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Application and research status of semiconductor refrigeration technology

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Abstract:

In recent years, global modernization has become an irreversible trend. However, the excessive use of energy has also brought about numerous severe challenges, including global warming, ozone layer depletion, light pollution, and the shortage of non-renewable resources. This article briefly introduces semiconductor cooling technology and provides a detailed explanation of how semiconductor cooling sheets work. By analyzing the current research progress in thermoelectric materials, the article predicts the future development direction of these materials. It then summarizes the optimal operating conditions for semiconductor coolers and discusses their heat dissipation methods, including natural convection, forced convection, water cooling, and heat pipe cooling. The aim is to highlight the importance of efficient energy utilization and enhanced heat transfer in improving cooling efficiency and reducing energy loss. Additionally, the article envisions the structure of semiconductor cooling sheets, optimizing them into pipes. Using SOLIDWORK software for modeling, it applies knowledge of heat transfer to imagine the usage conditions and suitable applications of this new structure. It also looks forward to the application prospects of semiconductor cooling technology in areas such as human protection, solar cooling, and infrared detection.

Keywords: Semiconductor refrigeration, enhanced heat transfer, thermoelectric materials, structural optimization

1 Introduction

Semiconductor refrigeration technology does not require the use of traditional refrigerants, offering higher energy efficiency and lower power consumption. It is characterized by a compact design, light weight, and ease of control. This technology uses special semiconductor materials, such as bismuth telluride, to form PN junctions that act as thermocouples, operating on the Peltier effect for cooling. It represents a new, environmentally friendly method of direct cooling using direct current electricity. Given China's resource profile of being' rich in coal, poor in oil, and scarce in gas, 'the country's energy structure is characterized as 'low-quality.' The economy, heavily reliant on coal, has led to severe environmental pollution[1].In the face of such a severe energy situation, new refrigeration technologies have emerged. This article will delve into the widely applied semiconductor cooling technology, optimize its structure to enhance heat transfer and reduce energy loss, and explore the future prospects and development trends of semiconductor cooling technology. However, both domestic and international researchers have not made significant progress in the study of thermoelectric cooling materials, and there is limited research on improving the design of heat dissipation systems at the cold and hot ends. These factors pose significant challenges to the advancement of semiconductor cooling technology[2].This paper will discuss this in detail and summarize the recent development of this technology.

2 Semiconductor Refrigeration Principle

The three major thermoelectric effects are the Seebeck effect, the Peltier effect, and the Thomson effect, with the Peltier effect being the most prominent. When a current flow through a circuit made up of different conductors, it not only generates irreversible Joule heat but also causes heat absorption and release at the junctions of the conductors depending on the direction of the current. When a pair of thermocouples, composed of N-type and P-type materials, is subjected to a direct current, the direction of the current will cause heat absorption and release at the junctions of the thermocouples, known as the Peltier effect. The fundamental formula for this phenomenon is:

$$Q = \pi_{ab} I = \alpha \cdot T_c$$

Among them, Q is the heat released or absorbed by the conductor, π_{ab} is the proportion coefficient (Peltier coefficient), I is the closed-circuit current, α is the temperature difference coefficient, and T_c is the temperature of the cold end node.

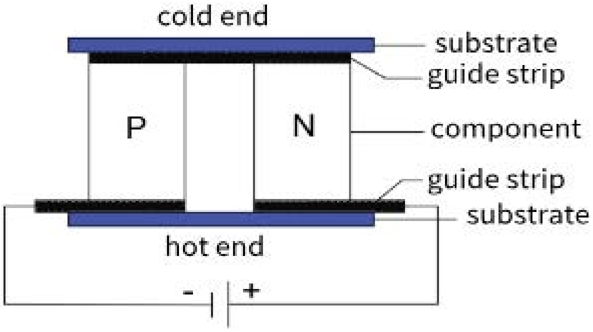


Figure 1 Schematic diagram of semiconductor refrigeration working principle

When an N-type semiconductor material and a P-type semiconductor material are connected to form a thermocouple, when a direct current is applied to the circuit, the charge carriers in the materials will cause heat absorption and release at both ends of the thermocouple due to the energy level difference, resulting in energy transfer. The current flows from the junction where the N-type semiconductor meets the P-type semiconductor, absorbing heat and forming the cold end, while the current flows from the junction where the P-type semiconductor meets the N-type semiconductor, releasing heat and becoming the hot end. The magnitude of heat absorption and release depends on the size of the closed loop current and the number of N-type and P-type semiconductors. By doping different elements into the semiconductor materials, one can obtain an N-type semiconductor with more electrons and a P-type semiconductor with more holes. From a thermodynamic perspective, the hot end experiences a high concentration of particles, intense collisions, and extremely high entropy, whereas the cold end has very few particles, which is reflected in the circuit as a concentration at the hot end and a scarcity at the cold end. The cooling plate consists of hundreds of pairs of thermocouples connected to form a thermoelectric stack, most of which are connected in series (since the current is equal everywhere) to enhance cooling (or heating). To evaluate its performance, the dimensionless thermoelectric figure of merit ZT value is typically used. Its value is:

