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Mechanical Stability of Power Device Materials High Temperature Hardness of SiC, AlN and GaN

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Abstract

The hardness of bulk single crystal 6H-SiC, GaN and AlN was measured by the Vickers indentation method under an applied load of 0.5–5 N in the temperature range 20–1400 °C. The average hardness of SiC, GaN and AlN of (0001) surfaces is about 25, 11 and 18 GPa, respectively, at room temperature. SiC, AlN and GaN show higher hardness than Si, GaAs and ZnSe at elevated temperatures. A high mechanical stability for the semiconductors is deduced.

INTRODUCTION

Silicon carbide (SiC), gallium nitride (GaN) and aluminum nitride (AlN) appear promising as wide-band-gap semiconductors for application as high power/high-frequency devices, high power switches, blue and ultraviolet light emitting-devices/photo detectors and chemically stable substrates for various materials. In addition, these materials are expected to be mechanically stable and available at high temperatures. However, up to now far less is known about the mechanical properties of these materials mainly on microhardness at room temperature. Information on the mechanical strength of materials at elevated temperatures is essential as a basis in order to control the dislocation generation and plastic deformation during crystal growth and device processing and also to improve the optical and electronic properties of the materials. The difficulty of bulk crystal preparation as GaN and AlN is a limiting factor in obtaining this information. Recently thick films of GaN and AlN have been successfully grown by using a hydride vapour phase epitaxy (HVPE) technique [1, 2]. These crystals can be regarded as bulk materials. The author's group has reported the hardness, which is a material parameter indicating resistance to plastic deformation, in the bulk single crystals GaN and AlN at elevated temperatures [3–5].

This paper reports the hardness of the wide-band-gap semiconductors SiC, GaN and AlN at elevated temperatures in comparison with those of other materials Si, GaAs, ZnSe and α-sapphire.

EXPERIMENTAL

The hardness of single crystal 6H-SiC, GaN and AlN of 0.5 mm thickness at elevated temperatures was measured by the Vickers indentation method in the temperature range 20–1400 °C. Here, GaN and AlN single crystals were prepared from high-quality thick film grown on substrates by the HVPE technique, the details of which were described elsewhere [1, 2]. Finally, the thick grown layer was removed from the substrate. The grown-in dislocation density in AlN was approximately 10^8–10^9 cm^{-2} and that in GaN was as low as 10^7 cm^{-2}.

Hardness measurements on the crystals were carried out by the conventional Vickers indentation method using a pyramidal diamond indenter. The applied indentation load P was 0.5–5 N. The dwell time was 30 s for every temperature tested in the range from room temperature (RT) to 1400 °C in a high-purity Ar gas atmosphere. At least four impressions were formed at every temperature for the basal plane surfaces.

RESULTS AND DISCUSSION

At room temperature, indentations formed on the basal plane surfaces of the GaN and AlN crystals sometimes exhibited fracture characteristics for brittle materials with radial cracks propagating from the impression corners under an applied load of more than 2 N.

Hardness H_v was estimated from the load P and diagonal lengths $2a$, measured by optical microscopy, of the impression using the following relation:

$$H_v = P/(2a^2) \quad (1)$$

The fracture toughness K_c was also determined from the radial crack length c:

$$K_c = \xi(E/H_v)^{1/2}(P/c^{3/2}) \quad (2)$$

where E is the Young's modulus and ξ is a calibration constant (equal 0.016) for brittle materials.

The hardness is almost comparable for the (0001) and (0001#) polar surfaces of the crystals with the hcp based structure at all temperatures investigated. At RT the hardness of GaN is estimated to be 10.8 GPa under the applied load 0.5–3 N, about twice and ten times the value of GaAs and ZnSe, respectively. The measured hardness of (0001) surfaces of GaN is similar to those 12 and 12.3 GPa reported by Drory *et al.* [6] and Hong *et al.* [7], respectively. The hardness of AlN at RT is 17.7 GPa under the applied load 0.5 N. The fracture toughness of GaN is measured to be 1.1 MPa m$^{1/2}$ under the applied load range 0.5–5 N using Eq. (2) with E = 295 GPa recently reported [8], which is also comparable to those by Drory *et al.* [6] and Hong *et al.* [7]. The fracture toughness of AlN is 0.4 MPa m$^{1/2}$ under the applied load range of 2–5 N using the Young's modulus $E \approx$ 308 GPa [9]. Table I compares the hardness and fracture toughness of GaN together with various semiconductors and a-sapphire at RT [3–5, 10–12]. As evident in the table, AlN is harder than GaN and softer than SiC and α-Al_2O_3 [12]. The result suggests that the hardness of semiconductors is related to the bonding distance, as proposed by Sher *et al.* [14]

Figure 1 shows the hardness H_v of SiC, GaN and AlN, obtained with an applied load of 0.5 N and dwell time of 30 s, plotted against reciprocal temperature in comparison with other material (111) or (0001) surfaces.

