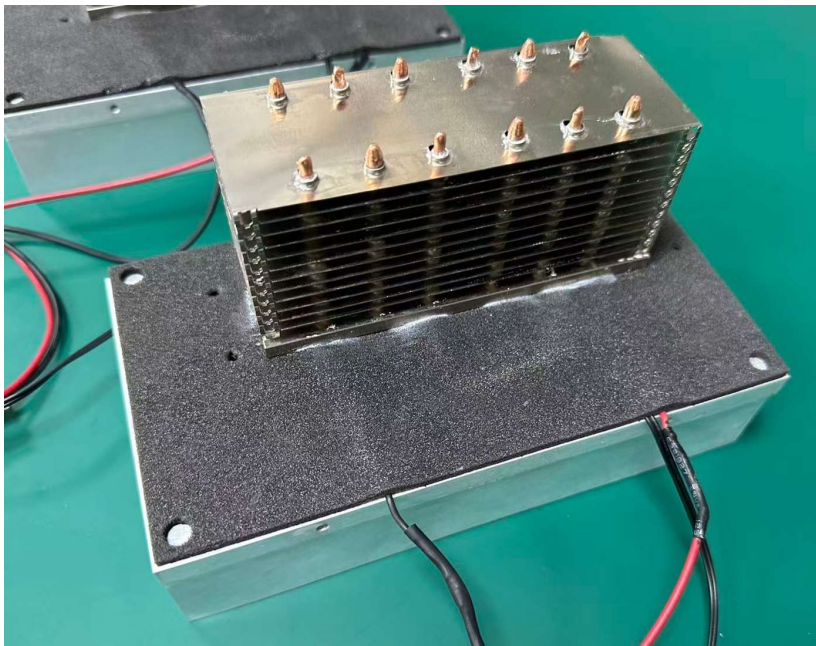


Zero-Basic Guide to TEC Refrigeration Modules: Internal Structure, Thermoelectric Chips and Ceramic Substrate Functions



Abstract: TEC (Thermoelectric Cooler) modules are core electronic components in the field of solid-state precision temperature control. Featuring refrigerant-free operation, zero mechanical moving parts, reversible cooling and heating, and fast response speed, they are widely applied in optical communication equipment, vehicle temperature control, smart home appliances, and high-precision medical instruments. Most entry-level developers and industry practitioners only understand the basic cooling and heating functions of TEC modules but lack in-depth knowledge of their internal structure and component working principles, which often leads to incorrect selection, improper installation, and poor heat dissipation performance. This paper systematically disassembles the complete internal structure of TEC refrigeration modules and elaborates on the core functions and operating logic of thermoelectric chips and ceramic substrates with plain language. Without complicated thermodynamic formulas, this article enables zero-basic readers to quickly master TEC fundamentals and provides practical guidance for TEC model selection, installation, debugging, and industrial application.

Keywords: TEC Refrigeration Module; Semiconductor Refrigeration; Thermoelectric Chip; Ceramic Substrate; TEC Internal Structure; Solid-State Refrigeration; Precision Temperature Control

1. Introduction: What Is a TEC Refrigeration Module?

TEC stands for Thermoelectric Cooler, a solid-state temperature control device developed based on the Peltier effect. It is the most fundamental commercialized unit of semiconductor refrigeration technology. Different from traditional compression refrigeration systems, TEC modules require no compressors, no fans, and no chemical refrigerants. With an integrated solid-state packaging structure, compact size, and reversible cold and hot switching by reversing current direction, TEC devices can achieve high-precision constant temperature control up to $\pm 0.05^{\circ}\text{C}$.

Currently, TEC refrigeration modules serve as the core temperature control components for miniature precision refrigeration, fixed-point local cooling, and portable temperature adjustment equipment. Many common problems such as weak cooling efficiency, abnormal overheating, shortened service life, and failed cold-heat switching are mainly caused by insufficient understanding of TEC internal structure and component characteristics. This article comprehensively disassembles TEC structural composition and explains the core functions of each part, helping readers fully grasp the basic working mechanism of semiconductor thermoelectric cooling.

2. Overall Internal Structure of TEC Refrigeration Modules

Standard commercial TEC modules adopt a symmetric layered precision structure, consisting of five major components: upper ceramic substrate, lower ceramic substrate, metal conductive electrodes, N/P-type thermoelectric chip arrays, and waterproof insulated lead terminals. All components are integrated through high-temperature vacuum welding, forming a seal-packed solid structure with no moving parts, high stability, and excellent durability.

The overall structural logic follows a clear hierarchical design: the outer ceramic layers undertake heat conduction and protection; the middle thermoelectric chip array realizes energy conversion; and the internal metal electrodes form a complete conductive loop. When connected to DC power, the module actively transfers heat directionally to realize refrigeration, heating, and constant temperature control.

General-purpose TEC modules are equipped with 127 pairs of thermoelectric chips, which is the industrial standard configuration suitable for most civilian and industrial precision temperature control scenarios. High-power industrial-grade TEC modules adopt increased chip pairs and optimized substrate sizes to enhance cooling capacity and load tolerance.

