Application Guide of Carbon Felt in Silicon Carbide Crystal Growth

CHAPTER 1: Importance and Application Fields of Silicon Carbide Crystals

1.1 Importance of Silicon Carbide Crystals

Silicon Carbide (SiC) is a wide-bandgap semiconductor material composed of carbon and silicon. Compared to first-generation semiconductor silicon, its core advantages stem from its unique physical and chemical properties.

The bandgap width of traditional silicon is about 1.12 eV, while that of SiC is about 3.2 eV. The bandgap width is the minimum energy required for electrons to transition from the valence band to the conduction band. A wider bandgap means the material is more "robust," capable of operating stably at higher temperatures, voltages, and frequencies without "breakdown" or failure. This allows SiC devices to operate at junction temperatures above 200°C, far exceeding the approximately 150°C of silicon devices.

The breakdown electric field strength of SiC is about 10 times higher than that of silicon. This means that for the same voltage rating, the epitaxial layer of SiC devices can be made thinner, and the chip area smaller, thereby reducing device capacitance and increasing switching speed.

The thermal conductivity of SiC is about 3 times that of silicon. Superior heat conduction means heat generated by the device can be dissipated more quickly, allowing for higher power density, simplified heat dissipation system design, and lighter, more compact equipment. Regarding high electron saturation drift velocity, it is about twice that of silicon, enabling SiC devices to operate at higher frequencies with lower switching losses.

In summary, SiC material integrates these excellent properties, enabling power electronic devices based on it to achieve a breakthrough in performance characterized by "higher efficiency, higher power, higher frequency, higher temperature, and smaller volume." This is precisely the key to addressing core challenges facing modern society, such as energy efficiency, energy saving, emission reduction, and power density.

1.2 Application Fields of Silicon Carbide Crystals

1.2.1 Power Electronics and Energy Conversion

This is currently the most mature and largest market segment for SiC industrialization, primarily replacing silicon-based IGBTs and MOSFETs.

In the new energy vehicle industry, the main drive inverter is the "killer application" for SiC. Using SiC MOSFETs can improve inverter efficiency by several percentage points, meaning a 5-10% increase in range with the same battery capacity. Simultaneously, its high-frequency characteristics reduce the volume of passive components like motors and inductors, aiding in vehicle weight reduction and increased space. When applied to on-board chargers (OBC), it enables faster charging speeds and miniaturization. Using SiC in DC-DC converters allows efficient conversion of high-voltage battery power to low voltage for in-vehicle electronic devices.

In the new energy power generation and energy storage industry, using SiC in photovoltaic inverters improves the energy conversion efficiency of solar panels, reducing system cost and size. Application in wind power converters enhances reliability and power density, adapting to harsh environments. For energy storage systems (ESS), it improves charge/discharge conversion efficiency and extends system lifespan.

In industrial and rail transportation, SiC is used in variable frequency drives (VFDs), significantly reducing energy consumption of industrial motors and enabling precise control. Application in rail traction converters gives high-speed rail and subway traction systems lighter weight and higher efficiency characteristics. For power supplies, it enables uninterruptible power supplies (UPS), providing higher efficiency and more reliable power protection.

In charging infrastructure, SiC is the core technology enabling high-power (e.g., 350kW and above) fast charging piles. It can reduce energy loss within the charging pile by about 30%, shrink its volume, and lower operational costs.

1.2.2 Radio Frequency (RF) Electronics

Leveraging SiC's high-frequency, high-voltage, and high-temperature resistance properties to fabricate RF microwave power devices.

For 5G communication base station power amplifiers, compared to traditional silicon-based LDMOS, SiC-based Gallium Nitride (GaN) devices offer higher output power, wider bandwidth, and higher efficiency, making them key technologies for 5G macro base stations and future 6G.

In defense and aerospace, SiC is used in phased array radars for transmit/receive (T/R) modules, providing longer detection range, higher resolution, and reliability. In satellite communications, it performs excellently in extreme temperature and high-radiation space environments.

1.2.3 Extreme Environment Electronics

Utilizing SiC's inherent high-temperature and radiation resistance capabilities. In aerospace and deep space exploration, it is used for engine sensors, flight control electronic systems, etc., operating directly in high-temperature environments without complex cooling systems. In nuclear energy and high-energy physics, it is used for monitoring sensors and control systems inside nuclear reactors, operating stably under strong radiation and high temperatures for extended periods. In oil and geothermal exploration, it is used for sensing and electronic equipment in downhole extreme high-temperature and high-pressure environments.

1.2.4 Other Special Applications

Certain lattice defects in SiC crystals can serve as luminescence centers and are being researched for use as solid-state qubits, representing a potential platform for quantum computing and quantum communication.

It can also serve as a substrate material for GaN LEDs (though it has been surpassed by sapphire and silicon substrates in terms of cost, and is mainly used for high-end or special wavelength products).

CHAPTER 2: Overview of Crystal Growth Methods

For silicon carbide, because it does not melt at high temperatures (it decomposes at about 2830°C under atmospheric pressure), traditional methods like the Czochralski (CZ) or Float Zone (FZ) methods cannot be used. This has given rise to unique and challenging growth techniques. Here, we primarily introduce three growth methods:

2.1 Physical Vapor Transport (PVT) Method

The PVT method is the only mature method for commercially producing 4-inch, 6-inch, and 8-inch conductive and semi-insulating silicon carbide single crystal substrates, occupying over 95% of the market share.

