

# Experimental Investigation on Thermoresistance between AlN, Bi-2223 and OFHC in High $T_C$ - Direct Cooling Technology \*

HL Wang, RS Rao, J Wang

Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan 430074, P.R.China

E-mail: whlclf@163.com

**Abstract.** In the development of high temperature superconducting (HTS) direct cooling technology, the high electric insulation high heat conducting AlN has become one of the important components. The thermal contact resistance between AlN, Bi-2223 and OFHC is investigated by experiment with a G-M cryocooler as the source of cooling. The heat conductivity of AlN is measured between 29 and 160 K temperatures. When the temperature on the interface layer side of Bi-2223 is 55 K, under the action of the contact pressure of 0.5469 MPa, the thermal contact resistance between AlN and Bi-2223 is 38.86 times to the thermal conduction resistance of a 10 mm thick AlN pad. Based on micro-nanocryogenics, it is proposed that the thermal contact resistance is one of the crucial techniques to be attacked in HTS direct cooling technology.

## 1. Introduction

The high heat conductance and high electric insulation aluminium nitride (AlN) ceramic material is widely used in fields such as the manufacture of electronic devices, power modules and the super-large-scale integrated circuit <sup>[1,2]</sup>. The heat conductivity of pure AlN single crystal with a hexagonal fibrous zinc ore structure at room temperature can be as high as 320 w/(m·K) <sup>[3,4]</sup>. Its high heat conductivity is nearly equivalent to that of copper. The usual heat conductivity value of actually supplied materials is between 100~170 w/(m·K) or thereabouts <sup>[3]</sup>.

Despite numerous investigations on the thermal characteristics of AlN at normal and high temperatures <sup>[5]</sup>, little has been done in learning about AlN material application in the

---

\* Project supported by National Science Foundation of China, No. 51276070.



cryogenic environment. Particularly in recent years, the development of high temperature superconducting materials and the advance of cryogenic refrigerators have enhanced the high temperature superconducting direct cooling technology<sup>[2]</sup>. The high heat conductivity and electrically insulating AlN has become one of the acknowledged materials for devices using in HTS direct cooling technology.

With HTS system using direct cooling, various joining pads (washers) made of AlN possess not only have characteristics such as high heat conductivity, high electric insulation (insulation resistivity being  $10^{12} \Omega \cdot \text{cm} \sim 10^{14} \Omega \cdot \text{cm}$ ). They also exhibit properties such as high mechanical strength, good chemical stability and freedom from toxicity and contamination. These excellent properties make them important joining components using in the cold head of cryogenic refrigerator, binary current lead and magnet, etc. So far, not much is reported on the heat conducting characteristics of actual application of AlN ceramics in HTS projects within the 30~50 K temperature range from the angle of micro-scale cryogenic engineering and 3-D interface resistance.

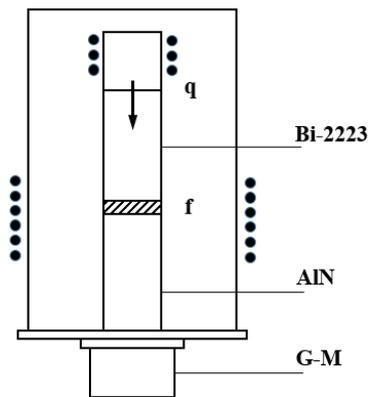
## 2. Experimental method

It can be seen from the angle of micro- and nano-cryogenics that there exists an interfacial layer at the interface between the two solids in contact. Neither the organizing structure nor property of this interfacial layer is the same as that of the two solids. The author has observed the micro-structure interface joined by copper-aluminium cold-pressing under a scanning electron microscope (SEM)<sup>[6,7]</sup> and found that the alloy content percentages each  $4 \mu\text{m}$  from the two sides of the so-called Cu-Al 2-D interface are: on the Cu side (Al: 16.37%; Cu: 83.63%); on the Al side (Cu: 1.4%, Al: 98.6%). Therefore, in high temperature superconducting direct cooling technology, research on the heat transport process and characteristics at the 3-D cryogenics interfacial layer<sup>[6]</sup> and the magnitude of the heat resistance at the 3-D cryogenics interfacial layer is of great significance.

