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Riviere et al.

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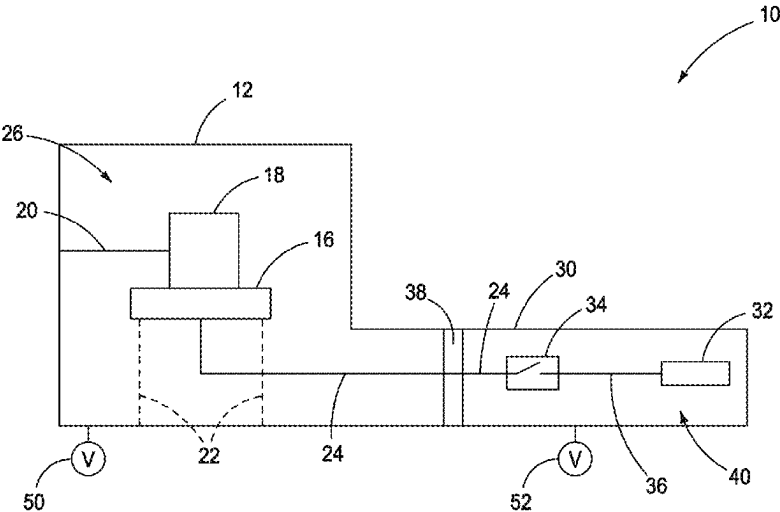
(54) **CRYOGENIC ANALYSIS SYSTEMS AND METHODS**
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(60) Provisional application No. 63/164,469, filed on Mar. 22, 2021.
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G01N 1/42 (2006.01)
G01N 25/14 (2006.01)
(52) **U.S. Cl.**
CPC **G01N 1/42** (2013.01); **G01N 25/145** (2013.01)

(58) **Field of Classification Search**
CPC G01N 1/42; G01N 25/145
See application file for complete search history.
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(57) **ABSTRACT**
Switch assemblies for a cryogenic device analysis system are provided. The switch assembly can include: a cold source conductive member extending lengthwise to a cold source; and a cryogenic device conductive member extending lengthwise to a cryogenic device and at least partially overlapping at least a portion of the cold source conductive member. Methods for closing a conductive connection between a cold source and a cryogenic device within a cryogenic analysis system are provided. Methods for opening a conductive connection between a cold source and a cryogenic device within a cryogenic analysis system are provided. Cryogenic device analysis systems are also provided.

22 Claims, 12 Drawing Sheets



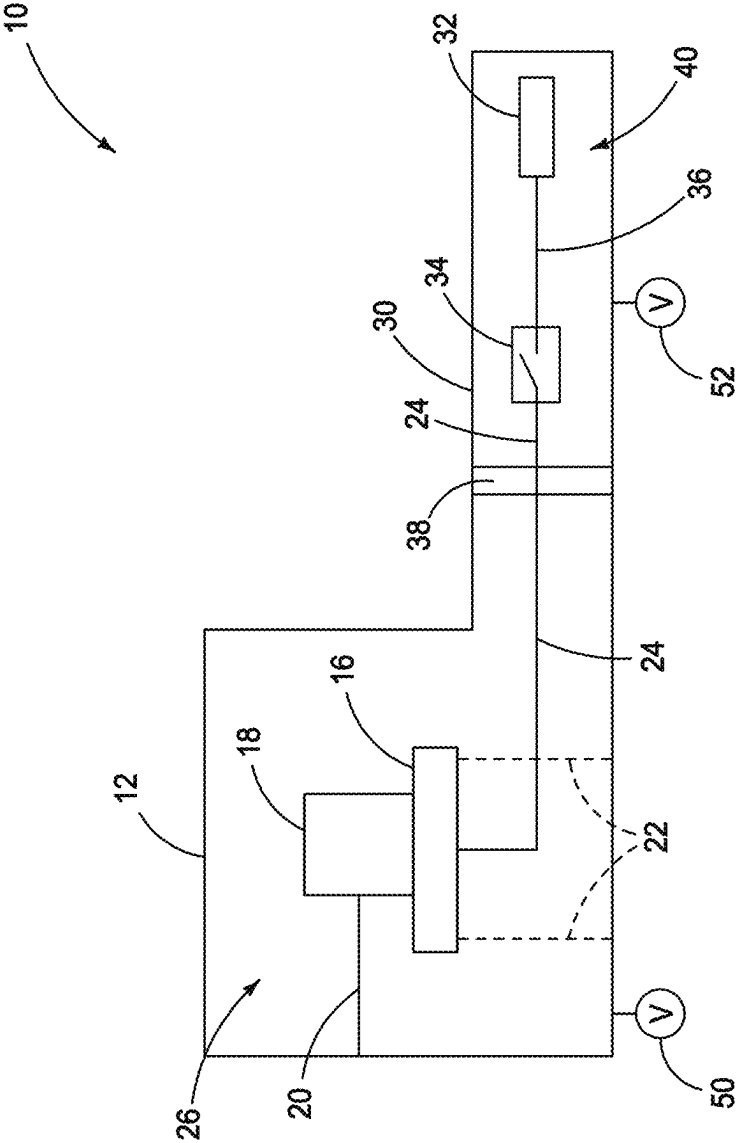


FIG. 1

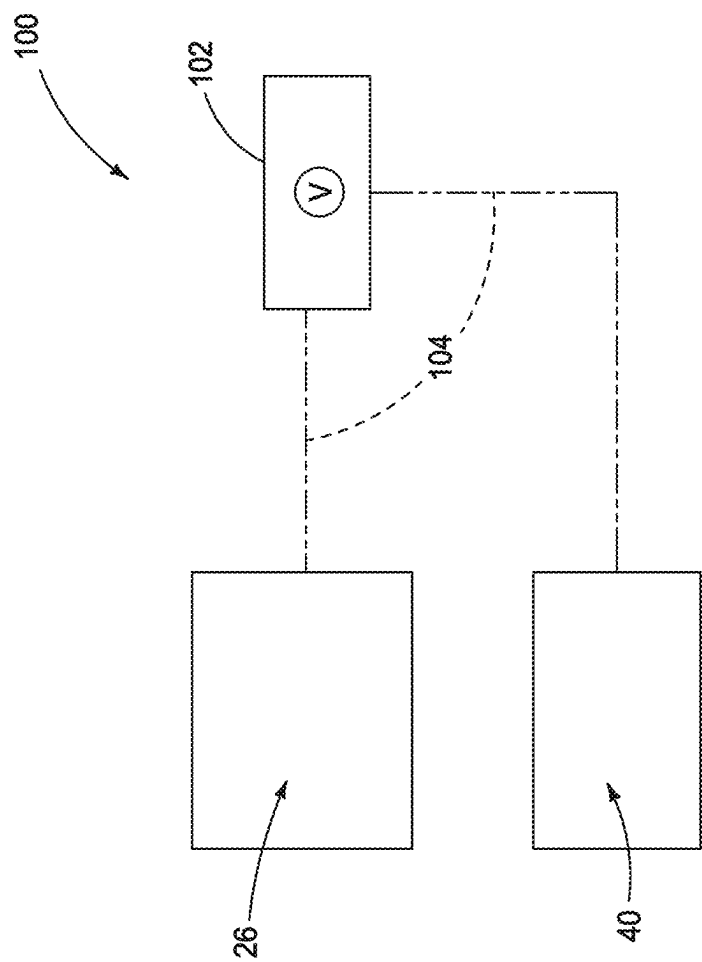


FIG. 2

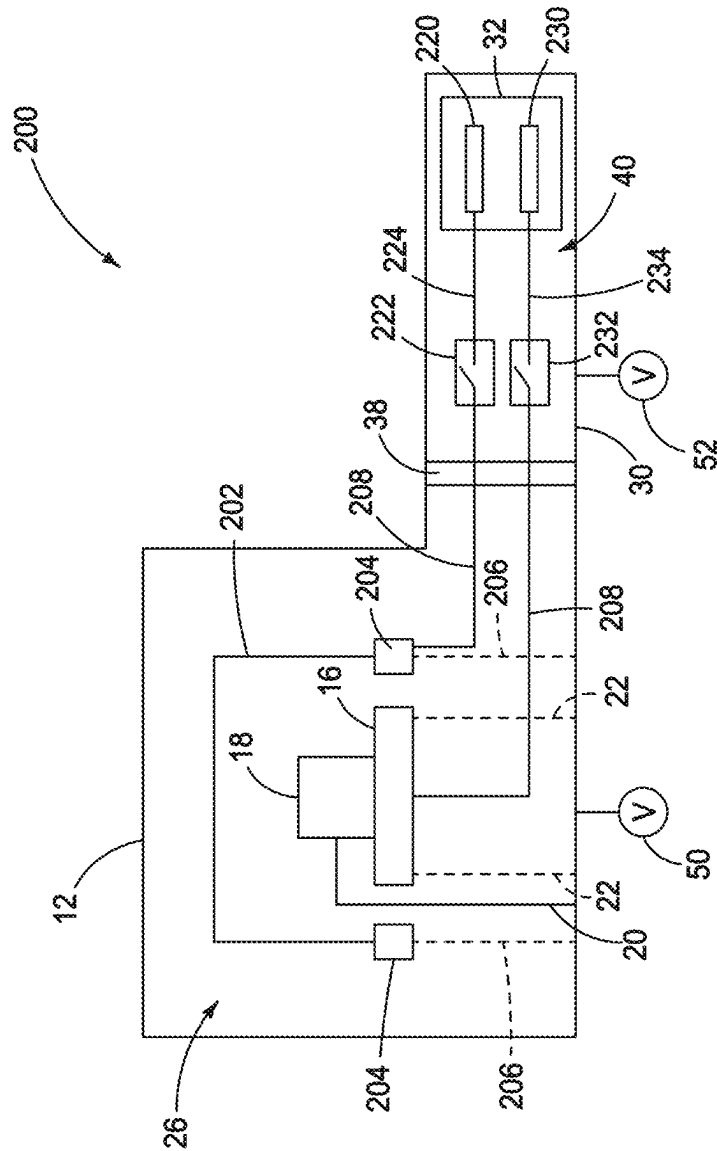


FIG. 3.

