Operating Manual

IMM-100

Deposition Monitor

074-722-P1D

INFICON

Two Technology Place

East Syracuse, NY 13057-9714

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1 Disclaimer/Copyright

Disclaimer

The information contained in this Manual is believed to be accurate and reliable. However, INFICON assumes no responsibility for its use and shall not be liable for any special, incidental, or consequential damages related to the use of this product.

Due to our continuing program of product improvements, specifications are subject to change without notice.

Copyrights

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-100 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:	August 23, 2019
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

WARRANTY AND LIABILITY - LIMITATION: Seller warrants the products manufactured by it, or by an affiliated company and sold by it, to be, for the period of warranty coverage specified below, free from defects of materials or workmanship under normal proper use and service. The period of warranty coverage is specified for the respective products in the respective Seller instruction manuals for those products but shall not be less than two (2) years from the date of shipment thereof by Seller. Seller's liability under this warranty is limited to such of the above products or parts thereof as are returned, transportation prepaid, to Seller's plant, not later than thirty (30) days after the expiration of the period of warranty coverage in respect thereof and are found by Seller's examination to have failed to function properly because of defective workmanship or materials and not because of improper installation or misuse and is limited to, at Seller's election, either (a) repairing and returning the product or part thereof, or (b) furnishing a replacement product or part thereof, transportation prepaid by Seller in either case. In the event Buyer discovers or learns that a product does not conform to warranty, Buyer shall immediately notify Seller in writing of such non-conformity, specifying in reasonable detail the nature of such non-conformity. If Seller is not provided with such written notification, Seller shall not be liable for any further damages which could have been avoided if Seller had been provided with immediate written notification.

THIS WARRANTY IS MADE AND ACCEPTED IN LIEU OF ALL OTHER WARRANTIES, EXPRESS OR IMPLIED, WHETHER OF MERCHANTABILITY OR OF FITNESS FOR A PARTICULAR PURPOSE OR OTHERWISE, AS BUYER'S EXCLUSIVE REMEDY FOR ANY DEFECTS IN THE PRODUCTS TO BE SOLD HEREUNDER. All other obligations and liabilities of Seller, whether in contract or tort (including negligence) or otherwise, are expressly EXCLUDED. In no event shall Seller be liable for any costs, expenses or damages, whether direct or indirect, special, incidental, consequential, or other, on any claim of any defective product, in excess of the price paid by Buyer for the product plus return transportation charges prepaid.

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 primarily for use in physical vapor deposition processes, IMM-100 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 this electronics unit and a sensor head containing a quartz crystal. This Operating Manual provides user information for installing, programming and operating the electronics unit. 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].

4.1 Specifications

Measurement

Sensor inputs	One
Measurement frequency range	6.0 MHz (new crystal) to 4.5 MHz
Reference frequency stability	±2 ppm 0–50°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 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

Timestamp	Indicates timestamp tick, updated 10 times per second
Timestamp 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
Device reset	Emulates a power cycle on the instrument
Exception reset	Clears latched exceptions
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	EtherCAT, 2 RJ45 jacks, supports data daisy chaining. Explicit device ID via switches.
Protocol	Protocol specialized for EtherCAT
Standard	ETG.5003.1: Part 1 Common Device Profile (CDP)
Data rate	100 Mbps
Node address	Explicit Device Identification
Physical layer	100BASE-Tx (IEEE 802.3)
EtherCAT connector	RJ45 (quantity = 2), 8-pin (socket) <IN>: EtherCAT Input, <OUT>: EtherCAT output
EtherCAT cable	Shielded, special Ethernet patch cable (CAT5e quality or higher)
Cable length	<100 m
Process data	Fixed PDO mapping and configurable PDO mapping
Mailbox (CoE)	SDO requests, responses and information

LED Indicators

Status	Unit status
Run	EtherCAT operating status
Err	EtherCAT error content
In LA	EtherCAT in port link/activity
Out LA	EtherCAT out port link/activity

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 (1.05 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 frequency 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-100 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.

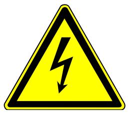
⚠ DANGER

Risk of Electric Shock

There are no user-serviceable components within the IMM-100 case. Potentially lethal voltages are present. Refer all maintenance to qualified personnel.

4.2.3 Earth Ground

A sealed three-core (three-conductor) power cable connects IMM-100 to earth ground. It 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 the 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-100 or disconnection of the protective earth terminal may cause dangerous voltages to be present on or inside IMM-100.

This symbol indicates where the protective earth ground is connected inside IMM-100. Never unscrew or loosen this connection.

4.3 How to Contact Us

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

- a Product Engineer with questions regarding applications for and programming IMM-100
- a Service Engineer with questions regarding troubleshooting, diagnosing or repairing IMM-100
- 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 IMM-100, please have the following information readily available:

- the serial number and IMM-100 software version numbers
- a description of the 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-100 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-100. 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-100 has not been removed from its shipping container, do so now.

1. Carefully examine IMM-100 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 [▸ 19].

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

4.5 Parts and Options Overview

IMM-100 Part Number

785-600-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 24V (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-100 mounting bracket with four shock absorbing, male-to-female, black Neoprene rubber mounting feet.

785-202-G1: IMM-100 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-P1	Ethernet communication cable, 1 m (3.3 ft.)
600-1190-P2	Ethernet communication cable, 0.3 m (0.98 ft.)

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

4.5.1 Optional Mounting Bracket Kit

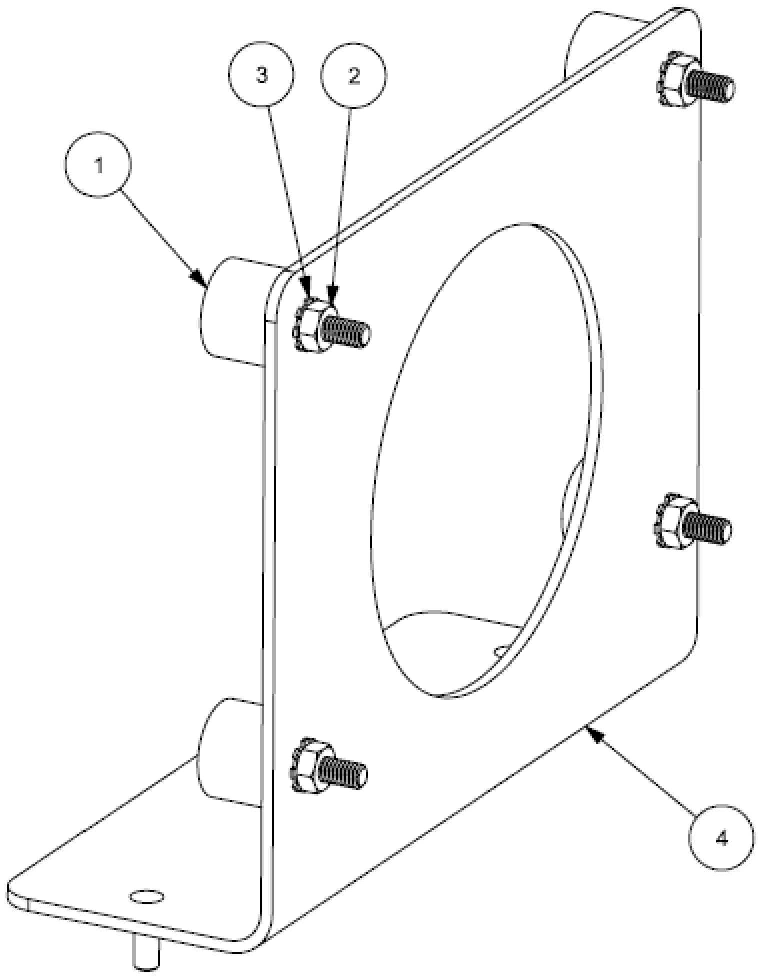
⚠ WARNING

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-100.

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-100 and the mounting bracket (approximately 0.68 kg (1.5 lbs.)).

NOTICE

When mounting IMM-100 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-100 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-100 can be made before installation. It is not necessary to have sensors or communication cables connected to do this.

The green instrument **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 a user supplied power supply with a power rating indicated by **Power**, in Specifications [▸ 9].

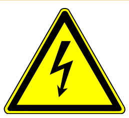
INFICON recommends the power connection to IMM-100 use a Kycon connector, part number KPPX-4P. Pins 3 and 4 carry +24 V (dc), pins 1 and 2 are ground. Whenever a user supplied power supply is used, the connector shield on the 24 V power cable must be connected to the mains protective earth ground terminal 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-100. If a good crystal is not connected, the **Status** LED illuminates 1 s on,1 s off, to indicate a crystal fail. IMM-100 is in **Idle** if the **Status** LED flash pattern is 1 s on, 4 s off.

If the **Status** LED light 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 light is off, confirm that the proper power is connected to IMM-100. 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-100. Never unscrew or loosen this connection.

See also

Parts and Options Overview [▸ 16]

5 Installation and Interfaces

Before permanently installing IMM-100, 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-100.

NOTICE

Use caution when mounting IMM-100 to a fixed position. Ensure there is enough room to disconnect the power cord when needed.

