Research on Structure Integration and Thermal Control Technology of RF Microsystem

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Abstract. The urgent demand for small volume and light weight of APAR brings new challenges to the integration of radio frequency (referred to as RF) structure. This paper reveals the importance and characteristics of RF microsystem structure integration. Then the new challenges and key technologies in the process of microsystem integration are studied, such as system level thermal management and application of high thermal conductivity, multiphysics simulation and so on. In the end the further thinking of the integration and thermal management technology is illustrated.

Keywords: APAR, antenna system, RF microsystem, thermal management.

1. Introduction
The RF system is strictly restricted by the limited load and the aerodynamic shape of aircraft. Meanwhile it has to face the electronic information battlefield with increasingly complex electromagnetic environment and more difficult to detect ultra-high-speed stealth combat targets[1-3]. Increasingly complex electronic information battlefield requires warning and detection system of airborne and space borne to have larger apertures to integrate radar, communications, and other functions; to have higher RF performance indicators, and at the same time to significantly reduce the size and weight of the RF system. These needs can only be solved by microsystem technology instead of traditional RF technology [4-5].

Microsystem structure and thermal management are an important part of the multifunctional front system and an important unit of module-level mechatronics and thermal integration [6-7], which include the module-level designs of microsystem structure integration, micro-nano thermal and chip internal thermal. Micro-nano thermal design technology involves new high thermal conductivity materials, structural interconnection, micro heat pipes, micro flow technology, etc. The design methods and performance parameters of phased array RF microsystem-level need to be verified by a more sophisticated micro-scale flow and heat transfer test system, and part of the performance can only be verified by system joint test [8].

2. RF Microsystem Architecture Design
Although the overall power and heat consumption of the RF system is not large, the local heat flux density (such as the power amplifier chip) is very high, whose volume and weight are also strictly limited. The resulting large heat flux density problem cannot be effectively solved with traditional heat dissipation technology. In the radar structure design, the integrated design of the RF radiator and the
cold plate structure is beneficial to solve the problem of the high heat flux density of the microsystem by transferring heat of power amplifier to the front-end cold plate for cooling. The research on the integrated thermal management technology of RF microsystem structure and function is significant. The structural and functional integration design of RF microsystems can deal with a series of urgent technical difficulties such as high heat flux density dissipation, packaging, and high integration.

3. RF Microsystem integration

Research on RF microstructure system integration technology must be necessary to closely integrate RF structure system layout technology, high-precision microstructure integration technology, new structure and thermal management material integration technology, high-efficiency thermal control technology, micro-coaxial high-density cascade technology, etc. Solve the problems of system-level layout, topological layout of RF equipment, RF transmission layout, thermal expansion technology, etc., and finally realize the integrated engineering application of RF microsystem structure and thermal control.

3.1. Three-dimensional stacked structure of RF microsystem

Through-Silicon-Via (TSV) silicon transfer substrate integration is a typical technology for the three-dimensional structure of microsystems, which has the advantages of high interconnection density, excellent thermal matching, reduced circuit parasitic influence, lower power consumption and ESD requirements. The TSV silicon interposer board integration process has broad application prospects in microsystem integration modules because it can realize the high-speed interconnection of multi-chips. At present, this technology has been widely used in FPGA chip integration. The thermal stress reliability demonstration of the ultra-large-scale FC chip welding assembly using the 2.5D TSV silicon transfer substrate is carried out to provide the reliability evaluation basis for the application of its high-reliability integrated circuit and SIP system integration module. Figure 2 shows the three-dimensional stacked structure of the RF microsystem.
Microsystem integration requires hybrid integration and reconstruction of different materials substrates such as silicon, organic materials, ceramics, glass, etc., to meet the multi-functional needs of microsystems, which can achieve high density of various forms of bare chips, plastic-encapsulated chips, ceramic-encapsulated chips, metal-encapsulated chips, and components Integration and spatial interconnection. The integrated substrate can achieve ideal system performance through individual design optimization, individual tape-out, individual testing, and re-positioning in space according to the microsystem integrated structure design.

Three-dimensional integration and high-density integration of system-in-package transceiver components make effective thermal management more challenging. Especially the heat dissipation and thermal conduction of high-power chips, which will undoubtedly affect the electrical performance and reliability of the components. Researchers have found that high-density vias can be used to transmit electrical signals and isolate electromagnetic interference as well as heat conduction. Therefore, via electricity and heat reuse are closely related to the thermal management of the three-dimensional stack structure of the microsystem.