2.1.1 Core Principle

Utilizes the process of sublimation-transport-recrystallization at high temperatures. Inside a sealed graphite crucible (growth chamber), extremely high-temperature gradients are generated via induction or resistance heating. The SiC source material (typically high-purity SiC powder or polycrystalline blocks) sublimates and decomposes into gaseous components containing silicon and carbon (e.g., Si, Si_2C, SiC_2, etc.) in the high-temperature zone (approx. 2300-2500°C). Driven by the temperature gradient and a low-pressure inert gas (e.g., argon) environment, these gaseous species are transported to a lower temperature region (typically 50-200°C lower), reaching a supersaturated state on a pre-placed SiC seed crystal, and subsequently recrystallize epitaxially according to the seed crystal's structure, gradually growing into a single crystal ingot.

2.1.2 Key System Components and Functions

Graphite Crucible: Serves as the growth reaction chamber, requiring high-purity, high-density graphite.

Thermal Insulation System: Typically constructed from multiple layers of graphite felt/carbon felt and graphite rigid felt, used to form a uniform, controllable temperature gradient, reduce heat loss, and protect peripheral equipment.

Heating System: Radio Frequency (RF) induction coil or graphite heating element.

Seed Crystal: A high-quality, homogeneous (typically 4H or 6H-SiC) single crystal thin wafer, fixed at the top of the crucible (growth face downward).

Source Material: High-purity SiC powder, placed at the bottom of the crucible.
Pressure and Atmosphere Control System: Maintains low pressure (typically 10-100 mbar) and an inert/reducing atmosphere within the growth chamber.

2.1.3 Brief Process Flow

- Loading: Fix the seed crystal to the crucible lid, place the source material into the bottom of the crucible.
- Evacuation and Heating: Evacuate the system and fill with inert gas, then begin heating to the target temperature.
- Growth: Precisely control the temperature field and pressure. Gaseous species transport from the source zone to the seed crystal zone and crystallize. Growth rate is slow, approximately 0.1-1 mm/h.

- Cooling: After growth completion, cool to room temperature at an extremely slow rate (which may take several days) to avoid crystal cracking due to thermal stress.
- Ingot Removal and Processing: Remove the crystal ingot. After orientation, cutting, grinding, polishing, and cleaning, the final product is a wafer (substrate) ready for epitaxy.

2.1.4 Advantages and Challenges

Advantages: Relatively the most mature technology, capable of growing large-size, high-quality single crystals. It is currently the only method achieving large-scale industrialization.

Challenges:

- Harsh Growth Conditions: High temperature, sealed, non-visible process, making control difficult.
- Difficult Defect Control: The density of crystal defects like micropipes, dislocations, and polytype inclusions still needs further reduction.
- Doping Uniformity: Controlling doping uniformity, especially for nitrogen doping, is technically challenging.
- Low Source Material Utilization: The sublimation process is not 100% efficient.

2.2 High-Temperature Chemical Vapor Deposition (HTCVD) Method

HTCVD is primarily used for growing extremely high-purity SiC, or as a complementary technology to PVT. It is particularly suitable for growing low-doped, semi-insulating thick films or bulk materials.

2.2.1 Core Principle

Unlike the "solid-gas-solid" process of PVT, HTCVD is a "gas-gas-solid" process. It involves introducing silicon and carbon precursor gases (e.g., methyltrichlorosilane, or a mixture of silane and hydrocarbons) directly into a high-temperature (approx. 1800-2200°C) growth chamber. The gases thermally decompose and undergo chemical reactions at high temperature, directly depositing and growing SiC single crystals on a heated SiC seed crystal surface.

2.2.2 Characteristics and Applications

- High Purity: Using high-purity gas sources, crystals with extremely low impurity concentrations ($< 10^{15}$ cm^{-3}) can be grown.
- Controllable Doping: Doping type and concentration can be precisely controlled by introducing nitrogen or aluminum-containing gases into the gas stream.
- Application Scenarios: Mainly used for growing semi-insulating SiC substrates, which are key for manufacturing GaN-on-SiC RF devices. Also used for growing special doping structures or homoepitaxial layers difficult to achieve with PVT.
- Challenges: High gas consumption, complex control of growth rate and uniformity, high cost. It has not yet become the mainstream method for large-size substrate growth.

2.3 Solution Growth Method

To fundamentally address the inherent high dislocation density problem in the PVT method, liquid-phase methods are widely researched.

2.3.1 Core Principle

At high temperatures (approx. 1500-2000°C), a metal solvent is used to dissolve carbon and silicon sources. By lowering the temperature or establishing a concentration gradient at the seed crystal, carbon and silicon become supersaturated and precipitate on the seed crystal, growing a SiC single crystal. Common solvents include silicon, chromium, iron, and various alloys.

2.3.2 Advantages and Potential

- Theoretically Very Low Defect Density: Growth occurs under conditions close to thermodynamic equilibrium, potentially reducing dislocation density by several orders of magnitude, enabling growth of nearly perfect crystals.
- Potential for Growing New Polytypes: Has the potential to stably grow new SiC polytypes difficult to obtain with the PVT method.

2.3.3 Challenges

- Low Carbon Solubility: Carbon solubility in silicon melt is extremely low, leading to very slow growth rates.
- Solvent Inclusion and Contamination: Prone to trapping solvent metals into the crystal, introducing impurities.
- Extremely Difficult Process Control: High temperature and highly corrosive melts pose significant challenges to crucible materials (e.g., graphite, tantalum).
- Crystal Size Limitation: Currently only capable of growing relatively small crystals. Although it has great potential, it remains far from industrialization.