$$ZT = \frac{S^2 \sigma}{\kappa} T$$

Among them, S is the Seebeck coefficient, σ is the electrical conductivity of the thermoelectric material, κ is the total thermal conductivity, and T is the absolute temperature. In order to obtain excellent thermoelectric performance, it is necessary to satisfy the Seebeck coefficient, high electrical conductivity and low thermal conductivity. Therefore, the thermoelectric conversion efficiency of the thermoelectric material can be obtained.

$$\eta = \frac{\Delta T}{T_{Hot}} \frac{\sqrt{1 + ZT_{avg}} - 1}{\sqrt{1 + ZT_{avg}} + \frac{T_{Cold}}{T_{Hot}}}$$

Here, T_{Hot} and T_{Cold} represent the temperature at the hot end and the cold end, respectively. ZT_{avg} is the average or integral value of all ZT values between T_{Hot} and T_{Cold}. The higher the ZT_{avg}, the better the thermoelectric performance of the material, leading to a higher thermoelectric conversion efficiency.

3 Research Status of Semiconductor Refrigeration Technology

3.1 Semiconductor material research and development

Currently, semiconductor cooling technology has made significant progress, and the research status in this field in China is showing a trend of continuous advancement. As early as the beginning of the 21st century, Guan Haiqing and colleagues proposed that reducing the lattice thermal conductivity can effectively enhance the thermoelectric figure of merit of materials. The three main types of high-performance semiconductor thermoelectric cooling materials are: P-type materials Ag0.58Cu0.29Ti0.29Te four-element alloys, ternary Bi2Te3-sb2Te3-sb2se3 solid solution alloys, and N-type Bi—sb alloys[3].After analysis, Xu Chenhui et al. found that the thermoelectric value Z of Mg3 (Sb, Bi)2 based thermoelectric materials reached 1.8 at present, which had higher practical value than traditional Bi2Te3-based thermoelectric materials[4].Zhang Haifeng et al. obtained stable cubic phase GeMnTe1.96 material, which made the thermoelectric value reach 0.85, injecting fresh blood into the waste heat collection in the medium temperature region[5].Liu Shan et al. proposed that p-type SnS-based thermoelectric materials with high Seebeck coefficient and ultra-low thermal conductivity will play an important role in the exploration of thermoelectric materials in the future[6]. Pan, Y et al. found that the magneto-thermoelectric effect in topological insulator Bi88Sb12 is very strong and has a high optimal value (ZT=2.0), which reaches the leading level in China[7].Abroad, Manzano V C et al. found that the dual nanostructure has great potential in optimizing the thermoelectric properties of CuNi and other materials with more green, economic stability and high quality, providing important insights for sustainable development[8]. Melzi B et al. prepared Ag8SnSe6 by plasma activated sintering technology and obtained the maximum thermoelectric value of 1.2. This method of obtaining large ZT quickly was promoted[9].Bhattacharjee J et al. studied a new thermoelectric conversion material made of graphene oxide-based nanosheets reduced at high temperature, and concluded that binary oxides doped with oxides can be used to manufacture low-cost thermoelectric materials under low temperature conditions[10]. Kahawaththa K et al. studied the thermoelectric properties of copper iodide (CuI) doped with different concentrations of potassium iodide (KI), and confirmed that this doping significantly improved the thermoelectric properties of CuI, which provided valuable suggestions for the future application of p-type semiconductors with non-toxic characteristics[11]. Cherniushok O et al. studied copper-based chalcogenide materials, which are cost-effective and environmentally friendly thermoelectric materials. At a relatively low temperature of 500K, they showed excellent thermoelectric performance with ZT value of about 1.1[12].These studies provide insights into the future research direction of this field in many aspects, such as the development of new thermoelectric materials and the preparation of conventional thermoelectric materials by special methods.

3.2 Best refrigeration working condition

Tang Yalin et al. analyzed the design of semiconductor refrigeration air conditioner and obtained the best refrigeration condition of air conditioner[13].Under the condition that the Sbeck coefficient, cold end temperature, thermal resistance of semiconductor material, total thermal conductivity of thermoelectric element and maximum temperature difference are constant, the figure of cooling capacity and working current is as follows.

