

Fabrication of magnetic recording heads and dry etching of head materials

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The fabrication of magnetic recording heads is briefly described and compared with the fabrication of semiconductor integrated circuits. Relevant dry-etching processes are then reviewed. The processes include broad-beam ion etching, the primary dry-etching method used in recording-head manufacturing, and reactive ion etching, a promising process technique for future recording-head fabrication. For broad-beam ion etching, process issues such as the angular dependence of the etching rate, redeposition, and etching selectivity are discussed. For reactive ion etching, chemical aspects of the etching of nickel-iron, copper, hard-baked resist, aluminum oxide, tantalum, and titanium carbide/aluminum oxide substrate are reviewed, and some relevant examples are discussed. Although still not a mainstream process in the recording-head technology, reactive ion etching is expected to play a more important role in that technology in the future.

Introduction

In 1993, the cost of one megabyte of storage capacity was about \$1, a dramatic decrease from \$10000 per

megabyte in 1956, when IBM first introduced the disk-drive technology. In 1998, the price of one megabyte had decreased further, to less than five cents. The rapid areal density increase and the stunning price/performance improvement have transformed the disk drive into the ubiquitous storage workhorse for computers of all sizes.

Since the first introduction of IBM's magnetoresistive head technology in commercial products in 1991, the areal density of disk drives has increased by about 60% per year. This increase is comparable to the growth in semiconductor industry described by the legendary Moore's law, which holds that the density of integrated-circuit chips doubles every 18 months. With the introduction of the giant magnetoresistive (GMR) technology in IBM disk drives in 1997, the impressive increases in the areal density of disk drives are expected to continue. The areal density increases have been achieved by shrinking sensor dimensions as well as developing new magnetic materials and improving head design. To sustain such progress, the technology of recording-head fabrication will need to continue to advance at a rapid pace. One desired improvement involves the use of dry-etching processes in fabricating high-density recording heads.

In this paper, the fabrication of magnetic recording heads is first briefly described and compared with the

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fabrication of semiconductor integrated circuits. The major challenges in advancing the head-fabrication technology are discussed. Relevant dry-etching aspects are then reviewed. Aspects that are reviewed include broad-beam ion etching, the primary dry-etching method in recording-head manufacturing, and reactive ion etching, a promising processing technique for future recording-head fabrication. For broad-beam ion etching, process issues in head fabrication such as the angular dependence of the etching rate, redeposition, and etching selectivities are discussed. For reactive ion etching, chemical aspects of the etching of materials commonly used in recording heads are reviewed, and some relevant examples are discussed.

Fabrication of magnetic recording heads

In many ways, the fabrication of magnetic recording heads resembles that of the on-chip interconnections of semiconductor integrated circuits. The processes used to fabricate a recording head comprise a combination of lithography, deposition (vacuum or plating), and etching steps. Review papers describing the details of recording-head fabrication have been published in the literature [1, 2]. Recording heads are usually fabricated on $\text{Al}_2\text{O}_3/\text{TiC}$ ceramic wafers, which provide excellent mechanical and tribological properties. Recording heads are eventually formed into sliders that "fly" over magnetic disks to perform "read" and "write" functions.

While several hundred silicon VLSI chips can be obtained from one silicon wafer, over ten thousand sliders can be produced from one recording-head wafer. One interesting comparison is that while each silicon chip contains millions of transistors, one slider contains only one read element and one write element. Besides the space taken by the read and write elements, the rest of the space on a slider is reserved simply for handling and mounting it on a suspension assembly after fabrication. This relatively low device density on a wafer lessens cleanliness requirements. This is justified because while a particle several microns in dimension on a silicon wafer will impede processing, such a particle may land harmlessly in a nondevice area on a recording-head wafer and be washed away during subsequent cleaning.

After wafer-level processing, in contrast to integrated-circuit fabrication, where chips are obtained by a dicing process, recording-head fabrication relies on many additional complicated processes, such as precise lapping, subsequent thin-film deposition, photolithography, and dry etching, to produce completed recording heads. As a result, a Si wafer with 40% final yield after wafer processing may be of great value, while a recording-head wafer of such a yield may not be worth processing further because of the continued yield loss and cost associated with subsequent operations. Typically, after dicing, a

semiconductor chip is encapsulated and mounted onto a ceramic substrate or directly onto a printed-circuit board; similarly, a head slider is mounted on a suspension to record and retrieve information on a magnetic disk.

A suspended slider and associated write element and read element (MR or GMR type) are shown in **Figure 1**. The write coil generates the magnetic flux in the pole pieces (P1 and P2), and the field generated between the pole pieces writes information on a disk. The layer between P1 and P2 defines the write gap; it determines the linear density of writing. The first pole piece of the write element is shared with the second shield of the read element. The shields sharpen the transition signal read from a disk because the read element cannot "see" the transition until it is within the gap between the shields. The distance between shield 1 and shield 2 is referred to as the read gap; it determines the linear density of reading. Hard bias layers on the edges of the read sensor provide a longitudinal biasing to suppress Barkhausen noise that arises from domain movement in the read sensor, and contact layers above the hard bias layers allow the lead conductor to be connected to the read sensor. The widths of the read element and second pole piece of the write element determine the track density of reading and writing, respectively. In an MR sensor, resistance depends on the angle between the current flow direction and magnetization direction of the MR film. Typically, a soft adjacent layer (SAL) provides a transverse biasing to produce the linear read signal. The SAL is usually a NiFeX alloy film, with X representing a third element [3]. In a GMR sensor, resistance depends on the spin state of the electrons in the free NiFe film with respect to that of the electrons in the pinned film. The antiferromagnetic exchange film provides the pinning field to the pinned film. More detailed descriptions of the write elements and MR (and GMR) elements can be found in the published literature [4–9]. While the fabrication of transistors in a semiconductor integrated circuit utilizes processes such as diffusion, ion implantation, and thermal oxidation to produce junctions and the gate oxide, fabrication of the read element in a recording head relies on thin-film deposition to form a multilayer structure for signal sensing. A typical GMR element, for example, comprises ten thin-film layers (including spin-valve multilayers, read gaps, hard bias film, and conducting leads) [4]. Many of the films are less than 100 Å thick, and some are even less than 10 Å thick. The performance of the read sensor depends critically on the thickness and magnetic properties of the thin films as well as their interfaces.