5.1 Sensor Types and Installation

Sensor Types

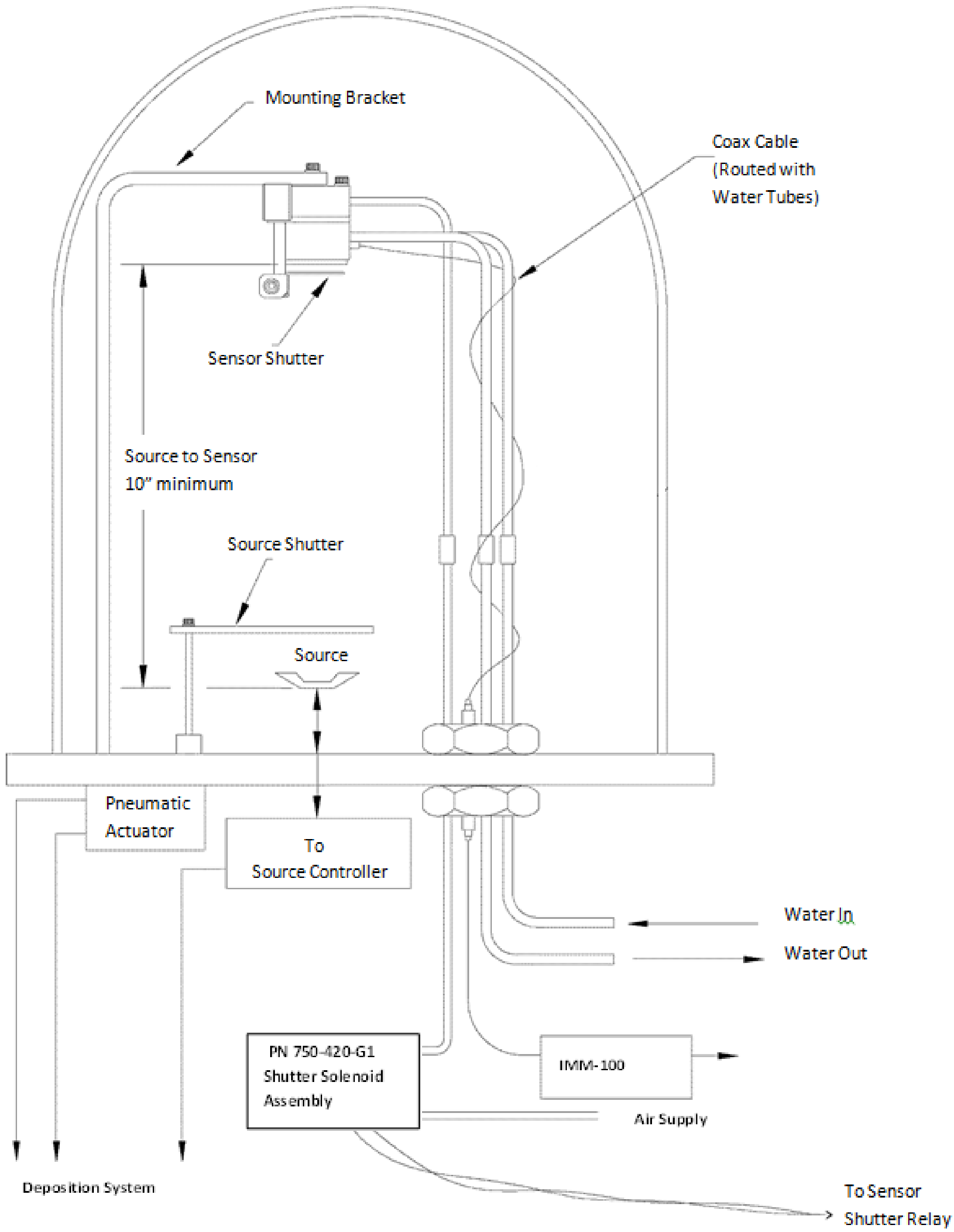
The choice of sensor type is dictated by the process, the deposition material and the physical characteristics of the process chamber. General guidelines for each sensor type produced by INFICON are outlined in the Sensor Data Sheets on the www.INFICON.com website. For specific recommendations, consult your INFICON representative.

⚠ CAUTION

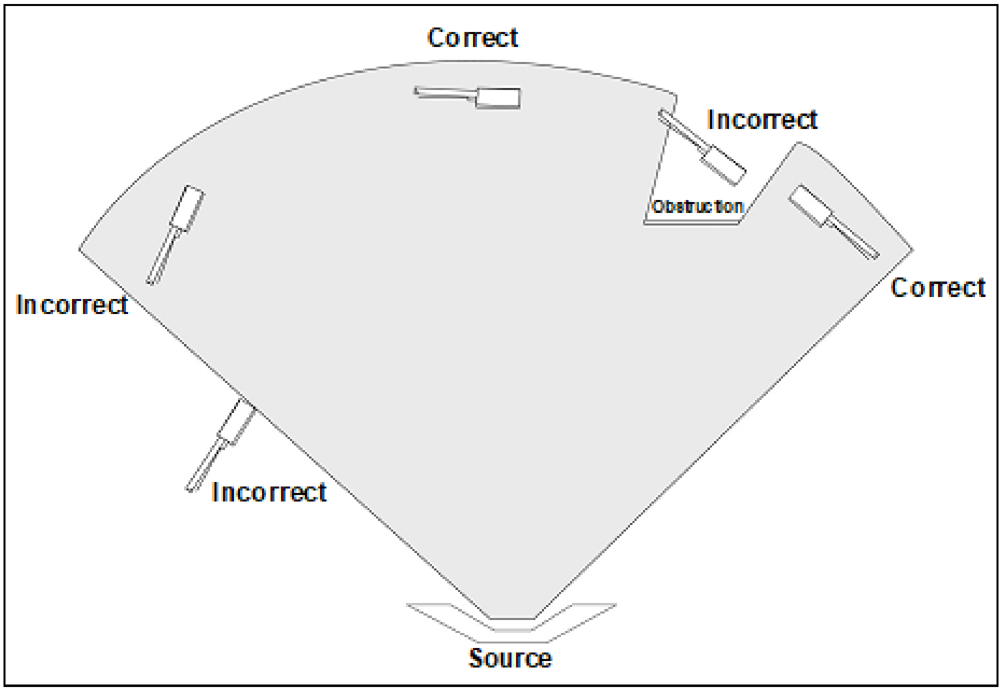
The performance of IMM-100 depends on the careful installation of the chosen transducer. Improper installation will cause problems with deposition repeatability, crystal life, and rate stability.

Sensor Installation

The figure below shows a typical installation of an INFICON water cooled crystal sensor in the vacuum process chamber. Use the illustration and the following guidelines to install your sensors for optimum performance and convenience.



Generally, install the sensor as far as possible from the evaporation source (a minimum of 25.4 cm (10 in.) is recommended) while still being in a position to accumulate thickness at a rate proportional to accumulation on the substrate. Proper sensor placement positions the face of the crystal normal to the evaporation source, is within the material flux plume, and is not obstructed from a line of sight to the source.



To guard against splattering, use a source shutter or crystal shutter to shield the crystal during the initial soak periods. If the crystal is hit with even a minute particle of molten material, it may be damaged and stop oscillating. Even in cases when it does not completely stop oscillating, it may become unstable. Follow these precautions:

- Mount the sensor to something rigid and fixed in the chamber. Do not rely on the water tubes to provide support.
- Plan the installation to ensure there are no obstructions blocking the path between the sensor and the source. Be certain to consider rotating or moving fixtures.
- Install sensors so their central axis (an imaginary line drawn normal to the center of the crystal face) is aimed directly at the virtual source being monitored.
- Be sure there is easy access for the exchange of crystals.

For systems employing simultaneous source evaporation (codeposition), try to locate the sensors so evaporant from each source is flowing to only one sensor. It is not generally possible to do this without special shielding or optional “material directors” (PN 750-201-G1).

5.2 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-100 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:

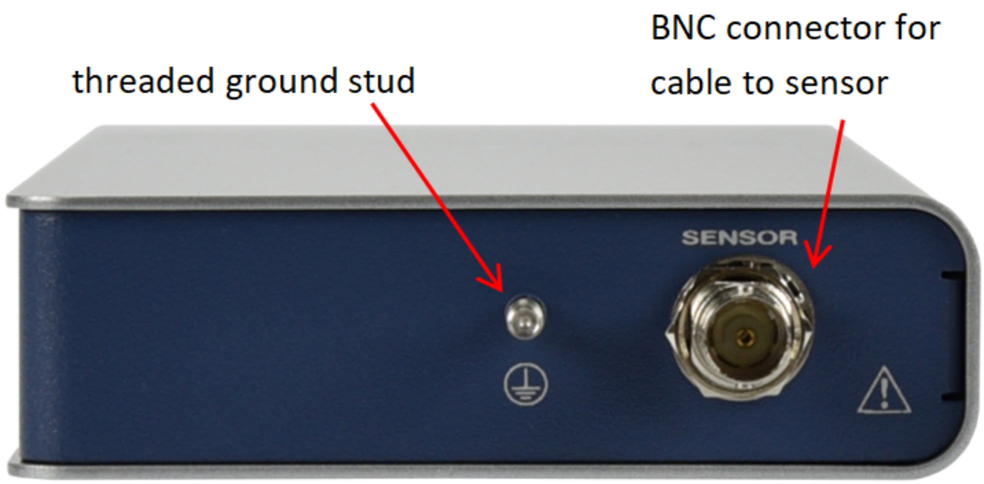
- Where soil conditions allow, drive two ten-foot copper clad steel rods into the ground six feet apart. Pour a copper sulfate or a salt solution around each rod to improve the ground's conduction. A near-zero resistance measurement indicates earth ground is achieved.