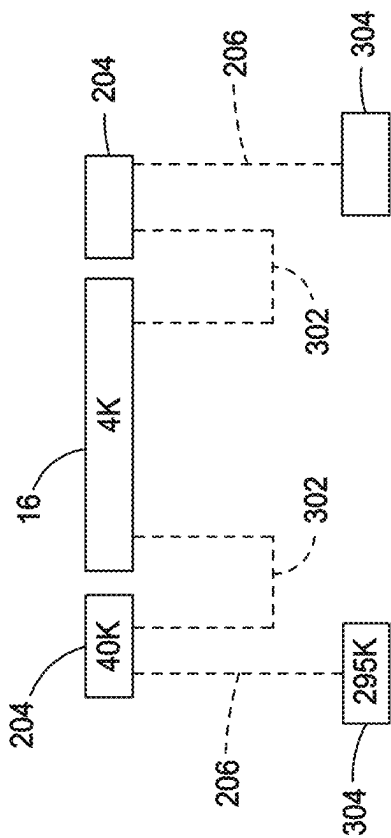


FIG. 4

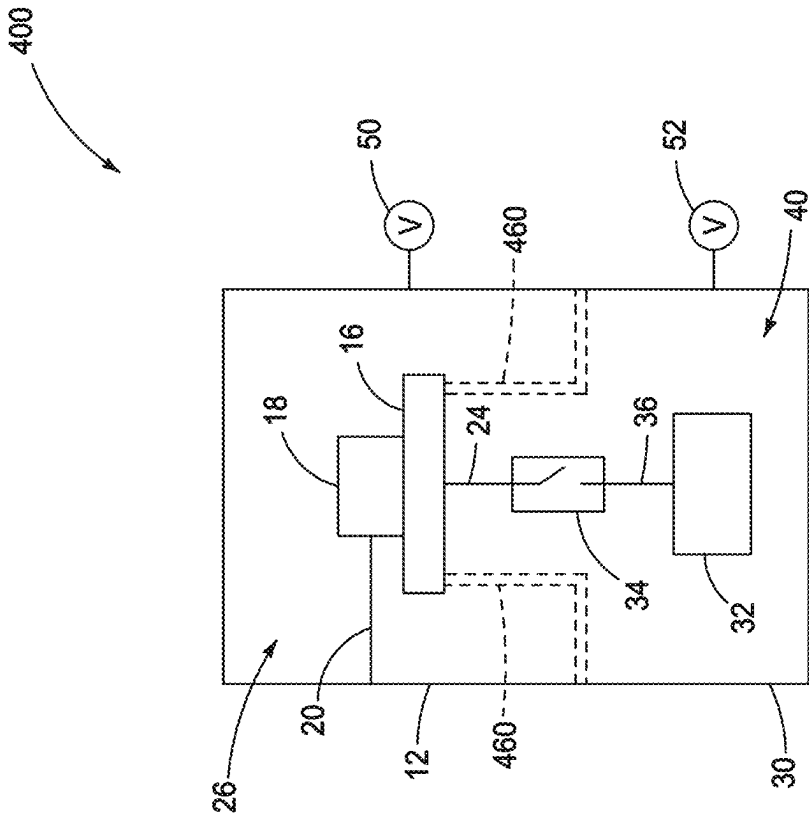


FIG. 5

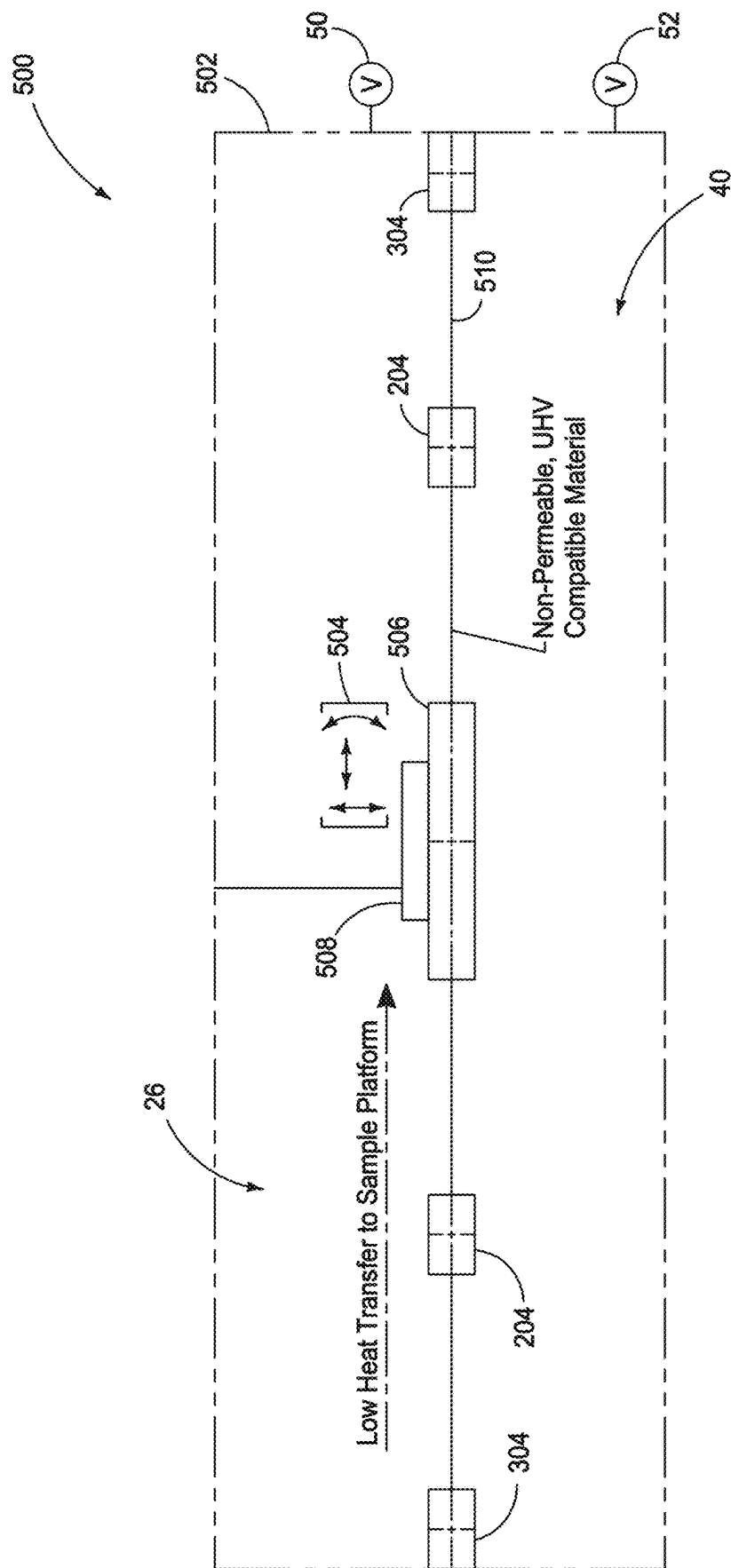


FIG. 6

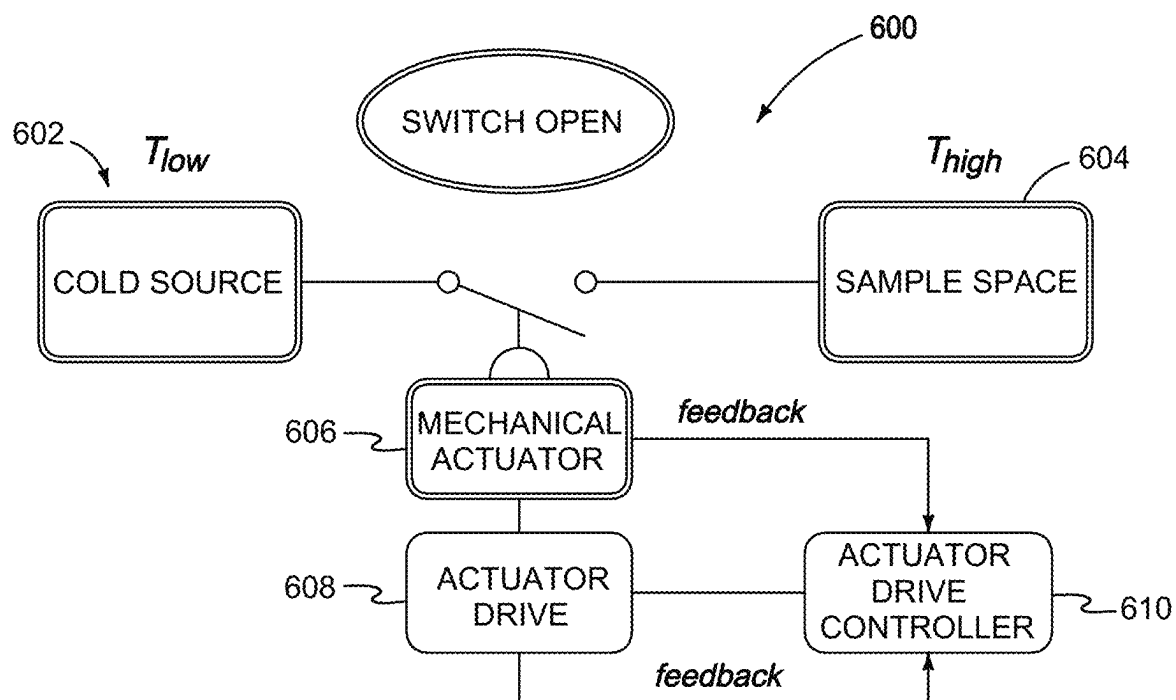


FIG. 7

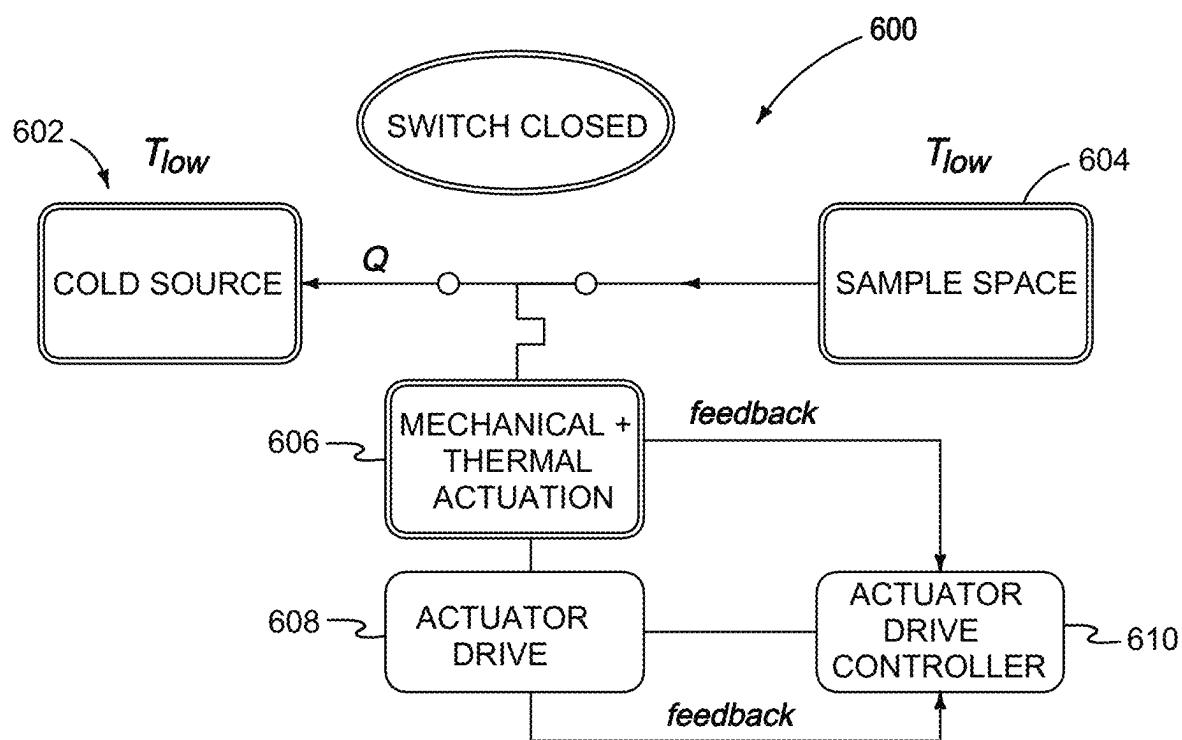


FIG. 8

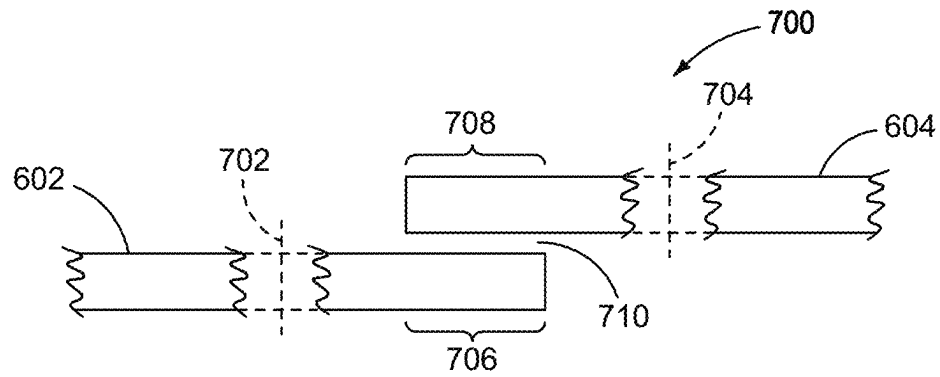


FIG. 9A

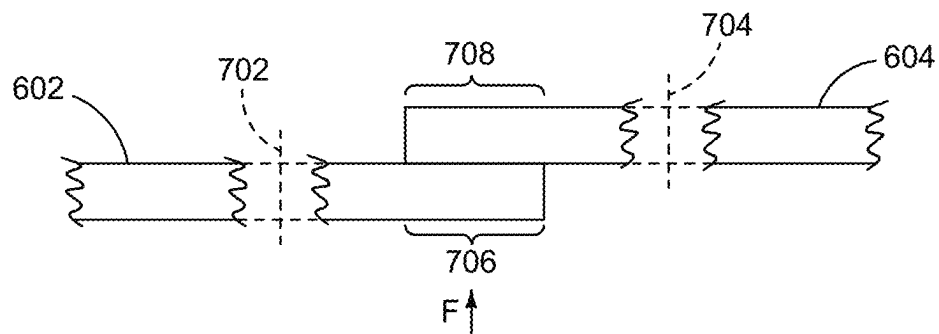


FIG. 9B

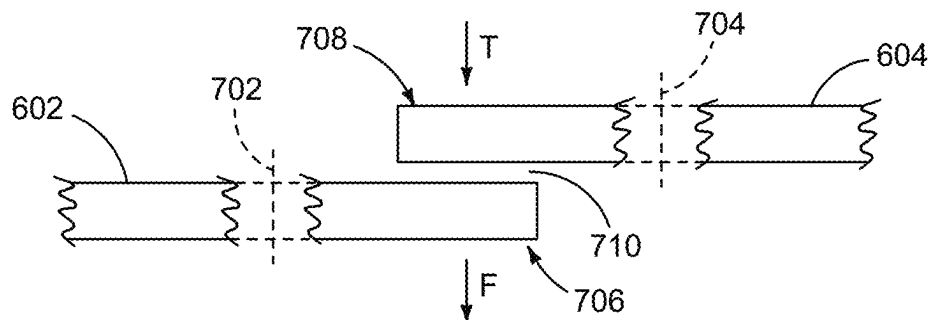


FIG. 9C

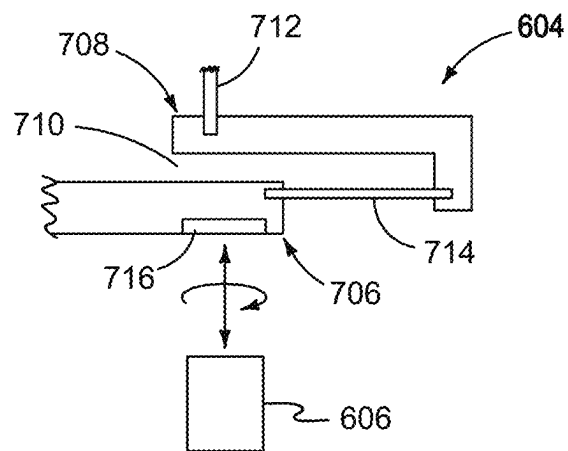


FIG. 10

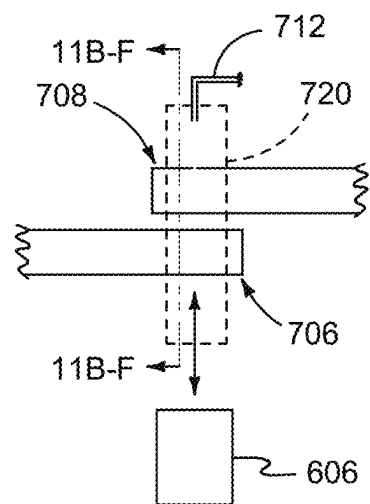


FIG. 11A

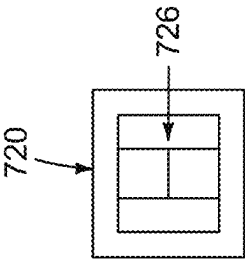


FIG. 11D

