x	x				F32	4	
Rate Filter Time	306	x	x				F32	4	
Crystal Cut Type	308	x	x				U32	4	
Sensor/Module									
Reset	404					x			
Default Parameters	405					x			
Calculate Checksum	406					x			
Zero Timer and Thickness	420					x			
Zero Thickness	421					x			
Zero Timer	422					x			
Stop Measuring	425					x			
Start Measuring	426					x			
Combination Commands	703			x	x		See notes		Write Attribute: Request Message contains list of PIDs (Data Type U16) preceded by the number of PIDs in the list (Data Type U08).
									Read Attribute: Response Message contains list of values returned in the listed order requested via the Write Attribute message. Data Type is PID-dependent

7.6 CRC Calculation

For a copyable version of the information below, contact a Product Engineer.

```
/*!

 ### CRC LOOKUP TABLE
 The following CRC lookup table was generated automatically by
 the Rocksoft &copy; Model CRC Algorithm Table Generation
  Program V1.0 using the following model parameters:
    Width : 2 bytes.
    Poly : 0x1021
    Reverse : TRUE.
*/
uint16_T const au16CrcTable[256] =
{
```

0x0000	0x1189	0x2312	0x329B	0x4624	0x57AD	0x6536	0x74BF
0x8C48	0x9DC1	0xAF5A	0xBED3	0xCA6C	0xDBE5	0xE97E	0xF8F7
0x1081	0x0108	0x3393	0x221A	0x56A5	0x472C	0x75B7	0x643E
0x9CC9	0x8D40	0xBFDB	0xAE52	0xDAED	0xCB64	0xF9FF	0xE876
0x2102	0x308B	0x0210	0x1399	0x6726	0x76AF	0x4434	0x55BD
0xAD4A	0xBCC3	0x8E58	0x9FD1	0xEB6E	0xFAE7	0xC87C	0xD9F5
0x3183	0x200A	0x1291	0x0318	0x77A7	0x662E	0x54B5	0x453C
0xBDCB	0xAC42	0x9ED9	0x8F50	0xFBEF	0xEA66	0xD8FD	0xC974
0x4204	0x538D	0x6116	0x709F	0x0420	0x15A9	0x2732	0x36BB
0xCE4C	0xDFC5	0xED5E	0xFCD7	0x8868	0x99E1	0xAB7A	0xBAF3
0x5285	0x430C	0x7197	0x601E	0x14A1	0x0528	0x37B3	0x263A
0xDECD	0xCF44	0xFDDF	0xEC56	0x98E9	0x8960	0xBBFB	0xAA72
0x6306	0x728F	0x4014	0x519D	0x2522	0x34AB	0x0630	0x17B9
0xEF4E	0xFEC7	0xCC5C	0xDDD5	0xA96A	0xB8E3	0x8A78	0x9BF1
0x7387	0x620E	0x5095	0x411C	0x35A3	0x242A	0x16B1	0x0738
0xFFCF	0xEE46	0xDCDD	0xCD54	0xB9EB	0xA862	0x9AF9	0x8B70
0x8408	0x9581	0xA71A	0xB693	0xC22C	0xD3A5	0xE13E	0xF0B7
0x0840	0x19C9	0x2B52	0x3ADB	0x4E64	0x5FED	0x6D76	0x7CFF
0x9489	0x8500	0xB79B	0xA612	0xD2AD	0xC324	0xF1BF	0xE036
0x18C1	0x0948	0x3BD3	0x2A5A	0x5EE5	0x4F6C	0x7DF7	0x6C7E
0xA50A	0xB483	0x8618	0x9791	0xE32E	0xF2A7	0xC03C	0xD1B5
0x2942	0x38CB	0x0A50	0x1BD9	0x6F66	0x7EEF	0x4C74	0x5DFD
0xB58B	0xA402	0x9699	0x8710	0xF3AF	0xE226	0xD0BD	0xC134
0x39C3	0x284A	0x1AD1	0x0B58	0x7FE7	0x6E6E	0x5CF5	0x4D7C
0xC60C	0xD785	0xE51E	0xF497	0x8028	0x91A1	0xA33A	0xB2B3
0x4A44	0x5BCD	0x6956	0x78DF	0x0C60	0x1DE9	0x2F72	0x3EFB

