

Formation of magnetic elements on a substrate, and MEMS devices including
such elements

Field of the Invention

5 The present invention relates to the formation of magnetic elements on a substrate, such as a silicon (Si) substrate. It further relates to MEMS devices incorporating such a substrate.

Background of the invention

10 Nowadays MEMS devices attract much interest. Many researchers are developing magnetic MEMS devices, which are MEMS devices such as actuators or sensors operated using magnetic force. To produce magnetic MEMS devices, a patterned permanent magnet on a substrate such as Si is
15 required.

One known method to form the patterned magnet is by deposition. In this method a thin film of magnetic material is deposited, e.g. by sputtering. Usually the thin film has very good magnetic properties in terms of H_c or M_r ,
20 but the magnetic force it generates is not sufficient for a magnetic MEMS device because the force depends upon the volume of magnetic material, and it is difficult to deposit a very thick magnetic thin film without cracking or peeling. The required thickness is several tens of micrometers.

25 Anodic Aluminium Oxide (AAO) is known for its very small pores. If we were able to form a layer of AAO on a substrate, and fill those pores with magnetic material, we could achieve very good magnetic properties in terms of H_c or M_r because of the magnetic anisotropy of the magnetic material in the pores. Moreover the magnetic material can be electroplated into the pores, and it is
30 possible to make it very thick because the structure of AAO prevents breakage of the plated material.

However, in order to realize such a thick AAO layer on a substrate, an Al film having a thickness of several $10\text{ }\mu\text{m}$ has to be deposited on a substrate first, and it is difficult to deposit such a thick Al on a substrate.

5 Summary of the Invention

In order to address this, the present inventors once contemplated forming such a thick Al layer by Al foil bonding on the substrate. Firstly Al foil would be bonded on the substrate by the same techniques used in wafer bonding
10 methods. The Al foil would have a seed layer on the side of the Al foil facing the substrate. Then, AAO would be formed on the bonded Al, and then the pores filled with magnetic material by electroplating using the seed layer. However, this method would suffer from two disadvantages.

15 Firstly, it requires that the pores in the AAO are through-holes, which reach the seed layer for the electroplating of the magnetic material. In order to make through-holes, the pores have to grow and reach the bottom of Al foil, and once the pores reach the bottom, the anodization process must be stopped immediately. Otherwise the AAO structure will be broken by generation of the
20 gas and will not be suitable for the electroplating of the magnetic material any more. But it is difficult to tell when the pores reach the bottom.

Secondly, the thickness of the AAO depends on the thickness of the Al, which means that the thickness of the Al foil has to be controlled very precisely. In
25 order to make an AAO layer with a thickness of several $10\text{ }\mu\text{m}$ in this way, we have to bond Al foil with a thickness of several $10\text{ }\mu\text{m}$ onto the substrate, and such foils are too thin to handle easily.

For all of the above reasons, this method is not suitable for the production of
30 magnetic elements on a substrate.

In general terms the present invention proposes that one or more magnetic elements are formed on the surface of a substrate by (i) treating a first surface of an aluminium foil to form a treated region containing elongate pores, the pores extending in the thickness direction of the foil, (ii) fixing the aluminium foil to a substrate with the first surface of the foil facing the substrate, (iii) etching away at least a portion of the remaining metal material of the aluminium foil to expose the treated region, and (iv) filling the pores with magnetic material.

Thus, the volume of magnetic material which is deposited on the substrate is limited only by the length of the pores, and yet the magnetic material may be firmly fixed to the substrate if the treated region of the foil is firmly attached to the substrate. The treated aluminium foil may, for example, be adhered to the substrate, such as by a bonding polymer. Thus, the magnetic material is held firmly in place by the treated metal material, which in turn is held firmly to the substrate by the adhesive.

Furthermore, the foil does not initially have to be very thin, since in any case its unnecessary portions (i.e. the portion furthest from the first surface of the foil) are etched away. In other words, the thickness of the magnetic material can be controlled independently from the initial thickness of the aluminium foil. Thus, in certain embodiments of the invention, the foil is initially thicker than the magnetic layer which is to be produced (e.g. an initial foil thickness of at least 0.1mm, or even at least 0.2mm, such as 0.4mm, may be used to produce magnetic elements which are less than 0.1mm thick), and therefore the foil may be easier to handle. For the same reason, it is not so critical to control the process which forms the elongate pores, since it is not required that the pores are formed with a length exactly as thick as the initial thickness of the foil.

Preferably, the treatment process is an anodization process in which the treated region of the aluminium foil is converted to AAO including the elongate pores.

Prior to the step of filling the pores with magnetic material, there may be a step of forming openings in the pores, through which the magnetic material can be inserted. Thus this process may include removing at least part of the AAO which is furthestmost from the first surface of the foil. This portion of the AAO is called a barrier layer and may act as a layer, preventing entry of the magnetic material.

Optionally, there may be patterning step, in which one or more portions of the treated region of the foil, at different respective areas of the first surface, are etched away.