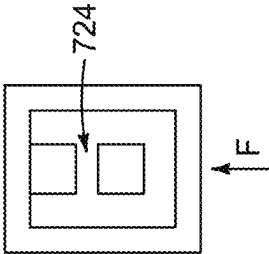


FIG. 11C

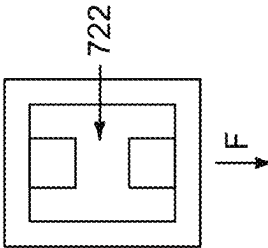


FIG. 11F

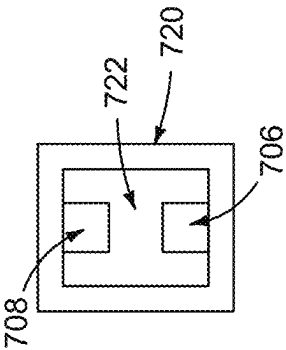


FIG. 11B

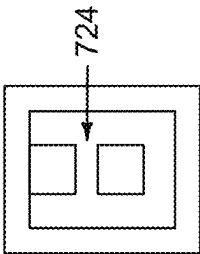


FIG. 11E

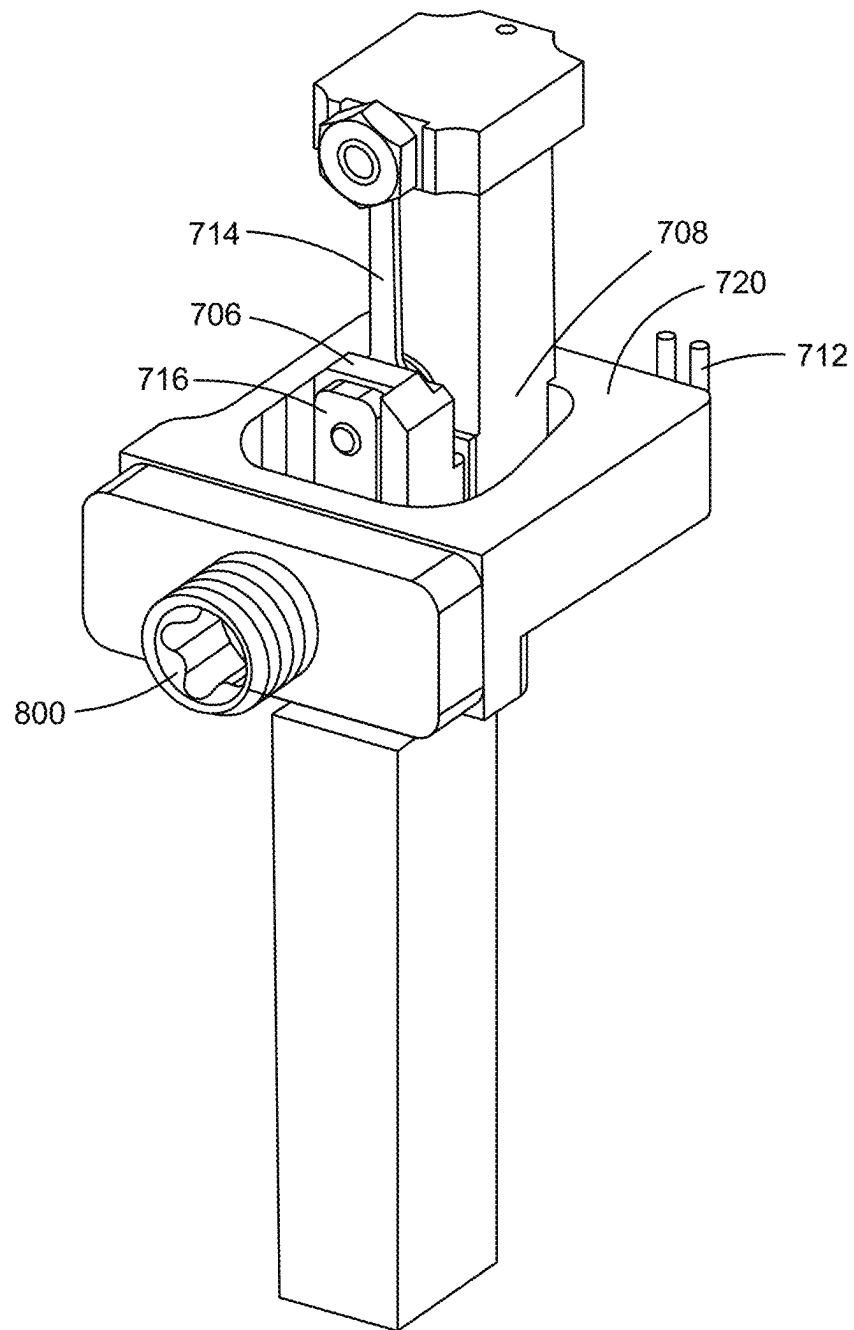
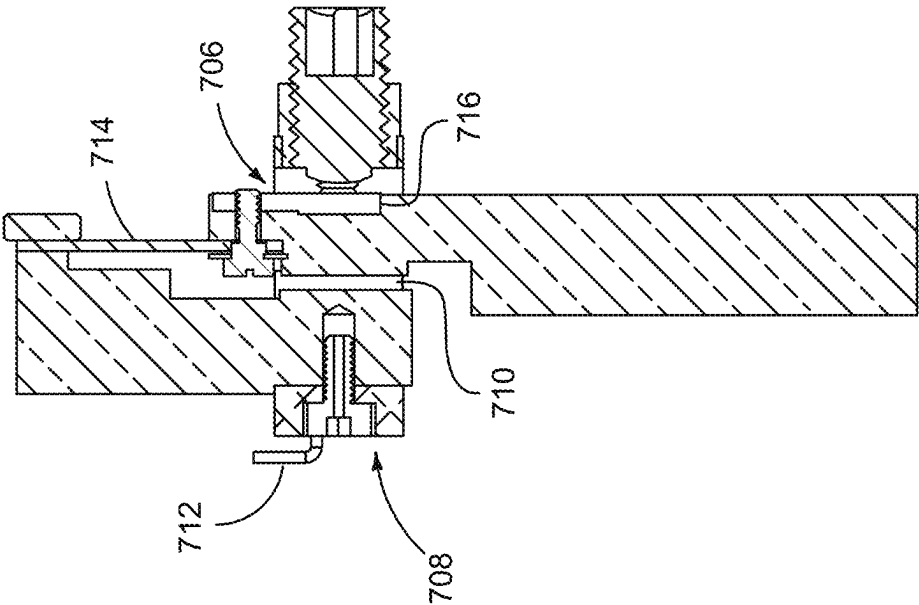
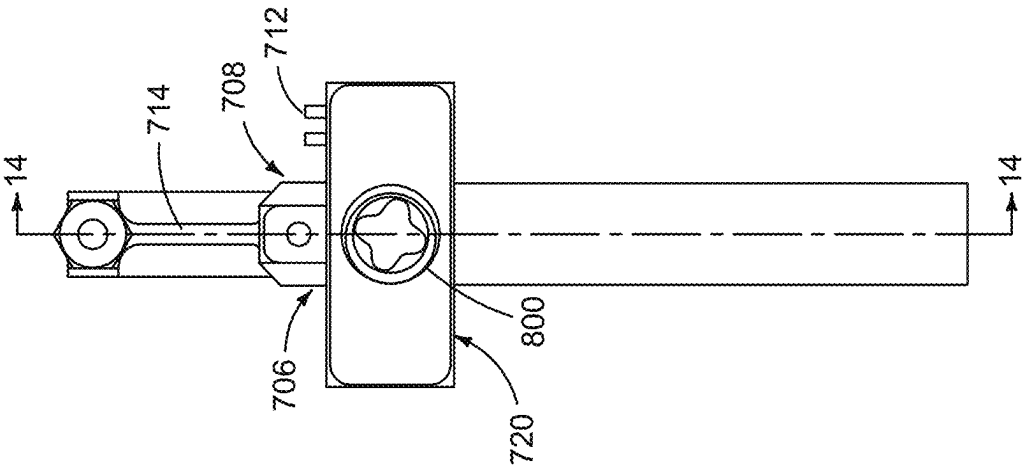


FIG. 12



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CRYOGENIC ANALYSIS SYSTEMS AND METHODS**CROSS REFERENCE TO RELATED APPLICATION**

This application is a continuation-in-part of U.S. patent application Ser. No. 18/582,621 filed Feb. 20, 2024, entitled "Cryogenic Analysis Systems and Methods", which is a continuation of U.S. patent application Ser. No. 17/698,764 filed Mar. 18, 2022, entitled "Cryogenic Analysis Systems and Methods", now U.S. Pat. No. 11,959,845 which issued Apr. 16, 2024, which claims priority to and the benefit of U.S. Provisional Patent Application Ser. No. 63/164,469 filed Mar. 22, 2021, entitled "Cryogenic Analysis Systems and Methods", the entirety of each of which is incorporated by reference herein.

TECHNICAL FIELD

The present disclosure relates to cryogenic device analysis systems and methods.

