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A METHOD OF MAGNETIC FIELD MEASUREMENT IN A SCANNING ELECTRON MICROSCOPE USING A MICROCANTILEVER MAGNETOMETER

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Abstract

Scanning electron microscopy (SEM) is a perfect technique for micro-/nano-object imaging [1] and movement measurement [2, 3] both in high and environmental vacuum conditions and at various temperatures ranging from elevated to low temperatures. In our view, the magnetic field expanding from the pole-piece makes it possible to characterize the behaviour of electromagnetic *micro- and nano-electromechanical systems* (MEMS/NEMS) in which the deflection of the movable part is controlled by the electromagnetic force. What must be determined, however, is the magnetic field expanding from the e-beam column, which is a function of many factors, like *working distance* (WD), magnification and position of the device in relation to the e-beam column. There are only a few experimental methods for determination of the magnetic field in a scanning electron microscope. In this paper we present a method of the magnetic field determination under the scanning electron column by application of a silicon cantilever magnetometer. The micro-cantilever magnetometer is a silicon micro-fabricated MEMS electromagnetic device integrating a current loop of lithographically defined dimensions. Its stiffness can be calibrated with a precision of 5% by the method described by Majstrzyk *et al.* [4]. The deflection of the magnetometer cantilever is measured with a scanning electron microscope and thus, through knowing the bias current, it is possible to determine the magnetic field generated by the e-beam column in a defined position and at a defined magnification.

Keywords: scanning electron microscope, magnetometry, microcantilever.

1. Introduction

The progress in micro- and nano-fabrication is closely correlated with the development and progress in micro- and nano-characterization. *Scanning electron microscopy* (SEM) is a perfect technique for micro-/nano-object imaging [1, 5] and movement measurements [2, 3] both in high or environmental vacuum conditions and at various temperatures ranging from elevated to low temperatures [6, 7]. In SEM technology the focused electron beam (e-beam) is used to probe a specimen and the reflected and/or scattered electrons or ions are analysed with the use of different types of detectors.

Since the analysed particles are not electrically neutral, an electromagnetic field is used for their control. In a so called immersion optics the magnetic field of a final snorkel objective lens is used to increase the electron detection efficiency and image resolution (throughout steering the first order of *secondary electrons* (SE)) [8]. This single-pole detector produces a strong magnetic field that expands from the pole-piece and embraces the specimen, which for examinations of various objects cannot be neglected. On the one hand this magnetic field could be the source of distortions, which are not trivial to eliminate, both from the viewpoint of hardware and software solutions [9], but on the other hand – it can be useful in the analysis of magnetic materials or devices. In this case the magnetic field can be used to test the properties of the structures deposited in a so-called *focused electron beam induced deposition* (FEBID) technology [10, 11]. The magnetic field generated by the e-beam column can also be applied to mount a magnetic sample with the highest precision, which enables its further application in the high-resolution magnetometry [7–9].

In our view, the magnetic field expanding from the pole-piece makes it possible to characterize the behaviour of electromagnetic *micro-electromechanical systems* (MEMS) in which the deflection of the movable part is controlled by the electromagnetic force [10]. In this case, since a scanning electron microscope is used as a vibrometer of 10 nm resolution [1, 2] and by controlling the bias current flowing through a current loop it is possible to exert the electromagnetic force and observe the mechanical response of the MEMS device. In this way a scanning electron microscope becomes not only the perfect tool for the advanced material science examinations, but also serves as a MEMS characterization setup, which is very versatile when combined with the optoelectronics, nano-manipulator and fibre technology and electrical characterization techniques. What must be determined, however, is the magnetic field expanding from the e-beam column, which is a function of many factors, like *working distance* (WD), magnification and position of the device in relation to the e-beam column. There are only a few experimental methods for determination of the magnetic field in a scanning electron microscope. The most precise one is based on the technology presented in [9]. In the conditions of a constant field, the beam displacement is measured. Two images of a characteristic specimen's element are registered: with and without the presence of the magnetic field. The difference between the positions of the element on the images is equal to the electron beam displacement.

