GigaDevice Semiconductor Inc.

Thermal management manual for GD32 MCU

Application Note
AN060

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1. Introduction

This article is specially provided for engineering designers who develop based on GD32 MCU. It mainly introduces the definition, parameters, measurement methods, influencing factors, heat dissipation methods, etc. of thermal resistance. With the development of semiconductor technology, the internal circuit integration of the chip is getting higher and higher, and the heat density of the chip is increased. As the Junction Temperature (T_J) of the chip increases, the lifetime of the chip decreases and the failure rate increases. Therefore, we will stipulate the maximum allowable junction temperature of the chip, and the chip must work below the maximum allowable junction temperature to ensure its performance and lifetime. The thermal resistance value is the parameter used to evaluate the thermal dissipation performance of the device, and it is very helpful for the engineering designer to correctly understand its physical meaning and how to use it.

2. Thermal Resistance

2.1 Definition

When there is heat transmitted on the object, the ratio between the temperature difference between the two ends of the object and the power of the heat source is the thermal resistance. Thermal resistance can be understood as the resistance that heat encounters on the heat transfer path, reflecting the heat transfer capacity of the medium or between mediums, that is, the degree of junction temperature rise caused by unit dissipated power, in K/W or ℃/ W.

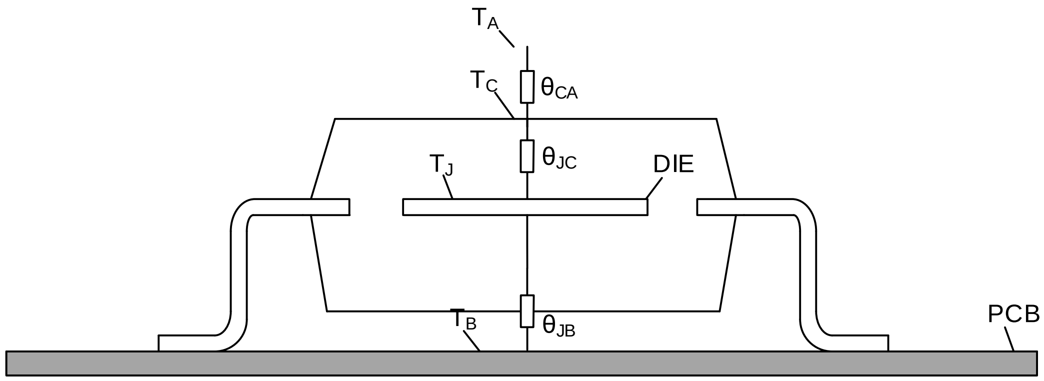
Taking an integrated circuit as an example, thermal resistance is a measure and ability of a package to conduct heat generated by the die to the circuit board or the surrounding environment. Defined as follows:

$$\theta_{JX}=\frac{T_J-T_X}{P} \quad (2\text{-}1)$$

The thermal resistance value is usually expressed by θ, where T_J is the temperature of the die surface (Junction Temperature) of the chip, T_X is the temperature of heat conduction to a target point, and P is the input dissipated power. In electronic design, if current flows through a resistor, a voltage difference will be generated. Similarly, if heat flows through a thermal resistance, a temperature difference will be generated. A large thermal resistance means that heat is not easily conducted, so the temperature rise of the device is relatively high, and the heat dissipation performance of the device can be judged by the thermal resistance.

2.2 Thermal resistance and thermal characteristic parameter

Figure 2-1. Schematic diagram of thermal resistance of LQFP packaged chip



T_A: Ambient temperature;

T_C: Case temperature which is monitoring on package surface;

T_J: Junction temperature;

T_B: Board temperature;

θ_{CA}: Thermal resistance from chip surface to ambient;

θ_{JC}: Thermal resistance from die to die surface;

θ_{JB}: Thermal Resistance from Chip Die to PCB。

θ_{JA}: The thermal resistance from the surface of the chip die to the surrounding environment, which is a measure of the heat dissipation performance of the IC package under specific test conditions, indicating the difficulty of heat dissipation from the chip die to the environment, θ_{JA} will be affected by PCB design, chip or package size, Die geometry, height, external ambient temperature, etc. Since it is difficult to achieve the conditions for measuring θ_{JA} in practical applications, using θ_{JA} to calculate junction temperature in practical applications will lead to larger error. But θ_{JA} can be used to compare the heat dissipation performance of the package, for qualitative comparison, the smaller the value of the device θ_{JA}, the better the heat dissipation performance of the device. It can be seen from the ***Figure 2-1. Schematic diagram of thermal resistance of LQFP packaged chip***: $\theta_{JA} = \theta_{JC} + \theta_{CA}$.

θ_{JB}: Thermal resistance from die surface of chip to board, the thermal resistance from the die surface of the chip to the circuit board, θ_{JB} includes thermal resistance from two aspects: the thermal resistance from the die surface of the chip to the reference point at the bottom of the package, and the thermal resistance from the bottom of the package to the circuit board.

θ_{JC}: The thermal resistance from the chip die to the package surface represents the heat dissipation capability from the chip die to the bottom or top of the chip package. When a heat sink is used in practical applications, θ_{JC} can be used to calculate the die temperature of the chip.

