

# Evolution of Surface morphology on Ion Sputtered of Some III-V (001) Semiconductors



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## Abstract:

Surface patterning of some III-V (001) compounds, under ion irradiation, has been investigated by means of Atomic Force Microscopy. The III-V(001) surfaces were exposed by Ar<sup>+</sup> beam with varying incident angles (from 0° to 80° off-normal) with energy 2.0 keV and fluence 8.8 x10<sup>16</sup> ion/cm<sup>2</sup> at room temperature. Depending on the ion incident angle and target materials, different kinds of nanostructures have been observed on the surfaces, such as nanocavities, nanodots and well-ordered ripples at the oblique incidence angle of irradiation. The orientation of the ripples has been found to be incident angle dependent and it elongates along the projection of the ion beam on the irradiated surface. The RMS roughness and wavelength of the developed nanostructures are dependent on the angle and type of material. The results have been discussed in terms of ballistic processes of sputtering and Bradley Harper theory for surface modifications.

**Keywords:** Surface patterning, Ion irradiation, Ripples, III-V semiconducting compound, B-H theory, Atomic force microscopy

## Introduction

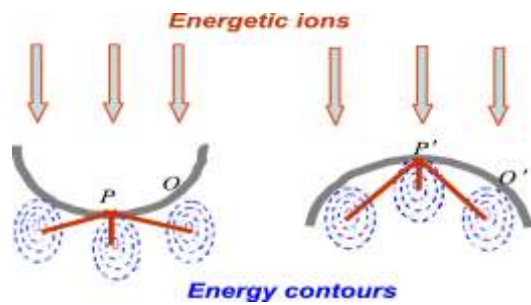
Due to the increasing demand of nanoelectronic and optoelectronic devices, well ordered nanostructure patterning and texturing of surfaces at nanometer length scales is required[1,2]

Self-organization during Low energy ion-beam-sputtering (IBS) appeared as an elegant, cost-effective, size controllable technique of generating large area of pattern in comparison with lithography techniques. The main mechanisms responsible of spontaneous formation of self-organized patterns can be understood in term the linear continuum model of Bradley-Harper (BH) theory [3]. The evaluation of surface height

$h(x,y,t)$  during ion bombardment can be written as:

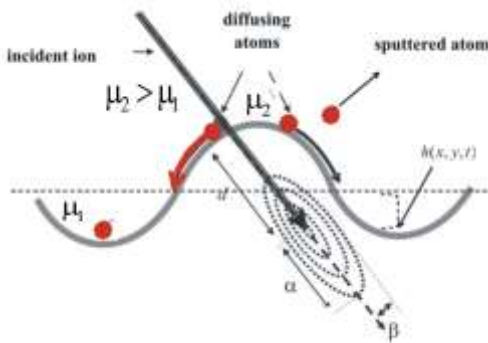
$$\frac{\partial h}{\partial t} = +v_x(\theta)\frac{\partial^2 h}{\partial x^2} + v_y(\theta)\frac{\partial^2 h}{\partial y^2} - D_T \nabla^2(\nabla^2 h) \dots \dots \dots (1)$$

here,  $v_x, v_y$  are the negative surface tensions in x and y direction, respectively, and  $D_T$  is the thermally activated surface diffusion. According to the BH theory, the surface morphology of amorphous solids undergoing oblique ion bombardment originate from the instability caused by curvature dependent sputtering of the surface which proposed by Sigmund [4], where, valley regions (depressions) sputter faster than the convex (hill) region(see Fig. 1).



**Fig. 1** The transferred energy contours in regions of positive  $\kappa > 0$  and negative  $\kappa < 0$  surface curvature  $\kappa \sim \partial^2 h / \partial x^2$ . The deposited energy is higher at point P than at P'.