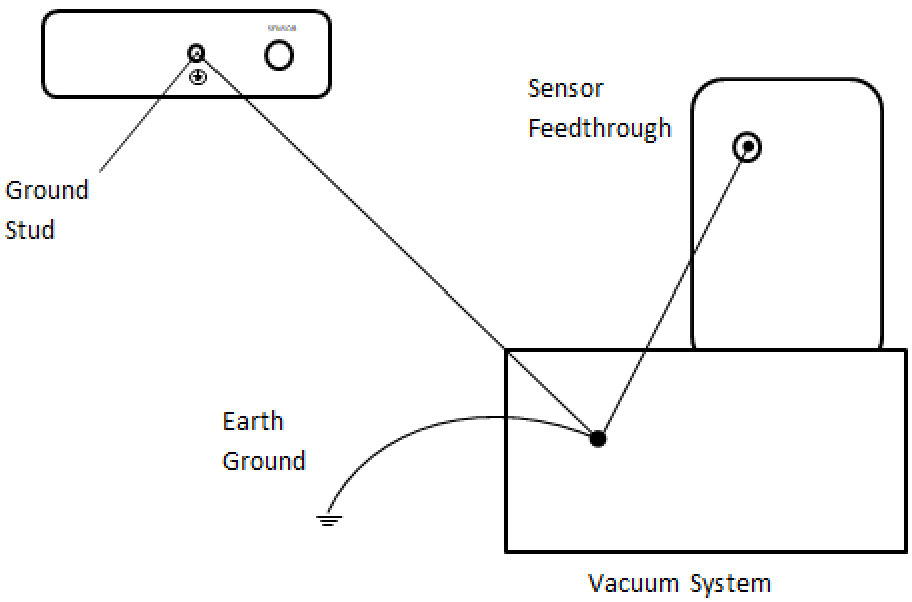
⇨ Keep the connections to this grounding network as short as possible.

Connections to Earth Ground

There are two required earth ground connections:

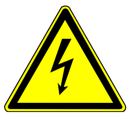
1. The earth ground connection on IMM-100 is a threaded stud with a hex nut. Connect a ring terminal to the ground strap, allowing a good connection and easy removal and installation. This connection must be made at installation. For best protection against high frequency noise, the length-to-width ratio of the earth conductor should not exceed a ratio of 5:1. The ground strap should connect from IMM-100 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-100 or disconnection of the protective earth terminal may cause dangerous voltages to be present on or inside IMM-100.

This symbol indicates where the protective earth ground is connected inside IMM-100. 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-100 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-100. 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 [▸ 23].
- Ensure that all IMM-100 covers are in place and tightly secured with the provided fasteners.

Always use shielded cables when making connection to IMM-100 to minimize electrical noise pickup.

5.3 Connecting the Instrument

For operating IMM-100 via EtherCAT, interface cables conforming to the EtherCAT standard are required.

If IMM-100 is the only connection on the network, a single cable is necessary. Connect the cable to the <IN> port.

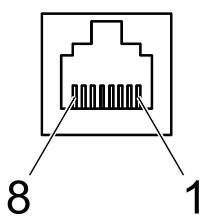
To form a daisy chain to other devices on the network, two cables are necessary. The cable from the previous device <OUT> port is connected to IMM-100 <IN> port. Then connect a cable from IMM-100 <OUT> port to the next device <IN> port.

When viewing the end of IMM-100, the <IN> port is on the right. The <OUT> port is on the left, near the power connector.

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 a FCC68 connector.

Pin Assignment



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

Pin	Signal	Description
5	nu	Not used
6	RD-	Receive data -
7	nu	Not used
8	nu	Not used

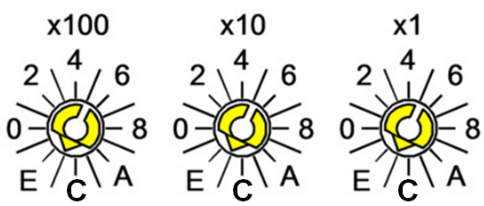
5.4 Indicators and Switches

5.4.1 Device Address Switch

EtherCAT allows for three device addressing schemes. The first is automatic addressing based on the relative location of the slave device in the EtherCAT network loop. The second is by setting address switches on the slave device. The third, which should only be used for compatibility reasons, is to set the **Configured Station Alias** in SII EEPROM. Normally, the **Configured Station Alias** should be set to 0. If using the **Configured Station Alias**, the **ID Selector** switches must be set to 0.

Three switches can be set by the user to select the slave device address.

The switches, as seen from the end of IMM-100, appear as:



Only the **Rotary ID Selector Switches** (**Explicit Device ID**) or the **Configured Station Alias** stored in EEPROM may have a non-zero value at any time.

During device initialization, the device address switches are read by the device firmware. This device address is reported to the master as the Explicit Device Identification.

Example: Value of the Explicit Device ID = 0xDDD (dec 3549):

0x100 * 0xD (dec 3328) + 0x10 * 0xD (dec 208) + 0x1 * 0xD (dec 13)

5.4.2 <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.

5.4.3 <RUN> LED

Green LED displays the EtherCAT operating status.

Run	Description
off	The unit is in INIT (initialization status) or there is no power applied to the device.
flickering (20 ms on 20 ms off)	The unit is in BOOT (bootstrap status).
blinking (200 ms on 200 ms off)	The unit is in PREOP (pre-operational status).
single flash (200 ms on 1000 ms off)	The unit is in SAFEOP (safe-operational status).

Run	Description
	There is a communication of cyclic data transfer running. Input values are available, and output values are written to the device, but not updated on the device output.
on	The unit is in **OP** (operational status).

5.4.4 <ERR> LED

Red LED displays the error content.

LED State	Description
off	There is no error or no power is applied to the device.
blinking (200 ms on 200 ms off)	An error has occurred.
single flash (200 ms on 1000 ms off)	A slave device application has changed the EtherCAT state autonomously, due to a local error.
double flash (200 ms on 200 ms off 200 ms on 1000 ms off)	An application watchdog timeout has occurred. The **Sync Manager Watchdog Timeout** or communication timeout occurred.
on	A critical communication or application controller error has occurred. The application controller is not responding any more (a PDI **Watchdog Timeout** detected by ESC).

5.4.5 <LA> LED under EtherCAT (<IN> Port)

Green LED displays the input link/activity status.

LED State	Description
off	The port is not connected or no power is applied to the device.
blinking	The port is connected and communication is active.
on	The port is connected but there is no communication.

5.4.6 <LA> LED under EtherCAT (<OUT> Port)

Green LED displays the output link/activity status.

LED State	Description
off	The port is not connected or no power is applied to the device.
blinking	The port is connected and communication is active.
on	The port is connected but there is no communication.

6 Special Features

6.1 Introduction

To enhance its performance and allow easier integration into a system having rotary sensor heads, IMM-100 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-100 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-100 measurements.

6.3 Start/Stop Measurement

The **Start/Stop Measurement** remote communications command indicates to IMM-100 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-100 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-100 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-100 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-100. To reduce the deposition thickness error on the substrate, the time between **Stop Measurement** and **Start Measurement** commands should be minimized.

6.4 Crystal Type

Crystals cut from different crystallographic orientations of quartz can be used with IMM-100. 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 the acoustic impedance of 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-100. 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 EtherCAT Communications

7.1 EtherCAT Introduction

Intended Use

This communication protocol contains instructions for operating EtherCAT interfaces (slaves) together with a master.

EtherCAT Interface

The following description of the EtherCAT interface is compliant to the EtherCAT specification of the EtherCAT Technology Group (ETG). This manual describes the functionality of an EtherCAT slave and supports ETG.5003.1 S (R) V1.0.0 : Part 1 Common Device Profile (CDP).

Product Identification

In all communications with INFICON, please specify the information on the product nameplate.

Via the EtherCAT interface, the following and further data are exchanged in the standardized EtherCAT protocol:

- frequency
- rate
- thickness
- activity
- crystal life consumed
- user timer
- zero commands
- start/stop measuring commands
- status, warning and error messages

7.1.1 Abbreviations

Abbreviation	Description
Access	SDO read/write access RO: object can only be read by the SDO service RW: object can be both read and written by the SDO service
CoE	CAN application protocol over EtherCAT
Index	Object Index (hex.) (address of an object)
NV	Nonvolatile; attribute value is maintained through power cycles.

