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Formation of self-organized nanostructures on semi-insulating InP by 100 keV Ar^+-ion irradiation

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ABSTRACT

We report on formation of self-organized nanodots on semi-insulating InP surface due to bombardment by 100 keV Ar^+ ions incident both normally and off-normally (0°, 30°, 60°, and 75° with respect to the surface normal) for three fluences viz. 1×10^{17}, 5×10^{17}, and 1×10^{18} ions cm^{-2} at room temperature and without any substrate rotation. The novelty of our work is that we have studied pattern formation, at this energy range, in a systematic manner as a function of incident angle of ions. It is seen that average dot-size, -height, and inter-dot distance decrease with increasing angle of incidence (for a given fluence), while dot density increases. This trend is followed for all the fluences under consideration. RMS surface roughness shows a decreasing trend with increasing angle of incidence. This is indicative of surface smoothening due to enhanced ion induced surface diffusion at higher incident angles. Dot formation is attributed to preferential sputtering. We do not observe any transition from dot to ripple pattern unlike low energy experiments performed on semi-insulating InP substrates. Although evolution of dot patterns on both *n*- and *p*-type InP surfaces, at intermediate energies, are known there are subtle differences in terms of variations in dot-size and -density for semi-insulating InP substrates.

1. Introduction

Patterning of regular nanodot arrays on semiconductor surfaces is of immense importance due to their potential applications in optoelectronics, photonics, and recording media [1]. Ion irradiation is a promising tool for nanopatterning of semiconductor surfaces because of its compatibility and reproducibility with easily controllable growth conditions [2]. In general off-normal ion incidence leads to ripple formation while normal incidence leads to dot formation [3]. Ion induced self-organized nanostructure formation on a large area is a single step process and is faster than the conventional lithographic techniques. Size and shape of ion-beam synthesized nanostructures are dependent on ion-energy, -fluence, -incident angle, and sample rotation.

Nanostructuring of III–V semiconductor surfaces has been a topic of recent investigation by using ion erosion at (∼0.25–1.2 keV) [4,5] and intermediate energies (50–100 keV) [6,7]. There have been several studies on evolution of self-organized surface nanostructures due to low energy (0.5–3 keV) ion bombardment on InP as well. For instance, it was observed that self-organized, ordered dot patterns form either for normally incident ions [8,9] or in off-normal geometries [10–12]. Sample rotation during exposure also plays an important role to govern the morphology [10,13]. This becomes quite contrasting when one compares results of Frost et al. [10] and Paramanik and Varma [12] where the former group observed dot coarsening followed by a saturation in dot size with increasing sputtering time but the latter group observe dot coarsening followed by inverse coarsening with increasing sputter time. In addition, Frost et al. observed smoothing of InP surface at higher incident angles. In a recent report, Sulania et al. [14] observed nanodot pattern at normal and near normal incident angles due to 1.5 keV argon bombardment to the fluence of 8×10^{16} at. cm^{-2}. The dot pattern transforms into well-ordered ripple pattern at higher incident angle of 63°.

On the other hand, there have been very limited studies on evaluation of surface morphology due to intermediate energy (50–100 keV) Ar^+-ion induced sputtering of InP. Mohanta et al. [2,15] and Som et al. [16] have reported that average dot size increases with increasing fluence for both *n*- and *p*-InP(1 0 0) samples in the range of 50–100 keV. Dot formation at oblique angles was also studied by these two groups [15,16]. However, these studies are mostly limited to temporal evolution of morphology on InP surface at selective angles and fluences and hence further systematically performed experiments are needed to address the issue of evolution of novel features.

