Low-Cost GaN Schottky Diodes Deliver SiC Performance

In the last decade, the wide-bandgap semiconductors silicon carbide (SiC) and gallium nitride (GaN) have become of interest for applications in high-voltage and radio-frequency (rf) switching power devices because of their superior electrical properties. Currently, SiC is commercialized in high-voltage power devices, while GaN is mainly utilized in rf power devices. However, the properties of GaN, such as high breakdown electric field (35×10^5 V/cm, compared with 6×10^5 V/cm for Si), high saturation electron drift velocity (1.5×10^7 cm/s, compared with 1×10^7 cm/s for Si), high electron mobility, and high thermal conductivity make GaN competitive with SiC for high-voltage devices such as Schottky diodes (semiconductor diodes with very fast switching times and a low forward voltage drop and hence very small conduction losses). In addition, the currently available 600 V SiC Schottky diodes are too costly for wide acceptance in the power supply industry. To take advantage of the superior properties of GaN for computer and telecommunications equipment power supplies, Velox Semiconductor is developing innovative AlGaN/GaN Schottky diodes that have the same or better performance than SiC diodes but are considerably cheaper.

Velox Semiconductor grows high-quality, crack-free AlGaN/GaN films with uniform thickness, controlled doping, and low-defect density on sapphire or Si substrates. Three factors—the semiconductor material's high breakdown electrical field, the epitaxial layer doping, and the epitaxial layer thickness (2–15 μm)—play critical roles in determining a Schottky diode's breakdown voltage and forward voltage drop. A low forward voltage drop indicates that conduction losses are very small when switching polarity.

To achieve the predicted GaN Schottky diode performance of >5000 V breakdown voltage requires optimizing material growth, device design, and device fabrication. In the reverse current–voltage characteristics of a Velox GaN Schottky diode, the leakage current is 180 μA under a reverse bias of 600 V at room temperature and climbs to 1.4 mA at an elevated temperature of 125°C. The same GaN Schottky diode's forward current–voltage characteristics demonstrates nearly ideal diode characteristics. (The Schottky ideal factor is close to 1, which indicates that electron transport at the junction between the Schottky metal and the GaN semiconductor is behaving as theoretically predicted.) The forward drop voltage is 1.8 V at 8 A forward current at 25°C and increases to 2.2 V at 125°C, indicating good forward voltage at elevated temperatures and hence low losses.

In its current design, the GaN Schottky diode exhibits a slightly negative thermal coefficient below 2 A (forward voltage drops with temperature) and a positive coefficient above 2 A (forward voltage increases with temperature). The company anticipates that it can improve the device to achieve the desired negative thermal coefficient of 10 A or above.

One of the first anticipated applications for the GaN Schottky diode is to be substituted for Si in a power conversion circuit to reduce the size and complexity. Due to its zero reverse-recovery characteristics, a GaN Schottky diode is more efficient than a Si diode. For circuit designers, the resulting GaN-based circuits should provide higher efficiency and lower operating temperatures than Si-based configurations. The developers said that compared with SiC diodes, their high-voltage GaN Schottky diodes are considerably cheaper and could be adopted for a broad range of applications.

Technology Advances provides up-to-date reports of materials developments that show potential to bridge the gap between research innovation and application of advanced materials technologies. If you encounter or are involved with materials research that shows potential for commercialization and would like to present these developments, contact Renée G. Ford, Renford Communications, renford@comcast.net.

Opportunities

Velox Semiconductor welcomes inquiries about their GaN devices as well as about the possibilities for joint development and licensing.

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Low-Impurity Binder System Enables Powder Injection Molding of Titanium and Other Refractory Metals

The present methods of extracting and processing titanium and of subsequently fabricating products from the raw metal are over 30 times more expensive on a per-pound basis than those employed in producing steel components. The key costs for titanium processing are its chemical reactivity and inherent solvency for a wide range of unwanted elements, particularly interstitials such as carbon, oxygen, and nitrogen, which are often undesirable even in small amounts because they significantly degrade the ductility of the material. Powder injection molding (PIM), the common method used for fabricating small-to-moderate-sized metal components in near-net shape, minimizes additional processing. However, PIM has found limited application with reactive metals such as titanium because the method by which the binder is removed in the process introduces residual carbon into the final sintered part, and control and reproducibility of the final shape and dimensions of the component are difficult. Researchers at Pacific Northwest National Laboratory (PNNL) have developed a binder system that uses an aromatic compound as the primary binder constituent. It can be easily and cleanly removed by sublimation and requires only a small amount of a secondary additive to ensure adequate handling strength in the part after binder removal.