Abbreviation	Description
Object	Abstract representation of a particular component within a device, which consists of data, parameters, and methods.
PDO	Process data object. Structure described by mapping parameters containing one or several process data entities.
PM	PDO Mapping Rx: object can be mapped into a RxPDO Tx: object can be mapped into a TxPDO
RxPDO	Receive PDO. A Process Data Object received by an EtherCAT slave.
SDO	Service data objects. CoE asynchronous mailbox communications where all objects in the Object Dictionary can be read and written.
SI	Subindex (hex.) (sub-address of an object)
SM	Sync manager
Type	Data type See Data Type Code [▷ 35]
TxPDO	Transmit PDO. A process data object sent from an EtherCAT slave.
ESC	EtherCAT slave controller

7.1.2 Data Type Code

BOOL, BIT	1 bit. Boolean (0 = false, 1 = true)
USINT, BYTE	8 bit. Unsigned byte
UINT	16 bit. Unsigned integer value
UDINT	32 bit. Unsigned integer value
ULINT	64 bit. Unsigned integer value
REAL	32 bit. Floating point
LREAL	64 bit. Floating point
STRING(X)	8×n bit. Visible string (1 byte for character)

7.1.3 Literature

[1] ETG.5003.1: Semiconductor Device profile – Part 1: Common Device Profile (CDP)

7.2 Object Structure

7.2.1 Object Dictionary Structure

This chapter describes the CAN Application Protocol over EtherCAT (CoE) Object Dictionary.

The objects in the CoE object dictionary are accessed with SDO services and many of the dictionary objects can be mapped for cyclic communication in PDOs. Each object is addressed using a 16-bit index and an 8-bit subindex.

The following table presents the overall layout of the standard object dictionary.

Index (hexadecimal)	Object Dictionary Area	
1000 – 1FFF	Communication profile area	
2000 – 5FFF	Manufacturer-specific profile area	
6000 – 6FFF	Profile specific area	Input area
7000 – 7FFF		Output area
8000 – 8FFF		Configuration area
9000 – 9FFF		Information area
A000 – AFFF		Diagnosis area
B000 – BFFF		Service Transfer area
C000 – EFFF		Reserved area
F000 – FFFF		Device area

7.2.2 Communication Profile Objects (0x1000…0x1FFF)

The objects of the communication profile describe the basic EtherCAT properties of IMM-100 and are common to all EtherCAT slaves using the CoE communication protocol. The objects are described in following table:

Index	SI	DataType	NV	Access	PM	Name
1000		UDINT		RO		Device type
1008		V_STRING (9)		RO		Manufacturer device name
1009		V_STRING (10)		RO		Manufacturer hardware version
100A		V_STRING (80)		RO		Manufacturer software version

Index	SI	DataType	NV	Access	PM	Name
1018				RO		Identity object
	0x01	UDINT		RO		Vendor ID
	0x02	UDINT		RO		Product code
	0x03	UDINT		RO		Revision number
	0x04	UDINT		RO		Serial number
10F8		ULINT		RO		Timestamp object

7.2.2.1 Process Data Objects (PDOs)

The TxPDO 1A01 and the RxPDO 1601 are designated for user mapping. These PDOs do not have default values and can be set up using the PDO configuration.

RxPDOs

Index	SI	DataType	NV	Access	PM	Name
1600		PM		RW		RxPDO receive PDO mapping
1601		PM		RW		RxPDO receive PDO mapping, user mapping

TxPDOs

Index	SI	DataType	NV	Access	PM	Name
1A00		PM		RW		TxPDO transmit PDO mapping
	0x01	ULINT		RW		Timestamp [100 ms]
	0x02	UDINT		RW		Timestamp warning
	0x03	UDINT		RW		Unit status
	0x04	LREAL		RW		Frequency [Hz]
	0x05	LREAL		RW		Value not in use
	0x06	LREAL		RW		Value not in use
	0x07	LREAL		RW		Rate raw [Å/s]

Index	SI	DataType	NV	Access	PM	Name
	0x08	LREAL		RW		Rate filtered [Å/s]
	0x09	LREAL		RW		Thickness [kÅ]
	0x0A	UDINT		RW		Deposition status
	0x0B	UDINT		RW		Activity
	0x0C	UDINT		RW		Stability accumulated [Hz]
	0x0D	UDINT		RW		Stability single [Hz]
	0x0E	UDINT		RW		Life consumed [%]
	0x0F	UDINT		RW		Crystal status
	0x10	UDINT		RW		Value not in use
	0x11	UDINT		RW		User timer [µs]
	0x12	UDINT		RW		Communication status
1A01		PM				TxPDO transmit PDO mapping, user mapping
1C00	0x01 0x02 0x03 0x04	BYTE		RW		Sync manager type
1C12 / 1C13	0x01 0x02	UINT		RW		Sync manager PDO assignment
1C33	0x01 - 0x20			RW		Sync manager parameter

7.2.3 Manufacturer-Specific Profile Objects (0x2000...0x5FFF)

The manufacturer-specific profile objects contain the manufacturer's model number and device configuration data, status, and diagnostic data.

There are no available objects here.

7.2.4 Input Area (0x6000…0x6FFF)

7.2.4.1 Input Common

Input Deposition Module

Index	SI	DataType	NV	Access	PM	Name
6001	0x01	ULINT		RO	tx	Timestamp [100 ms]
	0x02	ULINT		RO	tx	User timer [µs]
	0x03	LREAL		RO	tx	Rate raw [Å/s]
	0x04	LREAL		RO	tx	Rate filtered [Å/s]
	0x05	LREAL		RO	tx	Thickness [kÅ]
	0x06	LREAL		RO	tx	Value not in use
	0x07	LREAL		RO	tx	Value not in use

Timestamp

Subindex 0x01

A unique value that indicates the current timestamp tick of the sensor. The value is incremented once every 100 ms.

User Time

Subindex 0x02

This value indicates the current user timer value in microseconds.

Raw Rate

Subindex 0x03

IMM-100 State	Crystal Status	Raw Rate Value
Measure	Initializing	Default value of 0
Measure	Good	Most recent Raw Rate value in Å/s
Measure	Marginal or Failure	Delayed average of the previous Raw Rate values
Idle		Frozen at the last known value

Rate Filtered

Subindex 0x04

IMM-100 State	Crystal Status	Rate Filtered Value
Measure	Initializing	Begins at the default value of 0 on startup or the last known filtered rate value after a Start Measuring command
Measure	Good, Marginal, or Failure	Most recent calculated rate filter value in Å/s
Idle		Frozen at the last known value

Thickness

Subindex 0x05

IMM-100 State	Crystal Status	Thickness Value
Measure	Initializing	Begins at the default value of 0 on startup or the last known filtered rate value after a Start Measuring command
Measure	Good or Marginal	The most recent thickness value calculated in kÅ
Measure	Failure	Frozen at the last known value
Idle		Frozen at the last known value

Value not in use

Subindex 0x06

This value is not currently in use.

Value not in use

Subindex 0x07

This value is not currently in use.

Input Deposition Status

Index	SI	Data Type	NV	Access	PM	Name
6002	0x01	UDINT		RO	tx	Deposition Status
	0x02	INIT		RO	tx	Value not in use
	0x03	INIT		RO	tx	Value not in use

Deposition Status

Subindex 0x01

While IMM-100 is in Measure, deposition status value indicates the current deposition status.

Once the maximum thickness is reached, the deposition status is held at 1 until one of the following occurs:

The thickness is zeroed

OR

The density, Z-ratio or max thickness configuration values are altered. The deposition status is re-evaluated after one of these actions occurs.

While in idle the deposition status value is 99.

Deposition Status	
0	Thickness < Max Thickness
1	Thickness ≥ Max Thickness

Deposition Status	
98	Unknown
99	Not in Measure

Value not in use

Subindex 0x02

This value is not currently in use.

Value not in use

Subindex 0x03

This value is not currently in use.

Input Sensor Module

Index	SI	Data Type	NV	Access	PM	Name
6003	0x01	UDINT		RO	tx	Crystal Status
	0x02	LREAL		RO	tx	Frequency [Hz]
	0x03	UDINT		RO	tx	Activity
	0x04	UDINT		RO	tx	Life Consumed [%]
	0x05	UDINT		RO	tx	Value not in use

Crystal Status

Subindex 0x01

While IMM-100 is in **Measure**, the crystal status value indicates the current crystal status.

While in Idle the crystal status is 99.

Crystal Status	
0	Initializing
1	Good
2	Marginal
3	Failure
98	Unknown
99	Not in Measure

Frequency

Subindex 0x02

IMM-100 State	Crystal Status	Frequency Value
Measure	Initializing	Begins at the default value of 0,once available it is the most recent frequency value calculated in Hertz

IMM-100 State	Crystal Status	Frequency Value
Measure	Good	Current frequency value in Hertz
Measure	Marginal	Either frozen at last good value or current frequency value in Hertz
Measure	Failure	Frequency is frozen at last known value
Idle		Frequency is 0 while in Idle

Activity

Subindex 0x03

IMM-100 State	Crystal Status	Activity Value
Measure	Initializing	Begins at the default value of 0,once available it is the most recent frequency value calculated in Hertz
Measure	Good	The most recent value
Measure	Marginal	Either frozen at last known value or the current value measured. The frozen value occurs just before or after a crystal fail is detected
Measure	Failure	Frozen at the last known value
Idle		Activity value is 0

Life Consumed

Subindex 0x4

IMM-100 State	Crystal Status	Crystal Life Consumed Value
Measure	Initializing	Begins at the default value of 99, once available it is the most recent value calculated in percent
Measure	Good	The most recent life consumed value in percent
Measure	Marginal	Either frozen at the last known value or the current life consumed value. The frozen value occurs just before and after a crystal failure is detected The current life consumed value occurs just before the crystal recovers and the crystal status is good again.
Measure	Failure	Frozen at the last known value
Idle		Frozen at the last known value

Value not in use This value is not currently used.