There is a variety of magnetometers that are available and described in the literature, measuring the magnetic field in a range from 10^{-12} to 10^{14} T. They can be classified according to different criteria, most commonly to the physical effects involved in the examinations or a detection technology, like: SQUID, fibre optic or optically pumped magnetometers, search-coil, magneto-resistors, magneto-diodes and Hall-effect sensors [13]. Unfortunately, their sophisticated constructions are often too complex to use for the inside-chamber magnetic field measurement. For this reason, the choice should be limited to the Lorenz force and cantilever magnetometers. Despite the variety of constructions, most of the cantilever magnetometers are presented as sensitive tools for the study of single particles and thin magnetic layers, especially at high magnetic fields and over a wide

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temperature range [14–16]. The other types are mainly focused on the torque magnetometry [17, 18] or gradient field examinations [19] and none of these tools would be appropriate for the inside-chamber measurements. On the other hand, there is a whole group of modern Lorentz force magnetometers, with complex shapes and designs [20–22], and that does not make their constructions appropriate for the use in such a difficult and demanding environment as the SEM chamber.

In this paper we present a method of determining the magnetic field under the scanning electron column by application of a silicon micro-cantilever magnetometer. The micro-cantilever magnetometer is a silicon micro-fabricated MEMS electromagnetic device integrating a current loop of lithographically defined dimensions. Its stiffness can be calibrated with a precision of 5% using the method described by Majstrzyk *et al*. [4]. The deflection of the micro-cantilever magnetometer is measured with a scanning electron microscope and thus, through knowing the bias current, it is possible to determine the magnetic field generated by the e-beam column in a defined position and at a defined magnification.

2. Experimental setup

In our experiments we used an SEM and a *focused ion beam* (FIB) HELIOS NanoLab 600i SEM/FIB system which can be integrated with a set of 3 nano-manipulators (Kleindiek) and an electrical characterization instrumentation as the setup for MEMS characterization. The scanning electron microscope enables to image the surface details with a resolution of 5 nm. The FIB column, operating with a beam of gallium ions can be used to mill the MEMS device modifying its properties. The immersion lens technology combined with in-lens detectors can be used to improve the imaging resolution. In this technology a specimen is placed in a strong magnetic field generated by the column pole-piece. As mentioned before, the magnetic field coming out of the lens can induce an electromagnetic force needed to operate the electromagnetic MEMS. How the magnetic field is distributed in the vacuum chamber depends on many aspects. Starting from the microscope component chamber setup there are a few possible solutions [23], most commonly: an asymmetric pinhole lens, a symmetric immersion lens or an asymmetric snorkel lens (like in FEI Helios NanoLab 600i, a scheme in Fig. 1). The field distribution is also determined by the *working distance* (WD), *magnification* (M) and the specimen position. It must be noticed however, that the microscope control system made it possible to repeatedly define all these settings with a much precision.

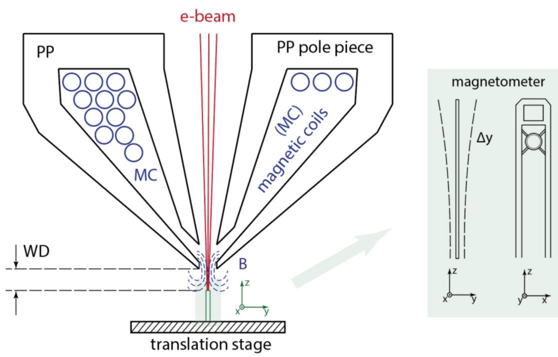

Fig. 1. A schematic of the immersion lens and the magnetic field area inside the SEM/FIB vacuum chamber (not in scale).

Prior to the magnetic field measurement, the electromagnetic cantilever must be calibrated. For that purpose a setup consisting of a reference magnetic field source, a precise current source biasing the cantilever loop and a high-resolution interferometer was used. In our experiments we applied a cylindrical Halbach array as the reference source of a uniform magnetic field (Fig. 2a). The value of the magnetic flux density inside was measured in the Central Office of Measures (Warsaw) and was equal to 317 mT with a measurement uncertainty of 1%. The deflection of the micro-cantilever magnetometer was measured by an SIOS SP-S 120 precise laser vibrometer, enabling traceable deflection measurements with a resolution of 0.1 nm in a bandwidth of 2 MHz. Its stiffness can be determined on the basis of the structure deflection [4]. In our experiments we measured the bias current with a Keithley 2000 multi-meter making it possible to determine the current flowing through the current loop with an expanded uncertainty of 10 μA.