CHAPTER 3: Key Roles and Significance of Carbon Felt in the Crystal Growth System

In PVT systems operating at extreme temperatures up to 2500°C, carbon felt (primarily graphite soft felt and graphite rigid felt) constitutes the main insulation layer and thermal field structural components of the growth furnace. Its porous, lightweight, high-temperature resistant, and chemically stable properties make it an almost irreplaceable core consumable.

3.1 Key Roles

3.1.1 Thermal Field Construction and Homogenization

This is the most core and direct role of carbon felt. The success of the PVT method relies on a precise and stable axial temperature gradient and radial temperature uniformity from the source zone to the seed zone.

- Axial Gradient Control: The thickness and density of carbon felt directly determine the longitudinal heat loss rate. By configuring carbon felt differently in various zones (e.g., thicker at the bottom, thinner at the top), the required temperature gradient (typically 10-50 °C/cm) from the high-temperature source zone (~2300°C) to the lower-temperature seed zone (~2200°C) can be precisely shaped. This gradient is the "engine" driving vapor transport.
- Radial Homogenization: Ideally, the growth interface (where the crystal contacts the vapor) should be a perfect isothermal surface. Carbon felt, as a uniform insulating body, effectively reduces non-uniform heat loss through the furnace sidewalls, smoothing out thermal field distortions caused by heating coils, crucible shape, and the material itself. This ensures consistent radial growth rate of the crystal. This is key to obtaining

crystals with low stress, no cracks, and low defects (e.g., polytype inclusions). Conversely, an uneven thermal field can cause crystal bending, cracking, or polytype defects.

3.1.2 Efficient Thermal Insulation and Energy Saving

- Reducing Energy Consumption: PVT furnaces often have power ratings of several hundred kilowatts. The extremely low thermal conductivity of carbon felt (especially under vacuum or low pressure, where its porous structure effectively suppresses gas conduction and convection) "locks" heat within the growth chamber to the maximum extent, significantly reducing the electrical energy required to maintain high temperatures, directly lowering production costs.
- Protecting Peripheral Equipment: Effective insulation lowers the furnace shell temperature to a safe range (typically <100°C), protecting expensive induction coils, water-cooling systems, viewing windows, seals, and furnace structure, extending the service life and safety of the entire equipment.

3.1.3 Thermal Inertia Buffering and Process Stability

Carbon felt has relatively high heat capacity and "thermal inertia."

Buffering Temperature Fluctuations: When there are minor power supply fluctuations or control system adjustments, the carbon felt layer can act like a "thermal sponge," absorbing or releasing some heat, slowing down drastic temperature changes in the core zone, providing reaction time for the control system, thereby maintaining thermal stability at the growth interface.

Ensuring Safe Cooling: The cooling process after growth completion must be extremely slow (tens of degrees per day) to prevent crystal explosion due to thermal stress. The excellent insulating properties of carbon felt naturally "slow down" the cooling rate, providing the physical basis for executing a safe, controlled cooling procedure.

3.1.4 Impurity Control and Atmosphere Conditioning

Physical Adsorption and Barrier: The vast surface area of the porous carbon felt can adsorb trace impurity gases (e.g., oxygen, moisture) released from the system. Simultaneously, being an ultra-high-purity graphite material itself, it is chemically stable at high temperatures, does not react with SiC vapor, and does not introduce additional metal impurities.

Creating Stable Gas Flow Channels: Its porous structure is not completely sealed, allowing gas to slowly permeate and flow under the set low pressure. This structure helps establish a stable, laminar vapor transport path, reducing turbulence, thereby avoiding uneven crystal growth or inclusion formation caused by flow disturbances.

3.1.5 Mechanical Support and Stress Buffering

Support and Positioning: Graphite rigid felt is often used to make specific support frames and pads for fixing and positioning internal core components like the graphite crucible and heating element.

Buffering Thermal Stress: During heating and cooling, different components (graphite, quartz, metal) generate significant stress due to their different coefficients of thermal expansion. Carbon felt, especially soft felt, possesses certain compressibility and resilience, acting as a flexible buffer layer to absorb some stress, preventing hard components from breaking due to squeezing, and indirectly protecting the brittle SiC crystal itself.

3.2 Strategic Significance

3.2.1 Direct Impact on Crystal Quality: The Lever of Cost and Performance

The configuration of carbon felt directly determines the thermal field quality, which in turn determines the crystal defect density (e.g., micropipes, dislocations). High-quality, low-defect crystal ingots mean higher yield and thicker usable substrate slicing layers. An optimized carbon felt design can elevate crystal quality by a grade, its value far exceeding the cost of the carbon felt itself. It is a key lever for leveraging product value and profit.

3.2.2 Support for Process Repeatability and Scalability

Industrial production demands highly consistent results for each run. The standardized, modular design of carbon felt is the foundation for achieving a "formula-based" process. Once the optimal carbon felt configuration (thickness, density, shape combination) is determined through simulation and experiment, it can be stably replicated, ensuring consistent crystal performance across different batches and different furnaces. This is the engineering core for transitioning from laboratory to large-scale mass production.

