Fabrication of micromirror-based magnetic sensor

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Abstract. A novel SOI wafer process was established for fabrication of micromirror-based magnetic sensor. The process offers stress-free micromechanical structures without the stiction problem encountered in conventional surface micromachining process. By using two-step etching, the thickness of suspension beams of a micromirror can be independently defined. The new process also made it possible to electro plate a permalloy layer on one side of a micromirror and to maintain a mirror like reflection surface on the other side. The magnetically actuated micromirrors have been characterised using a simple laser beam reflection and CCD camera recording system. Magnetic field detection sensitivity of about 1 degree of mirror deflection per $10^{-4}$ Tesla of field intensity has been achieved.

1. Introduction

Magnetic sensors have been widely used for non destructive evaluation (NDE) of engineering structures. By measuring eddy current induced magnetic field and its disturbance of the field caused by a hidden defect within a metallic engineering structure, the defect can be spotted. Current magnetic sensors for NDE applications include SQUID gradiometers, optically-pumped magnetometers, fluxgate or magnetoresistive magnetometers, search-coil magnetometers, Hall devices, etc [1-3]. Although these sensors are of relatively high sensitivity, they tend to be low-spatial resolution because these sensors are simply not small enough to resolve the details of magnetic field distribution. On the other hand, the magneto-optical imaging technique can have high spatial resolution, but suffers from low-sensing sensitivity and the instrumentation is expensive [4]. The advanced NDE application requires not only the detection of small defects, but also the shape and size of defects in an engineering structure. So far magnetic field measurement with high sensitivity, high spatial resolution and affordable cost remains as a challenging goal.
In this paper, a micromirror-based magnetic sensor has been developed for application in NDE of engineering structures. Unlike majority of current micromirrors which were fabricated by silicon surface micromachining process, the present magnetic micromirror structure is based on a novel silicon-on-insulator (SOI) wafer process. The process offers stress-free micromechanical structures without the stiction problem encountered in conventional surface micromachining process. By using two-step etching, the thickness of suspension beams of a micromirror can be independently defined. The new process also made it possible to electroplate a permalloy layer on one side of a micromirror and to maintain a mirror like reflection surface on the other side. Magnetic and micromechanical modelling were carried out to determine the geometry and configuration of micromirrors. Preliminary characterisation of the micromirrors was performed using a simple optical detection setup. The experiment has demonstrated that the magnetic micromirrors are able to detect weak magnetic fields, with sensitivity of 1 degree of deflection angle per $10^{-4}$ T of magnetic field intensity.

2. Fabrication process

The popular way of making micromirrors has been by surface micromachining [5]. It involves deposition of a polysilicon layer on top of a sacrificial layer. Subsequent removal of the sacrificial layer releases the mirror structure so that it can be freely movable under an external force. However, it is very difficult to deposit a stress-free polysilicon layer. Residual stress in the structure can effectively stiffen the micromirror and reduce its deflection sensitivity. The removal of the sacrificial layer without stiction problems is also tricky. A much simpler process has been developed for making the magnetic micromirrors in the present work. It is based on silicon-on-insulator (SOI) wafer processing. The SOI wafer offers the benefit of a stress-free top single crystal silicon layer on which the micromirrors are patterned. These mirrors can be released by etching removal of handle silicon from backside. The thicknesses of mirror plane and suspension beam are precisely defined by the top silicon layer. Fig.1 schematically illustrates the basic steps of SOI wafer process.

![Figure 1. Schematic of SOI wafer process steps](image)

The process starts with a 4” SOI wafer (a), purchased from Si-Mat GmbH. The SOI wafer has a 5µm thick top silicon layer (device layer) and 500µm base silicon (handle layer). They are separated by a 0.5µm thick oxide intermediate layer (insulator). Micromirrors are patterned by photolithography and deep reactive ion etching (DRIE) of the top device layer (b). Then another photolithography step is performed to pattern a thick photoresist layer (15µm thick), which defines the mirror plane area for
electroplating (c). At this stage, micromirrors have not been released yet and are very robust to handle for electroplating. Permalloy (Ni80Fe20) is deposited in the thick photoresist mould by electroplating using a mixture of NiSO$_4$+FeSO$_4$+NiCl$_2$ solution (d) [6]. After electroplating, the permalloy is magnetised in a strong magnetic field. Then the SOI wafer is etched from the back side by DRIE only in the areas where the micromirrors are located at the top (e). As the DRIE of silicon stops at the oxide layer, the backside silicon etching has no effect on the topside mirrors. Finally, a gentle reactive ion etching of the oxide insulator from the back side completely releases the micromirrors (f).