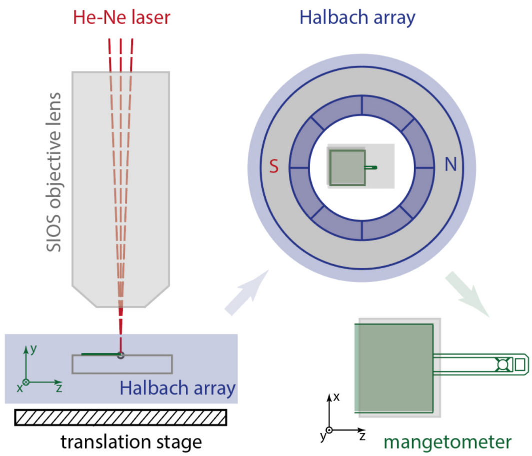

Fig. 2. A precise setup for the micro-cantilever magnetometer parametrization calibration: Halbach array under SIOS vibrometer for the deflection measurement.

3. Micro-cantilever magnetometer – tool parameterisation

3.1. Micro-cantilever as measurement tool

The micro-cantilever magnetometer used for determination of the magnetic field under the microscope column was fabricated in the *silicon on insulator* (SOI) technology [23]. The thickness of every single structure is then precisely defined and equal to 1.5 microns. As a result, the micro-cantilever exhibits low stiffness in a range of tens of millinewtons per metre. The structure legs are conductive due to a high level of boron doping ($\sim 10^{20}$ cm^{-3}) and the current loop resistance is of 1.5 kΩ. The current loop width is 100 microns within the active part of Lorentz line equal to 75 microns [4].

What is important, the manufacturing process based on the SOI and boron-doped silicon technologies ensures a high repeatability of the mechanical and electrical structure parameters which, combined with a high accuracy of the stiffness determination makes the electromagnetic cantilever a perfect measurement tool. The electromagnetic structures integrate two micro-mirrors, which can be used for the purpose of optical detection (here used for the optical calibration of the mechanical parameters, presented in Subsection 3.2), Fig. 3. They form two paths, where

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the bias current can flow and actuate the cantilever movement. For the uniform magnetic field distribution (like in the Halbach array) or quasi-uniform over a 125-micron distance (like in the SEM chamber), it can be assumed that the excitation is averaged.

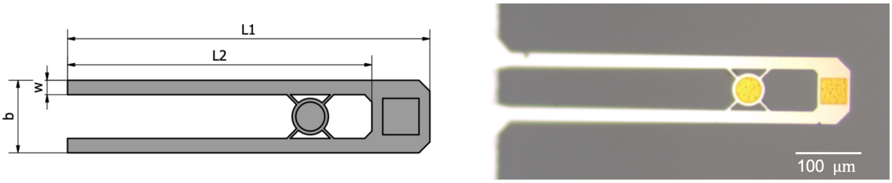

Fig. 3. A micro-cantilever magnetometer used for determination of the magnetic field under the e-beam column: a schematic (left) and a real view (right); dimensions: $L1$ = 515 µm; $L2$ = 465 µm; b = 100 µm; w = 20 µm.

The role of double-mirror construction is to enable the simultaneous actuation and detection with the use of two fibre optics glued together. Using the fibre optic interferometry instead, would highly increase the deflection measurement resolution (from 10 nm up to 100 fm). Having an additional mirror for the purpose of actuation makes it possible to isolate it from the rest of the structure. Under the upper mirror (detection one) there is also a Lorentz loop and – considering the Joule heating during electromagnetic actuation, a lower resistance of the loop is much better. Thus, having only one mirror, the stable thermal conditions would be maintained.