The "liftoff" patterning technique [10, 11] had been used extensively in semiconductor integrated-circuit fabrication. In a liftoff process, a full film is first deposited on top of a patterned photoresist layer and into the photoresist openings defined by the pattern. The resist is

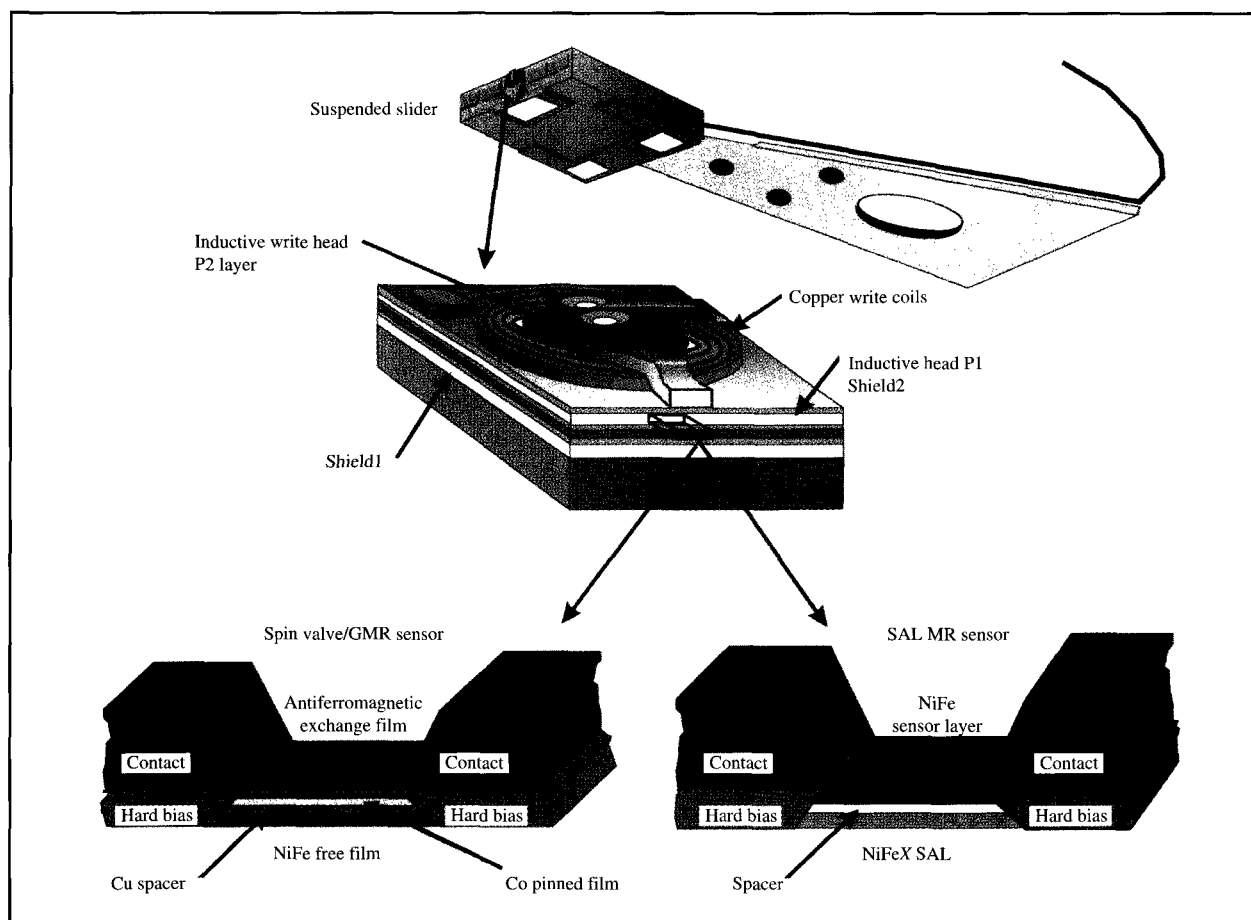


Figure 1

Schematic illustration of a suspended slider and associated read and write elements.

then removed by a solvent along with the thin film on top of it. The thin film deposited in the resist opening is, however, left intact, thus becoming the desired feature. As feature dimensions shrink, the semiconductor industry has replaced liftoff processing with a combination of reactive ion etching and chemical-mechanical polishing (CMP) processes. However, liftoff processing is still widely used in MR and GMR recording-head fabrication [2] because the films to be lifted off are typically thinner than those in a semiconductor device, and the features are wider than those in a semiconductor device. For the fabrication of increasingly higher-density recording heads, however, the applicability of the liftoff technique will become questionable.

Recording areal density is the product of track density and linear density. To increase linear density, the dielectric thickness that defines the magnetic gap must be reduced accordingly. Since this magnetic gap also provides

the electric insulation between a read sensor and the shields, its insulating integrity must be ensured. The current dielectric thickness (down to less than 1000 Å) in a read element is still an order of magnitude greater than that of the gate oxide (down to less than 100 Å) in a DRAM silicon device. However, while the gate oxide can be grown by high-temperature oxidation of an underlying silicon surface, the requirement that the gap material be deposited on magnetic materials prohibits the use of high temperatures for this critical step. The gap material should also have excellent thermal conductivity to dissipate the heat generated by the sensing current to the adjacent shields. For high-density recording heads, new gap materials and deposition methods that ensure robust electric insulation and effective heat dissipation are highly desired.

The most astonishing contrast between semiconductor integrated-circuit fabrication and recording-head

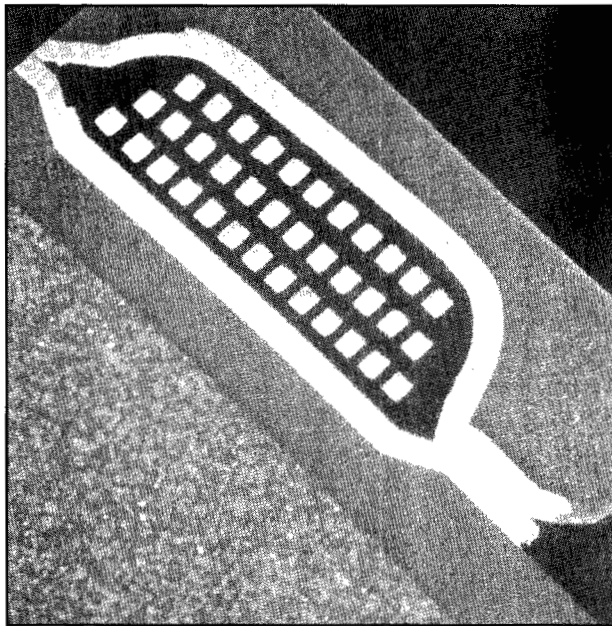


Figure 2

Cross-sectional view of a three-layer-coil recording head. The upper pole piece was fabricated above the coil/insulation stack. From [6], with permission.

fabrication today is the wafer topography during processing. **Figure 2** shows a cross-sectional view of an inductive write element, containing a lower pole piece, three layers of coils, an upper pole piece, and insulation between the coil layers and pole pieces. Currently, for integrated circuits, through the use of the CMP process, layers containing features down to $0.25\ \mu\text{m}$ in width are formed over an essentially planar surface [12]; for recording-head fabrication, severe topography is still present during wafer processing. For example, the upper pole piece shown in the figure is formed above a tall coil and insulation stack with a height of over $10\ \mu\text{m}$. The width of the upper pole piece is equal to the magnetic track width, currently approaching $1\ \mu\text{m}$. Constructing such a narrow pole piece over severe topography is one of the most critical process steps in head fabrication.

