A Nanoscale Plasma Etching Process for Pole Tip Recession of Perpendicular Recording Magnetic Head

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The pole tip of perpendicular recording head is constructed in a stacked structure with materials of NiCoFe, NiFe, Al2O3 and AlTiC. The surfaces of different materials are set at different heights below the air-bearing surface of slider. This paper presented a plasma dry etching process for Pole Tip Recession (PTR) based on an ion beam etching system. Ar and O2 mixed plasma at small incident angles have a high removal rate to the nonmagnetic material. It was utilised to etch the reference surface until it reaches the MT value. Low-energy Ar plasma at a small incident angle removes materials with selective ratios of 1 : 1.6 : 2.5 : 2.9 (AlTiC/Al2O3/NiCoFe/ NiFe). It was selected to form the PTR. High-energy Ar plasma at a large incident angle exhibits almost same removal rates for all materials. It was adopted to make overall removal while keeping the recessed profile. An atomic force microscope (AFM) was used for measuring the recessed heights of pole tip and the MT value of the base surface. A transmission electronic microscopy (TEM) was chosen to examine the thickness of subsurface damage. A batch of production showed that the recessed heights can be successfully nanofabricated with the three-step plasma etching process.

Keywords: pole tip recession, plasma etching, selectivity, removal rate, ion damage.

1. INTRODUCTION

The pole tip of perpendicular recording magnetic head in a hard disk drive (HDD) is constructed in a stacked structure with materials of NiCoFe, NiFe, Al2O3 and AlTiC. It is located at the front position of the head slider, as shown in Fig. 1 a. The flying height from the pole tip to the disk surface is less than 10 nm. With a small flying height and a perpendicular magnetic recording technique, this kind of pole tips result in a very high areal density [1, 2]. To prevent contact damage with a disk, surfaces of different materials are set at different heights of several nanometers below the air-bearing surface of slider, as shown in Fig. 1 b. The recessed topology is referred to as Pole Tip Recession (PTR) [3–5].

Mechanical polishing, chemically mechanical polishing and plasma etching are three typical methods for PTR [6]. Mechanical or chemically mechanical polishing belongs to a kind of wet polishing techniques, and there is damage in some degree to pole tip materials if chemical solvent is used. The recessed heights are difficult to control because the selectivity of removal rates to different materials is influenced by lapping pressure. Consequently, mechanical or chemically mechanical process cannot be applied in the final stage of PTR. Plasma etching is a promising one especially for plasma dry etching because there is no processing force during etching [7, 8]. Many studies have been carried out theoretically or experimentally on plasma etching [9–15]. At present, plasma etching is still facing some difficulties before use, for example, the selection of ion energy, controlling etch selectivity of different materials and acceptable etch uniformity.

In this paper, we adopted an ICP-type high-density ion beam etching system to generate Ar plasma, or Ar and O2 mixed plasma for nanofabrication of PTR. We first identified the selective effects of etching rates under different ion incident energy and different ion incident angles on different materials of pole tip. Then we designed a three-step plasma etching process to form the recessed nanostructure of pole tip. Finally, a batch of pole tips was etched for verification of the plasma etching process.

2. EXPERIMENTAL METHODS

2.1. The materials and recessed heights of pole tip

Fig. 1 b shows the stacked structure and material composition of a pole tip, where WS is the writing region or writing pole, OC is the overcoat for insulating, AlTiC (Al2O3-NiC) is the head base material. The material composition of WS is NiCoFe (83, 1, 16 wt.%), SF is NiFe (83, 17 wt.%), WS and SF are magnetic material. AlTiC and Al2O3 are nonmagnetic material.

AlTiC surface is also referred as reference surface. It forms the air-bearing surface (ABS) of slider after coating with diamond-like carbon (DLC) films. MT is an important parameter to describe the micro texture of AlTiC surface. As shown in Fig. 4 a and Fig. 10 a, AlTiC surface after etching is a composite of Al2O3 and TiOx showing two statistical peaks in height. The MT value refers to the difference in height of two statistical peaks of two materials. Because MT influences the flying status of slider, the base surface of AlTiC is qualified with MT.
Targets of plasma etching for PTR are, in achieving, 
HOC = –3.5 ± 1 nm (OC recession), HWS = –0.8 ± 0.5 nm (WS recession), and MT = 1.8 ± 0.2 nm (ABS protrusion), while minus sign (–) means height of material is lower than the reference surface and positive sign (+) means height of material is higher than the reference surface. The etched area was controlled within 30 μm × 60 μm.