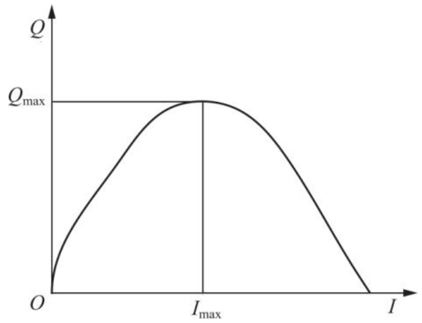


Figure 2 Relationship between cooling capacity and working current

When the external conditions are certain, the size of the refrigeration capacity is only related to the working current. The greater the Peltier heat, the smaller the Joule heat, and the greater the refrigeration capacity. When the current increases, the refrigeration capacity will reach the maximum value. After that, the larger the current, the smaller the refrigeration capacity. The refrigeration coefficient under the best refrigeration condition is:

$$\epsilon = Q_{max} / W = \frac{1}{2T_{hot}} \left[T_{cold} - \frac{2\Delta T}{ZT_{cold}} \right]$$

Among these, Q_{max} represents the maximum cooling capacity, and W denotes the operating power consumption. A higher cooling coefficient indicates better cooling performance. Zhang Huozai optimized the structure of a semiconductor cooler through research, effectively enhancing its cooling performance. Under optimal operating current conditions, the cooling coefficient of the cooler, with fixed temperatures and pressures at both the cold and hot ends, is:

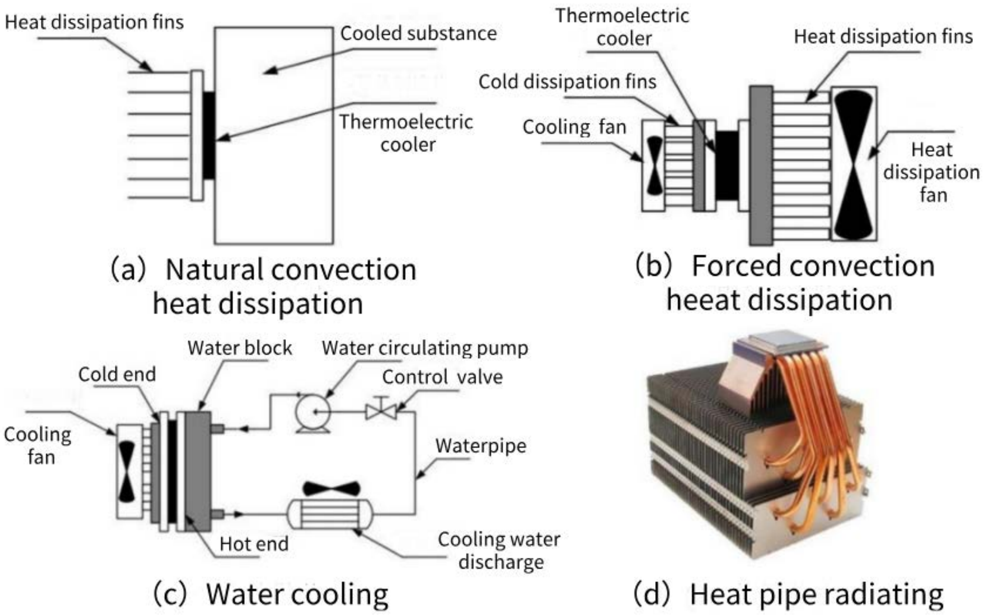
$$COP_{max} = \frac{T_{cold}}{T_{hot} - T_{cold}} \frac{\sqrt{1+Z\overline{T}} - \frac{T_{hot}}{T_{cold}}}{\sqrt{1+Z\overline{T}} + 1}$$

Among them, COP_{max} is the maximum refrigeration performance coefficient, and $Z\overline{T}$ is the thermoelectric optimum value and the average temperature of hot and cold ends[14].It can be seen that most refrigerators have the best refrigeration working conditions. Due to different shapes, sizes and other factors and working environments, the expression of refrigeration coefficient will be different, but it is the ratio of maximum refrigeration capacity to working power consumption.