Preferably, the portions of the treated foil which are to be removed are not filled with magnetic material. For example, this may be achieved by forming a patterned mask over the exposed treated region; filling the treated region with magnetic material in areas which are not covered by the mask; depositing a protective layer; removing the mask and the part of the protective layer over the mask; and then removing the portions of the treated region which are not covered by the protective layer. Note that this process requires only a single patterning step.

The step of forming the patterned mask is preferably performed before the step of forming openings in the pores. For example, if the mask layer is formed by depositing a photoresist material, curing it by a photographic process, and removing uncured portions, the step of forming openings in the pores is preferably performed after the uncured portions of the photoresist are removed. This means that photoresist material does not enter the pores because the barrier layer blocks its entry. If the photoresist material goes into pores, it is difficult to remove completely later and its residue may degrade the magnetic properties of the completed device.

The step of filling the pores with magnetic material may be performed by an electroplating process, using a seed layer between the treated region of the aluminium foil and the substrate. This seed layer may be formed on the first

surface of the aluminium foil prior to the step of adhering the aluminium foil to the substrate.

As a final step, the substrate, having the magnetic elements on its surface, is used to form a MEMS device.

Thus, this invention allows us to provide a MEMS device including at least one magnetic element exhibiting strong magnetic properties.

10 Brief Description of the drawings

An embodiment of the invention will now be described for the sake of example only with reference to the following drawings, in which:

FIG. 1 is composed of Fig. 1(a) to 1(l) which are cross-sectional views illustrating the steps of a process which is an embodiment of the invention to form patterned magnetic elements on a substrate.

FIG. 2 is a schematic diagram of the anodization setup used in the process of Fig. 1.

20 Detailed description of the embodiments

Referring firstly to Fig. 1(a), the starting point of a method which is an embodiment of the invention is a laminar body 1 which is an aluminium foil. In our experiments, the thickness of the Al foil 1 is 0.4mm and the purity of Al is 99.999%. A layer 2 of AAO is grown in a central portion of the foil 1. The thickness of AAO layer 2 depends on the requirements of the application, but is preferably at least about $10\mu\text{m}$, and may be higher. It is typically not as thick as 0.1mm. The AAO layer 2 defines a number of pores 12, which extend longitudinally in the direction which is vertical in Fig. 1(a).

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Figure 2 shows the schematics of the anodization setup used to grow the layer 2 into the foil 1. The foil 1 is held in a support mechanism 10 extending across an opening in a bath 8 containing acidic solution 6. We performed a

trial in which 1.7wt% H_2SO_4 was used as the acidic solution 6. Only one side of the Al foil 1 touches the acidic solution 6. The acidic solution further contains a Pt wire 4. An electrochemical reaction is performed in which a DC voltage (we used 25V) was applied between the Al foil 1 as the anode, and the Pt wire 4 as the cathode. This produced the layer 2 of AAO, having a thickness controlled by the anodization time. The pore growth rate was found to be about $10\text{ }\mu\text{m/hr}$ under these conditions of the trial, so it took 2 hours for an AAO layer 2 of thickness about $20\text{ }\mu\text{m}$ to be produced. The applied voltage, the kind of acid and the concentration of acid can all be selected to obtain a desired pore size.

Once the AAO layer 2 has been produced (i.e. giving the structure shown in Fig. 1(a)), a thin Cu film 3 is deposited on the surface of the AAO layer 2, e.g. by sputtering. As explained below, this layer will subsequently be used as a seed layer in an electroplating process. Instead of Cu, another metal such as Au, Ti which can be used as a seed layer for electroplating, may be used.

After the metal deposition, the Al foil 1 including the AAO 2 and the metal layer 3, is bonded onto a Si substrate (wafer) 7 using a bonding polymer 5 (which has a thickness of about $1\text{ }\mu\text{m}$). The side of the Al foil 1 carrying the AAO layer 2 and the metal layer 3 faces the surface of the Si wafer 7. This is shown in Fig. 1(b). The bonding process is as follows. First, the bonding polymer 5 is spin-coated on the Si wafer 7. Then the Al foil 1 is laid onto the bonding polymer 5. Then a pressure of 2 bar and a temperature of 160°C were applied for 30 minutes.

Then, as shown in Figure 1(c), the Si wafer 7 on which Al foil 1 is bonded is soaked in 10 wt % CuCl_2 solution, and the residual Al above the AAO layer 2 is etched away. This etching process is continued until the AAO layer 2 is uncovered completely. Instead of CuCl_2 solution, this etching process may use any acid which can etch Al.

As shown in Figure 1(d), a photoresist layer 9 is then deposited over the AAO layer 2 and the remaining portions of the upper surface of the Al foil 1. The photoresist layer 9 is patterned. This may be done by depositing the photoresist by spin-coating, exposing it to UV light through a mask, and then removing portions of the photoresist which have not been cured by the UV light.

Note that the upper portion 112 of the AAO layer 2 (i.e. the portion furthest from the substrate 7), which was originally beneath the bottoms of the pores 12, still remains, so that at this stage the ends of the pores 12 which are furthest from the substrate 7 are closed. That is, the upper surface of the AAO acts as a barrier layer 112. This is valuable because it means that the photoresist material 9 cannot enter the pores 12. If the barrier layer 112 were not there, the photoresist 9 would enter the pores 12, and it would be very difficult to remove the photoresist 9 completely later. Its residues inside the pores 12 might then degrade the magnetic properties of the product of the method.