Subindex 0x5 Input Common Module

Index	SI	Data Type	NV	Access	PM	Name
6004	0x01	UDINT		RO	tx	Unit Status
	0x02	UDINT		RO	tx	Communication Status
	0x03	UDNIT		RO	tx	Timestamp Warning

Unit Status This value indicates the current unit status.

Subindex 0x01

Unit Status	
0	Unknown/Error
1	Measure
2	Idle
100	Reserved
101	Reserved
102	Reserved

This value warns if IMM-100's internal communication is not operating.

Communication Status

Subindex 0x02

Communication Status	
0	None
1	Warning, Base Device not responding
2	Error, Base Device not responding

Timestamp Warning This value warns if the timestamp tick has reached the maximum value.

Subindex 0x03

Timestamp Warning	
0	None
1	Warning, timestamp tick value is at its maximum value

7.2.5 Output Area (0x7000...0x7FFF)

7.2.5.1 Output Command

Index	SI	DataType	NV	Access	PM	Name
7002	0x01	BYTE		RW	rx	Command Measure Start Stop
	0x02	BYTE		RW	rx	Command Zero

Command Measure Start Stop Subindex 0x01

Execution of this command causes the device to either start or stop measuring frequency. 0-stop, 1-start. All other values are invalid.

Command		
Byte 0		
	0	Stop
	1	Start

Command Zero Subindex 0x02

The execution of the **Zero** command causes the device to zero the following parameters: 1-thickness, 2-timer, 3-both. All other are values invalid.

Command		
Byte 0		
	1	Thickness
	2	User timer
	3	Thickness and user timer

7.2.6 Configuration Area (0x8000…0x8FFF)

7.2.6.1 Configuration Deposition 1

Index	SI	DataType	NV	Access	PM	Name
8003	0x01	STRING(29)		RW		Material name
	0x03	REAL	x	RW	rx	Material density
	0x04	REAL	x	RW	rx	Material Z-ratio
	0x05	REAL	x	RW	rx	Material tooling
	0x06	REAL	x	RW	rx	Material max thickness
	0x07	REAL	x	RW	rx	Material rate filter time
	0x08	UDINT	x	RW	rx	Crystal type, encoded

Material Name, Subindex 0x01: This value is a 29 character string.

Subindex 0x02: This value is not used.

Material Density, Subindex 0x03: The value range is 0.40 to 99.99 g/cm^3.

This parameter is specific to the material being deposited onto the crystal. It is one of two parameters that relate the mass loading on the crystal to a thickness. The default value is 1.00.

An alteration to the material density configuration causes the thickness values to be rescaled accordingly.

Material Z-Ratio

Subindex 0x04

The value range is 0.100 to 9.999.

This parameter is specific to the material being deposited. It is one of two parameters that relate the mass loading on the crystal to the material thickness accumulated on the crystal. The default value is 1.000.

Material Tooling

Subindex 0x05

The value range is 10.0 to 999.9%.

The default value is 100.0%

Material Maximum Thickness

Subindex 0x06

The value range is 0.0 to 9999.9 kÅ.

The **Material Maximum Thickness** parameter is the thickness threshold used in the deposition status calculations. The default value is 0.0 kÅ.

Material Rate Filter Time

The value range is 0.0 to 30.0 s in 0.1 s increments. The default value is 0.0.

Crystal Type

Subindex 0x08

Encoding	Crystal Type
0	AT
1	BT
2	IT
3	SC

The default value is 0.

7.2.7 Information Area (0x9000…0x9FFF)

This area is not used.

7.2.8 Device Area (0xF000...0xAFFF)

7.2.8.1 Industry Device Profile

Index	SI	DataType	NV	Access	PM	Name
F000	0x01	UINT		RO		Index distance

Index	SI	DataType	NV	Access	PM	Name
	0x02	UINT		RO		Maximum number of modules

Index Distance Subindex 0x01 Index offset between PDO entries of two consecutive modules (for ETG.5003 = 0x10), e.g. 0x6000, 0x6010.

Number of Modules Subindex 0x02 The instrument always has 1.

7.2.8.2 Module Profile List

Index	SI	DataType	NV	Access	PM	Name
F010	0x01	UDINT		RO		Profile Number Module 1

Profile Number Module Each subindex lists the profile number of the corresponding module.

7.2.8.3 Active Exception Status

Index	SI	DataType	NV	Access	PM	Name
F380		USINT		RO	tx	Active exception status

Active Exception Status

Bit 0	Device, communication status, or timestamp warning. The warning is set when crystal status is marginal (2), unknown (98), or base devicenot responding (1)
Bit 1	Not used
Bit 2	Device or communication error. The error set when crystal status is failure(3), base device not responding (2),or unit status is unknown/error (0)
Bit 3	Not used
Bit 4…7	0

7.2.8.4 Latched Exception Status

Index	SI	DataType	NV	Access	PM	Name
F390		USINT		RO	tx	Latched Exceptions Status

Latched Exceptions Status Latched version of the Active Exception Status (0xF380).

7.2.8.5 Input Latch Local Timestamp

Index	SI	DataType	NV	Access	PM	Name
F6F0	0x01	UDINT		RO	tx	Input Latch Local Timestamp. Mandatory if device has inputs (TxPDOs)

Input Latch Local Timestamp

Subindex 0x01

This parameter describes the local controller time corresponding to the input latch time in microseconds. It starts at zero on device power-up. This is mandatory if the device has inputs. If the device has no inputs defined, this parameter corresponds to the time immediately prior to writing to input sync manager (SM).

7.2.8.6 Configuration Device

Index	SI	Data Type	NV	Access	PM	Name
F840	0x01	UDINT		RW		AC Line Frequency, Encoded

Device AC Line Frequency

Subindex 0x01

0	50 Hz
1	60 Hz

The default value is 0.

7.2.8.7 Information Device

Index	SI	DataType	NV	Access	PM	Name
F940	0x01	USINT		RO		Number of sensors
	0x04	STRING(20)		RO		Firmware version base device
	0x07	STRING(20)		RO		Hardware version base device
	0x08	STRING(20)		RO		Firmware version adapter
	0x11	STRING(20)		RO		Hardware version adapter
F9F0		STRING(80)		RO		Manufacturer serial number

Index	SI	DataType	NV	Access	PM	Name
F9F1	0x01	UDINT		RO		CDP functional generation number module 1
F9F2	0x01	UDINT		RO		SDP functional generation number module 1
F9F3		STRING(80)		RO		Vendor name
F9F4	0x01	STRING(5)		RO		SDP device name module 1
F9F5	0x01	USINT		RW	Rx Tx	Output identifier module 1
F9F6		UDINT		RO		Time since power on
F9F7		UDINT		RO		Total time since IMM-100 powered on
F9F8		UDINT		RO		Firmware update functional generation number

Version IMM-100

If the device consists of several software portions, this parameter should be used.

Subindices 0x04, 0x07, 0x08, 0x11(F940)

Using standard a.b.c. format to describe a version:

Version (Index F940)	
a	Major revision
b	Minor revision
c	Timestamp

7.2.8.8 Measure Start/Stop Command

Execution of this command causes the device to either start or stop measuring frequency.

Index	SI	DataType	NV	Access	PM	Name
FB45	0x01	ARRAY [0..1] OF BYTE		RW		Command
	0x02	USINT		RO		Status
	0x03	ARRAY [0..1] OF BYTE		RO		Response

The Stop Measure command, followed by the Start Measure command, always includes a crystal initialization sequence.

A **Stop Measure** command is sent when the following byte sequence is sent:

Command

Subindex 0x01

Command	
Byte 0	0, mode
Byte 1	1, module

A **Start Measure** command is sent when the following byte sequence is sent:

Command	
Byte 0	1, mode
Byte 1	1, module

Status

Subindex 0x02

Status (supported values)	
0	Last command completed, no error, no response
1	Reserved
2	Last command completed, error, no response
3	Reserved
255	Command is executing

Response

Subindex 0x03

Response	
Byte 0	See Subindex 0x02

7.2.8.9 Zero Command

The execution of the **Zero** command causes the device to zero the indicated field(s).

Index	SI	DataType	NV	Access	PM	Name
FB46	0x01	ARRAY [0..1] OF BYTE		RW		Command
	0x02	USINT		RO		Status
	0x03	ARRAY [0..1] OF BYTE		RO		Response

Command

Subindex 0x01

A **Zero Thickness** command is sent when the following byte sequence is sent.

Command	
Byte 0	1, mode
Byte 1	1, module

A **Zero Timer** command is sent when the following byte sequence is sent.

Command	
Byte 0	2, mode
Byte 1	1, module

A **Zero Timer and Thickness** command is sent when the following byte sequence is sent.

Command	
Byte 0	3, mode
Byte 1	1, module

Status

Subindex 0x02

0	Last command completed, no error, no response
1	Reserved
2	Last command completed, error, no response
3	Reserved
255	Command is executing

Response

Subindex 0x03

Byte 0	See Subindex 0x02

7.2.8.10 Default Parameters Command

The execution of the **Default Parameters** command causes the device to default the parameters detailed in 0x8003, Configuration Deposition 1 [▸ 44].

