Enhancing SOI with Thin Film Diamond

Gerry Chandler, Jerry Zimmer
sp3 Diamond Technologies
Santa Clara, CA
www.sp3inc.com

***Abstract* - In the continuing thrust to extend Moore's law, silicon is beginning to confront several issues that require innovative materials solutions to increase transistor and interconnect speeds while dealing with the increasing thermal loads of advanced microprocessors. The unsurpassed thermal, electrical and mechanical properties of diamond can be used to solve some of the thermal issues and enhance the performance characteristics of silicon based circuits. This paper focuses on the integration of diamond with SOI technology for the manufacture of silicon on diamond (SOD) wafers. The primary use for this technology is for thermal control but other niche markets may exist where the mechanical characteristics of diamond can also benefit MEMS devices made on SOI type substrates.**

I. Introduction

Moore's Law in semiconductor manufacturing states that, for a given cost, the capabilities of technology double every eighteen months. Unfortunately, there are a number of issues which conspire to limit this progression with current technologies. Transmission speed on interconnect lines, mobility in silicon device channels, and dissipation of speed related heat generation are all beginning to challenge the current materials used in semiconductors. For some technologies such as SOI, the performance improvements gained with the SOI technology are offset eventually by the thermal problems caused by the SOI structure itself. The reality of today's semiconductor industry is that LED's, laser diodes, DC power devices, RF communication devices, graphics processors, and microprocessors are all wrestling with temperature management. Fortunately, diamond can help solve some of these problems by eliminating many of the thermal issues that currently limit SOI's performance.

II. Discussion

Diamond occupies a unique niche where it has both high strength and stiffness coupled with relatively low density and dielectric constant. When this is coupled to the high thermal conductivity and high breakdown voltage of undoped diamond there are several application possibilities for diamond as the insulator in the SOI structure.

The most interesting property of diamond is its high thermal conductivity. Fig. 1 compares the thermal conductivity of various materials used in the semiconductor industry with diamond and illustrates the dramatic difference between diamond and the silicon and silicon dioxide which are present in the thermal path of most semiconductor devices. Thermal conductivity is the most promising diamond property to enhance the current performance of silicon and other semiconductor devices.

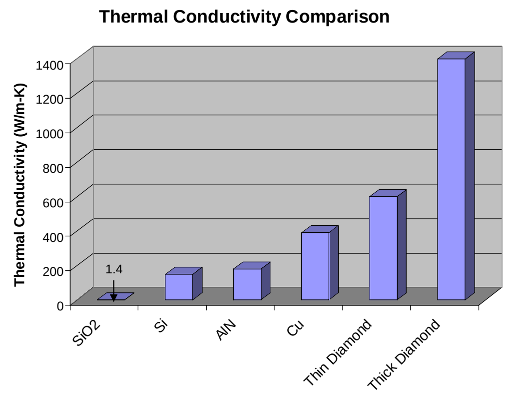

Fig. 1 - Thermal Conductivity of Various Materials

The obviously poor thermal conductivity of the oxide layer in a standard SOI structure leads to severe thermal issues as power densities increase. The solution to this problem is to replace the oxide layer with diamond. This generates the structure shown in Fig. 2 where a single crystal layer of silicon is placed on top of a layer of diamond on a silicon handle wafer. The resulting silicon on diamond (SOD) structure is analogous to an SOI wafer but now the "I" layer is made of diamond. The result is a structure where the thermal conductivity of the diamond layer immediately spreads heat away from the junction and into the underlying silicon with 1000X the efficiency of a traditional SOI structure. This reduces junction temperatures or correspondingly allows operation at much higher speeds or power levels for the same junction temperature.

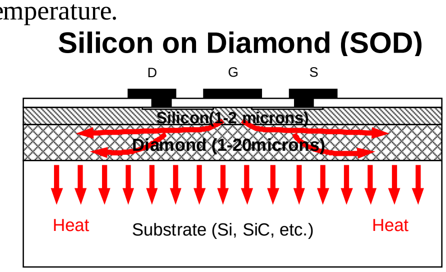

Fig. 2 – Silicon on Diamond (SOD) Cross Section

SOD substrates can be used directly for silicon devices or can be used as starting substrates for compound semiconductor layers such as GaN.

Fig. 3 illustrates another property of CVD diamond where the intrinsic stress in the diamond film can be tailored to a specific value determined by both the deposition parameters and the thickness of the film. Deposition temperature and process chemistry can be modulated to influence intrinsic stress in diamond and thus modulate stress in the silicon and the wafer shape. This capability is critical to successful use of diamond in SOI structures so that flatness of the finished substrate is maintained within acceptable limits.

