Monocrystalline Al$_x$Ga$_{1-x}$As heterostructures for high-reflectivity high-Q micromechanical resonators in the megahertz regime

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We present high-performance megahertz micromechanical oscillators based on freestanding epitaxial Al$_x$Ga$_{1-x}$As distributed Bragg reflectors. Compared with dielectric reflectors, the low mechanical loss of the monocrystalline heterostructure gives rise to significant improvements in the achievable mechanical quality factor Q while simultaneously exhibiting near unity reflectivity. Experimental characterization yields an optical reflectivity exceeding 99.98% and mechanical quality factors up to 20 000 at 4 K. This materials system is not only an interesting candidate for optical coatings with ultralow thermal noise, but also provides a promising path towards quantum optical control of massive micromechanical mirrors [1].

High-quality Bragg mirrors with small mechanical dissipation have generated recent interest due to their versatile use in both fundamental and applied sciences. Specifically, mechanical dissipation in optical coatings is known to limit the performance of high-finesse cavity applications, in particular gravitational wave interferometry [2] and laser frequency stabilization for optical clocks [3], because of residual phase noise, also referred to as coating thermal noise [4]. On the other hand, microstructures of high mechanical and optical quality have become a leading candidate to achieve quantum optical control of mechanical systems. One specific goal in this emerging field of quantum mechanics is to combine the concepts of cavity quantum optics with radiation-pressure coupling to generate and detect quantum states of massive mechanical systems such as the quantum ground state [5] [6] [7] or even entangled quantum states [8] [9] [10]. The recent demonstrations of cavity-assisted laser-cooling of mechanical modes [11] [12] [13] [14] can be considered an important milestone in this direction.

Most of these schemes rely crucially on mechanical structures that combine both high optical reflectivity R and low mechanical dissipation, i.e. a high quality factor Q of the mechanical mode of interest. In addition, entering the quantum regime will require operation in the so-called sideband-limited regime [5] [6] [7], in which the cavity bandwidth of the optomechanical device is much smaller than the mechanical resonance frequency. While toroidal microcavities have recently shown such performance [15], high-quality distributed Bragg reflectors (DBRs) in combination with Fabry-Pérot cavities have not yet reached this regime [12] [13] [16] [17]. For example, whereas DBRs based on SiO$_2$/Ta$_2$O$_5$ can achieve R values in excess of 99.99% [18], the mechanical quality factor of free-standing DBRs is limited to below 3000 due to internal losses in the Ta$_2$O$_5$ layers [19]. It is interesting to note that the low Q-value obtained with these devices is consistent with the coating loss angles observed in the LIGO studies of gravitational wave detector coatings of the same material [2] [4]. On the other hand, the use of SiO$_2$/TiO$_2$-based DBRs has led to the demonstration of mechanical quality factors approaching 10 000 at room temperature [12]; there, however, optical absorption in TiO$_2$ at 1064 nm both limits the reflectivity and results in residual photothermal effects.

The concept outlined here seeks to improve upon these previous works by fabricating the oscillator directly from a single-crystal Bragg reflector. In particular, the use of compound semiconductor materials such as GaAs and related alloys allows for the generation of arbitrary stacks of high-index-contrast materials, resulting in significant improvements in the achievable mechanical quality factor. Given the alleviation of the dangling bonds typically found in amorphous dielectric materials such as Ta$_2$O$_5$ [4], the use of a single-crystal mirror stack should allow for a significant reduction in the intrinsic damping, while maintaining excellent reflectivity. Neglecting support loss or modal coupling, mechanical dissipation in a single-crystal is ultimately limited by intrinsic processes such as thermoelastic damping, as well as phonon-phonon and phonon-electron interactions. Our devices do not approach this fundamental value but are most likely limited by extrinsic effects including process-induced damage (e.g. ion bombardment and surface roughness created during microfabrication) as well as acoustic loss to the surrounding support structure. For example, if thermoelastic damping were the lower limit to the mechanical dissipation of the device, we would expect a room temperature Q value of approximately $4 \times 10^8$ for a GaAs resonator [20].

