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Resistance Thermometry at Ultralow Temperatures

Resistance thermometry is perhaps the most popular way to measure low temperatures. This is due to its simplicity: the sensor's resistance value depends on temperature in a known way, so that it is enough to measure the resistance in order to find the temperature.

A sensor that is cooled down to a millikelvin temperature is often very sensitive to self-heating, caused by the measuring current. The main reason for this is that the thermal conductivity is poor at low temperatures. Usually, it is not very serious if the current heats a room-temperature sensor by 0.01 degrees Centigrade. But if a resistor, cooled to 0.01 degrees above the absolute zero, is heated by another 0.01 degrees, the error will be 100%! One has to use a current that heats the sensor by less than what is the expected accuracy of the measurement; sometimes a power as low as $10E^{-15}$ watts is required. A typical ohmmeter would use a 100 uA current for measuring a 10 kohm resistor, which means a $1E^{-4}$ watt heating power. Therefore, ordinary ohmmeters are not suitable for low-temperature resistance thermometry.

Five reasons to use a cryogenic resistance bridge

If an ohmmeter is applied for cryogenic resistance thermometry, a very low current must be used for the measurement. This is the first reason to rely on a specially designed instrument.

The voltage drop, generated by a sufficiently low current is so minuscule that it may be buried in fluctuating thermal and contact voltages, not to speak about offset voltages of the measuring instrument. An AC resistance bridge eliminates these error sources by using alternating current for the measurement. This is the second reason.

Wire leads that go from room temperature down to the cryostat must not conduct heat to the cooled parts. One can make the wires from a material that is a poor heat conductor. Unfortunately, such a material is usually a poor electric conductor, too. Some sensors, especially Platinum wire and Rhodium-Iron sensors, exhibit a very low resistance, from ohms to tens of ohms. In order to prevent the lead resistance and its changes from destroying the measurement accuracy, a 4-wire connection is necessary with low-ohmic sensors. 4-wire connection means, that the excitation current is fed to the sensor via two current leads, and the voltage drop is measured by using two additional voltage leads. The voltage leads do not carry any significant current, and therefore the voltage drop across the sensor can be measured accurately. The third reason to use a cryogenic resistance bridge is its ability to use 4-wire techniques together with AC-excitation.

Noise is a significant factor in low temperature thermometry because the measuring power is extremely low and therefore it is difficult to maintain a good signal-to-noise ratio. The cooled cryogenic sensor itself does not generate very much noise because of its low temperature, but most of the noise comes from the measuring apparatus. The fourth reason to use a specially designed instrument is the requirement for a low-noise input stage.

All multi-purpose ohmmeters have several measuring ranges. In addition to this, cryogenic thermometry requires also that the user has means to find the best trade-off between the sensor's self-heating error and the attainable signal-to-noise ratio. This is made possible by offering several selectable excitation current levels, which is the fifth reason.

Key features of the AVS-47

- Seven 4-wire resistance ranges from 0 to 2 Mohms
- Both manual and autoranging
- 4 1/2-digit output from 0 to 19999
- 2.5 readings/second
- Calibrated, continuous non-DAC analog output 0..2V
- Capable of handling 2*100 ohm lead resistance on the lowest 2 ohm range
- Seven excitation ranges from 3uV to 3mV nominal
- Equivalent input noise voltage 6..8 nV/sqrt(Hz), virtually no noise current.
- Operating frequency either 12.5/15Hz, taken from mains, or freely adjustable.
- Relay switch output for driving an alarm bell or on/off temperature controller.
- 8-channel input multiplexer is standard
- Built without using fast digital electronics. Very low RF emissions.
- The low-noise preamplifier is located in a separate unit and can be mounted near to the cryostat (= short sensor leads)
- Operation is possible using two 12 V batteries

- Low-EMI interfacing with a PC using a low-speed synchronous protocol. This "primary" interface is a standard feature
- The optional IEEE-488 "secondary" interface unit is located outside the bridge, providing physical distance from the noisy bus

About the design principles

The Input Stage

The AVS-47 was designed to be a general-purpose precision tool for AC resistance measurements using ultralow excitation power. Its main application is low-temperature thermometry using a variety of sensor types, but the low measuring current and AC operation may also be valuable in experiments where the sample's current-carrying capacity is small.

The resistance range that is encountered with cryogenic sensors is wide: Rhodium-Iron sensors start from below two ohms, Platinum wire resistors start from a decade higher. Thick-film resistors (Ruthenium Oxide, for example) have typically a resistance of some kilohms. The very important Germanium resistors range from kilohms to tens of kilohms at the lowest temperatures. Various carbon resistors can go up to hundreds of kilohms. We have heard about experiments with sensors that go even to some megohms. All sensors that are useful at the lowest temperatures have middle to high resistance. That is why the input stage of the AVS-47 was built using field-effect transistors, so optimising its noise performance for work with dilution refrigerators at low and ultralow temperatures.

Lead resistance

The measurement noise being the final limitation for resolution at low temperatures, there is an additional problem of lead resistance with low-ohmic sensors. If the sensor's resistance is 1.5 ohms, and the overall resistance of the current leads is 150 ohms, one needs an excitation compliance voltage of 0.1515 volts to produce a voltage drop of 1 mV across the sensor. With another sensor type, one may need 3 uV across a 10 kohm resistor. The excitation source of the AVS-47 was designed so that it can handle these both extremes without adding noise to the measurement.

The ability to deliver a high excitation compliance voltage means a potential danger to heat, or even to destroy, a high-resistivity sensor if the input is incautiously switched to it from a low-ohmic sensor while the low measurement range and high excitation are still selected. Therefore, the input of the AVS-47 can be kept grounded during the time a new sensor - and the proper range and excitation levels for it - are selected. This way, it is safe to use the standard 8-channel multiplexer to switch between very different sensors without danger of overheating them.

