New Materials Developments for Military High Power Electronics and Capacitors

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INTRODUCTION

The military is moving toward more electrical platforms. To effectively sustain US military superiority the Department of Defense continues to utilize the latest advances in state-of-the-art equipment. Invariably, these advanced systems continue to require an increase in energy and power density while maintaining safety, reliability, size and weight. Military platforms such as warships, tanks, and airplanes, continue to require higher power to enable electrical powered weapons and detection systems for both defensive and offensive missions. The need for more powerful detection systems, communication systems, and more demanding auxiliaries also contributes to the demand for reliable, efficient, and clean power and energy.

The Defense Advanced Research Projects Agency (DARPA) is currently funding the Wide Band Gap High Power Electronics Program and the Integrated High Energy Density Capacitor Program. The success of these programs depends upon the ability to integrate new materials into high power electrical system components. Power electronics* and capacitors are two of the major components that make up all solid state power distribution systems. The objectives of DARPA's programs in these areas are to increase power and energy density through materials, processing, and packaging innovations. For high-powered, hydrocarbon-fueled platforms, these programs drive the development of materials that have higher efficiencies and performance capabilities for power electronics and passive devices. This article provides an overview of some of the efforts to enhance military high power electronics and capacitors through new and improved materials.

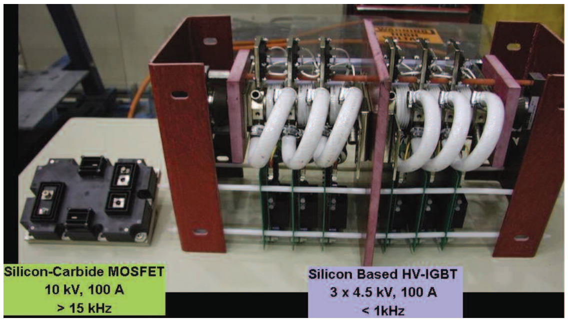

Figure 1. Comparison of size of silicon and silicon carbide converters courtesy of GE-GRC.

SEMICONDUCTOR MATERIALS FOR MILITARY HIGH POWER ELECTRONICS SYSTEMS

Solid state power electronics provides enhanced design flexibility and greater control of electrical power than analog systems. Increasingly, solid state silicon-based semiconductors are no longer able to meet the increased power demands of military platforms. Specifically, the need for higher voltages drives the complexity of silicon-based systems. A new class of semiconductor devices, based on silicon carbide (SiC), is now emerging into the market to meet the demands of the future military's high power converters, direct current (DC) distribution systems, electromagnetic guns, high energy lasers and propulsion systems.

Intrinsic Properties of SiC

Semiconductor materials are based on covalent bonds whereby the electrons in the outer shell are shared between host atoms. Elements in the upper rows on the Periodic Table have smaller atomic radii and stronger interatomic bond strength compared to those elements located in rows below these elements. The stronger covalent silicon-carbon bond in SiC results in a higher energy bandgap in the SiC semiconductor material, hence the name wide bandgap material. This bandgap is a fundamental characteristic of semiconductor materials because it is the energy needed to excite an electron from the conduction band into the conductive band. The three times higher band gap of SiC (3.28 electron-volts (eV) for 4H-SiC) compared to silicon (1.12 eV) results in a breakdown electric field in SiC that is ten times higher than that of silicon. This dramatically higher breakdown field in SiC, in turn, makes it possible to reduce the thickness of the drift region of a SiC power device by a factor of ten, resulting in a significantly reduced transit time for the carriers across the drift region of the device. This ultimately results in much faster switching and lower on-resistance for SiC power devices.

This higher breakdown field, coupled with the higher current densities that can be achieved in SiC power devices due to the higher thermal conductivity of SiC, means that it is feasible to replace silicon bipolar devices (e.g., Si insulated gate bipolar transistors (IGBTs) and PiN diodes) with SiC unipolar devices (e.g., SiC depletion mode metal-oxide semiconductor field-effect transistors (DMOSFETs) and Schottky diodes) in high voltage power electronics systems resulting in lower weight and volume as shown in Figure 1. SiC power devices have the added advantage of being capable of high temperature operation up to 225°C compared with the 125°C operating limit of silicon power devices. This not only significantly reduces the cooling requirements for SiC power devices, but also enhances their survivability in the event loss of cooling.

Material Development Status

Significant advances in the quality of SiC substrates and epitaxial layers have been made over the last decade. The catastrophic micro-pipe defects shown in Figure 2 have been reduced to an average of <0.7/cm^2 for 100 mm 4HN-SiC wafers as shown in Figure 3. There remains a need to reduce 1c screw dislocations to less than 100/cm^2. At high voltage levels (10 kV) 1c screw dislocations cause unacceptable leakage current as shown in Figure 4.