3.2. High-efficiency thermal design features of microsystem structure
Efficient thermal expansion technology is also a key technology for high-efficiency thermal design of micro system structure, which can effectively help the three-dimensional integrated design of RF micro system structure and break the severe restriction of heat dissipation capacity on the performance of micro-RF system. There are two main ways to achieve efficient thermal expansion: one is the application of high thermal conductivity materials; the other is the use of thermal expansion runners.

High thermal conductivity materials include carbon-based and metal-based thermal conductive materials. Companies such as DARPA, Raytheon and Norge lead related universities and scientific research institutions to conduct research on steam cavity diamond composite carbon-based high thermal conductivity materials. The thermal conductivity of diamond-based materials currently developed can reach 700W/ (m K), and carbon-based high-conductivity materials conduct lateral heat conduction the coefficient has reached 1700W/ (m K). The transverse thermal conductivity of the encapsulated carbon-based high thermal conductivity material (APG) has reached 700/ (m K) and the equivalent thermal conductivity of the steam chamber can reach 1000W/ (m K).

Corresponding research has also been carried out in domestic thermal expansion technology, and certain achievements have been made. In terms of thermal functional materials, the currently prepared diamond/copper (aluminum) material has a thermal conductivity of up to 50W/(m K), which has a linear expansion coefficient similar to that of the chip, and successfully developed a diamond/copper chip thermal layer engineering prototype, which has been applied through engineering; The thermal conductivity of the developed carbon-based high thermal conductivity material reaches 700W/(m K), but the material is too brittle to have the application conditions, and related research is still being further deepened.

The thermal expansion flow channel is mainly concentrated in the high-efficiency flexible microchannel fluid circuit, which can effectively transfer the heat consumption of the heat-generating electronic device to the special radiator. The micro-channel fluid circuit cooling technology uses the micro-scale effect of the flow and the boundary layer effect to increase the convective heat transfer coefficient between the cooling medium and the cold plate, thereby improving the heat exchange efficiency and reducing the requirements of the high heat flux density components on the coolant flow and volume. Compared with other heat dissipation technologies, microchannel circuits have higher heat dissipation capacity and greater heat dissipation potential. In addition to higher heat dissipation capacity, microchannel heat dissipation technology is also easy to integrate with modern electronic device substrates, so the development of microchannel heat dissipation technology has been relatively rapid in recent years. As shown in Figure 3, the integration of micro-channels and silicon-based microsystems is also a hot spot in the current thermal expansion technology research.
Figure 3. Micro-ribbed silicon adapter plate with micro-channel integrated in TSV.

The Micro heat sink structure integrated with TSV is one of the typical technologies for high-efficiency thermal management of microsystems. This technology allows heat to be transferred to the coolant through the surfaces of the surrounding cavity by making a large number of miniature heat sinks in the silicon adapter plate. Compared with the traditional micro channel, it can not only improve the heat dissipation capacity, but also ensure the high-density transmission of electrical signals.

4. Key technologies for micro-RF system realization

The first key technology is to combine system-level thermal management technology with microstructure technology to solve the problem of high heat flux heat dissipation. The second key technology is to use high thermal conductivity and low expansion packaging materials to solve the problem of large-area thermal expansion under limited weight. The third key technology is to use multi-physics simulation technology to study the problems of welding and ball planting in the process of micro-assembly. The simulation results are used to analyze the influence of the temperature field on the thermal deformation and electrical properties of the micro system during the micro-assembly process, and analyze the influence of the structural accuracy and unevenness on the micro-assembly process and electrical properties. Finally, according to the research results, the system equipment layout is optimized to solve the problems of radio frequency transmission and thermal deformation control.

4.1. System-level thermal management technology research

In order to minimize the size, some chips adopt the form of three-dimensional stacked SIP, which uses TSV to solve the high-density 3D stacked interconnection between multi-layer chips. This interconnection method can also greatly shorten the electrical connection distance between the chips and reduce parasitic effects. The GaN amplifier chip in the RF micro system not only requires high output power, but also requires a large duty cycle to work, which means that the heat accumulated by the chip will be greatly increased. Therefore, the research of system-level thermal management technology should pay attention to the thermal design optimization of the chip. According to the previous experience of high-power single-chips, local hot spots on the single-chip can be avoided, stability and reliability can be improved, by optimizing the through-hole process and layout, reducing the cell width, increasing the fence spacing, and symmetrical circuit components Design and derating design, improve sintering method, etc. The use of multi-level heat dissipation is an effective way to realize the thermal management of the micro RF system based on the system-level thermal management technology. In the chip manufacturing process, using the front-end process to embed graphene into the chip allows the small area of the channel heat to quickly diffuse to the entire chip surface, which greatly reduces the local hot spot temperature.