As shown in Fig. 2, the incident ray of plasma forms an angle with the normal of substrate surface. This angle is named as incident angle. More precisely, incident angle refers to the angle between an incident ray of plasma and the normal of substrate surface.

2.3. Experimental procedure
To find characteristics of plasma etching of elementary materials of pole tip, we designed the experiment as follows.

Experiment 1. We used a mixture of Ar and O₂ plasma to identify the influence of ion incident angles on etching rate and MT. Experiment parameters were RF power = 130 W, anode voltage = 300 V, cathode voltage = –400 V, etching time = 6.5 min, Ar:O₂ = 15:3, flow rate of Ar = 15 sccm (standard cubic centimeter per minute, sccm), flow rate of O₂ = 3 sccm, working pressure = 0.1 Pa.

Experiment 2. We used low-energy Ar plasma to investigate the influence of ion incident angles on etching rate and MT. Experiment parameters were RF power = 105 W, anode voltage = 285 V, cathode voltage = –400 V, etching time = 6.5 min, flow rate of Ar = 18 sccm, working pressure = 0.1 Pa.

Experiment 3. We used high-energy Ar plasma to find the influence of ion incident angles on etching rate and MT. Experiment parameters were RF power = 150 W, anode voltage = 285 V, cathode voltage = –400 V, etching time = 6.5 min, flow rate of Ar = 18 sccm, working pressure = 0.1 Pa.

Experiment 4. We used high-energy Ar plasma to find damage depth in the subsurface of pole tip profile. Experiment parameters were RF power = 180 W, anode voltage = 200 V – 500 V, cathode voltage = –200 V, etching time = 80 sec, flow rate of Ar = 18 sccm, working pressure = 0.1 Pa. After etching, surfaces of pole tip were coated with a layer of DLC film of 4 nm in thickness to prevent the substrate from oxidative corrosion. The DLC film was deposited by using a filtered cathodic vacuum arc (FCVA) physical vapor deposition (PVD) method.

Experiment 5. We etched a batch of pole tips with a three-step plasma etching process. The parameters adopted by each step, as detailed above, were shown in Table 1. We checked the recessed heights and MT value with an AFM for PTR process verification.

In above experiments, the etching rate can be measured with a substrate consisting of a protective zone and a non-protective zone. By etching the substrate within given time and measuring the step height of two zones with an AFM, etching rate is calculated as a ratio of step height to given time.

3. RESULTS AND DISCUSSION
3.1. Etching rate and MT in different incident angles of Ar and O₂ mixed plasma
Fig. 3 a shows the dependence of etching rates on the incident angles in the condition of using Ar and O₂ mixed plasma. When the incident angle is in the range of 30° to 50°, the etching rates of magnetic material, NiCoFe and NiFe are changed very little. Their etching rates remain at about 0.8nm min⁻¹.
Table 1. Three-step etching process for PTR

<table>
<thead>
<tr>
<th>Step</th>
<th>RF power, W</th>
<th>Grid bias, V</th>
<th>Incident angle, °</th>
<th>Pallet speed, rpm</th>
<th>Etch time, min</th>
<th>Gas flow rate, sccm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>145</td>
<td>316</td>
<td>−400</td>
<td>30</td>
<td>16</td>
<td>6.7</td>
</tr>
<tr>
<td>Step 2</td>
<td>105</td>
<td>220</td>
<td>−550</td>
<td>35</td>
<td>16</td>
<td>5.0</td>
</tr>
<tr>
<td>Step 3</td>
<td>150</td>
<td>285</td>
<td>−400</td>
<td>70</td>
<td>16</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Fig. 3. Etching rates of four materials vary with incident angle (a), and MT of base surface varies with incident angle (b) in a condition of Ar and O₂ mixed plasma.

Etching rates of nonmagnetic material, Al₂O₃ and AlTiC are greater than that of magnetic material. Their etching rates increase first and then decrease with the increase of incident angle. The etching rate of Al₂O₃ is greater than that of AlTiC. When the incident angle is 35°, etching rates of Al₂O₃ and AlTiC reach their maximum values. Fig. 3b indicates the trend of MT as first increasing and then decreasing with the increase of incident angle. When the incident angle is 35°, MT reaches its maximum.