TABLE 1

Vickers hardness and fracture toughness for 6H-SiC, GaN, AlN and other materials at room temperature [3–5, 10–12] with an applied load 0.5 N and dwell time 30 s together with bonding distance [13]

Material	Hardness, GPa	Fracture toughness, MPa m$^{1/2}$	Bonding, distance, nm
6H-SiC(0001)	22.9*	3.3 [10]	0.188
GaN (0001)	10.2 [3]	1.1 [4]	0.196
AlN (0001)	17.7 [5]	0.4 [5]	0.192
Si (111)	12.0	0.7 [10]	0.235
GaAs (111)	6.8	0.4 [11]	0.245
ZnSe (111)	1.1	0.9 [10]	0.245
α-Al_2O_3 (0001)	28**[12]	2.5 [10]	0.192

*At 300 °C.
**With an applied load 2 N and dwell time 15 s [12].

Throughout the entire temperature range investigated, the hardness of SiC, GaN and AlN exhibits a gradual decrease from RT to around 600 °C, then something of a plateau in the range to around 1000 °C, and subsequently a steep decrease. This temperature-dependent tendency is in common in semiconductors and sapphire, which have a *hcp*-based structure,

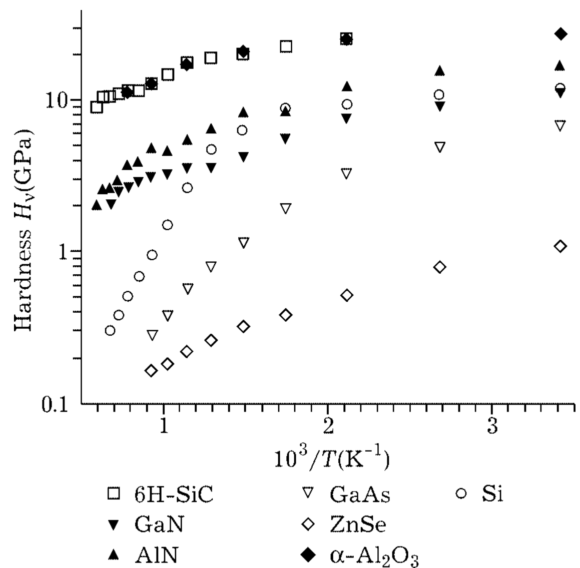

Fig. 1. Vickers hardness of bulk single-crystal 6H-Si, AlN and GaN plotted against reciprocal temperature, with an applied load of 0.5 N and dwell time of 30 s, together with those of Si, GaAs and ZnSe. The hardness of α-Al_2O_3 obtained with an applied load of 2 N and dwell time of 15 s is superimposed [12].

although the temperature range and hardness magnitudes of SiC or sapphire are higher than those of GaN. The plateau may appear in relation to the operation of different slip systems in the crystal structure. It is found that in the whole temperature range investigated the hardness magnitudes of AlN are greater than those of GaN but lower than those of 6H-SiC.

At low temperature regions, the hardness of GaN and AlN is comparable to, or a little lower than, that of Si. Phase transformation beneath the indentor may influence the hardness of Si since the phase transformation occurs at pressure of about 11.3 GPa. Surprisingly, up to about 1100 °C, GaN and AlN maintain their hardness and are harder than Si. Indeed, Si and GaAs exhibit a steep decrease in hardness from 500 and 200 °C, respectively, with increasing temperature, which indicates the beginning of macroscopic dislocation motion and plastic deformation. Thus, the present results imply that this macroscopic dislocation motion and plastic deformation of SiC, GaN and AlN may start at around 1100 °C. Over the whole temperature range investigated, ZnSe is known to be the most unstable of these materials.

The results imply that SiC, GaN and AlN have a lower susceptibility to deformation during device processing at high temperatures as compared with Si, GaAs, ZnSe and possibly other III−V and II−VI compounds with the sphalerite structure. A more complete physical understanding of hardness in order to derive the dynamic properties of dislocations is still lacking in the absence of sufficient theory and is a task in the future. However, we recognize that the present data provides a useful indication of material strength at elevated temperatures. Further work is required to determine the dislocation mobility in GaN and AlN bulk crystals under a defined stress distribution. Here, it can be mentioned that the activation energies for dislocation motion have been empirically estimated to have a linear relationship with the band gap energy dependent on the group of semiconductors, *i. e.*, the elemental and IV−IV compound, III−V compound and II−VI compounds [15].

CONCLUSION

The Vickers hardness for wide-band-gap semiconductors SiC, GaN and AlN was compared in the temperature range 20−1400 °C. The average hardness of SiC, GaN and AlN is about 25, 11 and 18 GPa, respectively, at room temperature. Up to about 1100 °C, these semiconductors maintain their hardness, being mechanically stable in comparison with Si, GaAs and ZnSe.

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