Ψ_{JT}: Thermal characterization parameters from the die surface of the die to the top of the package. Since the measurement of Ψ_{JT} is more in line with the actual application, Ψ_{JT} can be used to calculate the chip junction temperature in actual use. The calculation formula is as follows:

$$T_J=\Psi_{JT}\times P_D+T_C \tag{2-2}$$

Ψ_{JB}: Thermal characterization parameters from the die surface of the chip to the circuit board. Since most of the heat generated by the device is dissipated through the PCB, the value of Ψ_{JB} is close to θ_{JB}.

Case Temperature: Case temperature refers to the temperature at the top of the package used as the chip carrier. A smaller diameter thermocouple (type J or K) can be placed on the thermally conductive epoxy in the center of the top of the package.

If the thermal resistance of the package shell to the environment is much higher than the thermal resistance of the chip Die to the shell (at least an order of magnitude higher), then most of the chip generation is emitted through the PCB. If a little error is acceptable, the case temperature can be considered as the junction temperature.

Board Temperature: The temperature of the board is measured at the locations defined by JESD51-8 on the upper surface of the board using the method of thermocouple attachment. Since T-type thermocouples are easy to solder, T-type is the first choice, J-type or K-type can also be used. Board temperature and package junction-to-board thermal resistance are critical parameters when evaluating device thermal performance.

Under stable air conditions, most of the heat generated by the device is dissipated through the circuit board. The heat dissipated through the board can be 20 times higher than the heat dissipated through the top of the package. For example, for the JEDEC high conductivity test board, under steady air conditions, 95% of the device heat is dissipated through the board and only 5% is dissipated through the package. Because the test conditions are difficult to achieve in practical applications, θ_{JA} cannot be used to estimate the device junction temperature in practical applications.

Dissipated Power: The definition of dissipated power is: the difference between the total active input power and the total active output power of the grid components or the entire grid at a certain time, which can also be understood as the energy consumed and dissipated during the operation of the components.

We will provide the maximum dissipation power in the GD32 datasheet. In actual operation, the chip power consumption exceeding the maximum dissipation power may cause the chip junction temperature to be too high, which may cause the chip to be damaged.

Figure 2-2. The maximum power dissipation is marked in the GD32 datasheet

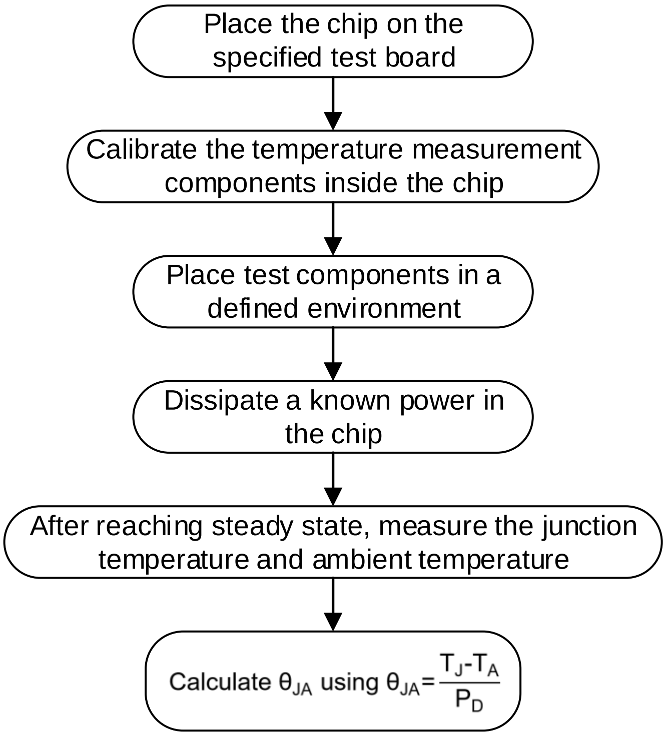
P_D	Power dissipation at T_A = 85°C of LQFP48	—	574	mW
	Power dissipation at T_A = 85°C of LQFP32	—	724	
	Power dissipation at T_A = 85°C of QFN32	—	939	
	Power dissipation at T_A = 85°C of QFN28	—	845	
	Power dissipation at T_A = 85°C of TSSOP20	—	595	
	Power dissipation at T_A = 85°C of LGA20	—	416	

2.3 Thermal resistance and thermal characteristic parameter measurement method

There are two methods of measuring thermal resistance: actual measurement and simulation. The following will introduce them one by one:

The steps for laboratory measurement of θ_{JA} are as follows:

Figure 2-3. θ_{JA} laboratory measurement procedure



The above steps are summarized in the JESD51 standard. For more detailed and accurate steps, please refer to the JESD51 standard.

The steps for laboratory measurement of θ_{JB} are as follows:

Figure 2-4. θ_{JB} laboratory measurement steps

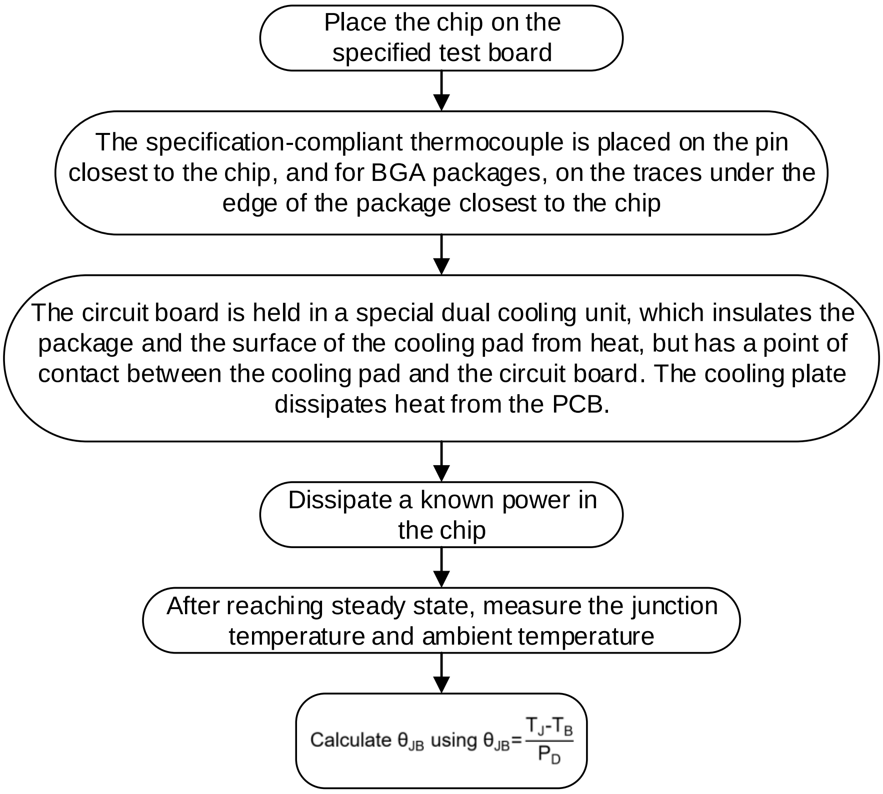
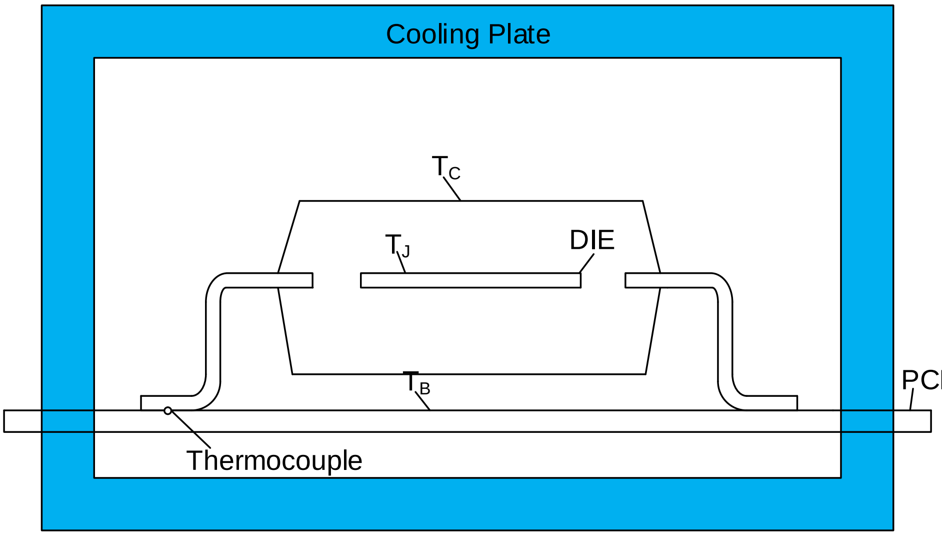


Figure 2-5. θ_{JB} laboratory measurement environment



The above steps are summarized in the JESD51 standard. For more detailed and accurate steps, please refer to the JESD51 standard.

The steps for laboratory measurement of θ_{JC} are as follows:

Figure 2-6. θ_{JC} laboratory measurement steps

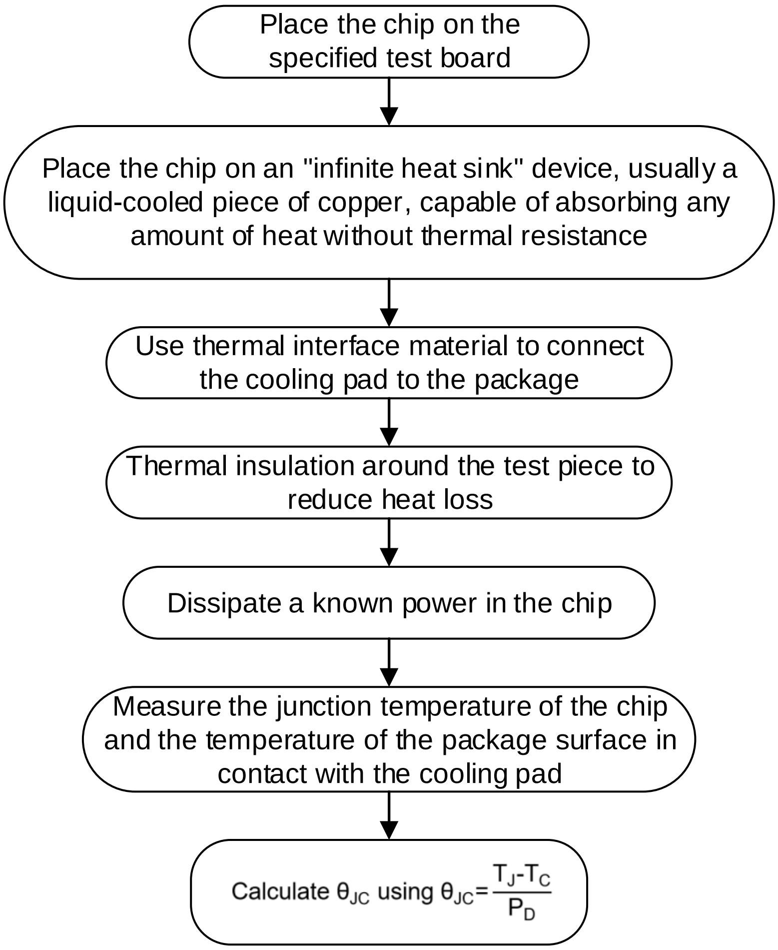


Figure 2-7. θ_{JC} laboratory measurement environment

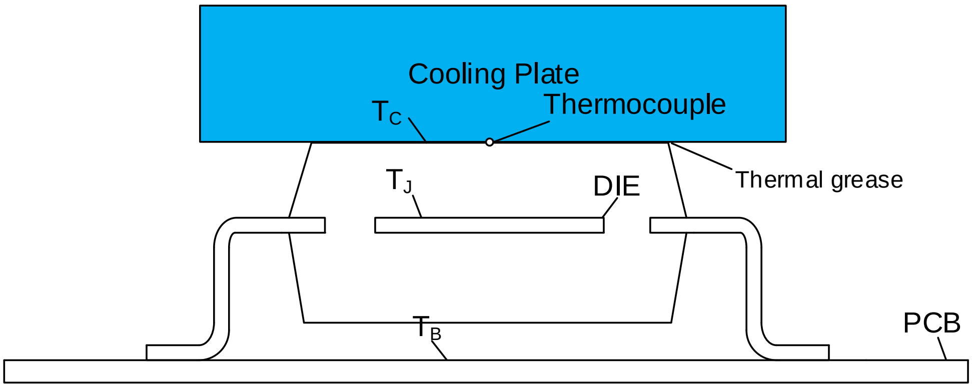
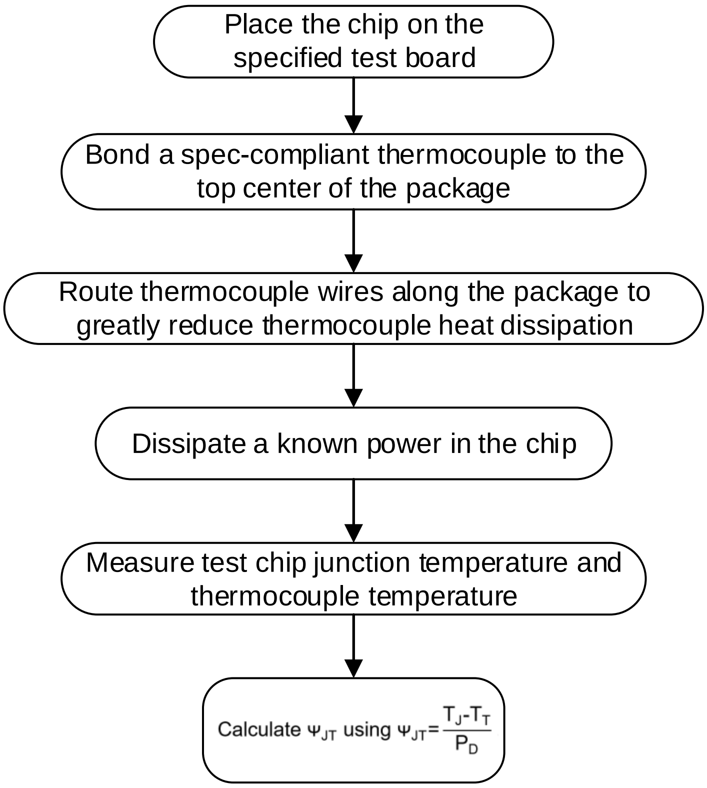


Figure 2-8. Ψ_{JT} laboratory measurement steps



Ψ_{JB} are similar to those of Ψ_{JT}, so they are not repeated here.

It can be seen from the above-mentioned actual measurement method of thermal resistance that the actual measurement of thermal resistance has extremely stringent requirements on the experimental environment and experimental equipment. Therefore, most semiconductor manufacturers use simulation software to measure thermal resistance, these simulation software contain complex thermodynamic models, which can obtain more accurate thermal resistance parameters. The chip thermal resistance values in the GD32 datasheet are all calculated by simulation software, the thermal resistance parameters of GD32F303xx series are shown in *Table 2-1. GD32F303xx series thermal resistance parameters*.

Table 2-1. GD32F303xx series thermal resistance parameters

Symbol	Condition	Package	Value	Unit
θ_{JA}	Natural convection, 2S2P PCB	LQFP144	48.76	°C/W
		LQFP100	47.19	
		LQFP64	61.80	
		LQFP48	64.40	
θ_{JB}	Cold plate, 2S2P PCB	LQFP144	35.00	°C/W
		LQFP100	27.43	
		LQFP64	42.83	
		LQFP48	42.32	
θ_{JC}	Cold plate, 2S2P PCB	LQFP144	12.03	°C/W
		LQFP100	8.57	
		LQFP64	21.98	
		LQFP48	22.47	
Ψ_{JB}	Natural convection, 2S2P PCB	LQFP144	35.32	°C/W
		LQFP100	31.42	
		LQFP64	43.05	
		LQFP48	42.42	
Ψ_{JT}	Natural convection, 2S2P PCB	LQFP144	1.86	°C/W
		LQFP100	1.00	
		LQFP64	1.58	
		LQFP48	1.74	