BACKGROUND

Cryogenics is a critical technology for the quantum information science and technology industry. Reaching stable, low temperatures near absolute zero is necessary to maintain qubit coherence, investigate quantum properties, and ultimately realize the potential of quantum applications in computing, sensing, and networking. Quantum systems rely on cryogenic devices including electrical, optical, RF, and microwave components that must operate at low, cryogenic temperatures near absolute zero. Despite advances cryogenic devices can prove unreliable due to challenges in designing and manufacturing of components that can withstand low temperatures and multiple thermal cycles across a wide temperature range.

Testing these devices can be cumbersome and tedious to perform because of the time necessary to cool a cryogenic device down to these very low operational temperatures. Today's closed-cycle cryostats can take more than 3 hours to cool a cryogenic device to 4K. This cryogenic device exchange time can limit the number of cryogenic devices that can be tested in a day and places a bottleneck on the pace of quantum discovery.

SUMMARY

To reduce the cryogenic device exchange time of conventional cryostats by greater than 10x, a new cryostat architecture is provided herein in which the temperature and vacuum control of the cryogenic device can be controlled independently from the rest of the cryostat. Such an architecture would allow the cryogenic device to be warmed, vented to atmosphere, and exchanged-all while keeping the remaining large mass components, including the cryocooler, cold and under vacuum. Cryogenic device exchange time can be performed significantly faster, since only the mass of the cryogenic device is thermally cycled (cooled down and warmed up) during an exchange.

It has been recognized that typical cryostats used to cool devices to cryogenic temperatures thermally engage to a cold source via a thermal conduit. In these typical systems the device and cold source are always thermally engaged and located within the same vacuum chamber. Despite the desire to thermally cycle just the cryogenic device, current

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systems require the entire system to be thermally cycled to exchange a cryogenic device. Current cryostat architectures utilizing solid conduction heat transfer cannot allow a cryogenic device to be exchanged any faster than the time required to cool down the cold source itself; typically 60-90 minutes for a 2-stage cryocooler for example. The cryogenic device is a fraction of the mass compared to that of the cold source, thermal conduit, and associated radiation shields such that the cryogenic device exchange time is significantly reduced when only the cryogenic device is thermally cycled.

The systems of the present disclosure provide a new cryostat architecture that can include, in particular embodiments, thermal and vacuum control of the cryogenic device independent from the remainder of the analysis system. The cryogenic device and cold source are in separate vacuum spaces, and a thermal switch can be utilized to engage/disengage thermal communication between the cryogenic device and the cold source, thereby allowing for the cryogenic device to be thermally cycled and exchanged without having to thermally cycle the entire analytical system.

Cryogenic device analysis systems are provided that can include: a cold source within a first vacuum chamber; a cryogenic device mount within a second vacuum chamber, wherein the first and second vacuum chambers are separated by a vacuum barrier; and a first thermal conduit extending from the cold source through the vacuum barrier to the sample mount.

Methods for performing analysis of a cryogenic device are provided, the methods can include: providing a cold source within a first vacuum chamber; thermally connecting the cold source to a cryogenic device mount within a second vacuum chamber through a vacuum barrier between the first and second vacuum chambers; within the second vacuum chamber reducing a temperature of the cryogenic device with the cold source; performing analysis of the cryogenic device while the cryogenic device is both operational and at cryogenic temperature; and disengaging the cold source from the sample mount and replacing the cryogenic device with another cryogenic device for analysis.

Embodiments of a switch assembly configured to connect/disconnect cold source conductive members from sample space conductive members in low pressure and/or low temperature environments are provided. Embodiments of the switch can include a structure, for example, a chassis, of higher coefficient of thermal expansion (CTE) than the conductive members. Implementations can allow for higher force on a cold closed thermal contact joint than at warm temperatures. Additionally, embodiments allow for the use of smaller components and less powerful power sources to control actuators. This can provide the user with more cooling power, faster cooldown times, and lower cryogenic temperatures.

Switch assemblies for a cryogenic device analysis system are provided. The switch assembly can include: a cold source conductive member extending lengthwise to a cold source; and a cryogenic device conductive member extending lengthwise to a cryogenic device and at least partially overlapping at least a portion of the cold source conductive member, wherein either or both of the conductive members are biased to define an insulative space between the conductive members at the overlap in an open orientation.

Methods for closing a conductive connection between a cold source and a cryogenic device within a cryogenic analysis system are provided. The methods can include: providing sufficient mechanical force to either or both of a portion of a cold source conductive member or a portion of an overlapping cryogenic device conductive member to at

least partially thermally engage the overlapping portions of the conductive members and thereby close a thermal connection between the conductive members.

Methods for opening a conductive connection between a cold source and a cryogenic device within a cryogenic analysis system are provided. The methods can include providing sufficient thermal energy to an encompassing member to provide freedom of movement between the overlapping portions of the conductive members.

Cryogenic device analysis systems are also provided. The systems can include: a pair of vacuum regions separated by a vacuum barrier; and a switch within either of the vacuum regions. The switch can include: a cold source conductive member extending lengthwise to a cold source within one vacuum region; a cryogenic device conductive member extending lengthwise to a cryogenic device within another vacuum region and at least partially overlapping at least a portion of the cold source conductive member, wherein either or both of the conductive members are biased to define an insulative space between the conductive members at the overlap in an open orientation; and at least one mechanical actuator operatively engaged with either of the portions of the conductive members.

BRIEF DESCRIPTION OF DRAWINGS

Embodiments of the disclosure are described below with reference to the following accompanying drawings.

FIG. 1 is cryogenic device analysis system according to an embodiment of the disclosure.

FIG. 2 is a vacuum system for use in a cryogenic device analysis system according to an embodiment of the disclosure.

FIG. 3 is a cryogenic device analysis system according to one embodiment of the disclosure.

FIG. 4 is a cryogenic device mount and radiation shield mount system for use in a cryogenic analysis system according to an embodiment of the disclosure.

FIG. 5 is a cryogenic device analysis system according to one embodiment of the disclosure.

FIG. 6 is a cryogenic device analysis system according to one embodiment of the disclosure.

FIG. 7 is a depiction of a cryogenic device analysis system having a switch assembly in one configuration according to an embodiment of the disclosure.

FIG. 8 is the system of FIG. 7 in another configuration according to an embodiment of the disclosure.

FIG. 9A is a more detailed view of portions of the switch assembly of FIGS. 7 and 8 in one configuration according to an embodiment of the disclosure.

FIG. 9B is a depiction of the portions of FIG. 9A in another configuration according to an embodiment of the disclosure.

FIG. 9C is yet another configuration of the portions of FIGS. 9A and 9B according to an embodiment of the disclosure.

FIG. 10 is another depiction of a switch assembly according to an embodiment of the disclosure.

FIG. 11A-F are different configurations of a switch assembly according to an embodiment of the disclosure.

FIG. 12 is an isometric view of a switch assembly according to an embodiment of the disclosure.

FIG. 13 is an elevational view of a switch assembly according to an embodiment of the disclosure.

FIG. 14 is a cross-sectional view of the switch assembly of FIG. 13 according to an embodiment of the disclosure.

DESCRIPTION

This disclosure is submitted in furtherance of the constitutional purposes of the U.S. Patent Laws “to promote the progress of science and useful arts” (Article 1, Section 8).

Cryogenic device analysis systems and methods will be described with reference to FIGS. 1-14.

Referring first to FIG. 1, a cryogenic device analysis system 10 is depicted that can include a cold source 32 within a first vacuum chamber 40 which can be defined by first vacuum chamber housing 30. A cryogenic device mount 16 can be within a second vacuum chamber 26 which can be defined by second vacuum chamber housing (walls) 12. Second vacuum chamber 26 defines feedthrough openings (not shown) configured to receive electrical or optical cables 20 for operative coupling to a cryogenic device 18 upon device mount 16 within second vacuum chamber 26. The feedthroughs can provide for electrical and/or optical access to cryogenic device 18. Vacuum sealing interfaces and features may be provided as part or a portion of walls 30 and/or 12 to provide user access to the cryogenic device.

First and second vacuum chambers are separated by a vacuum barrier 38. A first thermal conduit 36 in combination with conduit 24 can extend from cold source 32 through vacuum barrier 38 to cryogenic device mount 16. Vacuum barrier 38 can be a non-permeable physical barrier that can withstand a pressure differential of >15 psia. One portion of vacuum barrier 38 can be mounted or coupled to either or both of walls 30/12 and held at room temperature (295 K) while another portion is maintained at the cryogenic device temperature, for example 4K.

Vacuum barrier 38 can be configured to be thermally resistive to reduce the conductive heat load within the system and particularly to cryogenic device 18. For example, barrier 38 can be comprised of low thermally conductive materials including titanium, stainless steel, ceramic, and/or fiberglass components. Further reductions in conductive heat load can be reduced by configuring barrier 38 with low cross-sectional area and geometries that maximize the length of the conductive path. Additionally, vacuum barrier 38 can be constructed of vacuum compatible materials with minimal off-gassing and low leak rates, to support vacuum or UHV conditions. Barrier 38 may be composed of a single material, or potentially multi-material and joined using fasteners, epoxies, or various manufacturing techniques such as welding, brazing, 3D printing, and/or soldering (see U.S. Pat. No. 11,150,169 B2 issued Oct. 19, 2021, the entirety of which is incorporated by reference herein).

