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Research Paper

Temperature Measurement Techniques for RAON Cryomodule

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Abstract Conducting and semiconducting temperature sensors are calibrated and applied to cryomodules. The definition of temperature is introduced and the pressure in vacuum is shown as a function of temperature. The resistance of Drude model is shown as a function of carrier density and mean free path. Temperature sensors are calibrated with Physical Property Measurement System (PPMS). The temperature sensors are applied to measure temperature accurately in RAON cryomodules.

Keywords: Temperature sensor, Accelerator, Resistance measurement, Conductor, Semiconductor

I. Introduction

RAON which represents rare isotope accelerator complex for On-line experiments was designed for nuclear physics, material science and medical research [1]. The RAON is designed to provide various high-intensity stable ion beams for domestic and international users. The driver accelerator accelerates various ion beams ranging from proton to uranium beams, delivering more than a 400 kW beam power. The driver linear accelerator of RAON consists of a low-energy superconducting linac (SCL1), a high-energy superconducting linac (SCL2) and a low-energy superconducting linac (SCL3). Types of RAON cryomodule are quarter-wave resonator (QWR), half-wave resonator (HWR) and two single-spoke resonators (SSRs). The prototypes of all the cryomodule were fabricated. Half-wave resonator (HWR) cryomodule was tested in low temperature environment. Operation temperature for QWR cryomodule is 4.3 K and that of HWR and SSR cryomodule is 2.1 K. Temperature of a body can be measured with blackbody radiation in all range of temperature. Blackbody radiation is changed when its size becomes small. The size effect of blackbody radiation was investigated [2-4] and the thermal radiation from arbitrary dimension was studied [5]. The effective temperature was defined for non-uniform temperature distribution [6-8]. Helium leak detection techniques were introduced to construct cryogenic systems [9]. Molecular gas flow through a tube was investigated [10,11] and vacuum test of a cavity was performed with liquid nitrogen [12].

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In this paper we calibrate the temperature sensors of conductor and semiconductor and apply the temperature sensors to cryomodules. The general electrical properties of materials are introduced for insulator, semiconductor, conductor and superconductor. Drude model is shown and the resistance of conductor and semiconductor are measured with Physical Property Measurement System (PPMS). The measured resistance is explained well with the Drude model.

II. Theory

1. Temperature

When a body is described by stating its internal energy U, entropy S, volume V, and number of particle N, with $S = S(U, V, N)$, the temperature is defined as

$$\frac{1}{T} = \left(\frac{\partial S}{\partial U}\right)_{V,N} \tag{1}$$

Entropy is expressed as

$$\Delta S = \frac{\Delta Q}{T} \tag{2}$$

The entropy can also be expressed as

$$S = k_B \ln \Omega \tag{3}$$

where k_B is the Boltzmann's constant and Ω is the number of microstate.

Temperature can be measured from ideal gas law in low temperature range. The ideal gas law shows

$$PV = Nk_B T \tag{4}$$

where P is the pressure, V is the volume, N is the number of gas molecules, k_B is the Boltzmann constant and T is the absolute temperature. The kinetic energy of the gas molecules corresponds to the thermal energy. For high temperature range, photon pressure needs to be included as [13]

$$PV = Nk_BT + \frac{8\pi^5 k_B^4}{15h^3c^3}T^4 \quad (5)$$

where h is the Planck constant and c is the speed of light. The total pressure comes from gas molecules as well as photon. The critical temperature is $T_c = \left(\frac{15h^3c^3N}{8\pi^5k_B^3}\right)^{1/3}$.

Gas pressure is more important than photon pressure when its temperature is lower than the critical temperature and photon pressure is more important than gas pressure when its temperature is higher than the critical temperature. Figure 1 shows the photon pressure as a function of temperature in vacuum. Photon pressure is calculated for the volume of $V = 2.47\times10^{-2}m^3$. Photon pressure is 1 bar at T = 42515 K. There is the photon pressure which increases with temperature even if there is no gas molecules.