2.4 The difference between θ parameter and Ψ parameter

The following figures show the thermal conduction path when measuring thermal resistance and thermal parameters:

Figure 2-9. Heat conduction path when measuring θ_{JA}, Ψ_{JB} and Ψ_{JT}

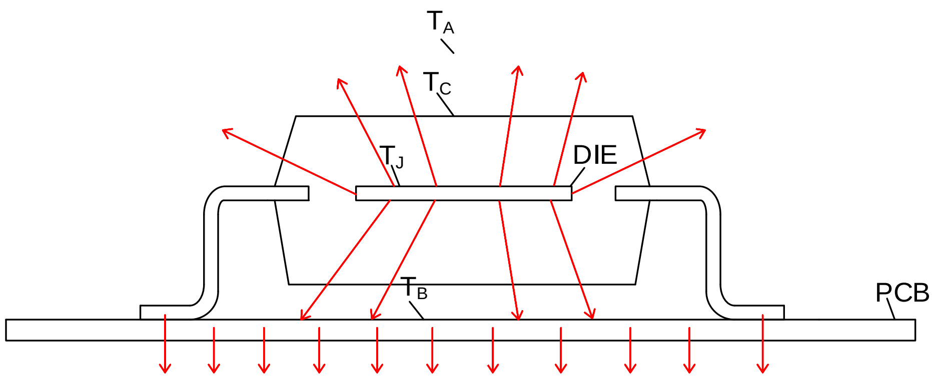


Figure 2-10. Heat conduction path when measuring θ_{JC}

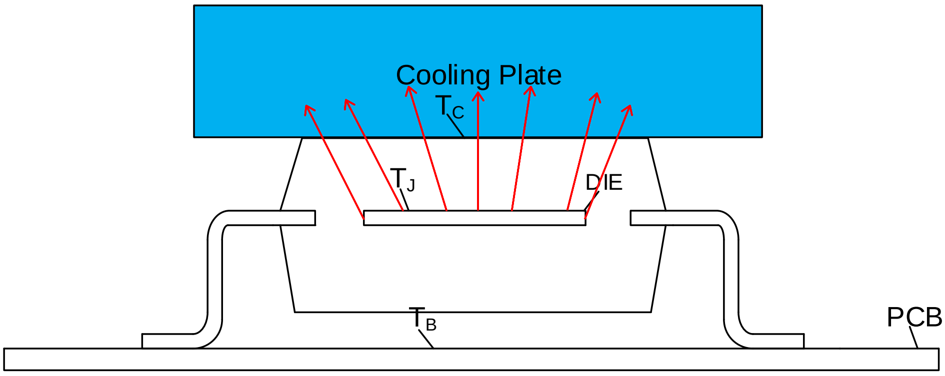
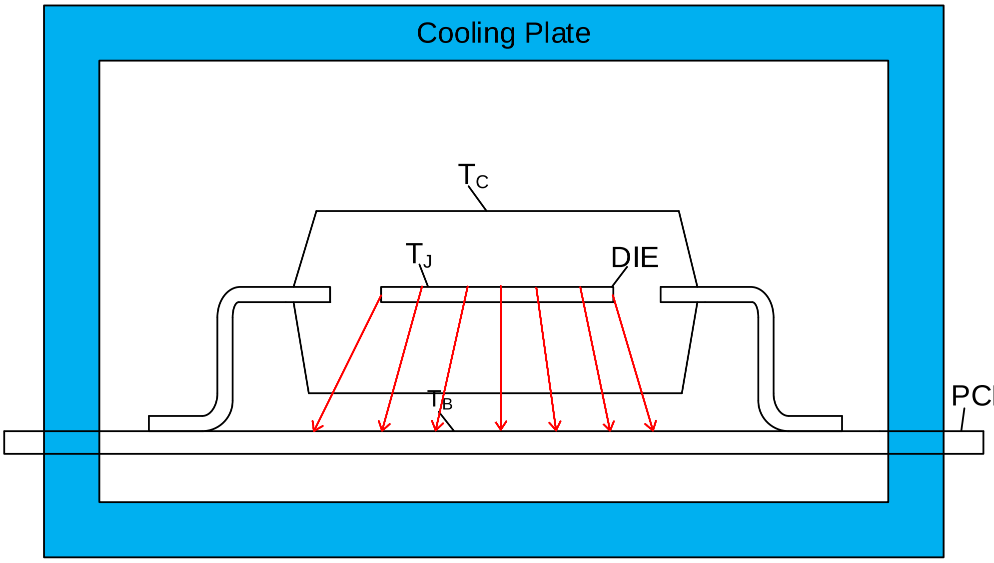


Figure 2-11. Heat conduction path when measuring θ_{JB}



As can be seen from the above figure and the definitions of Ψ and θ, although the Ψ and θ parameters look similar, Ψ refers to most heat transfer conditions, and θ refers to all heat transfer, so the Ψ parameter is not really the thermal resistance, but the thermal characteristic parameter. When dissipating heat in an actual electronic system, the heat will be transmitted from the top and bottom of the package or even around the package, not necessarily in a single direction, so the definition of Ψ is more in line with the application scenario of the actual system.

For example, when measuring θ_{JB}, almost all heat will be transferred from the chip surface to the PCB board, while when measuring Ψ_{JB}, only most of the heat will be transferred from the chip surface to the PCB board, and some heat will be dissipated from other directions, so the Ψ_{JB} measurement is more in line with the actual use situation.

