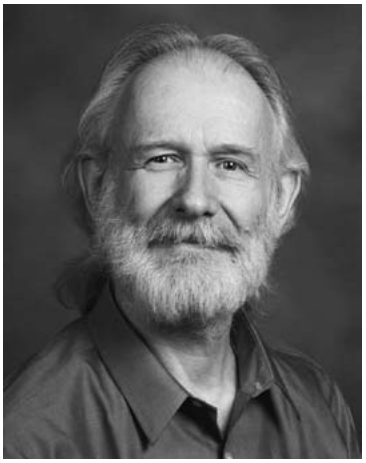
专辑寄语

Power Semiconductors Enabling Energy Management

可用于实现能源管理的功率半导体



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Over the past 50 years, power electronics has played an increasing part in energy management for humanity. It is estimated that more than 30 % of energy consumed by humanity today is processed by electronic power converters. With the current trends of full industry automation, and increased electrification and automation of transportation and agriculture, as well as anticipated dominance of distributed generation from sustainable energy sources, it is predicted that in several decades 80 % of the global energy consumption will be in the form of electricity processed by power electronics.

Power semiconductors have been the main technology drivers of power electronics ever since the discovery of silicon controlled rectifier (SCR) in 1957, which is recognized now as an IEEE Milestone and celebrated every June 20th as the Power Electronics Day. SCRs, and derivative p-n-p-n silicon devices, are still used in the highest-power applications for energy management in electrical grids, like high-voltage direct current (HVDC) and flexible AC transmission system (FACTS), although they are being supplanted by high-voltage and high-current insulated gate bipolar transistor (IGBT) modules. Over the last 35 years, silicon IGBTs and p-i-n diodes have been the "workhorse" devices for the medium-voltage (600 V to 10 kV), medium-power (kilowatts to megawatts) applications, like motor drives and grid-connected converters for industry automation, commercial buildings, data processing centers, and transportation. At the low-voltage end (<300 V), silicon power metal-oxide-semiconductor field-effect transistors (MOSFETs) and Schottky diodes have dominated the power supply applications, with wide variety of circuit configurations and packaging structures. It is important to emphasize that silicon devices, as well as the diverse application-optimized packaging technologies, are being continuously perfected through numerous engineering innovations, both in academia and industry. This is enabling ongoing enhancements of

■ 中文翻译（富士电机内部翻译）

最近 50 年来，对人类而言，电力电子技术在能源管理中发挥着重要作用。现在，估计人类能源消费的 30% 以上都经过了电力转换装置的处理。在工业领域正在推进全面自动化的背景下，运输和农业领域等也在向电气化和自动化推进。此外，预计今后利用可持续能源的分散发电将占据优势。数十年后，预计全球能源消费将会有 80% 经过电力电子设备处理。

自 1957 年可控硅整流器（SCR）问世以来，功率半导体一直是电力电子技术的主要引领者。而且，它被认定为 IEEE 里程碑，每年的 6 月 20 日被定为电力电子日。

SCR 以及由此衍生的 p–n–p–n 硅器件，尽管在 HVDC 和 FACTS 等配电网的高输出用能源管理中仍在使用，但正在逐渐被可支持高电压与大电流的 IGBT 模块所取代。在过去 35 年中，在工业自动化、商业大厦、数据处理中心、运输领域的电机驱动装置和电网连接变换器等中电压（600 V ～ 10 kV）和中容量（kW ～ MW）的用途中，Si–IGBT 和 pin 二极管承担着主力功率器件的作用。在低电压（< 300 V）条件下，通过各种电路结构和封装结构，功率 Si–MOSFET 和 SBD 在电源用途中扮演了主要角色。其中，需要特别指出的是，通过产学联合的众多技术革新，硅器件技术及按照各种用途进行了优化的封装技术不断地涌现。如上所述，通过高效率化、高开关频率化和高电力密度化，能源管理系统持续不断地强化功能，同时也改善了器件的生产率、可靠性和生命周期成本。

20 年来被人们寄予厚望的碳化硅（SiC）纵向器件和氮化镓（GaN）横向器件终于在电压和电流额定值范围逐渐扩大的同时，有望在商业上得到广泛使用。两者均可大幅降低损耗，提高开关频率和运行温度。但是，即使要将这些改善效果提高至系统级别，目前封装和无源器件（电容器、电感器、变压器、导体、绝缘体）等也存在技术局限性。为打破现有技术局限性，有必要大幅增加研究开发投资。此外，为实现在非常高的 d*v*/d*t*、d*i*/d*t* 及高温环境中具有高可靠性的可靠动作，对附带的栅极驱动、传感器、控制、保护、辅助电源等有源电子电路的安装，有必要重新进行全面研讨。因此，仅仅将功率转换器的硅器件更换为宽禁带器件，并无

energy management systems by increasing efficiency, switching frequency and power density, while improving manufacturability, reliability and life cycle costs.

