CVD Diamond
The Cost Effective Solution to High Heat Flux Thermal Challenges

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Abstract

One of the many outstanding characteristics of diamond is its high thermal conductivity. Some types of natural diamond can have thermal conductivity as high as 2000W/m-K. CVD diamond can be manufactured with thermal conductivities ranging from 1000W/m-K to 1800W/m-K. Many high technology applications are finding that performance growth is being constrained by thermal issues, with increased performance restricted by reliability or stability concerns. The electronics and communications industries continue to struggle with the challenges of thermal management. While new technology provides the path to smaller and smaller device geometries, this same scaling path further increases the difficulty of getting heat away from the active portions of the circuits.

This paper will address two diamond-based, high heat flux thermal management solutions developed by sp3 Diamond Technologies. While these technologies and manufacturing processes were developed and honed for cutting tool applications, the many unique characteristics of CVD diamond are applicable to technology applications as well. Additionally, the production processes developed to grow revenue and profits in the cost sensitive cutting tool market are enablers of cost-effective thermal management solutions.

The paper will discuss the transition of the manufacturing processes of freestanding diamond for cutting tools to the productization of heat spreaders. The paper will also discuss how the technology developed for thin film diamond for round tools and inserts serves as the foundation for work in diamond-on-silicon (DOS). DOS will be the enabling layer for the development of active circuits with thermal heat spreading as part of the basic device. Finally, the paper will provide an overview of the future “hot spots” in thermal management.

Introduction

Two of the many material characteristics of CVD diamond are high wear resistance and high thermal conductivity. From the time that polycrystalline CVD diamond was introduced in the 1980’s, companies have been focused on profitably commercializing either of those characteristics. The commercialization efforts of the thermal characteristics saw two significant surges during the 1980’s and 1990’s. The first was in support of large US government efforts from 1985 to 1992 in the development of missile defense systems and of supercollider installations. Both projects triggered significant funding for CVD diamond development as thermal enablers for high power RF devices and other high heat flux components. Neither project was commercialized due to political changes leading to eventual project cancellations. The second thermal diamond commercialization surge occurred in the late 1990’s with the installation of optical fiber networks. It was anticipated that the technology transitions to 10 Gigabit and then 40 Gigabit long distance networks would drive the use of diamond thermal submounts to transition from the small volume undersea cable application to the greater volumes of a worldwide fiber infrastructure. Unfortunately, the “dotcom bust” and the “telecom winter” intervened.

Throughout these swings of potentially huge market applications for thermal diamond, the rather mundane world of cutting tools continued its slow, but steady pace in the application of CVD diamond. The initial applications concentrated on the deposition of thin film diamond onto round tools and inserts. These diamond coated tools found their niche in harsh environments and long, high precision cuts where other materials did not provide the required life or accuracy. CVD diamond was found to do extremely well in abrasive non-metallic materials such as green ceramic and graphite. Fig. 1 illustrates the range of applications and characteristics that drove material choices in 2000. This included the use of thick film CVD diamond for tool tips and dresser bars.

The manufacturing technologies used for thin film and thick film CVD diamond are quite different, as are the pre and post processing steps. This is especially true when the goal is high volume, cost effective production, not development of “ideal” material characteristics. Critical to developing an ongoing, surviving product and business is the ability to scale manufacturing volume such that it can follow market demand growth and remain competitive with other technologies vying for the same application. With that it mind, it was found that large area hot filament CVD deposition reactors were the appropriate technology for thin film CVD diamond cutting tools. Likewise, it was decided that large area, DC torch deposition reactors were the correct tool for growing high wear resistant thick film CVD diamond.

As with any technology or manufacturing methodology, continuous improvement is a necessary survival skill. This includes experiments to improve adhesion, product development to improve control and repeatability as well as the “all important” cost reductions. Over the course of ten years, this philosophy led to the design of four generations of hot filament CVD reactors leading to the transition of an in-house tool to a salable commercial product. Some of those reactor generations are shown in Fig. 2. The concept of continuous improvement also led to refinements in component handling in order to reduce costs. This is very important for high quantity, low ASP (average selling price) products such as dresser bars shown in Fig. 3. Over the course of five years, such manufacturing improvements provided the path for cost improvements that allowed thick film diamond products to move from > $3.00 US to < $1.00 US per cubic mm.