3. Factors Affecting Thermal Resistance

Test Board: In the thermal resistance measurement method specified by JEDEC, the test board is similar to a heat sink. Taking θ_{JA} as an example, when testing θ_{JA}, most of the heat is dissipated through the test board. Changes in traces, copper laying, and vias on the test board have a huge impact on the thermal resistance. JEDEC specifies two test board types: 1S (single signal layer), 2S2P (double signal layer and dual power supply layer); GD32's The thermal resistance simulation measurements are all based on the 2S2P test board.

DIE and package size: With the increase of die size, the heat can be dissipated to a larger area, the heat dissipation speed will be increased, and the thermal resistance will be reduced accordingly; the change of the external package will lead to the change of the heat dissipation area and heat dissipation path, which will also lead to Changes in thermal resistance, thinning and shrinking of the external package will lead to an increase in thermal resistance.

External environment: When measuring thermal resistance, changes in the external environment (such as temperature, wind speed, altitude, etc.) will also lead to changes in thermal resistance. Altitude changes cause changes in air pressure, which in turn lead to changes in chip heat dissipation capabilities. Generally, devices operating at higher altitudes will dissipate heat more slowly than devices operating at sea level. The increase of wind speed will improve the heat dissipation speed of the chip, as shown in ***Table 3-1. QFN (4X4-0.65) thermal resistance simulation results at different wind speeds and temperatures (PD=0.24W)***, in the test environment of flowing air, the measured chip Thermal resistance will be significantly reduced.

Table 3-1. QFN (4X4-0.65) thermal resistance simulation results at different wind speeds and temperatures (PD=0.24W)

Environment	Junction Temp.(℃)	Board Temp.(℃)	Case Temp_ Top.(℃)	Ambient Temp.(℃)	Ψ_{JB}(℃ /W)	Ψ_{JB}(℃ /W)	θ_{JA}(℃/W)
Still Air	97.295	93.068	97.015	85	17.61	1.17	51.23
Force Air 1m/s	95.86	91.713	95.254	85	17.28	2.53	45.25
Force Air 2m/s	95.367	91.276	94.559	85	17.05	3.37	43.2
Still Air	38.075	33.89	37.801	25	17.44	1.14	54.48
Force Air 1m/s	35.914	31.822	35.314	25	17.05	2.5	45.48
Force Air 2m/s	35.421	31.371	34.617	25	16.88	3.35	43.42

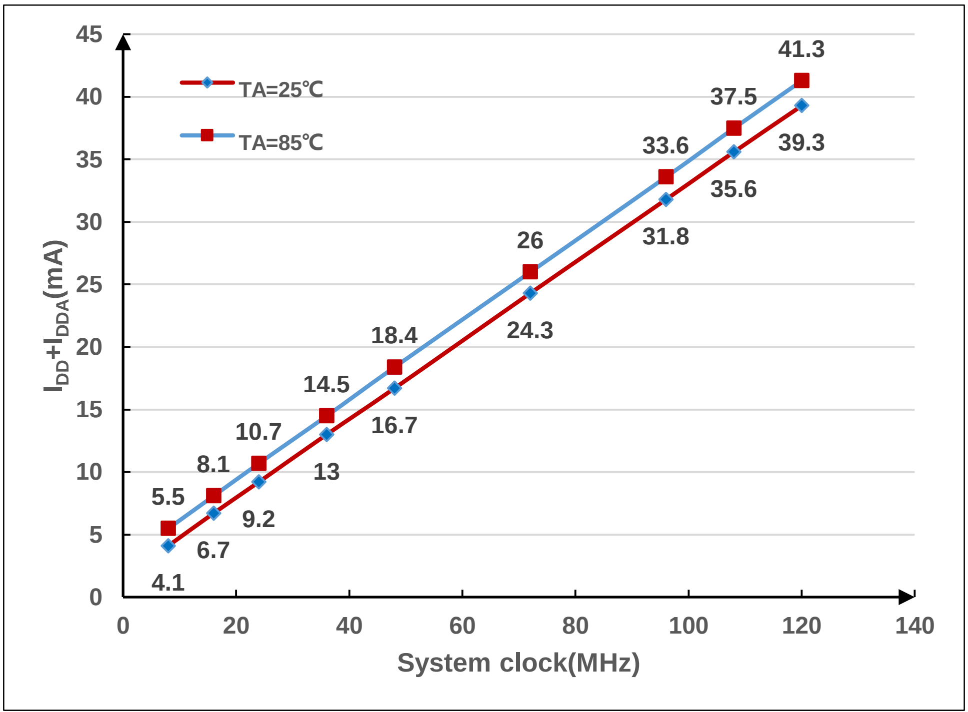
The order of the degree of influence on the thermal resistance is: PCB design> chip size> chip internal package shape> chip height> external ambient temperature> dissipated power.

Because the thermal resistance of the chip is related to many external factors, in most cases, the thermal resistance of the chip cannot be used to estimate the junction temperature, and it can only be used for qualitative comparison, that is, by measuring the thermal resistance of the approximate product, it is judged which product has better heat dissipation performance.

4. Choose The Right Cooling Method

Generally speaking, when the chip operates at a higher temperature, the power consumption will increase and the reliability will decrease, as shown in ***Figure 4-1. Power consumption of GD32F303xx series at different operating temperatures***. At high temperature, the power consumption of the chip is significantly improved. In order to work better and ensure the reliability of the chip, it is necessary to select the correct method of chip heat dissipation.