Therefore, many scholars have studied the optimal operating conditions for various semiconductor cooling devices. Yan Rui and colleagues conducted research on a 160g,7x3x6 cm³ human body cooling system with a core component cooling capacity of 21W, based on semiconductor cooling technology. They found that under optimal operating conditions, the cooling factor is 0.8, and the system can operate for up to 4 hours at an actual working voltage 11.1V[15].Sun Zhe et al. studied the air conditioning system combining evaporative cooling and semiconductor refrigeration. Under the condition of stable current, the smaller the temperature difference between the cold and hot ends of the semiconductor, the greater the refrigeration capacity, and the refrigeration coefficient was as high as 3.3 under the best working condition[16].Wang Han et al. analyzed the new semiconductor refrigeration cup and concluded that the optimal working condition was refrigeration at 6V[17].Zhang Zhiyu concluded through research that the necessary condition to ensure the maximum cooling capacity is good heat dissipation and within the rated working voltage range, so as to achieve the best working condition[18].Attar A studied the thermoelectric refrigeration system of electric vehicles and achieved a cooling capacity of 1000W under the best refrigeration conditions[19].

3.3 Hot and cold end heat dissipation method

When the semiconductor refrigeration equipment is working, the convective heat transfer between the cold end and the hot end to the outside world becomes an important prerequisite for the efficient and low energy consumption of the semiconductor. If the heat cannot be discharged in time, the thermal resistance will increase with the working time of the semiconductor refrigeration sheet, which will reduce the refrigeration efficiency and shorten the service life of the device[20-22].Common heat dissipation methods are air cooling, water cooling, heat pipe cooling, natural convection and forced convection cooling, as shown in Figure 3.



(a) Natural convection heat dissipation

(b) Forced convection heeat dissipation

(c) Water cooling

(d) Heat pipe radiating

Figure 3. Several common heat dissipation methods

Ding Shuo and his team found through their research on cooling garments that water-cooling heat exchange is more efficient than air-cooling. They used a semiconductor cold face to cool water, which then facilitated convection heat exchange with the human body, effectively lowering body temperature [24]. Hu Guoxi's analysis showed that water-cooling heat exchange is 200 times more efficient than air-cooling [25]. Dai Wei's study on the impact of semiconductor cooling heat dissipation intensity on cooling performance confirmed the importance of optimal heat dissipation intensity at the hot end during the cooling process. He also derived the relationship curve between the heat transfer coefficient and cooling capacity under different temperature differences, as shown in Figure 4 [26].

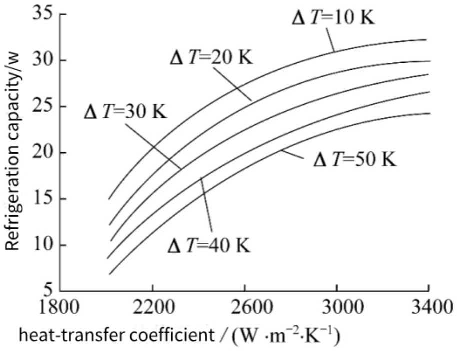


Figure 4 Variation curve of heat transfer coefficient and cooling capacity under different temperature differences

When the heat transfer coefficient increases, both the cooling capacity and efficiency of semiconductor devices improve. The smaller the temperature difference between the cold and hot ends, the higher the COP. Therefore, the choice of heat dissipation method for the hot end of semiconductor cooling devices is crucial for enhancing their cooling capacity and COP. Jiang Ping et al. studied the cooling performance of semiconductor cooling devices under evaporative cooling conditions at the hot end. They found that increasing the forced convection air velocity from 1.52m/s to 1.87m/s increased the COP to 26.3%[27]. Zhou Wuyang et al. also analyzed the heat dissipation methods at both the cold and hot ends, concluding that natural convection is less effective than forced convection, which is not beneficial for the cooling of semiconductor devices[28]. Jamradloedluk J et al. investigated water coolers with integrated heat pipe heat sinks. Compared to traditional water coolers, heat pipes offer higher cooling capacity and COP, highlighting the superior heat dissipation performance of heat pipes for the hot end of semiconductor devices[29].

4 Optimization of Semiconductor Structure

Because the semiconductor cooling sheet still has some shortcomings under certain conditions, I made a hypothesis on the structure of the semiconductor cooling sheet. The semiconductor cooling sheet is approximated as a circular pipe, as shown in Figure 5. Then the drawing was modeled by using SOLIDWORKS software, as shown in Figure 6.

