Review

Processing Design of Single Crystals and Textured Polycrystals for Advanced Electronic Devices

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Abstract

Development of high performance materials with environmental compatibility has been strongly desired for electronic device elements. One of the strategies is the design of a novel processing method to produce a material with the optimum microstructure for enhanced physical properties. Examples are shown as recently developed processing techniques; a single crystal growth method to dramatically decrease the dislocation density of compound semiconductors, and a texture engineering method to enhance anisotropic properties of polycrystals.

Keywords: Microstructural design, Processing design, Single crystal, Silicon carbide, Textured ceramics, Reactive template, Piezoelectric, Thermoelectric

1. Introduction

A wide variety of solid state electronic devices such as sensors, actuators and electronic control units are installed in contemporary automobiles and they are becoming increasingly essential. Materials for the electronic device elements must meet industrial demands for (1) high performance, (2) new function, and/or (3) environmental compatibility. The environmentally conscious society and recent strict regulations require non-hazardous materials and devices that contribute to the reduction of carbon-dioxide emissions. The typical former example is lead-free piezoelectric ceramics and the latter example is compound semiconductor power electronic devices with high efficiencies.

There are two types of approaches for developing desired materials: one is to find new substances or new compositions with desired performance, and the other is to enhance properties of known substances. Developing a unique process for materials with tailored microstructures is an effective strategy within the latter approach for solid-state device elements. Conventionally such process has been developed by the inductive method: the best combination of processing parameters is found by evaluating properties of materials which are fabricated under various conditions. The inductive method would, however, require time and cost for scanning many parameters, yet it might overlook the conditions leading to the real maximum of the material properties.

We have proposed the processing design through the deductive method: first, the optimum microstructure to elicit the best performance is envisioned; next, the processing method to produce a material with the ideal microstructure is theoretically designed. Using the deductive method prior to the inductive method would give us more opportunity to reach the real maximum of the material properties. This special issue features the design and development of processing methods through the deductive approach which will produce solid-state device elements with ideal microstructure and enhanced properties.

2. Processing design for high-quality single crystals

Bulk single crystals of inorganic materials have been used in the guts of various semiconducting, piezoelectric, ferroelectric, magnetic, and optical devices. The performances of devices are often limited by microscopic crystal defects such as dislocations and stacking faults even for a material with potentially superior properties. Bulk silicon crystals had once contained many defects but the combination of several epoch-making technologies such as the necking method had drastically reduced the defect density, and improved the performance of the silicon devices.

Silicon carbide, a wide band-gap semiconductor, has been expected to make excellent power devices with remarkably higher efficiency than devices which silicon can make. It still contains, however, a large number of crystal defects which could cause current leakage and/or reliability degradation.

Understanding the defect formation mechanism during crystal growth and design of defect-free processing are significantly important to extract the intrinsic performance of the materials. Nakamura, et al. have recently developed a novel processing method for bulk SiC single crystals, the repeated a-face growth (RAF) method, by which the dislocation density in the crystals has been dramatically decreased.[1] The developed method is expected to make a great contribution to the development of high-performance power devices.

3. Processing design of highly textured ceramics

For complex oxides, polycrystals have advantages in terms of mechanical toughness, compositional flexibility, and sometimes even compositional uniformity as well as processing cost in comparison with single crystals. Physical properties of a polycrystal are, however, generally inferior to those of a single crystal with the same composition, and the difference in the properties is especially large for a substance with anisotropic characteristics. Texture engineering of electronic ceramics has recently collected attention as an approach to extract the best performance from functional materials through powder processing. Texturing polycrystals by using plate-like particles are known mainly as the oriented consolidation of anisometric particles and the templated grain growth methods.[2-5] Computational modeling for isotropic and anisotropic grain growths on templates has also been made for understanding the development of texture during the process.[6, 7] The preparation of anisometric particles with a target composition is, however, difficult for a material with a complex composition or pseudocubic crystal structure such as simple perovskite-type.

The reactive-templated grain growth (RTGG) is the processing method in which reactive template particles are mixed with complementary reactants and aligned by a shear stress, and the product is formed *in-situ* during heat-treatment, preserving the orientation of the template.[8] The RTGG method exploits a reactive template material with a crystal structure (at least partially) similar to the target material which will be textured. This type of reaction sintering for textured bulk ceramics has been known as the fabrication of cordierite honeycombs,[9] spinel-type ferrite magnetic heads,[10] and bismuth layer-structured high-T_c superconductor.[11] In the RTGG method, it is important to design the most appropriate *in-situ* reaction scheme for the target material on the basis of crystallography and thermodynamics prior to the experiments.[12]

We consider the texture engineering to become a key technology to enhance piezoelectric properties of lead-free ceramics. Saito, et al. designed the process for fabricating textured lead-free $K_{0.5}Na_{0.5}NbO_3$ (KNN)-based ceramics whose Curie-temperature, piezoelectric properties and high-field strain properties were all comparable to those of commercial PZT-based materials.[13] The proposed texture engineering has also been extended to thermoelectric materials, including p-type layer-structured cobaltites and n-type homologous compounds with complex compositions.[14-17] By citing the examples, we emphasize the importance of processing design for high-performance polycrystals with ideal microstructures. The optimum combination of microstructural and compositional designs is expected to produce outstanding materials with superlative performances.

4. Conclusion

Design of a novel processing method for a functional material with the optimum microstructure is significantly important to extract the best performance of the material. Texture engineering is the technique to enhance physical performance of a material with anisotropic properties.

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(Report received on Apr. 25, 2006)

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