Figure 4-1. Power consumption of GD32F303xx series at different operating temperatures



Choose the right chip package: When choosing a chip package, in addition to the consideration of price, layout, and installation, the heat dissipation performance of the package should also be taken into account, especially when the chip is used in high power consumption occasions, a smaller thermal resistance value can be selected, choosing a package with a heat dissipation pad can also effectively solve the heat dissipation problem.

Heat dissipation through external devices: Adding heat sinks to chips and adding fans to dissipate heat are all good ways to dissipate heat.

Heat dissipation through reasonable board layout: Without adding external devices to dissipate heat for the chip, more than 70% of the heat generated in the chip is dissipated through the PCB, so a good layout has a crucial impact on chip heat dissipation. For chips that require heat dissipation, a large area of copper and heat dissipation vias on the PCB can effectively dissipate heat. Increasing the thickness of the copper laying can also increase the heat dissipation efficiency. Similarly, separating the chips with larger heat dissipation can also increase the heat dissipation efficiency.

5. Instance Measurement

In order to better show the relationship between power dissipation and chip temperature rise, two chips (GD32E103VBT6, GD32F450VKT6) were actually measured.

Test environment：Under the ambient temperature of T_A=25℃, the GD32E103V-EVAL circuit board and the GD32F450V-START circuit board were used for measurement. Both circuit boards were powered by 5V voltage, and the thermocouple was attached to the center of the top surface of the chip to measure the temperature T_C. The difference between the chip junction temperature T_J and T_C is small, and it can be approximated that T_J=T_C, and the dissipated power of the circuit board and the chip are measured respectively. The GD32E103V-EVAL circuit board is a double-layer PCB, and the actual picture is shown in ***Figure 5-1. The actual picture of GD32E103V-EVAL***, and the GD32F450V-START circuit board is a four-layer PCB (dual signal layer and dual power supply layer), the actual picture is shown in ***Figure 5-2. The actual picture of GD32F450V-START***. The test results are as follows:

Figure 5-1. The actual picture of GD32E103V-EVAL

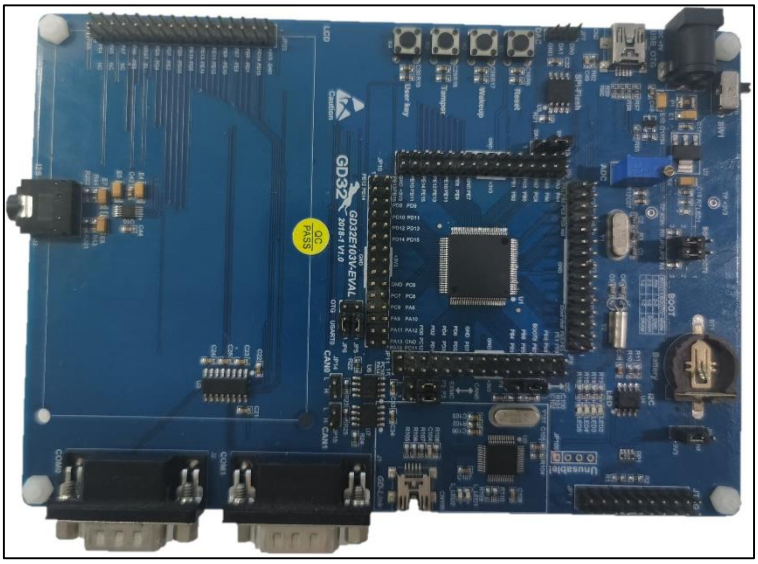


Figure 5-2. The actual picture of GD32F450V-START

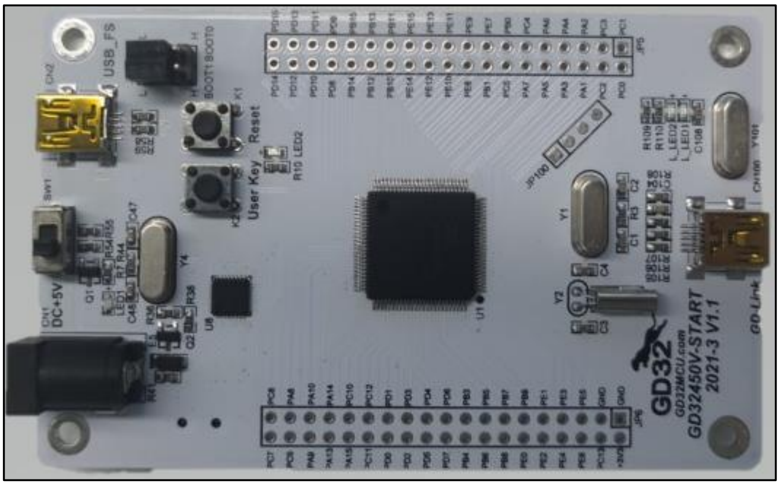


Table 5-1. GD32E103VBT6 power dissipation and temperature rise(On GD32E103V-EVAL board)

T_A (℃)	T_C (℃)	GD32E103V-EVAL(supplied with 5 V)		GD32E103V (supplied with 3.3 V)	
		Current consumption (mA)	Power consumption (mW)	Current consumption (mA)	Power consumption (mW)
25	30.45	81	405	30	99
25	30.11	76	380	24.23	79.959
25	27.42	71	355	19.84	65.472
25	28.59	66	330	14.8	48.84
25	27.22	58	290	7.41	24.45