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14. ABSTRACT
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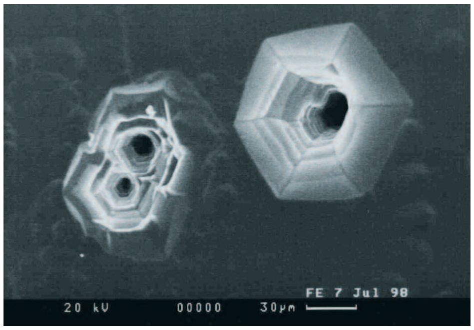
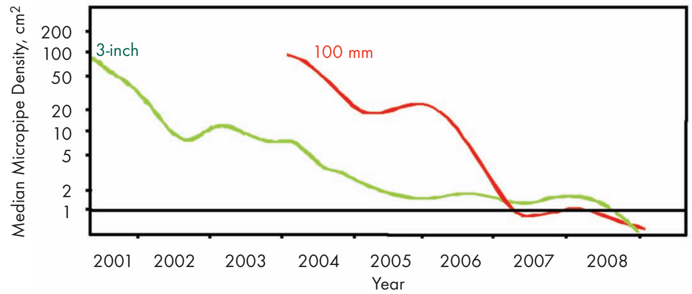


Figure 2. **Micro pipe defects. (Courtesy of CREE)**



100 mm work supported by ARL MTO (W911NF-04-2-0021) and DARPA (N00014-02-C-0306)

Figure 3. **Micro pipe defects in 100 mm SiC wafers.**

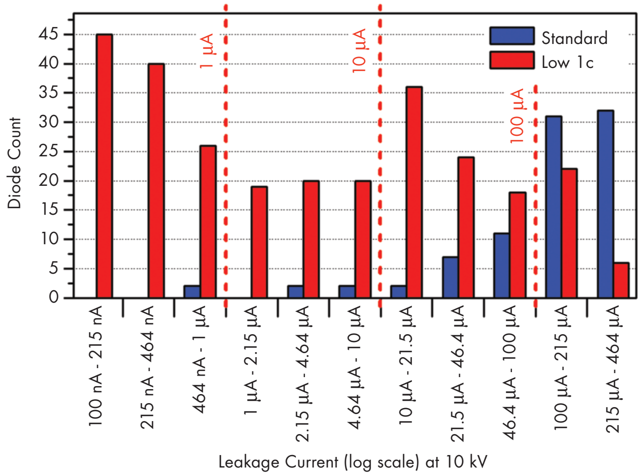


Figure 4. **Reduction of leakage current when low 1c dislocation (<200/cm^2) processes are used. (Courtesy of CREE)**

Basal Plane Defects are also present in SiC substrates but are handled through processing techniques to bend them to the outer edges of the boule†.

DIELECTRICS FOR CAPACITORS

To meet the high power demands for the future, improved passive electrical components are needed to keep pace with technical improvements in the state-of-the-art active power electronics. Today's capacitors take up to 50% of the volume of high power electrical systems and are a driving factor in thermal management overhead. Capacitor research today is attempting to provide energy dense capacitors beyond the capability of 1-2 J/cm^3 packaged to energy densities of up to 20 J/cm^3 packaged with high temperature capabilities (200°C), low losses (0.1% dielectric loss), and the ability for manufacturing scalability. A capacitor's performance is dependent upon the dielectric materials incorporated. To reach the 20 J/cm^3 packaged goal new dielectric materials will need to be developed in either polymer or ceramic materials with new processes and innovative configurations for higher packing density. Progress is being made towards a class of high power, high temperature capacitors that will enable future electronic weapons and pulsed power systems as well as more conventional high power distribution systems into smaller weight and volume.

Intrinsic Material Properties

The electrical energy stored in the electric field between the plate of an ideal capacitors (Figure 5) is in large part determined by two material parameters, permittivity and breakdown field strength, and can be given by equation 1.

$$U = \frac{\varepsilon \varepsilon_n E^2_{max}}{2} \qquad (1)$$

Where

U - energy density (J/ cm^3),

ε - relative material permittivity

ε_o - permittivity of free space (8.85418782 × 10^{-12} m^{-3} kg^{-1} s^4 A^2)

E_{max} (V/μm) - maximum field strength before material breakdown

Permittivity can be described as the ability of the material to polarize in response to an electric field through separation of ions, twisting permanent dipoles in the form of chemicals bonds, and perturbing electron orbitals. Greater polarizability results in higher permittivity. Dielectric breakdown strength can be described as the amount of electric field a material can handle before the electric field frees bound electrons. These electrons become accelerated and free other electrons through the material causing failure.

