

Thermal Power of Mobile Application Processor

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Abstract

Until recently, heat dissipation performance of the conventional mobile AP (Application Processor) and mobile phone hasn't been a critical issue because the level of heat generated from a low-frequency, single core AP was insignificant. However, as the mobile AP consumes more power by adopting high frequency multi-core CPU (Central Processing Unit) and GPU (Graphic Processing Unit), the heat dissipation performance of its application set, such as smart phone and tablet PC (Personal Computer) became a critical issue. The conventional stand alone type applications sets such as desktop PCs and servers could afford additional thermal management tools such as heat sink, heat pipe and cooling fan to improve thermal performances. On the contrary, the limited inside space of mobile set doesn't allow the use of conventional cooling methods so that the feasible thermal solutions for the mobile AP and mobile sets are limited. In addition, since mobile set is normally in contact with human skin during its operation, the criterion, Tcsmax (Maximum Case Skin Temperature) which determines the thermal power performance of the mobile set is different from the conventional criterion, Tjmax (Maximum Junction Temperature) of CPU. Therefore, the thermal performance of mobile AP and its mobile set should be carefully determined to satisfy the Tcsmax by considering AP operation power and heat dissipating performance of the its application set. This paper shows how to define the thermal power performance of mobile AP and its mobile application set and which technologies are important for future mobile AP and its application sets.

Keyword

TDP (Thermal Design Power), TPP (Thermal Peak Power), DTM (Dynamic Thermal Management), DVFS (Dynamic Voltage & Frequency Scaling), Thermal Throttling, TMU (Thermal Measurement Unit), AP (Application Processor), CPU, GPU

1. Thermal solution of the conventional CPU

The cooling solutions such as heat sink, heat pipe, cooling fan and water cooling have been applied to Desktop PC, Notebook PC and server to provide better thermal performance. The strongest driving force of these solutions is enough inner space of the above application sets to accommodate these cooling tools.



Fig. 1 PC, Sever and their Cooling Tools

Human body (skin) is not in contact with the above application sets during operation. Also, even though the conventional notebook PC is oftentimes called as a “lap-

top PC”, it must be classified as a portable set instead of a mobile set, because most operations were performed not on human body (skin) but on the desk or table. The main thermal control target of the above conventional electronic sets was thus the maximum junction temperature of IC such as CPU or GPU so that the set and IC makers have mainly focused on the cooling solutions like heat sink, heat pipe and cooling fan.



Fig. 2 Mems Cooler, Feltier Cooler

In spite of the introduction of conventional cooling solutions as well as newly advanced cooling solution like MEMs cooling, CPU makers had given up the development of high clock frequency single core CPU and launched multi-core CPU because there were technical and cost limitations to develop cooling solution for dissipating the huge amount of heat generated by the high clock frequency single core CPU. Finally, some various

architectures and algorithms have been simultaneously developed with multi-core CPU solution to improve power consumption efficiency as well as to reduce heat generation.

Consequently, the thermal solutions of IC and its application are closely related to both hardware solutions like low power IC, heat dissipation structure of PKG and set and heat spreading material and software solutions like architecture, operating algorithm and scenarios of IC and its application set. Therefore, it is very important for IC and set makers to provide total power and thermal solution considering system level performance to guarantee the best performance as well as to provide the lowest cost.

This paper focuses on the thermal power performance and solution of mobile AP and its mobile application sets such as smart phone, Tablet PC and ultra thin notebook PC.

2. Thermal power of mobile AP and its application set

The biggest difference between conventional stand alone or portable electronic sets and mobile electronic sets is whether human body is in directly contact with the electronic set during its operation. This difference results in the different criterion for determining thermal performance of the IC and its application set.

The external case temperature of the electronic sets should be the criterion to determine the thermal performance of mobile AP and its application sets such as smart phone and tablet PC, whereas Tjmax of IC, such as CPU or GPU, was the criterion to define the thermal performance of IC and its conventional application sets like PC.