In semiconductor integrated-circuit fabrication, metal features are typically defined by chemical vapor deposition (CVD) or physical vapor deposition (PVD), in combination with reactive ion etching. In contrast, electroplating is still commonly used in recording-head fabrication (for the copper coil, copper leads, nickel-iron magnetic shields, and nickel-iron write pole pieces). Up to seven plating process steps are used in wafer fabrication [2]. As an example, the upper pole piece of Figure 2 is usually fabricated by defining the pole-tip feature in a relatively

thick photoresist layer over topography, followed by plating several microns of a magnetic material into the resist-defined mask. Electroplating offers a cost-effective approach to metal deposition. It is interesting to note that electroplating is regaining its role as the preferred metal deposition method for copper wiring in the next generation of semiconductor devices.

The insulation layers in magnetic recording heads and in semiconductor devices are also fabricated differently. In integrated-circuit fabrication, a vacuum technique such as plasma-enhanced chemical vapor deposition (PECVD) is typically used to deposit a SiO_2 insulation layer, followed by the use of dry-etching and CMP processes to produce a planar structure. In recording-head fabrication, the commonly used insulation material is a photosensitive polymer [1]. After photolithographic patterning and heat treatment at a relatively high temperature, the polymer forms an insulating layer that remains in the recording head. Compared to the approach used for integrated-circuit fabrication, this insulation method is simpler and more cost-effective. The patterned insulation structure thus fabricated, however, produces severe topography (as discussed in the previous paragraph), leading inevitably to subsequent difficulties in forming the narrow upper pole piece.

While concerns have been raised regarding the ultimate limits of the semiconductor device technology (electron transfer uncertainty) and magnetic recording technology (magnetic domain instability), the more pressing need is to continue the path of shrinking feature sizes before those limits are reached. One important aspect of current silicon technology is its utilization of reactive ion etching. That technique is suitable for fine-feature definition because it offers residue-free etching, excellent image-transfer fidelity, and etching selectivity. Processes for the reactive ion etching of most materials used in integrated-circuit fabrication (Si , SiO_2 , Si_3N_4 , Al , W , etc.) are well established. For the processing of magnetic recording heads, however, a different set of materials must be considered. Materials in a GMR read sensor include Ta , NiFe , Cu , Co , CoPtCr , and FeMn or other antiferromagnetic alloys [4]. Magnetic shields and writing poles are usually NiFe -based materials. The coil of a write head is typically made of copper, and the interconnection materials used include copper, gold, and tantalum. Among the most commonly used dielectric materials, such as SiO_2 , Si_3N_4 , and Al_2O_3 , the last has been found to be the most viable gap material [6]. Al_2O_3 is also used in forming the first layer deposited onto the substrate (to provide a smooth surface for head fabrication) and in forming the last layer (to encapsulate the head structures when wafer-level processing is completed). The insulation material that separates the coil turns and insulates the coil from the pole pieces is a novolac-based polymeric material [1].

Finally, the substrate material is a sintered ceramic material consisting mainly of TiC and Al_2O_3 . This material must be etched to define the air-bearing surface that determines the flying height of a head over a disk.

In summary, although the feature size in recording heads still trails behind that of semiconductor integrated circuits, many unique challenges are present in the fabrication of recording heads of higher areal density and better performance. Some significant challenges include the development of 1) high-output read elements with robustness to withstand harsh processing and environmental conditions; 2) powerful write elements with improved structures for ease of manufacturing; 3) new gap materials and deposition methods to provide required electrical insulation and heat dissipation; and 4) improved patterning techniques to produce smaller head elements with tight tolerance control. To advance the patterning technology, residue-free dry-etching processes with good image transfer fidelity and high etching selectivity are highly desired. In the following sections, some of the processing issues and chemical aspects of dry etching in recording-head fabrication are discussed.

Broad-beam ion etching

Broad-beam ion etching has been used extensively for pattern delineation. Reviews have been published in the literature [13, 14]. At the present time, broad-beam ion etching is the primary dry-etching method for critical patterning steps in the fabrication of magnetic recording heads. Applications include read-element shaping, write-element pole-tip trimming, removal of the plating seed layer, and air-bearing-surface definition [15].

In broad-beam ion etching, ionization is achieved by a Kaufman source, which contains a hot filament, a radio-frequency (rf) source, or a microwave source. Ions are extracted through a series of grids and directed to the wafer to be etched. The ionic charge in the ion-beam etching chamber is neutralized by electrons which are generated by various mechanisms to avoid charging and arcing on the wafer. In ion-beam etching, the wafer stage is usually tilted with respect to the incident beam and rotated around the normal of the stage surface. The tilting and rotation of the wafer stage ensures that the areas which are normally shadowed by the device structure or resist mask are etched by the ion beam. The pressure in an ion-beam etching system is typically one to two orders of magnitude lower than that in a sputtering or reactive ion etching system. As a result, the scattering of the ions is minimized, and the etching is, in general, very directional.

In ion-beam etching, ion beams are typically slightly divergent, especially near the edge of the ion source. As a result of beam divergence, the pattern defined by ion etching can become asymmetrical, with feature sidewalls

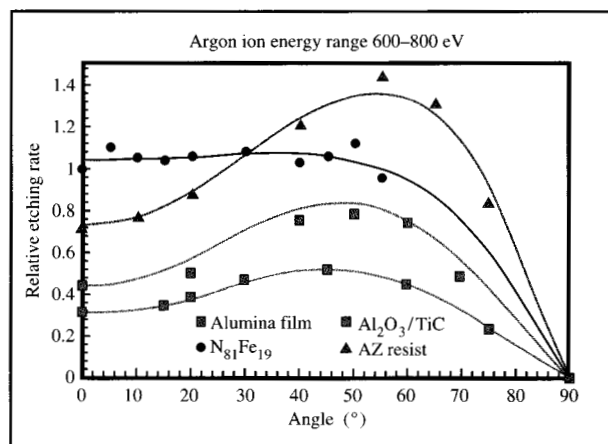


Figure 3

Relative ion-beam etching rates vs. ion-beam incident angle with respect to surface normal. From [15], with permission.

on the outer side of the resist mask (with respect to the center of the ion source) being more tapered than those on the inner side of the resist mask. One major challenge for the equipment vendor is to produce ion-beam systems with minimum beam divergence to eliminate such etching asymmetry. The use of ion grids that are much larger than the wafer to be etched has largely avoided exposing the wafer to the divergent beamlets near the edge of the ion grids. Planetary rotation of the wafer in a batch ion-beam etching system has also been adopted to reduce etching asymmetry.

The ion-beam etching rate is usually a function of ion incident angle [16]. The etching rate is essentially the product of sputtering yield and ion flux. At a higher incident angle θ , the ion flux is reduced by $\cos \theta$ because of the spreading of the beam, but the sputtering yield usually increases with the incident angle. For most materials, a maximum rate is observed at an incident angle of 45° – 60° . The angle at which the etching rate becomes maximum depends on the material to be etched and the mass and the energy of the bombarding ions.