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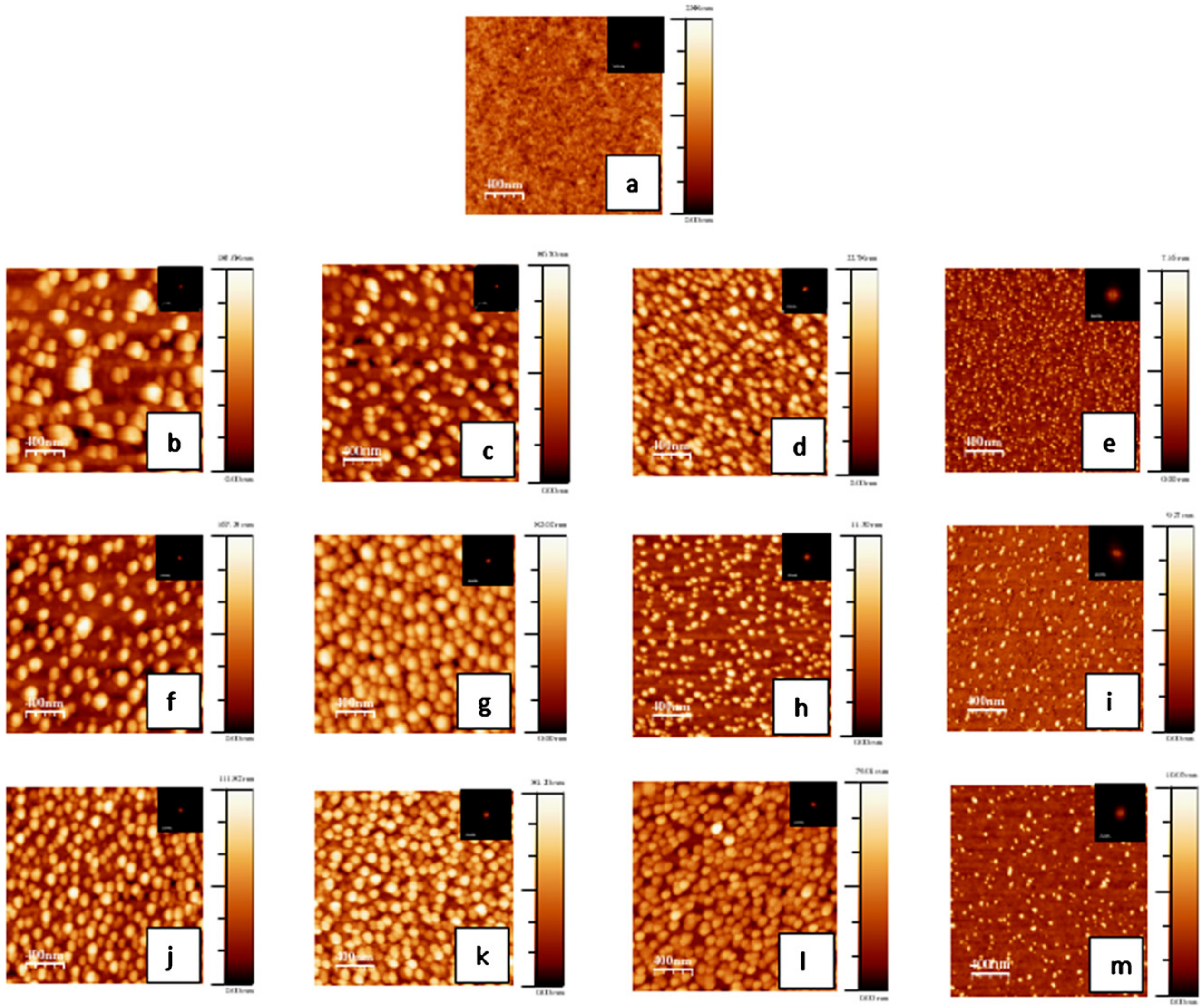

Fig. 1. AFM micrographs (2 μm × 2 μm) of *SI*-InP(1 0 0): (a) pristine; implanted with 100 keV Ar^+-ions to the fluence of 1×10^{17} ions cm^{-2} at incident angles of (b) 0°, (c) 30°, (d) 60°, and (e) 75°; fluence of 5×10^{17} ions cm^{-2} at incident angles of (f) 0°, (g) 30°, (h) 60°, and (i) 75°; fluence of 1×10^{18} ions cm^{-2} at incident angles of (j) 0°, (k) 30°, (l) 60°, and (m) 75°. The insets represent the 2D-FFT of the respective images.

The motivation of the present investigation is to explore the evolution of surface morphology on semi-insulating (*SI*) InP surface at intermediate ion energies, in a systematic manner, as a function of ion fluence and incident angle. This includes looking for the possibility of forming ripple patterns on *SI*-InP surface at higher oblique incident angles which would be complementary to the recent findings of Sulania et al. at low energies [14]. In addition, it may be mentioned that for intermediate energies different surface morphology evolves in case of *SI*–GaAs which is quite contrasting in nature compared to its *p*-and *n*-type counterparts [6,7,17]. Thus, we would also like to address this issue for *SI*-InP.

2. Experimental

For the present study, semi-insulating Fe-doped InP(1 0 0) samples were exposed to 100 keV Ar^+-ions, at room temperature (RT), which were allowed to fall both normally and off-normally (30°, 60°, and 75° with respect to the surface normal) and without any substrate rotation. The projected range of normally incident Ar^+-ions in InP, calculated by SRIM-2006, is about 84 nm [14]. We used an average current density of 10 μA cm^{-2} and three fluences were used, viz. 1×10^{17}, 5×10^{17}, and 1×10^{18} ions cm^{-2}. Experiments were carried out under a secondary electron suppressed geometry. An electron cyclotron resonance (ECR) based ion source was used and homogeneous irradiation was achieved by scanning the beam over the samples. The surface morphology of the implanted samples was imaged *ex situ* in AC mode by using a large area, high precision atomic force microscope (AFM) (make: Asylum Research-MFP3D, USA). A large number of images (of 1×1–20×20 μm^2 scan sizes) were collected to have high reliability of the extracted parameters. SRIM-2008 simulation provides the projected range of 100 keV argon ions which varies from 84 to 72.7 to 42 to 21.74 nm corresponding to normal and oblique incidences of 30°, 60°, and 75° respectively [18]. X-ray photoelectron spectroscopy (XPS) technique was used to study changes in the chemical composition of samples. XPS measurements of InP samples, before and after Ar-ion irradiation, were carried out using a monochromatic Al Kα X-ray source.

3. Results and discussion

Fig. 1(a)–(m) shows AFM images of InP surfaces obtained before and after exposure to argon ions to the fluences of 1×10^{17}, 5×10^{17}, and 1×10^{18} ions cm^{-2} (at different angles of incidence in the range of 0–75°). AFM results reveal that the pristine sample has a fairly smooth surface (RMS surface roughness 0.2 nm). For each fluence