0xD68D	0xC704	0xF59F	0xE416	0x90A9	0x90A9	0xB3BB	0xA232
0x5AC5	0x4B4C	0x79D7	0x685E	0x1CE1	0x0D68	0x3FF3	0x2E7A
0xE70E	0xF687	0xC41C	0xD595	0xA12A	0xB0A3	0x8238	0x93B1
0x6B46	0x7ACF	0x4854	0x59DD	0x2D62	0x3CEB	0x0E70	0x1FF9
0xF78F	0xE606	0xD49D	0xC514	0xB1AB	0xA022	0x92B9	0x8330

```
};
#define CRC_INITIAL     (0xFFFFu)
uint16_T CRC_u16InitCrc16(void)
{
 return (CRC_INITIAL);
}
uint16_T CRC_u16CalcCrc16( const uint8_T *pu8Data, const
uint16_T u16CrcInit, const uint16_T u16Len )
{
  uint32_T u32Calc = u16CrcInit;
  uint32_T u32Dec = u16Len;
  while (u32Dec--)
  {
    u32Calc = (au16CrcTable[(u32Calc ^ (uint32_T)*pu8Data++) &
0xFFu]) ^ (u32Calc >> 8);
  }
  return (uint16_T)(u32Calc);
}
bool_T CRC_bCheckCrc16( const uint8_T *pu8Data, const uint16_T
u16CrcInit, const uint16_T u16Len )
{
  uint16_T u16Crc;
  bool_T bReturnFlag = false;
  u16Crc = CRC_u16CalcCrc16(pu8Data, u16CrcInit, u16Len + 2u);
  if (u16Crc == 0u)
  {
    bReturnFlag = true;
  }
  return bReturnFlag;
}
```

8 Maintenance and Calibration Procedures

8.1 Importance of Density, Tooling, and Z-Ratio

A quartz crystal microbalance is capable of precisely measuring mass added to the face of an oscillating quartz crystal sensor. Conversion of the mass information into thickness is acheived when the user enters the material density and Z-Ratio into IMM-200. In some instances, where highest accuracy is required, it is necessary to make a density calibration as outlined in Determine Density [▸ 37]. Because flow of material from a deposition source is not uniform, it is necessary to account for the different amount of material arriving at the sensor compared to the substrate. This difference is accounted for in the tooling parameter. The tooling factor can be experimentally established by following the guidelines in Determine Tooling [▸ 38]. In IMM-200, if the Z-Ratio is not known it can be estimated from the procedure outlined in Laboratory Determination of Z-Ratio. [▸ 38]

8.2 Determine Density

The bulk density values retrieved in Appendix A: Material Table [▸ 57] are sufficiently accurate for most applications.

Follow the steps below to determine density value.

✓ 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.

1. Set the density to the bulk value of the film material or to an approximate value.
2. Set the Z-Ratio to 1.000 and set tooling to 100%.
3. Place a new crystal in the sensor and make a short deposition (1000–5000 Å) using manual control.
4. After deposition, remove the test substrate and measure the film thickness with either a multiple beam interferometer or a stylus-type profilometer.
5. Determine the new density value with equation [1].

⇨ A quick check of the calculated density is made by programming IMM-200 with the new density value and observing that the reported thickness is equal to the measured thickness, provided that the IMM-200 thickness has not been zeroed between the test deposition and entering the calculated density.

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

where: D_1 = Initial density setting, T_x = Thickness reading on IMM-200, T_m = Measured thickness

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

8.3 Determine Tooling

1. Place a test substrate in the system substrate holder.
2. Make a short deposition and determine the actual thickness.
3. Calculate tooling from the relationship shown in equation [2].
4. Round off percent tooling to the nearest 0.1%.
5. When entering the new value for tooling into the program, T_m equals T_x if calculations are done properly.

Tooling (%) = TF_i (T_m/T_x) [2]

where T_m = Actual thickness at substrate holder T_x = Thickness reading in IMM-200 TF_i = Initial tooling factor

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-Ratio values for materials commonly used is available in Appendix A: Material Table [▸ 57]. For other materials, Z-Ratios can be calculated from the following formula:

$Z = (d_q\mu_q / d_f\mu_f)^{1/2}$ [3]

$Z = 9.378\times10^5 (d_f\mu_f)^{-1/2}$ [4]

where:

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

μ_f = shear modulus (dynes/cm^2) of deposited film

d_q = density of quartz (crystal) (2.649 g/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 listing physical properties of materials.

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

1. Establish the correct density value as described in the section titled Determine Density [▷ 37].
2. Install a new crystal and record its starting frequency (F_{co}). It is necessary to read the frequency value at PID 231.
3. Make a deposition on a test substrate such that the percent crystal life reads approximately 50%, or near the end of crystal life for the particular material, whichever is smaller. Monitor the **Read Request Value** PID 234 to get the crystal life value.
4. Stop the deposition and record the ending crystal frequency (F_c) using the **Read Request Value** PID 231.
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.

$$T_f = (Z_q x10^4/2\pi zp)((1/F_{co}) \arctan (z \tan(\pi F_{co})/F_q)) - (1/F_c) \arctan (z \tan(\pi F_c)/F_q))) \quad [5]$$

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/cm^3)

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

1. If the thickness of material 1 is large compared to material 2, use material 1 Z-Ratio value for both materials.

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

9 Troubleshooting and Error Messages

9.1 Troubleshooting

If IMM-200 fails to work or appears to have diminished performance, the following Symptom/Cause/Remedy charts may be helpful.

⚠ DANGER

Risk of Electric Shock

There are no user-serviceable components within the IMM-200 case. Potentially lethal voltages are present. Refer all maintenance to qualified personnel.