The key to system-level thermal management technology is to ensure that the heat of the heating element can be quickly conducted to prevent heat concentration from causing system performance degradation and failure. Therefore, special heat dissipation measures can be taken for heat-generating chips such as power amplifiers by adding heat-conducting structures such as heat dissipation units or heat sinks.
4.2. Application technology of high thermal conductivity and low expansion packaging materials
Common metal-based composite materials are mainly divided into the following types: aluminum-based composite materials, copper-based composite materials, carbon/carbon-based composite materials. In addition, with the advancement of carbon nanotube preparation technology, the application of carbon nanotube-enhanced Cu, Al and other composite materials in RF microsystems has been launched abroad.

However, it is necessary to improve the thermal expansion efficiency to realize the integrated design of the micro-RF structure and thermal control. It can be found from the comparison of the thermal expansion capabilities of commonly used packaging materials, as shown in Figure 4, to carry out research on new high thermal conductivity carbon-based metal materials (such as diamond-copper aluminum, etc.) and carbon-based non-metallic composite materials (graphene, etc.) and engineering application is an effective way to solve the thermal control of RF microsystem.

![Figure 4](image)

**Figure 4.** Properties of several thermally expandable materials.

Graphene, as a typical carbon-based non-metal composite material, exhibits extremely high lateral thermal conductivity. The thermal conductivity of single-layer suspended graphene is as high as 5300W/(m.K). The high thermal conductivity and other excellent properties make graphene show great potential in the thermal control design of micro-RF systems. In recent years, the domestic and foreign research and application of ink-based heat dissipation have made very positive developments.

Graphene composite materials have the characteristics of enhancing heat dissipation, and some composite materials with a graphene mass fraction of 4% have the best heat dissipation performance. At this time, the maximum temperature of the device is about 10°C lower than that of the conventional metal substrate. However, when the mass fraction of graphene exceeds 4%, agglomeration will occur, resulting in a decrease in the thermal conductivity and adhesion properties of the composite material. From the perspective of practical applications, graphene needs to be in contact with the substrate. Therefore, reducing the contact thermal resistance between the graphene film and the substrate is a problem that must be considered in graphene thermal management applications. The van der Waals force between a single layer or a few layers of graphene and the substrate can ensure a good thermal coupling between the graphene and the substrate. However, due to the large thickness of the graphene film, the van der Waals force is far from sufficient for heat transfer from the substrate to the graphene film. Due to the low volume and thermal conductivity of the traditional thermally conductive adhesive between the connecting substrate and the heat sink, it can no longer meet the needs of practical applications, and other methods such as covalent bonds must be used to enhance the efficiency of heat transfer. In addition to the technical aspects, the cost control and industrialization of graphene are also a big challenge.
4.3. High-efficiency thermal management multiphysics simulation technology

The method of combining numerical calculation and experiment can be used to make full use of the existing thermal design software to carry out modeling simulation and thermal characteristic design of product samples. Through heat analysis, the heat dissipation problem of high heat consumption chips and high-density integrated micro-units is solved. For example, the steady-state thermal analysis CAD software developed by Wilkes College can quickly and effectively design the heat sink. Through the interactive computer thermal model of finite element analysis, the three-dimensional heat transfer system of the transistor package of the multilayer composite material with heat sink can be analyzed with numbers and graphics, and the subtle temperature of the entire package structure caused by the change of geometry can be displayed. Distribution.

Multi-physics simulation can shorten the design cycle and reduce the number of test verifications. Based on the HTCC substrate-based component material structure matching design and simulation, only the material matching (stress value) of the final state of the component can be simulated, and it does not have the ability to simulate mobile heat sources during laser welding. In part of the simulation analysis process, the linear elastic model is selected for the solder model, and the actual solder exhibits nonlinear viscoelastic characteristics with temperature changes, and the degree of simulation reduction is still different from the actual situation. Through research on the matching design and simulation project of the component material structure based on the HTCC substrate, the typical structural parameters and process parameters can be determined, and the spectrum-based shape can be established to guide the subsequent design.

5. Conclusion

The research and development of RF microsystem structure and thermal design technology need to solve many problems. However, we believe that with the development of Moore's Law, chip performance will be further improved, especially in the post-Moore's Law era that realizes three-dimensional different materials integration, and system performance and capabilities will surely be improved. In the future, RF microsystem structure and thermal design technology will make great progress in volume and weight, performance, efficiency and intelligence level, and promote the advent of higher performance microwave radar.

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