3.2.3 Bridge Between Theory and Practice: The Physical Entity of Thermal Field Simulation

Modern crystal growth heavily relies on computer thermal field simulation. In simulation software, the thermal conductivity, specific heat capacity, and emissivity of carbon felt are key input parameters. The simulation results ultimately need to be realized through the physical assembly of carbon felt. Therefore, carbon felt is the material carrier connecting virtual optimal design with the actual physical world. Accurate characterization of carbon felt performance is a prerequisite for improving simulation accuracy and reducing experimental trial-and-error costs.

3.2.4 Technical Barrier and Cost Control Point

- Technical Barrier: For top-tier crystal growth companies, their thermal field design (core being the carbon felt configuration scheme) is highly confidential core technology. A meticulously refined carbon felt wrapping scheme, embodying their long-term process accumulation, constitutes a substantive technical moat.
- Cost Control: Carbon felt is a major consumable in PVT growth, typically needing replacement after several tens of runs. Its procurement cost and service life (resistance to pulverization, shrinkage) directly impact the cost per substrate wafer. Optimizing its use is an important aspect of cost reduction and efficiency improvement.

CHAPTER 4: Fundamental Properties of Carbon Felt

4.1 Material and Structural Properties

4.1.1 Micro and Macro Structure

- Precursor: Typically made from polyacrylonitrile (PAN)-based or pitch-based carbon fibers. The former offers higher strength, while the latter offers better thermal conductivity and graphitizability.
- Morphology: A non-woven, flexible felt-like material formed by interlocking disordered or chopped carbon fibers through needle punching, bonding, etc., creating a three-dimensional network structure.
- Porosity: This is its most core structural characteristic. A large number of interconnected pores of varying sizes form between the fibers. Porosity is typically as high as 80%-95%. This structure is the physical basis for its excellent insulating properties.

4.1.2 Physical and Mechanical Properties

- Low Density: Due to its porous structure, the density is very low, typically in the range of 0.1 - 0.3 g/cm³ (for comparison, water's density is 1 g/cm³). This makes it very lightweight, easy to install, and reduces the system's thermal mass.
- Flexibility and Workability: Possesses good flexibility and compressive resilience, allowing it to be cut and wrapped into complex shapes, tightly fitting furnace walls and components, minimizing thermal short circuits. Graphite rigid felt is a variant hardened at high temperature, offering certain rigidity and can be used to make support components.
- Low Mechanical Strength: Tensile and compressive strength are relatively low, determined by its porous fiber structure. It mainly bears compressive stress. Sharp object piercing or excessive stretching should be avoided during installation and use.

4.2 Thermal Properties

4.2.1 Extremely Low Thermal Conductivity

This is the fundamental reason carbon felt is a top-tier insulating material. Its thermal conductivity at high temperatures typically ranges between 0.05 - 0.3 W/(m·K) (varying with temperature and density), far lower than most solid materials (e.g., stainless steel is about 15 W/(m·K)).

Mechanisms:

- Tortuous Solid-Phase Conduction Path: The point contacts between fibers make the path for heat conduction through the solid skeleton very long and inefficient.
- Suppressed Gas-Phase Conduction: Under the low vacuum or low-pressure inert atmosphere of a PVT furnace, gas molecules within the pores are sparse, gas convection heat transfer is essentially eliminated, and gas molecular heat conduction is also greatly reduced.
- Shielding of Radiative Heat Transfer: At high temperatures (>1000°C), radiative heat transfer becomes dominant. The numerous fiber surfaces and complex pore structure inside carbon felt act like countless shielding layers, repeatedly absorbing, reflecting, and re-radiating thermal radiation, significantly blocking radiative heat flow.

4.2.2 Excellent High-Temperature Stability

- High-Temperature Resistance: In inert or vacuum environments, carbon felt can operate stably long-term above 2000°C, and withstand temperatures approaching 3000°C short-term. Its melting point (sublimation point) is similar to graphite, about 3650°C.
- Low Thermal Expansion: The coefficient of thermal expansion is very low (approx. $(1\text{-}4)\times10^{-6}$ /K), providing dimensional stability under drastic temperature changes, preventing cracking or squeezing of internal components due to thermal expansion/contraction.

- Thermal Shock Resistance: Benefiting from low thermal expansion and the elasticity provided by high porosity, it can withstand rapid temperature rises and falls (i.e., thermal shock) without fracturing.

4.2.3 High Heat Capacity and Thermal Inertia

Possesses a relatively high specific heat capacity. Combined with its overall mass, it acts as an effective "thermal buffer," helping to stabilize the furnace temperature and mitigate fluctuations caused by external disturbances.

4.3 Chemical and Purity Properties

4.3.1 Chemical Inertness

- In Reducing/Inert Environments: Under typical PVT furnace conditions (hydrogen, argon, or vacuum), carbon felt is chemically extremely stable and does not react with SiC vapor (Si, Si_2C, SiC_2, etc.), graphite crucible, or heating elements.
- Poor Oxidation Resistance: This is its main weakness. In oxygen-containing atmospheres, it begins to oxidize significantly (ablate) at temperatures above 400°C, producing CO or CO_2. Therefore, the system must operate in a thoroughly deoxygenated environment.

4.3.2 High Purity Requirements

- Impurity Content: Carbon felt used for semiconductor crystal growth must be of high-purity grade. Key impurities such as metal elements (Fe, Al, Ca, Na, etc.), ash content, and sulfur must be extremely low (typically requiring total ash <100 ppm, premium products <50 ppm).
- Impact: At high temperatures, impurities may volatilize, migrate to the growth zone, and incorporate into the crystal, becoming charge carrier

scattering centers or deep-level defects, severely degrading the crystal's electrical properties (e.g., resistivity, carrier lifetime). High purity is a prerequisite for ensuring the intrinsic quality of the crystal.