⚠ CAUTION

The instrument contains delicate circuitry which is susceptible to transient power line voltages. Disconnect power whenever making any interface connections. Refer all maintenance to qualified personnel.

Troubleshooting IMM-200

SYMPTOM	CAUSE	REMEDY
1. The power ON LED is not illuminated.	a. A circuit breaker is tripped. b. The power cord is unplugged from the wall or the back of IMM-200. c. There is incorrect voltage.	a. Have qualified personnel reset the circuit breaker. b. Reconnect the power cord. c. Have qualified personnel verify the voltage.
2. IMM-200 "locks" up.	a. There is a high electrical noise environment.	a. Route the cables to reduce noise pickup (30 cm [1 ft.] away from high power conducting lines make a sizable reduction in the amount of noise entering IMM-200). Keep all ground wires short with a large surface area to minimize ground impedance (a solid copper

SYMPTOM	CAUSE	REMEDY
		strap with 5 to 1 length to width ratio is recommended).
	b. There is poor ground or a poor grounding practice.	b. Verify there is proper earth ground. Use an appropriate ground strap, (solid copper strap with 5 to 1 length to width ratio is recommended). Eliminate any ground loops by establishing the correct system grounding. Verify proper IMM-200 grounding.
3. IMM-200 does not retain parameters on power down (or there is a loss of parameters on power up).	There is a power supply problem.	Contact the service department.
4. The **crystal fail** message is always on	a. There is a defective cable from feedthrough to IMM-200. b. There is poor electrical contact in the transducer, the feedthroughs, or the in-vacuum cable. c. There is a failed crystal. d. There is no crystal. e. Two crystals are placed into the crystal holder. f. The frequency of the crystal is out of range.	a. Use an ohmmeter or DVM to check the electrical continuity or isolation, as appropriate. b. Use an ohmmeter or DVM to check the electrical continuity or isolation, as appropriate. c. Replace the crystal, d. Insert a crystal. e. Remove one of the crystals. f. Verify that the crystal frequency is within the required range.

9.2 Troubleshooting Sensors

Many sensor head problems can be diagnosed with a DMM (digital multimeter). 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 MΩ, 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 one Ω from the feedthrough to the transducer contact indicates a problem. Cleaning contacts or replacing the in-vacuum cable may be required.

Crystal life is highly dependent on process conditions of rate, power radiated from the source, location, material, and residual gas composition.

SYMPTOM	CAUSE	REMEDY
1. There are large jumps of thickness reading during deposition.	a. Stress causes the film to peel from crystal surface. b. Particulate or "spatter" from a molten source is striking the crystal. c. There are scratches or foreign particles on the crystal holder seating surface (improper crystal seating). d. Small pieces of material fell on crystal (for a crystal facing-up situation). e. Small pieces of magnetic material are being attracted by the sensor magnet and contacting the crystal (sputtering sensor head).	a. Replace crystal or use an alloy crystal. Consult the factory. b. Thermally condition the source thoroughly before deposition. Use a shutter to protect the crystal during source conditioning. c. Clean and polish the crystal seating surface on the crystal holder. Refer to the appropriate sensor manual. d. Check the crystal surface and blow it off with clean air. e. Check the sensor cover aperture and remove any foreign material that may be restricting full crystal coverage. Refer to the appropriate sensor manual.
2. The crystal ceases to oscillate during deposition before it reaches its normal life.	a. The crystal is struck by particulate or spatter from molten source. b. Material on the crystal holder partially masks the crystal cover aperture. c. There is an electrical short or an open condition.	a. Thermally condition the source thoroughly before deposition. Use a shutter to protect the crystal during source conditioning. b. Clean the crystal holder. Refer to the appropriate sensor manual.

SYMPTOM	CAUSE	REMEDY
	d. Check for thermally induced electrical shorts or open conditions.	c. Using an ohmmeter or DMM, check for electrical continuity in the sensor cable, connector, contact springs, connecting wire inside sensor, and feedthroughs. d. Using an ohmmeter or DMM, check for electrical continuity in the sensor cable, connector, contact springs, connecting wire inside sensor, and feedthroughs.
3. The crystal does not oscillate or oscillates intermittently (both in vacuum and in air).	a. There is intermittent or poor electrical contact (the contacts are oxidized). b. The leaf spring has lost retentivity (ceramic retainer, center insulator). c. There is RF interference from the sputtering power supply. d. The cables are not connected or are connected to the wrong input.	a. Use an ohmmeter or DMM to check electrical continuity. Replace the ceramic retainer. b. Bend the leaves to approximately 45°. Refer to the appropriate sensor manual. c. Verify earth ground. The ground strap should be adequate for RF ground (solid copper strap with a 5:1 length:width ratio is recommended). Change the location of IMM-200 and move the oscillator cabling away from RF power lines. Connect the IMM-200 power supply to a different power line. d. Verify that there are proper connections.