Although a somewhat uncommon materials system for the development of micromechanical structures, GaAs and its alloys exhibit a number of advantageous proper-
periods of alternating Al surface-normal photonic devices [24, 25, 26]. Previously demonstrated in micromechanically-tunable faces that are ideal for optomechanical structures, as chaining techniques to yield atomically flat optical surfaces may thus be processed using standard micromachining processes with a yield of 50% or more, assuming no absorption and atomically smooth interfaces, the maximum reflectivity (after stripping the protective Al₀.₉₂Ga₀.₈₈As layer and with air cladding top and bottom) is calculated to be 99.991% at 1064 nm for temperatures below 20 K and 99.976% at 300 K.

Fabrication of the resonators begins with the deposition of a SiNx hard mask via plasma enhanced chemical vapor deposition. Next, the device geometry is patterned lithographically using a standard positive photoresist. This pattern is then transferred into the SiNx via plasma etching with CF₄/O₂. Definition of the resonator geometry in the AlₓGa₁₋ₓAs epilayers relies on electron cyclotron resonance etching through the mirror stack using Cl₂/Ar, with masking provided by the resist/SiNx. To undercut the cantilevers, a buffered citric acid solution is utilized [28]. This selective wet etch allows for the removal of the binary GaAs, in this case the substrate, over the low-aluminum content ternary Al₀.₁₂Ga₀.₈₈As layers with excellent selectivity [26].

Room-temperature measurements were performed in a standard fiber interferometer [29] while temperature-dependent measurements were carried out using a cryogenic Fabry-Pérot cavity, in which the micromirror formed one of the cavity’s end mirrors (this setup is described in detail in Refs. 16 and 19). In the case of the fiber interferometer, the displacement power spectrum is directly obtained from the interferometer output, while in the case of the cryogenic Fabry-Pérot cavity, the noise spectrum of the Pound-Drever-Hall error signal of the cavity is used [19]. At room temperature we obtain mechanical quality factors of up to 7000 for singly clamped beams. We characterize the mechanical properties of the resonators optically via interferometric measurements of their displacement.

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In particular, we identified a doubly clamped resonator (150 \times 50 \mu m) with a fundamental frequency of 730 kHz and higher order resonance at 1.99 MHz. At low temperatures, i.e., operating inside a 4 K helium cryostat, we measure a quality factor of the high frequency mode of 20 000, compared to a Q value of 5000 at room temperature. We observe a similar increase of Q for the fundamental mode of the micromirror, namely from 2200 at 300 K to 12 000 at 4 K (see Fig. 2). As expected, the frequency of the resonator modes does not change significantly upon cooling. Cryogenic Q-values of a similar range (10 000 < Q < 30 000) have previously been reported for micromechanical resonators fabricated in this materials system \[31, 32\]; however, these examples exhibited insufficient reflectivity for our application. Although our devices are not optimized for force detection, we have estimated the thermal force noise of the resonator showing Qs of 5000 and 20 000 for frequencies of 1.997 MHz and 1.971 MHz at 300 K and 4 K, respectively.

In order to obtain the micromirror reflectivity we measure the finesse of the Fabry-Perot cavity (see above), which provides a measure of the overall intensity losses in the cavity. Knowing the independently determined reflectivity of the macroscopic input mirror (R_mic >= 99.91\%) one hence obtains a lower limit on the reflectivity R_mic of the micromirror. The observed finesse of greater than 5500 [Fig. 1(c)] yields a reflectivity R_mic >= 99.98\%, in good agreement with the expected values from theory. The reflectivity of our Al_{x}Ga_{1-x}As Bragg mirrors is comparable to that measured in high-finesse semiconductor microcavities \[35\].

We have demonstrated high-performance micromechanical megahertz oscillators based on free-standing monocrystalline Al_{x}Ga_{1-x}As DBRs. We observe optical reflectivities exceeding 99.98\% combined with mechanical quality factors up to 20 000 at 4 K for mechanical modes as high as 2 MHz. Given the alleviation of mechanical dissipation compared to previous high reflectivity dielectric stacks, this materials system is an interesting candidate for low-noise optical coatings as needed for example for gravitational-wave detection or for high-precision frequency stabilization of lasers as are used for optical frequency standards. The reported performance can readily achieve an optical finesse of up to 30 000, assuming a matched input coupler reflectivity of R_mic, allowing these micromechanical devices to operate in a regime of mechanical-sideband limited performance as is required to achieve ground state cavity-cooling of mechanical systems. As the microfabrication process does not deteriorate the reflectivity of the coating, higher finesse values should be achievable by further improving the initial DBR quality.

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