Figure 3 shows the relative etching rates of four commonly used head materials (NiFe , Al_2O_3 , AZ photoresist, and $\text{Al}_2\text{O}_3/\text{TiC}$ ceramic) as a function of ion incident angle [15]. While the maximum etching rates of the photoresist, Al_2O_3 , and $\text{Al}_2\text{O}_3/\text{TiC}$ ceramic occur between 45° and 60° , the highest NiFe etching rate is in the 10° – 30° range. The faceting phenomenon frequently observed in ion-beam etching can be explained by the angular dependence of the etching rate. When a feature is exposed to an ion beam with a low incident angle, the corners of the feature are first eroded, and small facets

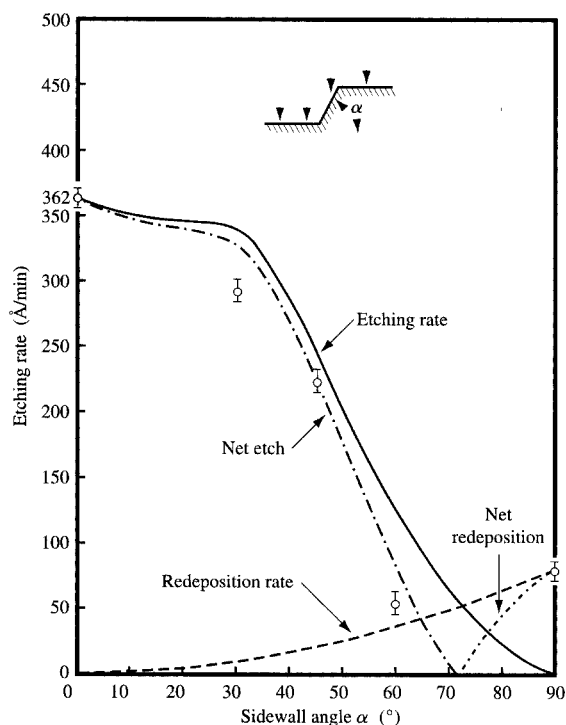


Figure 4

Illustration of sidewall etching and redeposition vs. incident angle measured with respect to the normal of the sidewall surface. From [16], with permission.

are produced. Once that occurs, the angle of the incident beam with respect to the facet normal becomes about 45°, and the etching is accelerated if the etching rate of the material being etched has a strong angular dependence. As a result, a large facet is developed. Faceting can be detrimental if the feature shape has to be preserved, or beneficial if the presence of sharp corners is undesirable for step-coverage or tribological reasons. Knowledge of the angular dependence of the etching rate can be used to control the faceting.

Since ion etching is a physical etching process, the etched material usually accumulates on the first surface it strikes after being ejected from the etching surface. Such "redeposition" typically forms on the sidewalls of the features being formed and on the sidewalls of their masks. When a wafer is tilted, the sidewalls are also etched by the incident beam. **Figure 4** illustrates the balance of sidewall etching and redeposition for gold etching [16]. The net redeposition rate is subtracted from the measured etching rate to establish a "net etch rate" of the sidewalls. As an example, when the sidewall surface normal is at 30° with respect to the incident beam (for a vertical sidewall,

this angle is the complement of the angle between the ion beam and the wafer surface normal), the net result is sidewall etching, because the etching rate is much higher than the redeposition rate. However, when the angle is greater than 70°, net redeposition results.

To minimize sidewall redeposition, a high-incident-angle (with respect to the wafer surface normal) etching process can be used. However, such an approach results in a more tapered etching profile. Alternatively, a low-incident-angle process can be used to produce near-vertical sidewalls followed by a high-incident-angle process to remove the redeposition on the sidewalls. In this approach, the endpoint control of the redeposition removal is very critical. While terminating the etching process too soon results in incomplete sidewall cleaning, terminating the process too late causes a feature dimension change due to etching of feature sidewalls. It has also been proposed that use be made of a rounded resist mask (formed by resist reflow bake) to reduce redeposition [16]. While redeposition can be reduced using this approach, etching of the rounding mask also produces difficulty in precisely controlling the final dimension. Another proposed solution to redeposition involves rendering the redeposition product water-soluble so that the redeposition can be eliminated by rinsing after etching. For example, using Cl_2 gas to etch NiFe, the reaction product is water-soluble, thus permitting redeposition-free features to be produced without using a high-angle etching step [17].

Selectivity in ion-beam etching is limited. As indicated in Figure 3, the selectivity of commonly used materials with respect to photoresist is usually less than unity. As a result, a relatively thick resist mask is required for etching a layer more than 2 μm thick. To further aggravate the selectivity problem, while the top of the resist mask is always exposed to the ion beam and etched, if the wafer is tilted, the area to be etched receives proportionally less exposure. A better etching selectivity can be achieved when inorganic materials are used as the etching mask. For example, as shown in Figure 3, the maximum etching selectivity for NiFe compared to an alumina layer is about 2.5:1. It has been proposed that this selectivity be used to etch NiFe with an alumina layer as the etching mask [18]. Another example of utilizing etching selectivity is the use of Ta as a mask with which to etch Cu or NiFe [19]. In this case, a Ta mask is defined by a photoresist process followed by a reactive ion etching process. Since the etching selectivity of Cu to Ta is about 2.5:1 at a 750-V beam voltage, Cu features can be defined with a Ta mask having a relatively low aspect ratio. However, even when inorganic masks are used, the etching selectivity achievable in ion-beam etching is still limited.

Efforts for improving etching selectivity have been reported. One approach is to reduce the etching rate of the mask material. For example, by mixing a small amount

of oxygen with the argon used for etching, the etching rate of metals such as Cr, Ti, and Al which form tenacious oxides on their surfaces can be reduced by a factor of 6 to 8 [20]. A twofold reduction in etching rate has also been reported for etching Ni when the oxygen partial pressure in an argon/oxygen mixture exceeded a threshold value [13]. Another example is mixing N_2 with Ar to reduce the etching rate of a Ti mask [21]. Polymerizing gases such as CHF_3 , CH_2F_2 , and CH_3F have been used to slow the etching of photoresist [22]. Another approach is to increase the etching rate of the material to be etched by utilizing certain chemical reactions. For example, the etching rate of SiO_2 can be increased dramatically by using a fluorine-containing gas: The ionized species such as CF_x^+ react with SiO_2 to form volatile product SiF_4 , thus accelerating the etching process [23]. In some cases, by adding a reactive gas, the etching rate of one material present may be increased while that of another material present may be reduced. For example, by using CF_4 gas instead of Ar, the etching rate of Al_2O_3 can be enhanced, while that of NiFe can be depressed. This approach has been applied for fabricating an Al_2O_3 mask for upper-magnetic-pole patterning [24]. Although the use of an inorganic mask and reactive gas species improves etching selectivity, the approach requires additional process steps, thus significantly increasing process complexity.

In summary, broad-beam ion etching has remained the primary dry-patterning technique in the fabrication of magnetic recording heads. Its popularity stems primarily from its characteristic directional etching and its ability to etch any material. However, since most ion-beam etching processes rely on physical sputtering as the material-removal mechanism, the capability of an etching process is limited by issues such as low etching rate, lack of etching selectivity, and redeposition.