3. Core Component: Working Principle and Functions

of N/P-Type Thermoelectric Chips

Thermoelectric chips are the core functional units of TEC refrigeration modules and the fundamental carriers of semiconductor refrigeration technology, directly determining the cooling efficiency, maximum temperature difference, and service life of the module. Commercially available TEC products mainly adopt bismuth telluride (Bi_2Te_3) semiconductor chips, which maintain the optimal thermoelectric conversion performance at room temperature.

Thermoelectric chips are divided into N-type and P-type semiconductors. These two types of chips are alternately arranged and connected in series. They are indispensable and cooperate closely to complete directional heat transfer.

3.1 Functions of N-Type Thermoelectric Chips

N-type semiconductors rely on free electrons as the main charge carriers and serve as the primary heat transfer units of TEC modules. When DC current is applied, internal electrons move directionally, continuously absorbing heat from the cold end and transferring thermal energy to the hot end for release. This reverse heat transmission mechanism constitutes the core principle of active TEC refrigeration. The purity, flatness, and doping process of N-type chips directly affect the overall cooling performance of TEC devices.

3.2 Functions of P-Type Thermoelectric Chips

P-type semiconductors use holes as main carriers. Their core function is to cooperate with N-type chips to form a complete closed circuit and balance the overall electrical and thermal performance of the module. During operation, P-type chips stabilize current transmission and share thermal stress, preventing local overheating and chip breakdown caused by unbalanced load distribution. This ensures stable overall operation and avoids circuit failure and performance attenuation.

3.3 Working Logic of Thermoelectric Chip Arrays

All N-type and P-type thermoelectric chips are connected in series via metal electrodes and work synchronously after power-on to achieve macroscopic temperature difference effects. In short, **thermoelectric chips act as solid-state heat carriers**. Without mechanical movement, they realize continuous cooling and heating through directional carrier movement, enabling TEC modules to feature silent operation, fast response, and high-precision temperature control.

4. Key Carrier: Core Functions of Upper and Lower Ceramic Substrates

The ceramic substrate is easily misunderstood as a simple protective shell, while in fact, it is a decisive component for the stability, efficiency, and durability of TEC modules. Mainstream TEC products adopt high-purity alumina ceramic substrates.

The symmetric upper and lower substrates undertake five core functions: electrical insulation, uniform heat conduction, structural support, anti-aging protection, and deformation resistance.

4.1 Electrical Insulation and Safety Protection

The internal chips and electrodes of TEC modules carry DC operating voltage during operation. Alumina ceramic features excellent insulation and high voltage resistance, completely isolating internal live circuits from external heat dissipation structures and equipment shells. This effectively prevents electric leakage, short circuits, and breakdown failures, improving equipment safety for high-standard scenarios such as medical devices, optical communication systems, and vehicle electronics.

4.2 Uniform Heat Conduction and Improved Temperature Control Accuracy

With flat surface and uniform thermal conductivity, ceramic substrates serve as high-quality heat equalizing media. The internal chip array generates dense temperature differences during operation, and the ceramic substrate quickly diffuses local cold and hot spots evenly across the entire plane, avoiding unbalanced temperature distribution. The cold-end substrate ensures uniform and precise temperature control, while the hot-end substrate rapidly exports accumulated heat, guaranteeing the high-precision performance of TEC temperature regulation.

4.3 Structural Support and Operational Stability Enhancement

Alumina ceramic materials feature high hardness, high temperature resistance, deformation resistance, and anti-aging properties. They firmly fix internal thermoelectric chips and electrode structures to prevent chip displacement and welding layer peeling under long-term power-on and alternating cold-hot working conditions. In addition, ceramic substrates isolate air, moisture, and dust erosion, enabling TEC modules to adapt to complex environments and greatly extending service life.

5. Auxiliary Structures: Functions of Electrodes, Leads and Packaging Layers

In addition to core thermoelectric chips and ceramic substrates, auxiliary structures ensure stable and reliable module operation. Metal conductive electrodes are made of high-conductivity copper materials, connecting all N/P-type chips to form closed circuits, reducing conduction resistance and lowering power consumption and heat loss. External lead terminals serve as standard DC power interfaces, featuring strong compatibility and convenient installation.

The insulating packaging layer fills structural gaps to achieve waterproof, moisture-

proof, oxidation-proof and anti-soldering effects, improving the overall tightness and environmental adaptability of TEC modules to meet long-term continuous industrial operation requirements.

6. Core Summary for Zero-Basic Learners

The core division of TEC refrigeration modules can be summarized clearly: **thermoelectric chips act as the energy conversion core to transfer heat and realize cooling and heating; ceramic substrates serve as the heat conduction and protection core to ensure insulation, uniform temperature and structural stability; electrodes and leads maintain circuit conduction and stable power supply.**

Compared with traditional refrigeration equipment, TEC solid-state temperature control technology features zero mechanical loss, refrigerant-free environmental protection, and fast response. With unique internal structural advantages, it has become the optimal solution for miniature precision temperature control, fixed-point refrigeration, and dual cold-heat adjustment. Mastering its internal structure and component functions effectively avoids incorrect selection, improper installation and poor heat dissipation, maximizing the application value of semiconductor TEC refrigeration modules.

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