This instability is opposed by a smoothing mechanism (see Fig. 2), e.g. surface diffusion. The chemical potential  $\mu$  of atoms at the surface is proportional to the curvature, in order to reduce surface energy, driving mass transport away from convex regions towards the impression region ( $\mu_2 > \mu_1$ ) causing the change of the height of the surface  $h(x,y,t)$  [5,6]



**Fig.2** Surface smoothing via surface diffusion. Adsorbed atoms (adatom) migrate from regions of high chemical potential  $\mu_2$  to regions of low chemical potential  $\mu_1$ .

The interplay between roughening and smoothing processes governs a characteristic wavelength for the pattern [3]. The surface patterning varies, depending on the experimental parameters during ion bombardment such as temperature of the substrate [7,8,9], angle of incidence of the

ion beam [10,11], fluence [12], ion energy [13,14], nature of the bombarding ion as well as the substrate material [11,15]. Another parameter is the crystal orientation but it seems that the most studied orientation is (001) orientation. In the present work, we have studied the surface topography of III-V compounds with varying incident angle for a fixed energy and fluence of the ion beam at room temperature. The surface topographies have been investigated by means of contact mode-Atomic force microscopy (C-AFM).

### Experimental

plasma ion source producing 2 keV  $\text{Ar}^+$  ion were used to bombard Epi-ready, polished Indium antimonide (InSb), Indium phosphide (InP), and Gallium antimonide (GaSb), from III-V (001) semiconductor group, purchased from Kelpin Crystals (Neuhausen, Germany). The *ex situ* pre-cleaning has been done with propanol and blowing by pure nitrogen gas to remove the residual contaminant occurring due to the cutting of the wafers. The *in situ* sample cleaning has been done in the preparation chamber following a standard procedure of annealing to 450 K for 2 h. The base pressure of the chamber was around  $4 \times 10^{-9}$  mbar and  $2 \times 10^{-7}$  mbar during bombardment. The experiments carried out using projectile ion fluence of  $8.8 \times 10^{16}$  ion/cm<sup>2</sup> corresponding to the average ion current density  $60 \mu\text{A}/\text{cm}^2$  at different incidence angles  $\theta_{ion}$  ( $\theta_{inc} = 25^\circ, 45^\circ, 60^\circ, 70^\circ$  and  $80^\circ$ ), as measured *wrt* the surface normal. The resulting surface topography has been analyzed by atomic force microscopy in contact mode (c-AFM) with the CP Park Scientific Instruments microscope using silicon Nitride tips. The apex of the tip has a radius of curvature of  $\sim 10$  nm. The average of the created structure wavelength and RMS roughness was measured directly from AFM topography images using WSxM 5.0 Develop 1.1 Image Browser.

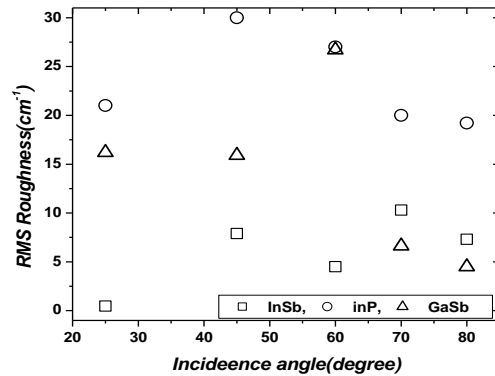
### Results and analysis

AFM images of irradiated three binary system from III-V(001) surfaces with 2keV Ar<sup>+</sup> ions at different angle of incidence 25<sup>0</sup>,45<sup>0</sup>,60<sup>0</sup>,70<sup>0</sup>,80<sup>0</sup> off-normal and fluence of 8.8x10<sup>16</sup>ion/cm<sup>2</sup> at room temperature shown in Fig.(3).