Reactive ion etching

Reactive ion etching utilizes the synergistic effect of ion bombardment and chemical reaction in a plasma. In a conventional parallel-plate reactive ion system, a wafer is placed on an electrode which is powered by an rf generator. The power is coupled into a chamber which contains a reactive gas to generate a plasma. Ions and chemical radicals in the plasma can react with the wafer material to cause etching. Since electrons are more mobile than positive ions in the plasma, a negative dc voltage is developed on the electrode where the rf power is introduced. Since the wafer is placed on this electrode, the wafer experiences the bombardment from the ions accelerated to the electrode. The ion bombardment causes physical damage of the wafer material and facilitates desorption of chemical reaction products. As a result, chemical etching in a reactive ion etching process is dramatically accelerated.

Since areas that are simultaneously exposed to the plasma and ion bombardment etch more rapidly than areas not reached by the ion bombardment, the reactive ion etching is an anisotropic process. In some cases, to further improve etching anisotropy, a gas is added to produce chemical species that passivate sidewalls and prevent lateral etching [25]. Since most etching products are volatile and are therefore pumped away, no redeposition is usually formed during reactive ion etching. Furthermore, because of the differing responses of different materials to chemical species in the plasma, a high etching selectivity can be achieved.

In recent years, several types of high-density-plasma etching systems have emerged to replace conventional reactive ion systems. The most commonly used types are electron cyclotron resonance (ECR) systems and inductive coupled plasma (ICP) systems. In both types, the wafer is placed on a cathode which is powered by an rf "biasing" source. However, the plasma is generated by a second source via a more efficient mode, and the power is introduced into the chamber through a dielectric window. For plasma generation, an ECR system uses a microwave source and a waveguide network, and an ICP system uses an rf source and an inductive coil. The plasma density in a high-density-plasma etching system is typically two orders of magnitude greater than that in a conventional reactive ion etching system. Furthermore, the plasma density and ion bombardment energy are decoupled, with ion bombardment energy controlled by the rf power applied to the cathode and the plasma density controlled by the source (ECR or ICP) power. This decoupling offers greater latitude for etching-process development. The etching in a high-density plasma system is usually accomplished at a lower pressure than in a typical reactive ion etching system. The use of a lower pressure improves etching anisotropy by reducing ion scattering, while the high density of the plasma enables the etching to proceed at an acceptable rate.

The magnetic materials in a recording head are difficult to etch chemically by reactive ion etching. For years no plasma chemical system was known to etch NiFe, the most commonly used magnetic material. The commonly used reactive ion etchants, fluorine- and chlorine-containing gases, do not form volatile reaction products at a practical processing temperature ($<200^\circ\text{C}$) [26]. The only known volatile Ni and Fe compounds are their carbonyls [27]. Nickel carbonyl $[Ni(CO)_4]$ has a boiling point of 43°C , and iron carbonyl $[Fe(CO)_5]$ has a boiling point of 103°C . Since CO is a toxic gas, we have attempted to use CO_2 to produce CO in a high-density plasma for NiFe etching; however, no NiFe reactive ion etching could be achieved, and ESCA analysis showed that Fe and Ni oxides were formed on the sample surface, impeding the formation of nickel and iron carbonyl. Recently, dry etching of

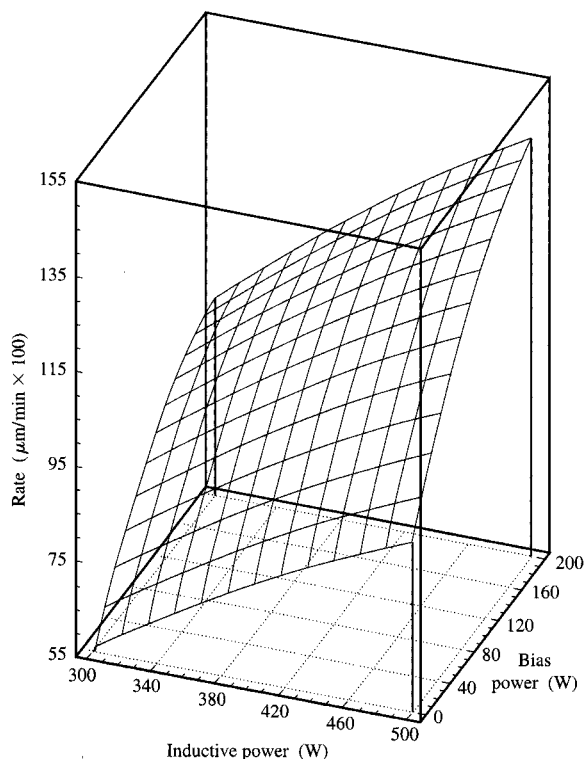


Figure 5

Etching rate of hard-baked polymeric insulation vs. inductive power and bias power in a high-density plasma etching system. From [35], with permission.

NiFe and other magnetic materials with $\text{CH}_4/\text{H}_2/\text{O}_2$ in a parallel-plate etcher has been reported [28]. A maximum etching rate was observed at about a 10% CH_4 gas composition. However, the maximum rate achieved was only $45 \text{ \AA}/\text{min}$ at a $0.4\text{-W}/\text{cm}^2$ power density. Since the bias voltage of the process was 850 V , which is appreciably higher than the threshold for NiFe sputtering, the reported etching was most likely a result of chemically assisted sputtering rather than true reactive ion etching. Another study conducted by Nakatani [29] of NiFe etching appeared to be more promising. In his work, a gas mixture of CO/NH_3 was used. A maximum etching rate was achieved at about 50% NH_3 . Interestingly, there was also a strong dependence of etching rate on process pressure; a maximum rate of $350 \text{ \AA}/\text{min}$ was achieved at about 2.5 mTorr . He claimed that the addition of NH_3 prevented (at least to some extent) the dissociation of CO into nonreactive carbon and oxygen. As a result, CO was preserved as the reactive etching species, and the formation of carbide and oxide on the surface was

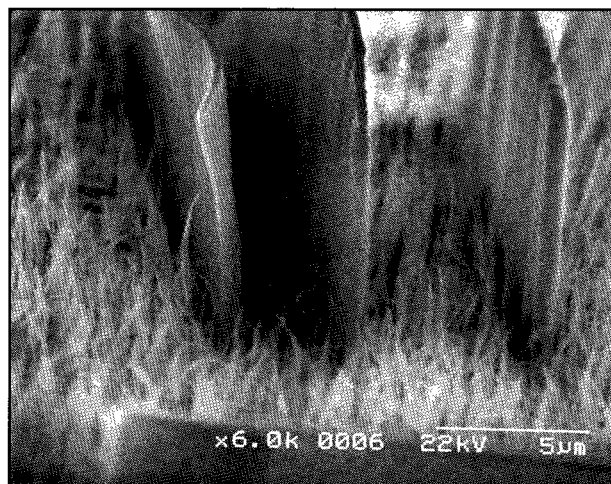


Figure 6

"Grasslike" residue produced in polymer etching as a result of sputtering and micromasking. From [43], with permission.

avoided. Using this etching method, patterns with a feature size of 0.25 μm were fabricated, and no redeposition was observed. However, for this plasma system, the formation of volatile nickel and iron carbonyl was still speculative. Fundamental studies directed at understanding the etching reactions should help further develop this approach.

