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Fabrication of finite aligned nano-hole and trench structures with atomically flat surface by using atomic hydrogen induced surface cleaning technique

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We fabricated finitely aligned nano-hole and trench structures on GaAs (001) by using atomic force microscope (AFM) tip-induced oxidization and atomic hydrogen cleaning. Highly aligned oxide dots and lines at nano-meter scale were patterned by using programmable AFM tip-induced oxidization. Then, the oxide structures were removed by atomic hydrogen cleaning technique. Finally, the nano-hole and trench structures with atomically flat surface were successfully achieved. The smallest diameter and depth for nano hole are 13.4 nm and 0.34 nm, respectively.

Key words: Nano-hole/trench, Atomic hydrogen, AFM oxidation, GaAs, MBE

1. INTRODUCTION

Atomic hydrogen has been an interesting element in semiconductors because it can be used for surface cleaning, dopant, band-gap tuning, hydrogenated, wafer bonding, hydrogen-assisted crystal growing, and passivation for semiconductor process [1-8]. One of the particular cases using hydrogen is surface cleaning of semiconductor materials. For the last two decades, many of researchers have confirmed the atomic hydrogen-induced surface cleaning to get a high quality epilayer during initial growth stage and atomically flat semiconductor surface for further processes.

Recently, zero-dimensional system at nano-meter scale has been widely studied in terms of both fundamental physics and potential device applications such as quantum coupling, quantum dot cellular automation, and quantum computation. In particulars for the application of the quantum electronic devices, it is necessary to effectively control the size and position with high quality. Most of the research works for the fabrication of site-controlled nano-structure by artificial techniques have been reported by using electron beam lithograph [11], scanning tunneling microscope (STM) tip-induced patterning [12], and AFM tip-induced oxide patterning [13-17]. A number of works demonstrated that AFM could be used for the oxidation on semiconductors, metals, and polymer films.

The fabrication of nano-hole and nano-trench structures has been used for the nucleation center of the site-controlled quantum nano-structure by manipulating the atomic migration. Nano-hole structures were introduced by depositing a thin GaAs layer on STM tip-induced patterning on GaAs (001) substrate [12] , electron beam lithograph combined with Cl_2 gas etching on GaAs [11], and locally strain-enhanced selective etching of a GaAs cap layer above an InAs QD layer [19]. Nano-trench structure was also fabricated by AFM tip-induced oxidization using NH_4F etching on Si (111) [18] and direct patterning using AFM on GaAs (100) surface [20]. To realize the site-controlled nano-structure based on the migration control of newly supplied adatoms, the atomically flat surface is also required after the formation of nano holes and trenches because the atomic migration on surface can be seriously affected by surface roughness. Therefore, it is also necessary to fabricate nano holes and trenches with atomically flat surface morphology.

In this work, in order to achieve highly aligned nano-hole and trench structures with atomically flat surface, well-defined AFM tip-induced oxidization and removing the oxidized structures on GaAs (001) by atomic hydrogen cleaning were used.

2. EXPERIMENT

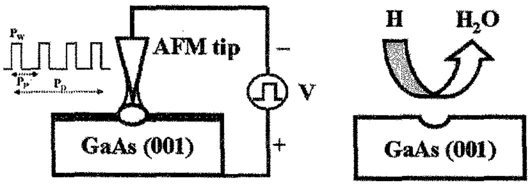
To obtain the atomically flat GaAs surface, the starting GaAs buffer layer was grown by Riber 32P molecular beam epitaxy on Si doped GaAs (001) substrates. After native oxide desportion by conventional thermal cleaning, the substrate temperature was set to 580 °C for the growth of 300 nm GaAs buffer layer, 10-period GaAs / AlGaAs superlattice, a 300 nm GaAs over layer, 6-period GaAs / AlGaAs superlattice, and a 10 nm GaAs top layer. The surface flatness of the starting GaAs layer was conformed by high-resolution AFM (Seiko SPA-4000).