SYMPTOM	CAUSE	REMEDY
4. The crystal oscillates in vacuum but stops oscillation after it is opened to air.	a. The crystal is near the end of its life. Opening to air causes film oxidation which increases film stress. b. Excessive moisture accumulates on the crystal.	a. Replace the crystal. b. Turn off the cooling water to the sensor prior to venting. Flow warm water through sensor while the chamber is open.
5. There are large changes in the thickness reading during source warm-up. (This usually causes the thickness reading to decrease.) There is thermal instability after the termination of deposition. (This usually causes the thickness reading to increase.)	a. There is inadequate cooling water or the cooling water temperature is too high. b. There is excessive heat input to the crystal. c. The crystal holder is not seated properly in the holder. d. There is crystal heating caused by a high-energy electron flux (often found in RF sputtering). e. There is poor thermal transfer from the water tube to the body (CrystalSix). f. There is poor thermal transfer.	a. Check the cooling water flow rate. The cooling water temperature must be less than 30^{o}C. Refer to the appropriate sensor manual. b. If there is heat due to radiation from the evaporation source, move the sensor further away from the source and use sputtering crystals for better thermal stability. Install a radiation shield. c. Clean or polish the crystal seating surface on the crystal holder. Refer to the appropriate sensor manual. d. Use a sputtering sensor head. e. Use a new water tube when the clamping assembly has been removed from the body. If a new water tube is not available, use a single layer of aluminum foil between the cooling tube and sensor body, if the process allows.

SYMPTOM	CAUSE	REMEDY
		f. Use an aluminum or gold foil washer between the crystal holder and the sensor body.
6. There is poor thickness reproducibility.	a. There is a variable source flux distribution. b. The sweep, dither, or position where the electron beam strikes the melt has been changed since the last deposition. c. The material does not adhere to the crystal. d. There is a cyclic change in rate.	a. Move the sensor to a more central location to reliably sample the evaporant. Ensure there is a constant relative pool height of melt. Avoid tunneling into the melt. b. Maintain consistent source distribution by maintaining consistent sweep frequencies, sweep amplitudes and electron beam position settings. c. Make certain the crystal surface is clean. Avoid touching the crystal with fingers. Make use of an intermediate adhesion layer. d. Make certain the source sweep frequency is not "beating" with the IMM-200 measurement frequency.
7. There is a large drift in thickness (greater than 200 Å for a density of 5.00 g/cm^3) after the termination of sputtering.	a. There is crystal heating due to poor thermal contact. b. The external magnetic field is interfering with the sensor's magnetic field (sputtering sensor). c. The sensor magnet is cracked or demagnetized (sputtering sensor).	a. Clean or polish the crystal seating surface on the crystal holder. Refer to the appropriate sensor manual. b. Rotate the sensor magnet to the proper orientation with the external magnetic field. Refer to the sputtering sensor manual.

SYMPTOM	CAUSE	REMEDY
		c. Check the sensor magnetic field strength. The maximum field at the center of the aperture should be 700 gauss or greater.
8. There is a rotary sensor crystal switch problem. (The sensor does not advance or is not centered in aperture.)	a. There is no relay or an incorrect relay output programmed (for instruments having outputs). b. There is a loss of pneumatic supply or the pressure is insufficient for operation. c. Operation has been impaired as a result of material accumulation on the cover. d. There is an improper alignment. e. A 0.057 mm (0.00225 in.) diameter orifice is not installed on the supply side of solenoid valve assembly (CrystalSix or Crystal12 sensors).	a. Program a relay. b. Ensure the air supply is regulated at 80-90 psi. c. Clean material accumulation as needed. d. Refer to the sensor operating manual for the alignment procedure. e. Install the orifice as shown in the CrystalSix or Crystal 12 Operating manual.

9.3 Troubleshooting Computer Communication

Symptom	Cause	Remedy
1. Communication cannot be established between the computer and IMM-200.	a. There is an improper communication cable connection. b. There is a defective communication cable. c. The incorrect IP address or submask being used.	a. Ensure that the cables are connected to the correct ports on IMM-200 and the computer. b. Verify that the cable is plugged in and is not damaged. Replace the communication cable.

Symptom	Cause	Remedy
		c. Verify that the IP address and submask in IMM-200 match the information in the computer.
2. There is an incomplete or erroneous response.	There is an incorrectly formatted message.	Verify that the communication message is formatted correctly.

10 Measurement Theory

10.1 Basics

A quartz crystal deposition monitor, or QCM, uses the converse piezoelectric properties of a quartz crystal to detect added mass. The QCM uses this mass sensitivity to measure 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 is reduced. This change in frequency is very repeatable and is precisely understood for specific oscillating modes of quartz. This 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 1950s it was noted by Sauerbrey[1,2] and Lostis[3] that the change in frequency, $\Delta F = F_q - F_c$, 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:

$M_f / M_q = \Delta F / F_q$ [1]

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:

$T_f = K (\Delta F) / d_f$ [2]

where the film thickness, T_f, is proportional (through K) to the frequency change, ΔF, 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 g/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 Å of aluminum (density of 2.77 g/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 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.