Vacuum barrier 38 can be a non-permeable physical boundary that separates first vacuum chamber 40 from second vacuum chamber 26. Vacuum barrier 38 may complete chamber walls of first vacuum chamber 40 and/or second vacuum chamber 26. Barrier 38 may also be separate from either or both of the walls of first or second chambers 40 or 26, for example as part of a conduit (not shown) extending between chambers 40 and 26 and configured to house thermal conduit 36 and/or 24. Barrier 38 separates the pressures within chambers 40 and 26.

A first thermal switch 34 can be operatively aligned along first thermal conduit 36 between cold source 32 and vacuum barrier 38. Thermal switches can be configured to connect/disconnect thermal communication between cold source 32 and cryogenic device mount 16 and/or device 18 under test.

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With the thermal switch **34** closed, heat flows from the cryogenic device **18** to cold source **32**. When switch **34** is opened, heat flow between cryogenic device **18** and cold source **32** is significantly reduced if not disconnected altogether. Various types of thermal switches, also known as heat switches, have been developed and could be employed. Examples include thermal gas-gap diodes, heat exchangers, heat pipes, superconducting heat switches, mechanical switches, and magneto resistive heat switches. The specific type of thermal switch technology can be optimized for different applications, either for use in sub-1K with low heat transfer rates or designed for low power usage for space-based applications for example.

Mechanical switches, which rely on the contact of two or more thermal conductors driven together by a mechanism, for example a screw driven by an electrical stepper motor, to close the switch may be utilized for 4K operation as it allows for thermal contact interface design freedom, ease of control using off-the-shelf force transducers, and motion components that support fully automated control. While shown to be within chamber **40**, in other embodiments thermal switch **34** can be located in chamber **26**.

Device analysis system **10** can also include first thermally insulative cryogenic device mount supports **22** extending between cryogenic device mount **16** and walls **12** of second vacuum chamber **26**. Vacuum barrier **38** can be a portion of first vacuum chamber **40**. Vacuum barrier **38** can have be a portion of second vacuum chamber **26**. Vacuum barrier **38** can be a portion of both first and second vacuum chambers (**40/26**).

In accordance with at least one example, cryogenic device **18** to be cooled is thermally engaged with cold source **32** via first and second thermal conduits **36/24**. Cryogenic device **18** resides in second vacuum chamber **26** and cold source **32** in first vacuum chamber **40**. Second vacuum chamber **26** and first vacuum chamber **40** can share walls. For example, chamber walls **30** may be contiguous with chamber walls **12** as shown. Alternatively, chamber walls **30** and chamber walls **12** may not be contiguous.

Cryogenic device **18** is mounted to and thermally engaged with a cryogenic device mount **16**. Cryogenic device mount **16** is mechanically supported by a cryogenic device support structure that can include first thermally insulative cryogenic device mount supports **22** (thermally insulative supports) extending between cryogenic device mount **16** and walls of second vacuum chamber **26**.

Thermally insulative supports can be a structure that mechanically supports substrates that are thermally coupled to cold source **32**, for example, cryogenic device **18** and/or cryogenic device mount **16**. Thermally insulative supports can be configured to minimize heat transfer from where the insulative support is mounted to the walls (substrate) of the vacuum chamber, typically at room temperature, to the cryogenic device. The supports can also be configured to reduce vibrations at the cryogenic device; the support can be a high-stiffness structure. The cryogenic device support structure **22** can be constructed of materials and in geometries resulting in a thermally resistive, stiff structure. For example, it may be composed of titanium, stainless steel, aluminum, ceramics, fiberglass components, G10, and/or PEEK materials.

It could be composed of a single material, or potentially multi-material and joined using fasteners, epoxies, or various manufacturing techniques such as welding, brazing, 3D printing, and/or soldering.

Conduits **36/24** transfer thermal energy (heat) between cryogenic device mount **16** and cold source **32** and, by

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example, to and from the cryogenic device **18** to cold source **32**. Thermal conduit **24** is in the second vacuum chamber **26** and thermal conduit **36** is in first vacuum chamber **40**. Thermal switch **34** is located between mount **16** and cold source **32** to engage/disengage thermal communication between cryogenic device **18** and cold source **32**.

Cryogenic device **18** can be a device or component to be analyzed at a cryogenic temperature of interest. Device **18** can be, for example, an electronic or optical device used in a quantum computer, including for example an RF amplifier, that is tested and qualified for use prior to installation in a quantum computer. Device **18** can include or be supported by processing circuitry that can be operatively connected to a quantum computing system for operation at cryogenic temperatures. Accordingly, device **18** can be configured to be coupled to and operated with electrical or optical cables **20**, which, in example embodiments can be operationally coupled to processing circuitry (not shown) that can be utilized to monitor and/or operate device **18** during analysis using the systems of the present disclosure.

Cold source **32** is a source of heat or cold energy that can be used to heat or cool cryogenic device **18**. Example cold source **32** can include a mechanical cryocooler, with either one or multiple cooling stages, or for example a dewar of fluid cryogen such as helium or nitrogen.

Thermal conduits of the present disclosure can be a conduit that can transfer heat to and/or from cold source **32** to a cryogenic device **18** via sample mount **16**. The conduits can facilitate heat transfer via solid conduction through, for example, a copper bar or rod (not shown). The conduits can also include a fluid conduit that transfers fluid cryogen to or from a cold source to cryogenic device **18**.

Chamber walls **30** and/or **12** can be a non-permeable structure capable of maintaining an interior vacuum pressure, for example <1E-7 Torr or possibly ultra-high-vacuum (UHV) conditions <1E-11 Torr. Walls **30** and/or **12** can be made of machined aluminum for example or a welded metal structure.

System **10** can include vacuum systems **50** and/or **52** for example. These systems can be a single system and/or multiple systems that may operate independently of one another. For example, chambers **40** and **26** can be independently controlled using vacuum control components **100** that are connected to each of the vacuum chambers **26** and **40** via vacuum hoses **104** as shown in FIG. 2. A vacuum control module **102** can include a vacuum pump, pressure gauges, valves, electronics, and software control to pull vacuum and vent either one or both of chambers **40/26**. The control of each pressure within the chambers can be independent, such that one chamber can be under vacuum conditions, <1E-7 Torr for example, while the other chamber is simultaneously vented to atmosphere.

The temperature of cryogenic device **18** can be controlled with a thermometer and heater either attached to cryogenic device **18** and/or the cryogenic device mount **16**. The temperature can be controlled via a PID loop or other control logic that controls the heater output, for example by increasing current applied to a resistive heater, to achieve a desired cryogenic device temperature. Accordingly, systems of the present disclosure may be operatively controlled with processing circuitry not shown.

In accordance with at least one example, when cryogenic device **18** and cold source **32** are cold and the vacuum chambers **26** and **40** are under vacuum, the process for cryogenically cooling a new cryogenic device can include:

- 1) Disengaging the thermal switch to stop or significantly reduce the heat transfer between the cryogenic device **18** and the cold source **32**.
- 2) Warming the cryogenic device **18** to room temperature by controlling cryogenic device heater (part of sample mount and not shown) and turning off the heater once it reaches room temperature.
- 3) Venting chamber **26** to atmosphere.
- 4) Exchanging cryogenic device **18** for alternative device for analysis.
- 5) Pulling vacuum to reduce the pressure within chamber **26**.
- 6) Engaging thermal switch **34** so cryogenic device **18** is thermally engaged with cold source **32**.

Utilizing the systems of the present disclosure, a cryogenic device exchange can be performed much faster because only the cryogenic device—whose mass is typically a fraction of the cold source mass—must be thermally cycled during a cryogenic device exchange.

FIG. **3** depicts another embodiment of the disclosure. In accordance with this embodiment, multiple thermal switches **222** and **232** are used to engage multiple components (shield mounts **204** and sample mount **16**) within chamber **26**. In accordance with example implementations cold source **32** within chamber **40** can include at least two cold source stages **220** and **230** configured to provide different temperatures from each stage. Accordingly, the first thermal conduit **234** can extend from second stage **230** through vacuum barrier **38** to sample mount **16**.

Within chamber **26** can be a thermal radiation shield **202** operatively aligned to shield either or both of cryogenic device **18** and/or device mount **16** from thermal radiation. At least one thermal radiation shield mount **204** supporting thermal radiation shield **202** can be provided. Thermally insulative shield mount supports **206** can be provided extending between the second mounts **204** and the walls of the vacuum chamber **26**. To facilitate thermal control of shield **202** and mounts **204**, thermal conduit **224/208** is provided extending from cold source stage **1** **220** to the thermal radiation shield mount **204**. System **200** can also include another thermal switch **222** along the thermal conduit **224/208** and operatively aligned between cold source **32** and vacuum barrier **38**.

Accordingly, inside chamber **26** is radiation shield **202** that shields cryogenic device **16** from radiative heat loads from walls **12** of chamber **26** when maintained at room temperature. Cold source **32** is shown to have two stages, representing for example a Pulse Tube or Gifford-McMahon cryocooler with two stages operating at different temperatures: **40K** on stage **220** for example and **4K** on stage **230**. Cryogenic device **18** is in thermal communication with the stage **230** cold source via thermal conduits **234/208** in chambers **26** and **40**. Thermal switch **232** engages/disengages thermal communication between cryogenic device **18** and cold source stage **230**. Cryogenic device **18** is thermally engaged with cryogenic device mount **16** that is supported by a cryogenic device support structure **22**.