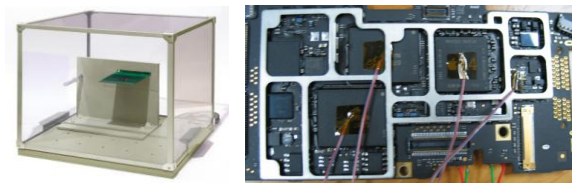
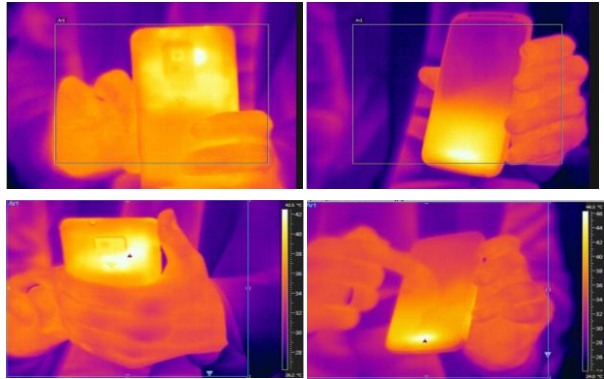


Fig. 3 Jedec Environment, Set Level Environment

Jedec standard 51-2 has been used to define the thermal performance of mobile AP package having single core 1GHz CPU because the maximum thermal power guaranteeing Tjmax of the AP wasn't high enough to heat up the surface of mobile phone to the Tscmax, 40~45°C even under the severest user scenario and benchmarking software. However, as the smart phones adopting >1.0GHz dual core CPU are launched since

2011, the external surface temperature of smart phone became higher than the allowable value, 40 ~ 45°C due to the heat generated by AP during operation of softwares like benchmark or 3D game for a certain period of time.



Smart Phone (AP with >1.0GHz Dual Core CPU)	A (Top L)	B (Top R)	C (Btm L)	D (Btm R)
Hot Spot (Front Display)	38.3℃	39.7℃	43.5℃ (upper)	46.3℃ (low)
Hot Spot (Backside Case)	41.6℃ (upper)	42.5℃ (low)	42.3℃	42.2℃

Fig. 4 Hot Spot position & Temperature of Smart Phone

Fig.4 and its table show that 4 kinds of smart phone with AP having >1.0GHz dual core CPU have >40°C hot spot on either front display or backside case after operating consecutive scenarios; phone call, internet map search @ daum.com (Korean Portal site), web surfing (Korean Sites) and Game (Angry Bird Rio) for 10 minutes under the ambient temperature of 27°C.

Since the hot spot positions and temperatures are different with mobile phones, the thermal performance of mobile set can be different with its thermal design, IC configuration. The mobile set users operate their mobile set on their body, mainly on their palm so that the heat dissipation from the mobile set to the outside environment consists of only 2 paths; Inside heat spreading + natural convection to air (display side) and inside heat spreading + conduction to human body.

Criterion	S/ Phone(4.3")	Tablet PC (7")	Tablet PC (10")
Tcs (45℃/Set)	~3.0 W	~4.0 W	~6.5 W
DRAM Tjmax (105℃/Set)	~4.3 W	~6.0 W	~9.5 W
DRAM Tjmax (105℃/Jedec)	2.4 W	2.4 W	2.4 W

Table 1 AP Thermal Power in Mobile Set

The maximum AP thermal powers on the Table 1 are based on only AP operation without operating other elec-

tronic components in mobile sets. Therefore, when the heats generated by other electronic components in mobile sets such as LCD, battery other ICs (Display driver IC, PMIC, Modem, RF, Camera sensor) are simultaneously considered, the actual maximum thermal power of AP in mobile sets becomes much lower than the values on the table 1.

According to "American Burn Association", the protein of human body starts to become necronic by contacting with hot material for 1hr @45°C, 3min@50°C, 8sec@60°C. Therefore, 45°C must be controlled as the maximum allowable surface (skin) temperature of mobile set which contacts with human body during its operation.

Although the AP operation power is higher than thermal design power (TDP) of mobile set, it is required for mobile sets to operate within limited time until the case skin temperature of mobile set reaches the predetermined maximum value of case skin temperature, 40~45°C. Thus, the care should be taken to regulate the external case temperature of the mobile set under the predefined value when the maximum AP operation power is applied.

TDP (Thermal Design Power) has been already used to define the thermal performance of CPU and its application sets, conventional PC and server.