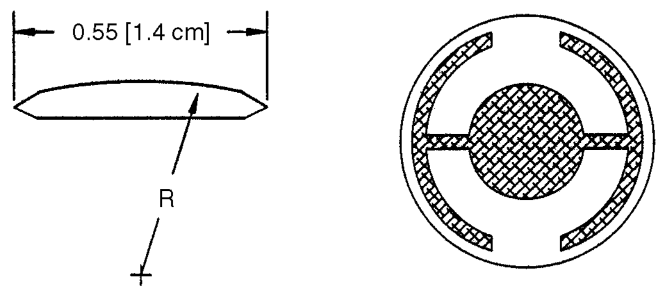
1.G. Z. Sauerbrey, Phys. Verhand .8, 193 (1957)

2.G. Z. Sauerbrey, Z. Phys. 155,206 (1959)

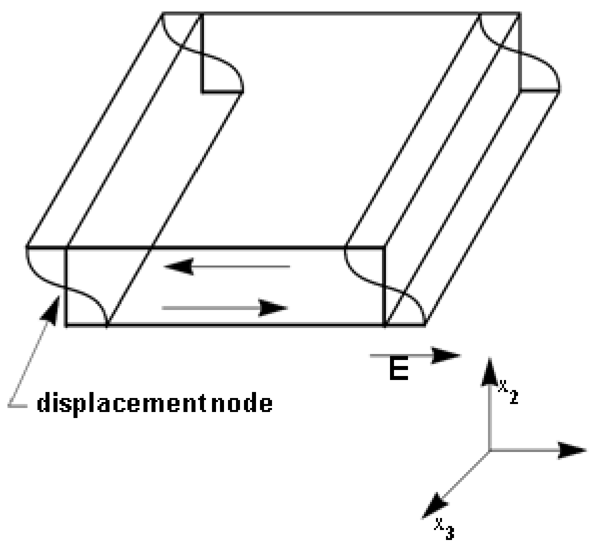
3. P. Lostis, Rev. Opt. 38,1 (1959)

10.2 Monitor Crystals

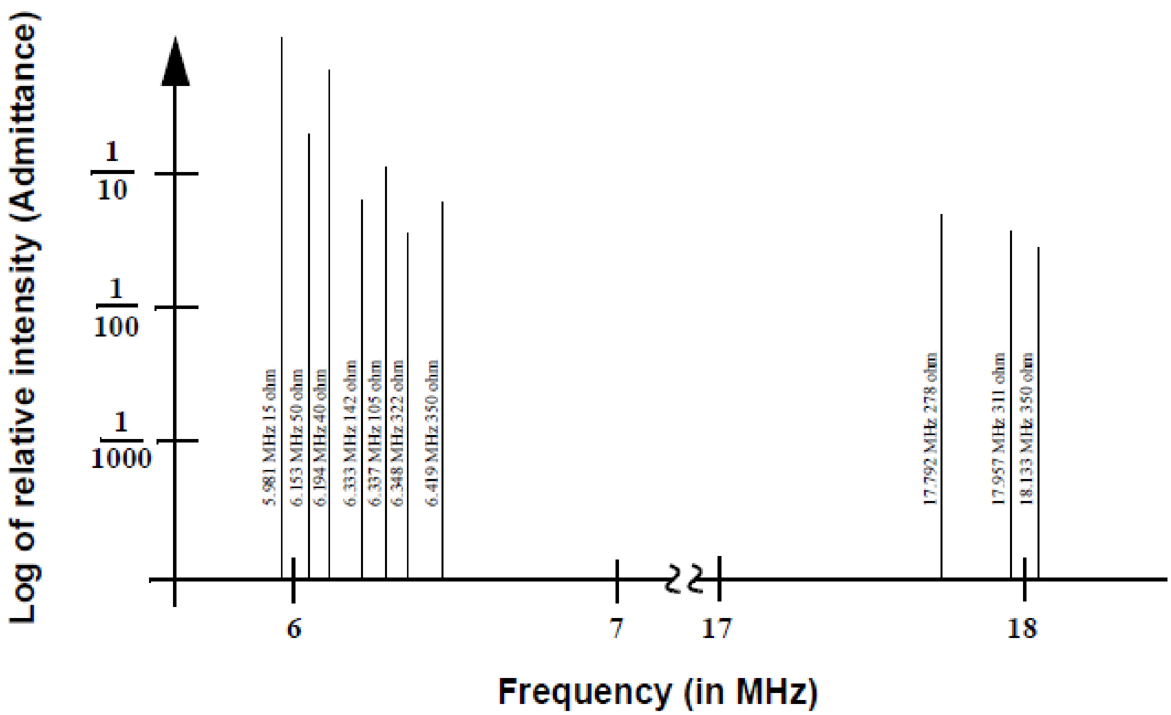
No matter how sophisticated the electronics surrounding it, the essential device of the deposition monitor is the quartz crystal.



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.



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 above 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 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.



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 is 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) from 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.

10.3 Period Measurement Technique

Although instruments using equation [2] were very useful, it was soon noted they had a very limited range of accuracy, typically holding accuracy for ΔF less than 0.02 F_q.

