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High-Q optomechanical circuits made from polished nanocrystalline diamond thin films

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ABSTRACT

We demonstrate integrated optomechanical circuits with high mechanical quality factors prepared from nanocrystalline diamond thin films. Using chemomechanical polishing, the RMS surface roughness of as grown polycrystalline diamond films is reduced below 3 nm to allow for the fabrication of high-quality nanophotonic circuits. By integrating free-standing nanomechanical resonators into integrated optical devices, efficient read-out of the thermomechanical motion of diamond resonators is achieved with on-chip Mach–Zehnder interferometers. Mechanical quality factors up to 28,800 are measured for four-fold clamped optomechanical resonators coupled to the evanescent near-field of nanophotonic waveguides. Our platform holds promise for large-scale integration of optomechanical circuits for on-chip metrology and sensing applications.

1. Introduction

Over the past decade, there has been a surge in applications of radiation pressure forces for optical tweezers [1–3], optomechanical cooling [4,5] and optical transduction of mechanical motion [6,7]. Optomechanical cooling by cavity feedback [8–10] recently allowed for preparing a macroscopic object in its quantum ground state [11], while active feedback cooling [12,13] is actively pursued. Using optical methods for read-out of mechanical vibrations provides unconstrained bandwidth and higher sensitivity compared to an electrical measurement, having enabled the observation of radiation pressure shot noise [14] and squeezing of light below the vacuum noise level [15]. In addition to purely optically transduced systems, optoelectromechanical systems using piezoelectric [16] and electrostatic [17–19] actuation combined with optical read-out are currently explored because of the benefit of stronger motion build-up.

A common requirement in optomechanical systems is the simultaneous realization of high optical measurement sensitivity and good performance of the mechanical resonator. In this respect materials that provide both good optical and mechanical properties are of special interest, making diamond a prime choice. Besides good optomechanical properties, diamond is highly interesting for fundamental research, due to the possibility of coupling to Nitrogen-Vacancy (NV) centers [20–23]. Because diamond is chemically inert and biocompatible, applications for sensing and detection of small compounds are on the horizon. Both research directions benefit from the large Young's modulus of 1100 GPa, which is one of the highest of all materials and allows for reaching high mechanical resonance frequencies. The high value of the Young's modulus of bulk diamond can be also achieved for thin films of polycrystalline diamond by carefully adjusting the deposition parameters [24]. Diamond mechanical resonators with high quality factors have since been successfully fabricated [25,26]. Recently we have shown that mechanical resonators made from unpolished polycrystalline diamond using a doubly clamped beam geometry can be integrated into photonic circuits [27]. Such circuits can be used for precision measurement of small displacements, forces and masses with the advantage of on-chip integration. However, the slot waveguide geometry used for such devices provides fabrication challenges when moving towards long mechanical resonators, for which high mechanical quality factors are expected.

Here, we report on the realization of extended diamond optomechanical devices. Using a resonator geometry suitable for the fabrication of long free-standing structures we obtain mechanical quality factors up to 28,800 at room temperature with high sensitivity. We fabricate four-fold clamped optomechanical resonators, so-called H-resonators [28], which are less susceptible to stiction forces and provide further flexibility for tailoring the mechanical resonance properties. By employing a chemomechanical polishing procedure, we reduce the as grown root mean square (RMS) surface roughness of polycrystalline diamond films below 3 nm RMS, measured on areas of 25 μm^2, enabling high-yield fabrication on a wafer-scale. Such optomechanical circuits are expected to provide lower propagation loss paired with higher mechanical quality factors for large-scale integration and advanced sensing applications.

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2. Diamond layer deposition and polishing

In the current work, optomechanical circuits were realized on diamond-on-insulator (DOI) wafers. Such templates consist of a diamond thin film of several hundred nanometer thickness deposited on a buried oxide buffer layer, supported by a silicon substrate in analogy to silicon-on-insulator (SOI) wafers. Due to the high refractive index of diamond (2.4 at 1550 nm wavelength) the diamond/SiO_2/silicon stack offers good refractive index contrast for efficient waveguiding of near infrared (near-IR) light. The resulting tight optical confinement can thus be used for realizing high-quality optical resonators and interferometers [29–34].

Nanocrystalline diamond films were deposited on atomically flat silicon wafers which are thermally oxidized to a thickness of 2 μm. To initiate the diamond growth, firstly, a diamond nanoparticle seed layer is deposited onto the SiO_2 film by ultrasonification for 30 min in a water based suspension of ultra-dispersed (0.1 wt.%) nano-diamond particles of typically 5–10 nm size [35]. Then the samples are rinsed with deionized water and methanol. After dry blowing, the wafer is transferred into an ellipsoidal 2.54 GHz microwave plasma reactor [36] where diamond films with a thickness between 800 and 900 nm are grown at 3.5 kW microwave power, using 1% CH_4 in 99% H_2, at a pressure of 55 mbar and a temperature of 850 °C. Substrate rotation is applied to avoid angular non-uniformities arising from the gas flow. Growth rates are in the range of 1–2 μm/h. After growth, the samples are cleaned in concentrated HNO_3:H_2SO_4 to remove surface contaminants.

