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Innovation and Integration Go Hand-in-Hand for Miniaturizing Switch-Mode Power Conversion Technology

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Over the years, switch-mode power conversion technology has achieved significant gains in terms of frequency, design simplicity, and mechanical and thermal efficiency. And yet, in comparison to the ever-shrinking, feature-rich integrated circuit arena, power conversion solutions appear frozen in time. Smaller, faster, cheaper solutions simply have not materialized in power conversion circuits. Fortunately, innovative power conversion technology and integrated circuit manufacturing methods have cleared the path to meeting end-user expectations.

This opinion piece will explore a variety of materials and devices that can be used to achieve the higher frequency levels that advanced power management applications demand. It will also identify existing fabrication and packaging strategies that offer a suitable manufacturing base while yielding a reduced IC count to accommodate smaller, portable power applications, such as laptops and mobile devices. By integrating new material systems into mainstream semiconductor manufacturing infrastructure, designers can achieve a power conversion solution that meets high performance levels, reduced real-estate requirements, and appropriate cost structures.

Materials to Support Higher Frequencies

A necessary component of any complex, feature-rich product is power, which often complicates the design process because of its size, complexity and cost. In some cases, the power section can take up to 75% of board space. Typically, if a power supply is running at frequencies of 500 kHz to 1 MHz, it needs a fairly large inductor whose bulk is dictated by the inductance required to satisfy the voltage and current specifications of a given application. But if you increase the frequency such that the power stage (controller, gate drive, MOSFETs) can withstand high frequency and still be efficient, then the inductor size can drop.

There are a number of existing and promising new materials and devices that can achieve the high frequency levels that advanced power management applications demand. Semiconductor power switches, for example, have migrated from bipolar to the widely used vertical diffusion metal oxide semiconductor (VDMOS), which allows normal operating frequencies to rise from ultra-sonic (30 kHz) up to today's multi-megahertz frequencies. The steady improvement in the cell density of VDMOS switches, with finer pitch trenches and finer lithography, has enabled the subsequent reduction in their on-state series resistance to unprecedented levels (as low as sub-milliohm). These performance improvements have allowed clear advances in power management technology supporting the very low-voltage, high-current revolution imposed by Moore's law.

Additionally, there have been numerous developments in the semiconductor arena to improve the performance of power semiconductor devices beyond VDMOS. A notable approach is silicon carbide- (SiC) based semiconductors, which have improved considerably over the years in terms of wafer availability, size, cost and yields. Converters based on wide band gap SiC switches exhibit reduced switching losses and superior electrical and thermal properties relative to silicon devices, including operation at much higher junction temperatures than silicon (300°C vs. 150°C). Careful tradeoffs in device design, utilizing existing manufacturers' crystalline structure offerings (e.g. 6-H, 4-H & 3-C), could allow the manufacture of high-speed, low-loss power switches to exceed today's figures of merit.

In addition to SiC is the emergence of gallium nitride (GaN) – a newer, and even more promising material, especially for power management circuits that demand speed, efficiency and high-power handling in a single platform. GaN is a compound, wide band gap semiconductor offering higher breakdown voltages than silicon, very high operating frequencies, as well as thermal and chemical stability. GaN is amenable to growth on large silicon wafers, providing a possible path to integration with existing silicon circuits and IP.

Another material suitable for advanced power management is silicon germanium (SiGe), which is commonly used in radio frequency applications. Solutions based on SiGe devices may need further development to match the needs of a power switch with the properties of SiGe transistors, particularly in terms of reduced static loss and reduced switching loss, coupled with appropriate high-voltage and high-current density capabilities. However, because SiGe-based power conversion is already compatible with standard fabrication processes and well-understood cost structures, a SiGe-based power management solution should be able to meet market cost targets more easily than either SiC- or GaN-based solutions in the near term.