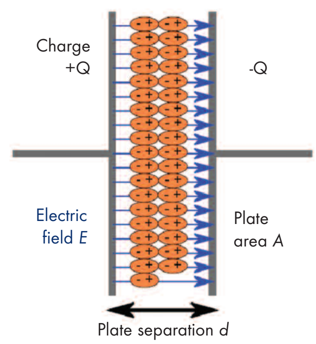


Figure 5. **Schematic of an ideal parallel plate capacitor. Charge separation within the parallel-plate causes an internal electric field. A dielectric inside reduces the field and increases the capacitance.**

Material Development Status

Currently, there are research initiatives to achieve high temperature, high energy density with long lifetime, fast discharge rate, high voltages, and low loss capacitor objectives through structural configurations of multiple materials. One example is the use of polymer extrusion technology to fabricate nanolayer structures of alternating polymer with different electrical properties. One polymer is chosen with high permittivity and the other possesses high breakdown strength. The resultant composite is an effective media with an overall increased energy density through the combined materials. Additionally, the multi-layered structure provides a barrier to the propagation of an electrical breakdown. Challenges include the ability to lay thin layers in a uniform manner over large areas and extrusion of high temperature polymers. Another approach toward high energy dense capacitor dielectrics uses a composite system of both polymer and ceramic dielectrics in an attempt to take the best properties of each and achieve a higher energy den-

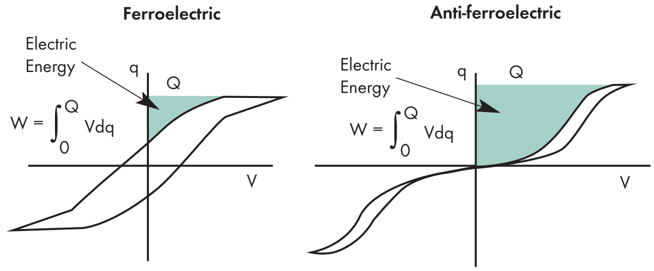


Figure 5. Schematic depicting the increased energy density from ferroelectric to anti-ferroelectric behavior.

sity. The polymer host provides the high breakdown strength while ceramic nanoparticles embedded within the polymer lend the high permittivity. There is also research using anti-ferrolectric nanoparticles to improve the energy density of dielectric materials (see Figure 5). As the electric field is increased, a phase change occurs within the material to enhance the permittivity in a nonlinear manner due to the polarization of the unaligned anti-ferroelectrics figure. The size of the anti-ferroelectric nanoparticle can be tailored to create an enhanced permittivity when high electric fields are applied. The challenges for embedding particles into polymers includes homogeneous dispersion as well as optimization of loading.

Lastly, research is currently underway to improve the energy density and reliability of ceramic capacitors. Ceramics inherently possess a high permittivity and high temperature capability. Current progress is focused on improving the breakdown strength and lowering the losses. It has been shown that ceramic material sintering parameters can be controlled to produce nanograin ceramics. The ceramic grains on the order of 300 nm indeed provide increased breakdown strength and longer operating lifetime. Challenges for this system include control of material defects and impurities.

CONCLUSIONS

As silicon carbide reaches maturity, both in materials processing and in device manufacturing, it will become prolific in commercial and military high power applications. The advances in material processing have reduced the defects such that the higher yield has reduced cost and made it an attractive alternative for low power circuits in which power efficiency is highly valued (e.g., commercial laptops). Recent advances in the development and testing of high power modules are realizing the reduced size and weight that silicon carbide brings to the table. In the future, power applications that require efficiency and clean power more than 10 kW will routinely incorporate silicon carbide switches over silicon. Magnetic material improvements will also have the effect of allowing smaller, more capable systems in the future to meet the ever growing need for higher and more efficient power. The ability to integrate the active and passive electrical components into smarter, more modular circuits will change the way electrical systems are designed.

NOTES & REFERENCES

* Power electronics involves the conversion and control of electrical power.

† Boule is a single crystal formed synthetically.

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Ms. Sharon Beermann-Curtin is currently a Program Manager in the Defense Systems Technology Office (DSO) at the Defense Advanced Research Projects Agency (DARPA). Her portfolio of programs is focused on power and energy, including alternative energies, batteries, fuel cells, thermoelectrics, magnetics, high power capacitors and high power semiconductor efforts. Prior to DARPA she spent 10 years at the Office of Naval Research (ONR) where she was most recently the Acting Deputy Department Head of the Materials and Physicals Sciences, and Ship Hull Mechanical & Electrical Science & Technology Department. She was a visiting scholar in the massachusetts Institute of Technology (MIT) Ocean Engineering Department (13-A program) in 2002. From 1999-2001 she was the Chief Technology Officer for the Program Executive Office–Aircraft Carriers responsible for the transition of new technologies to both in-service and future aircraft carriers. Earlier positions held at ONR include Technology Manager for Ship Systems in the Hull, Mechanical and Electrical S&T Division, and Underwater Weapons Countermeasures Program Manager. Ms. Beermann-Curtin holds a master's and bachelor's degree in Electrical Engineering.

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