Available online at www.sciencedirect.com
ScienceDirect
Thin Solid Films 515 (2007) 3011 – 3018
www.elsevier.com/locate/tsf

Effects of ion implantation on the mechanical behavior of GaN films

P. Kavouras *, Ph. Komninou, Th. Karakostas

Physics Department, Aristotle University of Thessaloniki, 541 24 Thessaloniki, Greece

Received 21 March 2006; received in revised form 2 August 2006; accepted 30 August 2006
Available online 12 October 2006

Abstract

The effects of ion implantation on the response to indentation in epitaxially grown hexagonal GaN films were studied by means of the static microindentation technique, utilizing Knoop and Vickers indenter geometries. Mg, O, Au, Xe and Ar ions were used as projectiles for the implantation process. Heavily damaged polycrystalline epilayers showed enhanced microhardness values and normal indentation size effect (ISE). Amorphised epilayers showed lower microhardness values, while they presented reverse ISE. The shape of the Knoop indentation print as a function of the implanted species revealed that reverse ISE is connected with plastic behavior. Implantation was also found to render films more receptive to fracture. Normal ISE curves were explained using models such as Meyer's law, Hays–Kendall approach, proportional specimen resistance (PSR), modified PSR and elastic/plastic deformation (EPD) models.

Keywords: Elastic properties; Fracture sequence; Hardness; Ion implantation; Nitrides; Semiconductors

1. Introduction

The investigation of radiation effects in III–V semiconductors is of current interest because of the potential application of ion implantation in the production of electronic and photonic devices. Of the plethora of III–V semiconductors, gallium nitride (GaN) has attracted keen interest, during the past decade, as direct wide band gap semiconductor for numerous applications, including high-power or high-frequency devices and high-power switches. High-dose implantation comprises an attractive method for several technological applications, in the fabrication of new GaN-based devices, such as selective area doping [1]. The implantation-induced lattice damage constitutes the main cause of the present limitations of implantation as a means of selective area doping [2], since *in situ* control of implantation damage has not been achieved yet; only post-implantation annealing is currently studied for irradiation damage removal.

Presently, there is considerable interest in determining the influence of ion implantation on the mechanical properties of GaN films [3]. This is because it is becoming increasingly evident that the successful application of implanted GaN will depend not only on the optoelectronic characteristics, but also on its mechanical properties [4,5]. Indeed, studies of the processes controlling hardness, contact damage and cracking at the small contact scales of epitaxially grown GaN films have significant technological importance [6,7], since they are involved in many wear processes that cannot be inferred from simple bulk hardness data. However, studies of implantation-induced effects on the mechanical properties of GaN films have received only scant attention.

In this work, we present the results of the application of the static microindentation technique, using Vickers and Knoop

Table 1
A list of the implanted species used to produce implantation damage presented with the width and structure of the implanted epilayer

Implanted ion	Implantation energy (keV)	Code name	Epilayer width (μm)	Epilayer structure
–	–	GaN	–	–
O	150	GaN:O	0.25	Heavily damaged
Mg	100	GaN:Mg	0.20	Heavily damaged
Au	400	GaN:Au	0.15	Amorphous
Xe	800	GaN:Xe	0.25	Amorphous
Ar	300	GaN:Ar	0.30	Amorphous

---

* Corresponding author. Physics Department, Solid State Physics Section, Aristotle University of Thessaloniki, 541 24 Thessaloniki, Greece. Tel.: +30 2310 998011; fax: +30 2310 998589.
E-mail address: pkavo@physics.auth.gr (P. Kavouras).

0040-6090/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.tsf.2006.08.032

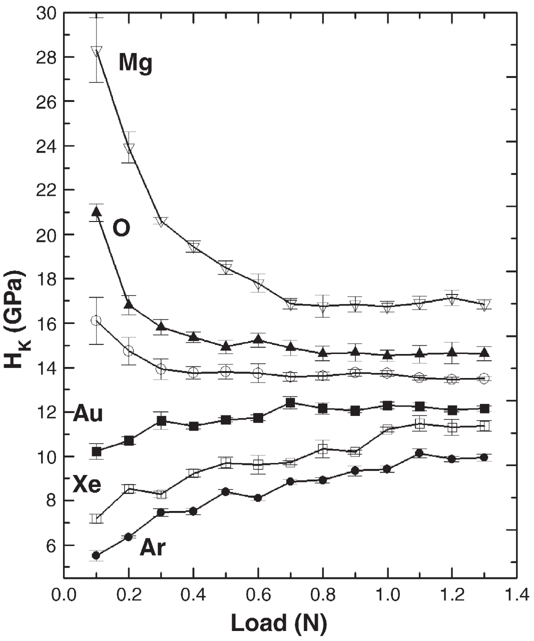

Fig. 1. ISE curves of (▽) GaN:Mg, (▲) GaN:O, (○) GaN, (■) GaN:Au, (□) GaN:Xe, (●) GaN:Ar films.