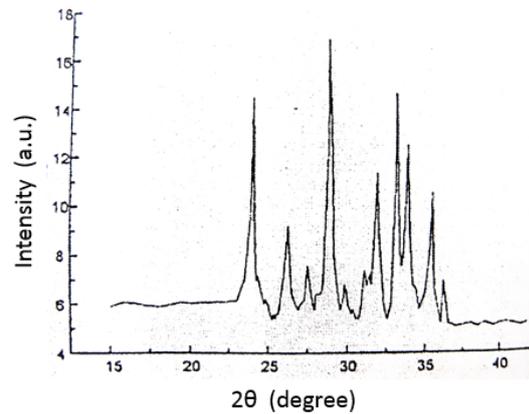
When the heat flow passes through the interfacial layer  $f$  formed by the two objects in contact, there will be generated a temperature drop  $\Delta T$  at the interfacial layer. The thermal resistance  $R_b$  at the interfacial layer is the ratio of the temperature drop to the heat flow density  $q$ ,

$$R_b = \Delta T / q \quad [\text{K} \cdot \text{m}^2 \cdot \text{w}^{-1}] \quad (1)$$

The principle of the experimental equipment is shown in Figure 1. In the experiment, the cooling is provided by the G-M cryorefrigerator while a controlled heat input to the sample is achieved with an electric heater. The AlN ceramics, Bi-2223 high temperature superconductor and oxygen-free copper (OFHC) specimens are all made into cylinders of nominal dimensions  $\text{Ø}10 \times 30 \text{ mm}$ . The two end-faces of a specimen are polished on a grinding machine, the end-face parallelism being  $< 0.008 \text{ mm}$ . The graph of the superconducting material Bi-2223 undergoing X-ray refraction is as shown in Figure 2.



**Figure 1.** Schematic of the experimental principle of AlN – Bi-2223 cryogenic interfacial heat resistance.



**Figure 2.** The x diffraction graph of the Bi-2223 specimen.

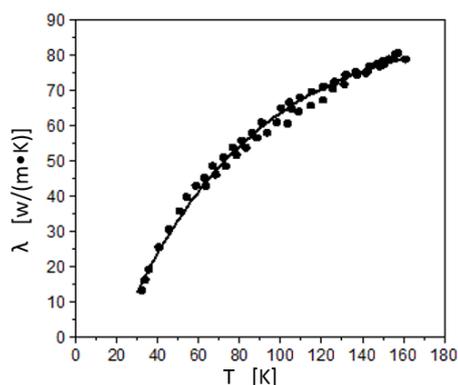
To satisfy the requirements of the 1-D axial steady-state method, a radiation screen is incorporated on the specimen shelf onto which a cryogenic rare-magnetic Cu-Fe thermocouple (NiCr-CuFe) is soldered [8,9]. A cryogenic temperature control is used for ensuring that the difference in temperature between the radiation screen and specimen is less than 1 K. A diffusion pump and G-M machine are used to ensure that the vacuum in the measuring Dewar is better than  $5.0 \times 10^{-4}$  Pa [10].

Self-developed rare magnet Cu-Fe cryogenic thermocouples (NiCr-Cu + 0.13% at Fe) [11] are used for experiment, with each of the thermocouples calibrated by our laboratory. The testing system is made up of US-made data collectors Keithley 2700 as the secondary instrumentation. Prior to testing, standard samples of copper and pure iron with known heat conductivity are used for measurement to verify the reliability of the experimental devices and measuring system.