These effects could be explained as follows. In the condition of using Ar and O₂ mixed plasma, the etching process is a combination of ion sputtering and ion assist chemical reaction. The former is referred as physical etching, and the latter is referred as chemical etching. In general, physical etching plays an important role to overall trends of etching rates and MT values because Ar gas is dominant in the gas mixture of Ar and O₂. The incident energy of Ar and O₂ mixed plasma will release in a form of surface diffusion at a big incident angle, or dissipate by ion implantation at a small incident angle. These result in low etching rates and small MT values at two ends of Fig. 3a and b. When the incident angle reaches a value around 35°, sputtering by Ar and O₂ mixed plasma and chemical etching by O₂ plasma will enhance the removal rates to all materials. For magnetic material of NiCoFe and NiFe, ion sputtering is suppressed by the oxides between NiCoFe or NiFe and O₂. This results in a non-obvious increase of removal rate of magnetic material. For Al₂O₃ material, negative charge will accumulate on its surface because of its insulating property. Local high-energy plasma is thus generated and results in a high removal rate of Al₂O₃. For AlTiC material, there is no negative charge accumulation on TiC surface because TiC is a conductive material. The removal rate of TiC is thus lower than that of Al₂O₃. In the same time, O₂ plasma reacts chemically with material elements of Al, C and Ti. TiC is further oxidised as TiOₓ forming the protrusion morphology of AlTiC surface. Fig. 4 shows that the MT value of micro texture at the incident angle of 35° is significantly greater than that at 85°.

Fig. 4. Micro texture etched at incident angle: a – 35°; b – 85°
As a result of Experiment 1, Ar and O₂ mixed plasma...
at incident angles around 30° can be used to fabricate the surface morphology of AlTiC with a high removal rate, until it reaches the MT value. This is a coarse stage of PTR nanofabrication.

3.2. Etching rate and MT in different incident angles of low-energy Ar plasma

Fig. 5 a shows the dependence of etching rates on the incident angles in the condition of using low-energy Ar plasma. In general, etching rates of all materials are relative low. Etching rates increase first and then decrease with the increase of incident angle. This phenomenon is caused by physical collisions between atoms of materials and Ar plasma. When the incident angle is too big, the energy of Ar plasma will release in the form of surface diffusion. The etching rates are thus low. When the incident angle is around 35°, ion sputtering effect will be enhanced and etching rates will increase. Under an incident angle of 35°, etching rates of NiFe and NiCoFe are significantly faster than that of AlTiC and Al2O3. The etching rate of NiFe is the fastest one. Removal rates of four materials are different obviously, showing a selective effect with selective ratios of 1:1.6:2.5:2.9 (AlTiC/Al2O3/NiCoFe/NiFe).

![Etching rate and MT](image)

**Fig. 5. Etching rates of four materials vary with incident angle (a), and MT of base surface varies with incident angle (b) in a condition of low-energy Ar plasma**

Fig. 5 b indicates that MT changes non-apparently in the condition of using low-energy Ar plasma. This phenomenon is caused by the weak striking energy of Ar plasma. Due to the lack of local high-energy, entire surface of materials suffers uniform collisions. In addition, the absence of O2 plasma results that there is no chemical reaction during etching. The chemical selectivity to material elements of C, Ti and Al in AlTiC will not appear. Therefore, in the case of low-energy Ar plasma, the selectivity of etching rates to different material elements of AlTiC is relatively small, and MT changes inconspicuously with the change of incident angle.

As a result of Experiment 2, we can use low-energy Ar plasma at an incident angle of 35° to remove materials with selective ratios of 1:1.6:2.5:2.9 (AlTiC/Al2O3/NiCoFe/NiFe) for the generation of PTR, while keeping the MT value unchanged. This is a fine stage of PTR nanofabrication.

3.3. Etching rate and MT in different incident angles of high-energy Ar plasma

Fig. 6 a shows the dependence of etching rates on the incident angles in the condition of using high-energy Ar plasma. In general, etching rates of different materials converge to similar values with the increase of incident angle. This phenomenon is caused by the physical collisions of Ar plasma. When the incident angle is small, the incident energy of Ar plasma is high. It strikes the surfaces and generates local high-energy in the sputtering direction. This results in an obvious selectivity of etching rates to different materials. While the incident angle increases continuously, the incident energy of plasma reduces dramatically. Low incident energy causes surfaces of all materials in a same excited state, and etching rates are thus reduced to small values.