In 1961, it was recognized by Behrndt[4] that:

$M_f / M_q = (T_c - T_q) / T_q = \Delta F / F_q$ [3]

where T_c and T_q 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 $\pm 2/F_r$ where F_r is the reference oscillator's frequency. The monitor crystal 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 parameters 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 measurement. The uncertainty of the measurement injects more noise into the control loop, which can be counteracted only by longer control loop 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.

4. K. H. Behrndt, J. Vac. Sci. Technol. 8, 622 (1961)

10.4 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 development of the micro-processor, made it practical to solve the Z-match equation in “real-time.” Most deposition process controllers sold today use this sophisticated equation, which takes into account the acoustic properties of the resonating quartz and film system as shown in equation [4].

$T_f = (N_{at}d_q / \pi d_f F_c Z) \arctan (Z \tan(\pi(F_q-F_c)/F_q))$ [4]

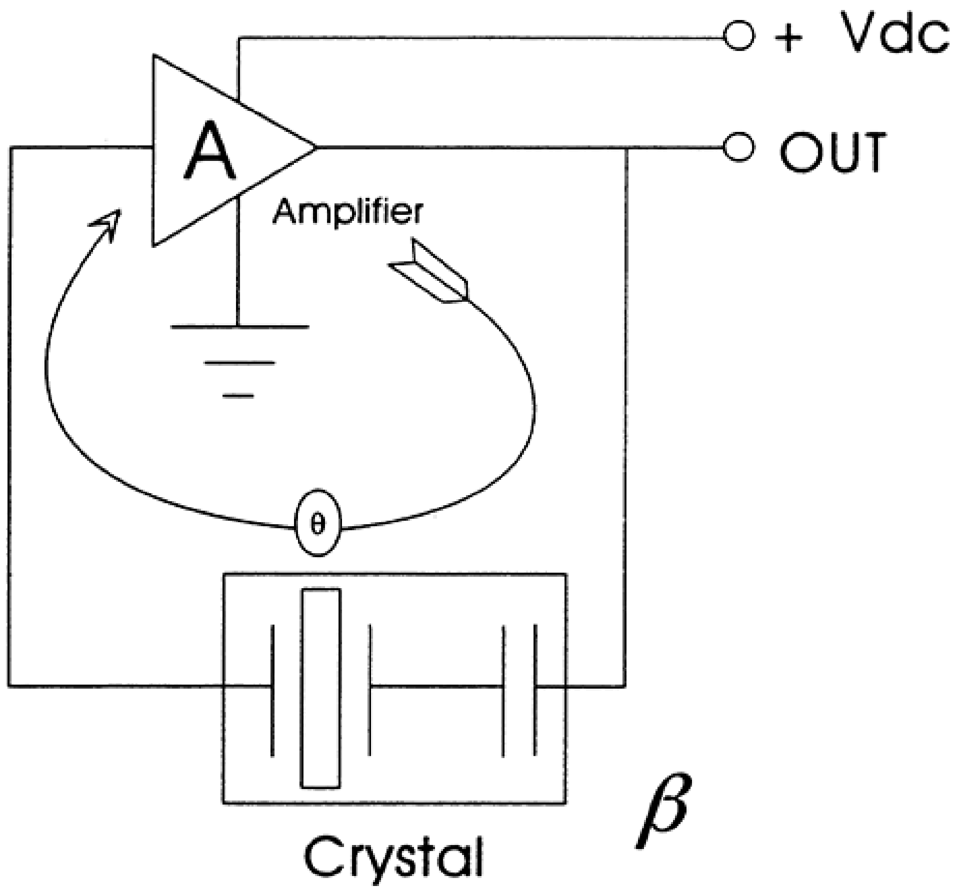
where $Z=(d_q\mu_q/d_f\mu_f)^{1/2}$ is the acoustic impedance ratio and μ_q and μ_f are the shear moduli of the quartz and film, respectively. Finally, there was a fundamental understanding of the frequency-to-thickness conversion that could yield theoretically correct results in a time frame that was practical for process control. To achieve this new level of accuracy it requires only that the user enter an additional material parameter, Z, for the film being deposited. This equation has been tested 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 [2] was valid to only $0.02F_q$ and equation [3] was valid only to approximately $0.05F_q$.