Thermal EMF's can cause errors, too

One possible, but usually overlooked, source of sensor self-heating error is the DC current originating from thermal EMF's in the input circuitry. With a good symmetry and no temperature differences between the measuring leads, the thermal EMF's can perhaps be kept below 1 uV. But if the symmetry fails, if the 300K difference between the room and cryostat temperatures causes somewhere a gradient of only a couple of degrees between two similar joints, the resulting EMF may rise up to some tens of microvolts. Depending on the design of the bridge input, this EMF may generate a DC current flowing through the sensor, and the heating effect can override the heating of the measuring current itself . In AVS-47 this possibility has been minimised by using a mismatch between the sensor and reference resistor ranges. Most of the heat is then generated safely at the room temperature.

The Operating Principle

The most prominent design features of the AVS-47 are its transformerless input stage and square-wave excitation. The user benefits from these features in the forms of a more affordable price and a smaller preamplifier unit.

The AVS-47 consists of two similar feedback loops, A and B, and of the series-connected reference resistor R_r and unknown resistor R_x. The purpose of loop A is to maintain an AC voltage drop V_{exc} of a constant amplitude across the room-temperature R_r, which means that an AC current of a constant amplitude flows through R_r to the sensor. This AC current generates a voltage drop across the sensor, whose magnitude is $V_{exc}*R_x/R_r$. The purpose of loop B is to convert this low AC voltage into a conveniently measurable DC voltage.

Square-wave excitation

Both the excitation and feedback are symmetrical square waves. This makes the AVS-47 different from other resistance bridges on the market. Square waveform has some important advantages: Such a waveform can be simply generated by using a chopper, so that its amplitude is accurately proportional to a DC voltage. One does not need old-fashioned non-linear and difficult-to-adjust analogue multipliers nor expensive high-resolution DACs and digital intelligence. Operation is purely analogue and therefore RF safe, but still linear.

Measurements of high-resistivity sensors may be affected by the capacitance of the measuring leads, and possibly also by the capacitance of the input filters to the cryostat. In a resistance bridge using sinusoidal waveforms, the nonlinearising effect of the capacitance is taken into account by having phase-sensitive detectors for the imbalance signals at both zero and 90 degree phases, which requires two PSD's instead of one. Digital intelligence can then be used to calculate the resistance from the two components. When square waves are used, the PSD can simply be inhibited for some time after the excitation has changed state in order to exclude the nonlinearising transients. Again, no digital overhead is needed.

A square wave contains a spectrum of higher frequencies, and it is sometimes asked, whether these can disturb other instrumentation. The excitation is generated using rather slow electronic circuits and components. Therefore, the amplitude of the higher harmonics has gone down by about 20 dB already at 200 Hz, compared with the amplitude of the fundamental at 12.5 Hz.

EMI Considerations

Although cryogenic thermometry using a resistive sensor is easy in principle, it is often bothered by unwanted extra heating of the sensor. Extra heating is usually caused by radio frequency interference that in one way or another couples to the sensor. The foremost goal in the design of the AVS-47 was to minimise this danger. The following list shows, how this goal has affected the bridge:

- The AVS-47 is a digitally controllable analogue instrument that does not contain microprocessors nor other fast digital circuitry.
- The preamplifier is located in a separate unit that can be placed in the immediate vicinity of the cryostat. This means short leads to the sensor.
- The optional IEEE-488 interface is also located in a separate unit, and the communications between the bridge and the GPIB unit is made using a slow protocol and a microprocessorless primary interface inside the bridge. This arrangement allows for a long physical distance between the cryostat and the noisy GPIB bus.
- The mains input filter is equipped with a ground choke for breaking ground loops. It is even possible to operate the AVS-47 using two 12 V batteries.

- The digital display is directly driven, instead of being multiplexed.

Computer Interfacing

Primary Interface

There are two ways to interface the AVS-47 with a computer. The Picobus primary interface implements a slow synchronous serial protocol, which is suitable for connecting the AVS-47 to one of the COM ports of a PC-type computer. We offer a small executable DOS program which makes interfacing simple. Little, if any, programming work is required. This program reads the instrument and performs other commands which are given as parameters on the command line or in a separate command file. The output can be directed to a file which is then read by the user's own program. The great advantage of this approach is that it can be used from most programming languages. The disadvantage is that it is very slow (but so is also the AVS-47: only 2.5 readings in a second). For customers wanting to write their own programs, we provide a Turbo Pascal 6.0 unit that contains the low-level routines needed for communicating with the bridge. Using these routines requires programming skills.

Secondary Interface

The optional model AVS47-IB interface for IEEE-488 provides a more general way, which is useful also with other than PC-type computers. This interface is located in a separate mains-powered unit, which communicates with the AVS-47 via the primary interface. The AVS47-IB is essentially based on a small computer. It offers, in addition to the basic low level commands managing the AVS-47, also many high level macro commands like averaging, scanning, digital filtering and even digital self-calibration for obtaining the best accuracy. The AVS47-IB can buffer data in order to reduce the host computer's workload. Scheduled measurements at pre-set intervals, and printing these on a printer, is also possible with this interface.

Temperature control applications

The AVS-47 has a calibrated, non-DAC analogue output. This output is suitable for temperature control at a high resolution.

Picowatt offers a precision PID (Proportional-Integrate-Differentiate, or Three-term) temperature controller TS-530A, which is also based on analogue electronics. The TS-530A has been designed mainly for dilution refrigerator temperatures. Its maximum heating power is limited to 1 watt into a 100 ohm heater.

The TS-530A receives its programming data from the AVS-47, so that both instruments are handled together via only one computer interface. Both devices use similar 19-inch enclosures, which can be stacked on top of each other.