4.3.3 Outgassing Characteristics

Release of Adsorbed Gases: The porous structure adsorbs moisture, nitrogen, oxygen, etc., from air. Under high-temperature vacuum, these gases are released, contaminating the growth atmosphere.

Pretreatment: Therefore, new carbon felt or felt exposed to air must undergo strict high-temperature vacuum baking (pre-firing) before use to remove adsorbed gases and some volatile impurities.

4.4 Functional Properties

4.4.1 Density and Thickness

These are the two most critical engineering design parameters, directly affecting insulation effectiveness and thermal field distribution.

- Density: Typically available in low-density (e.g., 0.1 g/cm³), medium-density, and high-density (e.g., 0.25 g/cm³) grades. Higher density improves mechanical strength and enhances solid-phase thermal conduction, but also improves radiation shielding capability. In practical applications, a "gradient density" design is often adopted: using high-density felt near the heat source to resist high-temperature erosion and enhance radiation shielding, and low-density felt in outer layers to further reduce thermal conductivity.
- Thickness: Directly determines thermal resistance. Increasing thickness significantly improves insulation but occupies more furnace volume, reducing effective capacity. A comprehensive optimization is needed.

4.4.2 Graphitization Degree

The degree to which the disordered turbostratic carbon structure of carbon fibers transforms into an ordered three-dimensional graphite crystal structure through high-temperature heat treatment (>2500°C). It influences:

- Thermal Conductivity: Higher graphitization degree increases thermal conductivity along the fiber axis (though the overall insulation of the felt is primarily determined by the pore structure and is less affected).
- Thermal Stability: Fibers with higher graphitization degree are more heat-resistant, exhibit lower high-temperature shrinkage, and have a longer service life.
- Purity: The high-temperature graphitization process further drives out impurities, improving purity.
- Cost: Higher graphitization degree requires more energy-intensive production processes, resulting in higher cost.

4.4.3 Evolution of Mechanical Properties

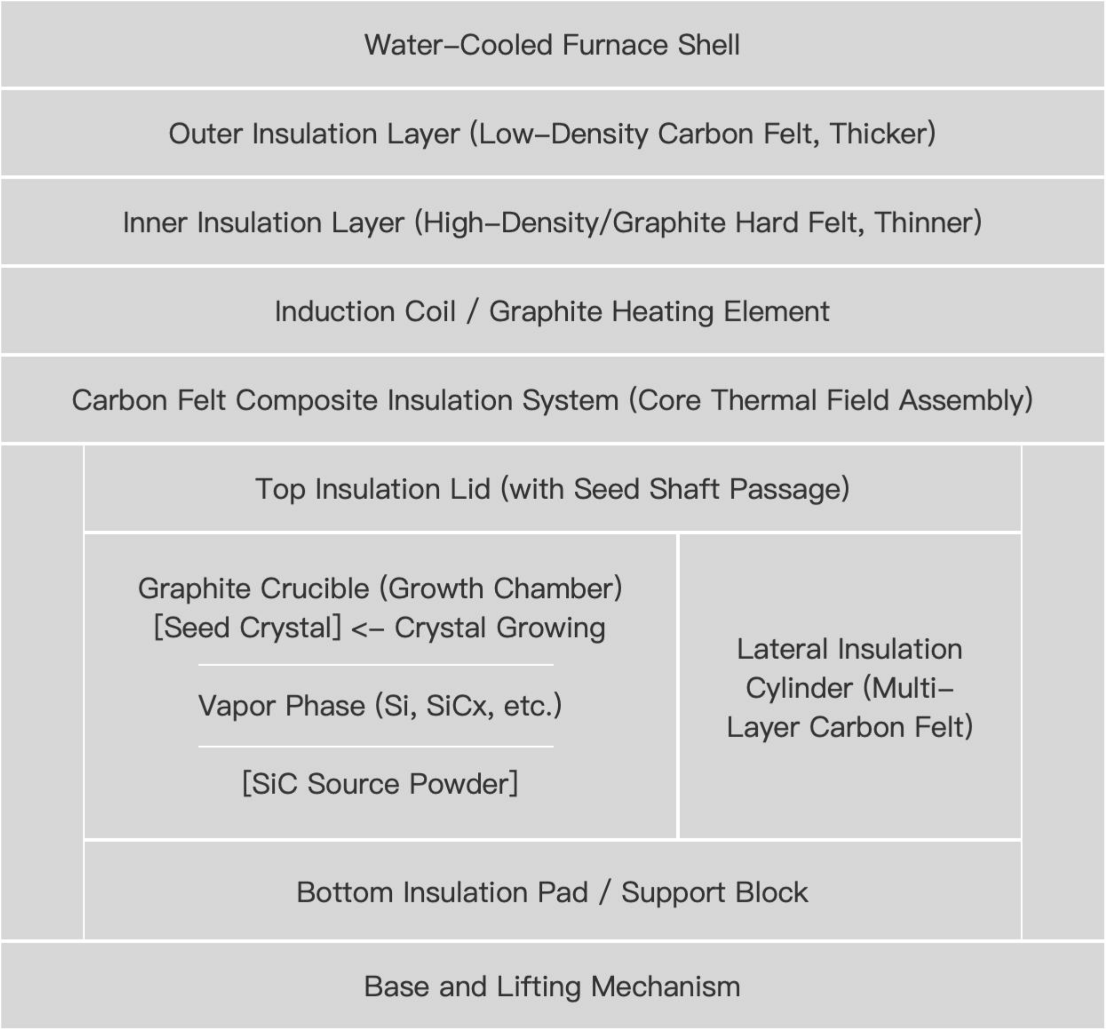
Under long-term high-temperature service, carbon felt undergoes slow fiber embrittlement, structural relaxation, and slight shrinkage. This leads to a gradual decline in its insulating performance and may affect thermal field stability. Therefore, it is a regularly replaced consumable.