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)

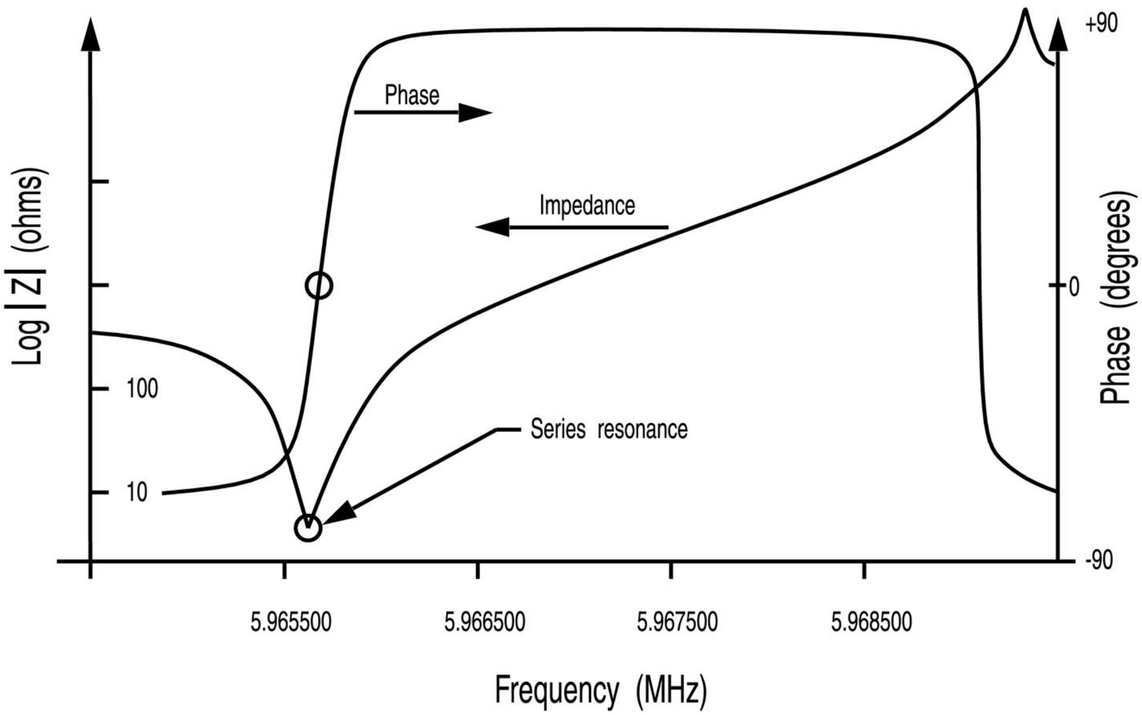
10.5 Active Oscillator

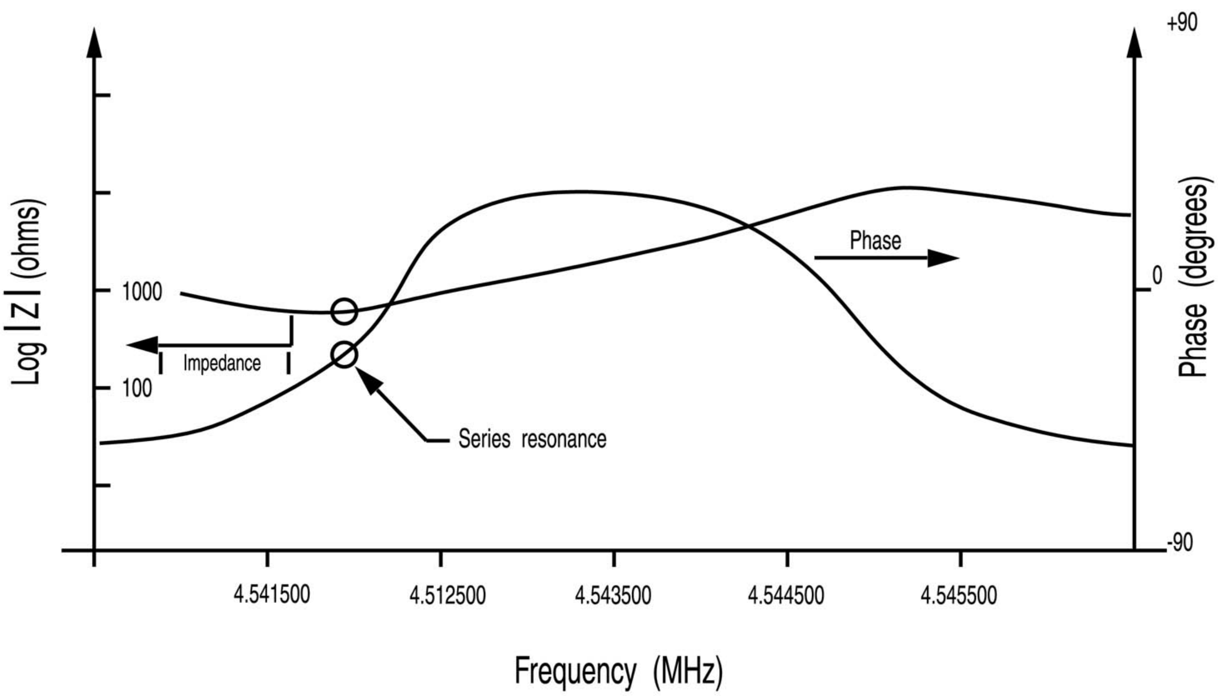
Much of the instrumentation developed to date has relied on the use of an active oscillator circuit, generally the type schematically shown in the figure below. This circuit actively keeps the crystal in resonance, so that any type of period or frequency measurement may be made. In this type of circuit, 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 stability is derived from the rapid change of phase for a small change in the crystal frequency near the series resonance point.