Radiation shield **202** is in thermal communication with the stage **220** cold source via thermal conduits **224/208** in chambers **40** and **26**. Thermal switch **222** engages/disengages the thermal communication between radiation shield mount **204** and cold source stage **220** via the cold source stage thermal conduit **224/208**. Radiation shield **202** is thermally engaged with radiation shield mount **204** that is supported by a insulative radiation shield mount support structure **206**.

Thermal switches **222/232** can be operated independently. For example, cryogenic device **18**, in thermal communication with cold source stage **230**, can be held at **4K** for example. Radiation shield **202**, in thermal communication with cold source stage **220**, can be held at **40K** for example. The temperature of cryogenic device **18** and radiation shield **202** can be independently controlled using heaters, thermometers, and processing circuitry (software) to control heater power to achieve desired temperature setpoints.

Radiation shield support **206** and cryogenic device support **22** are separate components. In other embodiments, the supporting structure may be a single component that includes an integrated radiation shield mount and a cryogenic device mount.

FIG. **4** shows an example embodiment of an example support structure. The structure can be mounted via fasteners to walls **12** of chamber **26**, held at room temperature, using the cryogenic device vacuum housing mount locations **304**. Thermally resistive supports **206** and **302** connect walls **12** to the radiation shield mount **204** and radiation shield mount to the cryogenic device mount, respectively. These supports are thermally resistive as to reduce conductive heat transfer through the supports to the radiation shield mount **204** and cryogenic device mount **16**. Cryogenic device **18** and radiation shield **202** can be mounted to cryogenic device mount **16** and radiation shield mount **204**, respectively, using fasteners.

In other embodiments, radiation shield **202** and radiation shield mount **204** in FIG. **3** could be replaced with other components that are in thermal communication with cold source stage **220** and thermal switch **222**. For example, radiation shield mount **204** could be replaced with a thermal lagging component that is used to thermally lag electrical wires, optical fibers, gas tubes, RF coax, and etc. that enter the cryogenic device vacuum space via feedthroughs in walls **12** of chamber **26** and are used to monitor or control cryogenic device **18**. Thermally lagging such components, at cold source stage **220** temperature of the thermal lagging component can reduce the conductive heat load such components add to the cryogenic device.

In FIG. **1** and FIG. **3**, both cryogenic device mount supports **22** and the vacuum barrier **38** are combined to have portions that are thermally cycled when a cryogenic device exchange is performed. These components are arranged to facilitate both the support and cooling/heating of device **18**. Because each is mounted to the vacuum housing maintained at room temperature, both bring in heat loads that reduce the available cooling power to reduce the cryogenic device temperature, thereby increasing the time required to cooldown the cryogenic device. A faster cryogenic device cooldown, and therefore cryogenic device exchange, can be achieved by either reducing the mass of the components that must be thermally cycled and/or reducing the heat loads on the cryogenic device.

Accordingly, FIG. **5** shows system **400** as another embodiment of the systems of the present disclosure, wherein the cryogenic device mount supports **22** and the vacuum barrier **38** components in FIG. **1** and FIG. **3** are combined in a single component **460**. Here, the vacuum barrier also serves as the physical support of the cryogenic device mount. By reducing the mass of the components that are thermally cycled during a cryogenic device exchange and the heat loads on the cryogenic device even further, the cryostat architecture in FIG. **5** can provide an even faster cryogenic device exchange time.

System **500** is depicted in FIG. **6** to include an example vacuum barrier **510** between walls **502** of vacuum chambers

26 and 40. Vacuum barrier 510 bridges a thermal gradient from 300K-4K while minimizing the heat load to cryogenic device 508. Barrier 510 also supports and reduces vibrations of cryogenic device 508. Accordingly, the vacuum barrier must be of a sufficiently high resonant frequency that the cryogenic device vibrations 504 are acceptable. Barrier 510 can provide thermal lagging/connections for a radiation shield and incoming electrical and/or optical connections to the cryogenic device. In isolating chamber 26, vacuum barrier 510 can provide an attractive option for UHV in sample chamber 26. To that end, the vacuum barrier may be designed and constructed of UHV compatible materials to enable use in future UHV applications. In accordance with example configurations, barrier 510 can include mounts 304, 204, and 506. Mounts 204 and 506 can be operatively engaged with stages 220 and 230 respectively and/or switches 222 and 232.

Referring next to FIG. 7, in accordance with example implementations and with reference to the orientation and placement of the thermal switches indicated above, system 600 is provided that is part of a cryogenic device analysis system and depicts a switch assembly in the open position. As shown, there can be a cold source 602 at one temperature that may be in a vacuum space different from a sample space 604 that can be at a higher temperature in this open position. Accordingly, a mechanical actuator 606 can be used to close the switch, and then provide the configuration shown in FIG. 8. The mechanical actuator 606 can be coupled to an actuator drive. Both mechanical actuator 606 and the actuator drive 608 can be coupled to an actuator drive controller 610. Actuator drive controller 610 and actuator drive 608 can be utilized to determine when the switch is in the open or closed position based on torque and/or temperature as well as rotations of the actuator drive as determined by the actuator drive controller 610. As shown in FIG. 8, the switch of system 600 is in the closed position, thereby allowing cold source 602 to be at the same temperature as sample space 604.

A current controlled drive can be used to provide more precise control of torque and therefore strain to the thermal switch than a mechanical torque drive system. This can assist with repeatability and dependable performance for each thermal cycle. In accordance with at least one embodiment, the switch assembly can include an encoder and/or torque measurement device as part of the drive controller.

Referring next to FIGS. 9A-9C, cold source conductive members and cryogenic device conductive members are shown overlapping one another at portions 708 and 706 to form an insulative space 710 therebetween. As shown, these members can extend to within vacuum spaces 604 and 602 respectively. The entirety of the overlap of portions 708 and 706 may be on one vacuum space side; for example, the entirety can be on the side of the cold source barrier 702, or the entirety can be on the side of the cryogenic device conductive or sample space barrier 704 respectively. The conductive materials of the present disclosure can be copper or aluminum for example.

In accordance with example implementations, and with reference to FIG. 9B, a force can be applied to pliable portion 706 to initiate thermal contact between 706 and 708, thereby closing the switch and arranging thermal conduction between 602 and 604. While shown as single application of force, this force may be applied to portion 708 as well or in the alternative to portion 708 alone. Accordingly, configurations include portions 706 and/or 708 that are sufficiently

flexible, pliable, and/or moveable to be transitioned from a biased position (FIGS. 9A and 9C) to a thermal contact position (FIG. 9B).

With reference to FIG. 9C, and in accordance with example implementations, to open the switch after conduction is established and thereby disconnect thermal connection between 602 and 604, force (F) can be removed from portion 706 and/or thermal energy (T) provided to portion 708, thereby causing portion 706 to revert to its biased configuration defining insulative space opening 710 therebetween and no thermal conductivity. While the thermal energy (T) is shown being provided to portion 708, alternative embodiments can include providing the thermal energy to portion 706 as well or in the alternative to portion 706, thus configurations can include removing force and providing thermal energy to the same portion.

Referring next to FIG. 10, in accordance with an alternative embodiment, a switch assembly can include overlapping portions 706 and 708, and a heating element 712, for example a thermal couple, operatively engaged with portion 708 of the cryogenic device conductive member. In accordance with example implementations, an actuator 606 can be operatively engaged with overlapping portion 706, and to limit thermal contact between actuator 606 and overlapping portion 706, having insulative portion 716. In accordance with example implementations, to assist with the bias in the open position of portion 706 in relation to portion 708, a biasing member 714 can be provided that mechanically connects portion 706 with another portion of the cryogenic device conductive member 604.

Referring next to FIG. 11A, in accordance with another example implementation, overlapping portions 708 and 706 can be arranged with structure 720 operatively engaged with either portions 706 or 708 to fix one of the overlapping portions in relation to the structure but allow bias and movement of the other of the overlapping portions. Structure 720 can be an encompassing structure configured to encompass at least overlapping portions 708 and 706. Accordingly, this configuration can assist with cold member disengagement and/or to minimize heat transfer to cold member when the switch is in the open position.

Referring next to FIGS. 11B-11F, multiple configurations of the thermal switch of the present disclosure are provided. Particularly with reference to FIG. 11B, a completely open switch configuration is shown that has overlapping portions 706 and 708 encompassed by encompassing structure 720, leaving a thermally disconnected space 722 therebetween. Referring next to FIG. 11C, upon the application of force to either one or both of portions 706 or 708, portions 706 and 708 are brought into contact to initiate a contact force 724 between the portions. In this configuration, the small contact force 724 is sufficient for the encompassing structure 720 to be in thermal engagement with both portions 706 and 708. Upon engagement of encompassing structure 720, encompassing structure 720 will constrict as shown in FIG. 11D. In FIG. 11D, this constriction brings a large contact force 726 between portions 706 and 708. Referring next to FIG. 11E, in accordance with example implementations, the switch can be opened by warming structure 720. This reduces the contact force between the portions and allows at least one of the overlapping portions 708 or 706 freedom of movement. Upon achieving that freedom of movement, force can be applied in the opposite direction to one or both of the portions and provide a thermally disconnected space 722 as shown in FIG. 11F.