The starting surface was mounted on programmable AFM with Si cantilevers (Hitatch SPF-200M) for making nano-oxide structures. AFM-induced nano-oxide patterning on GaAs surface was conducted at different humidity (55~65%) at room temperature. The oxidation on GaAs surface was achieved by applying a bias voltage between the AFM tip and GaAs surface. After patterning the oxide structure, the surface morphology of patterned surface was immediately obtained by using AFM (Seiko SPA-4000) with rhodium-coated cantilevers.

In order to remove the oxide structures from GaAs surface, the substrate was moved into MBE chamber immediately. Then the oxide structures were removed by using atomic hydrogen cleaning method. Atomic hydrogen was generated by molecular hydrogen cracking cell with a tungsten filament. During the surface cleaning, the substrate temperatures were kept below 500 °C in order to prevent Ga or As desorption from the surface. The oxide removal from the GaAs surface was conformed by the observation of high-energy electron diffraction (RHEED) pattern. After surface cleaning, the surface structures were confirmed by AFM.

3. RESULTS AND DISCUSSION

Figure 1 shows the schematic illustration of the experimental procedures for the formation of the oxide structures by AFM and subsequent removing of oxide structures by atomic hydrogen irradiation. The AFM tip-induced oxide structures are composed of Ga-oxide (Ga_2O_3) and As-oxide (As_2O_x). During the atomic hydrogen cleaning, the products of these reactions become water molecules as well as As_2, Ga_2O and metallic Ga [4].



(a) (b)

FIG.1 Schematic illustration for the formation of oxide structure by AFM (a) and removal of the oxide structures by atomic hydrogen cleaning (b)

Figure 2 shows selective AFM image for the oxide dots fabricated on the same substrate at different bias voltage (9-11 V). With an increase in the bias voltage, the diameter and height of the oxide dots were increased and the size distribution (***D_L-D_S/D_S***) are also increased from 32% to 80% (at humidity 55% and pulse period 20 ms). Similar results were demonstrated on silicon, silicon nitride (Si_3N_4), diamond, titanium and GaSb surface as a same manner [13-15].

Figure 3 shows the RHEED patterns for GaAs surface after atomic hydrogen cleaning for 30 minutes. We could not observe any RHEED pattern except a halo pattern before atomic hydrogen cleaning, because the amorphous oxide layer covers GaAs surface. When the sample is heated at a temperature up to 500 °C, only halo pattern was still observed indicating that an amorphous layer existed on the GaAs surface. The surface is then cleaned by using atomic hydrogen in the temperature range from 450 to 500 °C for 30 minutes. After cleaning process, a RHEED pattern with (2×4) reconstructions were clearly observed, indicating a clean and oxide free GaAs surface was obtained.

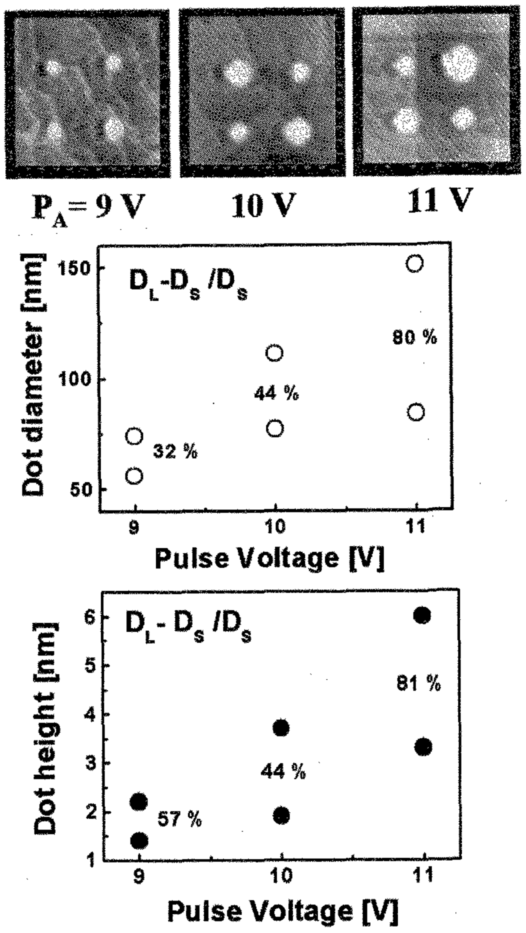


FIG. 2 Selective AFM image for the oxide dots at different bias voltage and oxide size distribution.