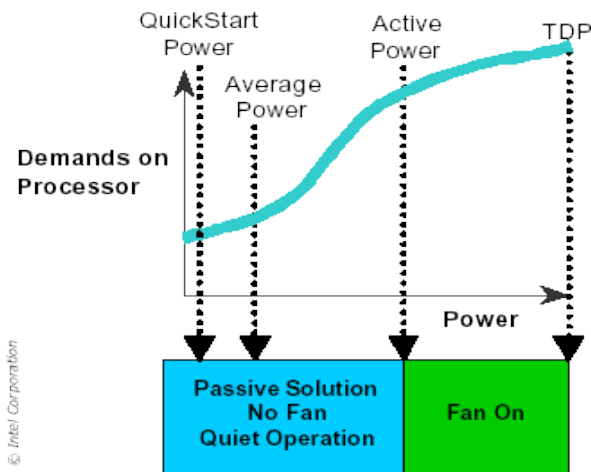


Fig. 5 TDP of Pentium 4-M (Intel)

According to the Intel's definition, TDP is the continuous operation power of CPU when operating cooling solution, which is mainly related to not time but power. The conventional PC and server also can use DTM (Dynamic Thermal Management) algorithm utilizing DVFS (Dynamic Voltage and Frequency Scaling) but DVFS is not popular for the conventional PC and sever because the CPU performance under the continuous operation is the most important factor for conventional PC and server.

2.1. DTM algorithm

The DTM conventionally has been used to maintain maximum junction temperature of CPU for desktop PC, notebook PC and sever by adopting on-chip thermal throttling logic as shown in Fig. 6.

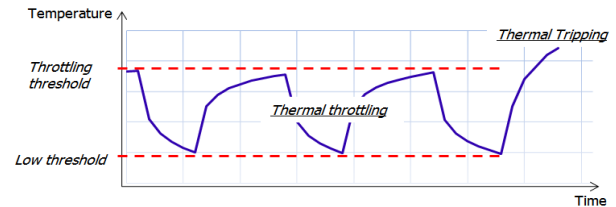


Fig. 6 Simplified Schematic of Thermal Throttling

The simplified thermal throttling mechanism shows that as a power control and temperature sensing measures, the conventional DTM adopts DVFS (Dynamic Voltage and Frequency Scaling) and TMU (Temperature Measurement Unit) respectively. DTM regulates IC temperautre between two reference threshold temperatures using the following scheme; Firstly, when the CPU temperature monitored by TMU reaches to the pre-determined high threshold temperature, the CPU (or GPU) clock frequency and core voltage are reduced to lower down the current drawn by PMU (Power Management Unit). This eventually reduces the amount of heat generated by the CPU (GPU) so that junction temperature goes down to the pre-determined low threshold temperature. Sencondly, when the TMU senses the pre-determined low threshold temperature, the frequency and voltage of CPU (GPU) are returned to high threshold value. When the above DTM scheme isn't properly operated under an abnormal case, thermal tripping (shutdown) is used to protect the CPU and its application set. [1-3]

2-2. Terminology of thermal power of mobile AP

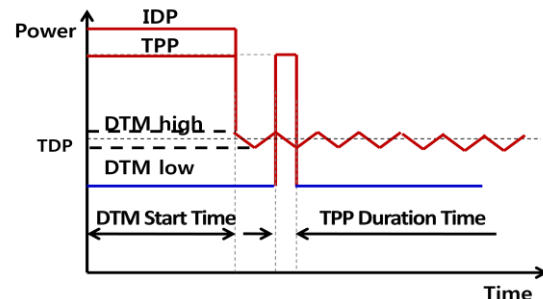


Fig.7 Terminologies of Thermal Design Power in SLSI

The definitions of the thermal power performance of the mobile AP and its application sets are different from the definition of conventional PC and server using cooling tools because case skin temperature should be moni-

tored as a DTM control target. Thus, it is required for business and engineering communication to clearly define the thermal power of mobile AP and its application, which are defined in Fig.7.

● **TDP (Thermal Design Power)**

RMS (Root Mean Square) power of DTM high and low power which maintains set case temp spec. Another expression of the mobile TDP is MSP (maximum sustainable power).

● **DTM (Dynamic Thermal Management)**

Power throttling to maintain set case temp or IC junction temperature by using DVFS

● **DVFS (Dynamic Voltage & Frequency Scaling)**

Voltage & Frequency control to maintain the required thermal specification of application set and IC

● **DTMST (DTM Start Time)**

Duration time when initially applied power (i.e., TPP) operates until activating DTM scenario

● **TPP (Thermal Peak Power)**

Max power which IC generates when operating benchmarking software or each scenarios like 3D game, camcording, web surfing, etc

● **TPP Duration Time**

Duration time when TPP is applied during the operation of user scenario, of which power is lower than TDP

● **IDP (IC Design Power)**

The sum of spec max powers of all IPs

● **SDP (Set Design Power)**

Max power which application set (PMIC) can provide, which is determined by considering TPP and IDP.