Subsequently, as shown in Figure 1(e), the barrier layer 112 of AAO at the upper ends of the pores 12 in the AAO 2 is selectively removed, in the areas not protected by the photoresist 9, by an etching process using 10wt% H_3PO_4 solution. This etching process may alternatively be done by a dry etching method, such as ion milling.

Then, as shown in Figure 1 (f), magnetic material 11 is electroplated into the pores 12, through their open ends. In this process, the Cu layer 3 acts as a seed layer.

As shown in Figure 1(g), an layer 13 of inert metal such as Ti, Au, etc. or oxide material such as SiO_x , AlO_x , etc. is deposited onto the surface of the AAO 2 and the photoresist 9. This layer 13 is placed there to protect the electroplated magnetic material 11, and the portions of the AAO layer 2 close to it, during subsequent process steps.

As shown in Figure 1(h), the photoresist 9 is etched away using acetone. This also removes the portions of the metal or metal oxide layer 13 which overlie the photoresist.

5 As shown in Figure 1(i), the portions of the AAO layer 2 which are not covered by the metal or metal oxide layer 13 are etched away completely. This is done using a solution which is 10wt% of H_3PO_4 .

10 As shown in Figure 1(j), the remaining parts of the Al layer 1 are etched away using a 10wt% solution of $CuCl_2$. This etching process may alternatively be performed using acid which can etch Al.

15 As shown in Figure 1(k), the now unnecessary Cu seed layer 3 is etched away using $FeCl_3$ solution. This etching process may alternatively be done by a dry etching method, such as ion milling.

20 As shown in Figure 1(l), the now unnecessary bonding polymer 5 is etched away using O_2 plasma. Finally, we obtain element 15 which are substantially patterned AAO, filled with magnetic materials, and securely joined to the Si wafer 7.

Note that by this method, we can control the AAO 2 thickness separately from the Al foil 1 thickness. Therefore, both the handling of Al foil 1 and the control of the anodization process are easy.

25 Although only a single embodiment of the invention has been described in detail, many variations are possible within the scope of the invention as defined by the claims. For example, the etching method, the type of etchants and the concentration of etchants, are not restricted to those which are
30 disclosed above.

Claims

1. A process for forming one or more magnetic elements on the surface of a substrate, comprising:
 - 5 (i) treating a first surface of an aluminium foil to form a treated region containing pores which are elongate in the thickness direction of the foil,
 - (ii) fixing the aluminium foil to a substrate with the first surface of the foil facing the substrate,
 - (iii) etching away at least a portion of the remaining metal material of
10 the aluminium foil to expose the treated region, and
 - (iv) filling the pores with magnetic material.
2. A process according to claim 1 in which the aluminium foil is fixed to the substrate by adhesion using bonding polymer.
- 15 3. A method according to claim 1 or claim 2 in which the foil is Aluminium and step (i) is an anodization process in which the treated region of the Aluminium foil is converted to AAO including the elongate pores.
- 20 4. A method according to claim 1, claim 2 or claim 3 further comprising a step, performed between steps (iii) and (iv), of forming openings in the pores, through which openings the magnetic material is inserted in step (iv).
5. A method according to any preceding claim in which, prior to step (ii), a
25 seed layer is deposited on the first surface of the aluminium foil, and step (iv) performed by an electroplating process using the seed layer.
6. A method according to any preceding claim further comprising removing one or more portions of the treated region of the foil, at different
30 respective areas of the first surface.
7. A method according to claim 6 in which the one or more portions of the treated regions are removed by:

- (a) between steps (iii) and (iv), forming a patterned mask over the exposed treated region;
- (b) in step (iv), filling the treated region with magnetic material in areas which are not covered by the mask;
- (c) depositing a protective layer;
- (d) removing the mask and the part of the protective layer over the mask;
- and
- (e) removing portions of the treated region which are not covered by the protective layer.

8. A method according to claim 7 in which the patterned mask layer is formed by:

- depositing a photoresist material,
- curing the photoresist material selectively by a photographic process,
- and
- removing uncured portions of the photoresist material.

9. A method according to claim 7 or 8 when dependent on claim 4, in which the step (a) of forming the patterned mask is performed before the step of forming openings in the pores.

10. A method of forming a MEMS device comprising:

- forming one or more magnetic elements on the surface of a substrate by a method according to any of claim 1 to 9; and
- using the substrate in the fabrication of a MEMS device.

11. A structure comprising:

- a substrate having a surface,
- one or more magnetic elements adhered to the surface of the substrate,
- the magnetic elements comprising an Al matrix including elongate pores

extending transverse to the surface of the substrate and filled with magnetic material, and

a layer of inert metal deposited on a surface of the matrix which faces away from the substrate to protect the magnetic elements.

12. A structure according to claim 11 in which the pores have a length of at least about 10 μm .

13. A MEMS device comprising at least one element having a structure according to claim 11 or 12.