2. Resistivity of material types

Figure 2 shows the cartoon of the resistivity of material types as a function of temperature. Materials can be classified

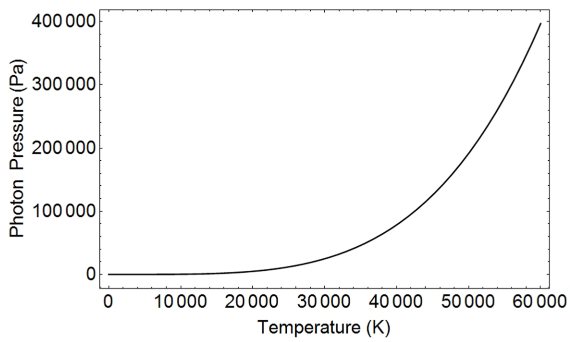

Figure 1. Photon pressure as a function of temperature in vacuum. Photon pressure is calculated for the volume of V = 2.47 × 10^{-2}m^3. Photon pressure is 1 bar at T = 42515 K in vacuum.

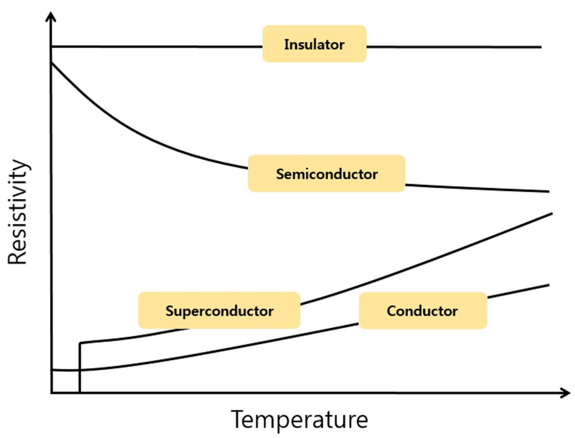

Figure 2. Cartoon of the resistivity of material types as a function of temperature.

as insulator, semiconductor, metal and superconductor according to resistivity. Insulator is a material with a very high resistivity (typically > 10^{12} ohm cm) that is independent of temperature. Semiconductor is a material with an intermediate range resistivity (typically 10^{-3} to 10^{11} ohm cm) that decreases as temperature increases. Metal is a material with a very low resistivity (typically <10^{-4} ohm cm) that increases as temperature increases. Superconductor is a material whose resistance is similar to that of a metal at high temperature, but whose resistance drops to zero below a critical temperature.

3. Drude model

Drude model is a free electron model. Free electrons have thermal energy. The free electrons are accelerated under external electric field. The electrons are continuously accelerated until they make collisions. The scattering comes from phonons, impurity particles, other electrons, etc. The electrons are accelerated, make collision, stop, and so on. The conductivity of the material can be expressed as

$$\sigma = \frac{ne^2l}{m^*v}, \quad (6)$$

where l is the mean free path, v is the average velocity of the carrier and m^* is the effective mass of the electron. The electron velocity comes from the applied electric field in the material. This is the most general expression for the conductivity, which works for conductor, semiconductor and insulator. Resistance can be expressed as

$$R = \rho\frac{L}{A} \quad (7)$$

where ρ is the resistivity, L is the length and A is the cross-section area. The resistivity is the property of the material. The conductivity can be expressed as $\sigma = \frac{1}{\rho}$ where σ is the conductivity.

The number of electron or the carrier density of a conductor is very high, which does not depend on temperature. The resistance of the conductor depends mainly on the scattering of phonon. The phonon scattering is linearly decreased as temperature decreases. So, the resistivity of the conductors such as platinum, gold and cooper is increased linearly as temperature increases. The conductivity of the conductor can be expressed as

$$\sigma(T) = \frac{ne^2l(T)}{m^*v} \quad (8)$$

The mean free path coming mainly from phonon scattering is linearly increased as temperature decreases. The resistivity of metal is increased as the temperature increases with

$$\rho = \rho_O + aT \quad (9)$$

where ρ_o is the zero temperature resistivity coming from the electron scattering due to impurities or imperfections, and a is the proportional constant coming from the electron scattering due to thermal vibrations of the atoms in the lattice. Drude model shows that the resistance of the metal increases as temperature increases with $R = \frac{lm^*}{Ane^2\tau} = \frac{laT}{A}$.