indenter geometries in the investigation of implantation induced effects on the mechanical properties and fracture of epitaxially grown GaN films. More specifically, we compare a number of physical characteristics that govern the elasto-plastic behavior, like the shape of microhardness value curves as a function of indentation load, namely the indentation size effect (ISE) curves, and the extent of elastic recovery as a function of implanted species, utilizing Knoop indenter geometry. ISE curves were fitted with various empirical laws in order to investigate whether they apply in the case of implanted films. Additionally, the gradual evolution of different cracking modes as a function of implanted species and indentation load, namely the brittle behavior, was studied with Vickers indenter geometry and connected with the observations made with the Knoop indenter.

2. Experimental details

Implantation was performed on high-quality (0001)GaN thin films grown on sapphire by molecular beam epitaxy [8,9]. The unimplanted film thickness was approximately 2 μm. The implanted species used to produce implantation induced damage were Mg, O, Au, Xe and Ar ions. The implanted epilayer widths, calculated utilizing the computer code TRIM97, are listed in Table 1 together with a description of the microstructure of the implanted epilayers. The microstructure was characterized by Rutherford backscattering of He ions in the case of O, Au, Xe and Ar ion implanted samples [10,11] and near-edge X-ray absorption fine-structure in the case of Mg ion implanted samples [12].

A Knoop indenter was utilized to obtain the microhardness values by the static indentation technique. Initially, a series of measurements was made, in order to obtain the microhardness value as a function of indentation load for all samples. It is widely known that for indentation loads below a specific value (P_{cr}), which varies with the material under study, the microhardness value is load depended, while above P_{cr} the microhardness value is load independent. This is the plateau region of the curve, where the experimentally used indentation loads should lie in order to obtain reliable and comparable microhardness values. The load region below P_{cr} is the indentation size governed region. With a decrease in load, the microhardness value in this region is increased in most cases [13], while the opposite effect, i.e. microhardness value decrease, has also been observed [14], less frequently though. In the former case, the material under study exhibits normal ISE, while in the latter it exhibits reverse ISE.

Each microhardness value of the ISE curves in the present work represents the mean value obtained from 14 indentation prints. The dwell time was 10 s and the loading rate was set at 0.2 N/s. Indentation loads varied in the range between 0.1 and 1.3 N. The upper limit of the load range was designated from the intention to avoid crack initiation in all samples. This precaution was taken, since cracking has been reported to have measurable effect on the size of indentation prints [15,16].

The ability to fit and explain normal ISE curves was studied using the following models: The Meyer's law [17], Hays–Kendall approach [18], proportional specimen resistance (PSR) [19], modified PSR [20,21] and elastic/plastic deformation (EPD) [22] models. The latter was originally termed as the deformation band model. Additionally, the indentation-induced cracking (IIC) model [23] was tested as to whether it can be used to fit and explain the reverse ISE curves.

The static microindentation technique was used to study the elastic recovery of all samples after indentation by measuring the ratio of the lengths of the shorter over the longer diagonal of Knoop indentation prints (d'/d). The indentation load was set at 1.3 N, in order to have relatively large indentation prints and, as a result, more accurate length measurements. In this case the measurements were conducted with oblique incident

Table 2

The microhardness value at the plateau region of the ISE or RISE curves (H_K), the nature of the ISE curves, some parameters from the models used to fit the curves of Fig. 2a–e, the ratio of the small over the large Knoop indentation print diagonal (d'/d), and the minimum load (P'_{cr}) needed to induce surface flaking

Film	H_K (GPa)	ISE	n	W (N)	c_0 (N)	α_1 (N/μm)	H_0 (GPa)	δ (μm)	d'/d	P'_{cr} (N)
GaN	13.67±0.15	Normal	1.890	0.016	0.014	0.176	12.60	1.13	0.113±0.004	–
GaN:O	14.75±0.22		1.783	0.030	0.040	0.370	12.61	2.21	0.107±0.003	3.1±0.2
GaN:Mg	16.87±0.13		1.655	0.057	0.064	0.736	13.71	3.17	0.112±0.006	1.3±0.2
GaN:Au	12.16±0.09	Reverse	2.151	–	–	–	–	–	0.127±0.002	2.7±0.2
GaN:Xe	11.35±0.12		2.428	–	–	–	–	–	0.139±0.002	3.1±0.2
GaN:Ar	9.98±0.14		2.615	–	–	–	–	–	0.131±0.002	2.7±0.2