Due to the difference in their substrate materials, the developed nanostructures are not equivalent over all the irradiated surfaces under the same experimental conditions. After bombarding flat and featureless samples with the mentioned parameters, different nanostructures such as nanodots, nanowire (worm like structure) and well-arranged nano pattern (ripples) were developed. The AFM images of the irradiated InSb(001) surface shows the trough and crest like pattern at 25<sup>0</sup> off-normal incidence angle, but at 45<sup>0</sup> off-normal, the elongated nanodots pattern is clearly seen in the AFM image . As the angle increased to 60<sup>0</sup>, more elongation of nanodots has been observed, as a result, worm like structure were created. Further increase to 70<sup>0</sup> incidence, clear worm like structure with some islands, aligned with the beam direction seen on the irradiated surfaces. With increasing the angle of incidence to 80<sup>0</sup>, more clearly uniform nano rode structure or ripple like structure was observed along the beam direction. In the case of InP(001), clear and bigger nano dots like pattern developed on the irradiated surfaces , with increasing the angle of incidence, denser and elongated with the direction of the ion beam observed especially at 80<sup>0</sup>, For near normal 25<sup>0</sup> incidences, nanodots pattern were observed for GaSb(001) which attributed to the dominating erosion term in the BH equation which makes the surface rougher (see figure 2) where the roughness of unbombarded samples around 0.6-0.8 nm. With increasing

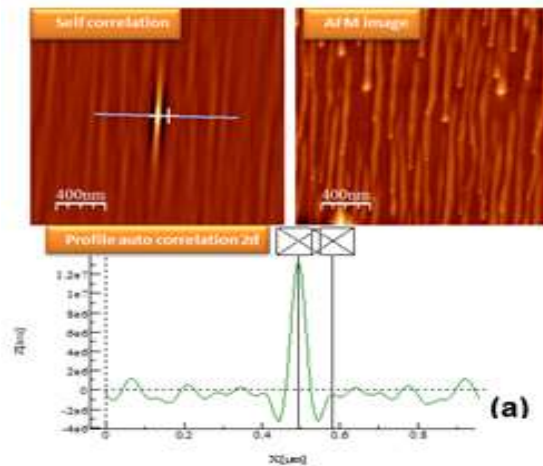
the angle of incidence the transition from nanodots or islands to ripple have been observed nearly from incidence angle of 60<sup>0</sup> (see Fig. 3).

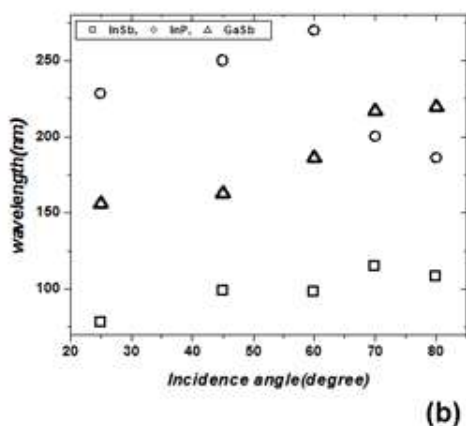
The variation of RMS roughness taken from AFM images (see Fig. 3) as a function of incidence angle shown in Fig. 4. The RMS roughness for the irradiated surfaces up to a specific angle increase with increasing incidence angle then started to decrease with a different amount relative to the substrate type.



**Fig. 4 the variation of RMS roughness as a function of incidence angle for the irradiated surfaces InSb, GaSb and InP.**

The variation of the wavelength of in-duced structures as a function of incident angle shown in Fig.5b, and calculated using WSxM 5.0 Develop 1.1 Image Browser following the procedure shown in Fig.5a.





