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Tapered-Surface Etching of GaAs Utilizing Low-Energy Ion Bombardment Effect

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Abstract: A technique for fabricating tapered-surface structures on GaAs crystals is demonstrated. GaAs crystals are bombarded with low-energy (5 keV) Ar^+ ions, and the partially masked surfaces are etched with an aqueous solution of $FeCl_3$–HCl. Effect of the ion bombardment-enhanced etching is utilized to proceed a high-rate lateral etching under the mask, and to reveal a surface with a taper angle of 10–45°, depending on the ion dose.

Keywords: GaAs, Ion bombardment-enhanced etching, $FeCl_3$–HCl, Tapered-surface

1. Introduction

The tapered-surface structures on GaAs substrates are often employed in integrated-optics applications, such as wave guides coupling and mode control for semiconductor lasers. For instance, the tapered couplers efficiently transfer light from one wave guide layer to another with a small disconnection error. The fabrication techniques of tapered-surface structures have been reported by many researchers with various methods, such as LPE$^{1)}$, MBE$^{1)}$, dry etching$^{2)}$, and wet etching$^{3)}$. However, it is difficult to obtain tapers with smooth surface and arbitrary taper angle by the conventional methods, and the taper angle tends to depend on the crystallographic direction.

The ion bombardment-enhanced etching can be employed for patterning of various crystals$^{4),5)}$. The bombarded layer is etched at a higher rate than that for the unbombarded region. If the bombarded layer is partially covered with resist, the fast etching of the bombarded layer proceeds in lateral direction under the resist, and a tapered-surface structure is produced. In order to obtain a uniform taper, it is desirable that the etching is isotropic, thus the choice of the etchant is very important.

In this paper, we report a technique for fabricating tapered-surface structures on GaAs substrates. The technique employs low-energy ion bombardment and subsequent wet chemical etching. We used an aqueous solution of 0.5M $FeCl_3$–1.2M HCl for the etchant$^{5)}$. The characteristics of the etchant are (1) the etching rate for the crystalline region is very slow, and (2) the etching rate is independent of the crystal orientation, and thus, we can obtain an isotropic undercut. It will be shown that the tapered-surfaces with angle of 10–45° are obtained, and the taper angle can be controlled by adjusting the ion dose.

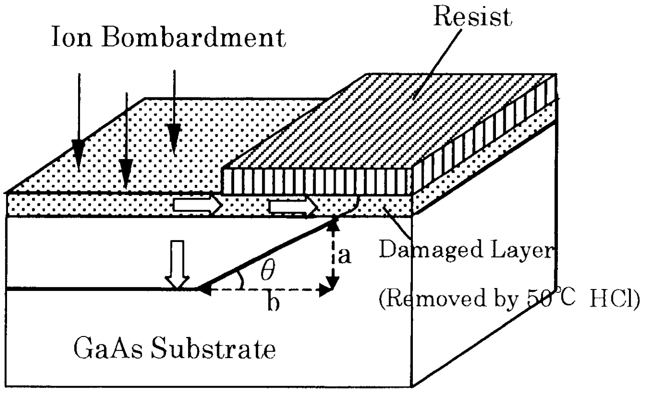

Fig.1 Schematic illustration of sample used for taper fabrication. The GaAs crystal bombarded with 5 keV Ar^+ is partially covered with resist and etched with 0.5M $FeCl_3$–1.2M HCl. The dotted region shows the damaged layer.

2. Experiment

Figure 1 schematically illustrates a sample used for fabricating the tapered-surface structures. In the experiment, (100) orientated n-type GaAs wafers were used. After a standard cleaning procedure, the wafers were bombarded with 5 keV Ar^+

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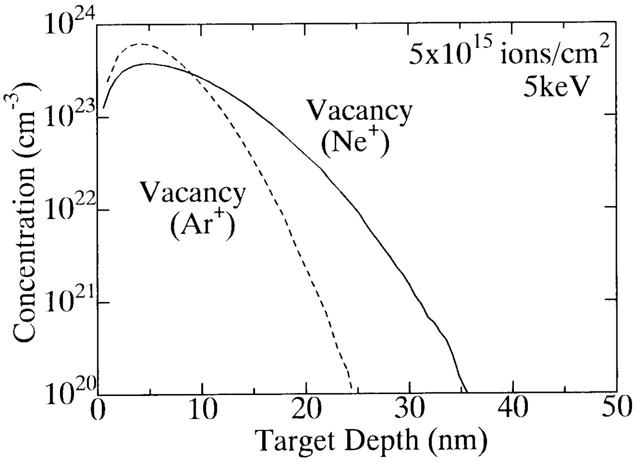


Fig.2 Vacancy concentration profile evaluated with the TRIM 90 code for samples bombarded with 5 keV Ar^+ (broken line) and Ne^+ (solid lines) to a dose of 5×10^{15} ions/cm^2.