2-3. TDP performance of mobile AP

TDP value of mobile AP mainly depends on size, thermal design of application set as well as the power efficiency of AP. Although the TDP value increases with the size of application set, its level is much lower than the IDP, due to the limited heat dissipation capacity of mobile set. (Fig. 8)

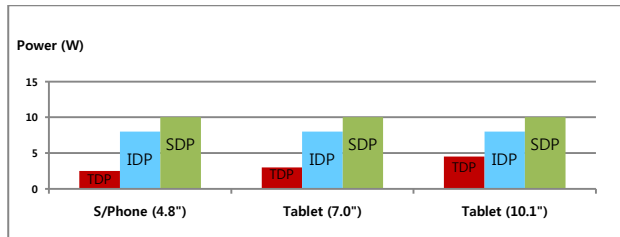


Fig.8 Thermal Power of Mobile AP

There are 2 references to determine the TDP of mobile AP; the first is Tcs (set case skin temperature) of mobile set when the applied power is low level (Fig.9) and the second is Tj of mobile AP when the applied power is high level (Fig.10). Therefore, 2 different temperature sensors are required to monitor Tcs and Tj simultaneously.

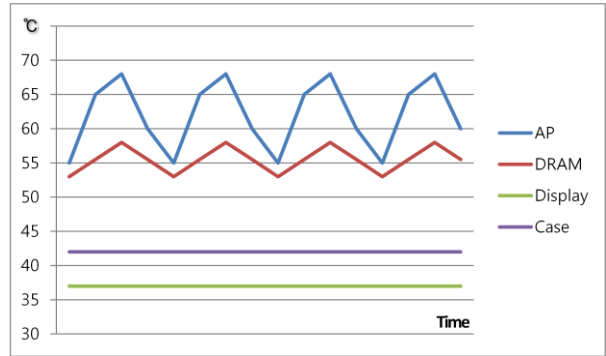


Fig.9 Components' Temp in Smart Phone (Low AP Power)

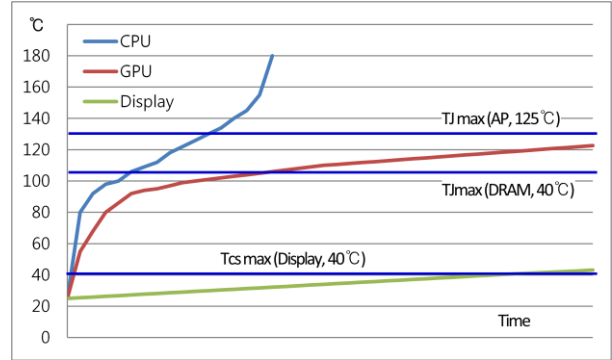


Fig.10 Components' Temp in Smart Phone (High AP Power)

The TDP and TPP of mobile AP considering DTMST and DTMDT vary with set size, set thermal design, spreading material as well as the powers of other electronic components used in the application set. Although the latest application set is used to define the thermal power of newly planning AP for future mobile sets, it is difficult to estimate thermal power (TDP, TPP and DTMST) performance of mobile AP because all electronic components spec, size, thickness and thermal design of set must be changed. Fig.11 shows how to estimate the thermal power of the newly planning ICs including mobile AP and its application.

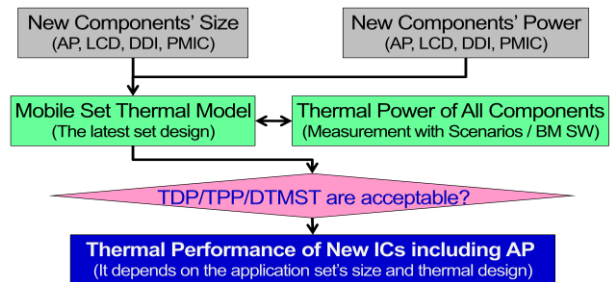


Fig.11 How to define thermal power of new AP and its application

2-4. Thermal power vs. mobile AP package solution

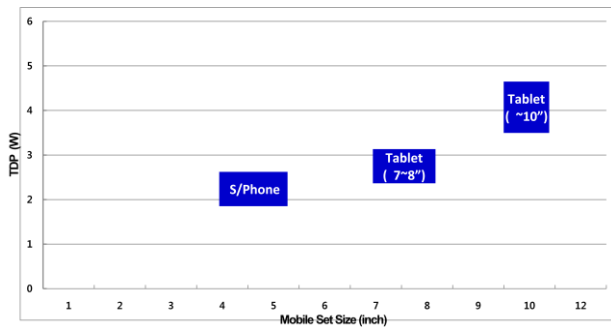


Fig.12 TDP based on Tcs of mobile sets

The TDP of mobile AP generally depends on the mobile set size but, even same mobile set size has some TDP range depending on the set level thermal design including heat dissipation structure and material of mobile set as well as configuration of electronic components in mobiles set. Granted that all components in mobile set are made of silicon, mobile TDP is much lower than TPP because of the limited inner space of mobile sets. This means that it is required for TPP operation to utilize DTM with DVFS even though the best set level thermal design is applied.