The coil in a recording head is usually fabricated from Cu, which is another material that is difficult to etch by means of reactive ion etching because of a lack of volatile compounds at low temperatures. Since Cu is also a preferred interconnection material for future semiconductor chips, reactive ion etching of Cu has been studied more extensively than that of NiFe. It has been found that Cu can be etched in chlorine-containing plasmas [30, 31]. In such a plasma, the Cu etching rate essentially depends on the desorption rate of the reaction product CuCl_x . Since the use of a high temperature favors the desorption from surface, a higher etching rate can be achieved at an elevated temperature. Another approach for etching-rate enhancement is to use infrared light radiation to increase the CuCl_x desorption rate during etching [32]. With this approach, an etching rate as high as $4000 \text{ \AA}/\text{min}$ has been achieved. Etching rates over $3000 \text{ \AA}/\text{min}$ at 25°C have also been reported in which use is made of an ECR plasma-etching system [33]. The high rate achieved is attributed to the effective removal of the CuCl_x by the high-density incident ions in the ECR reactor. Cu reactive ion etching has also been realized by using H_2/CH_4 at room temperature; in that case, CuH was believed to be the reaction product [34]. However, the

rate achieved was only 60 Å/min and, because throughput was therefore low, was not acceptable for etching Cu layers of interest (typically, at least 10000 Å if the Cu is to be used to form the coil conductor layers).

The hard-baked polymeric material that is normally used for separating pole pieces and Cu coil turns can easily be etched in an oxygen-based plasma. **Figure 5** shows the etching rate of such a polymer as a function of inductive power and bias power in an ICP reactor [35]. An etching rate greater than 1 μm/min could easily be achieved. In such a reactor, the oxygen neutrals and ions in the plasma etch organic material to form CO, CO₂, and H₂O (volatile species) as reaction products [36]. Etching without residues can thus be achieved. In some cases, however, when the rf biasing power is too high and when there are other materials exposed to the plasma, a "grasslike" residue can be produced. **Figure 6** shows such an example. The residue was formed when the polymer to be etched was micromasked by the inorganic particles that were sputtered off from surrounding features and deposited on the polymer.

Polymer etching by using an oxygen plasma is an ion-enhanced process (in contrast to an ion-induced process, such as SiO₂ etching). The lateral etching caused by reactive radicals, although slower than the vertical etching, usually still occurs under the mask that is used. **Figure 7** shows polymer "undercutting" under an SiO₂ mask as a result of such lateral etching. Lowering the pressure reduces the scattering of ions and the density of the radicals in the plasma, thus improving the etching anisotropy. However, since the etching is an ion-enhanced process, it is difficult to eliminate the lateral etching completely even at low pressure. Etching anisotropy can be improved by mixing O₂ with gases such as CO₂ [37], N₂ [38], and He and/or SO₂ [39]. It has been suggested that a passivation layer is produced on the sidewalls and that the layer prevents or slows sidewall etching. Another approach is to use substrate cooling during etching. At a low temperature, the chemical reaction on the sidewalls in the absence of ion bombardment is slowed down or halted completely; anisotropic etching thus can be achieved [40–43]. It has also been proposed that the anisotropic etching achieved at a lower temperature is due to the condensation of the reaction product, H₂O, which has a very low vapor pressure at low temperatures and thus becomes an effective passivation layer [44]. **Figure 8** shows an example of the type of vertical profile that can be achieved in the absence of lateral etching under the mask [43]. The mask in that case was an 800-Å-thick layer of Al₂O₃, which could not be resolved in the micrograph shown. Vertical etching was achieved by cooling the wafer chuck to –100°C. The etching of the organic insulation material has been used to fabricate the optical lapping guide, which is used to control the lapping process used in

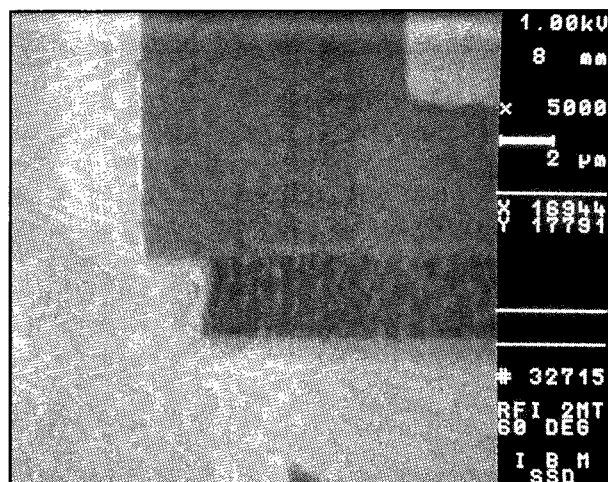


Figure 7

Polymer "undercutting" due to lateral etching.

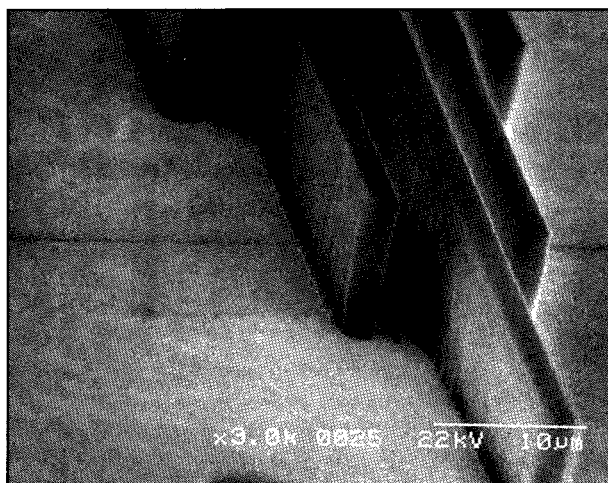


Figure 8

Anisotropic polymer etching achieved by etching at –100°C. From [43], with permission.

recording-head fabrication [45]. It has also been suggested that etching the insulating structure in a controlled manner be used to align the write portion of a magnetic recording head with its read portion [46].

Alumina layers are used to form the undercoat, overcoat, and gaps in recording heads. Such layers can be reactive ion etched in a BCl₃/CCl₄ plasma. In fact, in semiconductor processing, BCl₃ is usually used as the first step in aluminum etching to remove the native Al₂O₃ [47]. Chlorine-based reagents, however, are corrosive and may

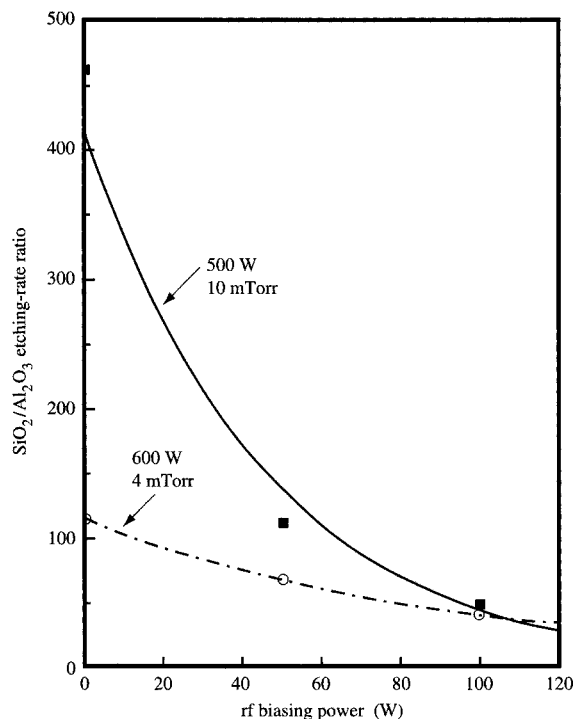


Figure 9

$\text{SiO}_2/\text{Al}_2\text{O}_3$ etching selectivity in a high-density SF_6 plasma. From [51], with permission.

