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Fabrication and characterization of micromechanical bridges with strain sensors deposited using focused electron beam induced technology

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ABSTRACT

In this paper we present a method of fabrication and characterization of strain sensors fabricated with a focused electron beam induced deposition (FEBID) technology from Pt precursor. The FEBID structures were used as deflections sensors and applied to read-out resonance frequency of micromechanical bridges. In our experiments we have investigated silicon nitride structures with an integrated metallization path on which the FEBID strain sensors were deposited. In order to modify mechanical properties of the microbridge we developed and applied a focused ion beam (FIB) milling technology which allowed to modify the distribution of mechanical stress and consequently increase the deflection detection sensitivity. An atomic force microscopy (AFM) technology was applied to both characterize the electrical properties of the deposited structures and characterize properties of the fabricated devices. In this way the gauge factor (GF) of the FEBID fabricated nanogranular resistors (NGRs) of 4.25 was determined for the static microbridge deflection.

1. Introduction

In recent years, many efforts have been devoted to study properties and potential applications of materials and structures fabricated from gaseous precursor compounds by means of a focused ion and electron beams [1,2]. When focused beam of ions or electrons are directed on the material surface secondary electrons (SEs), which are ripped out of the sample, react with the gaseous precursor leading to deposition of the material on the surface. This technology allows for miniaturization of manufactured objects, whose size is mostly limited by a diameter of the incident beam [3]. Focused electron beam induced deposition (FEBID) is a direct-write technology enabling nanostructure fabrication with nanometer resolution at a precisely defined location [1]. This is one of the most important strengths of the FEBID technology, which can be easily integrated with other microfabrication techniques enabling a fast device nanoprototyping [3]. Additionally, numerous gaseous precursor compounds based on metals like e.g. platinum, gold and cobalt are widely available making the described technology very flexible [1].

The FEBID nanostructures are often described as composites consisting of metal nanograins embedded in a non-conductive matrix, whereas the electron transport is defined as an inelastic tunneling process occurring among nanograins [3,4]. This phenomenon makes it possible to apply the FEBID structures as sensors of strain, which is induced by deflection of the device integrating FEBID nanogranular resistors (NGRs). The induced strain results in modulation of the distance between metal nanograins embedded in an amorphous matrix. As a result probability of electron tunneling between the nanograins is modulated, which can be observed as changes of the FEBID structure resistance. Since the tunneling phenomena are an quantum mechanical effect, it is believed that the deflection detection sensitivities should be very high. However, several measures must be undertaken in order to ensure stability and repeatability of the FEBID strain sensors. If an organometallic Pt precursor is used for fabrication the FEBID device, conductive platinum nanocrystallites will be immersed into carbon containing matrix. As a result the deposited material will gain high resistivity which makes high frequency (HF) measurements difficult [5,6]. Moreover, carbon can easily oxidize in ambient conditions, which strongly influences the carriers transport stability. Another important issue is process repeatability, since the electron beam parameters, precursor chemical composition and stability can differ from experiment to experiment. In recent years many measures have been proposed to purify [7,8] and increase the stability [9] of the FEBID material. For this purpose postgrowth electron irradiation [10,11], localized laser heating [12] and heating in reactive atmosphere of oxygen [13] were proposed. Despite the aforementioned limitations, the FEBID strain sensors are an attractive alternative to the piezoresistors produced by implantation of dopants in silicon, as their size can be reduced beyond the photolithography limits [16]. Moreover, the FEBID strain sensors can be integrated at arbitrary location, so that the maximal deflection sensitivity is ensured. Even though FEBID structures have been already successfully applied among the others for flexible transparent electronics [14] and

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magnetic nanostructures [15], more progress in the FEBID structure characterization is required in order to introduce the FEBID technology into a broader range of applications, beyond the research laboratories [10].

The FEBID NGR structures were applied as sensors to detect the micromechanical cantilever deflection [17]. The basic structure was a silicon cantilever and it was statically characterized using a micromanipulator. Recently the FEBID sensors have been applied for read-out of the cantilever resonance frequency and used in topography measurement using an atomic force microscope [18].

In our paper we present a method of fabrication and characterization of the FEBID NGR strain sensors made by basing the Pt precursor. The fabricated structures were used as the deflection detector of a silicon nitride microbridge with a Pt thin film metallization. It should be noted, that in contrast to the cantilever structures the deflections of the doubly clamped microbridges are much smaller, so that detection of the structure motion is much more challenging [19]. In order to increase the detection sensitivity of microbridge deflection we applied an focused ion beam (FIB) milling. The FIB process was conducted in the way, in which its influence on the structure stiffness and the resonance frequency was minimized. Moreover a Kelvin probe force microscopy (KPFM) technology was applied to monitor the deposition process by verifying voltage distribution along the biased NGR structure. The deflection sensitivity of the NGR strain sensor was verified using contact mode (CM) atomic force microscope, which enabled to probe the sensitivity for deflections smaller than then 2 μm in a defined and a controllable way.