So that, the thermal isolation formed by a mirror suspension prevents the structure from the parasitic thermomechanical effects, which can occur when a radiation of higher energy is directed to it.

The micro-cantilever magnetometer parametrization includes determination of all the structure parameters. The examined amplitude of vibrations was recorded when the beam was actuated by a known electromagnetic force. Two sets of resonant curves were measured. The first one was measured when the upper-mirror deflection was observed. In this case a structure stiffness of k = 67.72 mN/m and a quality factor Q equal to 22 were determined.

The second one was measured to describe the beam's bending at the lower mirror (Fig. 4a), so that the upper-to-lower mirror deflection coefficient could be calculated. For the structure in question it is equal to 1.53.

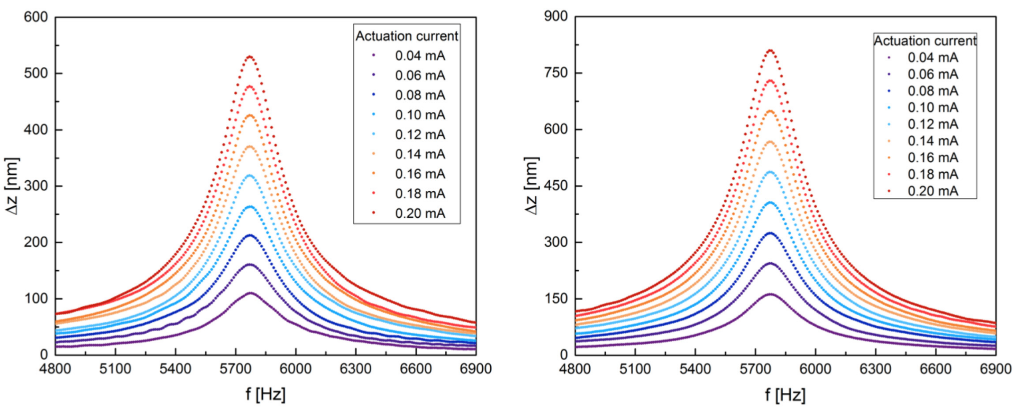

Fig. 4. MetMolMEMS resonant vibration amplitude: the lower mirror read-out (left), detection of the upper mirror read-out; measurement done with the SIOS vibrometer (right).

Since the structure of micro-cantilever magnetometer is U-shaped with thickness of 1.5 μm, and very low stiffness Q-factor values for non-vacuum and vacuum experiments are substantially different. These make them perfect structures for parametrisation in the air. However, the frequency sweep in the vacuum conditions would be too demanding from the data processing point of view (the frequency peak is too narrow). Thus, in the vacuum chamber we used SIOS vibrometry again, however with a different method.

A ring-down method has been used for measurement of the Q-factor in the chamber. The results are shown in Fig. 5.

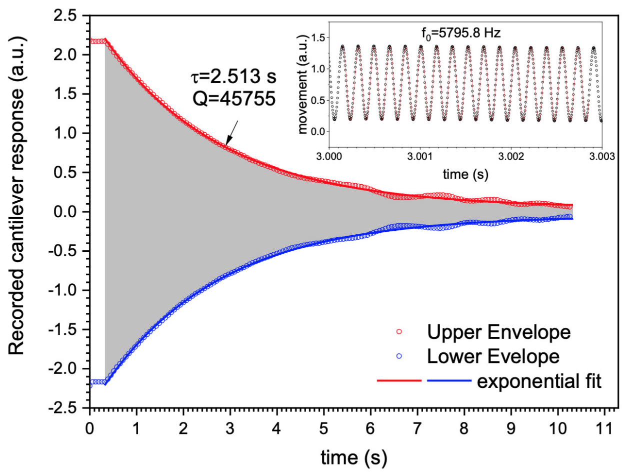

Fig. 5. The ring-down technique for quality factor evaluation: the upper and lower envelopes of the micro-cantilever response fitted with the exponential decay function (main plot) and the resonance frequency measurement by sine fitting to a section of the response (inset).