DTMST of smart phone is dramatically decreased as the AP power increases. Although some extent of DTMST is required for mobile set to run CPU or GPU benchmarking softwares, it isn't easy for mobile set to define the required DTMST of AP because the thermal power performance of mobile AP is affected by not only mobile set size, set level thermal design and the power (heat) effect of other electronic components but also AP power itself.

The relationships between Tcs(Tj) and operation time as well as between TPP and DTMST allow mobile sets to adopt AP-DRAM POP/SIP instead of discrete package because the thermal performances (TDP, TPP, DTMST) of mobile AP POP/SIP are the same level as discrete package under the mobile set environment. Therefore, Tablet PC can adopt POP/SIP instead of discrete package because the thin tablet PC doesn't adopt cooling tools like heat pipe and cooling fan. (Fig. 12)

Heatslug attached package provides conventional PC including ultra thin notebook with better AP thermal power solution than POP and overmold type discrete package because heat pipe and cooling fan are adopted so that its TDP becomes higher than mobile set's

2-5. User scenarios vs. TDP/TPP

There are several user scenarios used in mobile devices, such as 3D game, web browsing, camcording, video

playing, MP3 playing and the AP power levels of these scenarios are much lower than TPP which is utilized to run benchmarking software to check the performance of CPU or GPU of mobile AP.

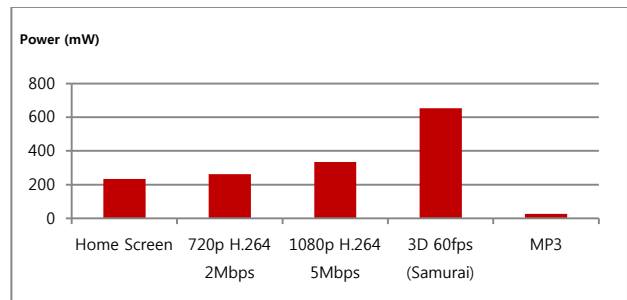


Fig.13 AP power usage vs. user scenarios (test board & set)

Fig.13 shows that 3D game is the severest scenario among the several user scenarios including home screen, web surfing, camcording, video playing and MP3. But even 3D game, the power level is much lower than TDP/TPP of mobile AP and this means there would be no thermal issue under the most operations for certain period of time. Although the power levels of user scenarios are much lower than TDP/TPP, the low power AP solution is still required because the accumulated heat by continuous operation can heat up the surface temperature of mobile set to the Tcsmax (max case skin temperature).

2-6. Effect of high colock frequency CPU

Based on the above data and analysis, it can be occurred why the high clock frequency CPU and GPU are required for mobile application sets because DTMST is too short to run the benchmarking software using TPP as well as the mobile TDP is much lower than TPP. But, fortunately, the higher clock frequency of CPU gives users much better user experiences by fast boosting user interface than lower clock frequency of CPU (Fig.14). Therefore, the higher colock frequency CPU and GPU are effective for mobile sets.

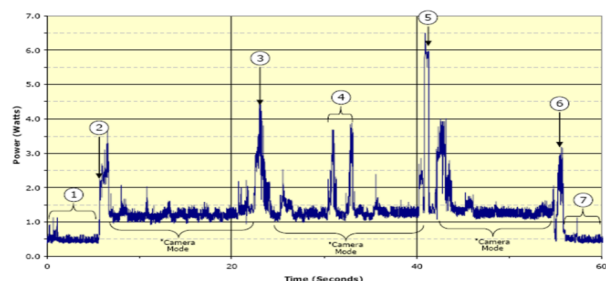


Fig.14 TPP operation during UI boosting

Although TPP operation within msec order is effective for the better user experience, the low power solution is still a major competitiveness of mobile AP because a lot of users want to operate the mobile set continuously for a

long time without DTM during operation of software like web surfing or 3D game.