2. Experimental details

2.1. The basic structure

Silicon nitride microbridge structures with thickness, width and length of 500 nm, 30 μm and 280 μm, respectively have been investigated. Pt metallization path with thickness and width of 150 nm and 10 μm respectively and metallization gaps with length of 15 μm were patterned in photolithography process (see Fig. 1). The detailed fabrication process of the microbridges can be found elsewhere [20,21]. The gaps in the metallization path were fabricated at the location where it was expected that the stress during microbridge bending was the largest (see Fig. 1). Chip containing two microbridge structures was packaged by fixing it to the printed circuit board (PCB) chip carrier and making electrical connections by Au wire bonds.

The microbridges were inspected and processed using a DualBeam FIB/SEM system (Helios NanoLab™ 600i FEI). The FEBID structures were deposited with tri-methylmethylcyclopentadienyl Pt [MeCpPt(Me)3] precursor.

2.2. The NGR structure preparation

The NGR structure was prepared in the shape of rectangle with length and width of 20 μm and 2 μm respectively. Deposition process was carried out with electron beam voltage and beam current of 2 kV and 1.4 nA, respectively. Prepared in such way NGR structure demonstrated very high resistance, on the order of few Megaohms which made an electrical measurements difficult. Moreover, the raw NGR structures were sensitive to a resistance drift.

This problem was solved by post-fabrication e-beam exposure which allowed, depending on the dose, for the reduction of the NGR resistance up to 2 to 3 orders of magnitude and good stabilization of this value over time [11]. The resistivity of the deposited in such manner material was in the range of 10^{-4} to 10^{-3} $\Omega\cdot\mathrm{m}$. The resistance value was stable during the measurements and did not change significantly over time with cycling the deflection. Moreover, long-term stability was achieved as a resistance changes was rather small over few months.

In order to obtain better deflection sensitivity and concentrate the mechanical stress in the area of the NGR piezoresistors the FIB milling was conducted. With the aim of conducting the FIB process in the most efficient way Comsol Multiphysics simulations of the mechanical stress distribution along the deflected microbridge were performed (Fig. 2). The FIB milling was performed in the close area of the microbridge supporting points in order to decrease the microstructure width, exactly where the NGR strain sensor should be located. Shape of the milling structure was semicircular in order to ensure the homogenous stress distribution along the NGR. As the deflection sensors received the entire stress associated with the microbridge movement their response was the highest.

After the microbridge modification deposition of the two NGRs was conducted. Fig. 3(a) and (b) shows the result of the FIB microbridge milling and the microbridge with raw FEBID NGR strain sensors. The presented structures were prepared with electron beam energy of

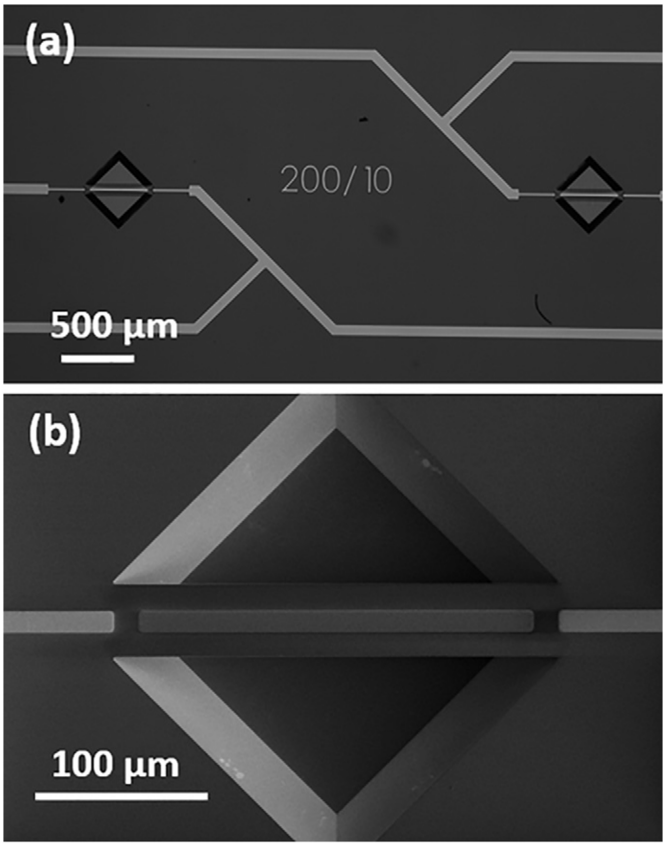

Fig. 1. SEM images: (a) chip containing two microbridges and (b) basic microbridge structure with gaps in the metallization path.

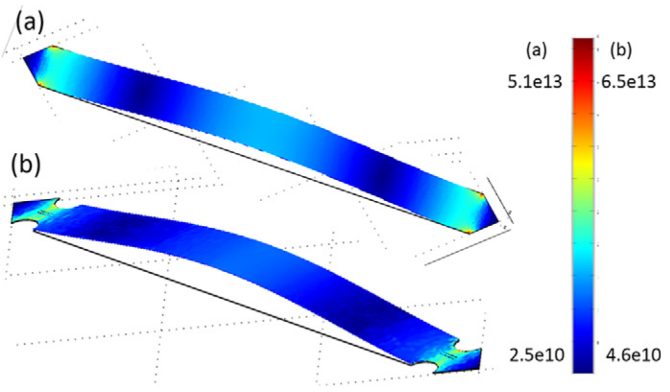

Fig. 2. FEM stress distribution simulations for: (a) basic microbridge and (b) after FIB modification.