The upper and lower envelopes of the response were calculated and fitted with the exponential decay function resulting in $\tau = 2.513$ s. The resonance frequency $f_0 = 5795.8$ Hz was evaluated basing on the sine fit to a short section of the measured data (inset in Fig. 4) [25]. The data obtained enabled to calculate the quality factor value $Q = 45755$.

3.2. Inside-chamber SEM magnetic field measurement

The parametrized micro-cantilever magnetometer was mounted vertically under the electron column (see Fig. 2 and Fig. 6a). The images were recorded with the use of an Everhart-Thornley detector (working in the standard mode), ensuring a bigger depth of focus when larger images were recorded. In the next step the immersion mode was turned on, so that the micro-cantilever magnetometer was immersed in the magnetic field exerted by the microscope lenses. The micro-cantilever magnetometer was actuated to the resonance vibrations ($f_0 = 5795.8$ Hz) of the amplitude $\Delta y = 6.47$ μm (Fig. 6b) with the current of $I = 9.8$ μA flowing through the current loop, exciting the electromagnetic force. Therefore, the force of $F = 9.74$ pN acting on the micro-cantilever was calculated basing on the formula $F = \mathrm{k}x$, taking into account the structure's quality factor and stiffness: $Q = 45755$, $\mathrm{k} = 67.72$ mN/m, $F = \dfrac{\mathrm{k}\Delta y}{Q}$. Finally, the forces, one resulting from the mechanics and the second from the definition of the electromagnetic, were

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compared, so that the magnetic flux density B (in one particular point where the micro-cantilever magnetometer was placed) was calculated: $B_{\mathrm{SEM}} = \dfrac{F}{IL} = 13.25$ mT (where L is the effective length of the current loop equal to 75 µm (as the one simulated previously in [4]).

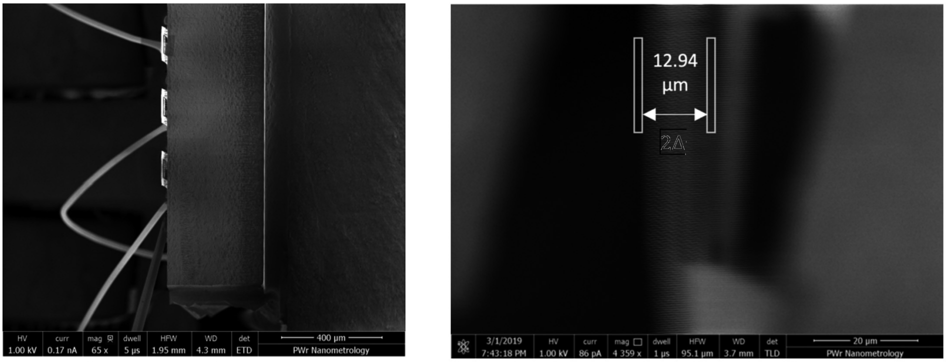

Fig. 6. The micro-cantilever magnetometer in FIB/SEM chamber: a top view from the adjustment process (left), SEM vibrometry – the measured displacement (righ).

4. Summary

In this paper we presented the application of a micro-cantilever magnetometer to measurements of the magnetic field generated by the e-column of a scanning electron microscope. The micro-cantilever is an electromagnetic MEMS device, whose sensing parameters were precisely determined using previously developed protocols. The measurement procedure is repeatable, as the position of the micro-cantilever magnetometer in the microscope chamber can be defined with a resolution of tens of nanometres. Moreover, an expanded uncertainty of the stiffness calibration of the micro-cantilever magnetometer is of 5%, which, combined with the accuracy and repeatability of the bias current measurement and setting, made the developed technology to be one of the highest interest. This correlates with the technology we propose, a so-called SEM-lab, in which a scanning electron microscope is used as a versatile microscopic station, enabling precise measurements of the MEMS and NEMS devices. The strength of the SEM-lab technology lies in the high imaging resolution guaranteed by the modern, state-of-the-art electron microscopes, vacuum conditions increasing the resolution of the MEMS/NEMS devices and the intrinsic magnetic field exerted by the microscope column. The possibilities of integrating the microscope with auxiliary instruments for optical and electrical device characterization increase the importance of the proposed solutions.

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