Discussion

In terms of thermal management, what is the significance of the above background information? Very simply stated, it is ALL directly applicable to the application of CVD diamond for high heat flux thermal applications. For thick film thermal segments used as heat spreaders for either optical device submounts, or as highly thermally conductive mount for packaged semiconductor or III-V compound power devices, the key barriers to design commitments are price and availability. The engineers who design products for the technology markets understand learning curves and how they drive cost reductions. For thin film CVD diamond applied to technology thermal challenges, the expertise developed in the areas of process control and repeatability all contribute to the knowledge necessary for depositing CVD diamond on materials like silicon in order to provide a thermal platform for circuit level integration of thermal heat spreading. In order to better understand these statements, it is necessary to understand the thermal challenges of the various technology markets. These are summarized in Fig. 4.

Illumination Markets – The worldwide illumination market is at the beginning of a transition from incandescent to solid-state lighting. This is driven by such factors as bulb life, form factors and cost. This transition is well under way in the automotive market and just starting to happen in the consumer electronics display market place. It is accelerating because of the high growth curve of flat panel displays, where it is forecasted that the 2006 shipments of flat-panel TVs 26 inch and larger will grow 110 percent to 32 million units. As shown in Fig. 5, the US Department of Energy (DOE) has aggressive lumens per watt targets for white-light LED with the High-Brightness LED market forecasted to be a $10.8 billion US market by 2010. Similarly, laser diodes are also vying to be the illumination device of choice for Rear Projection TVs and consumer projectors.

Thermal management is key to both LED and laser devices as they move into these new markets. It has been shown that light output drops by a factor of 4 as the junction temperature increases from 25°C to 115°C in red LEDs, with green devices also significantly affected. Junction temperature also has an effect on the light color of LEDs, with green seeing the greatest shift with increase of junction temperature. Lumileds states that every 10°C rise in junction temperature causes a one nanometer shift in the dominant wavelength. Control of this is critical in TV applications.

Communications Markets – High-density radars for defense and eventually commercial applications are driving heat densities of high power devices. Device level densities of $500W/mm^2$ are being targeted, while at the package level, $1KW/cm^2$ is expected. At both the device and the package level, thermal management is recognized as a key challenge to achieve targeted output and reliability.

Power Semiconductor Markets – The transportation markets shift to electric power (hybrid automobiles and electric trains) is requiring higher efficiencies combined with increased drive power. The power semiconductor market is focused on devices at >500V and 50A. At the same time that frequencies are increasing, power transistor modules are shrinking by as much as 50% in size. All of these lead to exponential increases in power densities. Fig. 6 illustrates the evolution of power devices and shows the size decreases that are occurring simultaneously with further integration. The continuance of both of these trends will be highly dependent on the continued development of cost effective thermal solutions.

Processor Markets – The processor market is divided into two major segments: the general-purpose processor market used for PCs, notebooks and servers; and the graphics processor market for video gaming. Surprisingly, it is the latter that is now driving technological development and in 2005 over $10.5 billion US was spent on gaming hardware and software in the US. Applications are driving the need for faster processors while manufacturing cost driven line width reductions are driving transistor densities into new territory. It is well known that a major general purpose processor manufacturer canceled a $4 billion US development project because of continuing thermal hurdles. It is clear that junction temperature management solutions are needed at the package and device levels.