For more detailed properties, you can refer to the product parameter table for Carbon Felt from Grand-Hope.

CHAPTER 5 : Application of Carbon Felt in PVT Crystal Growth Systems

This section focuses on the Physical Vapor Transport (PVT) method, detailing the specific applications of carbon felt in PVT crystal growth systems.

First, a simplified system cross-sectional diagram provides an intuitive understanding of the carbon felt layout:



Core Position Analysis:

- Lateral Insulation Cylinder: Wraps around the outer periphery of the graphite crucible, forming the main body of insulation, directly determining radial heat loss and temperature uniformity.

- Top Insulation Lid: Located above the crucible, controls axial upward heat loss. The connection area with the seed rod is precisely designed to ensure sealing while minimizing heat leakage.
- Bottom Insulation Pad/Support Block: Supports the entire thermal field assembly and controls downward heat loss.
- (Optional) Internal Thermal Field Regulator: Between the crucible and the lateral insulation layer, specially shaped graphite rigid felt or carbon felt cylinders are sometimes inserted for fine-tuning the temperature distribution of the crucible wall.

5.1 Thermal Field Design and Gradient Control

Carbon felt is the physical executor of thermal field design.

Axial Gradient Shaping: By adjusting the thickness and density of the top, bottom, and side carbon felt, the path of heat dissipation can be precisely controlled. For example:

- Increasing bottom insulation thickness → Reduces bottom heat loss → Bottom (source zone) temperature relatively increases.
- Reducing top insulation thickness → Increases top heat loss → Top (seed zone) temperature relatively decreases.
- This "cooler top, hotter bottom" differential design strengthens the axial temperature gradient required to drive vapor transport.
- Ensuring Radial Uniformity: Uniformly wrapped carbon felt layers ensure even heating of the graphite crucible, which is key to achieving an isothermal growth interface. Any local damage, uneven thickness, or installation gaps in the carbon felt will create "thermal short circuits" or cold spots, leading to uneven radial crystal growth rate, inducing stress, dislocations, or even cracking.

5.2 Construction of Multi-Level Composite Insulation System

Modern PVT furnaces commonly employ a "Graded Function" composite insulation design, with carbon felt as the core material.

- Inner Layer (High-Temperature Zone): Uses high-density graphite soft felt or graphite rigid felt. Higher density and more compact structure better resist high-temperature gas flow erosion, offer higher mechanical strength, and its denser fiber network provides better shielding against high-temperature thermal radiation (radiative heat transfer dominates above >2000°C).
- Outer Layer (Medium-Low Temperature Zone): Uses low-density carbon felt. Leveraging its higher porosity, it achieves extremely low gas-phase and solid-phase thermal conductivity in lower temperature zones (after heat has been attenuated by the inner layer), further "locking in" heat.
- Advantage: This design achieves optimal comprehensive insulation performance with minimal material cost and space occupation, and is optimized for the dominant heat transfer mechanisms in different temperature ranges.

5.3 Regulation of Gas Flow and Transport Environment

The porous structure of carbon felt directly participates in shaping the atmosphere environment inside the growth chamber.

Permeability and Flow Resistance: The carbon felt layer presents a certain resistance to gas flow, helping to establish a more stable, laminarized flow pattern within the growth chamber, reducing turbulence. Turbulence can cause irregular transport of source vapor, potentially forming inclusions or growth striations in the crystal.

Pressure Buffering: During rapid evacuation or gas filling, the pores in the carbon felt can provide a slight pressure buffering effect.

Impurity Adsorption and Release Management: New carbon felt is a major source of outgassing. Standardized pre-firing (heating in vacuum or inert atmosphere to above operating temperature and holding) is performed to allow the carbon felt to thoroughly release adsorbed gases (H_2O, O_2, N_2, etc.) before furnace loading, preventing their slow release during the growth process and contamination of the growth atmosphere.

5.4 Mechanical Support and System Protection

Support and Positioning: Graphite rigid felt is machined into various shapes of pads, pillars, and rings for precisely supporting and positioning internal components like the graphite crucible and heating element, ensuring their concentricity and verticality.

Stress Buffering: During heating and cooling, components like graphite, quartz, and metal have different expansion coefficients. The softness and elasticity of carbon felt can absorb some of the stress, preventing hard contact that could lead to component crushing and fracture. This particularly protects the expensive graphite crucible and the brittle SiC crystal.

Protecting Induction Coils: Effective carbon felt insulation lowers the temperature in the coil area to a safe range, preventing coil overheating, oxidation, or insulation failure, ensuring electrical safety and equipment lifespan.

