Industry Developments:

Diamond-Based Thermal Management Systems

The heat transfer conduction in diamond is very high (2000 W/m-K). That is attributable to the fact that Diamond is composed of carbon atoms with stiff chemical bonds between them. Heat transfer in diamond is carried by vibrations, known as phonons. In a crystal, atoms are arranged in an orderly fashion. The bond between these atoms is like a spring. When one set of atoms get excited, it creates a wave by exciting the other atoms. This phenomenon is called phonon. By comparison, heat transfer in metals is transmitted by free electrons. In copper, heat flows five times slower than in diamond. Early thermal management applications of natural diamond included microwave and laser diode devices. But, the availability and cost of natural diamond restricted its wider development. Industrial-made synthetic diamonds, however, opened new opportunities. [1]

Figure 1. Free Standing CVD Diamond Wafer [1]

The first industrial-made diamonds were created in the mid-twentieth century and their applications were limited. By the 1980s, CVD chemical vapor deposition provided a practical method for making polycrystalline diamond available for electronics thermal management. Today, microwave-assisted CVD polycrystalline diamond manufacturing provides the ability to spread diamond over large areas and on various substrates, with fine control over chemical impurities. [2]

Polycrystalline diamond is produced on wafers up to 140 mm in diameter, allowing its use in applications several centimeters across. While CVD diamond provides higher thermal conductivity than metals, it also offers insulating properties. Diamond also has a relatively low density (3.52 g/cm^3) and high stiffness characteristics.

Use with Semiconductors

A synthetic diamond's exceptionally high thermal conductivity makes it useful for the thermal management of packaged chips. Careful design is needed to integrate it into the package, particularly at the bonding interfaces. In particular, attention must be paid to the differences in thermal expansion, design of bonding interfaces and the metallization and joining processes. When properly used, CVD diamond can significantly lower junction temperatures by spreading the heat on a large surface where the diamond is deposited,

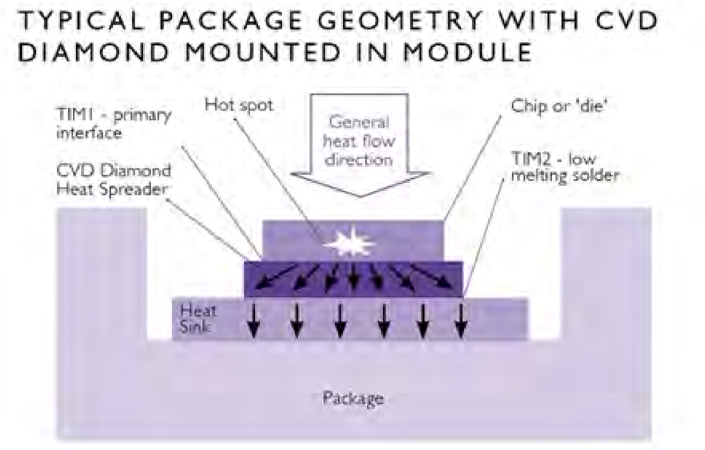

Figure 2. Typical Package Assembly with CVD Diamond Heat Spreader [4]

thereby enabling longer chip life and enhanced performance. [3]

CVD diamond's extreme stiffness and low coefficient of thermal expansion (~1 ppm/K) present a challenge for engineers, because they vary from those of commonly used semiconductors such as Si (2.6 ppm/K) and GaAs (5.7 ppm/K). Stresses from thermal cycling can have a negative impact on device lifetime and reliability. Methods for managing these stresses include pre-cracking the compound semiconductor, or using a diamond sandwich where the upper layer acts to balance stresses. When integrating diamond into a device package, the ideal geometry depends on factors ranging from the power density to the location of cooling channels – factors that can be modeled. [1]

CVD diamonds can generally be incorporated into a thermal solution in three different ways: first, free-standing, individual diamond units can be bonded through metallization and soldering, for example using Ti/Pt/Au sputter-deposited metal and AuSn eutectic solder; second, prefabricated wafers may hold multiple devices, allowing wafer scale processing at device manufacturers (like metallization and mounting); and, finally via direct diamond coating. [1]

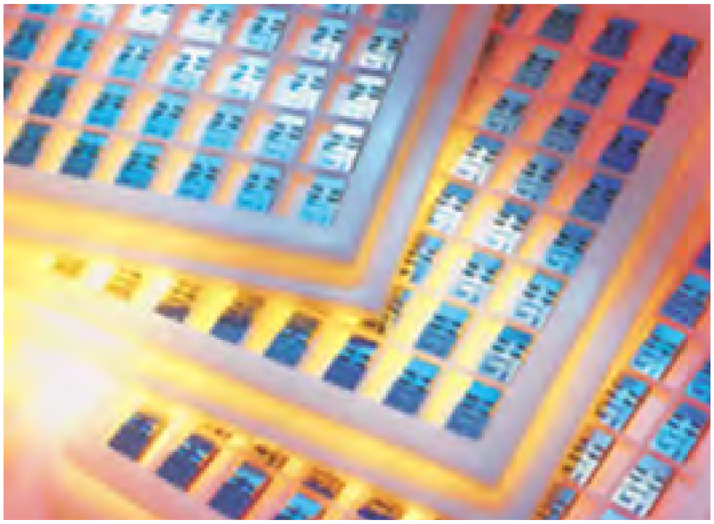

Figure 3. Metallized CVD Diamond Heat-spreaders [1]