Index	SI	DataType	NV	Access	PM	Name
FB47	0x01	ARRAY [0..1] OF BYTE		RW		Command
	0x02	USINT		RO		Status
	0x03	ARRAY [0..1] OF BYTE		RO		Response

Command

Subindex 0x01

A **Default Parameters** command is sent when the following byte sequence is sent.

Command	
Byte 0	1, mode

Command	
Byte 1	1, module

Status

Subindex 0x02

Status (supported values)	
0	Last command completed, no error, no response
1	Reserved
2	Last command completed, error, no response
3	Reserved
255	Command is executing

Response

Subindex 0x03

Response	
Byte 0	See Subindex 0x02

7.2.8.11 Device Reset Command

Execution of the **Device Reset** command causes the device to emulate a complete power cycle. This includes an ESC (standard) reset.

As a consequence of an ESC reset, all EtherCAT devices following IMM-100 for which the ESC reset has been performed are disconnected from the network.

There are two versions of the **Device Reset** command:

- standard reset (as described above)
- factory reset (not supported)

Index	SI	DataType	NV	Access	PM	Name
FBF0	0x01	ARRAY [0..5] OF BYTE		RW		Command
	0x02	USINT		RO		Status
	0x03	ARRAY [0..1] OF BYTE		RO		Response

Command

Subindex 0x01

A device reset is initiated when the following byte sequence is sent.

Command	
Byte 0	0x74
Byte 1	0x65
Byte 2	0x73
Byte 3	0x65

Command	
Byte 4	0x72
Byte 5	0x00 = Standard reset

Status

Subindex 0x02

Status (supported values)	
0	Reserved
1	Reserved
2	Last command completed, error, no response
3	Reserved
255	Command is executing

Response

Subindex 0x03

Byte 0	See Subindex 0x02

7.2.8.12 Exception Reset Command

Execution of this command clears the latched exceptions.

Index	SI	DataType	NV	Access	PM	Name
FBF1	0x01	ARRAY [0..4] OF BYTE		RW		Command
	0x02	USINT		RO		Status
	0x03	ARRAY [0..1] OF BYTE		RO		Response

Command

Subindex 0x01

A device reset is initiated when the following byte sequence is sent.

Command	
Byte 0	0x74
Byte 1	0x65
Byte 2	0x73
Byte 3	0x65
Byte 4	0x72

Status

Subindex 0x02

Status (supported values)	
0	Last command completed, no error, no response
1	Reserved
2	Last command completed, error, no response
3	Reserved

Status (supported values)	
255	Command is executing

Response

Subindex 0x03

Response	
Byte 0	See Subindex 0x02

7.2.8.13 Store Parameters Command

Execution of this command stores all parameters to non-volatile memory. If a device automatically saves all non-volatile parameters at the time they are set, this command does not take any action.

Index	SI	DataType	NV	Access	PM	Name
FBF2	0x01	ARRAY [0..3] OF BYTE		RW		Command
	0x02	USINT		RO		Status
	0x03	ARRAY [0..1] OF BYTE		RO		Response

Command

Subindex 0x01

All writable, non-volatile values will be stored in non-volatile memory when the following is sent.

Command	
Byte 0	0x73
Byte 1	0x61
Byte 2	0x76
Byte 3	0x65

Status

Subindex 0x02

Status (supported values)	
0	Last command completed, no error, no response
1	Reserved
2	Last command completed, error, no response
3	Reserved
255	Command is executing

Response

Subindex 0x03

Response	
Byte 0	See Subindex 0x02

7.2.8.14 Load Parameters Command

Execution of this command will load all parameters from non-volatile memory. If a device automatically saves all non-volatile parameters at the time they are written, this command will not take any action.

Index	SI	Data Type	NV	Access	PM	Name
FBF4	0x01	ARRAY [0..3] OF BYTE		RW		Command
	0x02	USINT		RO		Status
	0x03	ARRAY [0..1] OF BYTE		RO		Response

Command

Subindex 0x01

All writable, non-volatile parameters are loaded from non-volatile memory when the following is sent.

Command	
Byte 0	0x6C
Byte 1	0x6F
Byte 2	0x61
Byte 3	0x64

Status

Subindex 0x02

Status	(supported values)
0	Last command completed, no error, no response
1	Reserved
2	Last command completed, error, no response
3	Reserved
255	Command is executing

Response

Subindex 0x03

Response	
Byte 0	See Subindex 0x02

7.2.8.15 Calculate Checksum Command

The execution of this command calculates a checksum for all writable, non-volatile parameters as currently stored in non-volatile memory.

Index	SI	DataType	NV	Access	PM	Name
FBF3	0x01	ARRAY [0…3] OF BYTE		RW		Command
	0x02	USINT		RO		Status
	0x03	ARRAY [0…5] OF BYTE		RO		Response

Command

Subindex 0x01

Read: Returns information about the supported checksum type.

Command	
Bit 0	0 = no non-volatile parameters supported 1 = non-volatile parameters supported
Bit 7	1 = other algorithm

Write: Checksum type selection and start calculation.
A write access to this subindex shall only set one bit true in Bit [0…1].

Command	
Bit 0	1 = Use default checksum algorithm of the slave
Bit 7	1 = other algorithm

Status

Subindex 0x02

Status (supported values)	
0	Default value if the command has not been initiated. Not a supported value otherwise.
1	Last command completed, no error, reply there
2	Last command completed, error, no response
3-99	Reserved
255	Command is executing

Response

Subindex 0x03

Response	
Byte 0	See Subindex 0x02
Byte 1	Unused – shall be zero
Byte 2…5	Checksum return value

8 Maintenance and Calibration Procedures

8.1 Importance of Density, Tooling, and Z-Ratio

IMM-100 is capable of translating the resonance frequency shift of the QCM it is monitoring to a real mass density of a thin film deposited on the QCM. In order for the mass translation to be precise, IMM-100 uses the Z-Ratio, of the monitored film, provided by the user. The areal mass density is then converted to thickness using the density, of the film monitored, provided by the user. the user enters the material density and Z-Ratio into IMM-100 via an EtherCAT master. In some instances, where highest accuracy is required, it is necessary to make a density calibration as outlined in Determine Density [▶ 56]. 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. In IMM-100, if the Z-Ratio is not known it can be estimated from the procedure outlined in Laboratory Determination of Z-Ratio.

8.2 Determine Density

The bulk density values retrieved in Appendix A: Material Table 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 6 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-100 with the new density value and observing that the reported thickness is equal to the measured thickness, provided that the IMM-100 thickness has not been zeroed between the test deposition and entering the calculated density.

Density (g/cm^3) = $D_1 (T_x/T_m)$ [1]

where: D_1 = Initial density setting, T_x = Thickness reading on IMM-100, 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. Place a new 6 MHz AT-cut crystal in the sensor and make a short deposition (1000–5000 Å) using manual control.
3. Make a short deposition and determine the actual thickness.
4. Calculate tooling from the relationship shown in equation [2].
5. Round off percent tooling to the nearest 0.1%.
6. 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-100 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, normalized to acoustic impedance of AT-cut crystal, for materials commonly used is available in Appendix A: Material Table. For other materials, Z-Ratios can be calculated from the following formula:

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

$Z = 9.378 \times 10^5\ (d_f\mu_f)^{-1/2}$ [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 AT-cut 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 [▸ 56].
2. Install a new AT-cut 6 MHz crystal and record its starting frequency (F_{co}). It is necessary to monitor the TxPDO 1A00 subindex 0x04.
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 TxPDO 1A00 subindex 0x0E to get the crystal life value.
4. Stop the deposition and record the ending crystal frequency (F_c) by monitoring TxPDO 1A00 subindex 0x4.
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 AT-cut 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 small 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-100 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-100 **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-100

SYMPTOM	CAUSE	REMEDY
1. The **Status** LED is not illuminated.	a. A circuit breaker is tripped. b. The power cord is unplugged from the wall or the back of IMM-100. 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-100 "locks" up.	a. There is a high electrical noise environment.	a. Route the cables 30 cm [1 ft.] away from high power conducting lines to reduce noise.
	b. There is poor ground or a poor grounding practice.	b. Verify there is proper earth ground. Use an appropriate ground strap (a solid copper strap with 5:1 length:width ratio is recommended). Eliminate any ground loops by establishing the correct system grounding. Verify proper IMM-100 grounding.

SYMPTOM	CAUSE	REMEDY
3. IMM-100 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 INFICON Service department.
4. The **crystal fail** message is always on.	a. There is a defective cable from feedthrough to IMM-100. b. There is poor electrical contact in the transducer, the feedthroughs, or the in-vacuum cable. c. There is a failed crystal or there is no crystal. d. Two crystals are placed into the crystal holder. e. The frequency of the crystal is out of range.	a. Use an ohmmeter or DMM to check the electrical continuity or isolation, as appropriate. b. Use an ohmmeter or DMM to check the electrical continuity or isolation, as appropriate. c. Replace the crystal or insert a crystal. d. Remove one of the crystals. e. Verify that the crystal frequency is within the required range. Use INFICON crystals.
5. IMM-100 will not transition out of INIT state.	There are conflicting methods for setting the station address. The **Rotary ID Selector Switches** (**Explicit Device ID**) and the **Configured Station Alias** stored in EEPROM were both configured with non-zero values.	Set the **Configured Station Alias** in the EEPROM to 0 or set the **ID Selector Switches** all to 0.