There is one problem when using SOI wafer for making the micromirrors. The top silicon layer has determined the thicknesses of both the mirror plane and the suspension beam. Previous computer modeling has indicated that a thinner beam can produce larger deflection for the same external force. In order to make the suspension beam thinner than the mirror plane, a two-step etching process has been developed. The first DRIE step partially etches the device layer. The second DRIE step continuously etches into the device layer including etching of suspension beam as well. While the surrounding areas of mirror plane have been etched through, the thickness of suspension beam is also reduced because of the second etch. In fact, by controlling the etch depth of the first DRIE, the beam thickness can be precisely controlled.

Another issue is how to maintain a reflective surface of the micromirror. A previously reported magnetic micromirror was fabricated by magnetron sputter coating of a 0.5µm permalloy film onto polished silicon substrate, which was able to maintain a good mirror surface for optical reflection [7]. However, sputter coating cannot provide a magnetic layer sufficiently thick to generate high magnetic force. Electroplated permalloy is known to have a rough surface and cannot serve as the mirror reflection surface. Fig.2(a) is the optical image of a mirror before electroplating of permalloy. Fig.2(b) is the SEM image of a mirror after electroplating of permalloy. Fortunately, the SOI wafer process illustrated in Fig.5 is able to provide the top surface for electroplating of permalloy and the backside surface for mirror reflection of a laser beam. After etching through from the backside of SOI wafer to release the mirror, the backside of the mirror plane is of polished surface quality and can serve very well as the mirror reflection surface. Fig. 2(c) is a photo of a die from the 4” SOI wafer, which has different structures for experimental characterization of the micromirrors.

Figure 2. Micromirror surface before (a) and after (b) electroplating of permalloy, (c) a die with various geometries of micromirrors from the 4” SOI wafer

3. Characterisation of magnetic micromirror
In order to characterise the magnetic micromirrors, a simple optical measurement system was set up, as shown in Fig.3. Fig.4 illustrates the measuring principle. A permanent magnet shown in Fig.3 was moved horizontally towards the vicinity of the micromirror sample. The closer the magnet to the sample, the stronger the magnetic field exerted on the mirrors. The magnitude of magnetic field was quantitatively measured by a Hall sensor (SS495 from Honeywell) placed directly under the
micromirror sample. The Hall sensor has the accuracy of signal output at ±3%. A laser source illuminated the mirror sample and reflected light spots on a screen were recorded by a CCD camera. The laser illuminating area is a 500µm x 50µm stripe. Several light spots may be recorded from the reflection of a micromirror array. Each measurement was repeated twice. The sample was measured once, then rotated 90° and measured again, corresponding to measurements in X and Y direction along the micromirror array. The displacements of light spots, recorded by the CCD camera, were analysed as pixel count from the captured images, therefore, is in arbitrary length scale. From the distance between micromirror plane and recording plane, as illustrated in Fig.4, the displacement can be converted into the deflection angle of micromirrors. The CCD camera has effective pixel size of 7.4µm, which enables the conversion accuracy up to 2.5x10^4 of degree.

Micromirrors of different sizes and beam lengths were measured. Fig.5 shows the light spots captured by CCD camera from reflection of micromirrors, showing multiple spots reflected from an array of micromirrors. The displacement of light spot due to increase of magnetic field was recorded and processed. Generally, larger size of mirror plane and longer suspension beam produce greater displacement. A typical light spot displacement vs magnetic field is plotted in Fig.6.
The dynamic characteristics of the micromirrors have been analysed both analytically and numerically. The resonant frequency of the aforementioned micromirrors is in the order of kHz or less because of the thin slender beams which suspend the mirror. It is apparent that the micromirrors cannot be both of high sensitivity of magnetic field detection and of high frequency dynamic characteristics. Therefore, the application of these micromirrors in low frequency NDE is preferred. Increasing the size of the micromirror and decreasing the spring constant of the mirror suspension will certainly increase the sensitivity of the sensor. However, this will reduce the resonant frequency of the micromirror, thus resulting in an increased noise level and degraded signal to noise ratio due to external vibration. More optimal design and experimental tests will be investigated in the future.

4. Conclusions
Micromirror-based magnetic sensors have been fabricated using a novel SOI wafer process. The process offers stress-free micromechanical structures in silicon. The stiction problem encountered in conventional surface micromachining process has been avoided. By using two-step etching, the thickness of suspension beams of a micromirror can be independently defined. The new process also made it possible to electroplate permalloy layer on one side of a micromirror and to maintain a mirror like reflection surface on the other side. The micromirrors have been characterised using a simple laser beam reflection and CCD camera recording system. Magnetic field detection sensitivity of about 1 degree of mirror deflection per $10^{-4}$ Tesla of field intensity has been achieved.

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