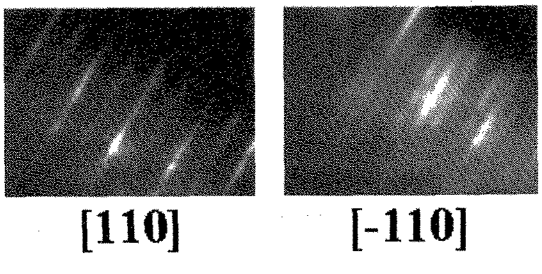


FIG. 3 Typical reflection high-energy electron diffraction (RHEED) patterns taken along the [110] and [-110] after atomic hydrogen cleaning at 400 °C.

Figure 4 (a) shows the taping mode AFM images for the nano-hole/trench structures after cleaning by atomic hydrogen at optimized conditions. Atomically flat surface with a few monolayer step are observed. From these results, the highly aligned nano-hole and trench structures with atomically flat surface can be clearly fabricated by atomic hydrogen cleaning. Fig. 4 (b) shows the summary on the size distribution of hole structures. The smallest diameter and depth for hole are 13.4 nm and 0.34 nm, respectively. In addition, the aspect ratio of hole (depth/diameter) is 0.057.

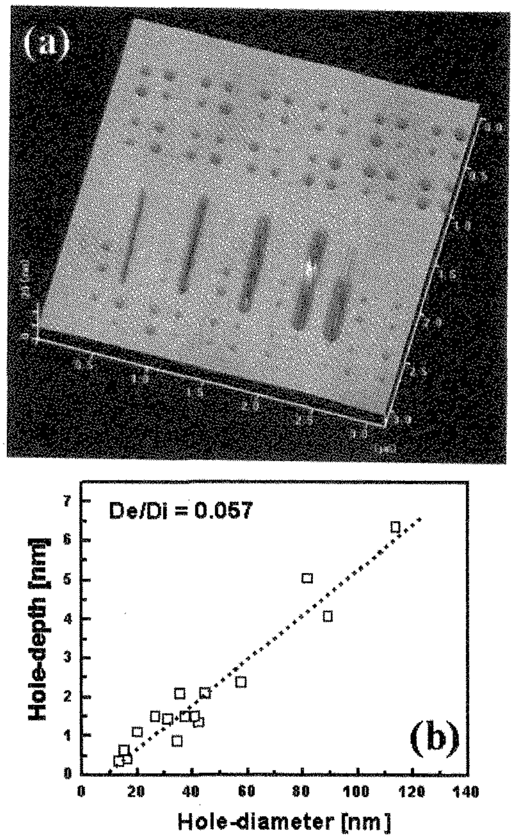


FIG. 4 (a) Tapping mode AFM image for nano-hole/trench structures. (b) Summary on the size distribution of nano-hole structures.

4. CONCLUSIONS

Finitely aligned nano-hole and trench structures with atomically flat surface were fabricated by using atomic force microscope (AFM) oxidization and surface cleaning by using atomic hydrogen on GaAs (001) surface. The nano-hole and trench structures reflected their initial size of oxide structure without any degradation in atomically flat surface. The smallest diameter and depth for nano-hole are 13.4 nm and 0.34 nm, respectively. From these results, we believe that this nano-structure with atomically flat surface can be important for the realization of the site-controlled nano-structures based on the atomic migration control.

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