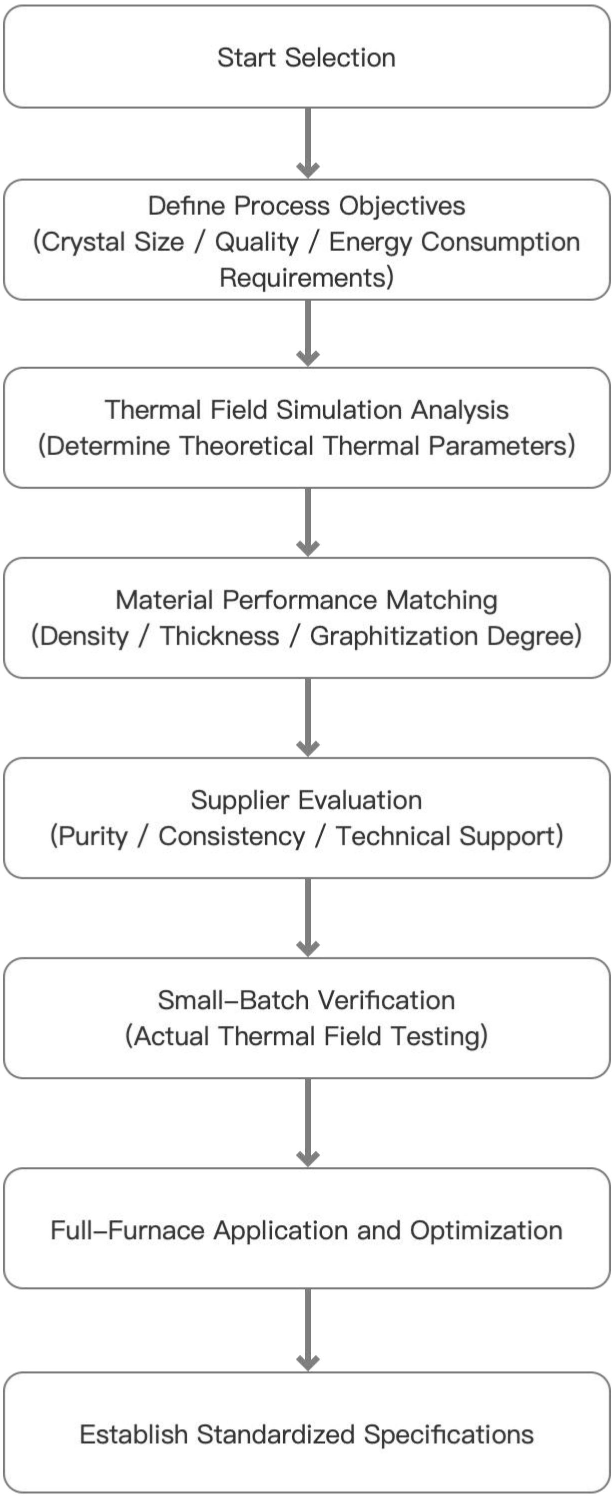
CHAPTER 6 : Carbon Felt Selection and Design Guide

6.1 Basic Selection Principles

SMART Principle:

- Specific: Tailored to furnace type, crystal size, and specific growth process requirements.
- Measurable: All parameters can be quantitatively measured and inspected.
- Achievable: Feasible within existing technology and cost constraints.
- Relevant: Directly serves thermal field performance and crystal quality goals.
- Traceable: Material batch, performance data fully traceable throughout.

6.2 Selection Decision Process



6.3 Key Parameter Selection Criteria

6.3.1 Density Selection

Density Grade	Range (g/cm³)	Applicable Zone	Main Function	Precautions
Low Density	0.08-0.15	Outer insulation layer / Low-temperature buffer layer	Ultimate insulation / Lightweight	Low mechanical strength / Prone to compression deformation
Medium Density	0.15-0.22	Intermediate transition layer / General insulation layer	Balanced insulation & strength / Cost-effective	Requires controlled thickness gradient
High Density	0.22-0.30	Inner thermal shield layer / High-temperature facing zone	Excellent radiation shielding / Resists gas flow erosion / Structurally stable	Relatively higher thermal conductivity / Higher cost
Graphite Rigid Felt	0.5-1.2	Support structure / Thermal field regulator	High rigidity / Precision forming	Reduced insulation performance / Requires special machining

Selection Recommendation:

- Adopt Gradient Density Design: Inner layer high density → Middle layer medium density → Outer layer low density.
- Density Change Gradient Suggestion: Adjacent layer density difference ≤ 0.08 g/cm³.
- For 6-inch crystal growth: Typical configuration is a three-layer structure of 0.25 / 0.18 / 0.12 g/cm³.

6.3.2 Thickness Design Specification

Total Thermal Resistance $R_{total} = \Sigma(\delta_i / \lambda_i)$

Where: δ_i = Single layer thickness, λ_i = Effective thermal conductivity of that layer.

Layered Thickness Recommendations:

Functional Zone	Recommended Thickness Range	Design Basis
Inner Thermal Shield	15-30 mm	Meets radiation shielding requirement above 2000°C
Main Insulation Layer	40-70 mm	Provides main temperature drop (~1500-2000°C)
Outer Buffer Layer	20-40 mm	Reduces temperature to below 800°C, protects furnace shell
Top Insulation	Total thickness 50-80 mm	Enhances axial gradient, typically 10-20% thinner than sidewalls
Bottom Insulation	Total thickness 60-100 mm	Support + insulation, typically the thickest

Space Constraint Adjustments:

- Maximum Thickness ≤ 35% of the effective furnace radius.
- Minimum thickness must ensure installation strength: Single layer ≥ 10mm.