As grown nanocrystalline diamond films with a thickness of 600 nm typically have a RMS roughness of about 15 nm with a typical grain size on the order of 100 nm while isolated peaks can have a height of up to several hundred nanometers. In order to facilitate fabrication of high resolution photonic structures with vertical sidewall profile, the diamond films are polished using slurry based chemical mechanical planarization (CMP). This approach is commonly employed in the IC fabrication industry for the polishing of dielectric and metal interconnects, where softer polyester based polishing pad is used with the aid of a colloidal silica at room temperature [37]. The technique does not require the use of expensive diamond grit, or cast iron scaifes. The CMP polishing was performed with a contact force of 120 N at a rotational frequency of 90 rpm and usage of 80 ml/min of polishing liquid containing silica particles. The polishing mechanism consists of the wet oxidation of the surfaces while the polishing fluid facilitates the attachment of silica particles to the diamond film. This is followed by shear removal of the particles due to forces from the polishing pad which is employed throughout. In our procedure, the experimental conditions closely follow the approach recently presented by Thomas et al. [38]. Using this CMP method, the thin film thickness variation of our diamond layers across the wafer surface can be polished without fear of film cracking.

After polishing, the average RMS roughness of the diamond layer is reduced from 15 nm down to 2.6 nm, on 25 μm^2 areas measured by a series of atomic force microscopy (AFM) scans. High resolution diamond nanophotonic circuits are fabricated using electron beam (e-beam) lithography on a JEOL 5300 50 kV system. We employ FoX-15 (HSQ 15%) negative tone resist with a thickness of 500 nm in order to provide sufficient protection against subsequent dry etching. The polished diamond surface now allows for fabrication of structures with smooth and straight sidewall profile. Fig. 1a and b shows scanning electron microscope (SEM) micrographs of developed HSQ resist after lithography, of the same device geometry on unpolished and polished diamond wafers, indicating the improved quality due to CMP. Comparing the patterns transferred from the resist halfway into the diamond layer by reactive ion etching (RIE) (Fig. 1c and d) shows clearly that the resulting diamond structures have smoother surfaces and sidewalls. As roughness leads to scattering loss, integrated photonic circuits made from polished diamond are expected to exhibit less propagation loss.

In order to fabricate optomechanical circuits, a three step electron beam (e-beam) lithography process is employed. The initial lithography step using positive tone PMMA 950k 8% e-beam resist is carried out to define alignment markers for the subsequent lithography steps. Electron beam evaporation of a chromium–gold–chromium tri-layer (5 nm–100 nm–5 nm) is then followed by lift-off in acetone resulting in metal alignment markers. The photonic and mechanical components are then patterned using HSQ. After development, the HSQ patterns are transferred into diamond by capacitively coupled RIE [39] with oxygen-argon plasma on an Oxford 80 Plasmalab system. In the final step, windows for releasing the mechanical resonators are patterned into PMMA. As PMMA does not sustain the diamond etch step in O_2/Ar chemistry, an additional chromium hard mask layer is used. After exposure, the PMMA pattern is transferred into the underlying chromium by

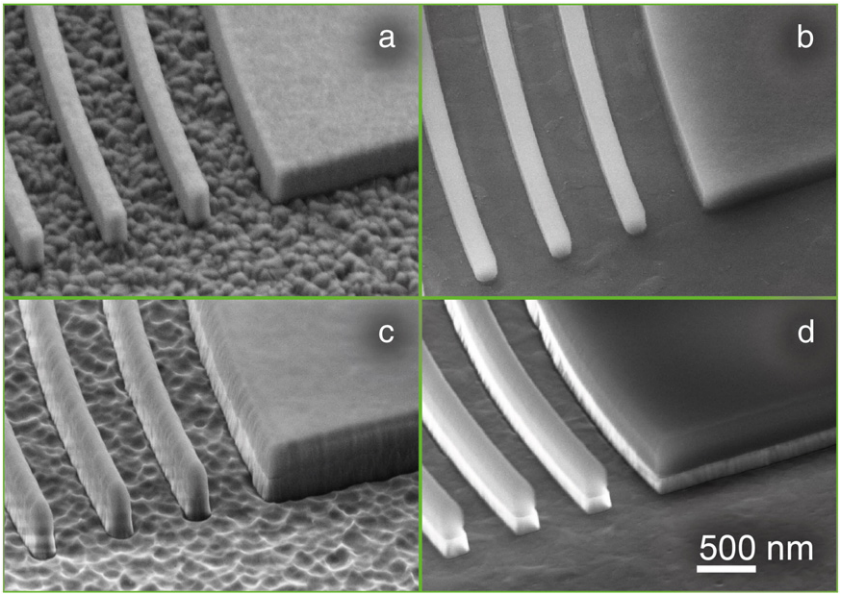

Fig. 1. SEM images of fabricated nanophotonic components on unpolished (a, c) and polished (b, d) diamond thin films. Shown are grating coupler devices after electron-beam lithography and developing (a, b) and after pattern transfer by reactive ion etching (c, d). The HSQ e-beam resist remains on top of the structures after etching.