Semiconductor has a band gap. The carrier density of the semiconductor is reduced as temperature decreases. Cernox temperature sensor such as CX-1050 is that ZrN, conductor, is embedded in the matrix of ZrO_2, insulator. The resistivity is increased exponentially as temperature decreases. The conductivity of the semiconductor can be expressed as

$$\sigma(T) = \frac{n(T)e^2 l}{m^* v} \quad (10)$$

The conductivity of semiconductor depends strongly on the carrier density, which depends on temperature. The conductivity of the semiconductor is exponentially increased as temperature is increased because the carrier density increases in which carriers are excited from valence band to conduction band as temperature increases. The resistance of semiconductor is expressed as

$$R(T) = R_0 exp(E/k_B T) \quad (11)$$

Therefore, temperature sensitivity is very high in low temperature region and the measurement time is also short. For the band gap, the optical band gap is almost the same as the electrical band gap in most materials.

Carriers do not make scattering in superconductor according to BCS theory. Scattering causes resistance. Electrons make coupling with phonons in superconductor, so the resistance becomes zero. The resistance of the superconducting material comes mainly from impurity scattering.

Insulator has high band gap. Diamond, glass and wood are called insulator. They do not have enough carrier density, so the conductivity of insulator is very low.

III. Experimental Measurement of Resistance

Physical Property Measurement System (PPMS) is shown in Figure 3. The resistivity of the sensors is measured using the Physical Property Measurement System (PPMS) from 2 to 325 K. The electric transport (ETO) measurement with the constant current of 0.01 mA and the resistivity measurement with 0.33 mA at 2 K and 0.99 mA at 325 K are used to measure the resistance of the sensors. Two methods have the same results.

Figure 4 shows the resistance measurement as a function of temperature for Pt100. The Pt100 represents 100 Ω at the temperature of 273.15 K. The resistance of the Pt100 shows the linear dependence with temperature for 40K-325 K. Electron-phonon scattering is decreased linearly as temperature decreases. The Pt100 is generally used for 40K-400 K in which the resistance shows the linear relation as a function of temperature. Impurity and non-crystal structure can cause the finite resistance as temperature goes down below 40 K.

Resistivity measurement is shown as a function of temperature for copper wire in Figure 5. Cu wire has the diameter of 0.33 mm and the residual resistivity ratio (RRR) of the copper wire is 126. The resistivity of the

Figure 3. Physical Property Measurement System (PPMS).

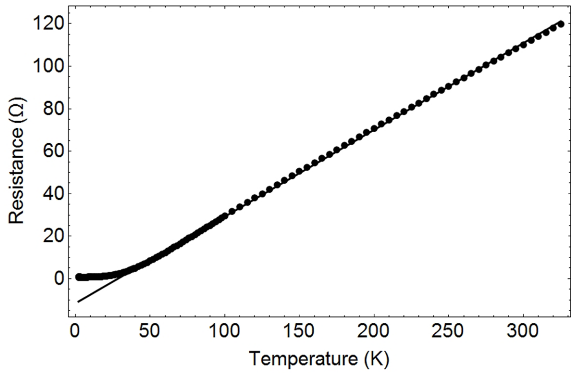

Figure 4. Resistance measurement as a function of temperature for Pt100. The resistance is fitted with $R = -11.553 + 0.408T$. The Pt100 shows the linear dependence with temperature for 40K-325 K. Impurity and non-crystal structure can cause the finite resistance as temperature goes down below 40 K.

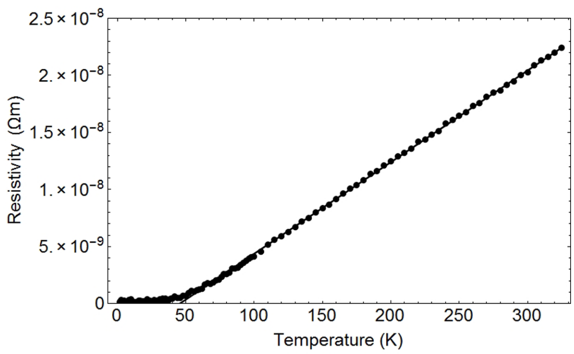

Figure 5. Resistivity measurement as a function of temperature for copper wire. The resistivity of the copper wire shows the linear dependence with temperature for 50K-325 K. Electron-phonon scattering is decreased linearly as temperature decreases. The Cu wire has the diameter of 0.33 mm and the RRR of the copper wire is 126.