Solutions

Where does CVD diamond play in all of these thermal management solutions? – RIGHT IN THE MIDDLE! Thick film polycrystalline CVD diamond is an excellent and cost effective solution as a material for first level mounting of solid-state optical devices and packaged semiconductor devices. With an isotropic thermal conductivity of 1000 to 1200W/m-K it provides a mounting surface with 3 times the thermal conductivity of copper and 5 to 6 times the thermal conductivity of more complex materials such as Beryllium Oxide (BeO) and Aluminum Nitride (AlN). An application of a titanium (Ti) layer to the diamond enables other typical metallization, such as platinum or gold to be used. This enables standard attachment materials such as solders or epoxies to be used. Additionally, thick film CVD thermal diamond can be polished and laser cut using the same methods and equipment developed for cutting tool tips and dresser bars, adding to its cost effectiveness.

Both laser and LED device manufacturers are using CVD diamond thermal submounts. Fig. 7 illustrates the integration of diamond heat spreaders in laser packaging. Depending on the specific application and laser type, the diamond may be a sufficient thermal solution. Other critical applications such a telecommunications devices may require the addition of an active thermo-electric cooler (TEC) to maintain a precise device junction temperature. Fig. 8 illustrates the typical assembly for lower cost LED packages. Even in that application, there are opportunities for small segments of diamond to enhance color output stability. As previously mentioned, the market driver behind higher power LED and lasers is the opportunity to replace high power incandescent lamps. Copper has typically been the material of choice because of its thermal properties and low cost. The problem is that a copper is not sufficient for the multiple emitter arrays being used in these consumer applications. Fig. 9 charts the per emitter power obtained using a diamond heat spreader and a copper mount. With a single emitter, there is no discernable difference, but for a 15 emitter array, a 33% increase in per emitter power was obtained.

CVD diamond is also making inroads into high heat flux communications and power semiconductor devices. This is occurring with the use of metallized diamond segments as the mounting surface for the active device as shown in Fig. 10, or as diamond “pins” placed in a base plate made of composite material for packaged high power components. Figs. 11 through 13 demonstrate the thermal benefit of this latter approach, with a device junction temperature reduction of 24°C.

A developing application of CVD diamond as a thermal management tool for both power devices and processors is the work being done with diamond-on-silicon (DOS). Using large area deposition reactors it is possible to produce in a single run single 300mm diameter DOS wafers, which are state of the art for CMOS processors, or multiple 100mm diameter wafers, which are state of the art for GaAs or GaN power devices. Using GaN devices for illustration, as shown in Fig. 14, the purpose of the diamond layer is to provide thermal spreading as part of the active device structure in order to move the heat quickly away from the device hot spots and broadly to the package heat spreader. Fig. 15 is a 3D thermal model comparison of the thermal benefits of a DOS structure versus a device grown on a sapphire structure, which is currently considered an advanced device substrate. This model shows an 85°C reduction in junction temperature AND a 19% increase in output power. The design engineer can choose how the variables are to be traded – maintain junction temperature and greatly increase power out; drop junction temperature and increase device life and reliability; or some combination of both. CVD diamond provides the opportunity to make such choices.

Summary

The high heat flux device thermal management opportunity is continuing to grow as government and business focused devices are performance limited because of thermal issues or are pushing performance in order to replace more traditional solutions. CVD diamond, either thin film or thick film has a place in the choice of solutions to many of these thermal issues. So, when can we expect to see the rush in orders and volume ramps? As we all know just having technology does not make a business. One of the remaining obstacles to full implementation is addressing the perception of diamond being "too expensive". As discussed earlier, the last major industry look at diamond as a thermal management tool was in the mid 1990's or even the late 1980's. There has been significant progress in coming down the manufacturing and cost learning curves. That needs to be communicated to a new generation of thermal engineers. Additionally, many of the researchers and graduates students have been exposed to diamond production using relatively expensive and difficult to scale CVD equipment. As shown in Fig. 16, hot filament and arc jet deposition technologies are the most cost effective means to produce cost effective thermal diamond. Yet, few reactors of either technology reside in university labs. This means not only does the CVD diamond need to pursue new applications and design-ins. We also need to increase the market message concerning incorrect price perceptions AND provide tools to the university communities so that future scientists learn on and therefore understand the benefits of cost effective, scalable CVD deposition technologies.