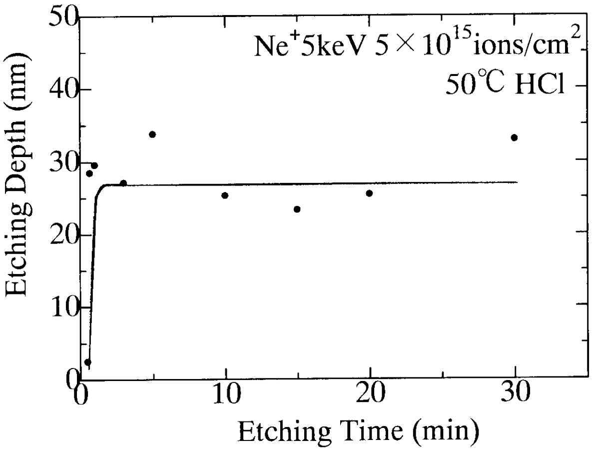


Fig.3 Etching depth as a function of etching time for samples bombarded with 5 keV Ne^+ to a dose of 5×10^{15} ions/cm^2 in 50°C HCl.

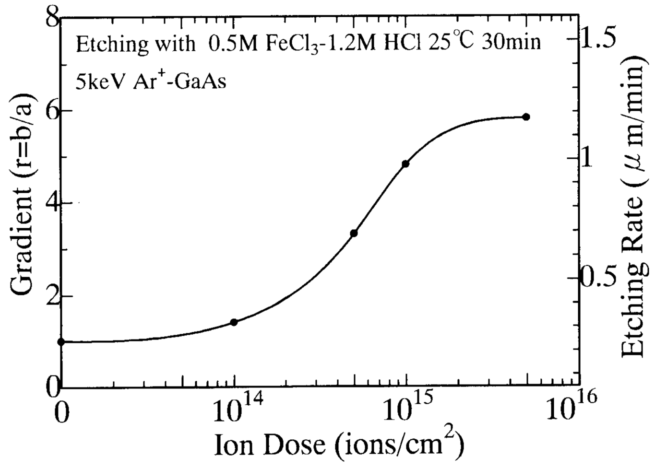


Fig.4 Ion dose dependence of taper gradient r (●) for samples bombarded with 5 keV Ar^+ and etched with 25°C 0.5M $FeCl_3$–1.2M HCl for 30 min. The corresponding etching rate of damaged layers is shown by the right axis.

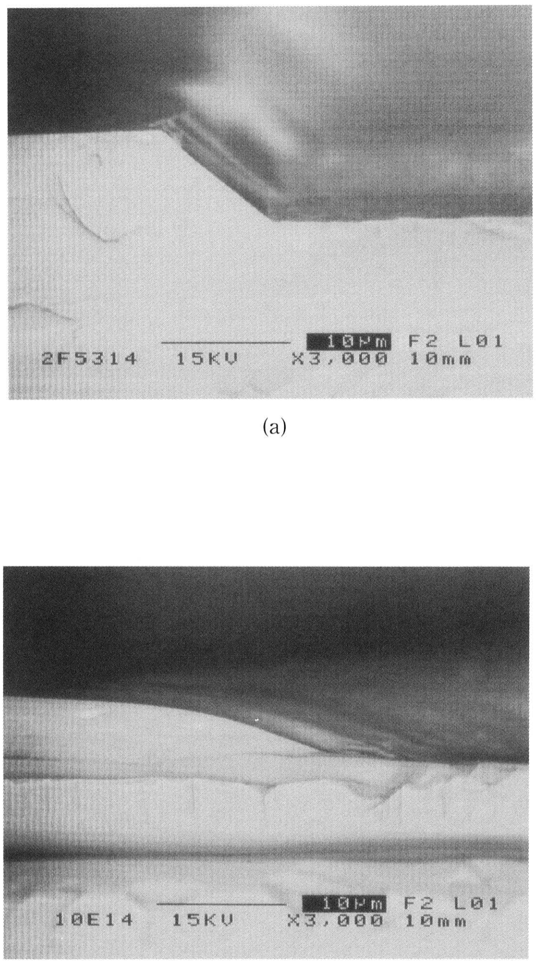
to a dose of 1×10^{14}–5×10^{15} ions/cm^2 at R.T. with dose rate of 6.3×10^{11} ions/cm^2s. In order to minimize the channeling effect, the wafers were tilted by 7° with respect to the incident beam. The bombarded samples were then partially covered with resist and etched with 0.5M $FeCl_3$–1.2M HCl at 25°C for 30 min. After removing the resist, the remaining damaged layer was etched off with 50°C HCl for 10 min. The lateral undercut b and the etching depth a were measured with the contract surface profiler Tencor AS500, and the gradient of the taper $r = b/a$ was estimated. The taper angle θ is obtained by $\theta = \tan^{-1}(1/r)$.