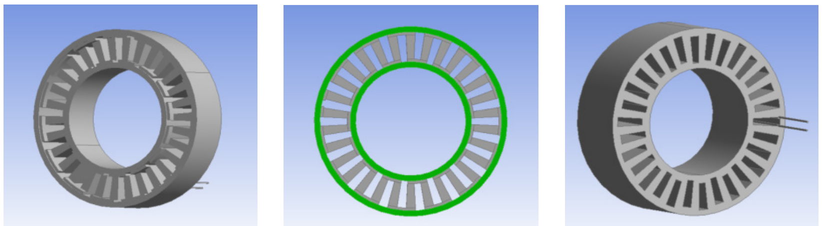


Figure 6 SOLIDWORK modeling diagram

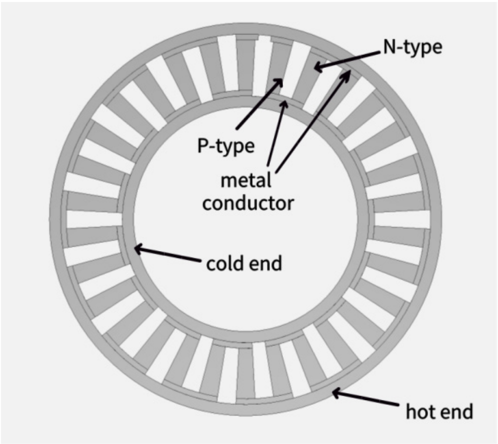


Figure 5 Schematic diagram of semiconductor refrigeration tube technology

We can equate the heat transfer method between the hot and cold ends of a semiconductor cooling plate to the convective heat exchange of a flat plate with external fluids, and similarly, we can equate this type of pipe to the forced convection inside a round tube and the natural convection outside. Because the semiconductor has both hot and cold ends, the structure of the round tube can be viewed as the convective heat exchange between two surfaces and the external environment under uniform wall temperature conditions. We can conclude that the convective heat exchange intensity of a semiconductor cooling plate in natural convection is superior to that of a semiconductor cooling tube [30-33]. Under forced convection conditions within the tube, the semiconductor cooling pipe exhibits strong heat exchange performance, but it is suitable for applications requiring very high cooling capacity, where its energy efficiency is relatively low, making it ideal for continuous flow fluid temperature control [34-36]. Although the structure of a semiconductor cooling pipe is more complex and expensive, it is suitable for large-scale continuous fluid cooling, which is beyond the capability of semiconductor cooling plates used for precise temperature control in small spaces. Optimizing semiconductor cooling plates into semiconductor cooling pipes and applying semiconductor cooling technology to fluid (air) cooling systems and fluid (liquid) heating systems is essential. This structural optimization must consider factors such as thermal conductivity, fluid properties, automatic control, mechanical design, and cost, to achieve bidirectional heating and cooling. To maximize cooling efficiency, it is crucial to ensure effective heat dissipation from the hot end and efficient heat recovery at the cold end. If the external circuit polarity is positive, the inside of the tube is the cold end, and the outside is the hot end; if the external circuit polarity is negative, the inside of the tube is the hot end, and the outside is the cold end. To ensure optimal cooling efficiency, the two scenarios are summarized: using a tube bundle with large sleeves (for air) on the outside and spiral fin tubes (for liquid) inside. This setup is similar to a heat exchanger, where the flow rate inside the tubes is controlled by a pump and flow control valve outside the tube bundle. The device is placed in a sealed space with fans installed at both ends to achieve effective heating and cooling. In winter, when the external circuit polarity is positive, the air outside the tubes is effectively heated and forced to flow out through the fans, providing air heating while maintaining cooling efficiency inside the tubes. The cooled fluid can be used for dehumidifiers and other devices in winter. In summer, when the external circuit polarity is negative, the air outside the tubes is effectively cooled and forced to flow out through the fans, providing air cooling while maintaining heating efficiency inside the tubes. The heated fluid can be used for water dispensers and other devices in summer. Since this device has the dual functions of heating and cooling and is located in a sealed space, heat naturally flows from the high-temperature side to the low-temperature side. To minimize this effect, measures such as adding fins outside and inside the tubes, converting natural convection to forced convection, and using longitudinal vortex generators are implemented to ensure that heat does not escape from the high-temperature side to the low-temperature side within the sealed space. This also qualitatively explains that the residence time of fluid in a closed space cannot be too long, and it must be used to eliminate it in time by forced convection. In the structure of semiconductor refrigeration pipeline, the cold end and hot end selected must meet the high thermal conductivity, and the space flowing out between the cold end and hot end.

5 Conclusion

This article provides a detailed overview of the research advancements in semiconductor cooling technology worldwide. It summarizes the current research findings in three areas: thermoelectric materials, optimal cooling conditions, and heat dissipation methods for both cold and hot ends. The article also speculates on future research directions in this field. Additionally, it briefly discusses the drawbacks of semiconductor cooling plates and proposes an ideal model by optimizing their structure into pipes, summarizing its advantages using heat transfer principles. It is anticipated that this innovative semiconductor cooling structure will gain widespread adoption in the future.

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