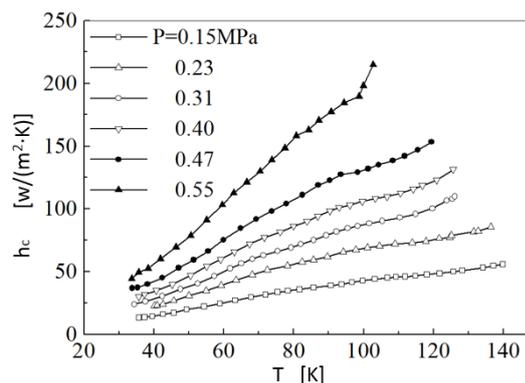
### 3. Experimental results

#### 3.1. The AlN cryogenic heat conductivity

Owing to the absence of free electrons in AlN, phonons play a significant role in the heat conductance of electrically insulated AlN. The measured thermal conductivity of the AlN sample is shown in Figure 3. Because of the excellent heat transmission ability of AlN at low temperature, the difference in temperature at the interface between AlN and HTS materials in contact such as oxygen free copper (OFHC) can be relatively small, which means the heat generated by the superconducting magnet is rapidly transmitted outside. In addition, the insulated resistivity of AlN is  $10^{12} \Omega \cdot cm \sim 10^{14} \Omega \cdot cm$ , the dielectric constant  $\epsilon'$  is 9.1 [3]. The good electric insulation and low dielectric loss make AlN very conducive to highly efficient and reliable operation of the cryogenic refrigerator.



**Figure 3.** The relation of variation of AlN cryogenic heat conductivity with temperature.



**Figure 4.** Variation of heat conductance at the interfacial layer between AlN and Bi-2223 with pressure.

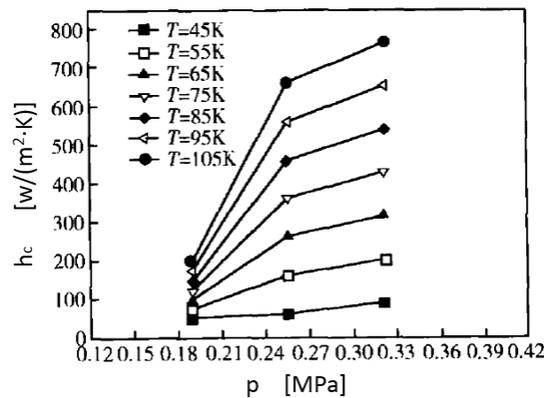
### 3.2. The heat resistance at the interface between AlN and Bi-2223

It is shown by experiment that, within the range of the experimental contact pressure (0.15 ~ 0.55 MPa), with the rise of temperature and contact pressure, the heat conductance at the interfacial layer increases. Shown in Figure 4 is the curve representing the relation of variation of the contact pressure in heat conductance at the interface between AlN and Bi-2223. It can be seen from the figure that, when the temperature on the Bi-2223 side of the interfacial layer is 55K, and the contact pressure rises from 0.23 MPa to 0.55 MPa, the heat conductance rises from 34.87 w/(m<sup>2</sup>·K) to 90.19 w/(m<sup>2</sup>·K), equivalent to a reduction in the interfacial heat resistance by 61.3%. So, within the allowable range of material stress intensity, appropriate increase in the contact pressure can decrease the heat resistance at the contact interfacial layer.

With a contact pressure of 0.55 MPa, suppose the AlN pad has the thickness of 10 mm. When the interface temperature are 35.2 K, 55.2 K, 73.5 K and 94.5 K, the interfacial layer heat resistance is 48.6, 38.9, 33.5 and 30.5 times that of the AlN pad, respectively. Therefore, in a direct cooling HTS magnet, the interfacial layer heat resistance has an important influence on the cooling efficiency and the thermostability of the superconducting magnet.

### 3.3. The contact heat conductance at the interface between AlN and oxygen free copper

It is shown by experiment that the interfacial contact heat conductance between AlN and OHFC increases with the rise of contact interface pressure, as shown in Figure 5. On the interface between ceramics and metals, such as AlN and OFHC, the heat carriers are mainly phonons (on the AlN side) and electrons (on the OHFC side). Increasing the interfacial contact pressure can improve the defects on the contact interfacial layer, contract and decrease the characteristics dimensions of the superficial local micro-defects. On one hand the interfacial heat conductance and, on the other, the average free path of heat carriers reaching the micro-sub-interface is relatively increased, leading to reduction of the contact heat resistance. Under the same pressure, the relation between the interface heat conductance and temperature is approximately linear.