After two decades of anticipation, both vertical silicon carbide (SiC) and lateral gallium nitride (GaN) devices are becoming widely commercially available in the continuously increasing spectrum of voltage and current ratings. They are offering major reductions in losses and increases in switching frequencies and operating temperatures. However, the impact of these improvements at the system level is severely limited by the existing technologies for packaging and passive components (capacitors, inductors, transformers, conductors and insulators); requiring significantly increased investments in research and development. Additionally, the implementations of ancillary active electronic circuits, such as gate drives, sensors, controls, protection, and auxiliary power supplies, need radical re-thinking in order to assure dependable operation in the very high dv/dt, di/dt, and temperature environments. Hence, direct replacement of silicon with wide-bandgap devices in (otherwise unmodified) power converters would rarely result in appreciable benefits. For the highest impact, innovative circuits and energy management architectures, which are custom tailored to fully utilize the new wide-bandgap device potentials, will need to be developed. On the other hand, these new semiconductor materials are opening the opportunities of using high-frequency-switching power conversion in applications where it was not possible ever before.

In the low-voltage range, lateral GaN devices are already enabling operation at unprecedented switching frequencies, in the megahertz range. This trend will allow substantial improvements in power density and efficiency, as long as the corresponding improvements in passive components and packaging are materialized. Increased monolithic integration of ancillary active electronic circuits with power devices into Power

显著效果。为获得最大效果，有必要通过开发创新电路和能源管理架构，使宽禁带器件所具有的新潜能得到全面利用。另一方面，这些新的半导体材料正在通过高频开关电力转换，在以往未曾触及的领域开辟新的道路。

在低电压领域，GaN 的横向器件已经可以在前所未有的兆赫带的开关频率下动作。如果相关的无源器件和封装技术得到改善，则可大幅改善电力密度和效率。如果 Si 和 GaN 均将功率器件和附带的有源电子电路进行单片化集成到功率 IC 中，则可持续地给大规模市场带来巨大贡献。在 300 V 到 1 kV 的离线用途中，预计近期将从 Si-pin 二极管全面替换为 SiC-SBD。另一方面，从转换器的成本、效率、尺寸及性能的观点出发，高电压的 GaN-HEMT 和 SiC-MOSFET 应该难以取代 Si 超结 MOSFET 及 IGBT。在通过将开关频率提高 1 位而获得益处的用途方面，宽禁带器件占有优势，这需要模块和转换器封装的改进及磁性技术的开发。

在 1～6 kV 用途方面，预计在 3～5 年内，SiC 将超过 Si。在此，封装技术在耐高开关频率、高电压、高温、长使用寿命方面的改进也给 SiC 带来了竞争优势，通过电力机械、无源器件和转换器的新设计而大幅改进的能源管理系统有望引起巨大变革。在中压及超过 6 kV 的高压用途方面，SiC 将成为主流。超过 20 kHz 开关频率的动作，使全新方案在兆瓦级电力的电能管理中的应用成为可能。如果在封装和无源器件中导入创新技术，出现新的能源处理架构，则创新型电力系统和用途的发展会成为可能。一旦开始构建新的“电子电网”，则该创新型电力系统会变得规模巨大。

本专辑中的论文，对上述趋势技术的优秀实例进行了介绍。

ICs – both Si and GaN – will continue to provide huge benefits in high volume markets. In 300 V to 1 kV (off-line) applications, SiC Schottky diodes will completely replace Si p-i-n diodes very soon. However, high-voltage GaN high electron mobility transistors (HEMTs) and SiC MOSFETs will have very hard time competing with Si super-junction MOSFETs and IGBTs based on converter cost, efficiency, size and performance! Only in applications that would benefit by an order of magnitude higher switching frequencies, the wide-bandgap devices could be a winner, provided better module and converter packaging, as well as magnetics technologies will be developed.

It could be expected that SiC could be overtaking Si within 3-5 years for 1-6 kV applications. Again, improved packaging for higher switching frequencies, higher voltages, higher temperatures, and longer lifetime will provide competitive advantage for SiC. Much improved energy management systems based on new designs for electrical machines, passives, and converters will be a "game changer." For medium and high voltage (>6 kV) applications, SiC could be the future! Ability to operate at switching frequencies exceeding 20 kHz will define completely new approaches to electrical energy management in the megawatt power range. Very innovative packaging and passive component technologies, as well as new energy processing architectures will enable development of completely new power systems and applications. This will become huge when a new "electronic grid" will start to be built.

Papers in this issue provide some excellent examples of the described trends.

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