![Etching rate and MT](image)

**Fig. 6. Etching rates of four materials vary with incident angle (a), and MT of base surface varies with incident angle (b) in a condition of high-energy Ar plasma**

When the incident angle reaches 70°, the selective effect of etching rates to different materials almost disappears, i.e. the removal rates of all materials close together. In this case, if we continue to increase etching time, the surfaces etched will overall sink while the recessed morphology is fixed.

Fig. 6 b indicates that MT shows non-obviously
changes with the increase of incident angle in the condition of using high-energy Ar plasma. The reason is that the absence of O\textsubscript{2} plasma results in no chemical reaction during etching. Under the striking of high-energy Ar plasma, the entire surface of AlTiC suffers uniform collisions. Therefore, the variation of etching rates to different material elements is small and MT changes non-obviously with the change of incident angle.

As a result of Experiment 3, we can use high-energy Ar plasma at a large incident angle of 70° to achieve an overall removal of surfaces of pole tip while keeping recessed morphology unchanged. With the increase of etching time, the required amount of material removal can be obtained accurately. This is a final stage of PTR nanofabrication.

3.4. The damage of subsurface of pole tip

Fig. 7 shows the effect of the grid positive bias (anode) on the thickness of damage layer of magnetic materials in the condition of using high-energy Ar plasma. While fixing the grid negative bias (cathode) as –200 V, with the increase of the grid positive bias, the thickness of damage layer of three different magnetic materials is also increased. If the grid positive bias is less than 300 V, thickness of damage layer changes smoothly. However, if the grid positive bias is greater than 300 V, thickness of damage layer increases obviously. If the grid positive bias reaches or exceeds 400 V, thickness of damage layer increases dramatically. This effect is explained by the increase of the grid positive bias leading to the increase of the plasma energy. With the grid positive bias increasing, electric field strength increases. When the ions pass through the electric field, they will be accelerated and gain more energy. Once the high-energy ions inject to the surface of a substrate, atomic lattices will be destroyed and result in subsurface damage [16, 17]. Fig. 8 shows two TEM images of damage layer of SF under the grid positive bias voltages of 200 V and 500 V.

As a result of Experiment 4, we should keep the grid positive bias less than 400 V in the final stage of etching.

![Fig. 8. TEM images showing the thickness of damage layer under grid positive bias: a – 200V; b – 500V](image)

![Fig. 9. AFM images of pole tip before etching (a), and after etching (b)](image)

3.5. Verification of etching process

We select 11 pieces of pole tips for verification of PTR etching process. We first use Ar and O\textsubscript{2} mixed plasma at an incident angle around 30° to fabricate the base surface of AlTiC. We then use low-energy Ar plasma at an incident angle of 35° to form PTR profile, and use high-energy Ar plasma at an incident angle of 70° to generate the recessed heights of H\textsubscript{OC}, H\textsubscript{WS} and H\textsubscript{SF}. After testing, we find that all pole tips satisfy the requirements of MT, H\textsubscript{OC}, and H\textsubscript{WS}. Nine pieces of pole tips satisfy the requirement of H\textsubscript{SF}. Only two pieces of pole tips cannot satisfy the requirement of H\textsubscript{SF}. This reminds that the uniformity of plasma density in the ion beam etching system should be optimised.
The density of plasma can be measured by etching a test substrate. Through rotation of the beam mask, the uniformity of plasma density is enhanced. Another batch of pole tips is fabricated for surface polishing as a tool for Plasma Treating and Metal Decoration. 

4. CONCLUSIONS

In this paper, the selectivity of removal rate of plasma etching to different materials of pole tip under different incident energy and different incident angles is well studied. A three-step plasma etching process is proposed for surface recession of pole tip of perpendicular recording magnetic head based on an ion beam etching system. In the first step, we use a mixture of Ar and O\textsubscript{2} plasma at incident angles around 30° to fabricate the morphology of reference surface of AlTiC with a high removal rate. In the second step, we choose low-energy Ar plasma at an incident angle of 35° to form the recessed morphology of pole tip. In the third step, we utilise high-energy Ar plasma at an incident angle of 70° to make overall removal of all materials while keeping the recessed profile unchanged. To avoid surface damage caused by high-energy plasma sputtering, the positive bias of electric grid is regulated less than 400 V. A batch of production shows that the required heights of PTR are successfully nanofabricated with the three-step plasma etching process.

REFERENCES