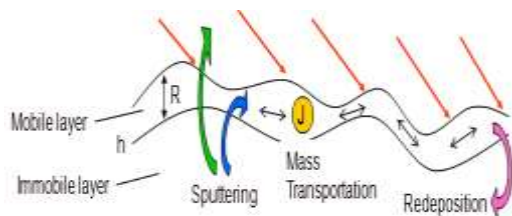
**Fig.5 (a) The procedure for calculation of the wavelength of the induced structures and (b) variation of the wavelength of the developed structure as a function of Incidence angle of AFM images of Fig. 3.**

We found that similar to the roughness, the wavelength increase with increasing angle especially for both InSb (001) and GaSb (001) samples where the nanodots changes to ripple like structure. The driving force of the incoming ion beam leads to sputtering of material from the surface that makes the surface rough. The topography evolution in the form of islands or dots can be explained in the light of preferential sputtering of one of the components in one side and the role of roughening and smoothing processes due to bombarding on the other side. Salah et al [9] determined Surface compositional information using a linear TOF SIMS spectrometer working in a static mode ,compared the Signal intensity of the sputtered  $\text{In}^+$ ,  $\text{Sb}^+$  and  $\text{In}_2^+$  secondary ions of pristine InSb (001) surface and for the same surface irradiated with the fluence of  $10^{16}/\text{cm}^2$  at normal incidence.  $\text{In}^+$  and  $\text{In}_2^+$  intensities for the irradiated sample are much higher in comparison to the pristine one, whereas  $\text{Sb}^+$  ions show a reversed tendency. This behavior suggests a significant (In) enrichment at the InSb (100) surface

occurring for ion modified samples. Due to the enhanced diffusion, (In) atoms agglomerate into (In) islands on InSb (001) surfaces. Frost et al. [16] concluded that (In) enrichment and agglomeration are behind the island formation in the initial stages of sputter erosion on the InP (001) surfaces. Facsko et al [17] and the enrichment of (Ga) by 30 at% in the dots on GaSb (001) were founded by using Auger electron spectroscopy. The main mechanism for the observed islands or dots is a result of (In) enrichment and agglomerations as the initial stages of ion sputtering. In general, one can categorize the obtained results into three main parts: (i) Dot formation at  $\theta_{\text{ion}} = 25^\circ$  and  $45^\circ$ ii) the transition from dots to ripples (around  $\theta_{\text{ion}} = 60^\circ$  and iii) the ripple formation (at  $\theta_{\text{ion}} = 70^\circ$  and  $80^\circ$ ).

As the angle increased from the specific window (specific angle) depending on the target type, roughness of surface is almost decreased, which attribute to the higher sputtering at the top part of the dots in comparison with the bottom part of the dots, which results in the surface smoothing. Further, the sputtered atoms are re-deposited in the forward direction causing the elongation of dots along the ion beam direction. The ion-induced surface diffusion leads to the elongation of the surface structures. Also, because of the agglomerations and enrichment of one component of the compounds due to preferential sputtering, can be considered as a mobile layer, less interaction with the target surface (immobile layer) which supplies (Ga) atoms to the mobile layer in the case of GaSb and (In) in the case of InSb and InP, two layers are introduced to describe different materials of a GaSb, InSb and InP substrate.

Seugjun Lee [18] summarize the previous mechanisms in to three parts: sputtering, redistribution, and mass transportations which shown in Fig. (6).



**Fig. 6 schematic diagram of the mechanism of surface nanostructuring [18]**

### Conclusion

It was demonstrated that low-energy Ar ion beam erosion could be used to produce different self-organized patterns on III-V (001) surface. The experimental results show different patterns by varying the ion incidence angle. Starting with near normal ion incidence, nanoscale dots emerge on the surface of InSb, InP and GaSb which transform into highly ordered ripples for approaching grazing incidence angles.

Further, nano ripples were start aligning and elongating along the ion beam direction which follow the prediction of Bradely and Harper [3]. The RMS roughness decreases with increase in incidence angle of the beam indicating the role of smoothing term. The size and order of the dot structures formed on the irradiated surfaces is angle dependent due to the ion enhanced surface diffusion and the erosion.