**Figure 5.** The variation of contact heat conductance of AIN and OFHC with pressure.

An analysis of the experimental curve variation shows that, with an increase in the interface pressure, the contact heat conductance value rapidly increases at the beginning. With further increase in the pressure, the amplitude of increase of the contact heat conductance tends to become gentle step by step as if being passivated. Meanwhile, the greater the interfacial pressure, the more abrupt the variation of the contact heat conductance with temperature.

#### 4. Conclusions

- Heat conductivity characteristics data on AIN material for HTS application using within the 29~160 K low temperature range have been measured by experiment. The total error is  $\pm 15\%$ . The heat conductivity of AIN material at 29 K is 9.24 w/(m·K) and is 80.61 w/(m·K) when the temperature reaches 157 K. Its heat conductivity is dozens of times that of HTS materials.
- Within the range of contact pressure 0.15 MPa ~ 0.55 MPa, the interfacial conductance AIN – Bi-2223 increases with the rise of the contact pressure and temperature. When the temperature on the Bi-2223 side of the interfacial layer is 55 K, with the contact pressure enhanced to 0.55 MPa, the heat conductance on the interfacial layer rises from 34.87 w/(m<sup>2</sup>·K) to 90.19 w/(m<sup>2</sup>·K), equivalent to a reduction of the heat resistance on the interfacial layer by 61.3%.
- In-depth investigation on the 3-D interfacial heat resistance and the 3-D layer heat transport mechanism based on micro- and nano-cryogenics is of important scientific significance <sup>[12]</sup>.

#### 5. References

- [1] Wang H L, Rao R S, Li J D, Tang Y J and Cheng S J 2001 Progress on cryogenic technology applied in superconducting electrical engineering *AEPS*. **17** 65
- [2] Iwase N, Anzai K 1985 Aluminium nitride substrates having high thermal conductivity *Toshiba Rev. (Int Ed)* **153** 49
- [3] Wang D F, Li W L, Zhuang H R and Guo J K 1998 Recent process in high thermal conductivity AIN ceramics *Materials Review*. **12** 29

- [4] Yu Y D, Hundere A M, Høier R 2002 Microstructural characterization and microstructural effects on the thermal conductivity of AlN(Y<sub>2</sub>O<sub>3</sub>) ceramics *Journal of the European Ceramic Society* **22** 247
- [5] Graebner J E, Jin S, Kammlott G W, Bacon B, Seibles L and Banholzer W 1992 Anisotropic thermal conductivity in chemical vapor deposition diamond *Journal of Applied Physics* **71** 5353
- [6] Wang H L, Wanger T and Eska G 2000 An aluminium heat switch made from cold-pressed Cu-Al composite *Physica B: Condensed Matter* **284-288** 2024
- [7] Shi L and Wang H L 2007 Investigation on thermal contact resistance by photothermal technique at low temperature *Heat and Mass Transfer* **11** 1179
- [8] Rao R S and Wang H L 2003 Identification and experimental investigation on thermal interface resistance for cryocooler cooled High-Tc superconductor *Chinese Journal of Low Temperature Physics* **25** 209
- [9] Chen J, Wang J R, Rao R S, Wang J, Zhang Y L, Li J D, Tang Y J and Wang H L 2003 Research on the temperature control of thermal properties experiment of superconducting material *Physica C: Superconductivity* **386** 544
- [10] Rao R S, Wang J R, Zhuang H R, Wang T C, Chen J, Li J D, Tang Y J and Wang H L 2003 An investigation on interface thermal resistance at superconductor cooling by cryocooler *Physica C: Superconductivity* **386** 547
- [11] Wang H L and Gao H C 1990 An investigation on the thermoelectric properties of dilute magnetic copper-iron alloys at low temperature *Physica B: Condensed Matter* **165-166** 41
- [12] Xie J B, Wang H L, Wu G, Zhao Y, Li J D and Tang Y J 2006 Experimental investigation of heat transport for 35 kJ superconducting magnet energy storage system *Cryogenics* **1** 31