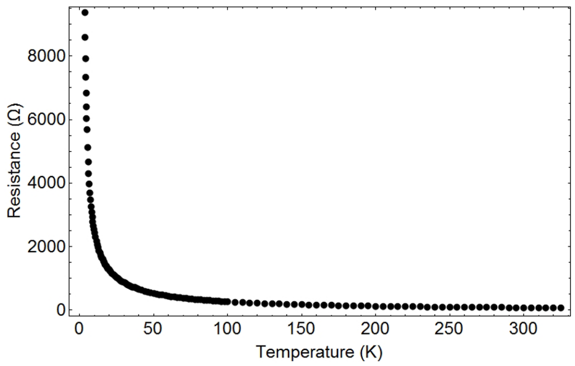

Figure 6. Resistance measurement as a function of temperature for Cernox sensor. The resistance is increased as temperature decreases.

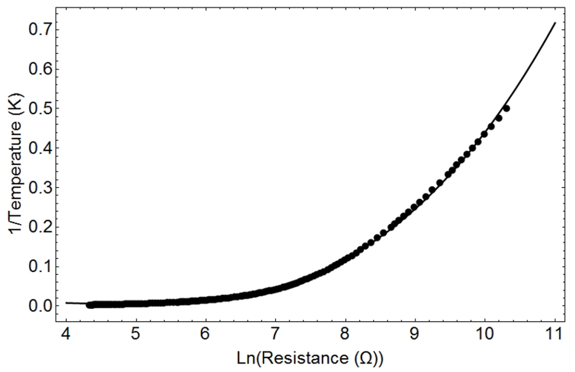

Figure 7. Theoretical fitting for the resistance measurement of Cernox sensor. The data is fitted with $\frac{1}{T}$ =-0.1443+0.1178ln(R))^2-0.0293(ln(R))^2+0.0023(ln(R))^3 and this fitting works well.

copper wire shows the linear dependence with temperature for 50K-325 K. Electron-phonon scattering is decreased linearly as temperature decreases.

Figure 6 shows the resistance measurement as a function of temperature for Cernox sensor. The Cernox sensor of p-type semiconductor is composed of a conducting zirconium nitride (ZrN) embedded in a non-conducting zirconium oxide (ZrO) matrix. The resistance of the Cernox sensor is exponentially increased as temperature decreases.

Figure 7 shows the theoretical fitting for the resistance measurement of Cernox sensor. Steinhart-Hart equation works for Negative Temperature Coefficient (NTC) thermistor materials, which works from 300 to 400K [14].

$$\frac{1}{T} = a_o + a_1 \ln(R) + a_2(\ln(R))^3 \tag{12}$$

where R is the resistance of the material and the square term is not considered. The Steinhart-Hart equation does not work well for the Cernox sensor. Square term needs to be included for better fitting as

$$\frac{1}{T} = a_o + a_1 \ln(R) + a_2(\ln(R))^2 + a_3(\ln(R))^3 \tag{13}$$

Eq. (13) works well for the Cernox senor.

A cryomodule consists of thermal shield, cavity and liquid helium reservoir. The cavity is made of niobium, which is operated at the temperature of liquid helium. The cryomodule is tested with liquid nitrogen and liquid helium. The liquid nitrogen is supplied to the thermal shield and the liquid helium is supplied to the liquid helium reservoir and cavity. The temperatures for the cryomdoule are measured with the conductor temperature sensor of Pt100 and the semiconductor temperature sensor of Cernox CX-1050. The Pt 100 represents 100 Ω at the temperature of 273.15K, whose resistance is decreased linearly as temperature decreases because electron-phonon scattering decreases as temperature is decreased. The Pt 100 works in the temperature range between 40 to 400 K. The Cernox semiconductor temperature sensor of CX-1050 is composed of zirconium nitride (ZrN) embedded in zirconium oxide (ZrO) matrix, which works in the temperature range between 1.4 to 420 K. The resistance of the semiconductor sensor is increased as temperature decreases due to the band gap. In order to monitor the temperature of the cryomodule, the Pt 100 sensor is used for the temperature range between 40 to 400 K and the CX-1050 is used for the temperature range between 2 to 400 K.

V. Conclusions

We have calibrated the conducting and semiconducting temperature sensors and applied to cryomodules. The definition of temperature is introduced and the pressure of photon is shown as a function of temperature in vacuum. The resistance of Drude model is shown as a function of carrier density and mean free path. Temperature sensors which include semiconductor and conductor are calibrated with Physical Property Measurement System (PPMS) from 2 to 325 K. The resistance of temperature sensors are explained well with Drude model. The temperature sensors are applied to measure temperature accurately in RAON cryomodules.

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