attack materials already present in partially fabricated heads. Etching of Al_2O_3 in a noncorrosive plasma is more difficult. For example, when exposed to F-containing plasmas, Al_2O_3 reacts with F to form a mixture of AlF_3 and $\text{Al}_x\text{O}_y\text{F}_z$ [48]. These reaction products are not volatile, so it is not expected that reactive ion etching of Al_2O_3 in an F-containing plasma would occur. Nevertheless, the etching of Al_2O_3 in F-containing plasmas has been found to be much faster than in an Ar plasma [49]. The enhancement of Al_2O_3 etching is attributed to the high sputtering yield of AlF_3 compared to that of Al_2O_3 . In contrast, another commonly used dielectric material, SiO_2 , can be easily reactive ion etched in F-containing plasmas. As a result, a high etching selectivity can be achieved with regard to these two materials [50–52]. **Figure 9** shows the $\text{SiO}_2/\text{Al}_2\text{O}_3$ selectivity as a function of rf biasing power and pressure in an ICP high-density-plasma reactor [50]. In general, in a reactive ion etching process, the increase of Al_2O_3 etching rate with increasing ion bombardment energy is more drastic than that of SiO_2 . As a result, a high $\text{SiO}_2/\text{Al}_2\text{O}_3$ etching selectivity can be obtained at a low bias power and high pressure [50]. This high etching

selectivity can be utilized to etch SiO_2 using Al_2O_3 as a mask or etch-stop layer. It has also been proposed that a SiO_2 layer be used to protect the Al_2O_3 gap material of a head from sputtering and chemical attack during processing, followed by removal of the SiO_2 layer with F-containing reactive ion etching [53]. Using SiO_2 and RIE processing to form a spacer structure to protect pole tips during head processing has also been proposed [54]. In another application, $\text{SiO}_2/\text{Al}_2\text{O}_3$ etching selectivity has been used to align a write head with an adjacent read head [55].

Tantalum can be used as the lead material for a read sensor. It can be easily reactive ion etched in fluorine- or chlorine-containing plasmas, since its fluoride and chloride are both volatile [56–58]. As an example, **Figure 10** shows the dependence of the Ta etching rate on the $\text{CHF}_3/(\text{CF}_4 + \text{CHF}_3)$ concentration ratio and the O_2 flow. The etching rate first increases when CHF_3 and O_2 are added to the CF_4 because more F is released into the plasma; it then

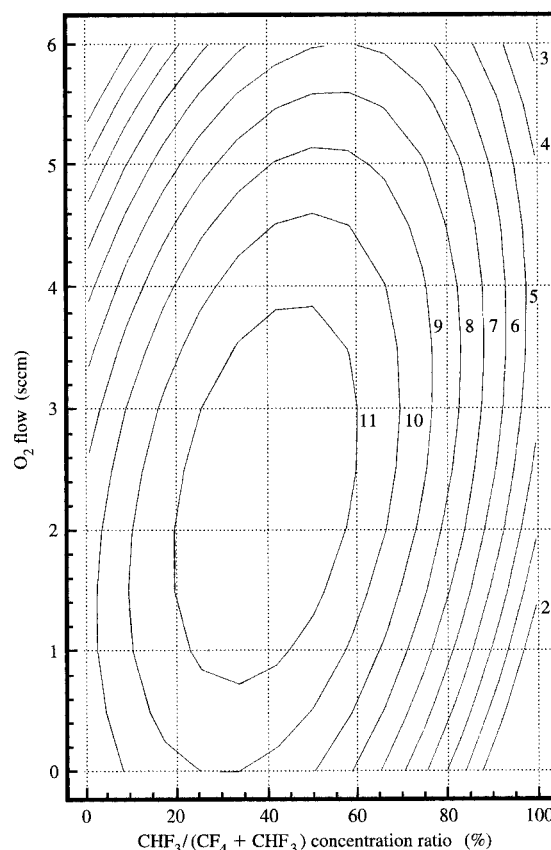


Figure 10

Dependence of Ta etching rate ($\text{\AA}/\text{min}$) on CHF_3 % and O_2 flow. From [56], with permission.

decreases with further CHF_3 and O_2 addition because of fluorocarbon formation from CHF_3 as well as Ta oxidation because of oxygen adsorption. **Figure 11** shows the dependence of the Ta etching rate on pressure and O_2 flow in SF_6/O_2 plasmas. Even though power was lower compared to that for Figure 10 (150 W source power and 50 W bias power vs. 200 W source power and 50 W bias power), the etching rate was found to be much greater in SF_6/O_2 plasmas because of the abundance of the fluorine-containing species. Compared to a CHF_3/CF_4 plasma, the etching selectivity in a SF_6 plasma is poor for photoresist and its etching is less anisotropic. Tantalum can be removed very selectively from NiFe [59]. **Figure 12** shows the effects of Ta over-etching on underlying NiFe. The NiFe loss was measured with a magnetic hysteresis loop which converts its measured magnetic moment to film thickness. It can be seen from the figure that the NiFe moment loss is only 12 Å for 100 Å of Ta over-etching

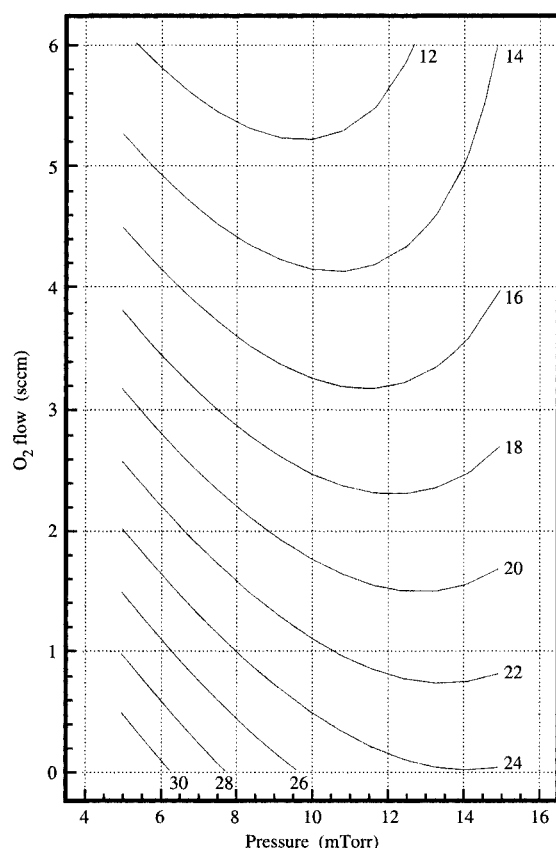


Figure 11

Dependence of Ta etching rate (Å/min) on pressure and O_2 flow in SF_6/O_2 plasmas. From [56], with permission.