6.3.3 Graphitization Degree Selection

Graphitization Grade	Heat Treatment Temp.	Advantageous Characteristics	Application Scenarios	Cost Factor
Carbon Felt	<1800°C	Low cost / Good flexibility	Outer low-temp zone / Non-critical areas	1.0
Semi-Graphitized	1800-2200°C	Improved purity / Reduced shrinkage	Middle general zone / Projects with limited budget	1.5-2.0
Fully Graphitized	>2200°C	Excellent high-temp stability / Minimal impurities / Longest lifespan	Inner high-temp zone / High-quality crystal growth	2.5-3.5

Selection Criteria:

- Areas with working temperature > 2000°C: Must use fully graphitized felt.
- For long-life requirements expecting >50 runs: Fully graphitized recommended.
- For extremely high crystal purity requirements (e.g., semi-insulating substrates): Must use fully graphitized.
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6.3.4 Purity Requirement Standards

Semiconductor-Grade Carbon Felt Impurity Limits:

Impurity Element	Maximum Allowable Content (ppm)	Main Hazard
Total Ash	< 100 (Premium <50)	Introduces deep-level defects
Metal Impurities (Fe, Ni, Cr, etc.)	< 20	Affects carrier lifetime
Alkali Metals (Na, K)	< 5	Causes crystal contamination
Sulfur (S)	< 10	Causes vapor-phase corrosion
Nitrogen (N)	< 50	Unintentional doping

Incoming Inspection Items:

- ICP-MS (Inductively Coupled Plasma Mass Spectrometry) full element analysis.
- Ash content test (850°C air combustion method).
- Gas adsorption-desorption test (evaluates outgassing characteristics).

6.4 Shape Design and Customization Schemes

6.4.1 Standard Shapes and Uses

Shape Type	Schematic	Main Use	Machining Points
Flat Sheet	▭	Top/Bottom insulation / Filler shims	Edges should be chamfered to prevent fiber shedding
Curved Sheet/Sector	◠	Wrapping cylindrical furnace chamber	Arc must precisely match furnace diameter
Cylinder/Sleeve	▯	Lateral insulation	Seams should be

Shape Type	Schematic	Main Use	Machining Points
		cylinder	staggered in design
Custom-Shaped Parts	⬡⬢	Thermal field regulating rings / Special support parts	Typically CNC machined from graphite rigid felt

6.4.2 Multi-Layer Composite Structure Design

Typical Three-Layer Composite Structure Example (for sidewall insulation):

Layer Structure (from inside out):

- Layer 1: 2mm Graphite paper (anti-permeation layer)
- Layer 2: 20mm High-density graphite felt ($0.25 g/cm^3$, fully graphitized)
- Layer 3: 50mm Medium-density carbon felt ($0.18 g/cm^3$, semi-graphitized)
- Layer 4: 30mm Low-density carbon felt ($0.12 g/cm^3$, carbon felt)
- Layer 5: 1mm Graphite paper (protective layer)

Design Guidelines:

- Density Gradient Decreasing: High inside, low outside.
- Thickness Increasing: Thin inside, thick outside (radiation shielding requires only a relatively thin high-density layer).
- Staggered Seams: Adjacent layer seams offset by at least 90°.
- Fixing Method: Use graphite cord stitching or ceramic fasteners; metal fasteners are prohibited.

6.4.3 Special Design for Key Areas

- Seed Shaft Passage Design:

[Option A: Multi-stage Aperture]

Outer diameter Φ150 → Φ120 → Φ90 → Φ65 (final aperture)

Each step height 20-30mm

[Option B: Tapered Sleeve Ring]

Use graphite rigid felt machined into a 15° tapered sleeve ring.

Maintain a 1-2mm gap with the seed rod.

- Viewport Area Design:

Use high-density, low-thickness graphite felt.

Cut-out size 10-15% larger than the viewport.

Reinforce edges to prevent fiber collapse.

- Thermocouple Outlet:

Use dedicated graphite sleeve guide.

Pre-formed holes in surrounding carbon felt.

Aperture 3-5mm larger than thermocouple diameter.

6.5 Supplier Evaluation and Quality Control

6.5.1 Supplier Evaluation Checklist

Evaluation Dimension	Specific Indicators	Weight
Technical Capability	1. Maximum producible size 2. Density control accuracy (±5%) 3. Graphitization equipment capability 4. Custom machining capability	30%
Quality System	1. ISO9001 certification 2. Batch consistency (Cpk >1.33)	25%

Evaluation Dimension	Specific Indicators	Weight
	3. Completeness of testing equipment 4. Quality traceability system	
Product Performance	1. Impurity content data 2. High-temperature shrinkage rate (<3% @2000°C) 3. Measured thermal conductivity values 4. Mechanical property data	25%
Service Support	1. Technical response speed 2. Sample provision capability 3. On-site technical support 4. Supply cycle stability	20%

6.5.2 Incoming Inspection Procedure

- Mandatory Inspection Items List:

Visual Inspection: Uniform color, no visible impurities, neat edges.

Dimensional Inspection: Thickness tolerance ±0.5mm, flatness <1mm/m.

Density Sampling Inspection: At least 3 samples per batch, measured values within ±5% of nominal value.

Purity Verification: Third-party test report attached for each batch; sent for external testing quarterly.

Performance Testing: Thermal conductivity test (comparative testing at least annually).

- Sampling Standard:

Batch size <50 pieces: Sample 10%.

Batch size 50-200 pieces: Sample 8%, minimum 5 pieces.

Batch size >200 pieces: Sample 5%, minimum 10 pieces.

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