Hand-in-hand with these semiconductor developments, we have also seen a migration from various bulk metal alloys used to manufacture magnetic cores to advanced ferrites that permit much higher frequencies of operation well into the MHz range, without significant loss penalties. As power conversion demands push the operating frequencies higher, ferrite manufacturers continue to improve the compositional make of the ferrites to optimize and adjust their loss properties for the specific flux, frequency and temperature conditions needed for multi-megahertz DC-DC converters.

In the MHz range and above, when the volumetric size of the magnetic material is small enough, thin metal alloy film systems may also be utilized. Alloys generally have very high saturation flux densities compared to ferrites. In addition, anisotropic alloys with preferential magnetization axes allow for the design of magnetically oriented cores in which rotational magnetization losses can be controlled more readily. Moreover, these types of films are compatible with silicon processing technology, which may ease integration and reduce costs. Finally, capacitor densities have also increased to provide higher capacitance in a smaller size, which translates into lower series resistance and higher self-resonant frequencies, both crucial to attain higher operating frequencies.

Manufacturing Schemes to Improve Size and Efficiency Metrics

Despite the focus thus far on suitable materials for achieving higher frequencies, it is important to note that obtaining higher frequencies is only valuable if size and efficiency metrics are also improved. There are numerous examples of technologies where the power circuits have been successfully switched at very high frequencies (even as high as 25-50 MHz), but where the desired reduction in size was not attained, and efficiency degradations became unacceptable to the end user. In addition, necessary refinements to adapt material systems to a specific power conversion application will undoubtedly incur additional costs when compared to established VDMOS or CMOS technologies. A key metric for success of any of these new technologies will be innovative manufacturing schemes, which permit integration of new material systems with existing manufacturing infrastructure so as to improve size and efficiency metrics and maintain favorable cost structures.

Fortunately, there are existing fabrication and packaging strategies that offer a suitable manufacturing base for power applications. Semiconductor process technology integration, for example, is a viable piece of the overall integration picture. It requires the careful choice of target semiconductor technologies that, when integrated, will yield a reduced IC count in the final solution while delivering similar, or better, power conversion efficiency, and maintain cost points. Other strategies include multi-chip module packaging approaches, passive component integration, and hybrid components.

Multi-chip module packaging approaches have been used for many years in various performance-driven, speed-critical applications or where parasitics affect electrical performance. In the meantime, the cost to place, assemble and test products containing known-good die (KGD) have steadily decreased, thereby allowing many more price sensitive applications to take advantage of these techniques. With a well-defined KGD strategy, bare silicon die can now be handled and placed in new multi-chip packages that provide much improved footprint savings.

Although usually a bottleneck with slower development cycles, passive technologies, such as filter inductors, transformers and bulk capacitors, have achieved many materials improvements. The advancements are the result of broader semiconductor drivers, such as high-k dielectrics, and trench technologies for integrated capacitors. Additionally, there have been many advances in radio-frequency inductors fabricated on semiconductor and MEMs fabrication processes that enable both new magnetic materials and smaller fabrication scales not currently applied in the power arena.

While none of these approaches are new or revolutionary, the specific combination of certain pieces and their application in power conversion create a very strong step forward to achieving density metric improvement coupled with an acceptable cost structure. There are solutions on the market today that have successfully capitalized on existing semiconductor geometry advances to enable a 10x switching-frequency improvement over existing solutions and reduce the size of the inductor so that it too can be integrated on the same chip as the control, gate drive, and MOSFET. These advances enable the design of a complete DC-DC converter in a very small form factor. In addition to reducing development time, a single power system-on-a-chip frees-up valuable board space for designers to use for other integral functions, and saves up to 70 percent on bill-of-materials costs. The miniature size, fast transient response, and voltage scaling ability of such a DC-DC converter makes it suitable for small, portable electronic devices.

It is becoming clear in the power conversion arena, as it did previously in the semiconductor arena, that higher operating frequencies and integration go hand-in-hand and that the two are inter dependant. By carefully selecting and refining the most appropriate material systems and integrating them into mainstream semiconductor manufacturing infrastructure, developers will be able to achieve a power conversion solution that meets the high performance levels, reduced real-estate requirements, and appropriate cost structures that end-users demand.