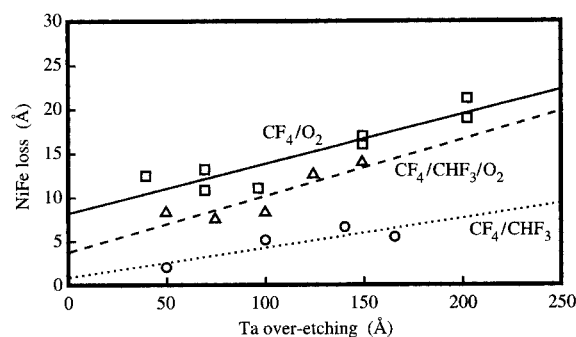


Figure 12

NiFe magnetic moment loss as a function of Ta over-etching. From [57], with permission.

with a CF_4/O_2 plasma, and this moment loss is further reduced to 5 Å when a CHF_3/CF_4 plasma is used. ESCA analysis showed that the moment loss could be attributed to the formation of nickel fluoride rather than physical thickness loss due to sputtering. In contrast, if an ion-milling process is used, since the milling rate of Ta is lower than that of NiFe, for a 100-Å Ta over-etch, the NiFe loss should be 125 Å. This etching selectivity has been proposed for achieving a planar structure during read sensor stripe definition [60].

In head fabrication, after wafer processing is completed, wafers are sliced and lapped. On the lapped surface, an aerodynamic pattern that determines the flying height of the head over a disk must be defined. This involves the etching of $\text{Al}_2\text{O}_3/\text{TiC}$ substrate material. The ion milling rate of this material is only about 300 Å/min [15]. This rate is limited by beam-current density and associated heating. Although efforts are being made to improve the ion-milling equipment used for this purpose, the nature of the etching (pure physical bombardment) limits the maximum achievable rate. Etching this substrate with fluorine-containing plasmas has been proposed [61]. Since the TiC etching product, TiF_4 , is volatile, a TiC etching rate of more than 1 $\mu\text{m}/\text{min}$ can easily be achieved in a high-density F-containing plasma.¹ However, as indicated earlier, since the reaction product of Al_2O_3 with an F-containing plasma is nonvolatile, the etching of $\text{Al}_2\text{O}_3/\text{TiC}$ ceramic material is limited by the rate of Al_2O_3 removal. Recently, $\text{Al}_2\text{O}_3/\text{TiC}$ etching in a high-density $\text{Cl}_2/\text{BCl}_3/\text{Ar}$ plasma has been reported [62]. Since titanium chloride and aluminum chloride are both volatile, an etching rate greater than 3500 Å/min was achieved, and no redeposition was observed on the sidewalls of the mask

¹R. Hsiao, D. Miller, S. Nguyen, and A. Kellock, private communication.

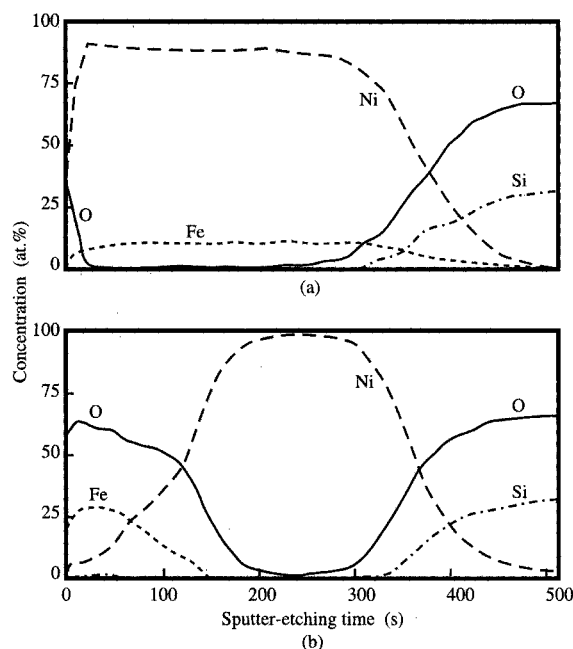


Figure 13

Depth profile of a 300-Å-thick NiFe layer (a) before and (b) after exposure to a high-density oxygen plasma for three minutes. From [35], with permission.

that was used. The etching roughness was minimized by optimizing process conditions to match the Al_2O_3 and TiC etching rates. The experiments, however, were conducted in a small laboratory reactor at a relatively high power density. It is questionable whether such a high rate is achievable for batch processing. Special precautions are probably needed to avoid possible corrosion due to the use of the Cl_2 and BCl_3 . Nevertheless, the approach appears to be promising for achieving clean, high-rate $\text{Al}_2\text{O}_3/\text{TiC}$ ceramic etching.

It should be noted that although minimal physical etching occurs when materials such as NiFe and Cu are exposed to an oxygen or fluorine-containing plasma with a low bombardment energy, some detrimental surface reactions may occur [35]. For example, **Figure 13** shows the depth profile (obtained by sputter-etching) of a 300-Å-thick NiFe thin film on a quartz substrate before and after it was exposed to a high-density oxygen plasma in an ICP reactor for three minutes. Iron was found to be segregated to the surface and oxidized. Not surprisingly, the magnetic properties of the film also changed drastically as a result of the plasma exposure. Copper was found to be oxidized very rapidly in such a high-density plasma. For example, an 800-Å-thick Cu layer was oxidized completely after one

minute of exposure. After exposing Cu to a CF_4 plasma, a Cu-F-O ternary compound layer was found on the surface (the oxygen was introduced by the etching of the quartz parts in the plasma chamber). Clearly, the implications of exposing the materials present in recording heads to plasmas during head processing should be taken into consideration.

Reactive ion etching has not been used extensively in recording-head fabrication for several reasons. First, as mentioned earlier, the chemical aspects of etching many materials in recording heads are complex, and reactive ion etching processes are more difficult to establish. Second, although the coil and pole tip of a head can be more than $3\text{ }\mu\text{m}$ thick, the relatively wide dimensions in recording heads have allowed them to be fabricated by defining features in a relatively thick photoresist layer, followed by electroplating. Third, the cost-effective approach of forming a patterned insulation layer in recording heads does not require the use of dry etching. The drawback of the current head-fabrication practice is that a severe wafer topography is produced, and the process is not extendible to the manufacture of recording heads with high-aspect-ratio features. Consequently, the advantages of planarization and reactive ion etching processes are expected to be useful in further extending recording-head fabrication technology.

Summary

In this paper, recording-head fabrication has been reviewed and compared with semiconductor integrated-circuit fabrication. The challenges in manufacturing high-density recording heads were discussed. Of the major processing challenges, the development and implementation of improved dry-etching techniques are highly desired. The processing aspects of broad-beam ion etching and reactive ion etching in recording-head fabrication, along with some relevant examples, have been reviewed. Currently, broad-beam ion etching remains the primary dry-etching manufacturing process. Reactive ion etching, because of its potential of offering residue-free etching with high selectivity and directionality, is expected to play a more important role in future efforts to produce recording heads with greater areal density and higher performance.

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