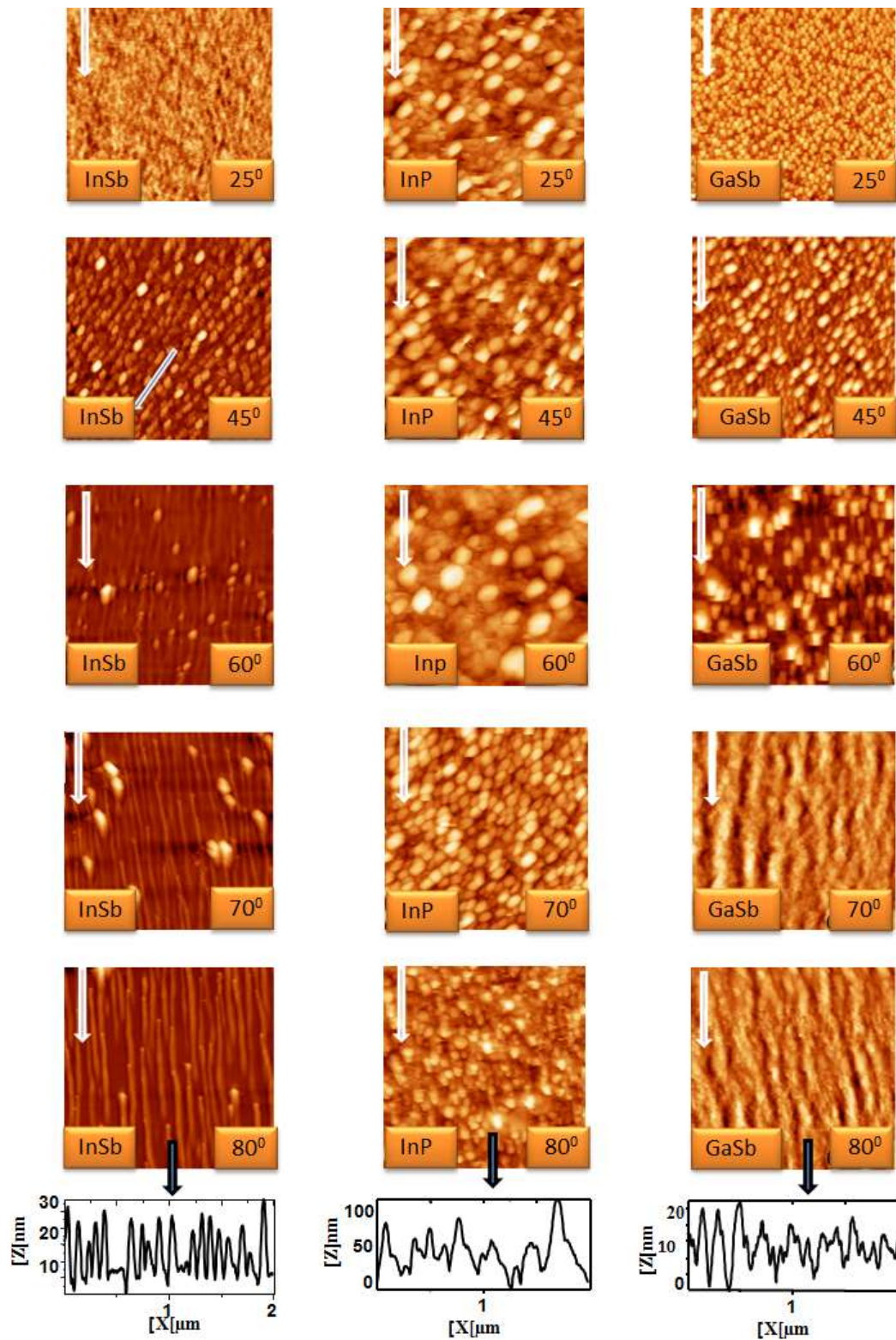
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**Fig. 3** AFM images of InSb(001),InP (001) and GaSb (001) surfaces in contact mode under the experimental parameters 2keV, fluence  $8.8 \times 10^{16}$  ion/cm<sup>2</sup> with different incidence angles 25°,45°,60°,70°,80° off-normal at room temperature.