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. A heavily loaded crystal loses it steep phase slope. 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. 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 an active oscillator monitor will frequently continue to operate under these conditions; in fact there is no way to tell this has happened except that the film thickness is suddenly apparently thinner by an amount equivalent to the frequency difference between the fundamental and the anharmonic that is sustaining the oscillation.





10.6 ModeLock Measurement

INFICON created a technology that eliminates the active oscillator and its limitations. This system constantly tests the crystal response to an applied frequency in order to not only determine the resonant frequency, but also to verify that the crystal is oscillating in the desired mode. This system is essentially immune to mode hopping and the resulting inaccuracies. It is fast and accurate, and determines the crystal frequency to less than 0.0035 Hz at a rate of 10 times per second. Because of the ability of the system to identify and then measure particular crystal modes, it is now possible to offer additional features that take advantage of the informational content of these modes. This “intelligent” measurement system uses the phase/frequency properties of the quartz crystal to determine the resonant frequency. It operates by applying a synthesized sine wave of specific frequency to the crystal and measuring the phase difference between the applied voltage of the signal and the current passing through the crystal. At series resonance, this phase difference is exactly 0 degrees; that is, the crystal behaves like a pure resistance. By separating the applied voltage and the current returned from the crystal and monitoring the output of a phase comparator it is possible to establish whether the applied frequency is higher or lower than the crystal resonance point. At frequencies well below the fundamental, the crystal impedance is capacitive and at frequencies slightly higher than resonance it is inductive in nature. This information is useful if the resonance frequency of a crystal is unknown. A quick sweep of frequencies can be undertaken until the output of the phase comparator changes, marking the resonance event. For AT crystals, we know that the lowest frequency event encountered is the fundamental. The events slightly higher in frequency are anharmonics. This information is useful not only for initialization, but also for the rare case when the instrument loses track of the fundamental. Once the frequency spectrum of the crystal is determined, the task of the instrument is to follow the changing resonance frequency and to periodically provide a measurement of the frequency for subsequent conversion to thickness.

The use of the “intelligent” measurement system has a series of very apparent advantages when compared to the previous generation of active oscillators, namely immunity from mode hopping, speed of measurement and precision of measurement. The technique also allows the implementation of a sophisticated feature that cannot even be contemplated using the active oscillator approach. The same capability that allows the technology to sweep and identify the fundamental can be used to identify other oscillation modes, such as the anharmonics and the quasiharmonic. Not only can the instrument track the fundamental mode continuously, but also it can be implemented to alternate between one or more other modes. This interrogation of multiple modes can be performed as fast as 10 Hz for two modes of the same crystal.

11 Appendix A: Material Table

The following represents the density and Z-Ratio for various materials. The list is alphabetical, by chemical formula.

WARNING

Some of these materials are toxic. 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 certain material. A value of 1.000 is defaulted in these situations.

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_2O_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
BaN_2O_6	3.244	1.261	barium nitrate
BaO	5.720	*1.000	barium oxide
$BaTiO_3$	5.999	0.464	barium titanate (tetragonal)
$BaTiO_3$	6.035	0.412	barium titanate (cubic)

Formula	Density	Z-Ratio	Material Name
Be	1.820	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 trisulfide
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
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

Formula	Density	Z-Ratio	Material Name
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 sulfide
Ga	5.930	0.593	gallium
Ga_2O_3	5.880	*1.000	gallium oxide (beta)
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
Ge	5.350	0.516	germanium
Ge_3N_2	5.200	*1.000	germanium nitride
GeO_2	6.240	*1.000	germanium oxide

Formula	Density	Z-Ratio	Material Name
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	holmium
Ho_2O_3	8.410	*1.000	holmium oxide
In	7.300	0.841	indium
In_2O_3	7.180	*1.000	indium 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	lanthanum 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
$LiNbO_3$	4.700	0.463	lithium niobate
Lu	9.840	*1.000	lutetium
Mg	1.740	1.610	magnesium

Formula	Density	Z-Ratio	Material Name
$MgAl_2O_4$	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 trioxide
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	32.00	*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
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	neodymium
Nd_2O_3	7.240	*1.000	neodymium oxide
NdF_3	6.506	*1.000	neodymium fluoride
Ni	8.910	0.331	nickel

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	rubidium 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	sulfur
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

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 fluoride
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_2O_3	4.600	*1.000	titanium sesquioxide
TiB_2	4.500	*1.000	titanium boride
TiC	4.930	*1.000	titanium carbide

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
Tl	11.850	1.550	thallium
TlBr	7.560	*1.000	thallium bromide
TlCl	7.000	*1.000	thallium chloride
TlI	7.090	*1.000	thallium iodide (beta)
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 disulfide
WSi_2	9.400	*1.000	tungsten silicide
Y	4.340	0.835	yttrium
Y_2O_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

Formula	Density	Z-Ratio	Material Name
ZnSe	5.260	0.722	zinc selenide
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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