Figure 2 shows the vacancy concentration profiles evaluated with TRIM 90 code[6) for samples bombarded with 5 keV Ar^+ and Ne^+ to a dose of 5×10^{15} ions/cm^2. It can be seen that the depth at which the vacancy concentration is the same value is deeper for Ne^+ bombardment than that for Ar^+, and the damaged layer induced by Ne^+ bombardment is thicker than that by Ar^+ bombardment. Thus, for the evaluation of the etching characteristics of the damaged GaAs with 50°C HCl, we employed samples bombarded with 5 keV Ne^+ to a dose of 5×10^{15} ions/cm^2.

3. Results and Discussion

In order to precisely obtain the values of a and b shown in **Fig. 1**, the remaining damaged layers must be removed. Thus, first, we have investigated the etching charateristics of damaged GaAs layer with HCl solution. **Figure 3** shows the etching depth as a function of etching time for samples bombarded with 5 keV Ne^+ to a dose of 5×10^{15} ions/cm^2 in the etchant of 50°C HCl. The damaged surface layer is etched completely in less than 1 min, and etching stops at an approximately constant depth. Considering the vacancy distribution calculated with TRIM 90 code shown in **Fig. 2**, it is found that etching stops at the depth where the vacancy concentration is about 1×10^{22} cm^{-3}. Thus, it is concluded that, for the case of Ar^+ bombardment, the 50°C HCl also completely etches off the damaged GaAs layers containing vacancies more than about 1×10^{22} cm^{-3} in the etching time of 10 min, and the etching stops after removing the layers.

Next, we have investigated the fabrication process of taper structures by using bombardment with



(a)

(b)

Fig.5 SEM cross-sections of GaAs taper structures. The samples were bombarded with 5 keV Ar^+ to dose of 1×10^{14} (a) and 1×10^{15} ions/cm^2 (b).

5 keV Ar^+ and subsequent etching with 25°C 0.5M $FeCl_3$–1.2M HCl for 30 min. The dose dependence of the gradient r (●) for samples bombarded with a dose of 1×10^{14}–5×10^{15}Ar ions/cm^2 and without the bombardment is shown in **Fig. 4**. The corresponding etching rate of the damaged layers is shown by the right axis, and it is found that the etching rate depends on the damage concentration induced by the bombardment. Since the etching is isotropic, the gradient r is 1, thus the taper angle is 45°, for the unbombarded sample.

If any bombarded layers exist under the resist, the etching rate for the layers is higher than that for the unbombarded region, and the lateral etching proceeds under the resist faster than the logitudinal etching. Thus, we can obtain tapered surfaces with an angle of 10–45°, which is precisely controlled by the degree of the damage at the surface layers. It is also shown in **Fig. 4** that the gradient r is nearly 1 for dose smaller than the critical value of 1×10^{14}Ar ions/cm^2. Under the critical dose, no damaged layers containing vacancies more than about 1×10^{22} cm^{-3} are formed, and thus the fast lateral etching of the surface layer does not proceeds under the resist.

SEM cross-sections of the tapered GaAs surfaces are shown in **Figs. 5 (a)** and **5(b)**. The surface of the taper is smooth, and no micro structures originated from the different crystallographic directions are observed. In the integrated optics application, the bombardment defects remaining in the devices may affect the performance. As shown previously in our experiment, the damaged layers are completely etched off by the treatment with 50°C HCl for 10 min, and the tapered-surface structures are formed in the crystalline region. Furthermore, the defects diffused from the damaged layers can be removed by annealing at low temperature of 600°C[5]. Therefore, though the present process utilizes ion bombardment, degradation of performance due to defects induced by the bombardment can be eliminated by the subsequent thermal processing, and we can take advantage of the controllability of the taper angle in fabrication of optical devices and optical integrated circuits.

4. Conclusion

Low-energy ion bombardment-enhanced etching has been investigated in order to fabricate tapered-surface structures. In the fabrication, we have employed the 5 keV Ar^+ bombardment and subsequent etching with 25°C 0.5M $FeCl_3$–1.2M HCl for 30 min. It has been shown that the etching is isotropic and the rate depends on the damage concentration induced by the bombardment. The taper angle can be precisely controlled by the ion dose, and the angle in the rage of 10–45° has been obtained for samples bombarded with 5 keV Ar^+ to dose of 1×10^{14}–5×10^{15} ions/cm^2. This method can be employed for the precise control of tapered-surface structures in fabrication of optical devices and optical integrated circuits.

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