Fabrication of Nanomechanical Resonators Using a Sequential Exposure of Opposite Tone Electron Beam Resists

CNF Project # STAFF
Principal Investigator: Lynn Rathbun
Users: Rob Ilic, Michael Guillorn, John Treichler, Keith Aubin

Affiliation: Cornell NanoScale Facility, Mechanical Engineering, Cornell University
Primary Funding: National Science Foundation
Contact: rathbun@cnf.cornell.edu, rob@cnf.cornell.edu, treichler@cnf.cornell.edu, kla22@cornell.edu

Abstract

We report a method for fabricating nanomechanical structures from a hydrogen silsesquioxane (HSQ)-based negative tone electron beam lithography (EBL) resist. This technique utilizes a sequential exposure of poly(methyl methacrylate) (PMMA) and HSQ to produce self supporting nanomechanical resonators. The first exposure is performed in the PMMA layer. This pattern is developed, HSQ is applied to the substrate over the PMMA, and a second exposure is performed registered to the first. The patterned PMMA film serves as a structural template for patterns written in the HSQ layer. HSQ exposed in patterned regions of the PMMA film becomes mechanically connected to the substrate. HSQ patterns connected to the substrate at multiple points can be released by removing the PMMA film using an oxygen plasma. Nanomechanical oscillators of different lengths were produced using this technique and the resonant frequency spectrum of these structures was examined using an optical excitation and detection technique. Resonant frequencies from 6 to 24 megahertz (MHz) with quality ($Q$) factors between 300 and 1500 were measured and found to be a strong function of oscillator length. The dynamic response of the system was modeled using the Euler-Bernoulli formalism and found to agree with the experimentally measured results.

Introduction

In the past decade, research on nanomechanical structures [1,2] has illuminated fundamental physical phenomena, enabled the fabrication of mass sensors with unprecedented sensitivity, and yielded a host of other unique structures. In 2001, Tanenbaum, et al., presented a simple process for forming nanomechanical resonators composed entirely of a hydrogen silsesquioxane (HSQ)-based negative tone electron beam lithography (EBL) resist [3]. These structures were created by performing a double exposure of the HSQ layer using two patterns exposed at different beam energies: 30 keV and 1 keV. The 1 keV electrons do not penetrate the entire HSQ film; they are confined to the near surface region. In contrast, 30 keV electrons completely penetrate the HSQ film and enter the substrate. Tanenbaum capitalized on this difference in beam penetration depths and used the 1 keV beam to expose patterns of nanoscale resonators. Portions of the pattern were selectively re-exposed using a 30 keV beam. During the HSQ develop process, the regions patterned at 30 keV remained rigidly fixed to the substrate while the patterns exposed at the lower energy were undercut by the developer releasing them.

Like Tanenbaum’s work, this process uses a double exposure. However, the first exposure is performed in a layer of poly(methyl methacrylate) (PMMA). Once this pattern is developed, HSQ is applied to the substrate over

---

Figure 1: Schematic of the fabrication flow.
the PMMA and a second exposure is performed registered to the first. The PMMA film acts as a structural template for patterns written in the HSQ layer. HSQ that is exposed in patterned regions of the PMMA film becomes “anchored” to the substrate forming a robust mechanical connection. HSQ patterns connecting multiple “anchor” points can be released by removing the PMMA creating self supporting structures.

Summary
An overview of the fabrication process is shown in Figure 1. 100 mm diameter Si (100) n-type wafers were used as the substrates for this work. An array of alignment mark structures was patterned onto these wafers using standard photolithography and dry etching techniques. These patterns consisted of an array of 10 µm wide squares etched 500 nm into the Si substrate. 500 nm of PMMA was spin-coated onto the wafers and baked at 170°C for 15 min (Figure 1-a). The substrates were exposed using a Leica VB6HR operated at 100 keV with a 5 nA beam current. The locations of the anchor points were exposed in the PMMA film using a dose of 1000 µC/cm². These patterns were developed in a solution of methyl isobutyl ketone (MIBK) and isopropyl alcohol, 1:3 (Figure 1-b). After inspecting the developed patterns, the substrates were coated in 4% HSQ in MIBK (Dow Corning, XR1541). This film has a nominal thickness of 120 nm when coated at 3000 rpm. The HSQ was applied to the PMMA using a static dispense process and allowed to puddle for 3 seconds before spinning. This puddle process facilitated coverage of the PMMA topography. Early experiments revealed that features in the PMMA layer less than or equal to 200 nm were almost completely planarized using this approach (Figure 1-c). After aligning to the predefined registration mark patterns, the locations of the anchor points were re-exposed. Patterns for structures that would ultimately become released or undercut were exposed such that they were connected to the anchor points. A dose of 2200 µC/cm² was used for these exposures. The HSQ film was developed using a commercially available 0.26 M aqueous solution of TMAH (AZ, 300 MIF). A 4 min immersion develop with no agitation followed by a deionized water rinse was used for this process (Figure 1-d). Following inspection of the developed patterns, the PMMA film was removed from the substrates using isotropic O₂ plasma etching (Figure 1-e). An oblique angle scanning electron microscope (SEM) image of a fully released bridge is shown in Figure 2-a. Optionally, completed structures could be coated with a layer of Al using electron beam evaporation (Figure 1-f). Beyond changing the optical properties of the released structures, this coating provides a way to produce electrical interconnects and probing pads that are connected to the released nanomechanical structures and isolated from the substrate. An example of a completed Al-coated HSQ nanomechanical structure fabricated using this process is shown in Figure 2-b. Figure 3 shows nanomechanical bug-like structures that illustrate the compressive stress state residing within the HSQ layer.

References