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 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 one ohm from the feedthrough to the transducer contact indicates a problem. Cleaning contacts or replacing the in-vacuum cable may be required. A more thorough diagnosis may be performed with the optional crystal sensor emulator, PN 760-601-G1.

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 "splatter" 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 the 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. Contact INFICON. 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 a molten source. b. Material on the crystal holder partially masks the crystal cover aperture. c. There is an electrical short or an open condition. d. Check for thermally induced electrical shorts or open conditions.	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. c. Using an ohmmeter or DMM, check for electrical continuity in the sensor cable, connector, contact springs, connecting wire inside sensor, and feedthroughs.

SYMPTOM	CAUSE	REMEDY
		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 (a solid copper strap with a 5:1 length:width). Change the location of IMM-100 and move the oscillator cabling away from RF power lines. Connect the IMM-100 power supply to a different power line. d. Verify that there are proper connections.
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 the 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	a. There is inadequate cooling water or the cooling water temperature is too high.	a. Check the cooling water flow rate. The cooling water temperature must be

SYMPTOM	CAUSE	REMEDY
decrease.) There is thermal instability after the termination of deposition. (This usually causes the thickness reading to increase.)	b. There is excessive heat input to the crystal. c. The crystal 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.	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 farther away from the source and use silver 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. 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.	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.

SYMPTOM	CAUSE	REMEDY
	c. The material does not adhere to the crystal. d. There is a cyclic change in rate.	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-100 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. 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 CrystalSix, Crystal12, or Generic rotary sensor crystal switch problem. (The sensor does not advance or is not centered in the aperture.)	a. There is no relay or an incorrect relay output programmed (for instruments having outputs).	a. Program a relay. b. Ensure the air supply is regulated at 80-90 psi. c. Clean material accumulation as needed. Refer to the CrystalSix

SYMPTOM	CAUSE	REMEDY
	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).	manual or Crystal12 manual for maintenance instructions. d. Realign as per the instructions in the CrystalSix manual or Crystal12 manual. e. Install the orifice as shown in the CrystalSix manual or Crystal12 manual.
9. IMM-100 is not reading rate accurately.	The material density, Z-ratio, tooling, rate filter time or crystal cut type is set incorrectly.	Verify that the material density, Z-ratio, tooling, rate filter time and crystal cut type are at the intended settings.

9.3 Troubleshooting Computer Communication

Symptom	Cause	Remedy
1. Communication cannot be established between the computer and IMM-100.	a. There is an improper communication cable connection. b. There is a defective communication cable. c. An incorrect ESI file is being used. d. IMM-100 is not recognized on the master device network.	a. Ensure the cables are connected to the correct <IN> and <OUT> ports. b. Verify that the cable is plugged in and is not damaged. Replace the communication cable. c. Verify that the correct ESI file is in use. Reboot IMM-100 then reboot the master device to reinitialize the network list.

Symptom	Cause	Remedy
		d. Reboot IMM-100, then reboot the master device to reinitialize the network list.
2. There is an incomplete or erroneous response.	a. An incorrect ESI file is being used. b. IMM-100 does not appear correctly on the master device network list.	a. Verify that the correct ESI file is in use. Reboot IMM-100 then reboot the master device to reinitialize the network list. b. Verify that the correct ESI file is in use. Reboot IMM-100 then reboot the master device to reinitialize the network list.

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.

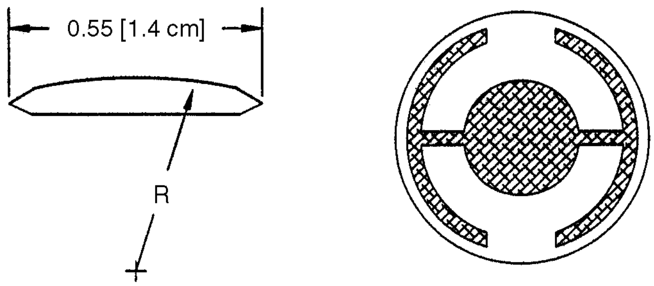
1.G. Z. Sauerbrey, Phys. Verhand .8, 193 (1957)

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

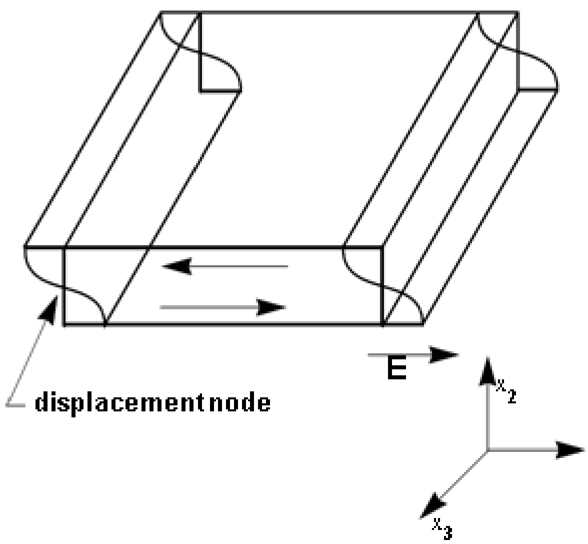
3. P. Lostis, Rev. Opt. 38,1 (1959)

10.2 Monitor Crystals

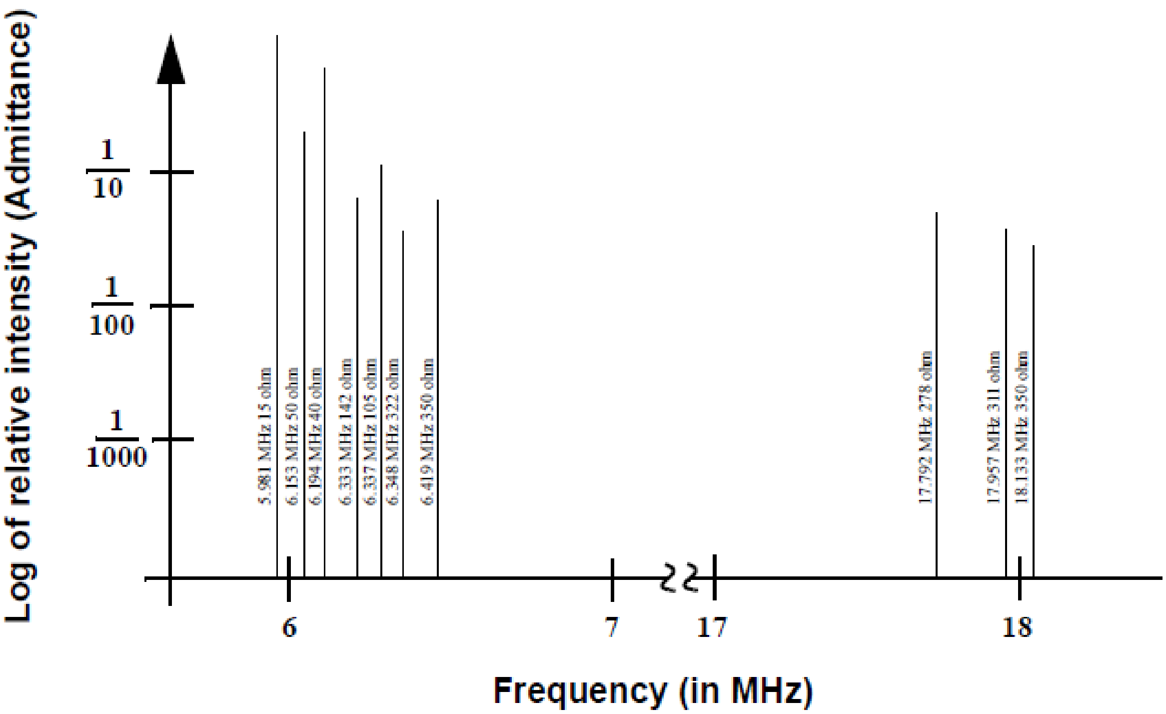
No matter how sophisticated the electronics surrounding it, the essential device of the deposition monitor is the quartz crystal.