2-7. How to improve thermal power performance

2-7-1. Set level thermal design

Although the same set size and same electronic components are applied to mobile set, the thermal performance of mobile AP can be different with the thermal design of mobile set. Case material, thermal pad, heat spreading sheet like graphite or Graphene and TIM between AP package and shielding metal lid, set board and display panel improve thermal performance of mobile AP and its mobile sets.

2-7-2. Low power AP and system solution

As the hardware type thermal solution including set level thermal design is going to be saturated due to the limited inner space and cost budget of mobile sets, the low power AP solution utilizing low power wafer fab process and more optimized DTM (DVFS) algorithm becomes important. And also, the optimized DTM algorithm should be determined under the set level thermal and power environment. In addition, the architecture and algorithm of system (AP and set) become much more important factors among all hardware and software thermal solution, to reduce the operating power of AP and its application set.

2-7-3. Low power effect of other ICs in mobile set

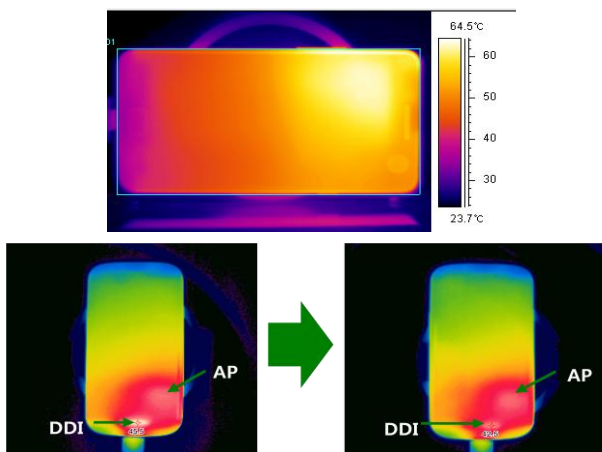


Fig.15 Hot spot effect thanks to other components in smart phone

Although the thermal powers of other ICs are much lower than one of mobile AP, some ICs are located near by mobile AP in the mobile set and can be a hot spot point during the mobile set operation. In this case, if the thermal power of the other ICs is low, the thermal power performance of mobile AP and mobile set also can be improved. And also, the hot spot point on the surface of

mobile phone varies with mobile set size, thermal design and thermal power level of its electronic components. Fig.15 shows that the hot spot of above photo is AP on the rear case but the hot spot of below photos are DDI (Display Drive IC) on the front display. below 2 photos show that the set level thermal performance, Tcsmax can be improved by adopting low power DDI. Therefore, the thermal powers of both AP and other electronic components should be estimated by considering the target size and thermal design of the mobile set.

3. Conclusion

The thermal powers of mobile AP and its application need to be redefined thanks to the relatively smaller and thinner set size, limited thermal design of mobile sets. Since TDP, TPP and DTMST of mobile AP varies with several factors; set size, set level thermal design including material and the thermal power effect of other ICs used in the application set, set level thermal engineering is essentially required to estimate the thermal power performance of both mobile AP and other ICs. Therefore, all data in this paper are just references.

In the case of mobile AP package solution, POP and SIP can be applied to mobile set like smart phone and tablet PC having no cooling tools like heat pipe and cooling fan because of the limited inner space and TDP/TPP/DTMST performances. POP and SIP save the board size of mobile set and also, provide the interconnection between AP and low power mobile DRAM with much better PI (Power Integrity) and SI (Signal Integrity) performance, compared to conventional discrete AP and DRAM package solution. In the mean time, heatslug attached package gives electronic set the better thermal power performance than other packages without heatslug, when cooling tools are applied.

In order to increase the AP power performance, there are three kinds of approaches, the first is to enhance the set level thermal solution by introducing thermal interface materials (thermal epoxy, thermal pad), higher conductive case material like aluminum and heat spreading sheet like graphite or Graphene, the second is to adopt low power wafer fab process and the last is to develop software solutions such as the optimized DTM and DVFS algorithm, low power architecture and algorithm for AP and its application system.

4. Acknowledgement

The authors would like to thank valuable support from Jaechoon Kim, YunHyeok Im, EunSeok Cho and JiChul Kim for Thermal Engineering, Chongkun Lee, Doyeon

Kim, Sunchul Kwon, Taeuk Lim and Jongin Kim for AP application engineering, Sunhee Park, Myungkyoon Yim and IL Park for AP design and architecture, Wook Kim and Woonghwan Ryu for AP power, Sangwook Ju, Jisung Kim, ManHyuk Park and Kyungil Sun for software engineering.

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