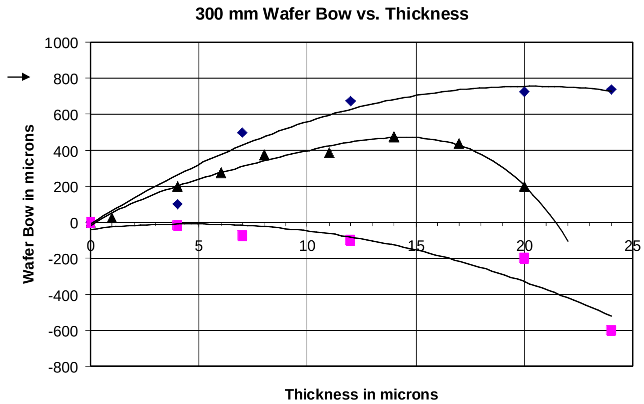

Fig. 3 – Effects of Process Parameters and Thickness on Film Stress [1]

III. Modeling and Performance Results

Given the possibility of SOD substrates, the logical question is how much improvement can actually be realized. Substantial modeling of the performance of silicon SOD devices has been done at various universities and professor Sitar's group at NCSU has actually produced test structures to measure the performance improvements. Fig. 4 shows the results of that work where SOI, silicon, and SOD structures are compared for performance at a constant junction temperature. The net effect is a 5X power density improvement over existing silicon devices and a 10X improvement over SOI technology. Fig. 5 shows similar results under constant power conditions where 100 degree drops in junction temperature are possible for both thin and thick SOI structures and thin and thick diamond layers.

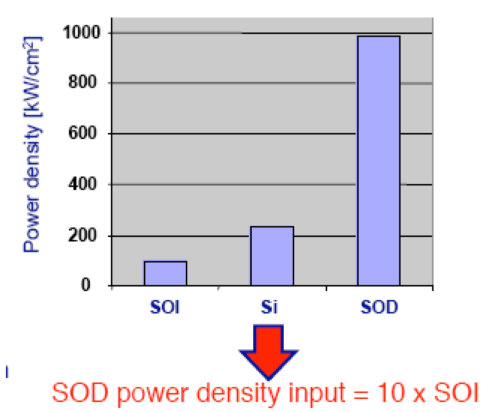

Fig. 4 – SOD Performance at Constant Junction Temperature [2]

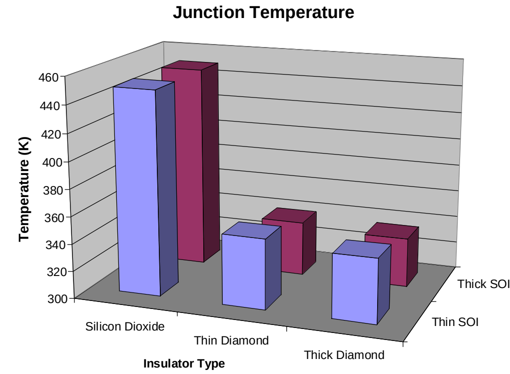

Fig. 5 – SOD Performance at Constant Power

The implementation of SOD substrates into production still faces significant challenges however. Building an SOD substrate requires stress controlled diamond growth expertise (Fig. 3) as well as silicon wafer bonding and polishing expertise. Wafer diameters must be at the 200 mm level or larger and cost per wafer will ultimately have to be at the $300 level for 300 mm wafers. This will require scaled reactors with deposition rates of 1-3 cm3/hr, 5% thickness uniformity, and 5 degree temperature uniformity across the substrate.

In addition to scaling issues there will be challenges in making both the device layer as well as the diamond layer with sufficiently high quality levels to obtain high yielding results from the device fabrication process. There will also be concerns about the interface between the diamond and silicon device layers but all of these issues have known engineering solutions.

IV. Conclusions

The unique properties of diamond can be utilized to continue scaling and performance enhancements of silicon devices. Existing SOI substrates can be enhanced by replacing the oxide insulator with diamond for thermal performance enhancement in the form of SOD substrates. This is feasible by utilizing diamond microstructure control and highly uniform deposition systems along with wafer bonding and other traditional silicon processing techniques. Experimental data has validated the performance improvements of SOD substrates and modeling results show that substantial performance advantages are achievable with all standard variations of SOD(SOI) substrate configurations.

References

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