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]

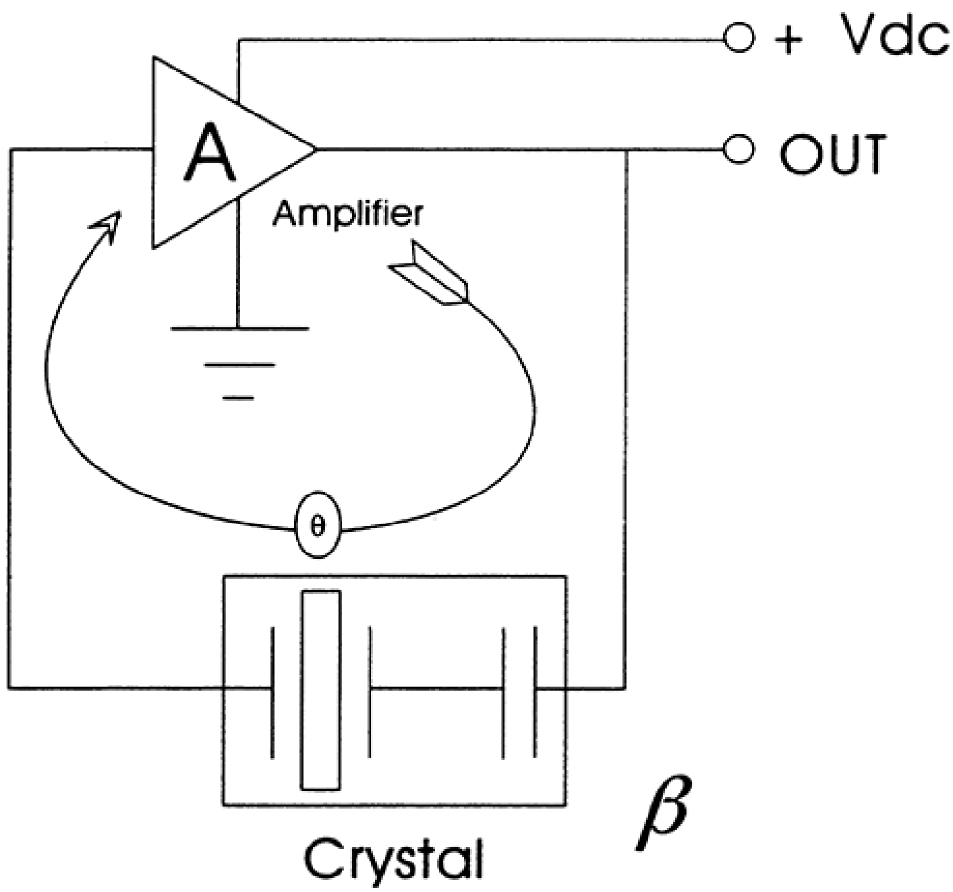
where $Z=(d_q\mu_q/d_f\mu_f)^{1/2}$ is the acoustic impedance ratio and μ_q and μ_f are the shear moduli of the quartz and film, respectively. Finally, there was a fundamental understanding of the frequency-to-thickness conversion that could yield theoretically correct results in a time frame that was 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)

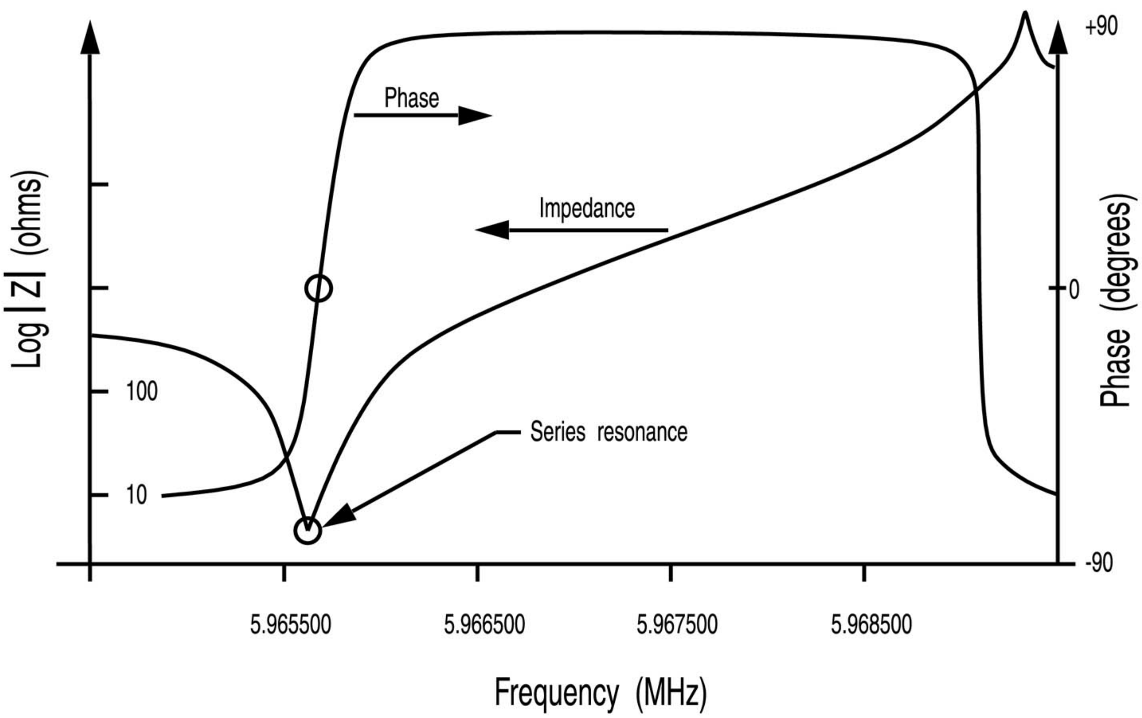
10.5 Active Oscillator

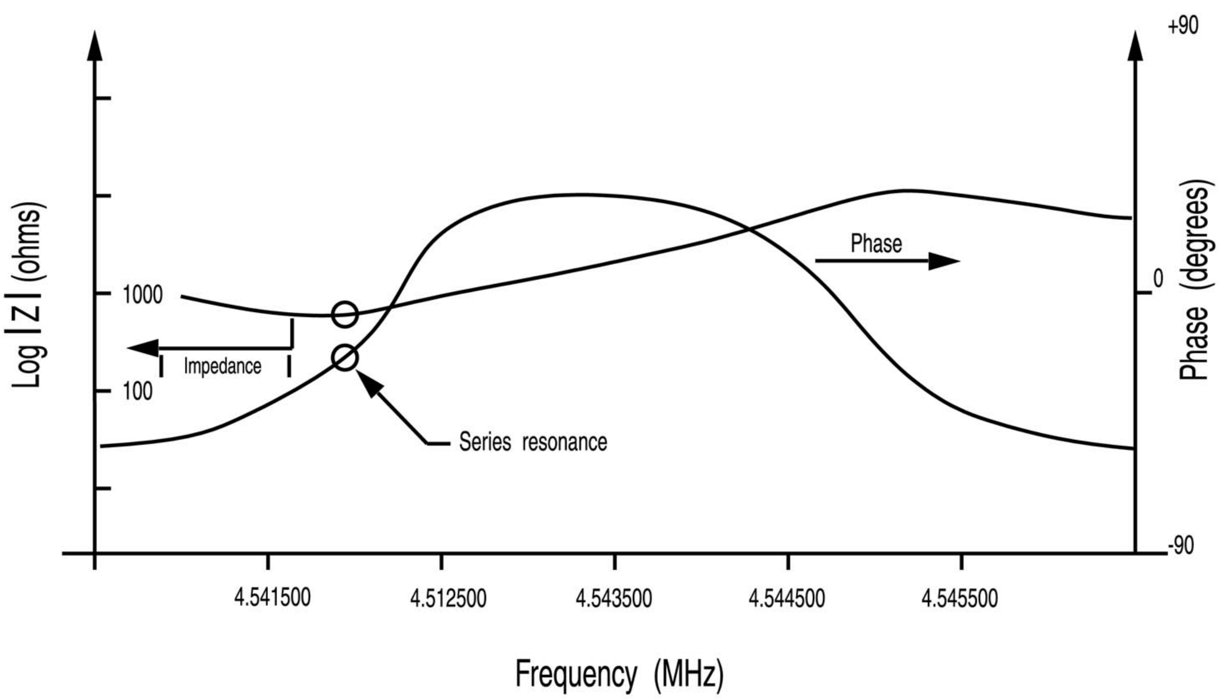
Much of the instrumentation developed to date has relied on the use of an active oscillator circuit, generally the type schematically shown in the figure below. This circuit actively keeps the crystal in resonance, so that any type of period or frequency measurement may be made. In this type of circuit, 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. The Z-Ratio values shown are normalized for AT-cut quartz crystals

⚠ 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. Z-Ratio values listed here is for AT-cut quartz crystals only. When using BT-cut, IT-cut, or SC-cut please select the correct encoding to indicate to IMM-100 the type of crystal. Failure to do this will result in incorrect thickness translation of the resonance frequency shift by IMM-100.

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

Formula	Density	Z-Ratio	Material Name
$BaTiO_3$	5.999	0.464	barium titanate (tetragonal)
$BaTiO_3$	6.035	0.412	barium titanate (cubic)
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
$CaO-SiO_2$	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

Formula	Density	Z-Ratio	Material Name
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 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

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	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

Formula	Density	Z-Ratio	Material Name
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 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

Formula	Density	Z-Ratio	Material Name
NdF_3	6.506	*1.000	neodymium fluoride
Ni	8.910	0.331	nickel
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

Formula	Density	Z-Ratio	Material Name
Sc	3.000	0.910	scandium
Sc_2O_3	3.860	*1.000	scandium oxide
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

Formula	Density	Z-Ratio	Material Name
TiB_2	4.500	*1.000	titanium boride
TiC	4.930	*1.000	titanium carbide
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

Formula	Density	Z-Ratio	Material Name
ZnO	5.610	0.556	zinc oxide
ZnS	4.090	0.775	zinc sulfide
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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