In the microwave industry, aluminum diamond metal matrix composites (MMCs) are proving to be the most effective way to remove heat from discrete RF power transistors and MMICs. The MMCs are used as heat spreaders between active devices and their mounting surfaces. Thermal models and IR scans of MMC applications show a significant reduction in transistor junction temperature of about 25% when compared to a copper/tungsten heat spreader. [5]

Figure 4. Aluminum Diamond Metal Matrix Composites (MMCs) [5]

Lower Temperature CVD Process Expands Use of Diamond

While the thermal properties of diamond thin films suggest their use as heat sinks to use with semiconducting materials, high temperatures are an issue. The deposition temperatures for the diamond films typically exceed 800°C (1500°F), which limits the feasibility of this approach.

Recently, however, a lower temperature CVD method has enabled diamond film to be applied on graphene and gallium nitride semiconductor materials. Developed at the Argonne's Center for Nanoscale Materials, the technique alters the deposition process of the diamond films. Researchers were able to reduce the temperature to close to 400°C and tune the thermal properties of the diamond films by controlling their grain size. This permitted the eventual combination of the diamond with graphene and GaN.

In a related study, the Center used the same technology to combine diamond thin films with GaN, which is used in high-power light emitting devices (LED). After depositing a 300 nm-thick diamond film on a gallium nitride substrate, the researchers noticed a considerable improvement in the thermal performance. This in turn could prove beneficial to maintaining the performance of LEDs. [6]

CTE Matched Heat Spreader Technology

sp3 Diamond Technologies, Inc. a leading supplier of diamond products, deposition equipment and services, was recently awarded US patents for its DiaMatch™ coefficient of thermal expansion (CTE) matched heat spreader technology. The diamond-based multilayered structure described in the patents solves several technical challenges to deliver the high heat spreading and CTE matching required for reliable semiconductor and laser packaging. DiaMatch™ technology offers variable CTE-matching, copper-level thermal conductivity, a choice of conductive or insulating die attach surfaces, precise edges and no compositional variability from point-to-point in the material. [7]

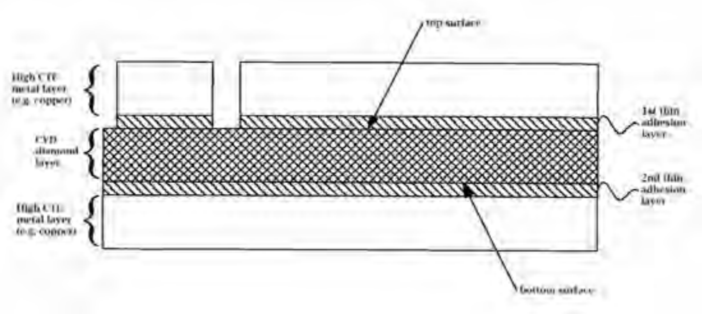

Figure 5. Cross-Section of a Multilayered DiaMatch Structure, from sp3 Diamond Technologies [7]

Future Diamond-based Cooling – and a Promising Alternative

Adopting CVD diamond as a heat spreader for the semiconductor industry is still in its early stages. Demand for superior thermal management solutions for opto-electronics, power and RF devices will drive a broader adoption of this engineering material. When combined with the growth rates of these markets, the increased use of diamond should drive significant investments in synthetic diamond manufacturing capacity. These should in turn promote economies of scale which will enable diamond to operate in segments of the semiconductor market it previously could not compete in. [1]

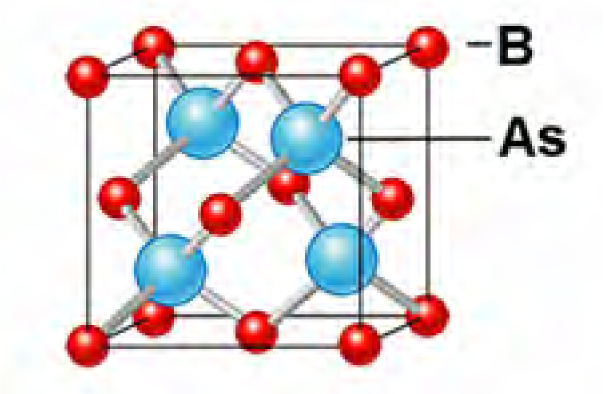

Figure 6. Structure of Cubic Boron Arsenide, BAs [8]

Are diamonds the ultimate solution for thermal management? There is a constant demand for materials with extremely high thermal conductivity to improve cooling performance, and thus research continues. As recently reported in Physical Review Letters, researchers using newer calculation methods have found that cubic boron arsenide, BAs has a thermal conductivity above 2000 W/m-K, as high as diamond. [8]

At higher temperatures, the thermal conductivity BAs theoretically exceeds diamond. And, due to the relatively lower cost of its constituent elements – boron and arsenic – BAs has the potential to be much cheaper than diamond if an effective growth method is developed. [9]

References:

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