In accordance with example implementations, when overlapping portions are not in thermal communication (i.e., at

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substantially different temperatures) structure 720 can also be thermally disengaged. When portions 708 and 706 are sufficiently proximate to have thermal engagement, structure 720 may likewise be thermally engaged. As a result of this engagement, structure 720 may constrict about portions 708 and 706 to completely thermally engage portions 708 and 706. Structure 720 may be warmed to loosen constriction about portions 708 and 706 and thus allow for less thermal engagement between the portions. Mechanical driven withdrawal of the portions can then be provided to space the portions far enough apart to provide a thermal disconnect. These stages of opening and closing the thermal switch are shown by example in FIGS. 11A to 11F.

Accordingly, heat application significantly reduces the force required to disengage the thermal switch. Structure 720 can be configured or referred to as a chassis component and/or comprise a material with a higher CTE than either of portions 706 and 708. Accordingly, when 720 cools, it contracts more than 706 and 708, thereby imparting a substantial contact force between 706 and 708 for low contact resistance and high heat transfer from one member to the other. Utilizing structure 720 in this way can reduce motor/actuator size, drive current and electronics, drive shaft, gears and linking components, thermal switch, reliability and cycling longevity, for example. More detailed evaluation of the materials of structure 720 are provided with reference to Table 1 below.

TABLE 1

Chassis Material	Preload Torque (in * lbs)	Preload (lbf)	Additional Force due to CTE (lbf)	Total Force when Cold (4K)	Torque to Loosen w/No Heat on Chassis (in * lbs)	Torque to Loosen w/Heat on Chassis (in * lbs)
Low CTE Material C101 Cu	4.7	100.00	262.00	362.00	5.7	~4.7
High CTE Material 6061 Al	4.7	100.00	565.30	665.30	10.48	~4.7

A low CTE and a high CTE structure 720 material is compared to illustrate the advantages provided by a high CTE material on Total Force and to illustrate why heating structure 720 is useful.

A Preload Torque from a mechanical driver applies an initial Preload Force between the two conductive members. This can initiate cooling and allows the chassis (i.e., structure 720) to begin cooling as well. As the chassis cools, additional force is applied by the constriction of the chassis to the conductive member interface. If the chassis is a low CTE material such as C101 Copper, then the additional force will amount to 262 lbf. If the chassis is made of a high CTE material such as 6061 Aluminum, then the additional force will be much higher, 565.3 lbf in this specific example.

This results in a much higher Total Force when the system is at base temperature, 4 Kelvin in this example.

Accordingly, the breakaway torque to loosen the connection of the portions is much higher for the High CTE Material due to the added load from CTE. To reduce the breakaway torque, heat can be applied to the chassis to warm it up and reduce the force applied due to the difference in CTE between the chassis and the conductive members (assumed to be C101 Copper in this example).

With a heated chassis, the motor torque required to loosen the joint will be similar to the initial Preload Torque (although it will not match it exactly in reality, it will be similar). Therefore, by adding heat to the chassis this design

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allows for a lower torque motor, smaller thermal switch components, and less stress on the thermal switch assembly overall during the process of opening the switch. An encompassing structure 720 having a larger CTE than portions 706 and/or 708 and can exert a large mechanical force pushing the portions in contact 726.

Accordingly, structure 720 can be affixed to portion 708 while leaving portion 706 sufficiently moveable to be put into contact with overlapping portion 708. In accordance with at least one embodiment, structure 720 is depicted as a chassis encompassing both portions; however, the structure can be affixed within the vacuum chamber of the system itself to a wall of the vacuum chamber, for example, and affixed thereto by insulative materials.

In accordance with yet another embodiment of the disclosure, another switch assembly is shown in FIGS. 12-14. This switch assembly is presented first in an isometric view in FIG. 12 that includes overlapping portions 706 and 708 having a structure 720 thereabout, and heating element 712 that extend through 720 and into overlapping portion 708 while actuator coupling device 800 extends through structure 720 to mechanically engage overlapping portion 708 at insulative portion 716. As shown, actuator coupling device 800 can be configured to receive a drive from the actuator. Device 800 can be constructed of insulative materials and engage insulative portion 716.

In accordance with example implementations and utilizing the systems and components shown herein, methods for closing conductive connection between a cold source and a cryogenic device within a cryogenic analysis system are provided. These methods can include providing a sufficient mechanical force to either or both of a portion of a cold source conductive member or a portion of an overlapping cryogenic device conductive member to thermally engage the overlapping portions of the conductive members and thereby close a thermal connection between the conductive members. This mechanical force as described can be provided from a mechanical actuator. This actuator can also be configured with an actuator drive coupled to an actuator drive controller. As a way of measuring and determining whether the connection between the conductive members is open or closed, the torque and/or rotations of the actuator can be measured using the drive controller.

In an additional embodiment, the methods include disconnecting these conductive members utilizing heat provided to one or both of the overlapping portions. In accordance with example implementations, providing heat can return at least one of the portions to its biased position in relation to the other portion which provides an insulative space between the members. Additionally, to provide this space, the mechanical actuator can be withdrawn to remove force applied to at least one portion of an overlapping conductive member.

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In compliance with the statute, embodiments of the invention have been described in language more or less specific as to structural and methodical features. It is to be understood, however, that the entire invention is not limited to the specific features and/or embodiments shown and/or described, since the disclosed embodiments comprise forms of putting the invention into effect.

The invention claimed is:

1. A switch assembly for a cryogenic device analysis system, the assembly comprising:

a cold source conductive member extending lengthwise to a cold source; and

a cryogenic device conductive member extending lengthwise to a cryogenic device and at least partially overlapping at least a portion of the cold source conductive member, wherein either or both of the conductive members are biased to define an insulative space between the conductive members at the overlap in an open orientation.

2. The switch assembly of claim 1 wherein one or both of the overlapping portions of the conductive members are sufficiently flexible, wherein the application of mechanical force to either one or both closes the insulative space to provide thermal contact between the portions.

3. The switch assembly of claim 2 further comprising a mechanical actuator operatively engaged with at least one of the overlapping portions of the conductive members.

4. The switch assembly of claim 3 further comprising a mechanical actuator drive and controller operatively engaged with the mechanical actuator.

5. The switch assembly of claim 1 further comprising an encompassing structure about the overlapping portions.

6. The switch assembly of claim 5 further comprising a heater assembly operatively engaged with the encompassing structure, wherein application of heat from the heater assembly to the encompassing structure lessens the mechanical contact force between the portions.

7. The switch assembly of claim 2 further comprising insulative members between the at least one overlapping portion and the mechanical actuator.

8. The switch assembly of claim 1 further comprising an insulative biasing member extending between the conductive members.

9. The switch assembly of claim 5 further comprising a structure operatively engaged about the overlapping portions and wherein the structure defines a collar or chassis.

10. A method for closing/opening a conductive connection between a cold source and a cryogenic device within a cryogenic analysis system, the method comprising providing sufficient mechanical force to either or both of a portion of a cold source conductive member or a portion of an overlapping cryogenic device conductive member to at least partially thermally engage the overlapping portions of the conductive members.

11. The method of claim 10 further comprising providing the mechanical force from a mechanical actuator.

12. The method of claim 11 further comprising operating the mechanical actuator using an actuator drive coupled to an actuator drive controller.

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13. The method of claim 12 further comprising monitoring the torque provided to the mechanical actuator to determine the closing of the thermal connection.

14. The method of claim 12 further comprising monitoring the rotations of the mechanical actuator to determine the closing of the thermal connection.

15. The method of claim 10 further comprising constricting an encompassing structure about both the portion of the cold source conductive member and the portion of an overlapping cryogenic device conductive member to close the switch and thermally connect the members.

16. The method of claim 15 wherein the mechanical actuator is engaged to initiate the cooldown of the overlapping cryogenic device conductive member as well as the encompassing structure.

17. The method of claim 15 further comprising warming the encompassing structure to provide freedom of movement between the portion of the cold source conductive member and the portion of an overlapping cryogenic device conductive member.

18. The method of claim 17 further comprising providing sufficient mechanical force to thermally disconnect the portion of the cold source conductive member and the portion of an overlapping cryogenic device conductive member and open the switch.

19. The method of claim 15 further comprising using an insulative member operatively engaged between the portion of the cold source conductive member and the portion of an overlapping cryogenic device conductive member to bias the members to define an insulative space between the members.

20. The method of claim 10 further comprising operating a mechanical actuator to provide the mechanical force.

21. The method of claim 20 further comprising monitoring the torque provided to the mechanical actuator or rotations of the mechanical actuator to determine the opening of the thermal connection.

22. A cryogenic device analysis system, the system comprising:

a pair of vacuum regions separated by a vacuum barrier; and

a switch within either of the vacuum regions, the switch comprising:

a cold source conductive member extending lengthwise to a cold source within one vacuum region;

a cryogenic device conductive member extending lengthwise to a cryogenic device within another vacuum region and at least partially overlapping at least a portion of the cold source conductive member, wherein either or both of the conductive members are biased to define an insulative space between the conductive members at the overlap in an open orientation; and

at least one mechanical actuator operatively engaged with either of the portions of the conductive members.

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