Figure 5-3. GD32E103VBT6 power dissipation and temperature rise curve(On GD32E103V-EVAL board)

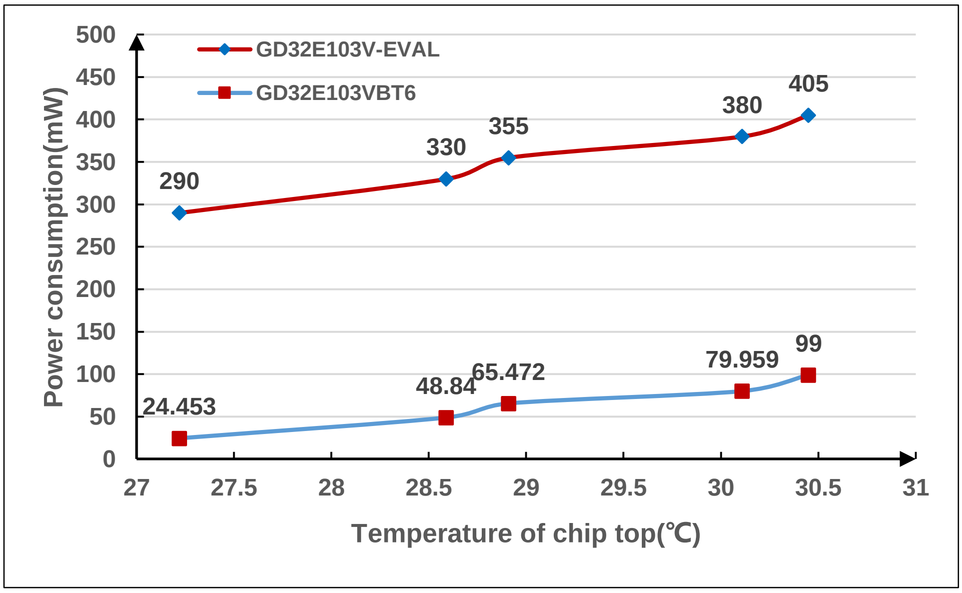
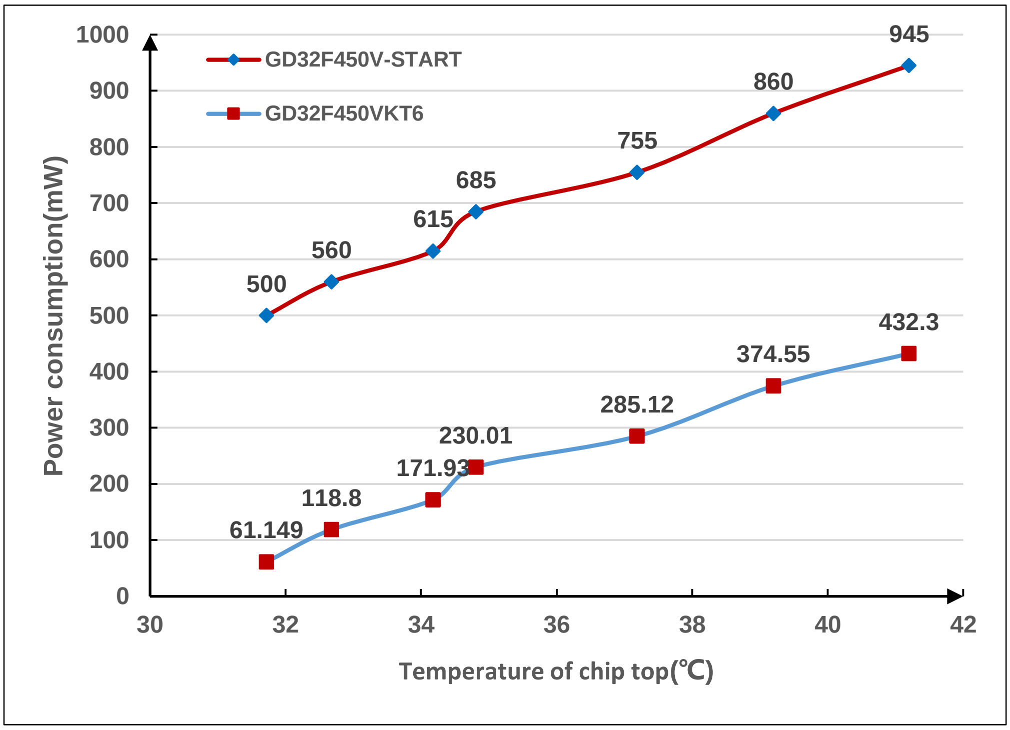


Table 5-2. GD32F450VKT6 power dissipation and temperature rise(On GD32F450V-START board)

T_A (℃)	T_C (℃)	GD32F450V-START(supplied with 5 V)		GD32F450Vx (supplied with 3.3 V)	
		Current consumption (mA)	Power consumption (mW)	Current consumption (mA)	Power consumption (mW)
25	41.2	189	945	131	432.3
25	39.44	172	860	113.5	374.55
25	37.19	151	755	86.4	285.12
25	34.81	137	685	69.7	230.01
25	34.18	123	615	52.1	171.93
25	32.68	112	560	36	118.8
25	31.72	100	500	18.53	61.149

Figure 5-4. GD32F450VKT6 power dissipation and temperature rise curve(On GD32F450V-START board)



6. Revision history

Table 6-1. Revision history

Revision No.	Description	Date
1.0	Initial release	Jun.10 2022