PIM comprises four main steps: (1) mixing of the metal powder with a plasticizing binder to form the feedstock material, (2) liquefaction and injection of the feedstock into a mold, (3) removal of the binder, and (4) sintering or densification. The use of easily removed fugitive phases in the feedstock mixture and control of the debinding and sintering heat treatments allow the porosity of the component to be optimized, which affords a significant advantage in specialized applications such as the design of self-lubricating parts and biomedical implants.

Examples of titanium parts that have been fabricated by PIM using the new binder are shown in Figure 1. Detailed features such as fine screw threads and intricate part geometry can be readily formed using the new binder, as exemplified by the threaded ring component in the figure. Chemical analysis conducted on as-sintered parts indicates that when sintering is carried out under appropriate conditions, no significant increase in carbon content (<80ppm) occurs above that measured on the initial titanium powder used in the feedstock. Although aromatic compounds have a higher molar concentration of carbon than do aliphatic compounds, the new binder composition takes advantage of the high vapor pressure and low sublimation temperature of the ring-structured organics, naphthalene in particular, allowing them to be readily and cleanly removed from the as-molded component prior to sintering.

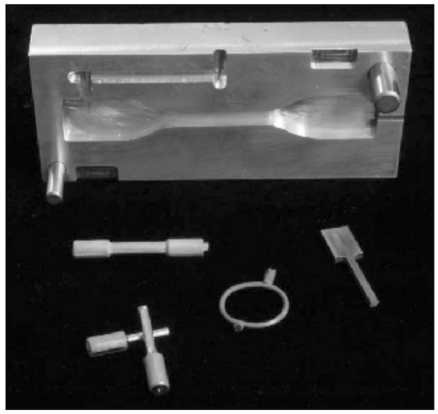

Figure 1. Examples of titanium components fabricated using the aromatic powder injection molding (PIM) binder system.

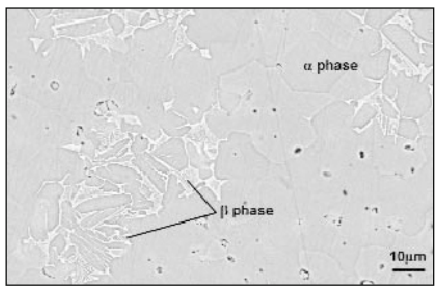

Figure 2. Scanning electron micrograph of the as-sintered microstructure of a specimen prepared by PIM with blended elemental Ti-6,4 powder.

The resulting ultimate tensile strengths measured in PIM-produced bars prepared from commercial-purity titanium powder were comparable to Grade 4 wrought material, with an average value of 580 MPa. Recent research on removing the binder indicates that the use of the aromatic-based binder offers substantial control over the size and amount of porosity that can be formed within a given component. In addition, under the appropriate conditions, it appears that the porosity can be tailored or graded from the outer surface to the center of the part.

A preliminary indication of this type of microstructural control was recently published in *Materials Transactions* **46** (7) (2005) p. 1525. It was demonstrated that tensile bar specimens could be fabricated in which a dense outer rim measuring ~250 μm thick forms over an inner core that was found to be graded with respect to the size and amount of porosity. In approximate fashion, the microstructure is reminiscent of the cancellous and compact tissue found in natural bone. Work is continuing on this concept to determine the extent of microstructural gradation that can be incorporated into the material and to examine the resulting effect on elastic modulus and other mechanical properties.

Additionally, demonstration studies have been conducted to investigate coupling the new PIM process with a means of *in situ* alloy formation (which is inherent in all-powder metallurgy processes) using blended elemental powders. An example of a Ti-6,4 alloy prepared using blended titanium, aluminum, and vanadium powders in the new feedstock formulation is shown in Figure 2.

This strategy offers a potentially useful means of rapidly developing, testing, and eventually manufacturing novel alloy compositions in complex component geometries. It is particularly amenable to highly specialized applications, such as biomedical alloys, where the implementation of larger-scale wrought-based processes would increase the cost and time of development. This approach also affords the chance to investigate novel, nonequilibrium titanium alloy compositions and microstructures and titanium-matrix composite materials that only can be prepared by solid-state methods.

Opportunities

This PIM technology, which can be used in fabricating components from titanium and other early transition metals or refractory metals and alloys, is available for collaborative research and licensing through Pacific Northwest National Laboratory.

Source: For further information on collaborative research: Scott Weil, Materials Division, Pacific Northwest National Laboratory, PO Box 999/K2-44, Richland, WA 99352, USA; tel. 509-375-6796 and e-mail scott.weil@pnl.gov. For technology commercialization: Eric Lund at 509-375-3764, fax 509-375-2323, and e-mail eric.lund@pnl.gov.